The American Philosophical Society

announces that an award will be made in the year 1921 of the

HENRY M. PHILLIPS PRIZE

The subject upon which essays are to be submitted is

The Control of the Foreign Relations of the United States: The Relative Rights, Duties, and Responsibilities of the President, of the Senate and the House, and of the Judiciary, in Theory and in Practice.

The Essay shall contain not more than one hundred thousand words, exclusive of notes, and must be in the possession of the Society on or before December 31, 1920.

The Prize for the crowned essay will be Two Thousand Dollars, in gold coin of the United States, to be paid as soon as may be after the award.

Attention is called to the following regulations governing the award of the Prize:

Competitors for the prize shall affix to their essays some motto or name (not the proper name of the author, however) and when the essay is forwarded to the Society it shall be accompanied by a sealed envelope containing within the proper name and address of the author and on the outside thereof the motto or name adopted for the essay.

At a stated meeting of the Society in pursuance of the advertisement, all essays received up to that time shall be referred to a Committee of Judges, to consist of five persons, who shall be selected by the Society from nominations made by the Committee on the Henry M. Phillips Prize.

Essays may be written in any language, but, if not in English, must be accompanied by an English translation.

No essay which has been already published or printed, or for which the author has received any prize or profit of any nature whatsoever, shall be accepted in competition for the prize.

Essays must be typewritten on only one side of the paper, and six copies must be furnished by their respective authors for the use of the Committee of Judges.

The literary property of such essays shall be in their author, subject to the right of the Society to publish the crowned essay in its "Transactions" or "Proceedings."

The Society reserves the right not to award the prize if none of the competing essays is deemed worthy of it.

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The essays must be sent, addressed to the President of the American Philosophical Society, No. 104 South Fifth Street, Philadelphia, U. S. A.

PROCEEDINGS

OF THE

AMERICAN PHILOSOPHICAL SOCIETY

HELD AT PHILADELPHIA

FOR PROMOTING USEFUL KNOWLEDGE

DETECTION OF SUBMARINES.

By HARVEY C. HAYES, Ph.D.

(Read April 26, 1919.)

Outline.

1. Introduction:
   Research and development work carried out by two groups of scientists, one group backed by private companies, the other by the U. S. Navy.
2. Two general methods for detecting the presence of a body:
   a. Through energy radiated from the body.
   b. The presence of a field of force surrounding the body.
3. Both methods applicable to case of moving submarine.
4. First method most effective (radiated energy being sound), second method weak, due to limited range (field of force being magnetic).
5. Sound (physical characteristics).
6. Resonance and pressure type submarine receivers.
7. Types of submarine receivers:
   a. Acoustic.
   b. Microphonic.
   c. Magnetophone.
   d. Electrostatic Condenser.
8. Requirements for a perfect submarine detector.
9. Methods for determining direction:
   a. Maximum-minimum principle.
   b. Binaural principle.
10. Types of submarine detectors developed by:
    a. England—Mark I, Mark II, Mark I and Mark II, Nash Fish and Ryan Fish.
    b. France—Perrin Shielded Microphones and Walser Plate.
    c. United States—
        I. Submarine Signal Company.
            (1) Tuned Microphone.
            (2) Oscillator.
        II. General Electric Company.
            (1) C-Tube.
            (2) Three-Spot Devices:

Introduction.

The development of submarine detectors in this country started shortly after the United States entered the war. In April, 1917, the Submarine Signal Company, General Electric Company, and the Western Electric Company combined for the study of submarine detector apparatus and started a station at Nahant, Massachusetts. A foreign commission from France and Great Britain visited the United States in June, 1917, and laid before those most interested all the knowledge of submarine detection at that time in the hands of the French and the British. As a result of this visit, the United States Naval Experimental Station was started at New London, Connecticut, under the control of the United States Navy, and several physicists and engineers from different parts of the country were called together to carry on the research and development work at this station under the direction of the Special Board on Anti-Submarine Devices.

In the following paper no attempt has been made to give credit to individuals, but the developments brought about at the Naval Experimental Station and at the Nahant Station have been carefully stated in the hopes that proper credit may be given to each group of experimenters and in order that the excellent results accomplished by the United States Navy in this comparatively new field may be made known to the public.

General Methods.

The presence of a body beyond our reach can be detected by intercepting some form of energy radiating from the body or through the presence of some field of force surrounding the body. The first method promises detection at a greater range than the second since the intensity of radiant energy varies as the inverse square of the distance from the source while the strength of a field of force surrounding a polarized body varies as the inverse cube of the distance.

Both methods are applicable to the case of a moving submarine. The steel shell of the submarine must be surrounded by a magnetic field, due to polarization induced by the earth's magnetic field and also due to such permanent polarization as it may have taken on during construction. Also a certain amount of sound must radiate from the motors and propellers and other moving parts of the submarine.

Magnetic Methods Unsatisfactory Because of Limited Range.

The intensity of polarization which a submarine takes on through the action of the earth's magnetic field can be predicted with some accuracy and, as a result, the range at which it can be detected by magnetic methods foretold. Both theory and practice show this range to be about ⅔ the length of the submarine. This range, which is too slight to be helpful in searching or avoiding an operating submarine, is hardly sufficient for detecting any but the largest submarine when lying at rest on the bottom at maximum depth. No satisfactory method for determining the presence of a submarine lying at rest at considerable depth, say from 100 to 150 feet, has yet been perfected, but one or two promising methods are in the process of development.

Sound Methods Promise Greater Range.

Water is an excellent medium for transmitting sound. Its homogeneity and low viscosity makes the dissipation due to reflection, refraction, and transformation into heat comparatively slight.

The relation between intensity and distance is more favorable than that given by the inverse square law, because of the fact that the surface and bottom reflect the sounds and tend to keep them within two dimensional motion, much as the speaking tube confines sound to motion of one dimension. Because of this fact, sounds can be heard farther than they could if they were not confined.

A submarine sound having an amplitude of $1/10^{10}$ inches is near the limit of audibility. This represents a movement of the particles of the medium through a distance less than $1/30$ the diameter of the smallest atom.

The fact that water transmits sound energy with slight loss and that the relation between intensity and distance is more favorable than the inverse square law makes it appear reasonable that sounds can be heard at great distances in water if the energy of sound waves of such minute amplitude can be efficiently collected and brought to the ear.

General Nature of Sound.

Sound is a longitudinal wave motion having some vibrating body as a source. It travels through any material medium with a definite velocity depending upon the physical properties of the medium. The ratio of the velocity of sound in air to the velocity in water at a temperature of 60 degrees Fahr. is about $23/100$.

A sustained sound or tone has three physical characteristics: loudness, pitch and quality. Loudness or intensity depends upon the amplitude, (the distance the particles of the medium vibrate back and forth); pitch, the highness or lowness of the tone, depends upon the frequency or number of waves which pass a fixed point per second; quality depends upon the number and intensity of overtones or harmonics present in the sound. It is the quality of a sound that enables a listener to name the instrument upon which it is produced.

A sound which varies from moment to moment, as it does when produced by an engine or rotating propeller on a boat, has other characteristics, the most important of which is rhythm. Rhythm is more or less a characteristic of each type of boat. A trained listener can detect the faint rhythm of a distant boat through a mass of louder confusing noises and can tell the type of boat and judge its speed by the character and the period of the rhythm.

The general laws of reflection, refraction, and interference of light hold for sound, but there are certain practical differences because the wave-length of sound is much greater than the wave-length of light. As a result of this greater wave-length, sound has a greater tendency than light to bend around the edges of obstacles and not travel in straight lines. It results also from this that mirrors or lenses for altering the direction of sound must be very large, so large indeed that their use is impractical.

Methods for Collecting Submarine Sound Energy.

There are two methods by which submarine sound energy can be efficiently brought to the ears. The first method makes use of the principle of resonance, the second method makes use of the difference in hydrostatic pressure between the dense and rare portions of a sound wave.

A tuned diaphragm in water can be thrown into violent agitation by a comparatively faint sound source if the frequency of the sound wave is the same as the natural period of the diaphragm. Calculation shows that in this way the diaphragm can be given an amplitude of vibration about 1,000 times the natural amplitude of the sound waves. And since the intensity of the sound from the diaphragm is proportional to the square of the amplitude this would result in multiplying the sound intensity given out by the diaphragm by something like one million. The Germans have made use of this principle in the listening gear installed on U-boats as also have the British in much of their earlier work.

A sound receiver operating on this principle can detect a submarine at a great distance providing the submarine gives out sound of the same frequency to which the receiver is tuned and also providing there are no other sound sources in the neighborhood giving out this same pitch.

An analysis of the sound emitted by a submarine shows a continuous sound spectrum throughout the range of the audible. No characteristic frequency is emitted. There is every reason to believe this is also true for all surface craft having a metallic hull and it follows that no distinct advantage is to be gained by using highly sensitive resonant receivers since the undesirable sounds, which are always more or less present, are intensified in the same proportion as the sound which it is desired to locate. Sensitivity alone, beyond a certain point ,is of no advantage and may prove to be a disadvantage.

The resonant receiver has two serious weaknesses. First, it only responds to sounds of one frequency, the natural frequency of its diaphragm. As a result all boats sound alike. The quality of their sound is lost and, as has been stated, it is the quality of a sound that enables the listener to name the instrument on which it is produced. Secondly, resonant receivers do not faithfully reproduce phase and therefore are not well suited for use with devices operating on the binaural principle or which employ multiple receivers.

In this country emphasis has been laid on the development of non-resonant receivers. Such receivers are of the pressure type and though they are not so sensitive as the resonant type, and as a result can not give as great range when entirely free from disturbing noises, yet they do give a faithful reproduction of the sound thus making it possible for a trained listener to distinguish a submarine from other boats or water noises or noise from his own engines by the quality of the sound. Such receivers are suitable for use in binaural and multiple unit devices.

These receivers consist of a flexible chamber or a rigid chamber carrying a flexible diaphragm, preferably rubber. Since the volume of the receiver changes readily under variation of hydrostatic pressure, the water in the neighborhood of the receiver will be subject to less or greater pressure than at other points in the wave front, depending upon whether the volume change in the receiver is positive or negative. In order to establish pressure equilibrium the particles of the highly incompressible medium will be forced toward or from the receiver for a considerable distance beyond its surface. The receiver therefore absorbs the sound energy from a comparatively large volume of water which fact accounts for its rather high sensitivity.

Types of Submarine Receivers.

Five types of submarine receivers have thus far been developed. Plate I shows the principle of each of these five types.

The *Acoustic Receiver* consists of a flexible chamber connected through a tube to the ear. The walls of the chamber are made of rubber or thin metal.

The *Geophone* consists of two metallic plates between which is compressed a flexible rubber ring. The upper plate is made massive to give it inertia while the lower one is made lighter in order that its inertia may not seriously interfere with its motion. The intervening air space connects by tube through the inert plate to the ear. Such a receiver when attached to the inside of the skin of a boat well below the water line is fairly sensitive to submarine sounds. The ordinary stethoscope is an example of the geophone.

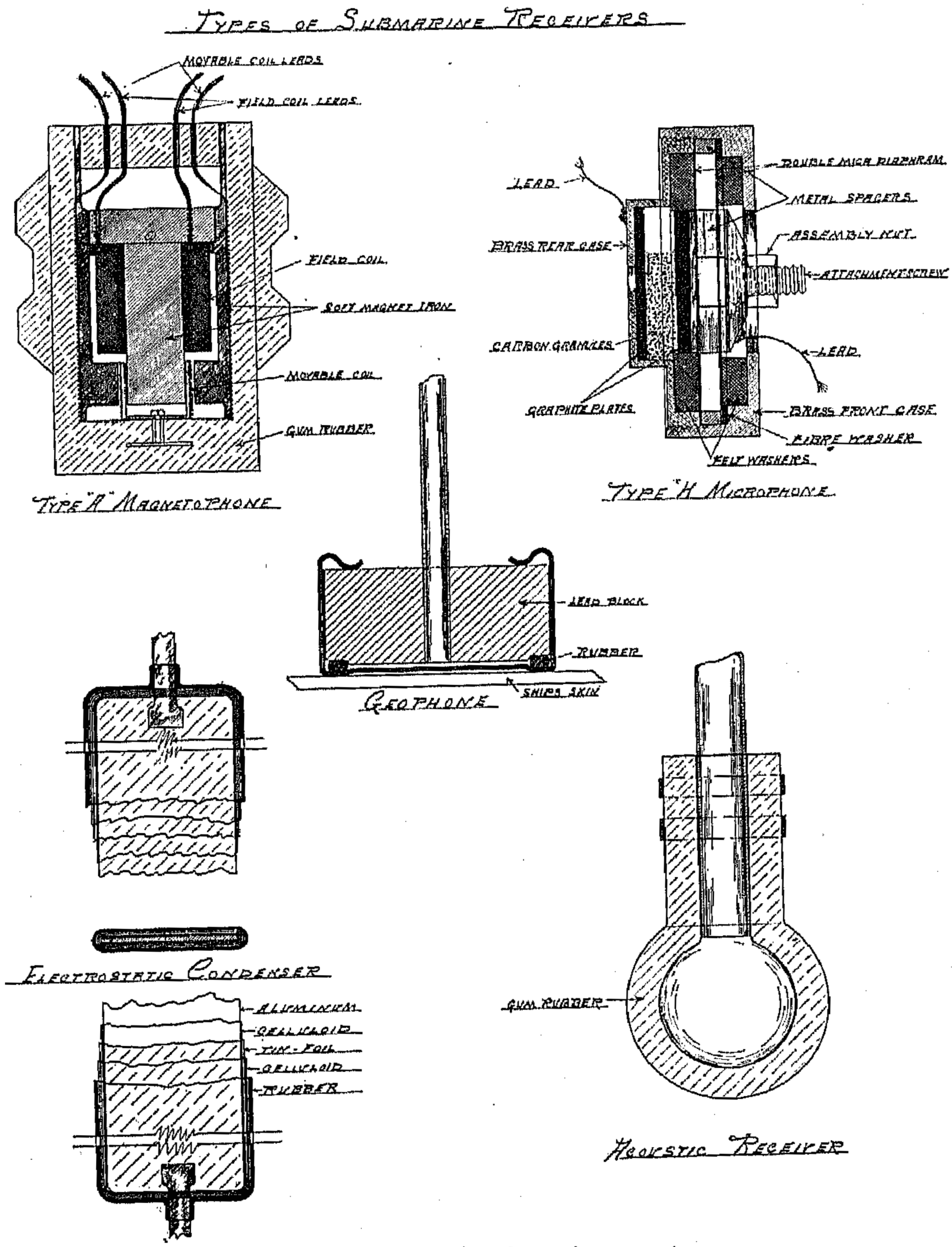

PLATE I. Types of submarine receivers.

The *Microphone* consists of two polished graphite plates placed parallel to one another and separated about $\frac{1}{16}$ of an inch. The intervening space is partially filled with fine carbon granules. One plate is attached to a diaphragm which allows it to move back and forth along a line perpendicular to its surface, thus compressing and releasing the carbon granules. The cylindrical surface enclosing the space between the graphite electrodes must be made a non-conductor.

In operation the movable plate is rigidly attached to the inside of a diaphragm enclosing a water-tight space. Two electrical leads pass into the chamber through a water-tight stuffing-box and connect to the two plates respectively. The motion of the diaphragm produced by the sound waves causes corresponding changes in the pressure between the carbon granules, since the inertia of the body of the microphone is sufficient to prevent it from responding to the very rapid sound vibrations of the diaphragm. The electrical resistance through the microphone varies with the pressure between the carbon granules and therefore causes fluctuations in the electric current when a battery is connected across the microphone leads. These current fluctuations can be passed through a telephone and converted into sound at the listener's ear. In practice the telephone connection is made through a coupled circuit. Three types of coupled circuits which have been successfully used are shown in Plate IX.

