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SOUND TRANSMISSION IN SEA WATER

A PRELIMINARY REPORT

Prepared By The
Woods Hole Oceanographic Institution
For The
National Defense Research Committee

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SOUND TRANSMISSION IN SEA WATER

CHAPTER I

INTRODUCTION

During the last 20 years or more commercial and naval ships have made increasing use of a variety of instruments in which the transmission of sound in sea water plays an important part. Throughout this development the engineers and physicists have devoted most of their attention to the instruments, both sending and receiving units, for from the beginning it seemed likely that through improvements in design and construction very great gains would result in the usefulness of such equipment. This has proved to be the case, and the instruments have now reached a high state of technical perfection, yet from the standpoint of naval tactics the great fluctuations in the effective range of some types of underwater sound equipment has been disappointing.

While improvements in oscillators or projectors (sending elements) and hydrophones (receiving elements) still continue, it now seems clear that one important part of the problem, namely the role played by the sea water, has perhaps received too little attention. Especially when sound must travel horizontally and near the surface, the distribution of temperature and dissolved salts at depths of less than 100 fathoms determines the range. At some seasons and in some areas these and other physical characteristics of the water can be very favorable to lateral sound transmission, and at other times or in other regions the reverse may be the case.

One result is that it has been difficult to make a reliable comparison of the performance of different types of equipment. Another is that full confidence cannot be placed in supersonic methods of detecting submarines, unless the sound transmitting qualities of the water are known to be good. This report is an attempt to summarize existing knowledge in a manner which will throw light on these difficulties, and also to explore the problem in such a way as to provide a basis for future investigations. Special attention will be given to the possibility of predicting the effective range of supersonic signaling methods in various parts of the ocean and at various seasons.

In studying the transmission of sound in sea water two fields of science must be utilized, physics and oceanography. The physics of the problem is relatively well known, but the oceanographic factors seem, until now, to have been generally overlooked. Thus in this preliminary report the latter will be emphasized. In order to round out the discussion a brief summary of the development and uses of the various types of sound equipment has been included.

DEVELOPMENT OF THE ART OF SUBMARINE SIGNALING

1. HISTORICAL BACKGROUND

Leonardo da Vinci (1452-1519) knew that water was a particularly good conductor of sound. He recorded the fact that ships could be heard "at a great distance" by use of a trumpet-shaped tube, one end of the tube being placed in the water and the other held to his ear. Presumably the sound heard was the splash of galley oars.

To signal between boats, the native fishermen in Ceylon produce a sharp sound by striking an earthenware pot, known as a "chatty", held underwater. This sound can be heard at considerable distances by placing the ear against the hull of the boat.

In 1826 J. D. Colladon and J. K. F. Sturm made the first reliable measurement of the speed of sound in water in Lake Geneva. They used a 140 lb. church bell, held 10 ft. under water and struck with a hammer, as a sound source. The flash from a charge of gunpowder which exploded when the bell was struck, signaled the instant of origin of the sound. The detector was a large ear trumpet held with one end in the water. They were able to signal to distances of 14000 yards in water which averaged 70 fathoms in depth. In 1841 Colladon repeated his experiment using a very much heavier church bell, and could still detect the sound at a distance of 35000 yards. He stated that the use of suitable equipment would permit ranges of several hundred kilometers under favorable conditions. He was thus the first to recognize and clearly point out the possibility of practical use of underwater sound signaling.

In 1888 M. Banare published "Les Collisions en Mer" in which he discussed fully the status of underwater sound technique. He developed an underwater microphone and gave a method for using the sound shadow of the ship to determine the bearing of the sound source. At about this time several British and German investigators made studies on underwater sound but none of them developed apparatus suitable for practical use. By 1898 it was evident that submarine signaling was feasible, but the apparatus which would make it commercially available had not been perfected.

2. EARLY DEVELOPMENTS

Starting in 1898 A. J. Mundy and E. Gray, later joined by J. B. Millet to form the Submarine Signal Company, developed a system which could be adapted to commercial use. In this system, the sound from a submerged bell could be heard at a considerable distance by means of a submerged microphone, but the microphones could only be used when cast overboard from a motionless vessel in a calm sea. Following this, Gray mounted the microphones in a fish-like housing and obtained satisfactory performance while towing it behind a moving ship.

