THE SIGNIFICANCE OF PRECISION ECHO SOUNDING IN THE DEEP OCEAN

by J. Crease, A. S. Laughton & J. C. Swallow
National Institute of Oceanography, Wormley, Surrey, England

Introduction

In the past ten years or so there has been a gradual increase in the demand for, and use of, precision echo sounders that are able to determine the ocean depth to one part in 3 000 (Luskin *et al*, 1954). The need for these arose initially from the requirement to examine the very small changes of depth on the abyssal plains. It has been recommended at various international meetings on bathymetry that all echo sounders used in the deep ocean should have this accuracy, but it has not always been accepted that such an accuracy is possible or meaningful (Gabler, 1961). It is our intention in this paper to clarify some of the principles underlying precision echo sounding, and to examine the accuracy available in the light of our present knowledge of the physical properties of sea water, and the possible variations with time in the velocity structure.

Minimum travel time charts

Basically the measurement made by an echo sounder is the time of travel of the leading edge of a pulse of sound from the surface of the sea to the sea bottom and back to the surface. In many places there may be several discrete echoes of the transmitted pulse from reflectors at different ranges within the beam angle of the transmitter-receiver system (side echoes), or the pulse may be lengthened by back-scattering from parts of the bottom adjacent to that from which the main pulse is reflected (reverberation). In nearly all cases there is a sharp beginning to the first reflected pulse, and the travel time has a value unique to the position from which the sounding is taken.

It is therefore possible to make a chart of the ocean bed in terms of this minimum travel time, and this will bear a close relationship to a chart of the bottom topography, especially in places where the slopes are small. The accuracy that can be achieved in making such a chart depends on, (*a*) the accuracy with which the time interval can be measured, and (*b*) the constancy of this interval when measured from the same place at different times.

The measurement of time intervals can be made with considerable accuracy using a tuning fork or crystal as a time standard. The resolution possible with a 10 Kc/s pulse in a depth of 3 000 fathoms is of the order of a few cycles at 10 Kc/s, say 0.5 m/sec in 7.5 sec, or 1 in 15 000.

The constancy of this interval with time, however, depends on variations in the mean vertical velocity of sound at the position, and will be affected by changes in the depth of boundaries between water masses, and in the changes in temperature and salinity of the masses themselves. The most important changes are those in the water temperatures near the surface where seasonal and other fluctuations can occur, the shifting of the boundaries of water masses due to changing current systems (such as the meanders of the Gulf Stream), the movement of isolated patches of water differing from the surrounding water, internal waves and changes of sea level. The analysis given below of the variability of mean vertical sound velocity, calculated from hydrographic stations, suggests that, apart from occasional exceptional conditions, the variations give rise to errors in depth of the order of 1 to 2 fathoms in 3 000. Further evidence supporting this conclusion is given by the consistency of depths obtained by precision echo sounding on the abyssal plains, where position errors have a negligible effect on the depth.

Thus it is justifiable for most parts of the ocean to construct charts of the minimum travel time. It is, however, convenient to change its dimensions from time to length, and a nominal velocity of sound of 800 fm/sec, 820 fm/sec or 1 500 m/sec is often used for this purpose. The scale marks of a precision echo sounder usually make this assumption, and charts are often constructed by direct readings from the sounding record in fathoms or metres at a nominal velocity, without any attempt at correction.

Apart from the simplicity of this process, charts of this sort have an obvious merit. If a second ship is traversing the area and uses a precision echo sounder with the same nominal sounding velocity, the depth indicated will agree with that on the chart to an accuracy of a few parts in 3 000 (assuming navigational errors to be negligible) without any estimate being made of the true sounding velocity. If the chart was originally constructed with a precise navigational control, then it can be used as an aid to navigation for the second ship, not only by looking at qualitative features such as the edge of an abyssal plain, but by using contours as position lines.