The *Magnetphone* contains a movable coil of wire rigidly attached to the inside of a diaphragm enclosing a water-tight space. The leads from this coil pass from the chamber through a water-tight stuffing-box. The movable coil is placed in a radial magnetic field furnished by either a permanent or an electro-magnet. The vibration of the diaphragm causes the coil to cut across the lines of force, thereby generating electromotive forces which set up fluctuating currents through the coil when electric connection is made between the coil leads. These fluctuating currents can be passed through a telephone receiver and converted into sound at the listener's ear.

The *Electrostatic Condenser Detector* consists of a flat strip of metal, preferably aluminum, surrounded by a thin film of celluloid and this in turn surrounded by a layer of tin-foil. The whole is encased in rubber tubing, the ends of which are vulcanized so as to make the condenser water-proof. One rubber insulated electric lead passes in through the rubber housing and attaches to the aluminum strip and a second lead in a similar way is attached to the tin-foil. These rubber-covered electric leads are both vulcanized to the rubber condenser-housing so as to give water-tight joints. The electric charge held by the condenser, when a battery is connected to the two leads, depends, among other things on the separation between the tin-foil and the aluminum strip. The variation in hydrostatic pressure in a submarine sound-wave causes this distance to vary slightly when the condenser is placed in the water, thereby producing slight current fluctuations through the battery and leads. These current fluctuations can be carried through a telephone receiver and converted into sound at the listener's ear.

The magnetophone and the electrostatic condenser give a more faithful reproduction of the sound than does the microphone, but they have the disadvantage of requiring an amplifier to increase their sensitivity. As a result only two types of receivers have been generally used—the microphone and the acoustic receivers.

Requirements of a Submarine Detector.

The requirements of a listening apparatus which embodies all that is desired may be stated as follows: It must be able to detect a submarine at considerable distance without interference from noise produced by other shipping, or by wave noise, or by noise produced by the boat upon which it is installed. It should be able to give the distance and direction of the submarine accurately. It should be seaworthy, of robust mechanical construction, convenient and rapid of operation.

No instrument has been devised that satisfies all of these requirements. In fact no single instrument can give the distance of the submarine. The other requirements have been fairly satisfactorily met. These instruments are being continually improved, but even in their present state they give results far beyond what was considered probable or even possible at the time the developmental work was first started.

Determination of Direction.

Maximum and Minimum.—A submarine receiver can be made more sensitive to sound coming from certain directions with respect to the orientation of the receiver than from other directions by means of screening, etc. By rotating such a receiver about a vertical axis, the direction of a sound source can be roughly determined by judging the position of the receiver for maximum or minimum sound intensity. Such a receiver is shown in principle in Fig. 1, Plate II. The receiver, represented by the small circle, is placed within a heavy lead cone. The English have utilized this principle in all of their listening devices.

Binaural Principle.—Experiment proves that the direction of a sound can not be judged with any degree of accuracy by one ear alone, unless the pitch of the sound is fairly high (above 800 or 1000), but by using both ears the listener can locate the direction with considerable accuracy for any pitch within the range of the audible and the accuracy proves to be greatest when the direction of the sound is about normal to a line joining the two ears.

Suppose the sound source is to the right of the listener. The sound received by the left ear will differ in two respects from that received by the right ear. First, the left ear receives the sound later than does the right ear and secondly, the intensity of the sound is somewhat less in the left ear because of the sound shadow cast by the head. The difference of intensity in the two ears is very slight for sounds of low frequency but becomes greater as the pitch is raised, due to the fact that the dimensions of the head are such that it only serves as an efficient screen for sounds of short wave-length. A single ear therefore becomes a screened receiver for high pitch sounds. The determination of direction, when both ears are used, depends largely on the difference in the time between reception at the two ears. This is especially true for sounds of low frequency, although the fact that intensity is slightly different at the two ears may also be of some help. Whenever a sound reaches the two ears at the same time, it appears to come from a direction perpendicular to the line joining the ears and the listener judges the sound to be somewhere in the plane which is the perpendicular bisector of this line. If the sound source is to the right of this plane, the sound reaches the right ear first and the listener judges the sound to come from this direction. Sound is judged as coming from the right or left, depending whether it reaches the right or left ear first respectively.

It is evident that the difference in time of reception at the two ears varies most rapidly, as the head is turned from a direction normal to a line joining the two ears and for this reason the listener can judge this direction with greatest accuracy.

This so-called "binaural principle" for determining the direction of sound is not new. It has been used for determining the direction of sounds in air, and was early recognized and tested by the British for determining the direction of sounds in water. These tests were unsatisfactory mostly for the reason that the apparatus was not properly designed. All the listening devices developed in this country make use of this principle for determining direction.

The direction of a submarine sound can be readily determined if two like receivers (one connected to each ear of the listener) are attached to a horizontal arm which can be rotated about a vertical axis. In general, sound will not strike both receivers simultaneously and as a result the impulses will not reach the listener's ears at the same instant. Suppose the sound impulse reaches the listener's right ear first, then the sound will appear to come from the right in accordance with the binaural sense, and if the path by which the sound travels from the submarine receiver to the ear is the same for both receivers, it must follow that the direction of the sound source is along a perpendicular to the arm carrying the two receivers when this arm is so oriented that the impulses reach the two ears in phase.

A consideration of Fig. 2, Plate II., shows that the sound would appear to be centered, were it coming from the direction given by either of the arrows 1 or 2. This ambiguity in direction of 180 degrees can be removed by rotating the two receivers from the position marked L and R to the position marked L' and R'. Let us suppose that the receiver marked R attaches to the right ear and the one lettered L attaches to the left ear. With the receivers in this second position, if the sound comes from the direction given by arrow 1, it would appear to the listener to come from his right since it would reach the right ear first. If, however, the sound should come from the direction marked by arrow 2, it would appear to the listener to come from his left since it would reach his left ear first. The ambiguity in direction can therefore be removed by rotating the receivers somewhat from the position in which the sound appears to be centered and noting whether this shifts the apparent direction to the right or to the left.

The rule which is generally followed in determining the direction of a sound by a rotating device operating on the binaural principle is as follows: If the sound appears to come from the right, rotate the receivers in a clockwise direction until the sound appears

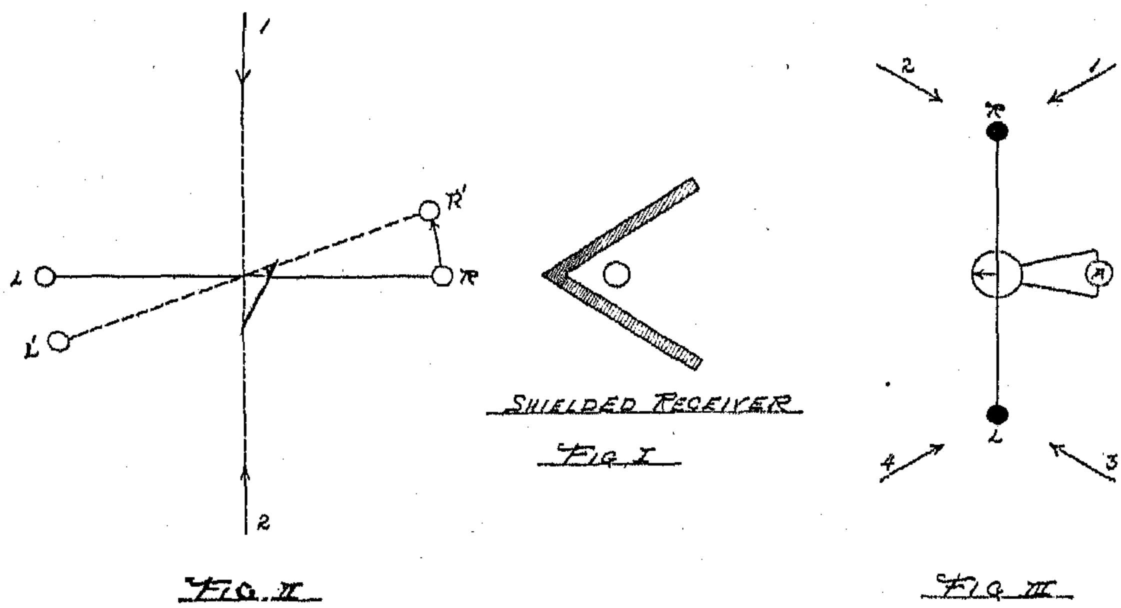

Plate II. Methods for determining direction.

to be centered. If the sound appears to come from the left, rotate the receivers in an anti-clockwise direction until the sound appears to be centered.

A consideration of Fig. 3, Plate II., shows that this rule is general. Suppose the sound is coming from the direction of arrow 1, it evidently strikes the right receiver first and would appear to the listener to come from his right. Rotating the receivers in a clockwise direction will at first increase the length of time between the arrival of the sound at the two ears but a continuation of the rotation will decrease this time difference in arrival until finally when sound appears binaurally centered the small arrow at the center of the line joining the two receivers will point in the direction of the sound. If the sound comes from the direction represented by arrow 2, it is evident that a clockwise rotation would be employed and when the sound is binaurally centered the arrow will point its direction. In case the sound is coming from the direction represented by either arrow 3 or arrow 4 it reaches the left ear first and will therefore appear to the listener to come from his left. It is readily seen from the diagram that a rotation of the receivers in an anti-clockwise direction will make the sound appear binaurally centered when the small arrow at the center of the line of receivers points in the direction of these sounds respectively.

In order to make this rule effective, the importance of attaching the proper receiver to the proper ear is obvious.

A device that depends upon rotation for determining direction has two distinct disadvantages: first, it cannot be operated when the boat is running and second, it must be lowered before taking a bearing and hoisted before the boat can again get under way, thus causing considerable labor and loss of time. This defect was early recognized and overcome by the workers at the Naval Experimental Station who developed a method whereby the binaural principle for determining direction could be employed without the inconvenience of rotating the two receivers. This development opened up a wide field for research which has resulted in the most serviceable types of submarine detectors.

The Principle of Binaural Compensation is readily understood by referring to Fig. 1, Plate III. Suppose the two receivers R and L are connected to the right and left ear respectively and sound comes from the direction indicated by arrow 1. This sound reaches R first and as a result appears to the listener to be located on his right. If the tube leading to the right ear is lengthened by an amount equal to $^{23}/_{100}$ the distance from R to C, the impulses from receiver R will be delayed so that the impulses from both receivers reach their respective ears simultaneously and the sound will appear to the listener to be binaurally centered. The same result could obviously be accomplished by shortening the sound path to the left ear or by lengthening the path from R half the amount and at the same time shortening the path L by the same amount, the only requirement for binaural centering being that *the path difference* be made equal to $^{23}/_{100}$ of the distance R to C ($^{23}/_{100}$ being the ratio of the velocity of sound in air to the velocity in water).

The path difference between the two receivers is directly dependent on the angular separation between the line of the receivers and the direction of the sound. This relation between the path difference and the direction of the sound is readily seen to be:

$$d = 0.23\, a \sin \theta,$$

where d represents the path difference in air, a the distance between the two receivers, and θ the angle the sound makes with the line joining the two receivers.

Since this definite relation exists between path difference and

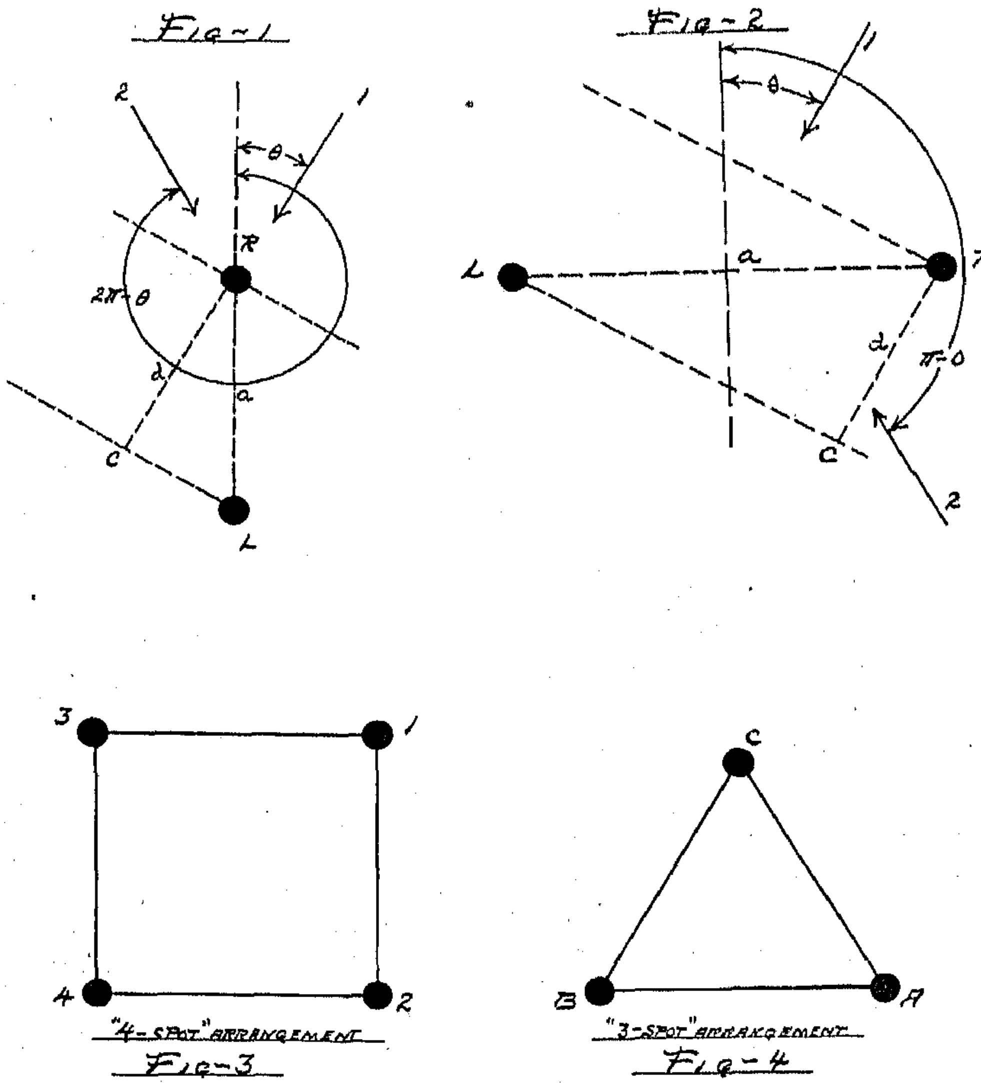

PLATE III. Principle of binaural compensation.

the direction of the sound, a device for varying the air paths can be introduced and calibrated directly in terms of angle.

Two weaknesses in this method for determining direction are apparent. First, if the angle approaches zero or 180 degrees a large variation in angle requires but slight change in air path and as a result a very slight error in determining the difference d in air path lengths will result in a large error in determining the angle. Secondly, the direction so determined will be ambiguous.

Fig. 1 shows that the time difference between the reception of the sound at receivers R and L will, from conditions of symmetry, be the same whether the sound comes from the direction indicated by arrow 1 or that indicated by arrow 2. It is, then, impossible to tell from the value of d whether the sound comes from the direction of θ or from the direction $2\pi-\theta$.

Both of these weaknesses are readily overcome, as will be seen by a consideration of Fig. 2, Plate III. Suppose the line connecting the two receivers R and L is perpendicular to the direction from which θ is measured and suppose the sound is proceeding from the same angle θ that is represented by arrow 1 in Fig. 1. The time difference between the reception of the sound at the two receivers R and L is represented by the water path R–C, Fig. 2. But sound proceeding from the direction represented by arrow 2, would, from conditions of symmetry, give a time interval between reception at the two receivers represented by the same length of water path. It will be impossible then to tell from the value of d whether the sound comes from the direction θ or $\pi-\theta$.

The direction of the sound as determined by two receivers oriented as in Fig. 1 is determined as being either θ or $2\pi-\theta$ while the direction as determined from a pair of receivers oriented as in Fig. 2 is determined as θ or $\pi-\theta$. It must follow that the angle common to the two determinations, viz., θ, gives the true direction and thus the ambiguity is removed. Moreover, it is to be noticed that the angular range within which the determination of direction is subject to most error when the two receivers are oriented as in Fig. 1 is the region wherein direction is determined with greatest accuracy when the receivers are oriented as in Fig. 2. It therefore becomes possible to determine direction accurately at all angles provided that reliance is placed on the proper pair of receivers.

