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ASW SONAR
TECHNOLOGY REPORT

# THE MEASUREMENT OF SOUND SPEED IN THE SEA: VELOCIMETERS AND OTHER DEVICES

ARTHUR D. LITTLE, INC.
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DEPARTMENT OF THE NAVY
NAVAL SHIP SYSTEMS COMMAND

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# THE MEASUREMENT OF SOUND SPEED IN THE SEA: VELOCIMETERS AND OTHER DEVICES

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# SUMMARY

Data on the speed of sound in the sea is a prime requirement in Navy operations. Only relative accuracy in the measurements of sound speed as a function of depth is needed in tactical situations because it is the shape of the velocity profile that is of major importance to hull mounted sonar. Absolute accuracy in the measurement of sound speed is desirable, however, in order to exploit longer range propagation in the deep sound channel.

The sound speed can be measured either indirectly, by computation from temperature and salinity or density data, or directly, by using "velocimeters". In tactical situations, temperature data alone has sufficed for the indirect method except under certain near shore conditions, where skilled guesswork has been required.

Present velocimeters based on the "sing-around" principle are adequate for oceanographic survey purposes, from the points of view of accuracy and depth capability. However, their connecting cables render them unsuitable for tactical use; in general, the manufacturers of velocimeters are aware of and have been attempting solutions to the problems that arise from this application.

The value of temperature data alone for defining the presence of a surface duct in shallow water where sharp salinity changes can occur should be studied. We believe that there exists a case for the development of an expendable instrument or of a synoptic technique for tactical use to supplement the now successful expendable bathythermograph.

# I. THE MEASUREMENT OF SOUND SPEED IN THE OCEAN: REQUIREMENTS FOR THE NAVY

## A. Introduction

Knowledge of the local sound velocity field in the ocean is one of the limiting factors in naval operations. Generally, this knowledge involves the surface velocity (v) and the variation of the velocity with depth $(\frac{dv}{dz})$. Various factors such as required accuracy, available time, convenience, and system cost can dictate the choice of measuring instruments used. All systems measure sound speed rather than the vector velocity.

The speed of sound in sea water is affected by the temperature, the salinity, and the pressure (which depends on the depth) and increases with increase of any of these factors. The composite effect can be well represented by the empirical equation.

$$v = 1449 + 4.6t - 0.055t^2 + (139 - 0.012t)(s - 35) + 0.017d \qquad (1)$$

where

v is the velocity in meters per second

t is the water temperature in °C

s is the salinity expressed in parts per thousand

d is the depth below the surface in meters

This equation is a simplification of more complicated equations obtained by Wilson (Reference 1) and others as a "best fit" to experimentally measured data. Equation (1) is accurate to about one meter per second for those conditions commonly occurring in the various oceans. The

sound speed in surface sea water at 0°C and with salinity of 35 parts per thousand is thus 1449 meters per second as contrasted with 1403 meters per second for fresh water at the same temperature and pressure.

Equation (1) shows that change in temperature has the greatest effect on v. In the upper 10 meters of the ocean considerable temperature variations may exist. Below 100 meters in deep water the temperature generally decreases more regularly. Often in the upper 100 meters a surface layer of water that is almost isothermal (the surface duct) overlies a thermocline of rapidly decreasing temperature. Areas where variations in salinity become important are: near the mouths of larger rivers or in estuaries and deltas, where appreciable amounts of fresh water run into the sea; in the vicinity of large ocean currents; in shallow water or water close to the surface (where rain and evaporation have greatest effect); and near fields of melting ice. Other serious possibilities about which little is known may occur on a smaller scale due to thermohaline convection or "salt fingers".

Variation of the velocity with depth caused by the increasing pressure is quite regular, i.e., 0.017 meters per second increase per meter increase in depth. This effect is masked by temperature effects in the upper region of the ocean except in the case of an isothermal surface layer. However, at depths greater than about 1000 meters, the temperature is very nearly constant (nearly the temperature of maximum density), and the velocity then increases at the pressure effect rate. Thermal anomalies may exist at abyssal depths and in any water column, from a few meters above the bottom to the bottom.

For sonar operations a knowledge of the sound speed profile

at least in the vertical direction is necessary for determining the path of the transmitted sound signal. The data should be sufficiently accurate to define $\frac{dv}{dz}$. For sophisticated ray tracing techniques, knowledge of higher derivatives may be useful. More sophistication might require knowledge of horizontal variations in v due to ocean patchiness as well as measurements of the sound speed structure in the ocean bottom.

The needs for sound speed data may be divided into "tactical" and "survey." Their requirements overlap in certain cases, e.g., the propagation of sound in deep sound channels, and where bottom-bounce is utilized. The required absolute accuracy in the measurement of v(z) varies. For those active sonars where the upper portion of the water column is used, knowledge of the shape of the profile v(z) is sufficient, and only relative accuracy is required. For range estimation based on propagation in the deep sound channel absolute accuracy in the knowledge of v(z) is desirable.

There are two methods of determining v(z) and $\frac{dv}{dz}$. The indirect method consists of measuring the variation of temperature in the vertical direction and computing the sonic velocity from equations such as Equation (1). Generally, the salinity term is taken from reference tables but alternatively, the salinity is measured simultaneously either in situ or from collected water samples. The temperature profile is measured with bathythermographs, thermistor chains or reversing thermometers.

The direct method uses sound velocimeters which measure the local sound speed at the instrument by transmitting an acoustic signal across a path determined by the instrument size which is generally of the order of a few centimeters. Because of this short path length the

acoustic signal is usually of ultrasonic frequency, perhaps several megacycles.

Combinations of these systems are sometimes used in experiments for comparison of the data measured by each. S.V.T.P. systems (e.g., Reference 2) measure salinity, sound speed velocity, temperature and pressure; and "birdcage" systems have been used consisting of Nansen bottles and velocimeters in a protective enclosure.

## B. Requirements for Tactical Situations and Prediction

The problem of using active sonar to best advantage involves analysis of the ocean environment in order to decide the optimum operation modes and probable detection ranges. The shape of the velocity profile is of prime importance and so the requirement is principally for relative accuracy. A detailed discussion of accuracy requirements for range prediction is given in Reference 3.

Several kinds of information are typically available to a sonar officer. Echo sounders give bottom depth and variability. In general, successful bottom bounce operation is not possible when the bottom slope exceeds a few degrees. Elementary geometry suffices to predict approximate detection ranges for various beam depressions. Thus if

$\phi_o$ = sonar beam depression angle

$R$ = range

$z$ = depth of the bottom

then

$$R = \frac{2z}{\tan \phi_o}$$

In order to predict the sound field for hull-mounted sonar operation, the sound speed must be known as a function of time and space. The speed of sound increases with temperature at roughly 3.0 meters per second per °C, with salinity at 1.3 meters per second per mille and with depth at approximately 1.7 meters per second per 100 meters. In general, the speed of sound in sea water varies from approximately 1460 to 1530 meters per second.

A sonar officer generally has temperature data, (i.e., temperature vs. depth data) for the upper part of the ocean. It is usual to assume that the speed of sound varies only in the vertical direction. Salinity measurements are not usually made in fleet operation, but charts of "average surface salinity" as a function of latitude and longitude are readily available to him. Pressure versus depth charts are also available. Usually pressure is assumed to be uniquely related to depth, although differences in latitude alone may introduce sound speed errors as high as one meter per second. The data are usually furnished in ft-lb-sec units. In order to synthesize velocity profiles then, a sonar operator depends on temperature data, using the empirical relationships previously mentioned which give the sound speed as a function of temperature, pressure and salinity.

The Woods Hole Oceanographic Atlas of the Atlantic Ocean (Reference 4) contains both bathythermograph data and independent temperature and salinity measurements made by sampling techniques for identical parts of the ocean. Some examples are shown in Figure 1. Nansen bottles were used to obtain samples at depths from which salinities were determined; reversing thermometers gave the temperatures. The estimated experimental errors involved in sampling were: temperature $\pm$ 0.01°C depth $\pm$ 5 meters, salinity $\pm$ 0.01 parts per thousand. The mechanical bathythermograph used had

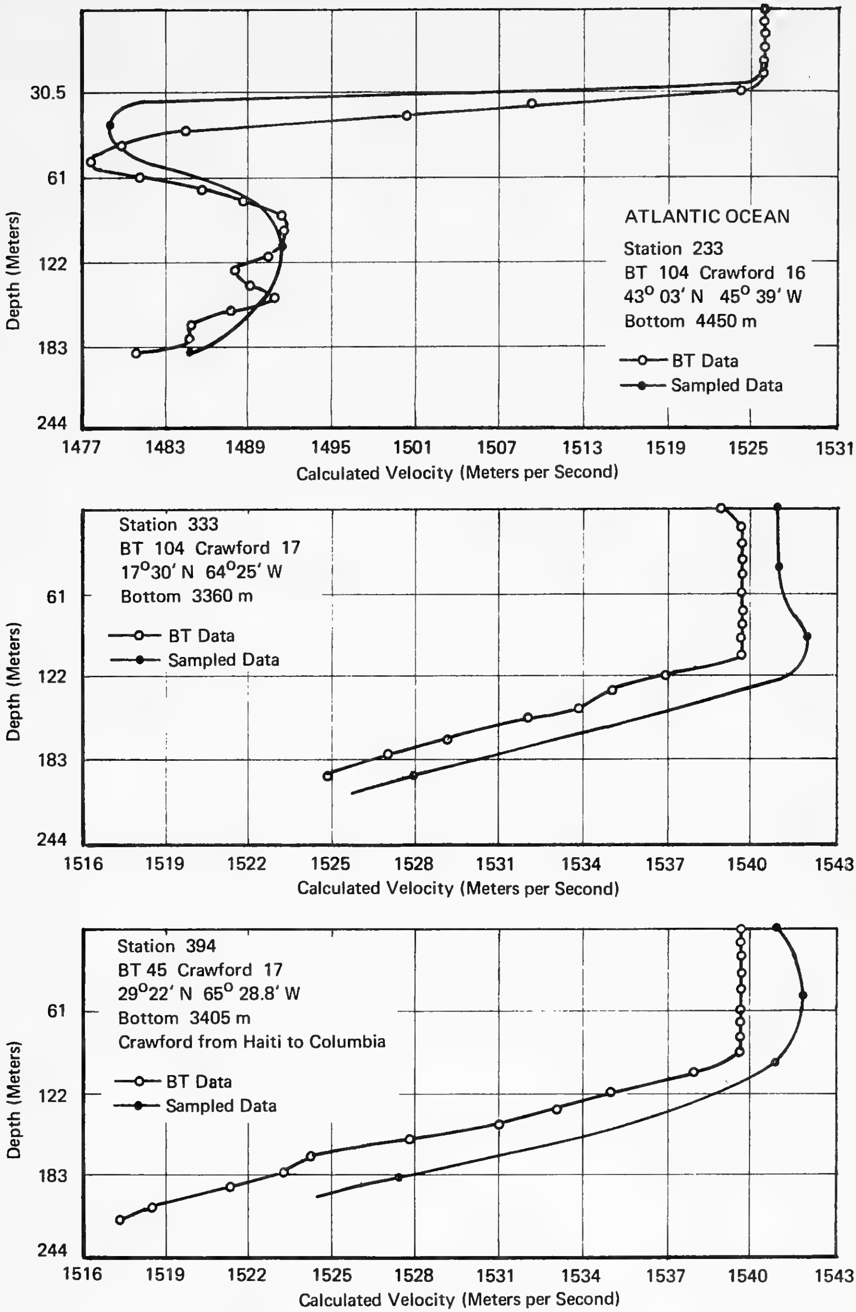



**FIGURE 1 COMPARISON OF SOUND VELOCITY PROFILES DETERMINED FROM MECHANICAL BATHYTHERMOGRAPH DATA AND REVERSING THERMOMETER, NANSEN BOTTLE CASTS (Reference 4)**

an error of approximately $\pm$ 0.2°C.

It is immediately clear (Figure 1) that these profiles may be very complex. A few scattered points are not sufficient to give an accurate picture of the profile. The shape of the profiles obtained with a small error in temperature measurement or depth location may be indeterminate. The absolute values of velocity may differ by only a fraction of a percent but the sign of the velocity gradient in the surface duct may differ.

