

## A Radio-Acoustic Method of Locating Positions at Sea: Application to Navigation and to Hydrographical Survey

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XVIII. *A Radio-Acoustic Method of Locating Positions at Sea\**: Application to Navigation and to Hydrographical Survey. By A. B. WOOD, D.Sc., F.Inst.P., and Captain H. E. BROWNE, O.B.E., R.N

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ABSTRACT.

A description is given of a series of experiments carried out to test the possibilities of the Radio-Acoustic method as a means of locating positions at sea. In this method, as applied to navigation, for example, the ship requiring her position makes a W/T "dash" at the same instant as a small charge is fired in the sea. A station on shore records the arrival of the W/T signal and also of the explosion wave at a number of hydrophones suitably disposed in known positions on the sea-bed. The times of travel of the explosion wave, and hence the distances from the charge to each hydrophone, are indicated by an Einthoven galvanometer photographic recorder.

The method permits of great accuracy and has important applications in navigation and hydrographical survey. For navigational purposes great accuracy is sacrificed to speed—it being possible to give a ship her position within a radius of half a mile within 10 minutes of receiving her request for a location. A 9 oz. charge of explosive can be located at 40 miles. In hydrographical survey work the method has already been used successfully in fixing accurately the positions of certain buoys and light vessels.

The possibility of screening and distortion effects produced by sandbanks has been investigated.

The radio-acoustic method has been thoroughly tested under working conditions. It has proved accurate and reliable by day or night, in rough or in foggy weather and at all seasons of the year. Many locations have been given by the method and no failures have been experienced.

The R/A system should be regarded as a serious competitor to the method of location by directional wireless.

I. INTRODUCTION.

THE principle of measurement of distance by means of two waves propagated with different velocities has long been known; but it is not until recently that the method has received practical application in the determination of positions at sea. Joly† has described the method in some detail, and has proposed the use of various forms of it for navigational purposes. The underlying principle of the method is briefly as follows: The ship to be located emits simultaneous signals having different velocities of propagation. These signals are received in a suitable manner at a fixed station, the time interval " $t$ " between the arrival of the two signals being measured.

\* Work carried out at Admiralty Station, St. Margaret's Bay, Dover, under the joint direction of the Director of Torpedoes and Mining and the Director of Scientific Research, Admiralty. The authors desire to acknowledge their indebtedness to the Department of Scientific and Industrial Research for financial aid in respect of the investigation. Thanks are also due to the Admiralty for permission to publish the results of the experiments, to those who were concerned in the laying and surveying of the hydrophones, and to many others who rendered assistance and advice.

† See Phil. Mag., 36, June (1918), and Proc. Roy. Soc., A, 94, August (1918).

Knowing  $V_1$  and  $V_2$ , the velocities of propagation of the two types of signal, the distance  $D$  of the ship from the fixed station is at once obtained from

$$t = \frac{D}{V_1} + \frac{D}{V_2}.$$

Thus, if the ship originated simultaneous acoustic waves in air and in water, the respective velocities being 338 and 1,510 metres/sec., the distance  $D$  in metres would be approximately  $435t$  from the receivers. If light waves and acoustic waves in air were simultaneously emitted (as in the case of a gun firing),  $V_1$  is 338 metres and  $V_2$  is  $3 \times 10^8$  metres per second; then  $D$  is equal to  $V_1 t$  practically—i.e.,  $338t$  metres.

If two or more fixed receiving points in *known* positions are employed, it is a simple matter to locate the source of the double signal, for the observations give the ranges of the source from each of the known fixed points.

In the experiments described in this Paper a method has been developed which employs the simultaneous emission of a wireless signal in air and an explosion wave in water. The distances measured in such a case are solely dependent on a knowledge of the time interval and velocity of propagation of the explosion wave in water, for the time of propagation of the wireless wave is negligible by comparison. Recent experiments by the authors at St. Margaret's Bay, Dover, have given very accurate data for the velocity of propagation of an explosion wave in sea water.