The next improvement was introduced by Gray and Mundy in 1902. It consisted of placing the microphones in water filled tanks built inside the hull well below the water line so that the hull formed one side of the tank. When such tanks were placed on both sides of the hull it was possible to determine the approximate bearing of the sound source. Specially designed submarine bells were constructed for use on lightships, the first being installed on Lightship No. 54 in Boston Harbor in 1903. The service given by this bell proved so valuable an aid to navigation under conditions of poor visibility that within a few years the system was adopted on many important lightships of the United States and also in other parts of the world. This system was installed on a number of naval vessels for signaling purposes, but the bell was not a particularly suitable instrument for sending signals in Morse code.

Many other investigators sought to find sound generators more suitable for sending Morse code. Water sirens, both the rotor and the oscillator type, were tried. Water-blown organ pipes and large underwater electromagnetic telephones were tested, all without success.

3. THE FESSENDEN OSCILLATOR

In 1912 R. A. Fessenden of the Submarine Signal Company produced an electrodynamic oscillator which, in contrast with previous electromagnetic types, exerted great forces on a diaphragm on both the "push" and the "pull" phases of the cycle. This device greatly increased the range of underwater sound signaling and permitted rapid transmission of Morse code. At the outbreak of war in 1914 it became standard equipment for our submarines and following the war it replaced the bells on many lightships, giving remarkable improvement in range and quality of the signals emitted. The Fessenden oscillators used in the United States had a frequency of 540 or 1050 cycles per second.

4. ECHO DEPTH SOUND

When suitable transmitters and receivers for underwater sound became available it was a natural step to apply them for measuring the depth of water by timing echoes from the ocean bottom.

In 1914 R. A. Fessenden tested his oscillator during the ice patrol cruise of the Coast Guard cutter MIAMI, in an effort to obtain echoes from icebergs. He detected signals from the ocean bottom, and the travel time of the echoes could be used to calculate the depth of water. In later tests he was able to measure echoes from 3000 fathoms off the Azores.

Following the world war development of echo sounding equipment was achieved by providing one of the Fessenden oscillators with an arrangement for accurately timing the echoes. This development was largely due to H. G. Dorsey. Various other systems have since been invented in America, France, Germany and Great Britain, which are similar to

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this system in that they use sound in the audible range of frequencies (usually about 500 to 1000 cycles per second). They differ only in details of the methods for generating, receiving and timing the sound waves.

In June 1922 the U.S.S. STEWART conducted an epoch-making test between Newport and Gibraltar. While maintaining a constant speed of 15 knots she averaged 100 echo soundings per day. A Fessenden type oscillator was used for transmitting sound signals and a Navy Sonic Depth Finder, developed by H. C. Hayes, was used for timing the echoes. Depths as great as 3200 fathoms were measured without difficulty. During November and December 1922 the U.S.S. CORRY and the U.S.S. HULL made hydrographic surveys from San Francisco to Point Descanso, Mexico, the results of which were shown on Hydrographic Office Chart No. 5194. These voyages were of greatest scientific interest and opened a new era in knowledge of oceanic depths.

5. HIGH FREQUENCY SOUND

The proposal to use supersonic waves (20,000 to 100,000 cycles per second) for submarine signaling was put forward by an Englishman, E. Richardson. He pointed out that at these frequencies it would be possible to produce directional beams of sound which could be directed like the beam of a searchlight. To produce such a beam, either the source of sound itself or a suitably shaped reflector must have dimensions several times as large as the wave length of sound used, and this is practical only when the waves are short. Richardson was unable to produce a suitable generator for sounds of high frequency.

About 1915 two Frenchmen, P. Langevin and M. Chilowsky, began experiments on production of high frequency sound by means of the mechanical action between the plates of a condenser, but this system could not be made to give sufficient intensity for practical use. The problem was simply one of transforming high frequency electrical oscillations into mechanical oscillations, and it was solved when Langevin thought of using the piezo-electric properties of quartz. If plates cut from these crystals at suitable angles are used as the insulator in a condenser and subjected to electric fields, they undergo changes in thickness. Conversely the same plates will generate electric charges on the condenser if they are subjected to mechanical pressure. A "piezo-electric sandwich" was constructed by placing a mosaic of thin quartz slabs between two plates of steel which were used as the plates of a condenser. By suitable choice of thickness of quartz and steel the resonant frequency of the "sandwich" could be given any desired value in the supersonic range. In 1924 a device of this type, about 4 inches in diameter, mounted in the hull of a ship with one steel plate in contact with the water gave a directional sound beam with sufficient power to transmit signals 4.9 miles, to obtain echoes from floating objects at 2200 yards, and to take soundings up to 245 fathoms. The same unit was used as a transmitter of the sound beam and receiver for the echo. It was not quickly taken into general use because the apparatus appeared too complicated for use at sea.