The line connecting the second pair of receivers need not necessarily be at right angles to that connecting the first pair, and the second pair of receivers may utilize one receiver of the first pair.

The minimum number of receivers is three. All of the listening devices developed at the Nahant Station except the C-Tube, make use of three receivers located at the vertices of an equilateral or isosceles triangle. Such a device is often called a "3-Spot." Devices of this character developed at the Naval Experimental Station employ four detectors located at the four corners of a square. Such devices are commonly named "4-Spots." The "4-Spot" can still be operated

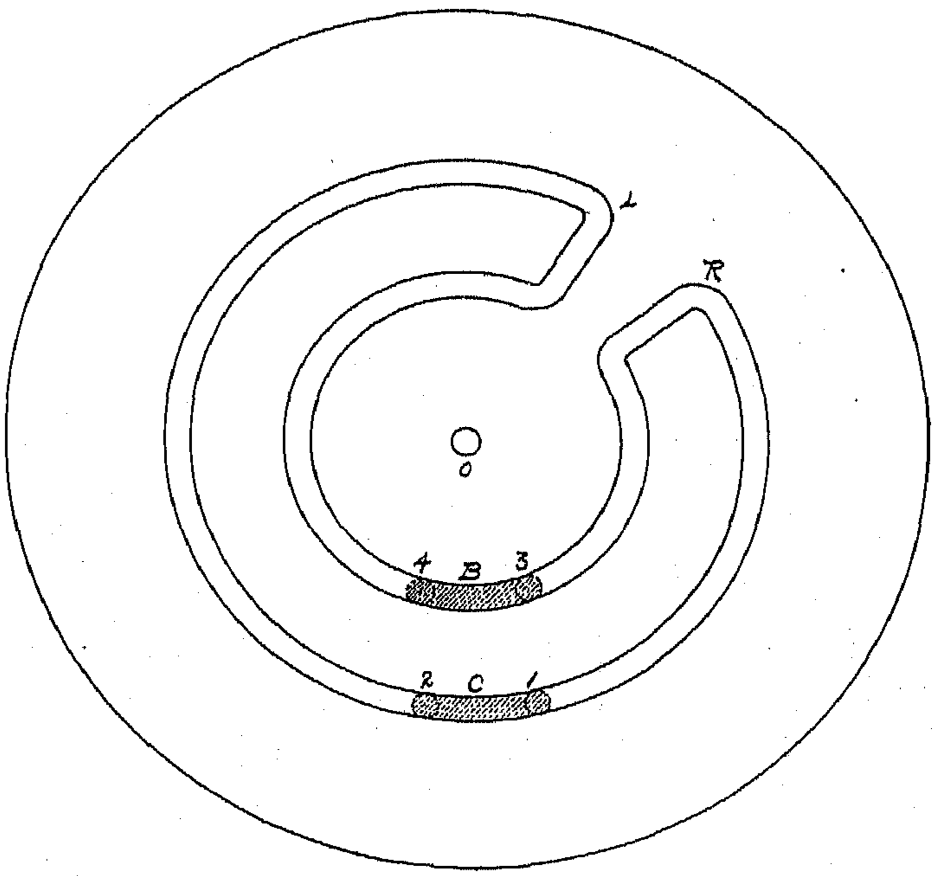

PLATE IV. Diagram of double-groove compensator.

if any one receiver becomes damaged but the "3-Spot" becomes useless under such conditions.

An instrument called a *compensator* has been developed by which the path difference between the two receivers and the ears can be varied. Compensators are made in various forms for different special purposes. Plate IV. shows the principle of one of the simplest forms. It consists of an upper brass casting with grooves as shown by the full lines. This casting seats on a lower brass plate upon which it can be rotated about a central pivot (o). The lower plate carries two projecting blocks carefully formed to give a sliding fit in the grooves of the upper plate. The lower plate is perforated by four holes, numbered 1, 2, 3, and 4 in the figure, which open respectively through the ends of the two blocks *B* and *C*. Thus two con-

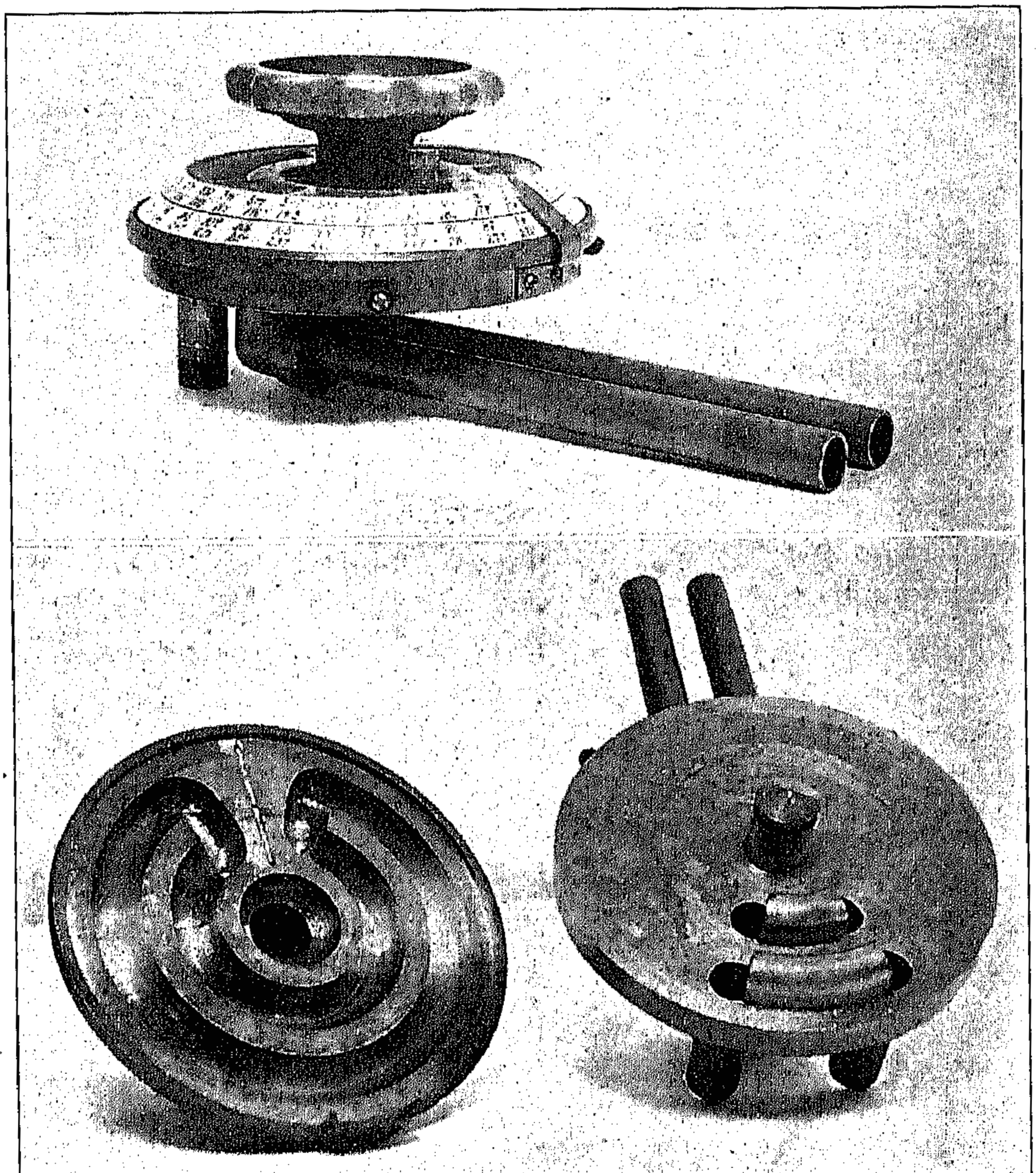

PLATE IV. *a*. Double-groove binaural compensator.

tinuous air-paths traverse the compensator, one connecting from 1 to 3 through that part of the groove marked *R* and the other connecting from 2 to 4 through the other part of the groove marked *L*. By rotating the top plate the difference in the length of the two air-paths can be varied at will up to the capacity of the compensator.

In operation each path through the compensator is connected in series with one of the two paths leading from the receivers to the ears, care being taken that the path lengths outside of the compensator are equal. Any sound striking the two receivers can be binaturally centered by turning the compensator to a position such that the impulses from the two receivers reach the ears simultaneously. The high development of the binaural sense may be appreciated from the fact that an untrained listener can make a compensator setting accurate to within 10^{-5} seconds while a trained listener can do better than 5×10^{-6} seconds.

The compensator is provided with a special switching device by which different pairs of receivers can readily be connected through the compensator. The movable plate of the compensator carries four scales arranged in pairs, each pair referring to a definite set of receivers. The scales are arranged in pairs because of the ambiguity in direction at each setting of the compensator. The direction of a sound source is determined by making a binaural setting on one pair of receivers and noting the two angles on the double scale belonging to this set of receivers. Then throw the switch so as to connect in the second set of receivers and make a second binaural setting and note the two angles given by the double scale which refers to this second set of receivers. The common angle on the two settings gives the direction. Due to errors in setting the common angle will in general not give perfect agreement, and the angle is taken from the scale least subject to errors for the angle in question. In Plate IV. *a*, Figs. 1 and 2 show the Type *T* compensator assembled and dissembled respectively.

Submarine Detectors Developed in England.

The principle of the English listening devices is shown in Plate V. The *Mark* I. consists of a tuned diaphragm mounted within a somewhat massive ring carrying a microphone within a small rigid watertight housing at the center of the diaphragm. One side of the diaphragm is screened by a heavy plate. This receiver is highly resonant and is most sensitive to sounds coming from the side opposite to the screen. The receiver is rotated in the water and the direction is determined by the maximum-minimum principle, and since neither the maximum nor minimum is well defined it is impossible to determine direction with any degree of accuracy.

The *Mark* II. receiver is very similar to the Mark I. except that it carries no sound screen. It is equally sensitive to sounds striking

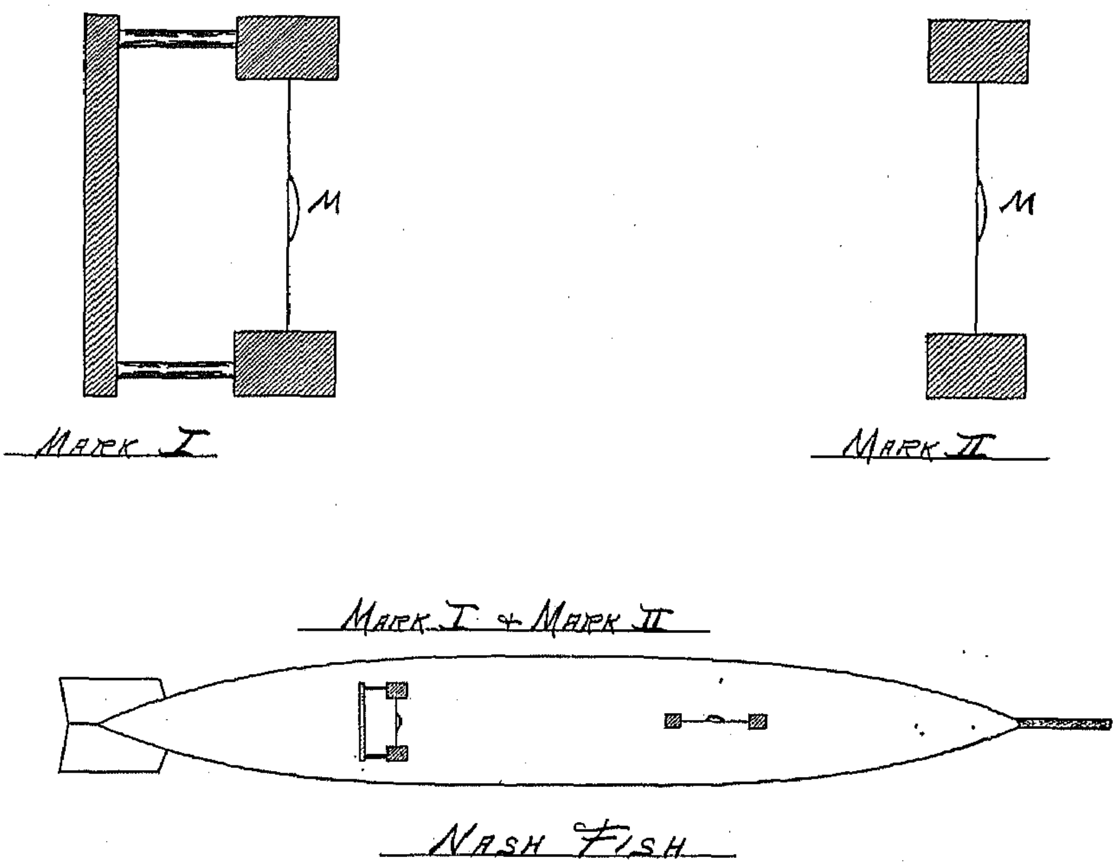

PLATE V. Principle of English listening devices.

either side of the diaphragm. Thus there are two positions for the receiver where the sound intensity will be at a maximum and neither of these positions is sharply defined. A sound proceeding in a direction parallel to the diaphragm affects the two sides equally and in opposite sense so there is no motion of the diaphragm and the intensity of the received sound is practically zero. This minimum position is very sharply defined and will determine the direction of a sound with high accuracy except for an ambiguity of 180 degrees.

In the *Nash Fish* and certain submarine installations both the Mark I. and the Mark II. are used, the line of direction being determined by the minimum setting on the Mark II. and the ambiguity being removed by the Mark I. These installations, especially the Nash Fish, are complicated due to the fact that remote control motors are required to rotate the receivers. They are also subject to the defects which are inherent in resonance receivers, viz., their sound response is devoid of quality and their operation is strongly interfered with by local noises and noises from neighboring shipping.

Submarine Detectors Developed by the French.

Two types of submarine detectors have been developed by the French—the "Perrin Microphone" and "The Walser Plate." The

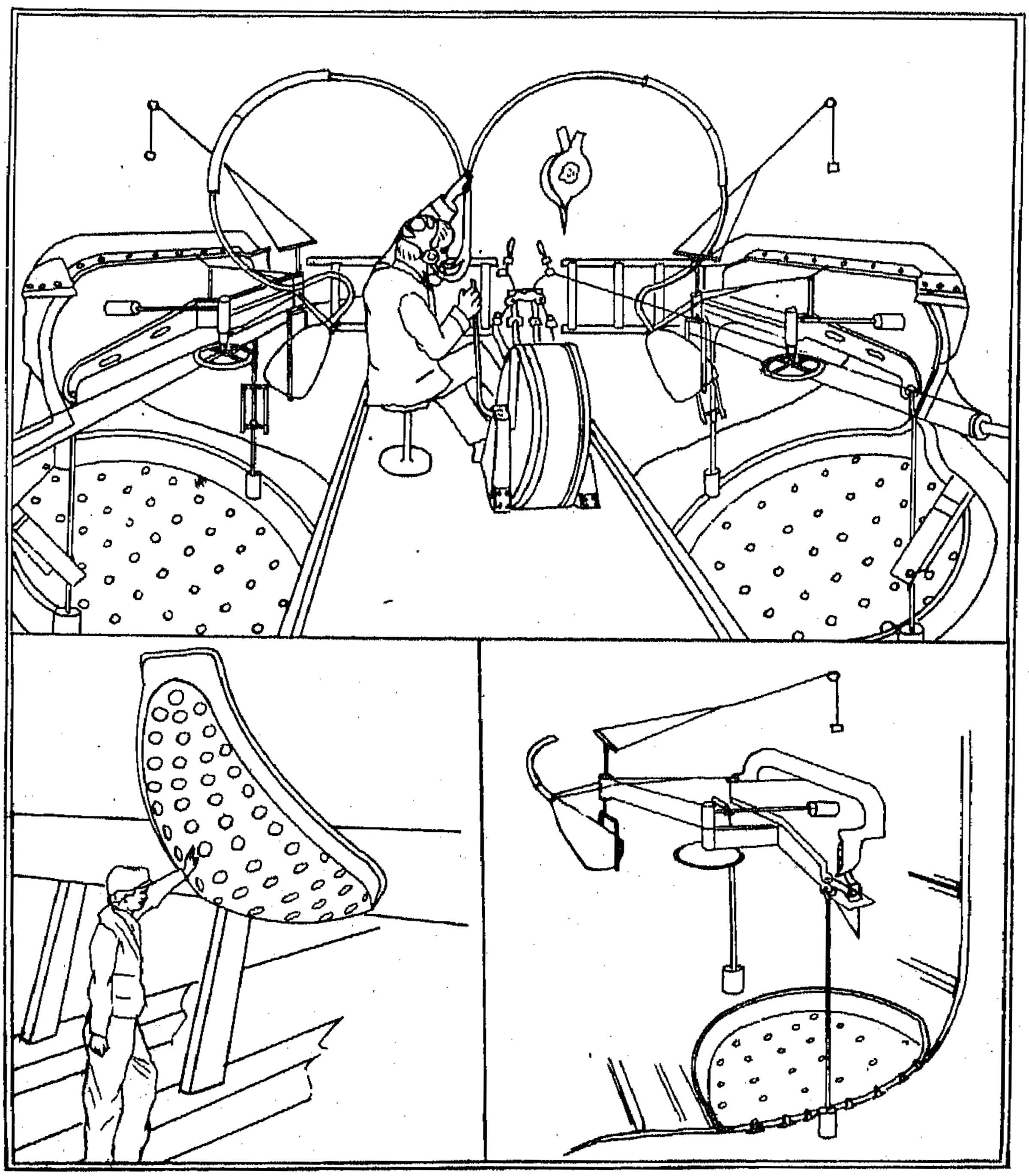

Plate VI. Installation of Walzer Plate (sound lens) apparatus.