Charts of true bathymetry

To construct a chart of the true depths of the ocean it is first necessary to use the true mean vertical sound velocity. This can be calculated from the physical properties of sampled water. Tables are available (MATTHEWS, 1939; KUWAHARA, 1939) in which the oceans are divided into areas, to each of which an average sound velocity profile is assigned. These have been extensively used to construct true bathymetric charts and are satisfactory provided a high accuracy is not required. However, the relatively large changes in tabulated sound velocity in adjacent areas can give rise to spurious " steps " in the topography. The boundaries of the areas are poorly defined on account of the sparseness of the data, and the basic formulae from which the velocities have been calculated have required modification. Accuracy of correction would be improved by water sampling in the area being surveyed, and subsequent velocity calculation, but this is very often not possible when a ship is on passage. Difficulties arise when old soundings corrected with old tables of sound velocity are collected together with new soundings corrected with new tables. The discrepancies introduced here are not due to errors in obtaining the echo soundings but arise from subsequent variations in treatment.

The second sort of correction necessary to obtain the true bathymetry is much more complex and in general is not capable of being applied. On account of the finite beam width of the transducer-receiver system, the echo with minimum travel time may not come from a point vertically beneath the ship. An echo-sounding profile in rough country often shows overlapping hyperbolae representing echoes obtained from peaks within the beam, and one over a slope gives a spuriously shallow depth since the nearest point to the ship is upslope. The geometry of these effects has been extensively discussed in the literature (e.g., KRAUSE, 1962) and many correction techniques used. In general these assume all echoes to arise from a line under the ship's track. But to make a complete interpretation of the records in terms of the bathymetry it is necessary to consider echoes from the side, and unless one has a very complete survey or special sideways-pointing transducers no complete interpretation is possible.

For these reasons, most bathymetric charts make no attempt to correct for rough topography and the data presented is the depth obtained from the first arrival. It is apparent therefore that to construct a chart attempting to show true bathymetry, using true velocity and topographic correction, is very much more difficult and in many ways less satisfactory than plotting directly the minimum travel time, converted to depth using a nominal velocity. Only where there is intensive water sampling, or *in situ* velocity measurement, and where the spacing of sounding profiles is small compared with the depth, can a true bathymetric chart be produced.

Time-variation of mean vertical sound velocity

A series of hydrographic stations lasting from June 1959 to August 1960 were made by R.V. *Aries* and R.V. *Crawford*, of the Woods Hole Oceanographic Institution, in the western North Atlantic. The majority were in the area 30°-32° N, 67°-70° W and are labelled " western stations " in Fig. 1. They should be well representative of Area 14 in MATTHEWS' tables (1939). The " eastern stations " are a few that were made at 30° N to the south of Bermuda and some to the north-east at approximately 34°30′ N, 62° W. Both sets are in Area 13. All months of the year except January to March are represented.

Sound velocities were computed from the hydrographic data using WILSON's (1960) formula. The results for each station were integrated (using linear interpolation) from the surface to a given pressure and divided by the pressure to give the mean sound velocity down to that pressure. These mean velocities are plotted in Fig. 1 for pressures of 2 000 and 5 000 decibars, which also shows the number of stations per 0.2 m/sec interval.

It is clear from the 2 000 decibar data that the great majority of the " western station " velocities lie within 1 part of 1 500 of the mean, and that in general in Area 14 it is quite possible and reasonable, given a precision echo sounder, to quote depths to this precision.

The few Area 13 stations indicate a lower mean velocity, in agreement with MATTHEWS, although the present sounding velocities in both areas are of the order of 2 m/sec greater than those given by MATTHEWS. This difference in the absolute value of the sound velocity between various authors has been much discussed in the literature but need not concern us in considering variations with time. A negligible discrepancy, (less than 0.2 m/sec) is introduced by the use of the arithmetic mean velocity, instead of the harmonic mean tabulated by MATTHEWS, in the area discussed.

The constancy of velocity with time is likely to be upset on occasions. A specific example is shown in the figure where the data labelled " patch stations " has come from samples in Area 14 taken through an 80-mile diameter lens of water extending from the surface to 1 000 m. It was characterized by being more closely isothermal than its surroundings over a depth of several hundred metres. Here we have a considerable disturbance of the upper layers resulting in changes in the mean vertical velocity to the 2 000 decibars level of 3 m/sec, giving a possible error in depth determined by echo sounding of 1 part in 500, or 4 metres. Since the difference arises from changes in the near-surface water, the depth error remains approximately 4 metres at greater depths, though the effect on mean velocity decreases, and at 5 000 decibars is only 1 part in 1 200. (The number of hydrographic stations in the patch bears no relation to its size or its duration in the working area).