When the velocity profile is known, much can be easily predicted. The application of Snell's law allows one to trace sound rays through the ocean represented by the profile. Useful ranges and so-called "shadow zones" may be distinguished. The velocity gradient, $\frac{dv}{dz}$, determines the curvature of rays. If $\frac{dv}{dz}$ is positive, the rays curve upward; if $\frac{dv}{dz}$ is negative, the rays curve downward. Since ranges and acoustic travel times for active sonar are relatively short, the prediction of target range does not require high accuracy in the absolute value of v(z), provided that the path taken by the sound is known approximately; the sign of $\frac{dv}{dz}$ (i.e., whether the gradient is positive or negative) is most important to determine the probable path.

In Appendix A, Figures A-1, A-2, and A.3 are rays plots produced by a computer which show the bending for positive, negative, and zero curvature conditions. Simple graphical techniques have been worked out and prepared for use by sonar operators.

In order for convergence zone operation to be possible, what is known as a "velocity excess" must exist. Velocity excess is the difference between the velocity at the bottom of the ocean and the velocity at the bottom of the layer depth. A rule of thumb is that the velocity

excess should be greater than or equal to 10 meters per second for successful convergence zone operation. This insures enough rays getting to the surface for a zone strong enough to be potentially useful. (A velocity excess identically equal to zero would allow the bottom grazing ray to pass; if slightly greater, the first convergence zone ray would pass.) Whether this condition exists or not is simply determined from the velocity profile. Figures A.4 and A.5 in Appendix A are ray plots illustrating convergence zone conditions.

The SOFAR path is the propagation path which employs the deep sound channel whose axis is normally located at depths of 1000 to 1500 meters. Propagation conditions are excellent and signals can travel distances of the order of a thousand kilometers with only cylindrical spreading loss. Although SOFAR propagation is a multipath phenomenon with different paths arriving at different times on a given signal, it has an abrupt ending corresponding to $\frac{x}{V_o}$, the time to travel in a great circle along the channel axis where $V_o$ is the velocity at the channel axis. The time of travel along longer paths is less than $\frac{x}{V_o}$ since the sound travels at a speed greater than $V_o$. Because of this abrupt ending, accurate timing is possible, and if the time of arrival of a signal is measured at more than one location (say 3), the geographical position of the source can be determined in a manner similar to LORAN.

The deep sound channel is characterized by a velocity profile which shows first a decrease in velocity with increasing depth below the surface or surface layer and then a more gradual increase in velocity with increasing depth. The depth of the minimum velocity occurs near 1300 meters in the mid-latitudes of the North Atlantic. Data from

Reference 5 show remarkable spatial and temporal persistence of the channel in the mid-Atlantic. In a survey lasting twelve days and extending over some 1000 kilometers, the velocity minimum changed by less than 2 meters per second and remained at practically constant depth. At all the measurement stations the velocity below the minimum increased at the pressure rate. However, a different study (Reference 6) carried out south of Bermuda showed considerable fine structure in the sound channel region there, with sound velocity changes of about one meter per second in a few hours at the same depth, raising the question whether a single sound velocity profile is sufficient to describe the deep channel in a large area for any length of time. Probably extreme temporal variations in the deep sound channel are due to fronts and may be of a local and predictable nature.

More data on SOFAR studies in the South Atlantic are given in Reference 7. Reference 8 discusses long range sound propagation in the Southern Ocean or Antarctic Ocean (Project Neptune). The Antarctic Ocean appears to have a different velocity structure from the Atlantic or Pacific. The depth of the SOFAR channel decreases rapidly between 40°S and 60°S and no true SOFAR channel exists further south.

To make use of this propagation there is a requirement for absolute rather than relative accuracy since for accurate location an exact value of $V_o$ is required instead of a knowledge of the velocity profile which suffices for predicting the ray paths in the channel. Possible errors in SOFAR location are similar to errors in location by LORAN due to timing errors. These are discussed in detail in Reference 9. The location of the source is determined from the intersections of hyperbolae which describe positions having fixed differences in distance from the listening stations.

An error in travel time or knowledge of $V_o$ causes the points of intersection of the hyperbolae to become areas. The size of the area depends on the bearing angles $\phi_1$, $\phi_2$ of the listening stations. Let us consider a simple example. The travel time in the sound channel for an acoustic pulse over a distance of 3000 km to each of two stations at 90° to each other would be approximately $2 \times 10^3$ seconds. If there is an error in the value of $V_o$ of $\pm$ 2 meters per second, then the source of sound may lie anywhere in an area of 64 square km. If the bearing between the stations is much less than 90°, this area can become a long, thin band so that rapid location of a moving source is difficult. The persistence of the sound channel indicates that accurate measurements in the channel can possibly define the channel over considerable distances for periods of time as long as a day. Probably a single profile is not sufficient to fully define the channel over a large area, however. For optimum ranging an accurate value of $V_o$ is required. It is worth noting in our example that $\pm$ 2 meters per second corresponds to a temperature error no greater than about $\pm$ 1°F, or in considering the pressure correction to a depth error of 110 meters at a depth of 1500 meters coupled with a possible temperature error of $\pm$ 0.2°F. From the point of view of current technology we should note that velocimeters are quoted by the manufacturers to be accurate to 0.15 meters per second. For field use we might safely double this. The temperature error in XBT measurements is $\pm$ 0.2°F and the error in depth location (from relatively shallow tests) is currently quoted as 2 - 3% of depth implying an error in $V_o$ of $\pm$ 0.7 meters per second at 1500 meters.[(1)]

Obvious questions with regard to tactical situations are:

1. Would present systems benefit if either deeper data or data with higher absolute accuracy were available.

(1) See Conclusions - Section V.

2. Will future systems benefit from or require such data?

The first question should be considered from the point of view of both deep and shallow water conditions. In some shallow water conditions such as deltas where there are strong salinity changes and the possibility of fresh water overlying sea water, BT data may be inadequate to predict sound velocity. Here a need for reasonably accurate data implies direct measurement of sound speed. It is possible that there may be horizontal changes in velocity in shallow water and that ranging will be in error. Nevertheless, the shape and variability of the vertical profile is required to determine operating mode. In particular in tactical situations a knowledge of the existence of a surface duct is the most important requirement.

In deep water, the knowledge of velocity to greater depth would be of value now if it indicated the occurrence of a convergence zone which current sonars could exploit. Generally we can state that the accuracy required for current active sonar operation is rather in the profile shape than in absolute value of the velocity. The accuracy to which the profile should be known depends entirely on the sophistication which is employed for shipboard prediction in tactical situations.

The exception to this requirement for only relative accuracy is in the use of the deep sound channel for passive location.

## C. Requirements for Oceanographic Survey

There is considerable value to the Navy in surveys of large areas of the oceans. The ideal from the point of view of naval operations is long term mapping of velocity profiles and surface duct depths and deep sound channels as regards occurrence and short-time and seasonal persistence.

Some work on persistence of surface channels has been carried out from BT measurements (Reference 10) and several surveys of the deep sound channel have been referenced. The main requirement for such surveys is that the instruments used are accurate and have a good depth capability, to at least 5000 meters. This accuracy must be good in both the relative sense, to ensure that $\frac{dv}{dz}$ is known, and the absolute sense. In such survey work much valuable information could be obtained on various problems such as horizontal variations, interfaces, internal waves and the sea bottom. For surveys, temperature and salinity should be measured as well as sound velocity. SVTP systems are commonly used.

## D. Problem Areas

### 1. The velocity of Sound in Ocean Patches

It is well known that while the temperature variations in the vertical direction tend to exhibit a layer structure, the horizontal variations, due to the turbulence in the upper layer, are more in the nature of random patches. The patch size spectrum ranges from diameters of the order of the layer depth (i.e., about 50 meters) to small diameters which correspond to the dissipation of the thermal structure by molecular heat conduction. Details of the temperature variations are given in References 10, 11; generally a dominant patch diameter of the order of twice the measurement depth is noted until the thermocline depth is reached. The temperature fluctuations are generally less than 1°C but may be sufficiently large to be of the order of 1 - 2°C. The spectrum of patch size apart from the largest might be expected to follow the well known Kolmogorov distribution law for turbulent eddies.

The investigation of these patches has always been with the thermal transducers, although several attempts have been made to correlate this data with observed fluctuations in acoustic transmissions due to scattering by the patches (e.g., References 11, 12).

The question arises as to whether a knowledge of the distribution of sound speed in these patches would be of value and whether current velocimeters are suitable instruments to investigate them.

The patches cause a transmitted acoustic signal to fluctuate in intensity by ± 6 db due to scattering. However, the distribution and size of the patches are functions of both space and time. Thus, it seems unlikely that any finer data would be of value in a tactical situation.

For scientific or survey purposes, two problems arise in measuring the sound velocity in patches. These are

1. Most currently used instruments measure during vertical transects. How could they be adapted to measure the horizontal changes?

2. How can the spatial and temporal behavior of the patches be distinguished and recorded.

It seems quite feasible to adapt current instruments to such studies by towing at fixed depths. One variation would be to use a velocimeter together with an isotherm follower system and measure changes in velocity along an isotherm. The ship velocity would necessarily be quite low. Another possibility would be to use free-swimming vehicles such as the University of Washington Applied Physics Laboratory Self Propelled Underwater Research Vehicles, already equipped to perform this task. The time response of the instruments appears perfectly adequate for all likely spatial or temporal rates of change of temperature or salinity.

Similar remarks might be expected to apply to the case of velocity changes caused by internal waves. There has been considerable interest in this subject(e.g. Reference 13).

The space-time aspects can only be separated by a stationary experiment holding velocimeter arrays at various fixed depths, an expensive experiment.

2. Interfaces

Anomalous effects may occur at both the sea water-sea bottom interface, which depends on bottom type; and at the water-air interface, which depends on sea state.

Sound reflected at anything beyond normal incidence is affected in both cases.

a. Bottom Interface Sometimes an increase in temperature of deep water close to the ocean floor has been observed. This is attributed to the geothermal flux through the floor, a heat flux which amounts to some $1 \times 10^{-6}$ cals per $cm^2$ per second for the Atlantic (e.g. Reference 14). The depths concerned are approximately 4000 meters (see e.g., Gerard *et al*. Reference 15). Such an increase in temperature would cause an increase in sound velocity. Descents with a deep submersible should indicate any such effect.

Any small changes in velocity at the lower interface would only affect grazing angle of the sound travelling in a deep channel. Although this would not be a tactical consideration to surface ship sonars, present instruments usually have sufficient depth capability to investigate this effect where it occurs.

b. Air-water Interface The behavior of the upper interface is tactically more interesting because sound transmission in the duct can

involve reflection at the surface at grazing incidence and because the sound might travel long distances near the surface, in an obviously disturbed layer. Measurements of the depth of this layer as a function of sea state would be interesting from the point of view of sound velocity. In this case it seems unlikely that temperature or temperature and salinity measurements would be at all meaningful by themselves, the effects of surface geometry and entrained air being so much stronger.

3. Velocity in the Sea-bottom

A knowledge of the density and the velocity in sea-bottom sediments in specific locations would be of interest from the points of view of sonar reflectivity, seismic reflection and refractive profiling. Reflectivity is currently measured by large pulsed sources or explosives.

The velocity of sound in sediments is a function of several variables and is strongly dependent on any trapped gas. The dependence of sound speed on pressure in marine sediments is unknown. Measurements at ultrasonic frequencies may be of little value to the Navy if dispersion frequencies occur, since extrapolations to low frequencies might allow gross errors.

Many of these factors could be determined by laboratory experiments. However, velocity measurements in areas known to have bottoms which are suitable for sonar operation would be of both short and long term value.

An instrument for making velocity measurements in situ in ocean sediments (Reference 16) has been under development by Hudson Laboratories and the Benthos Company. It is a combination of a sound velocimeter and a free-falling boomerang corer. The transmission frequency is 0.5 MHZ; the path length is 15 cm. The data is recorded on magnetic tape in the buoyant section which is separated from the free-fall vehicle by a timer.

The buoyant section containing the electronics withdraws the transducers and a core sample and returns to the surface.

### 4. Velocity Dispersion in Sea Water and the Pressure Coefficient of Velocity

The possibility of variations in the speed of sound in sea water with frequency is a basic question in the use of velocimeters to measure the speed. Sonar frequencies are typically less than 10 KHZ. Velocimeters work at ultrasonic frequencies. The frequency in the pulse is perhaps 3 MHZ. Velocity dispersion in sea water is always assumed absent in this frequency range. No dispersion has been reported in ultrasonic measurements and no dispersion has been observed in pure water. There are theoretical reasons why dispersion in pure liquids can only occur at very high frequencies (say greater than 50 MHZ). It seems then that the assumption is reasonable that the velocity measured by the velocimeter is the same as for sonar frequencies or that the discrepancy is extremely small. However, this is a vexed question which has not been totally answered, primarily because of the difficulties of making velocity measurements at long wave lengths.