Perrin Microphone, see Fig. 1, Plate II., consists of a sensitive microphone mounted within a massive conical-shaped shield. Like the Mark I. it determines direction by the maximum-minimum principle and is not capable of giving accurate bearings for the reason that neither the maximum nor minimum is well defined.

Some idea of the construction and operation of the *Walser Plate* detector can be gained from Plate VI. The plate proper forms a portion of the ship's skin. The surface is convex outward, the curvature being such that a sound wave passing from the water through the plate is brought to a focus within the boat. The plate is perforated with numerous holes, each of which is closed by a thin metal diaphragm, in order that the sound may pass more freely. One such plate is installed on each side of the boat.

Each plate really serves as a sound lens and the direction of the sound source is determined from the position of the sound focus within the ship. The position of this focus is located by means of a movable trumpet which connects with the listener's ears. The framework upon which the trumpet arm is pivoted is suspended fore and aft on gimbals and counterbalanced so that the trumpet remains in the same horizontal plane that contains the focus.

In many respects the Walser Plate is a superior device. Due to its focusing effect the disturbance from local and other undesirable sounds is greatly reduced while desirable sounds are concentrated and intensified. The device can be operated while moving at considerable speed and good results both as regards range and bearing are claimed. It has, however, the double disadvantage that it is expensive and difficult to install. In fact its dimensions are such that it cannot be installed on many types of boats.

Submarine Detectors Developed in the United States.

Plate VII. shows the principle of two types of submarine sound detectors which were developed by the Submarine Signal Company for locating submarine bell signals installed on light-ships. Each of the small tanks attached to the ship's skin carries a *microphone receiver tuned to the submarine bells.* These microphones each connect with a single telephone receiver on the ship's bridge. These tanks are filled with oil or water. By comparing the intensity of a sound as received in the two phones its source can be located as to port or starboard. By swinging the boat until the intensity is the same in both phones the direction of the sound can be somewhat accurately located as dead ahead.

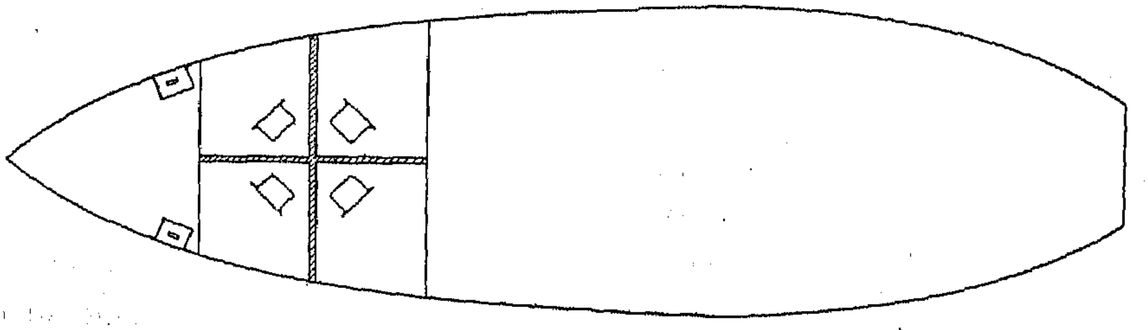

PLATE VII. Hydrophone installation of Submarine Signal Company.

The second installation consists of four *Fessenden oscillators* placed one in each of the four quadrants of a large tank within the ship. Each quadrant is separated from the others by a sound-screen. By comparing the intensity of sound as received on each of the four oscillators the direction of the sound source can be located to within 90 degrees.

Detector installations were early developed at both the Naval Experimental and the Nahant Stations that were superior both as to range and bearing accuracy and the above named devices were abandoned.

Two types of detectors have been developed at the Nahant Station—the "C-Tube" and the "3-Spot." One type, the C-Tube, has been partially explained. It consists of two rubber acoustic receivers spaced about four feet apart on a horizontal arm which can be rotated about a vertical axis. Each receiver connects to one ear respectively through metal tubes ending in stethoscope leads. The direction of a sound is determined by the binaural principle in a manner that has been described.

The C-Tube is a superior detector device. It is capable of giving good range and accurate angular bearings, but its operation is seriously interfered with by local noises and noises from neighboring shipping and it cannot be operated while the boat is moving. Moreover, it must be lowered before taking a bearing and must be raised before the boat can get under way. Plate VIII. *a* shows one form of the C-Tube developed at Nahant. (See page 30.)

The "3-Spot" detector operates on the principle of binaural compensation and was developed soon after this principle was established at the Naval Experimental Station. An improved type of microphonic submarine receiver called a "rat" was developed which proved highly sensitive, non-resonant, and durable. The construction is shown in Plate VIII. *b*. The microphone is carried by a rubber diaphragm which encloses a water-tight space housing the micro-

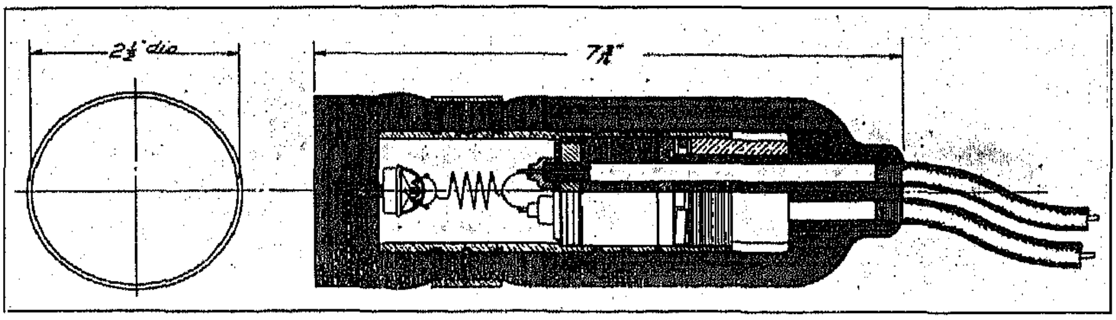

PLATE VIII. *b*. The microphone housing or "rat," developed by the General Electric Company for "3-Spot" detectors.

phone. The leads to the microphone pass through a water-tight stuffing-box at the end of the cylindrical shaped chamber opposite to the diaphragm. Three of these receivers are fixed in position at the vertices of an equilateral triangle four feet on a side. One lead from each microphone attaches to a common lead into which a battery is connected in series. The other three leads, one from each receiver, pass through small inductance coils and thence to the common. A special type of telephone receiver connected in series with a condenser is shunted across the inductance. This wiring scheme is shown in Fig. 1, Plate IX. Figs. 2 and 3 show other schemes used for connecting in the telephone which are employed in devices developed at the Naval Experimental Station.

The two telephone receivers are attached respectively to the two inlets to the compensator so that the sound is required to pass through the compensator and the stethoscope leads before reaching the ears.

A neatly designed switch arrangement makes it possible to connect either one of the three pairs of microphone receivers to the two telephone receivers so that not only can the ambiguity in direction be removed, but a pair of receivers favorably oriented for accurate determination of direction can be used.

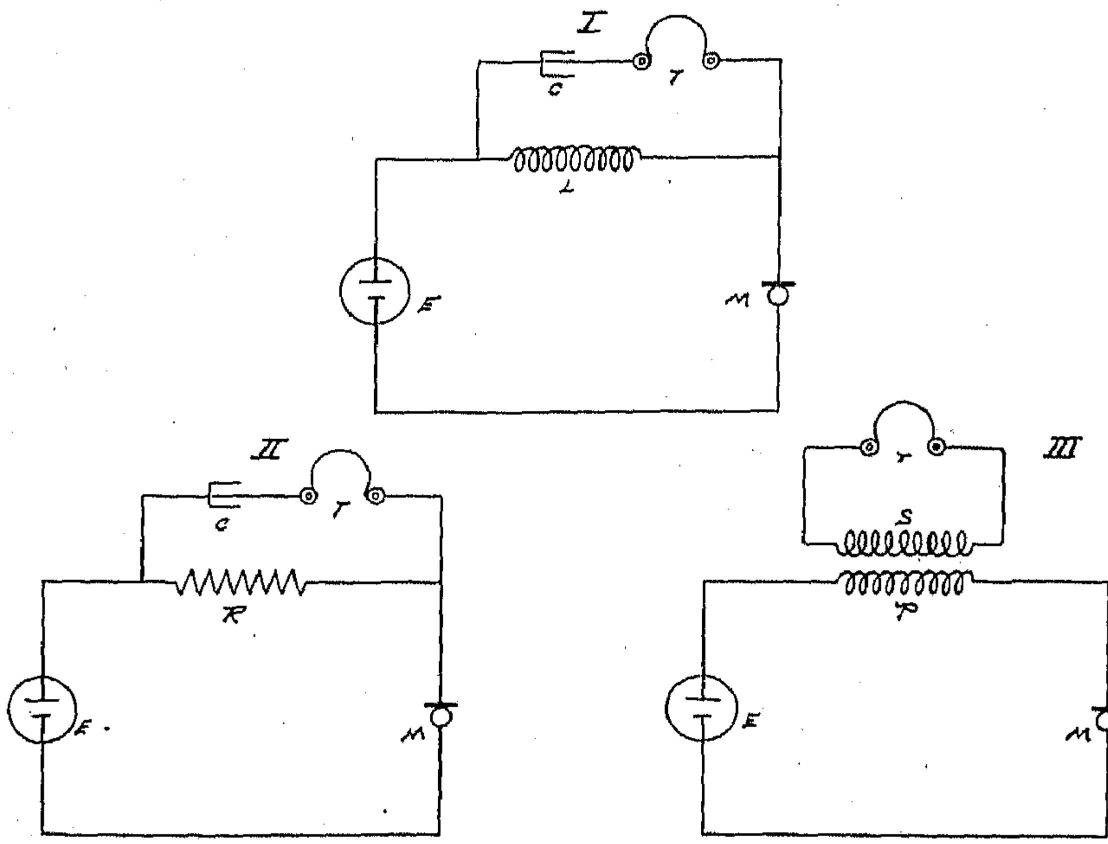

Plate IX. Types of microphone circuit.

This triangular arrangement has been mounted in several different ways to meet special conditions. When the three "rats" are mounted on a light frame suspended from a float for use as a drifter set it is termed a "K-Tube"; when mounted on a streamline frame attached to the deck or keel of a submarine it is called a Y-Tube: when mounted suitably for suspending beneath a light-ship it is termed an "X-Tube"; when mounted within a tank inside the ship's skin it is termed a "Delta-Tube"; and when arranged for towing behind a moving boat it is called an "OS-Tube," or an "OV-Tube," or an "OK-Tube" depending upon its form.

The "3-Spot" in all its forms is an excellent listening device. It is durable, easy to install, determines bearing with considerable accuracy, is simple and rapid in operation, and is capable of giving long range *if there are no disturbing noises present.*

The chief difficulty in submarine detection by sound lies in the fact that under normal operating conditions the detecting apparatus is mounted in the midst of numerous sound sources such as propeller and machinery noises on the listening boat, breaking of waves and slapping of waves on the boat, noises from promiscuous shipping, etc. The range at which a submarine can be detected is largely dependent on the ratio of the intensity of the sound from the submarine as compared with that from other sources. Increasing the sensitiveness of the receivers beyond a certain limit is of no advantage since the disturbing noises are magnified in the same proportion as are the sounds from the submarine.

Under such circumstances it becomes necessary to devise an instrument that will magnify the sound coming from a definite direction without correspondingly magnifying sounds from other directions.

This result can be accomplished by using sound lenses or mirrors, an example of which is the "Walser Plate," but because of the length of sound waves in water their area must be so great if they are to give a marked advantage that their use is practically prohibited. As soon as the principle of compensation was recognized it became evident that instead of a single receiver connecting with each ear it would be advantageous to have several receivers spaced some distance apart, provided a compensator could be devised that would not only make it possible to binaurally center the composite sound reaching each ear from its respective group of receivers but at the same time would compensate the separate air paths to the individual receivers so that the sound response from all would arrive at the listener's ears in phase. By properly adjusting such a compensator the response from the several receivers to sound from any particular direction could be brought to the listener's ears in phase and since under these conditions the intensity of the sound will be equal to the sum of the intensities from the several receivers the sound reception from this particular direction will be magnified.

It is evident that for this same setting of the compensator the response from the several receivers to sound from any other direction will not reach the listener's ears in phase and as a result will not be magnified in the same proportion. Indeed, the sum total may be less than that given by a single receiver through destructive interference.

Although several types of detectors employing a single receiver for each ear, as in the "3-Spot," have been developed at the Naval Experimental Station for special purposes such as equipping lightships, hydroplanes, dirigible balloons, etc., yet the major part of the efforts of this Station have been directed toward the development of the so-called "multi-unit" detector devices.

Except that the "4-Spot" arrangement of receivers has been used throughout in preference to the "3-Spot" arrangement, these special single-unit types of detectors are very similar to the "3-Spot" type which has been described. Therefore a detailed description will not be given. The principle and operation of the more effective devices, those employing multiple units, follows:

The so-called "*M-B Tube*" is a rotating listening device employing multiple unit receivers. The principle may be understood by considering Plate X. In Fig. 1 let the numerals 1, 2, 3, and 4 represent four similar acoustic receivers equally spaced in a line and connecting through equal length tubes with the stethoscope leads *R* and *L* at the common junction (*A*). Sound coming from a direction perpendicular to the line of receivers actuates all the receivers simultaneously and the response from all four reaches the ears in phase. Under such conditions the intensity of the sound heard is four times the intensity from a single receiver.

Sound from any other direction, such as represented by arrow 2, does not reach the receivers simultaneously and, as a result, the responses from the various receivers do not arrive at the ears in phase. The intensity of the resulting sound will therefore be less than four times that from a single receiver. The difference will vary for the different components of the sound depending upon the wave-length.