Rochelle salt crystals exhibit the phenomena of piezo-electricity more strongly than quartz and can be used to construct efficient sound projectors suitable for high frequency operation. These projectors have the advantage that they can be made to work efficiently without taking advantage of mechanical resonance, which is necessary in the case of quartz. Many of the projectors in use today are Rochelle-salt units.

Some of the projectors in use at present operate on the principle of magnetostriction. When placed in a magnetic field, a magneto-strictive metal changes its dimensions. High frequency changes in magnetic field, produced by high frequency electric currents, are used to set nickel tubes or plates into vibration at supersonic frequencies.

6. SUBMARINE DETECTION

For several reasons supersonic waves are far more useful than sound of lower frequency in detecting submarines. High frequency sound transmitters and detectors are strongly directional in their action, and they are less disturbed by noises originating in the ship or in the movement of the ship through the water. Furthermore a smaller target will serve as an efficient reflector for supersonic waves than for those of audible frequencies. Finally, when a supersonic detector is used in listening for sound generated by a submarine, it exhibits the same directional properties which it possesses in its application in echo ranging.

When water conditions are suitable for effective transmission of sound, supersonic methods are highly effective for submarine detection.

Supersonic echo ranging has been used by submarines travelling below periscope depth for determining both the bearing and the range of a target. For listening to sounds generated by the target, it is often preferable to use a detector sensitive to the supersonic components of these sounds instead of one designed to receive the low frequency components because the former can be made with far more directional sensitivity than the latter.

PHYSICS OF SOUND IN SEA WATER

1. THE SPEED OF SOUND IN SEA WATER

General Statement

The speed of sound in sea water depends on the temperature and composition of the water. In general these quantities vary from time to time, from place to place, and with the depth beneath the surface. Variations in the speed of sound play a most important part in echo ranging and in other methods of signaling in which sound is transmitted horizontally through sea water. Obviously changes in the speed of sound will cause changes in the time required for a signal to travel between two given points, but in echo ranging this effect is small and never serious. The important point is that changes of velocity with depth, even slight ones due to warming of the surface water on a bright calm day, deflect the sound beam from the horizontal plane and may cause it to undershoot or overshoot the target. These deflections of the sound beam are far more important than any other factor in the horizontal range of underwater sound.

The increase in the speed of sound per foot increase in depth is called the vertical velocity gradient. It usually varies with depth. It is the factor which determines the deflections of a sound beam, and it is therefore the most important property of the water from the viewpoint of echo ranging.

Factors Which Determine The Speed Of Sound.

The speed of sound at any point in the ocean may be calculated if the temperature, salinity and pressure of the water at that point are known. The temperature is determined by lowering a suitable thermometer to the desired point. The salinity, which is defined as the number of grams of salt in 1000 grams of sea water, can be determined chemically, electrically, or by use of a hydrometer, provided a sample of water from the point in question is available. The pressure depends primarily on the depth beneath the surface, and may readily be calculated.

In echo ranging work, where depths greater than a few hundred feet are not involved, the temperature is far more important than either of the other factors in determining the speed of sound. A temperature variation of only 0.1°F per hundred feet of depth can produce a marked influence on the range of a sonic beam, and changes many times larger than this are commonly present.

The salinity of the water in the open ocean is reasonably constant and does not introduce serious changes in the speed of sound. In coastal waters there are frequently larger variations in salinity due to the presence of river water which has not become thoroughly mixed with the sea water, but in nearly all situations thus far examined the temperature exerts more influence than salinity in determining the speed of sound.

The velocity changes caused by pressure are not large because the depths involved in echo ranging are slight. Although the pressure effect is small it is quite important in cases where the temperature and salinity are both constant, as in a thoroughly mixed surface layer. It will be shown later that in such cases the rays of the sound beam are bent upward into circles whose centers lie approximately 280,000 ft. or about 47 nautical miles above the surface. This situation is favorable for sound ranging, and maximum ranges will be obtained provided the mixed layer extends deep enough so that the lower rays of the beam do not run out of it before recurving.

All three factors change the velocity in the same direction. An increase in temperature, salinity, or pressure causes an increase in the velocity of sound. For purposes of comparison the following list shows the changes in temperature or salinity which produce velocity changes equal in magnitude to that caused by the effect of pressure alone:

- 1°F in 76 fm at 32°F
- 1°F in 61 fm at 50°F
- 1°F in 48 fm at 68°F
- 1 part per thousand salinity in 39 fm.