In this work the sounding velocities have been referred to levels of constant pressure (for convenience in other calculations). Admittedly, there may be small changes in depth, without change in pressure, due to changing water masses. In this respect sounding velocities referred to constant depth will show a slightly different distribution from those in Figure 1, but the differences will be negligible (see later discussion).

Other possible errors in determining the sound velocity may arise from errors in salinity, temperature and pressure. For the majority of stations water samples were available at equally spaced depths, not more than 200 m apart, from surface to bottom. Errors in measurement of salinity, both random and systematic, are estimated at less than 0.005 $^0/_{00}$ and may thus be discounted as a source of error in the sound velocity. Temperatures may be in error by ± 0.02° C, equivalent to a variation in sound velocity of ± 0.05 m/sec which we may also neglect. The pressure may be in error by 1 %, the resulting errors in sound velocity being $1.6 \times 10^{-4}\, p$ m/sec, where p is in decibars. The resultant error in sounding velocity, assuming a systematic error of this order, is thus $0.8 \times 10^{-4}\, p$ m/sec, equivalent to 0.16 m/sec at a depth of 2 000 m.

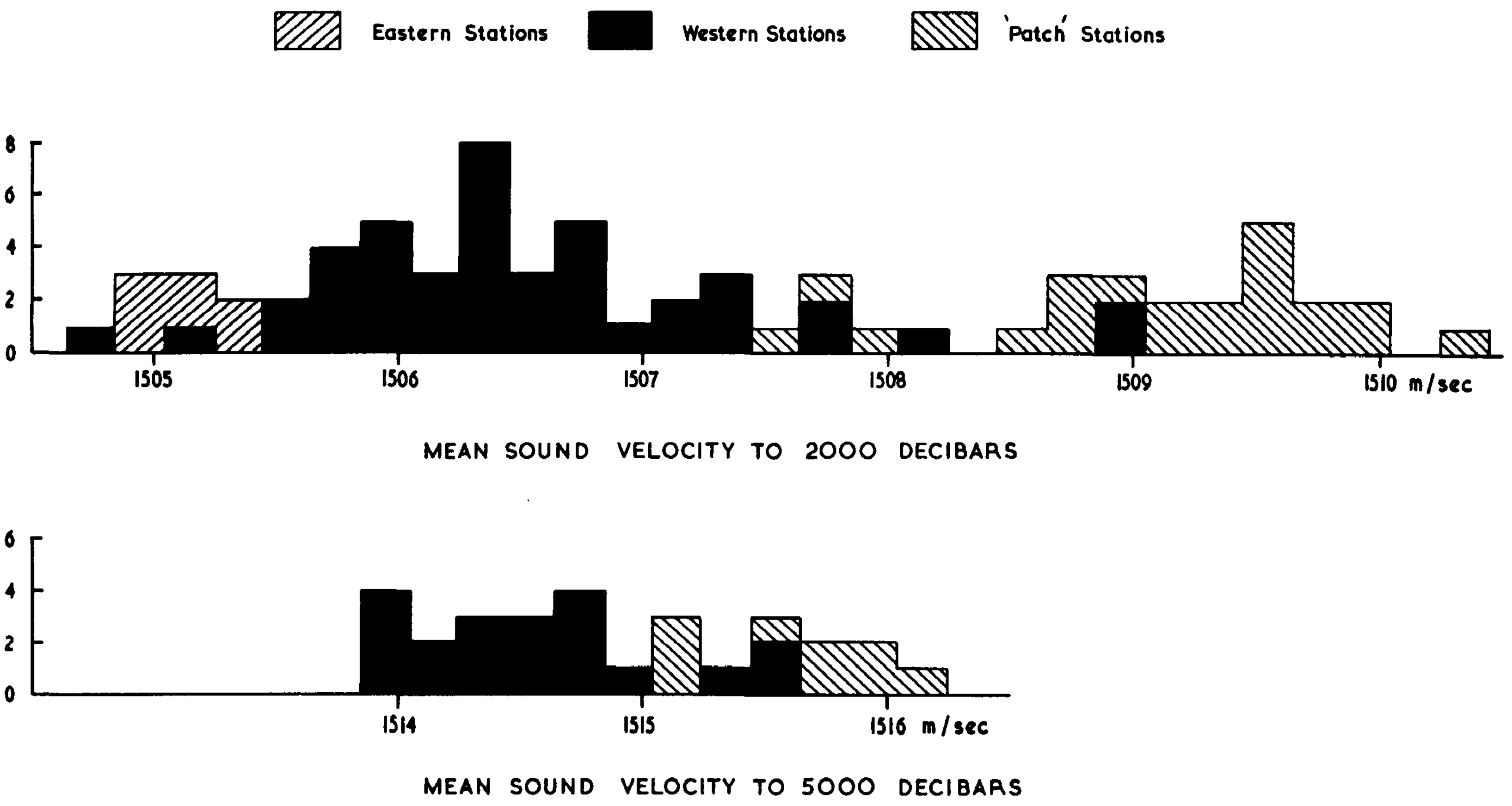

Fig. 1. — The mean sound velocity to 2 000 and 5 000 decibars calculated, using Wilson's equations, from a series of hydrographic stations made in the region of Bermuda during 1959-1960.

Some examples of variability of observed soundings to be expected from changing hydrographic conditions

The way in which sound velocity varies with temperature, salinity and pressure can be seen from the following table, derived from the observations of WILSON (1960) :

T° C	0	5	10	20	30
$\frac{\partial v}{\partial t}\left(\frac{\text{m/sec}}{°\text{C}}\right)$	4.5	4.1	3.6	2.7	2.1
$\frac{\partial v}{\partial S}\left(\frac{\text{m/sec}}{{}^0/_{00}}\right)$	1.4	1.3	1.3	1.2	1.1
$\frac{\partial v}{\partial p}\left(\frac{\text{m/sec}}{100\ \text{decibar}}\right)$	1.6	1.7	1.6	1.7	1.7

These derivatives are independent of salinity and pressure, to within 0.1 m/sec, over the range of variables usually encountered. More than 99 % of the water in the world ocean has salinities in the range 33 $^0/_{00}$ to 37 $^0/_{00}$, and temperature between 0° C and 28° C (MONTGOMERY, 1958). Clearly the temperature variations are much the most important in their effect on the sounding velocity.

The change in apparent sounding (δs) is given approximately by :

$$\delta s = -h \frac{\delta v}{v}$$