Such an instrument is capable of determining direction by means of the maximum-minimum principle except for an ambiguity of 180 degrees. If, as in Fig. 2, half of the receivers is connected to each ear respectively, then advantage can be taken of both the maximum-minimum and the binaural principles. The sound response from each receiver of each group reaches its respective ear in phase, thereby giving a maximum intensity for any sound traveling in a direction perpendicular to the line of receivers, as represented by arrow 1′. Moreover, the resultant sound at the two ears will be in phase so the listener will hear the sound binaurally centered. Sounds

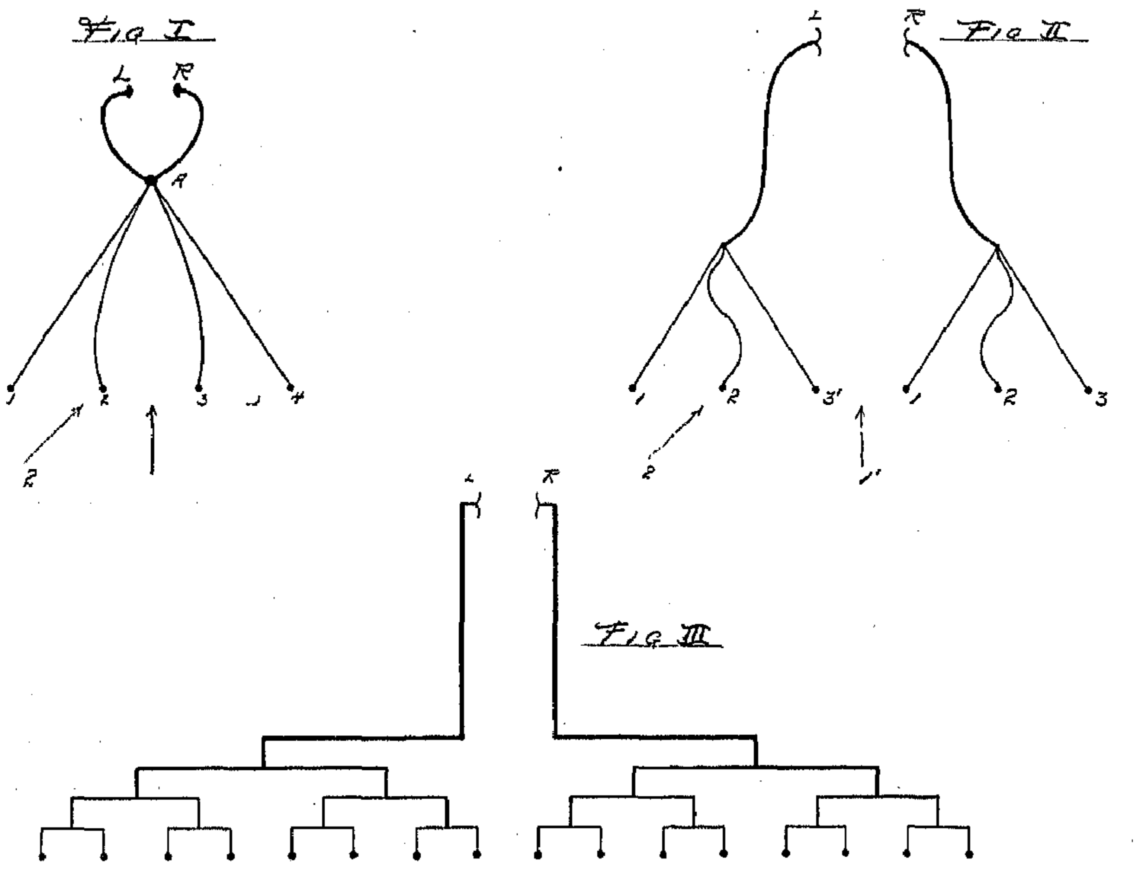

PLATE X. Principles of M-B tube.

from any other direction, such as represented by arrow 2′, will not reach the ears in phase and therefore will be weakened in intensity in both ears. As represented, the composite sound reaching the left ear will arrive in advance of that from the group of receivers connecting with the right ear. This weakened sound will therefore not be binaurally centered but will appear to be located to the left of the listener. Such sounds are often spoken of as being "out of focus."

The intensity of sounds "in focus" is directly proportional to the number of receivers connecting with each ear. The intensity of sounds out of focus depends upon the length of line, the spacing of the receivers, the wave-length of the sound, and the angle by which it is out of focus.

In practice an eight foot line has been used carrying sixteen receivers, eight connecting with each ear. Fig. 3 gives the scheme by which the receivers are connected. It is to be noticed that the path from each receiver to the ear is the same. Care is also taken to preserve the cross-section of the path. The cross-sectional area of the tube joining each ear is twice that of the branching tube into which it terminates. This branching tube has twice the cross-section of the two branching tubes at its terminals, etc. Sound reflection within the instrument, and hence resonance, is minimized by this means.

Like the C-Tube, the M-B Tube has the disadvantage that it must be lowered and raised when bearings are taken, but it possesses several advantages over the C-Tube. It is most sensitive to sound from a direction at right angles to the tube and is, therefore, relatively insensitive to sounds from other directions. This makes it possible to pick a particular ship out of a mass of disturbing shipping much more readily with the M-B Tube than with the C-Tube. The M-B Tube hears the boat at which it is pointed with much greater intensity than other boats, whereas the C-Tube, or any detector employing a single unit to each ear, hears all boats with the same relative intensity. Furthermore, the M-B Tube is much less disturbed by local water noise than is the C-Tube as a great part of this noise is out of focus. The M-B Tube is only focused on noise in a plane perpendicular to the tube at its central point.

It is obvious that two boats separated by 180 degrees will both be in focus because of the bi-directional properties of the M-B Tube.

The principle of the *M-F Tube* is shown in Plate XI. Suppose (A) and (B), Fig. 1, represents two receivers spaced a unit distance apart and that sound is proceeding in the direction from (A) to (B), as represented by the arrow. If the two receivers are joined by a tube there is some point, (p), where the sound from the two receivers arrives in phase since the sound wave travels from A to B through the water in less time than it travels from A to B through the air in the tube. This point can readily be shown to be $^{65}/_{100}$ of the distance from A to B. A branch tube leading from point (p) will receive the impulses from both receivers in phase.

A line of receivers connected in the manner shown in Fig. 2 is termed an M-F Tube. Only sounds from one definite direction, that shown by the arrow, reach the listener's ear in phase and this results in eliminating to a great extent all local surface noises. Such a line of receivers arranged to rotate in a horizontal plane makes an

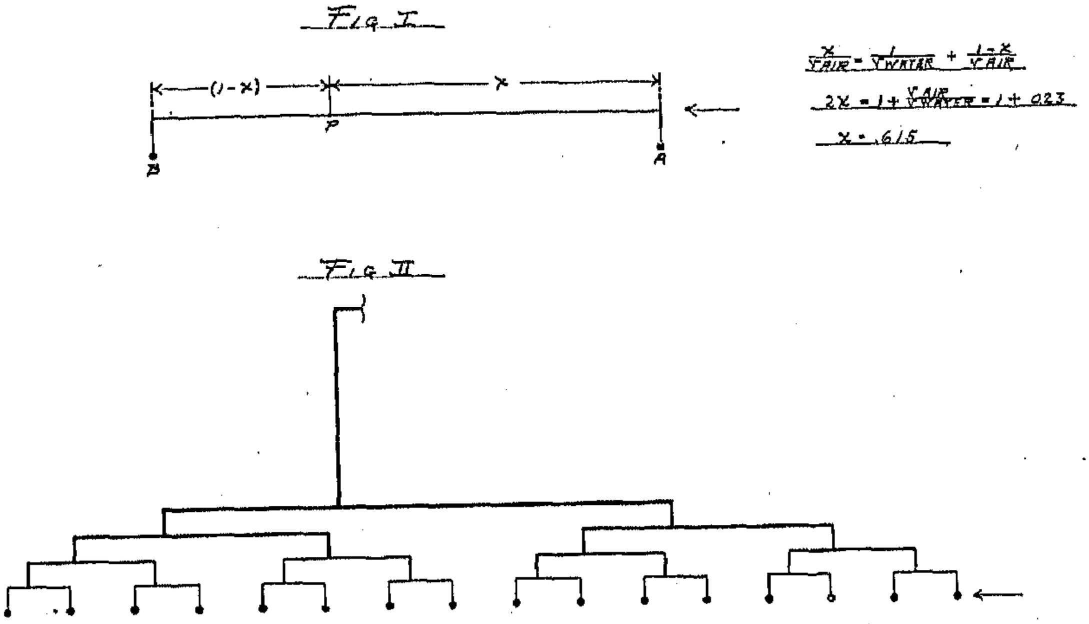

Plate XI. Principle of M-F tube.

excellent maximum instrument. In practice two such lines are mounted side by side with a horizontal separation of about four feet. By connecting the outlet from each line of receivers to the two ears respectively the binaural principle for determining direction can be utilized. In Plate XI. *a* is shown one type of the double M-F Tube designed for use on submarine chasers.

An instrument of this kind gives a binaural centering of sound at the same time that it is at a maximum, precisely as does the M-B Tube. It is at the same time much freer from water noise than the M-B Tube because it is in focus for sound from only one direction. The M-F Tube has no ambiguity of 180 degrees as has the M-B Tube and the C-Tube. Because of the combination of these desirable properties, the double M-F Tube is the best rotating hydrophone device that we have.

The "M-V Tube" is a listening device employing multiple receivers equally spaced in a line and mounted in a fixed position

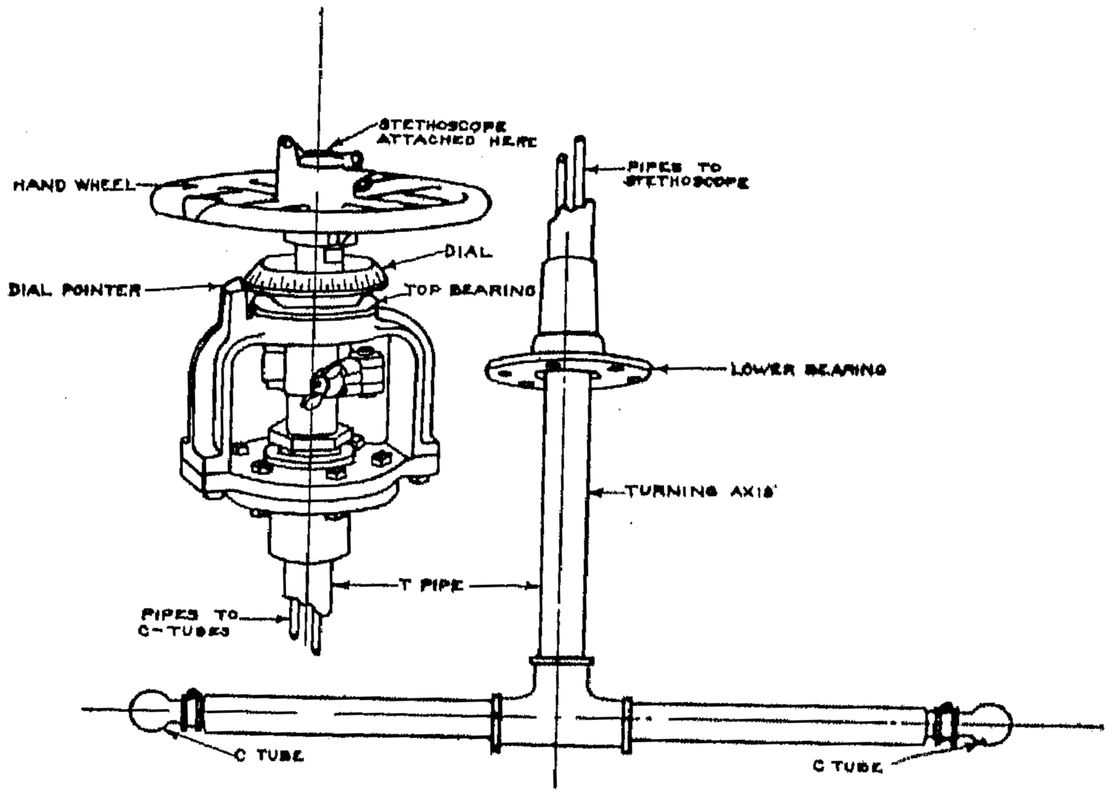

Plate VIII. *a.* One form of "C-Tube" developed at the Nahant Station.

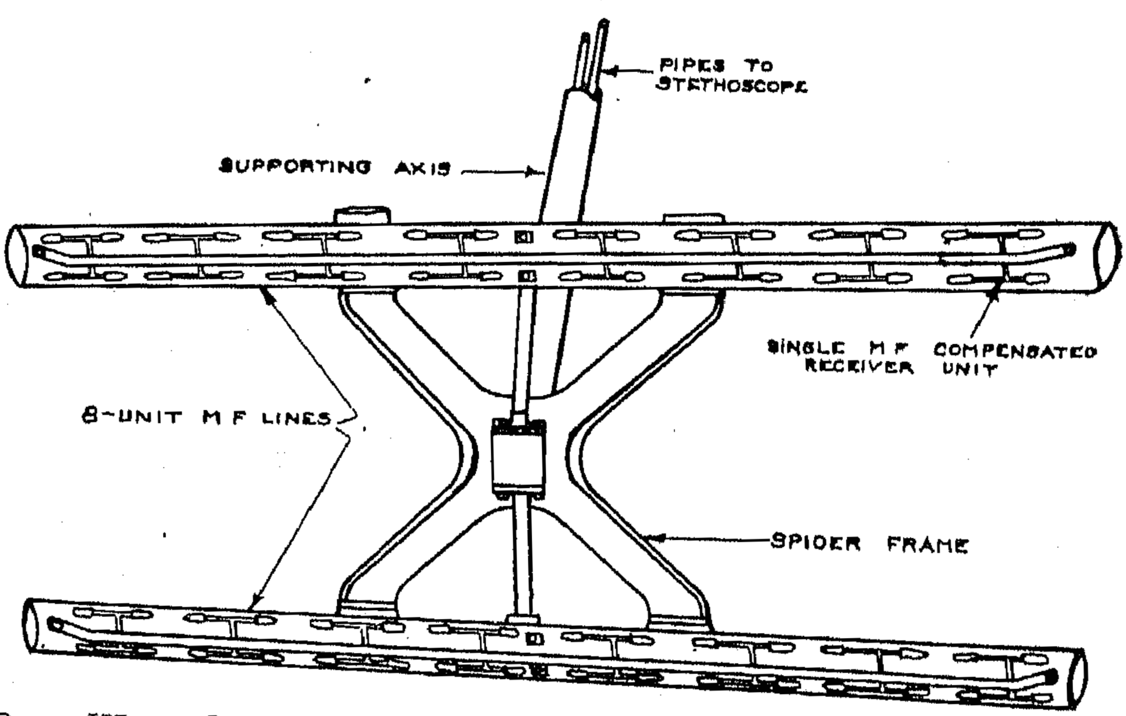

Plate XI. *a.* One form of Double M-F Tube. Portion of casing removed to show receiver units.

within a large tank inside the ship or more usually underneath a protecting blister on the outside of the ship's skin. The line of receivers is in all cases mounted as near parallel to the ship's keel as conditions will permit, one such line being mounted on each side of the ship and directly opposite one another. The receivers in each half of the line are grouped together, each group connecting with one ear respectively, in order that the binaural principle may be employed in determining direction.

Theoretically the focusing effect is intensified by increasing the length of line and the number of receivers, but practically the mechanical difficulties encountered in compensation tends to limit both the length of line and the number of receivers. The principle of operation of a line of twelve receivers is shown in Plate XII.

In Fig. 2 let numerals 1, 2, and 3 represent three receivers equally spaced and connecting to the common junction through the three separate paths *a*, *b*, and *c* respectively. Paths *a* and *c* are provided with a trombone arrangement such that their length can be varied at will while path *b* has a fixed length equal to that of both *a* and *c* when the trombone slides are adjusted to have equal paths. The response from the three receivers will reach the junction *A* in phase for sound travelling in a direction perpendicular to the line of the receivers, that represented by the arrow.