Calculation Of The Speed Of Sound

The two graphs in Figure 1 may be used for computing the speed of sound in sea water. The main part of this graph gives the speed in feet per second at zero depth and at any desired temperature and salinity. The auxiliary graph gives the correction which must be added to allow for the effect of pressure at a point beneath the surface.

In echo ranging work the vertical velocity gradient is more important than the velocity itself. It is most conveniently computed from the gradients of salinity and temperature. The salinity gradient is the rate of increase of salinity with depth, in parts per thousand (‰) per foot. The temperature gradient is the rate of increase of temperature with depth, in degrees Fahrenheit per foot. The vertical velocity gradient in feet per second per foot, may be computed from the formula:

Vertical velocity gradient = 0.0182 + (K x temperature gradient) + (4.3 x salinity gradient), where 0.0182 is the gradient due to pressure and K, the coefficient of the temperature gradient, may be read from the graph of Figure 2 for the mean temperature of the range involved. These gradients are positive if the quantity in question increases with depth, negative if it decreases.

The graphs for computing the speed of sound are based on tables published in the "Hydrographic Review" Vol. XVI, pp. 123-40, 1939, by S. Kuwahara.

Sample Computations

(a) Depth = zero	From Figure 1, Temperature and salinity, . . .	5022.0
Temperature = 75.2°F.	" " Pressure,	0.0
Salinity = 36.5 ‰	Sound speed	5022.0
Find the sound speed		ft/sec