where $\frac{\delta v}{v}$ is the fractional change in mean sounding velocity through a depth range h. Some examples of variations of water characteristics likely to be encountered in the ocean, and their effects on the apparent sounding, are given below :

(a) *Seasonal changes near the surface*

In most parts of the oceans the seasonal variation of sea temperature is less than 5° C averaged over the upper 100 metres of water depth. If we take an extreme case of 10° C change averaged over 100 metres, the change in velocity is about 40 m/sec and the change in apparent sounding is less than 3 metres.

(b) *Vertical displacement of subsurface isotherms*

Time-variations of the depths of isotherms, of the order of several tens of metres, are often observed. In an extreme case reported by COOPER (1960) there was an average displacement of 75 m in the depths of all isotherms between 300 and 4 000 metres, in an interval of one month at a repeated station in the Bay of Biscay. If we imagine a more exaggerated vertical displacement of 100 m throughout the whole depth of a station, at which the temperature decreases from 15° C in the top 100 metres to 2° C at 4 000 metres, removing the top layer and inserting an extra 100 metres of bottom water below, there will be an increase of apparent sounding amounting to $\frac{3\,900 \times 1.7}{1\,500}$ or 4.4 metres due to decreased pressure on most of the water column, but this is partly compensated by the higher sounding velocity in the bottom water substituted for surface water. Possibly a greater change of sounding could be produced by inserting the extra layer of water at the depth of the velocity minimum (Sofar channel) and elevating the isotherms only in the upper layer. However, using typical values it seems unlikely that a displacement of 100 metres in all the isotherms above the velocity minimum would produce a change of sounding greater than 5 metres.

(c) *Patches of Mediterranean water in the Atlantic*

Variations of temperature and salinity are often found at depths around 1 200 metres, in the Eastern North Atlantic, due to the presence of greater or less amounts of water of Mediterranean origin, and these variations are naturally more pronounced in the neighbourhood of the Straits of Gibraltar. A hydrographic section made by the R.R.S. *Discovery II* along 9° W across the Gulf of Cadiz in November 1958 showed this patchiness clearly : a pair of stations, one in the middle of a patch and one just outside it, revealed a difference of sound velocity averaging 6 m/sec over the depth range 700-1 900 metres. This corresponds to a change in sounding of $\frac{1\,200 \times 6}{1\,500}$ = 4.8 metres.