Sound proceeding in a direction as represented by the arrow in Fig. 1 does not actuate the three receivers simultaneously but in the order 1, 2, 3. It is evident that a proper lengthening of the path *a* and the same shortening of the path *c* will bring the responses from the three receivers in phase at the junction *A*. If the sound comes from a direction as indicated in Fig. 3 the variation of the paths *a* and *c* must be in the opposite order to bring the responses from the receivers in phase at junction *A*.

Consider a line of twelve equally spaced receivers divided into four groups of three receivers each, as shown in Fig. 4. Receivers 1 and 3 connect to the junction *A* through a simple "2-Spot" compensator of the type already described, while receiver 2 is connected to *A* through a fixed path equal to that from both receivers 1 and 3 when the compensator is so adjusted that their path lengths are equal. The responses from the three receivers can be brought to *A* in phase for sound coming from any particular direction by properly adjusting the compensator. Also a similar adjustment of each compensator in the other three groups will bring the response from the three receivers of each group in phase at their respective junctions *B*, *C*, and *D*.

For convenience the four junctions *A*, *B*, *C*, and *D* may be regarded as four separate receivers located at points 2, 5, 8, and 11 respectively. The responses from *A* and *B* can be brought together

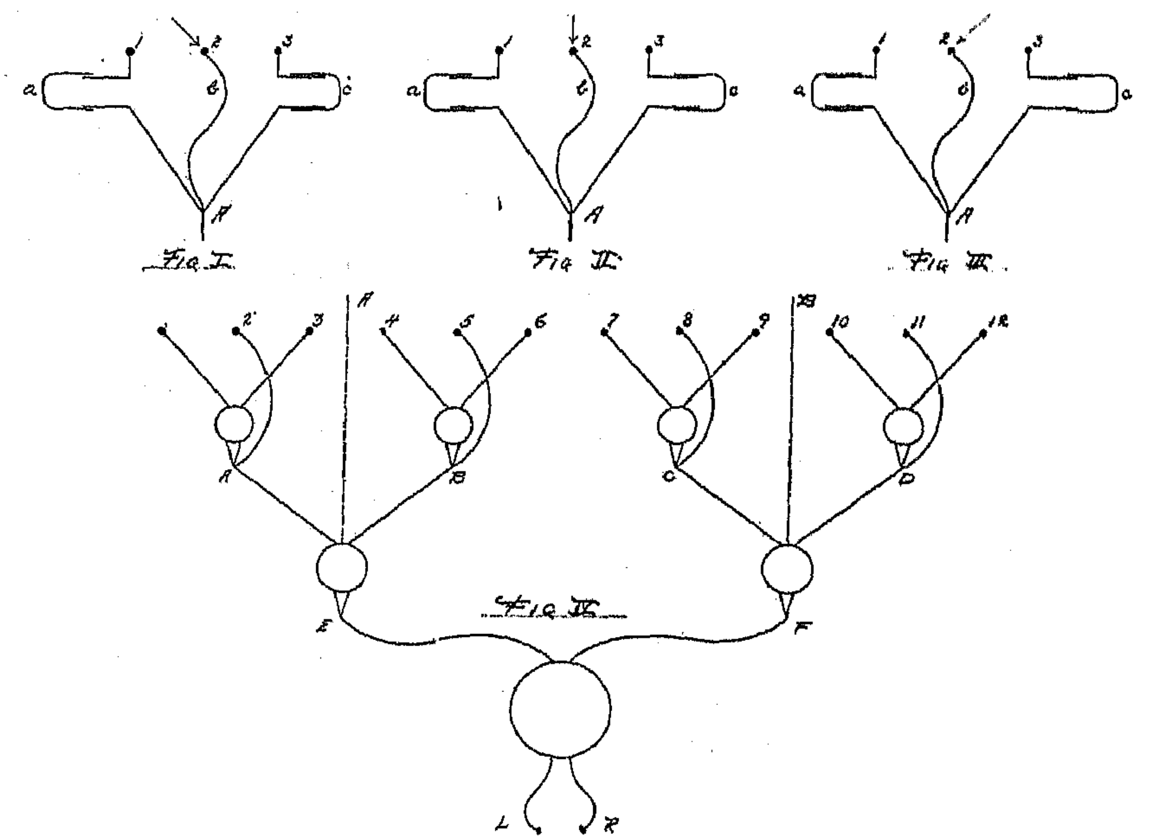

Plate XII. Principle of M-V tube.

in phase at *E* by means of another "2-Spot" compensator and similarly the responses from *C*, and *D* can be brought in phase at *F*.

Points *E* and *F* may, for convenience, be regarded as two separate receivers located at a point midway between 3 and 4 and between 9 and 10 respectively. These two receivers connect with the ears through another compensator and the stethoscope leads *L* and *R*, and by properly adjusting the compensator the sound can be binaurally centered and the direction of the sound source determined with an ambiguity as to port or starboard. This ambiguity is readily removed by comparing the intensity of the sound as given by the port and starboard lines since the ship acts as an efficient sound screen.

From the description it is obvious that the complete compensation of a line of twelve receivers is accomplished in three separate stages. First, the 4 groups of the receivers are compensated by means of four similar compensators. The maximum compensation to be effected in this stage is, in terms of water-path, equal to the distance between two adjacent receivers. Second, these four groups are compensated in pairs by two similar compensators. The maximum compensation to be effected in this stage is, in terms of water-path, equal to one and a half times the distance between two adjacent receivers. Third, these two groups are brought into phase to give a binaural centering. The maximum compensation to be effected in this last stage of compensation is, in terms of water-path, equal to three times the distance between two adjacent receivers.

Since the amount of compensation effected in the three separate stages is in the ratio of 2:3:6, it follows that all the compensators will require the same angular setting if the average radius of the grooves for the compensators of the three stages has this same ratio respectively. Under such conditions the seven compensators can be geared together so that a rotation of the binaural compensator by the operator will produce the same angular motion in all, and when a sound is binaurally centered all the compensators are so adjusted that the intensity of the sound is a maximum. The compensation, which as described requires seven separate compensators, is all accomplished by a single compensator known as the "Type H," the principle of which is shown in Plate XIII.

The four groups of three receivers each connect through the bottom plate of the compensator to the points represented by numerals 1 ··· 12. The path from receiver 1 includes the groove from 1 through *s* and back to *A* in the movable upper plate of the compensator while the path from receiver 3 includes the groove 3–*T*–*A*. Receiver (2) connects directly to point 2 on the compensator plate through a path length equal to that of receivers 1 and 3 when each groove path is the same. The other three groups of three receivers are similarly connected to the grooves of the other three quadrants.

Sound from receivers 1, 2, and 3 can be brought into phase at *A* by rotating the groove to a proper position with respect to the fixed openings 1, 2, and 3. At the same time the three receivers of each of the other three groups will be brought into phase at the points *B*, *C*, and *D* respectively.

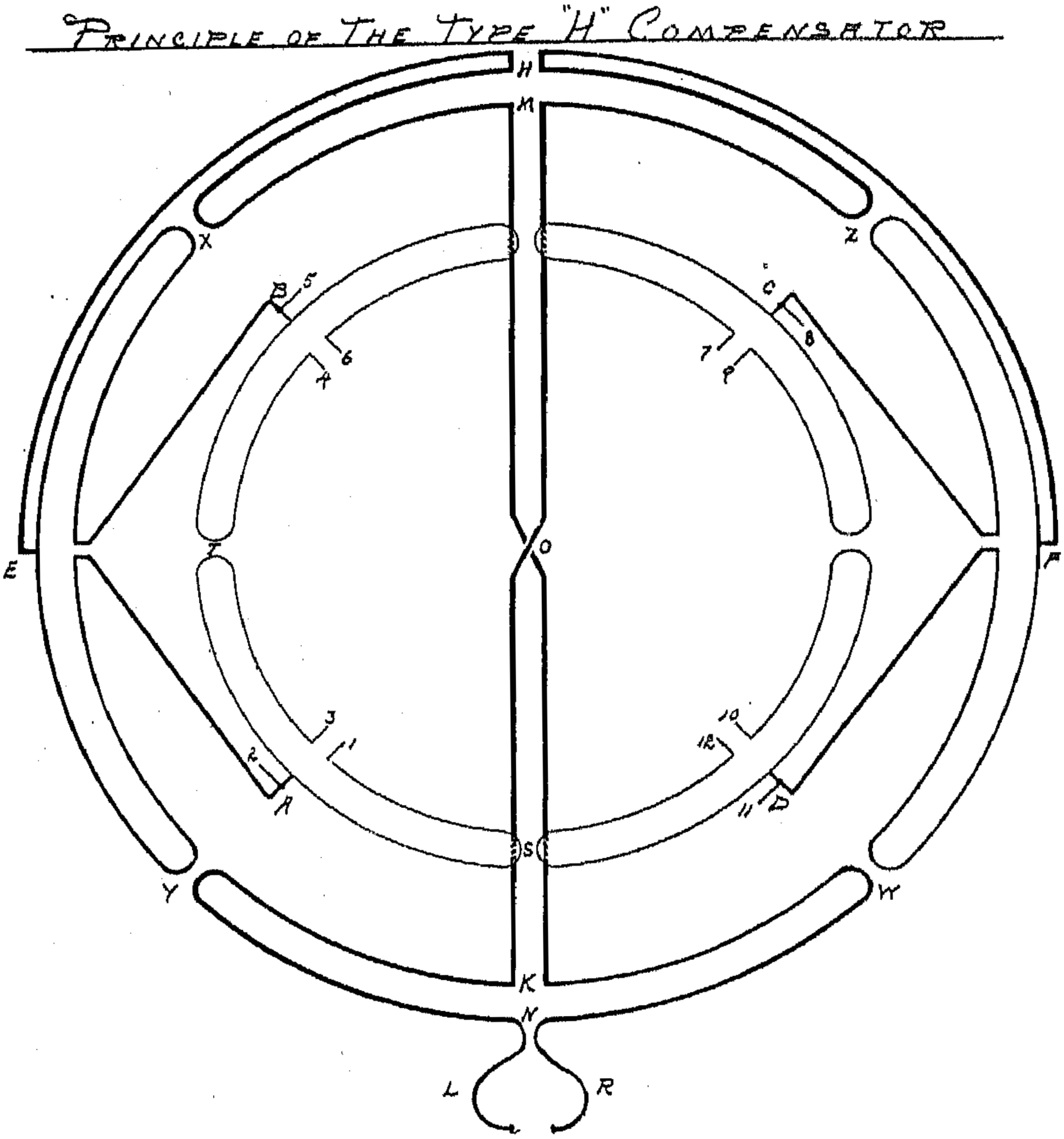

PLATE XIII. Principle of Type-H compensator.

Sound from points *A* and *B* are conveyed through two fixed grooves of equal length in the lower plate to another compensating groove in the movable plate, the sound from *B* passing around the end marked *X* and that from *A* passing the end marked *Y*. Both sounds unite in a single path at *E*. The sounds from *C* and *D* are similarly united in a single path at *F*.

The two sets of grooves are so made that their average radius has the ratio 2:3 in order that the compensation effected in the second stage may be one and a half that effected in the first stage which has been shown to be necessary. It remains to be shown that the

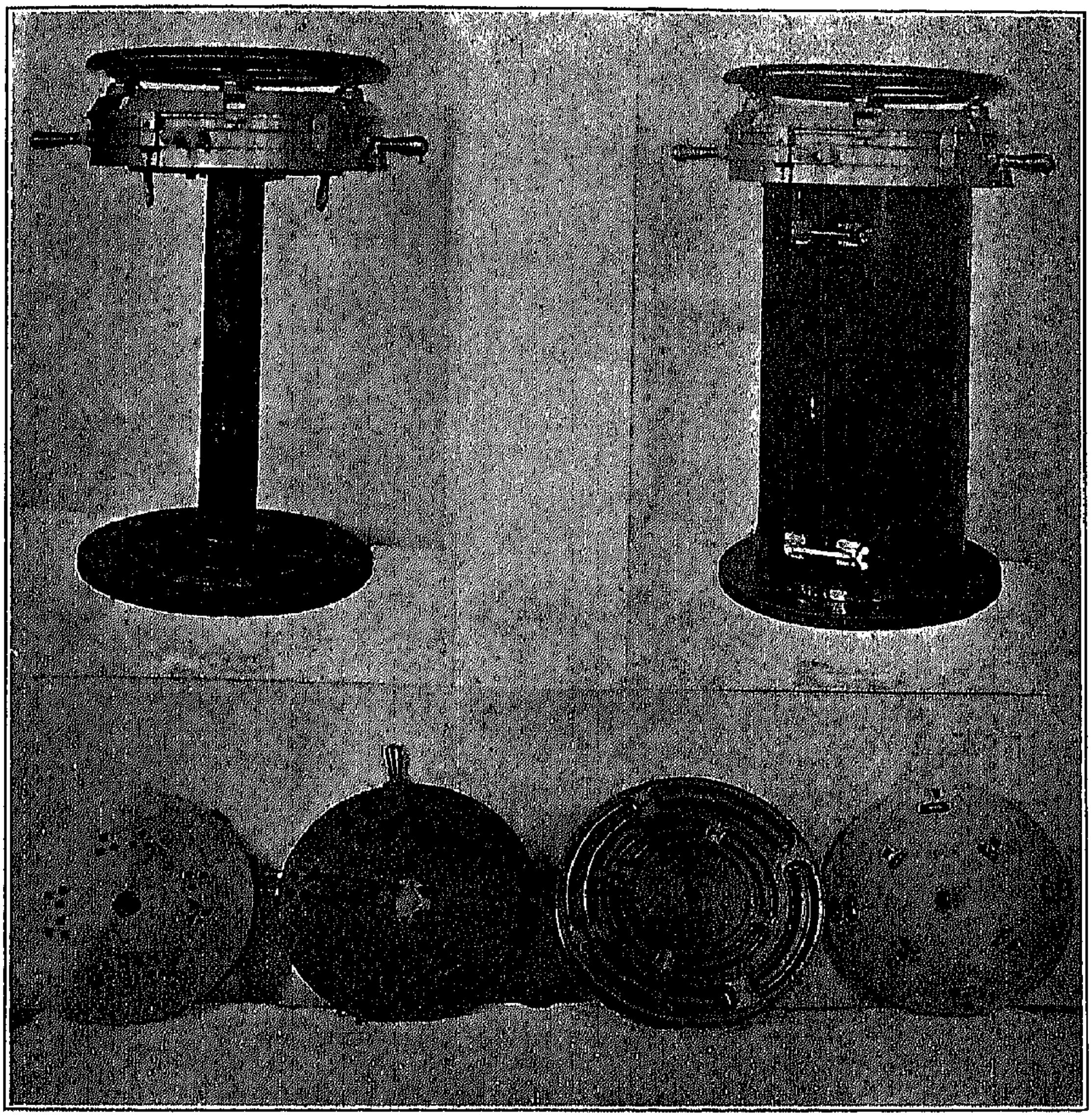

PLATE XIII. *a*. The Type-H compensator, showing structure of grooved plates for compensating twelve acoustical units.

sound from the two points *E* and *F* suffers during the third or binaural stage three times the compensation effected in the first stage whenever the top plate is turned.