Between the temperature-limits  $6^\circ$  to  $17^\circ\text{C.}$  and with the salinity in the neighbourhood of 35‰, the velocity is expressed by the relations

$$V = 4756 + 13.8t - 0.12t^2 \text{ (ft./second)}$$

or

$$V = 4626 + 13.8t - 0.12t^2 + 3.73S \text{ (ft./second)},$$

where  $t$  is the temperature in degrees centigrade and  $S$  the salinity in parts per thousand.

With this information as a basis, ranges have been measured and positions located accurately at distances greater than 50 miles.

## II. METHOD.

The location of a source of simultaneous wireless waves ( $W/T$ ) and acoustic waves is a simple application of the above method of range measurement. There is required—

- (a) A means of producing the double signal—e.g., a means of producing a  $W/T$  dash at the instant of explosion of a charge.
- (b) Two or more acoustic receivers under water—the positions being accurately known—and a  $W/T$  receiving set at the recording station; and
- (c) A means of recording and timing the radio-acoustic signals.

### *Transmission of the Double Signal.*

(a) The radio-acoustic signal can be produced in several ways, according to the degree of accuracy required in the location or "fix."

In the simplest case, where only an approximate fix is desired, the  $W/T$  operator on the ship presses his transmitting key when he hears or feels the shock of the

explosion. In such a case the explosive may be a small charge of guncotton fitted with a fuse, the charge being thrown overboard at the position to be located. Such a method, of course, involves the personal error of the *W/T* operator, there being necessarily a certain, somewhat variable, lag between the explosion of the charge and the pressing of the *W/T* transmitting key.

For more accurate work a double key can be used, one part of the key firing an electrical detonator in the charge, the other part transmitting the *W/T* dash. If still greater accuracy is required, a simple automatic arrangement can be employed, whereby the shock of the explosion automatically closes a circuit and transmits the *W/T* signal. Up to the present the double-key method has been found quite sufficient to meet all practical requirements. In that method it is essential, of course, that a sufficiently high voltage be employed to fire the detonator in order to reduce time-lag to a minimum. Usually 80 volts are applied to the detonator, whereas 2 or 3 volts would be sufficient to fire it; the lag in the former case is of the order of 0.001 second.

#### *Reception of the Double-signal.*

(b) The acoustic receivers employed to detect the arrival of the explosion impulse through the sea are hydrophones of the microphone type, laid in carefully surveyed positions. Four hydrophones are used, laid on a line approximately N. & S., just to the eastward of the Goodwin Sands. The positions are given in the following table :—

TABLE I.

Hydrophone No.	Latitude North.	Longitude East.
1	51° 24' 1.5"	1° 36' 38.5"
2	51° 20' 26"	1° 35' 27"
3	51° 16' 38.5"	1° 36' 33"
4	51° 12' 29"	1° 35' 55"

These positions are shown on Fig. 1.

The distances apart and relative orientations of the various pairs of hydrophones are given below :—

TABLE II.

Hydrophone Pair.	Distance apart, Feet.	Angle from true North (measured clockwise).
1—2 ... ..	22,279	11° 43.5'
1—3 ... ..	44,850	0° 26.5'
1—4 ... ..	70,245	2° 15.5'
2—3 ... ..	23,413	349° 42'
2—4 ... ..	48,409	357° 54'
3—4 ... ..	25,456	5° 27.5'

The four hydrophones are connected by twin-core armoured cable to the recording station.

#### *Recording and Timing the Signals.*

(c) The electrical circuits of the hydrophones consist essentially of a battery in series with the microphone and primary of a transformer, the secondary of which

is connected directly to one of the strings of a six-stringed Einthoven galvanometer set. Four of the strings of the galvanometer are connected in this way to their corresponding hydrophones, a fifth string records (through a microphone circuit) the half-second ticks of a Greenwich chronometer, whilst the sixth string records the W/T signals. The latter are received by a suitable aerial and standard receiver, amplified by six valves in cascade, rectified by a seventh valve and then passed through the line circuit of a Brown microphone relay. The circuit of the microphone of this relay consists of a dry cell, an adjustable resistance and the moving coil of a Weston relay. The resistance is so adjusted that the local circuit of the Weston relay is *just* closed, and a small current flows through the contacts and the galvanometer string. When a W/T impulse is received, the microphone of the Brown relay is disturbed and its resistance increases, causing the local contacts of the Weston relay to open and cut off the current through the galvanometer string. With this arrangement W/T signals can be recorded quite satisfactorily provided the rate of transmission of the signals is not too rapid for the Weston relay to recover in the intervals between the signals.