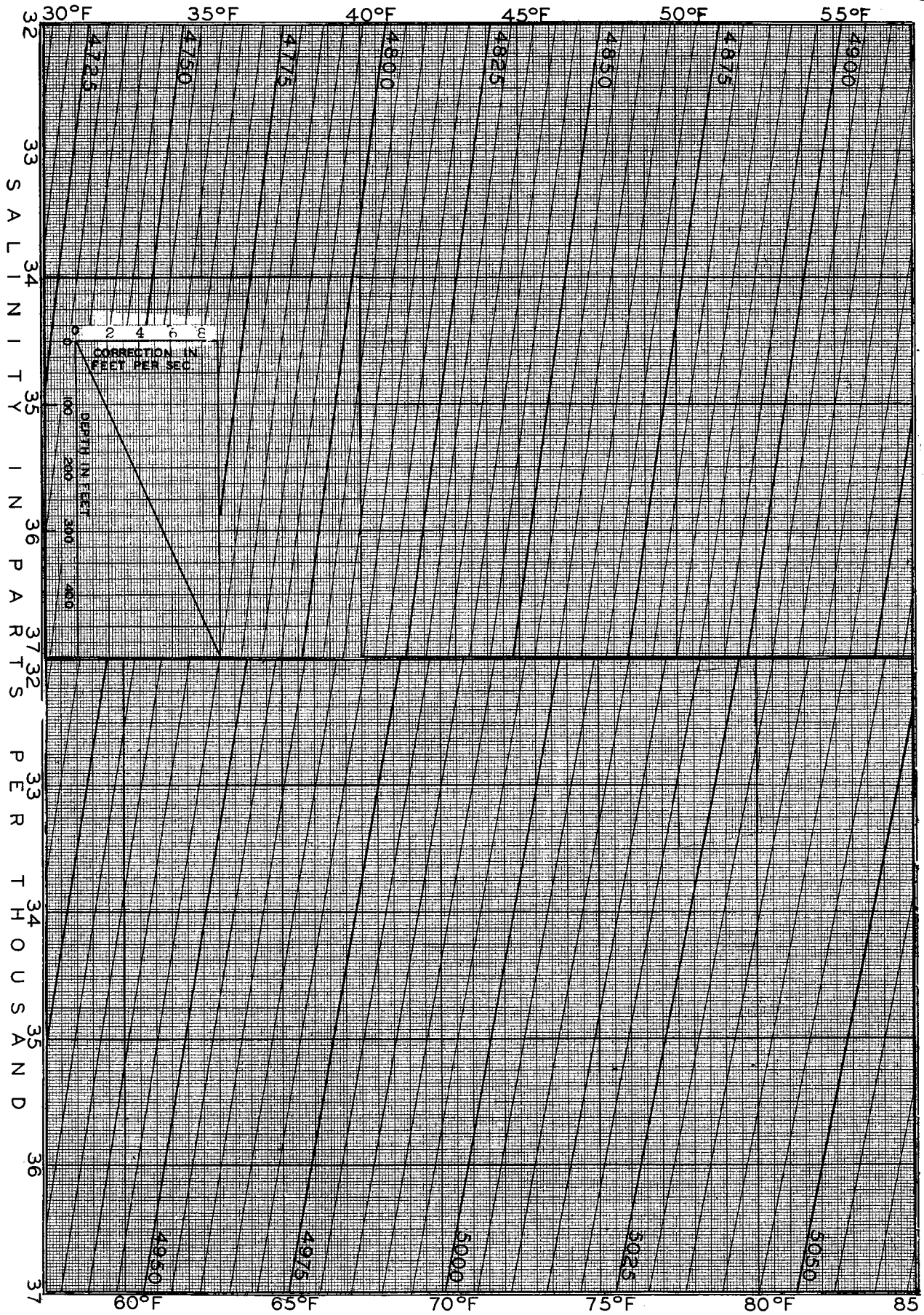


Fig. 1. SPEED OF SOUND IN SEA WATER

(b) Depth = 230 ft.
Temperature = 70.7°F
Salinity = 36.5 ‰
Find the sound speed-

From Figure 1, Temperature and salinity, 5001.1
" " Pressure 4.1
" " Sound speed 5005.2
ft/sec

(c) Temperature constant
Salinity constant
Find the vertical gradient of sound speed-

From Figure 2, Temperature effect . 0.0
" " Salinity effect . . 0.0
" " Pressure effect . . 0.0182
0.0182
ft/sec/ft

(d) Temperature, 42.5°F at surface, 40.0°F at 65 ft.
Salinity, 32.3 ‰ at surface, 32.4 ‰ at 65 ft.
Find the vertical gradient of sound speed by assuming constant temperature and salinity gradients from surface to 65 ft.

Temperature gradient = $2.5/65 = -0.0384^\circ\text{F}$ per ft.

From Figure 2, K at $41.3^\circ\text{F} = 7.5$

Gradient of sound speed due to temperature = $7.5 \times -0.0384 = -0.288$

Salinity gradient = $0.1/65 = 0.00154$ ‰ per foot

Gradient of sound speed due to salinity = $0.0015 \times 4.3 = 0.006$

Gradient of sound speed due to pressure = 0.018

GRADIENT of sound speed (in ft. per sec per ft.) = 0.018
-0.264

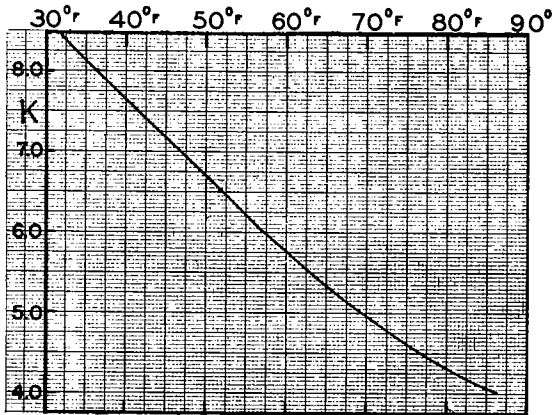


FIG. 2. GRADIENT OF THE SPEED OF SOUND.
It is computed by the equation:
 $0.0182 + (K \times \text{temp. grad.}) + (4.3 \times \text{sal. grad.})$.
The temperature gradient is in degrees Fahrenheit
per foot and the salinity gradient is in
parts per thousand per foot.

Measurement of Temperature and Salinity

Surface water. For the water at the surface a technique for the measurement of temperature with simple apparatus has been evolved which is well known and widely available. The salinity also could be determined for surface water to useful accuracy by means of a relatively simple apparatus. From these two measurements the speed of sound in the surface water could be derived. This value alone would have practically no value for predicting the performance of echo ranging apparatus because the variation of speed with depth is the controlling factor.

Nansen bottles and reversing thermometers. This is the standard apparatus for oceanographic research at the present time. The Nansen bottles with reversing thermometers attached are lowered to the desired depth by means of a wire. A "messenger" is then released at the surface and allowed to slide down the wire. The messenger causes the frame which holds the bottle and thermometer to invert itself, closing the water bottle and breaking the mercury thread in the thermometer in such a way that the reading of the thermometer will not change while the apparatus is being hauled to the surface. Thus a

reading of the temperature and a sample of water for salinity determination are obtained from any desired depth. Usually two thermometers are attached to each bottle, one having its bulb protected and the other having its bulb exposed to the water pressure. The difference in the two thermometer readings indicates the depth, giving a more accurate value of depth than can be obtained from the length of wire paid out and its inclination at the surface. In actual practice ten to twelve water bottles are attached to the wire at suitable intervals, giving data for a number of depths for a single lowering. While this technique yields accurate observations, its drawback is that the ship must be stopped for half an hour or more each time readings are obtained.