(d) *Meandering of the Gulf Stream*

The presence of strong horizontal gradients of temperature and salinity across the Gulf Stream, and the possibility of its meandering by several tens of miles, imply that large variations in mean sounding velocity may occur near such a current. The order of magnitude of changes in apparent sounding has been estimated from a pair of stations (*Atlantis* 5297 and 5299) on either side of the stream, given in the Atlantic Ocean Atlas (FUGLISTER, 1960). The average difference in sound velocity is 21 m/sec, over the upper 1 000 metres, which corresponds to a difference in apparent sounding of 14 metres. This is, of course, recognised by MATTHEWS (1939) in the sharp changes of corrections in going from Area 9 to Area 13, but MATTHEWS takes no account of meanderings which will cause time-variations of the same order of magnitude at any one place in the neighbourhood.

These are some of the more extreme examples of changes in temperature and salinity that may be expected to occur in a vertical column of deep water. The effects of other possible variations may be examined by means of the table of derivatives. It seems improbable that, outside the region of the Gulf Stream and similar fast-flowing currents, the variation in apparent sounding due to changes of sounding velocity will amount to as much as 10 metres, and may often be less than 5 metres.

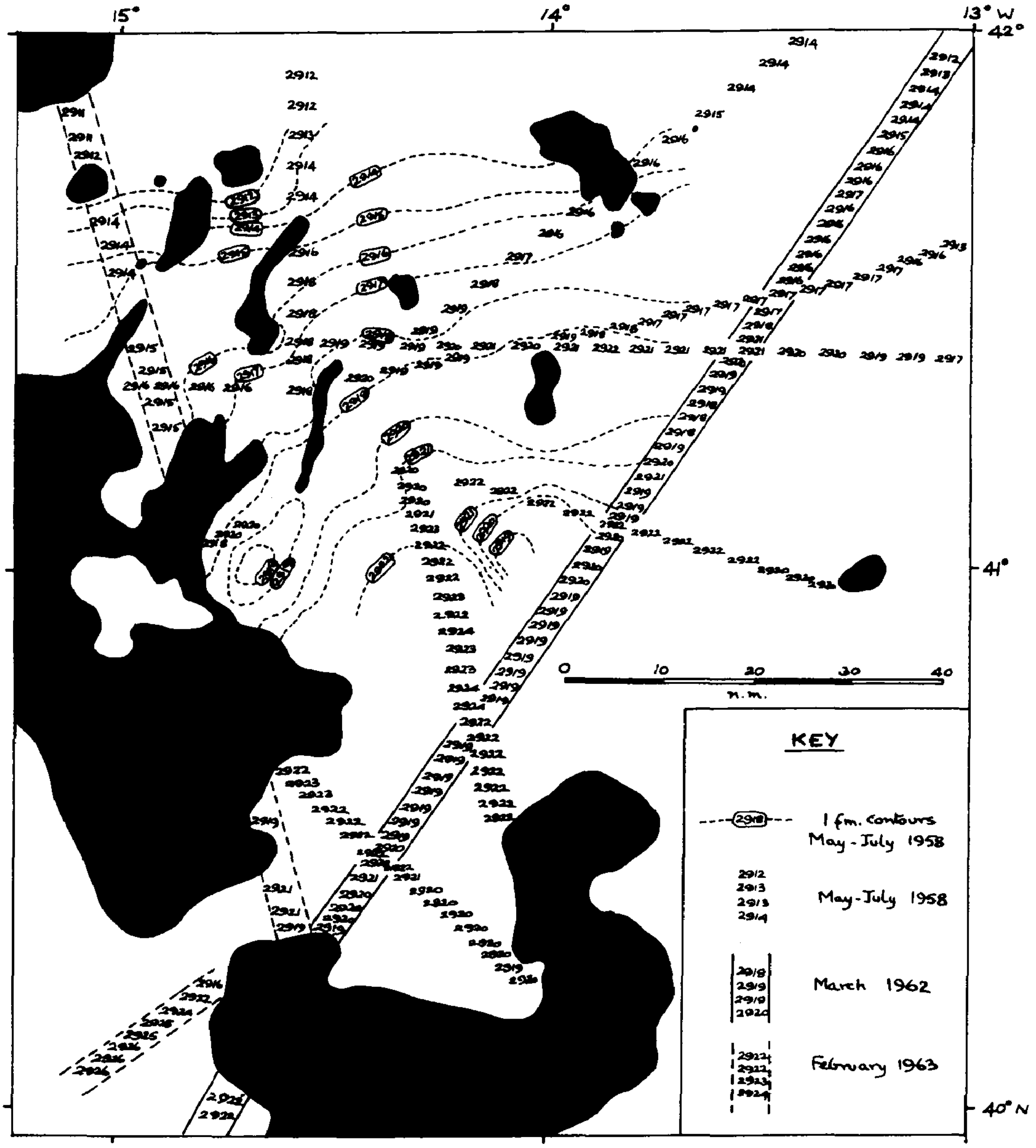

FIG. 2. — Precision echo soundings made on the western side of the Iberian abyssal plain in 1958, 1962 and 1963.

Constancy of depth measurements over an abyssal plain

A practical demonstration of the constancy of sounding velocity in a given area can be made by examining soundings taken with a precision echo sounder in a limited area over an abyssal plain over the course of several years. On account of the low gradients on abyssal plains (less than 1:1 000), errors of navigation do not contribute appreciably to apparent depth errors.

An area of the Iberian abyssal plain was surveyed in detail during May, June and July 1958 by the R.R.S. *Discovery II* using the N.I.O. Precision Echo-Sounder Mk. I. During these months the area was covered by soundings with a mean separation of 1 to 2 miles. These were sufficiently self-consistent for the plain to be contoured at 1-fathom intervals. These contours are shown in the northern part of Figure 2. A few of the sounding lines leading into and out of the area are also shown.

Subsequent passages across the area were made in March 1962 and February 1963 using N.I.O. Precision Echo-Sounder Mk. II and these are indicated between parallel lines.