The photographic record (on bromide paper) is crossed by a series of fine lines marking seconds, tenths, and hundredths—for very accurate work thousandths of seconds can be estimated. The time marks are made by a phonic wheel controlled by a 50  $\sim$  tuning fork electrically maintained.

With the apparatus outlined above, a radio-acoustic signal will give the following information :—

(1) The total time interval from the charge to each hydrophone ; and (2) the time of passage of the explosion wave between each pair of hydrophones.

From (1) we can at once deduce the distance of the charge from each hydrophone, whilst from (2) we obtain a bearing of the charge from the mid-point of each pair of hydrophones.

When the method is used in navigation where rapid “fixes” are required, the total distances and bearings need only be approximate, in which case the bearing may be taken as the asymptote of the hyperbola for the corresponding time interval. In accurate work both total distances and bearings must be accurate ; consequently, all bearings must have the asymptote correction applied. The location by plotting in the radio-acoustic method permits of great accuracy in that it is in all cases determined by lines crossing almost at right angles. The bearing lines from the mid-points of hydrophone pairs, always cut the range arcs from the individual hydrophones in a large angle (comparable with  $90^\circ$ ), whereas the intersection angles of the various bearing lines or of the range arcs amongst themselves respectively are usually small. At long ranges this point is of great importance, and indicates the fundamental reason why radio-acoustic sound ranging is so much more reliable than the three-point system, where only time-differences and therefore bearing lines only are obtained.

In the R/A method the intersecting lines which locate the explosion are mutually at right angles, whereas in the three-point method they tend at greater distances to become parallel and the location correspondingly indefinite.

### III. PRELIMINARY EXPERIMENTS.

The first experiments were made with the object of testing the accuracy of the method in giving rapid and approximate locations of the charge fired by a destroyer

in known positions. Many such observations were made, charges being located at distances ranging from 10 to 40 miles from the hydrophones. In these preliminary tests the time intervals on the record were read to  $\pm 0.05$  second only, in order to reduce the total time taken to obtain a location. An average time from calling up by the destroyer to giving the position was about 10 minutes. In all cases, with certain exceptions to which we shall refer later, the position given by the R/A method agrees, within the limits of error of the destroyer's estimate, with the position of firing the charge.

During these preliminary experiments a study was made of the screening effect of sandbanks, and it may be of interest to refer briefly here to the main results obtained. Charges were fired at various points around the Goodwin Sands. In no case when a charge was fired to the westward of the sands (the hydrophones lying to the eastward—see Fig. 1) was any effect recorded, the explosion wave failing

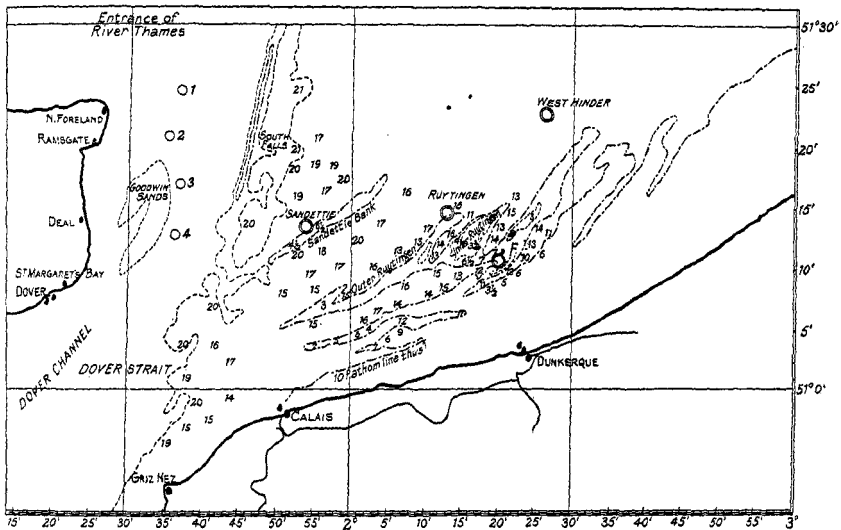


FIG. 1.