The indirect method of sound speed measurement using bathythermographs relates the pressure dependence of the speed with depth in the ocean. The pressure dependence of the speed is determined in general from laboratory experiments at ultrasonic frequencies.

There is some detailed discussion in the literature (Reference 17) that the values of the depth term may be in error and there are certainly discrepancies up to 3 meters per second between laboratory measurements by Wilson (Reference 18), the tables by Kuwahava (Reference 19), and in situ measurements (Reference 17).

## II. REVIEW OF INDIRECT METHODS FOR THE MEASUREMENT OF SOUND SPEED

### A. Introduction

As indicated in section I, the indirect method of measuring the sound speed profile consists of measuring the vertical temperature profile and computing the sound speed from this. At present, there are five types of instruments in use to determine the vertical temperature profile. These are the thermistor chain, the reversing thermometer, the mechanical bathythermograph, the expendable bathythermograph, or XBT, and the electronic S.T.D.

### B. Thermistor Chain

This instrument is intended entirely for survey purposes and would never be used in a tactical situation. The thermistor chain used by USNEL is a string of 34 temperature sensors that operates in essentially a subsurface vertical line as the ship moves on the surface (Reference 20).

The signals from the sensors are scanned electronically and interpolated for all whole degree centigrade isotherms which are printed on a continuous chart. In addition to this analogue output of two dimensional temperature distribution, the water temperatures at the 34 levels are planned to be recorded on punched tapes. The depth of the array is monitored by a pressure transducer at the submerged end, and ducted current meters monitor shear currents. An accelerometer is being applied for stability monitoring.

The chain hoist is a self-powered winch designed for work requiring measurements to 250 meters depth at slow ship speeds, and to about 160 meters depth at a speed of 13 knots.

The 34 thermal sensing heads are type GB 32 P168 thermistors placed at intervals of 9 meters. The beads are matched to one part in two thousand which is 0.02° at the matching temperature. The chain is designed so that a defective thermistor can easily be changed by unplugging a small unit and inserting a new one.

The contouring temperature recorder plots the vertical distribution of temperature as a continuous record. Each isotherm is displayed as a depth profile similar to that given by an echo sounder. The recorder uses a helical drum and blade principle and writes on electrosensitive paper.

The measuring circuits cover a range from -20°C to 32°C and 10 isotherms can be plotted for this entire range. When gradients allow finer plotting, 0.1° or 0.05° isotherms can be recorded. The rate of scan can be varied, but 12 seconds is the optimum time for taking the temperature information for the near vertical column of water, a surface bead and the pressure sensor. The isotherms are obtained in 8 seconds; the remaining 4 seconds are used for the depth and surface measurements.

The depth sensor is a Bourdon tube driving a potentiometer. The d-c output signal from this potentiometer is balanced against the d-c feed back from the feed back potentiometer in the depth servo-mechanism. The balanced signal is then amplified by a conventional 400 cycle servo-amplifier. The depth is recorded on the lower portion of the paper record.

Although the thermistor chain is admirably suited to survey purposes in the upper 300 meters of the ocean, the time taken for reeling out and in, and the fact that the ship's velocity must be low to ensure that the chain is quasi-vertical, preclude the use of such devices in tactical situations. There seems to be little reason why, considering current ability in towing technology, a similar system could not be adapted to considerably greater depths and be used to survey the semi-permanent deep sound channels, but it might not be competitive with a system using fixed vertical stations and research submersibles investigating the heterogeneity between the stations. It also seems possible that the use of suitable powered depressors on the fish could make it possible to hold the chain stable at steep angles at higher ship velocities.

## C. Reversing Thermometers and Bathythermographs

Reversing thermometers and mechanical bathythermographs are the usual methods of obtaining temperature profiles in the ocean and our present records of subsurface temperature structure consist almost entirely of data by these two instruments. Both systems are well established and are described in many references (e.g., Reference 21). Table II-1, taken from that reference, compares the two systems and also the author's suggestion of an "ideal" general purpose instrument. In fact the numbers quoted there for the mechanical bathythermography are generally too optimistic.

## D. Expendable Bathythermograph

The need for apparatus improved for tactical situations from

TABLE II - 1

| | Reversing Thermometer | Mechanical Bathythermograph | Ideal |
|---|---|---|---|
| **Temperature** | | | |
| Range: | -2 to 30°C or -2 to 10°C | -2 to 30°C | -2 to 30°C |
| Accuracy: | Between 0.03 & 0.01°C | Between 0.2 & 0.1°C | 0.01°C |
| Discrimination: | Between 0.01 & 0.005°C | ∿0.05°C | 0.003°C |
| Time Constant: | ∿20 seconds | Down to 0.2 second | <0.1 second + 0.5 sec/km |
| **Depth Correlation** | | | |
| Range: | 0 to 5 km | 0 to 250 meters | 0 to 5 km |
| Accuracy: | Up to ±4 meters + 0.2% of the depth; usually not as good as this | ±3 meters | ±10 cm + 0.1% of the depth |
| Discrimination: | As above | ±1 meter for unidirectional movement | As above |
| Time Constant: | ∿20 seconds | <0.1 second | 0.1 second at max rate of 4 m/sec |
| Readout: | Linear at constant temperature | Linear at constant temperature | Linear or logarithmic |
| **Presentation** | In instrument. Requires visual reading for record. | In instrument. Record can be detached and stored | "On deck" with the alternatives of meter, recorder or digital output |
| **Connection to Parent Vessel** | Cable and messenger | Cable | Cable with single or multiple conductors, or acoustic signal (for expendable probe) |
| **Sampling** | Compatible with sample collection | Compatible with sample collection | Compatible with sample collection or simple in situ analysis |

the points of view of cost, reliability, precision and time available for measurements has led to recent interest in and development of expendable devices. These consist of a free falling transducer which returns its output to the ship by a cable link. XBT is a generic name for expendable bathythermographs.

The design of expendable instruments illustrates nearly all the problems and advantages which can occur with particular oceanographic instrumentation. Thus expendable instrumentation offers the advantage of speed for tactical situations because the ship does not have to slow down to take the measurement. However, the device must be inexpensive and, further, problems may occur in the telemetry of the information and the depth location of the device. For details of XBT design see Reference 22.

The use of a pressure sensor to indicate depth with the required accuracy and uniformity would add greatly to the cost. Consequently, depth is computed by relating elapsed time after launching to the sink rate. This method has received wide application with expendable devices and is discussed in the references.

The current XBT is wire connected to readout and recording equipment on board ship. In December 1964, it was announced that the Navy Bureau of Ships was evaluating and testing expendable BT's from three instrument companies, Bissett-Berman, G.M. Defense Research Laboratories, and Francis Associates. The basic designs of these XBT's are similar. The instruments consist of a thermistor probe in a housing containing a spool of wire which connects to a second spool of wire in a launching unit. When the probe is launched the wire from both spools is free to unwind allowing the probe to fall at a precalculated rate. The dual

spooling technique ensures that no drag is exerted on the wire because of the ship's travel or the falling probe and the probe falls vertically. Thus a low strength, small diameter wire may be used.

Changes in the resistance of the thermistor, due to temperature changes in the water are recorded on shipboard via the wire link. The rate of descent is precalculated and so depth can be recorded. At some depth, say 500 meters, the wire supply is exhausted and the probe is expended.

The advantages of these expendable systems may be summarized as follows:

1. They can be used from a vessel travelling at high speed.
2. A suspect record can be easily checked by a second sensor.
3. They can be employed in weather conditions which would forbid the use of conventional equipment.
4. Since the vessel need not slow to take a measurement there will be economical and tactical advantages.
5. They exhibit greater accuracy and precision than the mechanical BT.
6. The cost per observation is low.

Considerable detail on the mechanical and electrical design of these instruments is given in References 3, 22, 23. A detailed description of the results of an experimental evaluation of the accuracy, precision and reliability of the three instruments, which was carried out under the management of the U.S. Navy Underwater Sound Laboratory, is given in Reference 24. A detailed discussion of the economic and tactical advan-

tages of XBT's versus mechanical BT's, as suggested in point (4) above, is given in Reference 23. As a result of the evaluation, the Navy chose the XBT system of Francis Associates.

The Francis Associates' probe is capable of obtaining water temperatures to 500 meters with an accuracy of ±0.1°C over a range of -2°C to +30°C. Depth accuracy is said to be ±3% over the range. Thus at a depth of about 600 meters the error in velocity due to the error in the pressure correction term approximately equals that due to temperature error. The recorder is a modified strip chart null balance positioning system. Two compensating lead wires and a sea water path are used to the probe. Measurements can be made with a ship underway at speeds up to 30 knots as demonstrated in sea tests carried out by the Navy. Sea tests have been performed to test XBT capability to 1500 meters and the results are currently being analyzed.

A detailed discussion of the adequacy of the XBT to satisfy current accuracy requirements for technical active sonar is given in Reference 3.

## E. S.T.D. Instrument

Twenty years ago Jacobson (Reference 25) described an S.T.D. developed at W.H.O.I., which included a conductivity cell, a resistance thermometer, and a pressure transducer connected by multiple conductor cable to a deckside unit containing amplifiers, salinity computing circuits, and a three-channel recorder. Salinity was ±0.3‰ over the range of 20 to 40‰; temperature covered a range of 28° to 90°F., and depth to 1200 feet. This became a "production" instrument and several were built.

Equivalent instruments are now being utilized in our national oceanographic programs with resolutions, accuracies (and price) from ten to 100 times as high, but about the same size. Expendable S.T.D.'s are being developed by several groups, but no obviously superior technique or apparatus has emerged.

# III. REVIEW OF VELOCIMETERS

## A. Introduction

The existing instruments belong essentially to two classes: laboratory apparatus and instruments for oceanographic survey work. There have been prototype expendable instruments constructed. The measurement in the laboratory of the speed, possible dispersion, and absorption of sound waves does not concern us here directly, even though such results are of course the basis for the design and in particular for the calibration of all field instruments. Equation (1) describing the speed of sound in sea water as a function of temperature, salinity, and pressure, is the result of laboratory velocimetry and the relative sizes of its terms indicate the precision required in the measurement of the respective parameters.

Velocimeters for oceanographic survey work, Table III-1, (Reference 26, 27, 28) require almost the same accuracy as the laboratory apparatus, because the results obtained in the ocean are of course to be compared with laboratory data and with other oceanographic data obtained at different locations and times. In addition, scientific velocimetry in situ will in general require the simultaneous measurement of other parameters in equations of the type of (1). When the speed is being measured and the velocity profile is therefore known, the true depth can of course be obtained very accurately from sonic measurement, as for example by inverted echosounder. The instruments must be capable of maximum depths, they must be repairable in the field, and their power supply must be capable of prolonged operation. On the other hand, the price for such oceanographic

instruments can be high enough to cover all these requirements. Representative devices, based on the "sing around" circuit, are sold for $1700 to $3000, to which one must add about $2000 for readout electronics or about $5000 for printout electronics, in addition to a cable and winch.

The third group, the expendable velocimeters, Table III-2, (Reference 29, 30, 31) are intended mainly for taking the velocity profile in tactical situations. The instrument must have fine resolution and fast response, while absolute accuracy is of secondary importance.

As Tables III-1 and III-2 show, several instruments for oceanographic work are available commercially and at least two manufacturers have designed and demonstrated expendable velocimeters for naval tactical applications (Reference 29, 30), and one system designed along the lines of, and of little more complexity than, the present expendable bathythermograph has been proposed. (Reference 31).

We do not intend to judge in this report the performance and quality of instruments without having actually performed tests ourselves. We do, however, quote specifications and other information on design that is available from the manufacturers so that we may discuss this material critically. The US Naval Oceanographic Instrumentation Center has a test and evaluation program for velocimeters and the results, issued as "fact-sheets" (Reference 32), were also used in the preparation of this report. In addition, users of velocimeters were interviewed and the large body of literature on the measurement of the speed of sound was studied. A number of basic engineering problems emerged, all apparently recognized by the manufacturers, and in addition we heard opinions about the performance of specific instruments. The section on the comparison of instruments and

the potential for improvement is partly based on this material, with the exception of opinions which may have pertained to one particular specimen of unknown history and which are as likely to reflect a user's skills and prejudices as the quality of an instrument.