The course of the sound from *E* to the listener's ear is: *E* to *H* through fixed path in lower plate; *H–X–M* through compensating groove in upper plate; *M–O–K* through fixed groove in lower plate;

K–W–N through compensator groove in upper plate; *N–R* through stethoscope lead to right ear. The sound from *F* traverses a similar course, viz.: *F–H–Z–M–O–K–Y–N–L* ending at the left ear. It is readily seen that the compensation effected between *E* and *R* and between *F* and *L* when the upper plate of the compensator is rotated

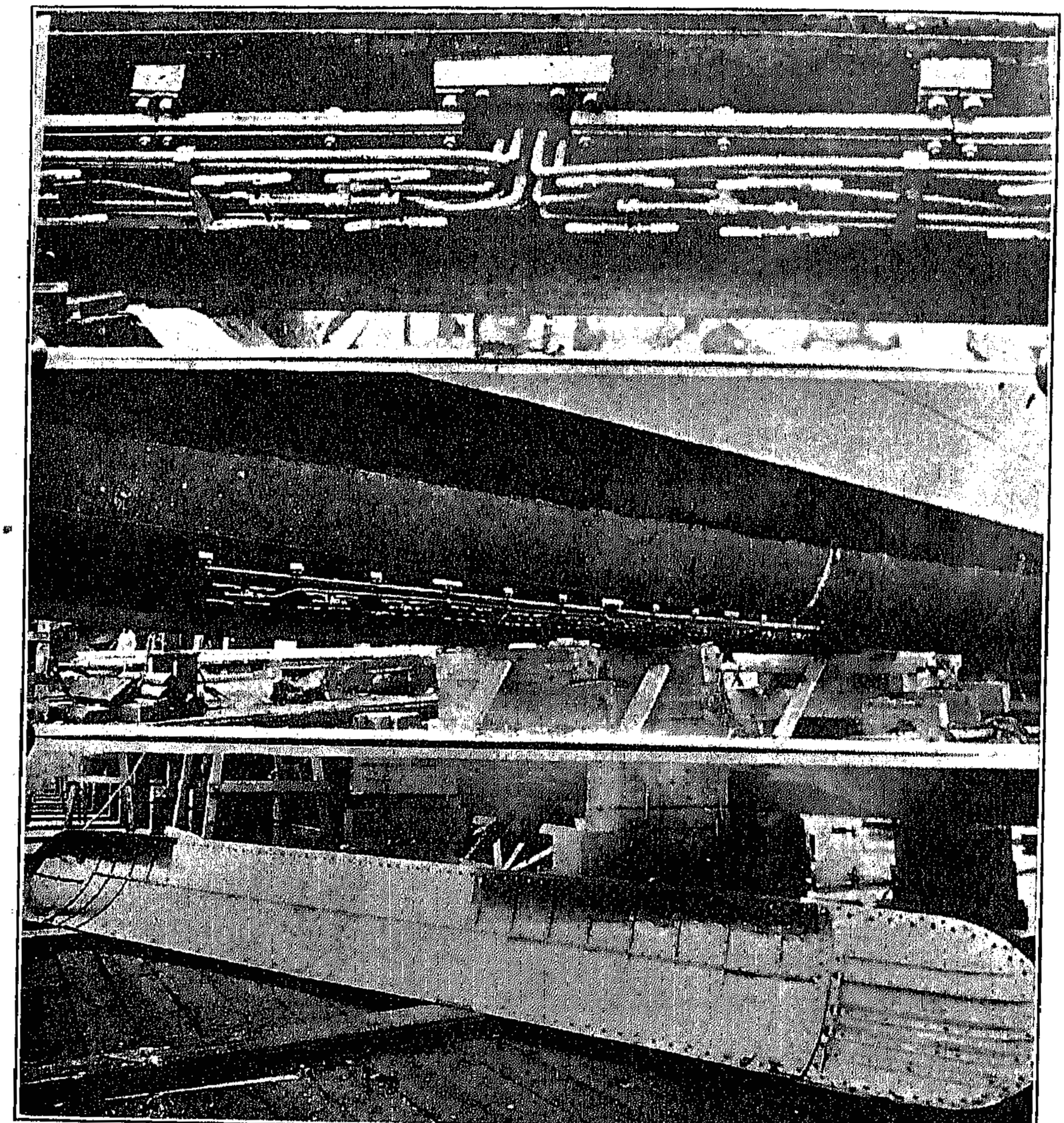

PLATE XIII. *b*. The acoustical M-V installation and protective blister.

is double that effected between *E* and (*B* or *A*) since in the former case two grooves are connected in series. Thus all the requirements for complete compensation of twelve equally spaced receivers mounted in a line are met.

The dimension of the grooves through the compensator are such as to preserve uniformity of cross-section. A third bottom plate is provided and so arranged that by rotating the second plate, which carries the fixed grooves and stethoscope leads, upon this through a small angle either the port or starboard line of receivers can be connected through the compensator.

The three figures in Plate XIII. *a* give the appearance and construction of the Type H Compensator in detail. Plate XIII. *b* shows the manner of mounting the line of receivers beneath a streamlined protecting blister on the outside of the hull.

The M-V Tube determines direction by means of variable compensation instead of by rotating the line of receivers and therefore is free from the weaknesses inherent in the M-B Tube and the double M-F Tube. Its focusing effect is superior to either of these devices because of the greater length of its line of receivers. It is more rapid and easy to operate since it only requires the rotation of the compensator plate to center a sound binaurally. And, finally, it can be operated while the boat is moving. The M-V Tube is without doubt the best "on-board" listening device thus far developed. Some idea of its ability to locate a submarine can be gained from Plate XIV.

The full line curves represent the true course of a submerged submarine. The coördinates of the curves have time for abscissæ and angular bearing with respect to the listening boat as ordinates. The round circles represent bearings as determined on an early form of M-V Tube. The speed of the listening boat, a destroyer, is given by the broken line curve at the top of the sheet and the distance in yards of the submarine is marked at various points along the curve.

The M-V Tube in its later forms makes use of twenty units instead of twelve. These installations are capable of giving better results than those recorded in Plate XIV. The possibilities of the M-V Tube will not have been reached until a compensator is devised which will take care of a line of receivers spaced about fifteen inches apart and extending the entire length of the boat upon which it is installed. Experimental results however seem to suggest that the advantage to be gained by extending the line of receivers much beyond forty or fifty feet is scarcely worth striving for.

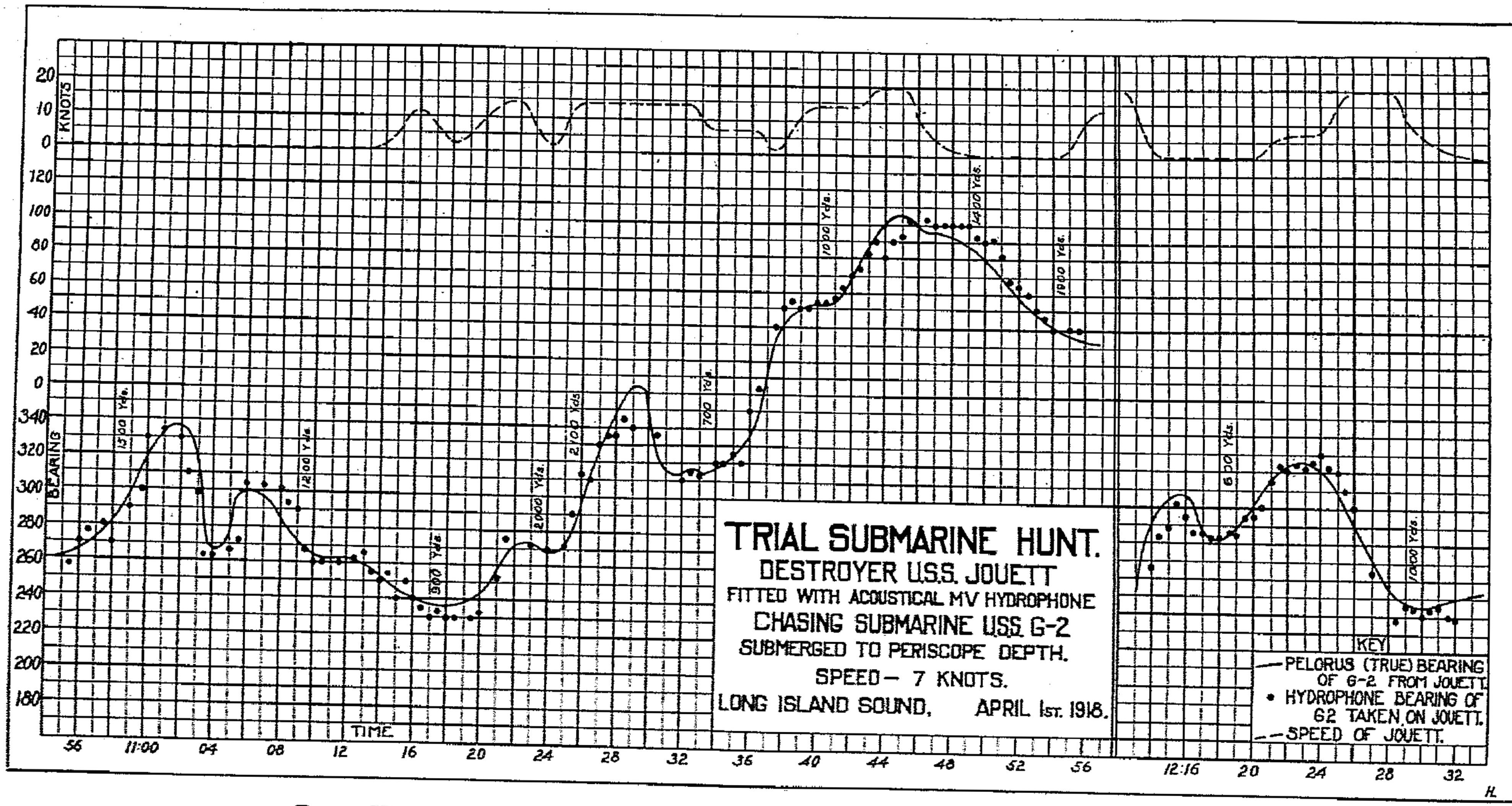

PLATE XIV. Typical curve taken on submarine hunt with acoustical M-V equipment.

The statement that no increase in range is to be gained by increasing the sensitiveness of the receivers beyond a certain point obviously does not apply when the receivers are used in multiple since the local and other disturbing noises are not intensified in the same proportion as the sound upon which the receivers are focused. More sensitive receivers can be effectively employed in multiple unit devices than in single unit devices such as the "3-spot" and "4-spot."

The sensitiveness of the acoustical receivers is not as high as can

A

B

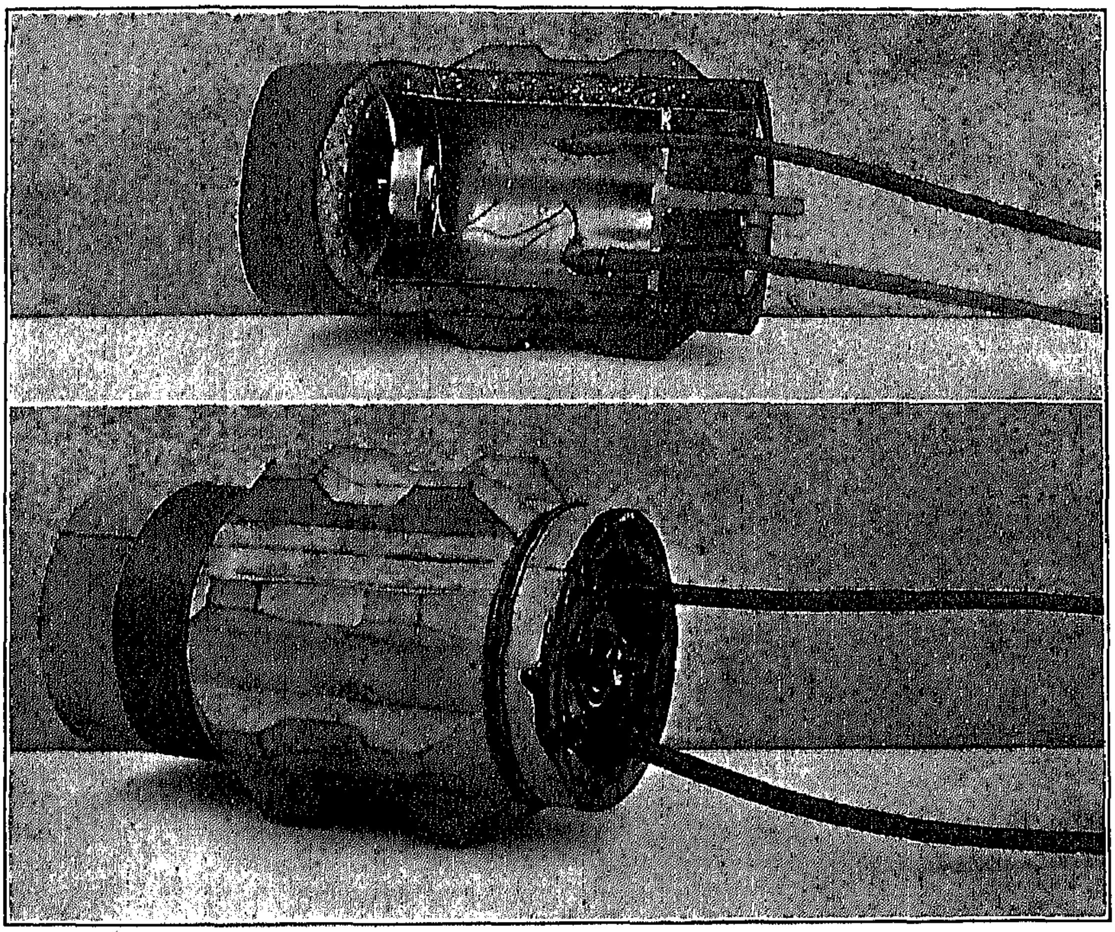

PLATE XV. The microphone housing developed at the U. S. Naval Experimental Station. *A,* Section through interior showing microphone. *B,* Complete receiver unit, about ½ natural size.

be advantageously used in multiple unit devices. This fact, together with the need for a long range listening device led to the development of several types of electrical listening devices employing multiple receivers. A description of these devices follows:

The U-3 Tube is a submarine sound-detecting device which can be towed astern from a moving boat at any desired distance. In principle it is an electrical copy of the M-V Tube above described. Two lines of twelve equally spaced microphone receivers are connected through a multiple unit electrical compensator to a head set

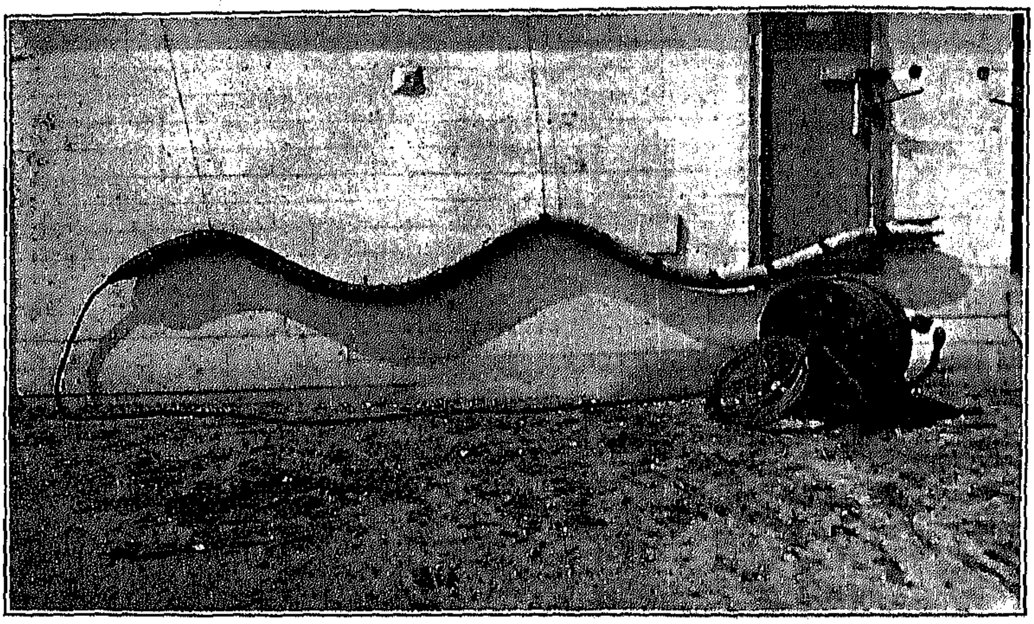

PLATE XVI. The twelve-spot microphone eel and cable reel.

of two carefully matched telephone receivers. The microphone receiver developed for these lines is fully as sensitive as the "rat" and gives a more faithful reproduction of phase, a requirement for receivers used in multiple. The construction of this receiver is shown in Plate XV.