It will be seen that the maximum error at track intersections is 3 fathoms in about 3 000, and in most places it is less than that. The possible instrumental errors that may give rise to this are (*a*) misreading of record, and (*b*) uncertainty in depth of towed transducer. The error is of the same order of magnitude as that discussed in the previous sections, due to secular changes in the mean vertical sounding velocity.

Although this is only a small sample of the ocean, examined over a limited time, there are many other places where a similar constancy of depth has been found and this example seems to be typical.

Conclusions

In most parts of the oceans where the water movements are relatively slow, time-variations in sound velocity may give rise to depth errors of the order of 3 fathoms or less. Near the boundaries of water masses these errors may be about twice as large.

It is reasonable, therefore, to aim at measuring the depth to the nearest fathom, in order both to examine the small detail on a single profile and to correlate soundings with other profiles obtained by different ships at different times.

References

COOPER, L. H. N. (1960) : Massive upward displacement in the deep ocean. *Journal of the Marine Biological Association, U.K.*, Vol. 39, pp. 209-215.

FUGLISTER, F. C. (1960) : Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data from the International Geophysical Year of 1957-58. *Woods Hole Oceanographic Institution Atlas Series*, Vol. 1, 209 pp.

GABLER, H. M. (1961) : Limits of accuracy of echo soundings in oceanic regions. *Intern. Hydrog. Review*, Vol. 38, No. 2, pp. 7-24.

KRAUSE, D. C. (1962) : Interpretation of echo-sounding profiles. *Intern. Hydrog. Review*, Vol. 39, No. 1, pp. 65-123.

KUWAHARA, S. (1939) : Velocity of sound in sea water and calculation of the velocity for use in sonic soundings. *Hydrog. Review*, Vol. 16, No. 2, pp. 123-140.

LUSKIN, B., HEEZEN, B. C., EWING, M., & LANDISMAN, M. (1954) : Precision measurement of ocean depth. *Deep-Sea Research*, Vol. 1, pp. 131-140.

MATTHEWS, D. J. (1939) : Tables of the velocity of sound in pure water and in sea water. 2nd Ed. *Hydrographic Department, Admiralty.*

MONTGOMERY, R. B. (1958) : Water characteristics of the Atlantic Ocean and of the world ocean. *Deep-Sea Research,* Vol. 5, pp. 134-148.

WILSON, W. D. (1960) : Speed of sound in sea water as a function of temperature, pressure and salinity. *Journal of the Acoustical Society of America,* Vol. 32, pp. 641-644.