Many of the data shown in Table III-1 and III-2, mostly in the manufacturer's own terms, are very much defined ad hoc, and they are difficult to translate into absolute terms. The "accuracy" of velocimeters is usually defined as the maximum deviation of measured velocity values, which have been derived according to a calibration formula similar to Equation (1), from "true" values. The so-called "true" velocity in the calibration tank of distilled water is calculated (Reference 1, 17, 33) from pressure and temperature. This method of calibration is, however, difficult due to the strong dependence of velocity on temperature and due to the high demands on purity of the water. The temperature must be known, for example, within 0.02° at 0°C to avoid velocity errors greater than 0.1 meters per second from this source alone (see Equation 1).

## B. Tabular Listing of Velocimeters

The following, Tables III-1 and III-2, give a tabular listing of velocimeters followed by explanatory notes.

TABLE III-1

Oceanographic Survey and nonexpendable Instruments

| CHARACTERISTIC | MANUFACTURER | | | (Footnotes in parentheses) | |
|---|---|---|---|---|---|
| Company Name: | ACF (1) | RAMSAY (4) | LOCKHEED (7) | DYNA-EMPIRE (11) | HYTECH (PLESSEY) (15) |
| Type No. | TR-4/TR-3 (2) | MK-V | 40900/AA | AN/BQH-1 (12) | M030/31 (16) |
| Principle | Sing around | Sing around | Sing around | Time-distance (13) | Sing around |
| Max. Depth (m) | 12000 | 12000 | 12000 | 1000PSI test (12) | 2000 |
| Accuracy (±m/s) | 0.15 (3) | 0.1 (5) | 0.3 (8) | 0.7 (21) | 0.15 |
| Stability (±m/s) | 0.01 | 0.01 | | 0.3 (22) | |
| Repeatability (±m/s) | | | 0.1 | 0.7 (21) | |
| Temp. Coefficient (m/s °C) | 0.015/0 (6) | 0.03 (6) | ≈0 | | ≈0 |
| Flow Error (1/ft/s) | $2.10^{-5}$ | $<10^{-4}$ | $\approx 2.10^{-4}$ (9) | (12) | $<<10^{-4}$ (17) |
| Sampling Period (μs) | 140 | 170 | 70 | 31 (12) | |
| Material Defining Acoustical Path | Stl.St/Invar | Stl.St 17-4 PH | Invar | Stl.St | Invar |
| No. of transistors | | 12 | 8 | 13 | ≈12 |
| No. of transducers | 2 | 2 | 2 | 2 | 1 |
| Transducer Ringing Freq. (MHZ) | 3.6 | 4 | 3 | 3 | 5 |
| Telemetry Output | ≈3800 HZ | ≈3000 HZ | ≈7500 HZ | 1V/100 ft/s | ≈5000/15000 HZ |
| Weight (lb) | 19.5/16.5 | 28 | 8.5 | 40 (14) | 7 |
| Max. Diam (inch) | 9/15 | 17 | 7 | 12½ (14) | 24 (19) |
| Price w/out Cable or readout or power supply | $2650 | $2950 | $1680 | | about $2500 (20) |
| Lit. Reference (18) | 32 | | 28 | | |

## FOOTNOTES TO TABLE III-1

(1) The former "ACF" instrument is now made by: NUS Corporation, Underwater Systems Division, Hackensack, New Jersey. Tel: 201-265-2400.

(2) NUS ("ACF") make two types, TR-3 and TR-4. The TR-3 is shorter but its sound path is determined by the dimensions of a bulkhead of stainless steel and a temperature and pressure correction is hence required. The TR-4, the later model, defines the path by three freestanding Invar rods and therefore has practically no temperature or pressure error.

(3) According to the manufacturer, the Navy Oceanographic Office, Instrumentation Center, issues a Fact-sheet (1FS-001-64) in which they state:

> "The relationship between the sound velocity (C), and the "Sing-Around" frequency (F), as stated by the manufacturer is: C = .205916F ±.15 m/sec. This equation was observed to result in an error of ±.31 to -.05 m/sec. However, if the relationship for this particular instrument is changed to: C = .206451F - 3.96 m/sec, the error is within ±.1 m/sec."

(4) Made by Ramsay Engineering Company, 707 North Anaheim Boulevard, Anaheim, California, Tel: 714-774-5511.

(5) The Navy Oceanographic Office, Instrumentation Center, tested this instrument (Reference 32) and issued a fact-sheet (1FS-006-66) in which they state:

> "The relationship between sound velocity (C) and the sing-around frequency (F) as stated in the manufacturer's specifications is C = 0.5 F. Using the MK-V Deep Sea Probe, sound velocity measurements were made in distilled water for the temperature range of 0°C to 30°C. Comparison of test results with standard values (Martin Greenspan and Carroll E. Tschiegg, "Speed of Sound in Water by a Direct Method," Journal of Research of the National Bureau of Standards, 59:4

(October 1957), Research Paper 2795, p. 253.) showed an error range of +0.5 m/sec at 1405 m/sec to -0.1 m/sec at 1505 m/sec when the manufacturer's equation, C = 0.5 F, was used. However, if the equation for this particular instrument is changed to C = 0.499565 F + 0.025 (t - 20°C) + 1.15 m/sec, the error based on the same test results is within a range of ±0.1 m/sec.

A calibration equation which includes a term to compensate for effects of temperature change on the sound-path length of the instrument is used. The equation is of the form $C = a + b\ (t - t_0) + dF$ where (a), (b) and (d) are constants and $(t - t_0)$ is the difference between instrument temperature (t) and the temperature ($t_0$) at which the manufacturer has established zero temperature correction."

(6) This temperature coefficient is due to the use of stainless steel as a base for the acoustical path. Why the temperature coefficient of the ACF instrument should be half this value is not clear. The expansion of the stainless steel base should result in a T. C. of velocity of: $\alpha = 18 \times 10^{-6} \times 1500 \approx 0.027$ m/s deg.

(7) Made by Lockheed Electronics Company Avionics and Industrial Products Division, 6201 East Randolph Street, Los Angeles 22, California, Tel: 213-722-6810.

(8) With temperature of velocimeter known to 5°C.

(9) As this velocimeter does not fold the acoustic path, the full component of flow in the direction of the acoustic path adds to or subtracts from the sound velocity.

(10) Transducers protected by 0.002" steel diaphragm.

(11) Made by Dyna Empire, Inc., 1075 Stewart Avenue, Garden City, New York, Tel: 516-741-2700.

(12) This velocimeter was originally designed for use on submarines and a large number has been delivered to the Navy. Its oceanographic version, "Depth-sound Speed Measuring Set," including a pressure gauge, is described here.

(13) On a 20 cm path, 3 MHZ pulses at crystal controlled 32.4 KHZ repetition rate travel from transmitter to receiver. The phase of their arrival determines the duty-cycle of a flip flop, thus providing an analog DC output.

(14) In transit case.

(15) Made by Plessey, England; sold in the US by Hytech Marine products, the Bisset Berman Corp., G-Street Pier, San Diego, California 92101, Tel: 714-234-6755.

(16) Hytech supplies two different models, one to produce an output frequency directly proportional to the speed of sound in ft/sec (M030) and the other in m/sec (M031).

(17) As measured at 25 knots, according to Hytech, this is a particularly small value due to the use of one transducer with folded path, thus letting the pulse travel around an exactly closed path.

(18) Recent company-issue sales literature should be consulted. The quoted open-literature references are necessarily somewhat dated.

(19) Only 2" diameter.

(20) Approximate price, including power-supply on deck.

(21) According to "Informal Manuscript Report" I-04-65 (unpublished), Naval Oceanographic Office.

(22) According to private communication from Dyna-Empire (1966).

TABLE III-2

Expendable velocimeter prototypes submitted to the Naval Oceanographic Office

"Expendable Sonic Velocimeter," Dyna Empire, Inc. (Reference 30)

It is a sing around device operating at about 5000 HZ. It uses one transducer and reflector, four transistors and a single wire, sea return, to lead 16 MA DC power down and ≈5000 HZ pulses up. The electronic delay is only 20ns or 0.02% of the period. It is planned for use up to 1500 ft depth, free falling with one wire reservoir in the probe and one on the ship. The instrument was tested by the Navy Oceanographic office and a report submitted on January 7, 1965 to the Bureau of Ships.

According to Table I of that report, the velocity readings taken in one complete temperature cycle during the first 200 hours of submergence show a standard deviation of 0.11 m/s, calculated after subtracting a constant error of 1.4 m/s. This is only about twice the error of the calibration facility, estimated to by 0.05 m/s by the Oceanographic office. The velocimeter was not pressure tested and after 200 hours of submergence the prototype failed. It worked again after it was dried and the exposed wiring coated with epoxy.

This performance appears to be altogether satisfactory for sonar range prediction.

"The Aquasonde", Teledynamics (Reference 29)

It is a sing around device operating at about 18 KHZ with a carrier frequency of 1 MHZ. It uses one transducer and one reflector. It is capable of about 1500 ft depth.

The instrument Model 7100 A, was tested by the Navy Oceanographic Office, Instrumentation Center, and a Fact-sheet (Reference 32) IFS-002-65 was issued in January 1965. The Fact-sheet quotes:

| | |
|---|---|
| Absolute accuracy: | ±2.7 m/s |
| Relative accuracy: | ±2 m/s |
| Repeatability: | ±0.6 m/s |

According to "Informal Manuscript Report" No I-55-66 (unpublished), Naval Oceanographic Office (the basis of Fact-sheet IFS-002-65), the units that had been submitted for testing performed inconsistently and not within the manufacturer's specifications. According to Teledynamics, the instrument has since been improved and is now called: Model 7100B.

C. Discussion of Direct Methods

Tables III-1 and III-2 show mostly instruments built around the so-called "sing around" principle, which was first put to practical use in oceanography by Greenspan and Tschiegg at NBS (Reference 26). The "sing around" velocimeter uses a time-distance method which is made regenerative by closing the loop from the receiving transducer through an amplifier to the transmitting transducer. The resulting repetition rate forms directly the telemetry output of the instrument. Only one instrument, the Dyna Empire ANBQH-1, differs in principle--it measures without regeneration directly the travel time between two transducers and produces an analog output voltage proportional to the speed of sound. The market for velocimeters in oceanography is necessarily rather small and there is hence limited money available for development and for new designs. This may be one of the reasons for the dominance of the "sing around" principle--it was shown by NBS to work and to produce useable oceanographic data and no commercial manufacturer wanted to argue with success.

Other methods to measure velocity of sound in the ocean, based on measurement of standing waves in resonant cavities, have been proposed and tried (Reference 34, 35). These methods, however, did not establish themselves in oceanography, even though some are quite successful in the laboratory and some have been used experimentally in the ocean.

There are two basically different methods of measuring the speed of sound: by propagating a pulse or by setting up standing waves. These two methods measure two different quantities: the group velocity and the phase velocity. The group velocity is the quantity that describes the

propagation of energy (and hence information), while phase velocity is the product of wavelength and frequency in a single frequency wave. Only in the absence of dispersion, i.e. only when the phase velocity is independent of frequency, are the two velocities identical, and only then will a measurement of a propagating transient yield the same result as a measurement of standing waves. In other cases the group velocity has to be calculated from a knowledge of phase velocity as a function of frequency, or it has to be measured directly.

All velocimeters that are presently commercially available measure the group velocity of high frequency pulses. High carrier frequencies are needed in this method to keep the length of the pulse (the "group") small compared to the acoustical path, which in turn is limited by the linear dimensions of the instrument. All "sing around" velocimeters use pulses of 3-4MHZ carrier frequency, i.e. about 1000 times higher than common sonar frequencies. A velocimeter does have the fundamental advantages of a direct method over an indirect method, and of many possible principles the "sing around" method seems at present the most attractive from an engineering standpoint. It is, in fact, almost a text book example how in a difficult and exact experiment the burden of accuracy can be placed on a single rugged element, in this case the mechanical base for the acoustical path, and the influence of all other elements made negligible. Effects of dispersion and frequency response in the transducers and in the amplifier can be suppressed by reshaping the pulse before it is transmitted again and the time delay in amplifiers and transducers is easily made very small compared to the time it takes the pulse to travel through the measured distance in sea water.