Each line of twelve receivers is housed in a flexible gum rubber tube which is stopped at either end by properly streamlined forms. A line of receivers so housed is called an eel. Electrical connection between the receivers and compensator is made through a 14-conductor cable which can be payed out or in from a specially designed reel without breaking the electrical circuits. Plate XVI. shows the eel with its cable and reel. Plate XVII. shows the Type AE-2 electrical compensator, used to compensate the receivers in the eel.

The U-3 Tube consists of two similar eels towed abreast, each by its own separate cable. The eels, because of their flexibility, do not skid when eddies or cross currents are encountered and thus keep their relative position without the use of a spreader. Their horizontal distance remains the same as that between their respective cables at the boat's stern with but slight variation.

Every unit in the construction of an eel (head, tail, housing tube, and each of the twelve receivers) is carefully designed to have neutral buoyancy in sea water when the eel is filled with fresh water. This assures that the line of receivers will lie in a horizontal plane

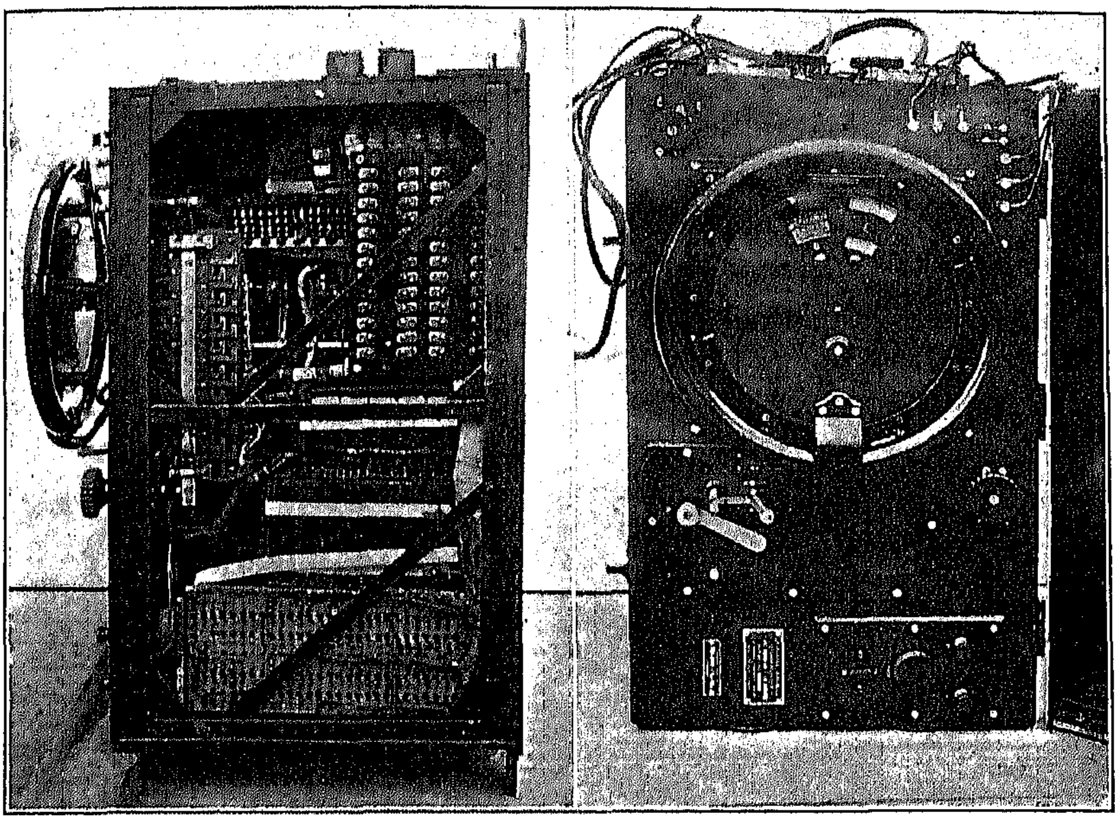

PLATE XVII. The AE-2 electric compensator designed to accommodate two sets of 12-spot microphone lines.

so long as there is any appreciable relative motion between the eel and the water. The depth at which the eels trail depends upon the length of cable and the speed of the boat. In practice this depth is kept within 100 feet.

The electrical impulses from the microphone receivers, produced by sound from any particular direction, are brought into phase at the two telephone receivers by means of a rotating switch arrangement which introduces the proper amount of loaded line into the separate microphone circuits. The 6 microphones in the forward half of the receiver line attach to one telephone and the rear 6 connect with the other. The construction of the compensator is such that the same setting which brings a sound into focus causes it to appear binaurally centered and the rotating switch carries a scale and pointer indicating the bearing (ambiguous of course as to port or starboard).

The ambiguity cannot be removed by comparing the intensity of the sound as given by each line of receivers (the method employed for an "on-board" installation) since there is no sound screen between the two lines. It therefore becomes necessary to make a second compensator setting on two groups of receivers which have their line of centers in a different direction. This can be done by using six receivers in each eel. The direction will then be the common angle of the two compensator settings as has been shown.

A switching arrangement is provided whereby the twelve receivers in the port eel, or the starboard eel, or the six forward receivers of both eels, or the six rear receivers of both eels can be connected through the compensator to the two telephones. Furthermore the compensator is so designed that the last stage of compensation, the binaural stage, can be uncoupled and varied independently of the other two stages which may be termed the maximum part of the compensation. Whenever compensation is effected across the two eels, *i. e.*, between the head groups or tail groups of receivers, it will be seen that the binaural part of the compensation must be made independently of the maximum part.

Suppose a binaural setting has been made on a sound when the 12 receivers of, say the starboard eel, are connected through the compensator. The maximum part of the compensation is properly adjusted to bring the impulses from each group of 6 receivers—the head group and the tail group—into phase. The resultant of each group is brought into phase by the binaural part of the compensation and the compensator is so designed that the same angular rotation is required for both stages. Now if the six receivers in the head of the port eel are substituted for the rear six in the starboard eel and in the same order, it is evident that the compensator adjustment for maximum still holds for the reason that this is determined by the angle between the line of the receivers and the sound. This angle remains the same in both cases since the two eels are parallel. But the phase difference between the resultant of the two groups will in general be different in this second case so that the binaural part of the compensation will need to be changed to give a binaural center.

The switching arrangement in the compensator is designed so that whenever the receivers are connected in for cross-compensation a clutch which connects the maximum and binaural parts of the compensation is automatically released leaving the binaural part free to turn while the maximum part remains fixed. This clutch automatically falls back into position whenever the port or starboard line of receivers is switched to the compensator.

The direction of a sound source is then determined on the U-3 Tube as follows: Connect the receivers in either eel to the compensator and make a binaural setting, then connect either the head or tail groups to the compensator and make a second binaural setting. The common angle on the two double scales is the direction.

The compensator is provided with two electrical filters either of which can be connected in series with the telephones at will. These filters allow all sounds above a certain definite frequency to readily pass but eliminate almost entirely the lower frequencies. One filter limits the passage to frequencies above 450 and the other to those above 900. Very often disturbing noises can be largely eliminated by using one filter or the other without weakening the comparatively high pitched sound from a submarine.

The U-3 Tube is one of the best listening devices that has thus far been devised. It can readily be installed on any boat without docking, is durable and easily repaired and rapid in manipulation. It can be operated at fairly high speeds because its streamlining is such that it produces very little water noise itself while it can be towed far enough astern to reduce the water noise and other noises on the listening boat to a minimum. It has the longest range of any of the various types of submarine detectors due to the fact that it employs highly sensitive receivers in multiple combination, operates at sufficient depth to largely eliminate surface noises, and at a sufficient distance from the listening boat to largely eliminate local noises, and due to its focusing qualities desirable sounds are intensified while other sounds are relatively weakened.

The use of multiple unit electrical lines is not limited to towing devices. As an "on-board" installation the electrical MV has certain advantages over the acoustical. It is more sensitive and therefore capable of giving greater range. It can be housed within a water-tight blister in such a way that the line of receivers can be withdrawn through a hand-hole opening in the skin of the ship and repaired or replaced without docking the boat. The installation as a whole has proved more durable than the acoustical lines. If a receiver becomes defective it can be cut out and the line can still be used, whereas a leak in the acoustical line allows the installation to fill with water and thus become useless. Finally, the compensator can be placed on or near the bridge whereas the listening station for an acoustical MV must be placed near the inlets through the ship's skin. This location must necessarily be near the keel of the boat and as a result considerable distance from the bridge.

On the other hand, the quality of the sound and the selectivity given by the acoustical MV is superior to that given by any electrical MV thus far produced because of the fact that the acoustical receivers are better matched than are the microphone receivers. However, improvements in the construction and matching of the microphonic receivers are continually being made and there is all reason for believing that the electrical MV will soon be made to compare very favorably with the acoustical MV as regards quality of sound and selectivity.

The perfection of the electrical MV has made possible the use of two or more lines of receivers with the same compensator. The type AE-2 electrical compensator developed for use with the multiple microphone eels is provided with a multiple unit switch whereby it can be connected with either the two eels, as described, or to two "on-board" lines enclosed in blisters. This combination is very favorable for searching submarines for the reason that the eels can be used for picking up faint or distant sounds thereby directing the listening boat to a point where the submarine can be heard and followed by means of the "on-board" lines. Moreover, the distance of the submarine can be judged with some accuracy by determining its bearing on both the eels and the "on-board" lines. The distance between the eels and the blisters being known the range of the submarine is readily determined by triangulation. While this method does not determine range with sufficient accuracy for bombing purposes it is sufficiently accurate to be helpful in making an approach.

Plate XVIII. shows the range chart used in connection with this type of installation. Range curves are plotted in terms of the angular bearings on the two installations. As an example, suppose the

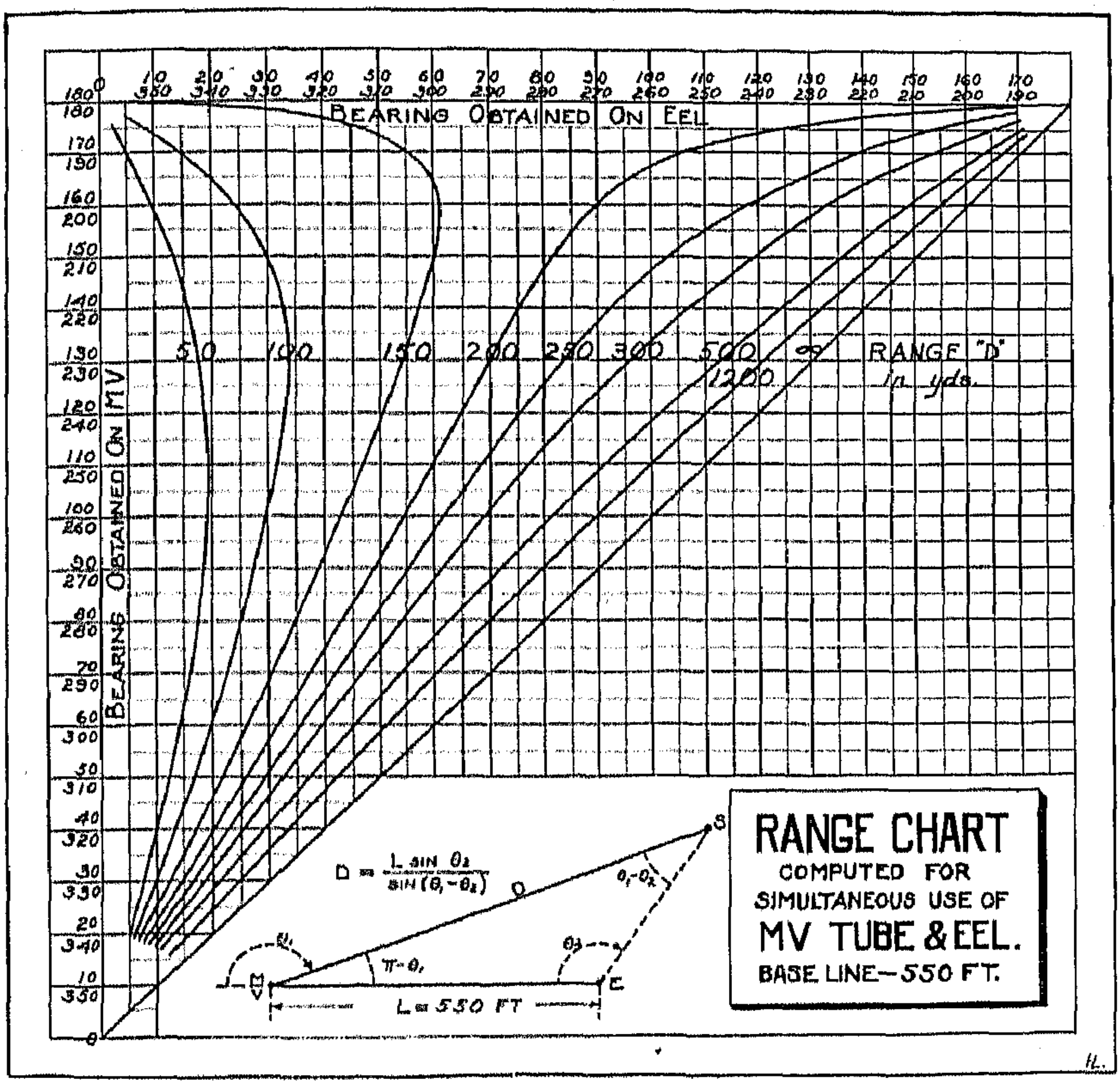

PLATE XVIII. Range chart—computed for two detectors with base line of 550 feet.

bearing of the submarine as given by the eels and the "on-board" lines are 43 degrees and 120 degrees respectively. The range of the submarine would be 125 yards.

The development of the principle of electrical compensation has made possible the use of long lines containing many receivers so it would seem that the limiting possibilities of the submarine sound detector have by no means been reached. In fact the usefulness of these devices in peace times as well as in war times is but imperfectly realized, but it is a safe prediction that the future will find them a distinct safeguard to navigation.

The Value of the Submarine Sound Detector as an Instrument of Warfare is not to be measured by the number of "U-boats" that by its aid have been located and damaged or sunk but rather by the resulting curtailment of their radius of operation and the effect on the morale of their officers and crews. The U-boat in operation was never safe after the perfection of the submarine detector. When traveling at sufficient speed to cover any distance it could be heard and accurately located at a range of several miles. The same was true whenever it lay on the surface charging its batteries. It could, in some localities, lie at rest on the bottom or if the depth prevented this it could run very slowly, about one and a fourth knots, at a depth of from 100 to 200 feet and thus be reasonably free from detection but under such conditions it was comparatively harmless.

Submarine sound detectors promise to become a distinct aid to navigation during conditions of low visibility. Its aid is two-fold: first, approaching vessels can usually be heard and located in time to avoid collision and second, harbor entrances can be safely made by taking bearings on properly placed submarine signals.

The U. S. S. destroyer *Parker* while maneuvering in the North Sea in a dense fog reported that she avoided two collisions in one day by locating an approaching boat with her listening gear.

Some idea of the aid which can be given in entering a harbor is shown by the results of recent experiments. By means of an electrical MV-Tube on one of our transports, the writer recently located the Nantucket Light-ship within two degrees at a distance of 37 nautical miles by picking up its submarine bell signal, and this was accomplished while the transport was steaming at 15 knots. Had the transport slowed down to ⅓ speed the bell could without doubt have been heard at a range of over 50 miles. While entering New York Harbor from one to three bell signals could be heard and accurately located at any time and as a result the vessel could have safely entered harbor in a dense fog.

It would seem that navigation during conditions of low visibility can be made perfectly safe if each boat is equipped with a good submarine sound detector and a submarine signal device such that its signals can be distinctly heard at a distance of at least five miles. During fog each boat should periodically signal by code its course and possibly its speed. By picking up such signals on its listening device any boat can avoid collision since it will know the bearing, course, and speed of all ships within a radius of five miles.

Such an arrangement should not only eliminate all possibility of collisions *but should enable our whole Merchant Marine to keep moving at practically full speed at all times,* thereby placing it in a better condition for competing with the Merchant Marines of other nations than it otherwise would be.

U. S. Naval Experimental Station,
New London, Conn.