The electrical resistance thermometer. This thermometer consists of a resistor whose change in resistance with temperature is accurately known. The resistor is lowered to the desired depth by means of an insulated cable and the resistance is measured on board ship by means of a suitable bridge circuit. The principal advantage of this type of thermometer is that the temperature can be read at many different depths during a single lowering. This type of thermometer has not been widely used for sea water temperatures, its principal disadvantage being that it is difficult to read the galvanometer at sea.

The bathythermograph is an instrument for obtaining a continuous record of temperature against depth. It consists of a pressure responsive element which moves a small glass slide parallel to the length of the instrument, and a temperature responsive element which moves a pen across the slide. The instrument is convenient to use and has given satisfactory performance to depths of 500 feet while operating from a vessel moving as fast as 14 knots. It seems to be the ideal instrument for detailed measurements in the first few hundred feet of water, its greatest advantages being that it measures temperature continuously and that it can be used while the ship is under way.

Regional And Seasonal Charts Of Water Conditions

The easiest way to find out how sound speed varies with depth at a given time and place would be to read it off a suitable chart. The need for such charts is new and the data necessary for their preparation are not plentiful because oceanographers have not concentrated their attention on the first few hundred feet of water. The sections and diagrams in Chapters IV and VI include most of the information which is available at the present time, and they can serve as a valuable guide. Additional data are being collected for use in the preparation of a more extensive set of charts. In Chapter V methods are given for determining the performance of underwater sound apparatus from these charts.

2. DENSITY OF SEA WATER. STABILITY

Factors Which Determine The Density

The density of sea water may be considered as the ratio of the weight of a given vol-

ume of sea water to the weight of an equal volume of distilled water at 4°C. The values of density observed at the surface fall between about 1.020 and 1.030.

The factors from which the density of sea water is determined are temperature, salinity, and pressure. The density increases with increasing salinity and pressure, but decreases with increasing temperature because water expands when heated. In the range of depths involved in echo ranging, the effect of pressure upon density is slight, but the effects of temperature and salinity are important and must be understood before one can grasp the principles governing variations of sound speed in the upper layers.

By the use of the graph in Figure 3 the density of sea water under surface pressure may be determined for given values of temperature and salinity. An auxiliary graph for allowing for the effect of changes in pressure is shown at the bottom of Figure 3.

Calculation Of Density Of Sea Water

The following calculation of the density of the water is given for the temperatures and salinities observed at a station in coastal water in 41 fathoms off Block Island, April 13, 1938. The temperature decreases down to 20 meters but increases from there to bottom, becoming higher at the bottom than at the surface. The salinity increases all the way to the bottom, its effect upon density more than offsetting the effect of the rise in temperature of the lower part of the water column. This example confirms the general rule that density increases all the way to the bottom.

Depth		Temp.		Salinity	Density	
meters	fathoms	OC	OF	o/oo	at surface pressure	at actual pressure
1	0.55	5.84	42.5	32.39	1.02554	1.02554
10	5.47	5.09	41.2	32.31	1.02556	1.02560
20	10.94	4.46	40.0	32.47	1.02575	1.02585
30	16.40	4.55	40.2	32.56	1.02581	1.02596
40	21.87	4.85	40.7	32.74	1.02592	1.02611
50	27.34	6.35	43.4	33.39	1.02626	1.02650
60	32.81	6.59	43.9	33.49	1.02631	1.02660

The densities are calculated in two ways: first the potential density, which is the density the sample would have if brought to the surface, and second the actual density, which is the density of the sample in place. In much oceanographic work the potential density is the quantity considered, because it indicates directly whether the water from one level would be heavier or lighter than its surroundings if it were transported to another level.

This discussion of density has not been introduced for use in calculating the speed of sound because the equation $velocity = \sqrt{\frac{elasticity}{density}}$ is not convenient for use in this calculation. It has been included to enable the reader to understand stability of the water column, the vertical circulation which occurs when the stability is destroyed, and the vertical distribution of temperature to which this circulation can lead.