The repetition rate of the pulses is directly a measure of the speed of sound in sea water, according to the following relations:

$$f = \frac{1}{t_e + d/v} \qquad (2)$$

where

$f$ = repetition rate

$t_e$ = electrical delay

$d$ = acoustical path

$v$ = speed of sound

The following relation holds normally:

$$t_e \approx 0.1\mu s << \frac{d}{v} \approx 100\mu s \qquad (3)$$

This reduces (2) in first approximation to the more convenient expression:

$$v \simeq f \cdot d\ (1 + ft_e) \qquad (4)$$

The frequency f is transmitted up the cable to the deck where the computation according to (4) can be performed in a digital frequency counter directly or a small correction according to (4) can be added to the measured frequency to obtain the velocity.

The alternative to the pulse propagation methods is the measurement of standing waves, and these latter methods, in contrast to the former, are particularly suited to lower frequencies. A resonating cavity is usually employed which is either excited by a wideband pulse and observed after all but the resonant frequencies have died out or made part of a manual or automatic feedback loop with only its resonant modes excited (Reference 34, 35). Suitable shape of the resonator and selective amplifiers are used to suppress

unwanted modes and to excite only those modes that have low damping and which are far away in frequency from the next possible mode, and afford therefore accurate and unambiguous measurement of phase velocity.

It appears that one of the difficulties encountered with the standing wave apparatus is the definition of the boundary conditions, i.e. of the terminating walls. Even small amounts of dirt (Reference 34) have been reported to ruin the performance. While this poses no insurmountable problem in the laboratory, it makes the instrument useless for oceanographic runs of long duration. In an expendable tactical instrument, however, the walls would probably stay clean during the single descent of the instrument and these objections to the use of resonant cavities would probably not hold.

Most other methods of indicating standing waves and hence of measuring wavelength or phase velocity are restricted to the laboratory. Among others there is Debye-Sears' method of forming a diffraction grating from a standing wave of high frequency, and Toepler's method of producing a Schlieren image of a standing wave to determine the wave length directly. These optical methods, however, appear to be unsuited for marine use.

An important refinement in standing wave techniques is the scanning interferometer, where instead of scanning the frequency in a fixed resonator one scans the dimensions of a resonator at constant frequency and uses the reaction of the wave on the exciting transducer to indicate resonance. The output of a suitable transducer is recorded while the dimensions of the resonator are changed by, for example, a precise lead screw. From a record of sufficiently many "fringes", to borrow a term from optical interferometry, as a function of the position of the moveable boundary one

can determine the wavelength very accurately. Since it is easy to measure frequencies with far higher accuracies than required by this experiment, this method is well suited to high quality laboratory apparatus, and it could, for example, form the heart of a superior calibration facility for velocimeters under the assumption, of course, of no dispersion. Some experiments to compare these different methods have been done: a progressive wave at 2.6 MHZ was sampled by leadscrew and phase sensitive detector and agreement with time-distance methods, but slight disagreement with interferometry, was found (Reference 36). Also a "freefield" propagation experiment in a large tank a 1 MHZ yielded velocities about 0.6 m/s lower than "sing around" velocimeter data (Reference 37). These discrepancies, however, are not necessarily due to some real effect, such as dispersion, but probably rather illustrate the difficulties of setting up a clean experiment: Reflections must be avoided in propagation methods and corrections for walls, posts, etc., must be included in standing wave methods.

## IV. COMPARISON OF METHODS AND RECOMMENDATIONS

### A. Comparison of Direct and Indirect Methods

In Table IV-1 we have compared these various devices on the basis of depth capability, measurement accuracy in deep and shallow water, the initial cost, the required time on station for a profile, the speed of readout and the potential for improvement. In Table IV-2 we have outlined some of the Navy's needs for information on sound velocity and the instruments which can satisfy them. In both tables we have assumed the existence of a suitable expendable velocimeter. Table IV-2 may be briefly summarized as follows:

1. For survey needs, existing instruments are adequate in both deep and shallow water. (By "survey" we imply that the ship can be either stationary or proceeding slowly.) The available velocimeters are well suited to any survey work, and their performance is quite adequate when care is taken in their operation.
2. For tactical needs, expendable instruments are required.

The question arises as to the potential of the velocimeter to fulfill future needs.

TABLE IV-1

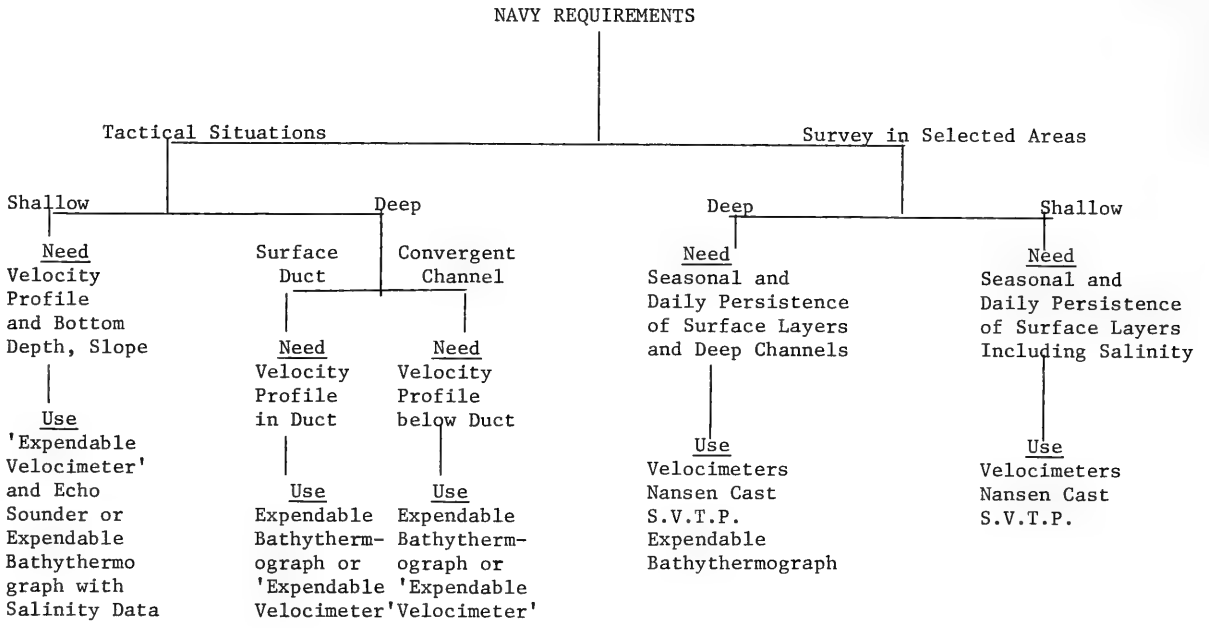
Comparison of Devices

| | Nansen | B.T. | X.B.T. (2) | Velocimeter | Expendable Velocimeter |
|---|---|---|---|---|---|
| Depth | 5000 meters | 200 meters | 500 meters | 12,000 meters | 1500 meters |
| Accuracy | ±4 m + 0.2%d | ±3 m | ±3% | (1) | ±2% |
| Accuracy (velocity) | | | | | |
| Deep | | ±1 m/sec | ±0.4 m/sec | ±0.15 m/sec | ±1 m |
| Shallow | | in doubt Depends on importance of salinity - see text. | in doubt Depends on importance of salinity - see text. | ±0.15 m/sec | ±1 m |
| Cost | | | | | |
| Initial | | $100 | $17 | $3000 | |
| Time on station | 4 hours | minutes | seconds | 2 hours | |
| Data reduction time | hours | hours | zero with digital readout | zero | zero |

NOTE: (1) Depends on depth gauge employed - best is ±0.1%

(2) Experiments have been performed to investigate use to 1500 meters depth

TABLE IV-2


NAVY REQUIREMENTS
Tactical Situations
Survey in Selected Areas
Shallow
Need
Velocity Profile and Bottom Depth, Slope
Use
'Expendable Velocimeter' and Echo Sounder or Expendable Bathythermo graph with Salinity Data
Deep
Surface Duct
Need
Velocity Profile in Duct
Use
Expendable Bathytherm-ograph or 'Expendable Velocimeter'
Convergent Channel
Need
Velocity Profile below Duct
Use
Expendable Bathytherm-ograph or 'Expendable Velocimeter'
Deep
Need
Seasonal and Daily Persistence of Surface Layers and Deep Channels
Use
Velocimeters
Nansen Cast
S.V.T.P.
Expendable Bathythermograph
Shallow
Need
Seasonal and Daily Persistence of Surface Layers Including Salinity
Use
Velocimeters
Nansen Cast
S.V.T.P.

## B. Problems and Recommendations

### 1. Depth Accuracy

Accurate depth location is required for two reasons: to ensure correct profile determination and, in the case of indirect methods, for the application of a correct pressure correction to the sound speed measured.

Expendable instruments are necessarily located by a precalculated sink rate and elapsed time. Possible errors in depth location by this method have been considered and compared with experimental data. The analyses have neglected some possible hydrodynamical problems (e.g. Reference 38). Other instruments are located in depth by means of pressure transducers or by inverted echo sounder. When using pressure transducers, such as the "Vibrotron," depth is calculated from hydrostatic pressure. Problems may arise when measuring great depths in regions of gravity anomalies or when the exact density of the water is in question. The inverted echo sounder, on the other hand, is particularly suited for use in this system. This is a method where depth is calculated from the round trip time of a pulse from the echo sounder which is attached to the velocimeter to the sea surface and back to the echo sounder at the velocimeter. Because the velocimeter measures sound velocity during descent, the output of the echo sounder can be reduced using these true velocity data directly, thus avoiding all errors due to uncertainties in water density and local gravity.

### 2. Velocity Accuracy

The accuracy of the available velocimeters as listed in Table III-1 is excellent for any naval requirement. Temperature-coefficients of the acoustical path and of the gain and delay of transducers and amplifier, as well as pressure coefficients due to buckling of bulkheads, etc. and other

systematic errors can be removed by applying suitable corrections. However, certain defects can occur under field conditions which cause errors which would be significant even in a tactical situation. The most serious of these defects are spurious triggering due to precursors (i.e., the second and later echoes of previous pulses ) and triggering on cycles other than the first in the transmitted pulse.

Thus with the usual N.B.S. type of velocimeter, a triggering error of one period of the carrier frequency leads to a velocity error of about 3 meters per second. The causes of spurious triggering are listed below:

a. Depending on the geometric arrangement of the transducers and reflectors that determine the sound path, multiple reflections of past pulses could arrive almost simultaneously with the desired directly transmitted pulse.

b. Random noise could add or subtract from the signal amplitude, thus shifting the moment of triggering.

c. The attenuation in the sound path can change in operation, either by misalignment of the transducers or reflectors, by changes in the gain of the electronics or of the transducers, or by changes in the attenuation of the sea water. The resulting change in signal level at the receiver input will then change the moment of triggering.

d. A transmitting transducer that is relatively undamped will put out a train of waves rather than one pulse and these extra oscillations can confuse the receiver input.

Problem (a) can be solved by proper layout of the sound path, by suppressing spurious oscillations (as in Problem (d) ) and by gating the receiver "on" during a predetermined "window" only.

Noise, Problem (b), can be overcome by providing sufficient signal.

The influence of attenuation, Problem (c), can be eliminated by an automatic gain control circuit to adjust either the transmitted output power or the receiver amplification so as to deliver a constant peak amplitude signal to the threshold circuit. The T.R.G. under development by NUS Corporation will include A.G.C.

In view of these possible problems and the relatively large investment of time in each run, it seems therefore advisable to use two velocimeters together whenever possible for oceanographic survey purposes.

### 3. Expendable Velocimeters

For the specific purpose of sonar range prediction, a velocimeter should be designed to be able to distinguish the fine structure, so that the first derivative of the velocity profile can be reliably computed. The absolute values of depths and velocity, i.e. scale of the velocity profile, are of lesser importance.

It is in this respect that the B.T. methods can prove unsatisfactory, because they cannot take into account any salinity anomalies and therefore may not always reproduce the velocity profile in the upper layers above the main thermocline correctly in shallow water.

Any instrument useful for sonar-range prediction must therefore have high sensitivity to small changes in velocity, small hysteresis, i.e. good short term reproducibility, and its speed of response must be appro-

priate to its sinking rate. If it operates on a digital principle or if it has digital readout, its output must be quantized sufficiently finely so as not to obscure any detail that occurred in the velocity profile, even though this detail may be finer than the long term stability or accuracy of the instrument. On the other hand, the comparatively modest absolute accuracies required in this special application may permit the use of principles probably not accurate enough for oceanographic work. Thus, phase measurements on free propagating continuous waves, simple time/distance methods, or the counting of modes of high order in resonators which operate at fixed frequencies could be employed. It is, however, difficult to think of anything more simple and efficient than the sing around circuit.

Taking advantage of these special conditions, it would be reasonable to consider the design of an expendable instrument of bulk and cost comparable to the expendable Bathythermograph. Two such designs, the "Expendable Sound Velocimeter" of Dyna Empire, Inc., and the "Aquasonde" of Tele-Dynamics Division of American Bosch Arma Corporation have already been tested by the Naval Oceanographic Office (see Table III-2). Other systems, such as a freefalling expendable single wire system similar in appearance to the XBT (Reference 31) have been proposed and undoubtedly others have been thought of, designed, and tested.

#### 4. Possibilities of Hybrid Systems for Maximum Cost Effectiveness, and Recommendations

Not the least among the considerations that must be kept in mind by instrumentation system designers is that users of successful systems place great and unquestioning faith on the system and its performance. This

is especially so in a military instrumentation system where doctrine may establish the manner of utilization of a system or of its components. The user comes to rely on the schemata of the system rather than upon an interpretation of the meanings of each of the measured variables in the system.

A particular problem in system performance arises when there is no alternative method either for measuring an important variable or for assessing the context in which the measurement is being made. A case in point which particularly applies here is the use of a bathythermograph aboard a ship in an ASW exercise. In most operating areas, it would be quite reasonable to assume a fairly uniform salinity structure and therefore be able to infer local sound speed structure from the temperature trace recorded. However, if the area is a so-called shallow water area, that is, one where internal waves or strong salinity gradients are present, the temperature profile measurement at only one point may not provide adequate information useful to the sonar operator. In fact, it may lead him to erroneous conclusions. Historical data will allow him to hazard a guess as to the utility of the measurements he is receiving, but in coastal areas or off the mouths of sizable rivers, the exact meander of the fresh water plume and its consequent eddies may be unknown. Some indication of the existence of such a problem can be gained by monitoring the intake water salinity, but it is unlikely that under stress the sonar crew will be able to quickly recognize such indications, even if they are capable of interpreting them.

A study has been made (Reference 39) which shows that a rather careful measurement of conductivity must be made in order to yield sound velocity structure to the accuracy a sonar officer would like to have in

areas of brackish or "marble-ized" water. The complexity and expense of a suitable device (XSTD), at this time may be too high to be justified as an expendable instrument in normal situations, but such a determination cannot be made until the instrument, currently under development at NAVOCEANO, is field tested. Interim alternatives in the form of hybrid systems are possible, however, and while they would be compromises, they would add only a fraction to the cost of an expendable BT cast, and need by made only as frequently as necessary to determine the oceanographic conditions. The first involves salinity recognition and the second direct sound speed measurement.

When the XBT probe is falling through water that is of lower salinity than inferential sound speed calculations would permit within accuracy requirements of the tactical situation, an indication can be obtained.

It is possible to modify the expendable BT so that the output of the XBT is modulated, that is, interrupted when it is in brackish water. This rate of interruption would vary with conductivity below any given value of conductivity, with no interruption above that value. It is possible that such a circuit could give sufficient information that the BT information derived could be used within certain depth intervals if perhaps not in others. It would not be necessary that every BT cast use the modified device, but only one every nth cast when in waters where oceanographic conditions are known to be variable. The record would show where brackish water existed, and appropriate action could then be taken, such as use of an XSV.

Upon casual examination, it appears possible that the only modification required to the ordinary XBT would be addition of one semi-conductor and one extra electrode, in addition to the one already used on the XBT, since no accurate measurement is being attempted. Since there would be no requirement for batteries or extra cable conductors, the hydro-dynamics and operational requirements would not be altered.

Availability of such an XCT would allow more judicious use of the XSV suggested in the previous section and would considerable raise the permissable cost of the XSV since it would then only be used when its particular capabilities were necessary. Thus it appears possible that a family of expendable devices may be found to be a more practical solution than any one type of expendable device, regardless of how inexpensive it may be possible to make it.

The XBT can be modified (Reference 31) to measure the sound velocity profile (SVP) in the ocean directly by installing a hydrophone tuned to the corner frequency of the ships pinger in the freefalling probe unit. The p.r.f. of the pinger would be varied on a sing around basis by signals from the XBT. The direct measurement of SVP circumvents the necessity of approximating salinity effects in using the temperature profile for range prediction and would be useful for tactical ASW purposes. The modified XBT unit could simultaniously provide temperature profile data for synoptic prediction purposes. A preliminary error analysis indicated that a sound velocity profile could be produced with a precision which is roughly comparable with the ±0.15°C temperature capability of the XBT.

This XSV would be the only mobile velocimeter system to measure true group velocity a low frequencies, because its long acoustical path

between probe and ship permits pulse propagation measurement at low carrier frequencies.

However, if dispersion can be proven to be a negligible problem, this advantage disappears. On the other hand the XSV has the inherent disadvantage of its principle of measuring the integral of sound velocity over the full instantaneous depth of the probe and this adds one differentiation to the computation of the velocity profile.

In summary, it can be said that further study may show that the most cost-effective shipboard routine for ascertaining oceanographic conditions for sonar pupposes may include one or more hybrid or special purpose devices in addition to the regular expendable BT. It is thus our finding in this limited study that the Navy should continue the development and deployment of the expendable BT, that the development of the XSV should be investigated, and that a hybrid expendable conductivity-temperature device (XCT) be explored as a means of determining the variability of onshore and shallow-water sonar oceanographic conditions, pending the availability of an XSTD.

## V. CONCLUSIONS

As a result of this study we have reached the following conclusions:

1. The accuracy requirements for acoustic velocity data may be either relative or absolute. Relative accuracy in the shape of the velocity profiles is usually sufficient for tactical needs. However, for long range surveillance in the deep sound channel, high absolute accuracy may be required.

2. Velocimeters are well suited to surveying the deep sound channel. The use of velocimeters can reduce the error in location of a distant object by a factor of at least 2 to 4 times the possible error which would occur if X.B.T.'s were employed. The principle error in the use of an X.B.T. at great depth is in the pressure correction term because of the error in depth location. The projected range error due to computed velocity at the sound channel axis using an X.B.T. based on a temperature error of ± 0.2°F and 2 to 3% projected depth error at about 1500 meters depth is between 0.04 and 0.06%.[(1)]

3. The present velocimeters are adequate for survey purposes. The manufacturers are aware of the problems and attempt solutions. However, there has been in fact little development beyond the original sing-around system, presumably since the returns from limited sales of velocimeters do not warrant extensive development programs.

(1) Comprehensive tests performed in May 1968 aboard the NRL research vessel Mizar have shown that the standard deviation of the fall rates of 6,000 ft. deep X.B.T.'s is less than 1%. If any bias on this data is shown to be less than 1% then the absolute values of the fall rate at various depths will be known to an accuracy of 1%. Thus this precision between X.B.T.'s would allow prediction of B.T. depth to 1%. A report detailing these tests is now in preparation for NAVSHIPS, Code 00V1H.

4. The present expendable bathythermograph is adequate for current tactical needs in determining the sound velocity profile in deep water. A possible problem area which, however, does not often occur in the deep ocean is the case of a nearly isothermal surface duct where salinity data may be necessary to determine the velocity gradient. The development of the surface vessel launched X.B.T. is complete.

5. A study should be made of the adequacy of temperature data alone to indicate the presence of a surface duct in shallow water where sharp discontinuities in salinity can occur. The study should indicate what advantage might be gained by the use of expendable velocimeters or conductivity probes if such were available. The study should include possible errors in the pressure correction term due to sharp changes in density which will be common to all expendable instrumentation.

6. Dependent on the results of the study (5.) a development program should be aimed at producing an inexpensive expendable velocimeter and/or conductivity probe, not to compete with the X.B.T., but to supplement it for use in areas where temperature data might not suffice. There have been several attempts at and suggestions of designs. The program need not necessarily first compete with the current price of the X.B.T., but rather should aim at producing an accurate instrument at a cost of perhaps $100 to $200. If such an instrument were successful the decrease in cost for large scale production could be predicted.

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## APPENDIX A

Insonification of the ocean is strongly dependent on the structure of the velocity profile. Figures A-1, A-2, A-3 show three velocity profiles (VP-1, VP-2, VP-3) and associated ray plots for a source at 15 feet below the surface. A semilogarithmic depth scale was used on the ray plots to emphasize the shallow depths. Rays were terminated after a maximum of nine surface bounces. VP-1 has an initial positive gradient, the velocity is 5022.0 ft/sec at the surface, and 5024.5 ft/sec at 100 feet. VP-3 has an initial gradient that is the negative reflection of VP-1, i.e., it has a velocity of 5026.0 ft/sec at the surface and 5024.5 ft/sec at 100 feet. VP-2 has an iso-velocity layer down to approximately 400 feet with a velocity of 5024.5 ft/sec.

Figure A-4, A-5 shows ray plots of convergence zones. The first and second convergence zone are shown for VP-1; the first convergence zone is shown for VP-3. Rays were allowed a maximum of three surface bounces and two bottom bounces before termination. The structure of the layer depth is relatively insignificant when considering zone operation.

FIGURE A-1

VP-1 POSITIVE INITIAL GRADIENT

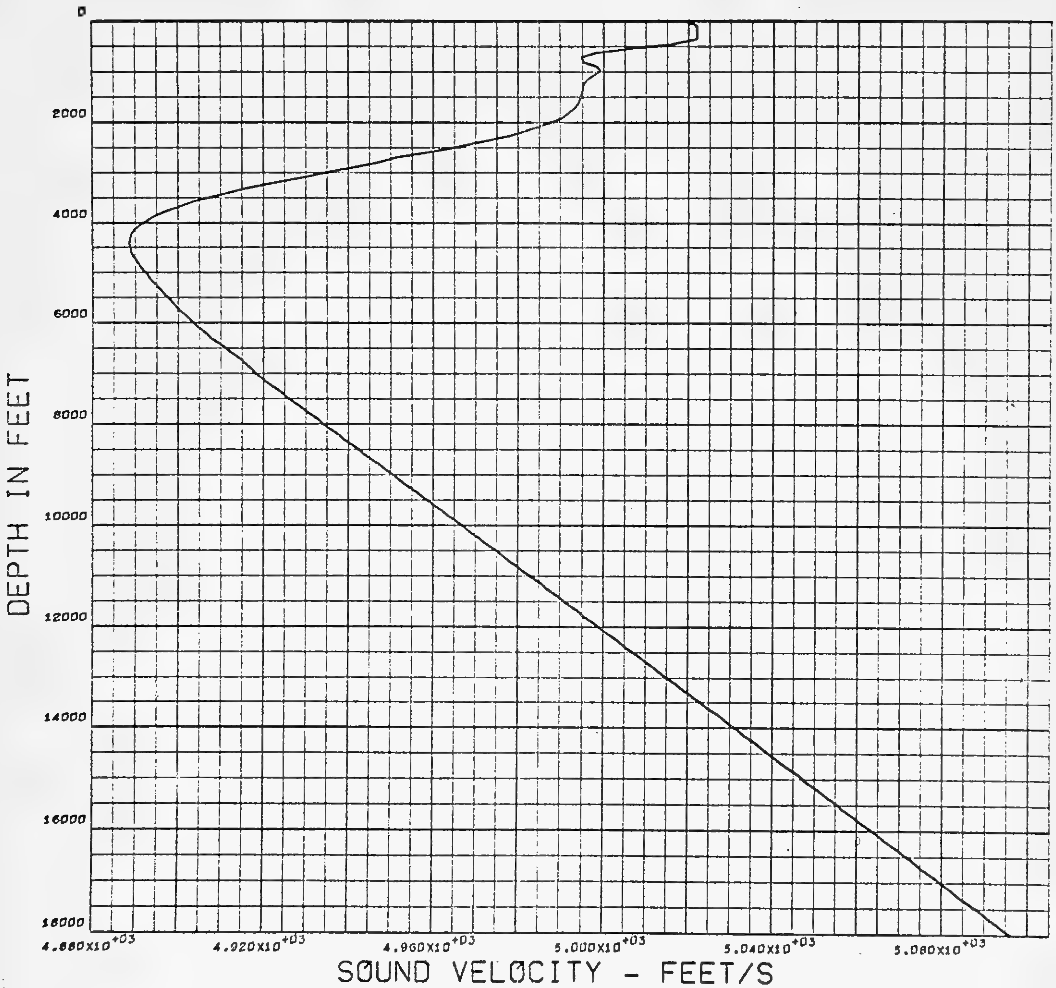


FIGURE A-1 (Continued)

RAY PLOT FOR VP-1

INITIAL ANGLES -1.5 to +1.5 in 0.15° STEPS

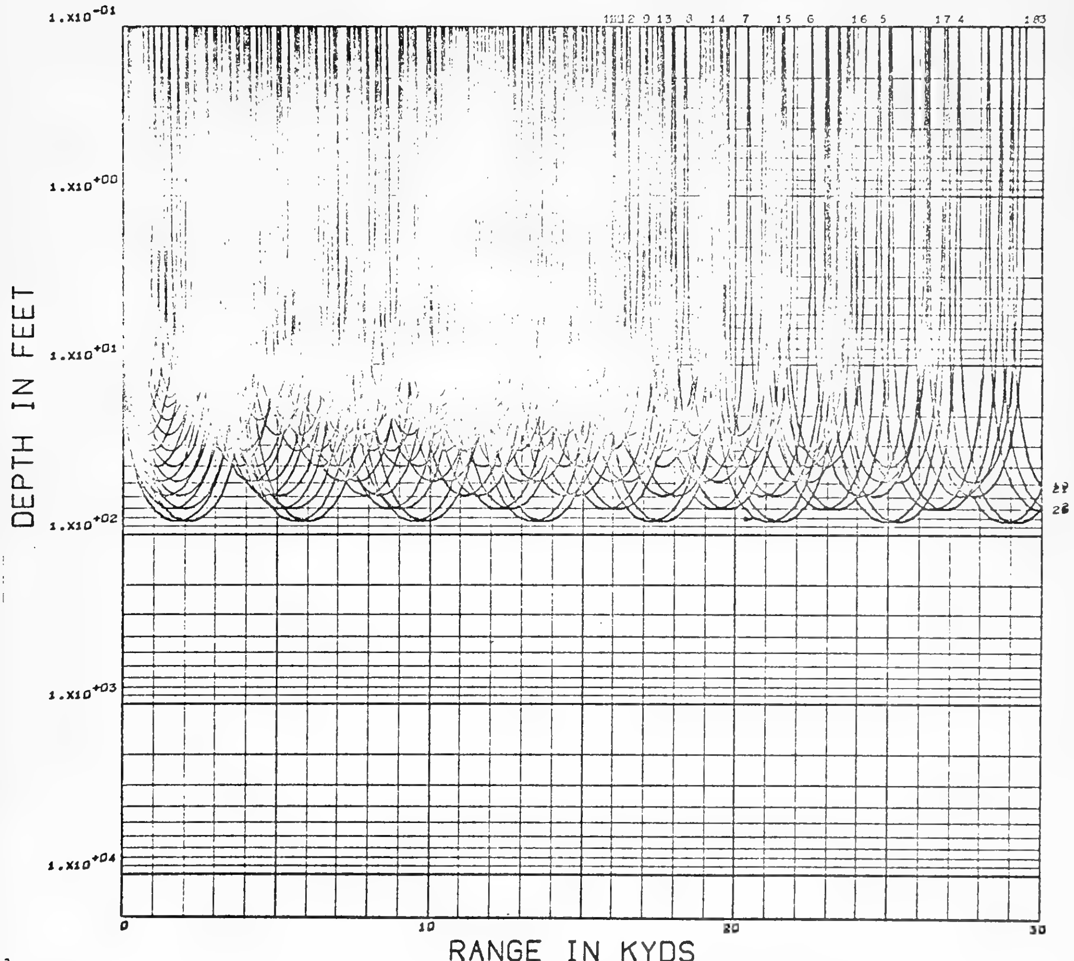


FIGURE A-2

VP-2 ISOVELOCITY INITIAL GRADIENT

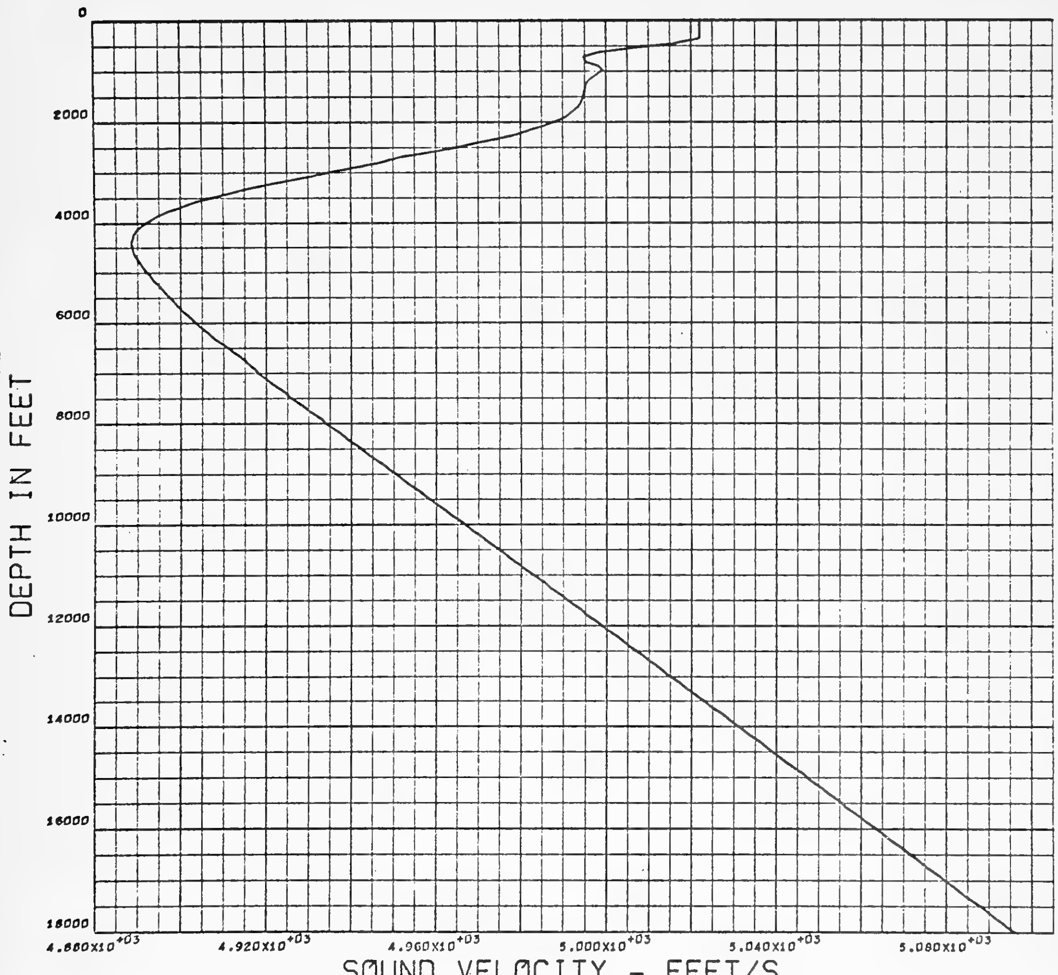


FIGURE A-2 (Continued)

RAY PLOT FOR VP-2

INITIAL ANGLES -1.5 TO +1.5 IN 0.15° STEPS

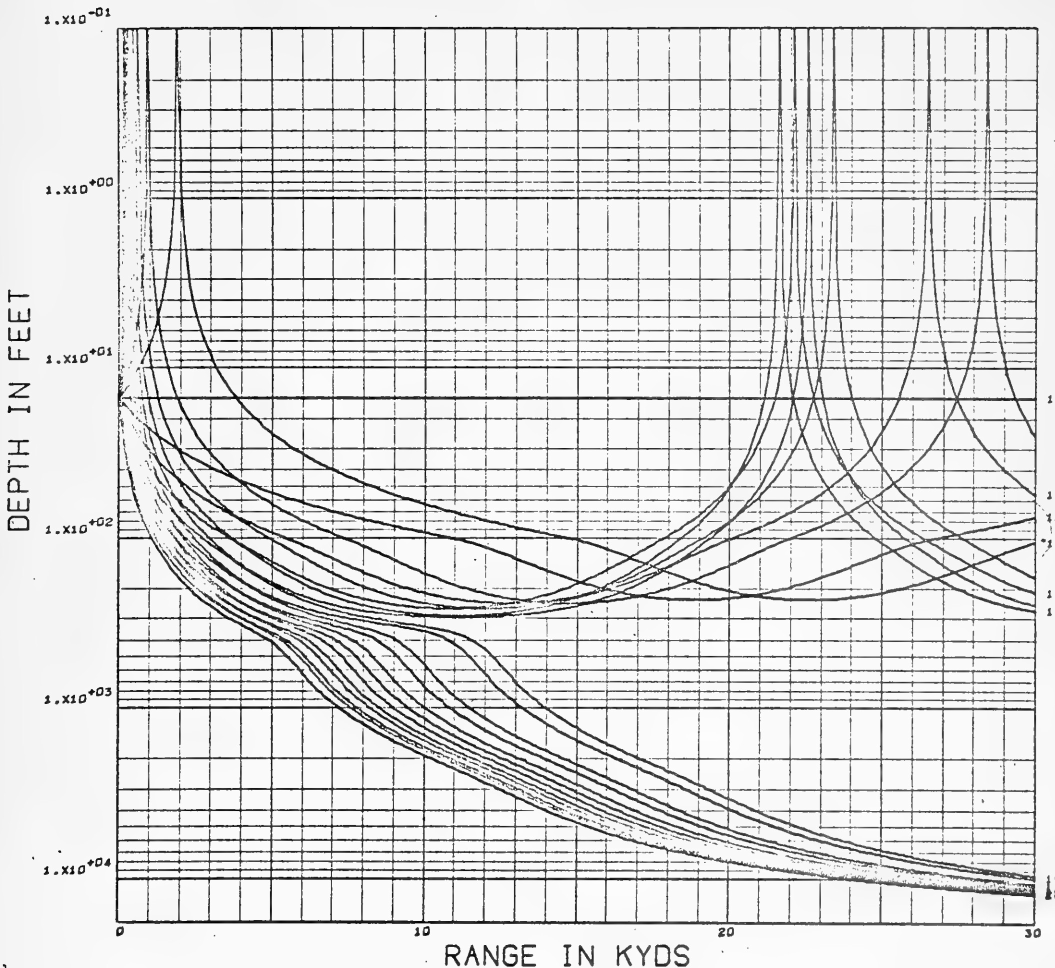


FIGURE A-3

VP-3 NEGATIVE INITIAL GRADIENT

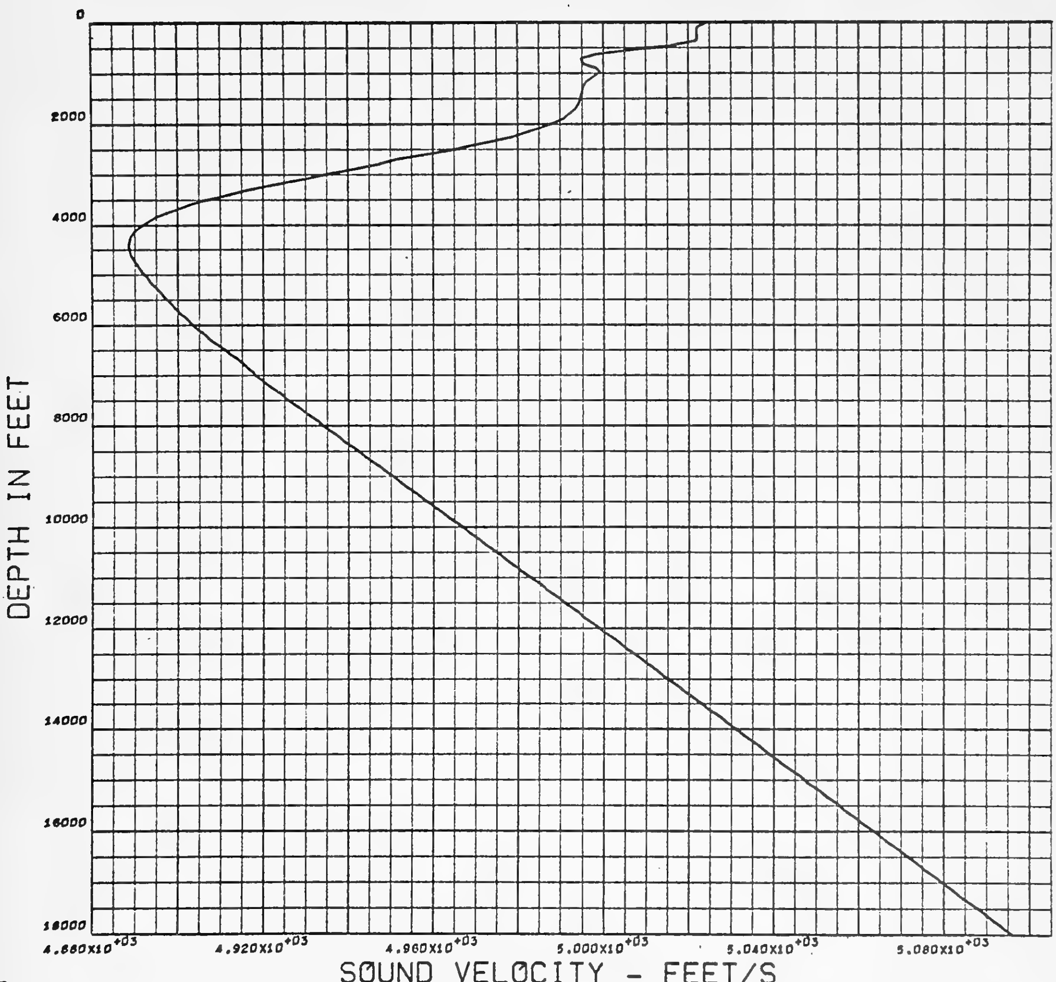


FIGURE A-3 (Continued)

RAY PLOT FOR VP-3

INITIAL ANGLES -1.5 TO +1.5 IN 0.15° STEPS

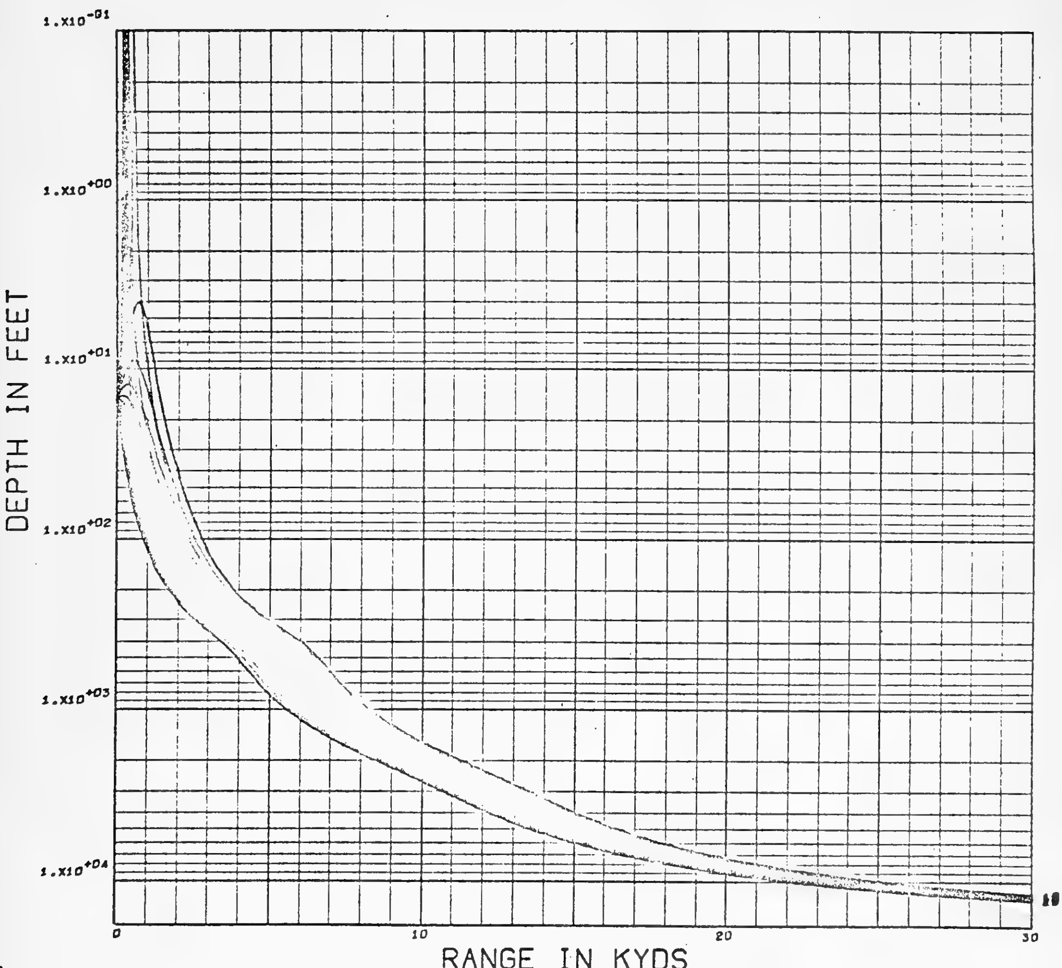


FIGURE A-4

RAY PLOT SHOWING CONVERGENCE ZONES FOR VP-1

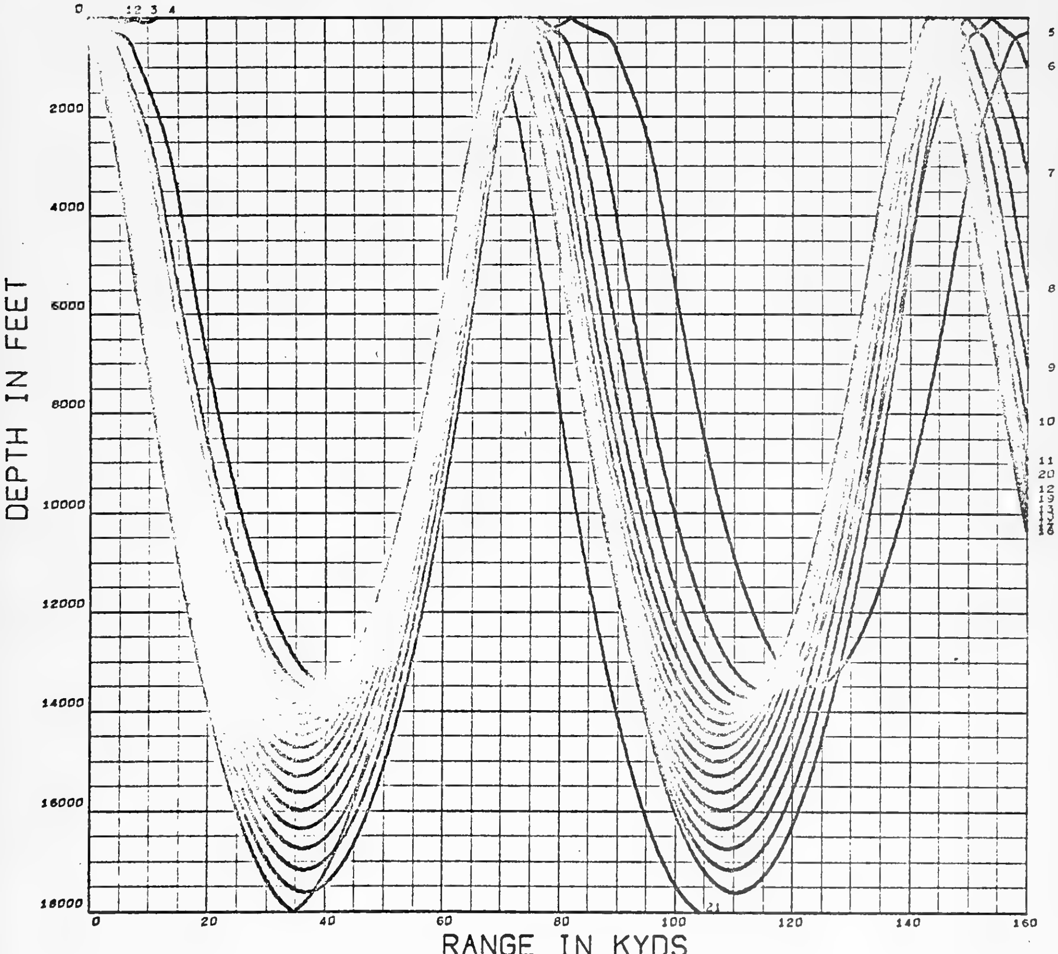
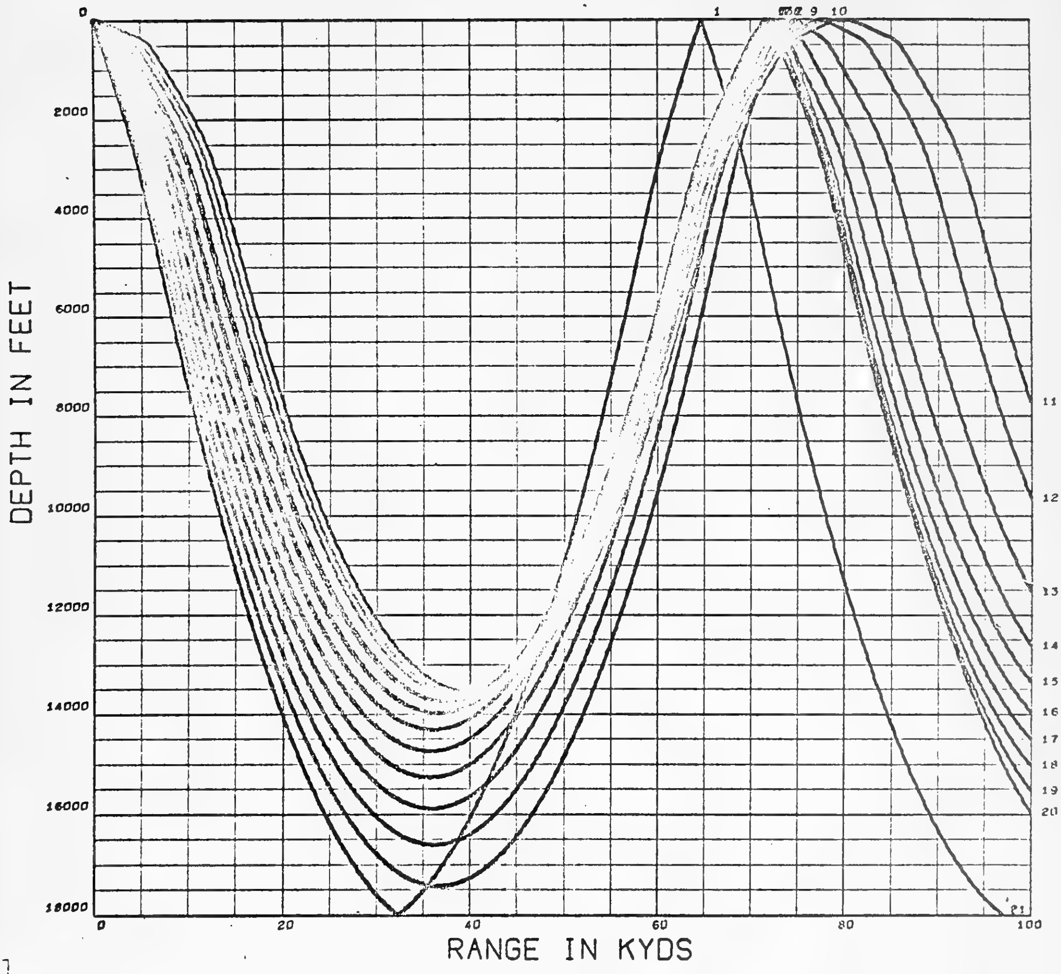


FIGURE A-5

RAY PLOT SHOWING CONVERGENCE ZONE FOR VP-3



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13. ABSTRACT


Data on the speed of sound in the sea is a prime requirement in Navy operations. Only relative accuracy in the measurements of sound speed as a function of depth is needed in tactical situations because it is the shape of the velocity profile that is of major importance to hull mounted sonar. Absolute accuracy in the measurement of sound speed is desirable, however, in order to exploit longer range propagation in the deep sound channel.

The sound speed can be measured either indirectly, by computation from temperature and salinity or density data, or directly, by using "velocimeters". In tactical situations, temperature data alone has sufficed for the indirect method except under certain near shore conditions, where skilled guesswork has been required.

Present velocimeters based on the "sing-around" principle are adequate for oceanographic survey purposes, from the points of view of accuracy and depth capability. However, their connecting cables render them unsuitable for tactical use; in general, the manufacturers of velocimeters are aware of and have been attempting solutions to the problems that arise from this application.

The value of temperature data alone for defining the presence of a surface duct in shallow water where sharp salinity changes can occur should be studied. We believe that there exists a case for the development of an expendable instrument or of a synoptic technique for tactical use to supplement the now successful expendable bathythermograph.


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