to penetrate the sands or to pass over the shallow water (3 or 4 feet) covering them. The distance of the charge in this case from the nearest hydrophone was about 5 miles, the same hydrophone having recorded the effect of a charge of the same size at 50 miles when no shoals intervened. Firing charges in other positions only partially screened by the sandbank indicated that the latter was casting a very efficient acoustic shadow. In one experiment some evidence of distortion at the edge of the sandbank was obtained, the record suggesting that an acoustic wave (of long wave length) resulting from the explosion was either diffracted round the edge of the sandbank or that the main pressure wave was retarded in velocity and changed in wave form as it passed over the shallows at the edge of the bank.

The observations in general, however, indicated the complete screening effect produced by a sandbank such as the Goodwins. A distortion effect such as that

quoted is a rare exception which would be unlikely to occur in ordinary practice, and even then would easily be detected. Other factors which influence the range of detection of the explosion wave have been examined experimentally, but the results of the investigation will be published later.

#### IV. NAVIGATIONAL EXPERIMENTS.

The preliminary experiments just outlined indicated at once the possibilities of the radio-acoustic method when applied to the navigation of ships. These experiments showed that it was possible to give a vessel an accurate position within 10 minutes of receiving her request for a "fix." Consequently several trial cruises were organised in which the destroyer should proceed to any position selected by her navigating officer, and, of course, within range of the station, and ask for a "fix." The results of these experiments were entirely satisfactory, in every case the rapid R/A "fix" agreed with the position estimated by the navigating officer of the destroyer. A long list of observations of this character could be given in evidence of this agreement, but they are omitted to save space. A specimen record and location is, however, shown in Fig. 2. On one occasion the destroyer found herself between dangerous sandbanks off the Belgian coast (*see F* in Fig. 1), a mist preventing her from distinguishing shore objects. An R/A fix, however, cleared up all doubt as to her position and she returned to Dover Harbour in safety.

Such experiments as these were carried out throughout the winter of 1921-22, in very rough and in misty weather, and on every occasion the R/A locations have been found more reliable than those determined by the ship's navigating officer by ordinary methods (*e.g.*, by time-distance-bearing, or by sighting light-vessels).

There should be little further difficulty in applying the R/A method to ships in general. Most ships requiring to make a good landfall after a long voyage carry wireless apparatus. It has been found that a small 9 oz. charge can be located up to about 40 miles, and this would be a convenient size to carry.

The R/A method of locating ships at sea in foggy weather should now be considered as a competitor to the Directional Wireless Method. The R/A method possesses the very great advantage of being equally accurate and reliable day or night, at all seasons of the year and under all weather conditions—whereas directional W/T locations are often open to doubt, peculiar errors of several degrees in bearing being of frequent occurrence.

#### V. HYDROGRAPHICAL SURVEY.

In the foregoing remarks particular importance has been attached to the "rapid" and approximate R/A location for navigational purposes, rather than to the more accurate location which the Einthoven galvanometer record is capable of revealing.

On certain occasions when the destroyer "Thruster" asked for a "fix" whilst in the neighbourhood of the West Hinder Lightship (*see* Fig. 1), the rapid R/A location appeared to be considerably in error. The experiments were consequently repeated, the destroyer estimating her position as accurately as possible, and the Recording Station calculating the position of the charge by the accurate method. In this method the recorded times are estimated with an accuracy of  $\pm 0.001$  second, and the asymptote correction is applied to the calculated bearings. The calculated position of the charge was still found to disagree with the destroyer's estimated

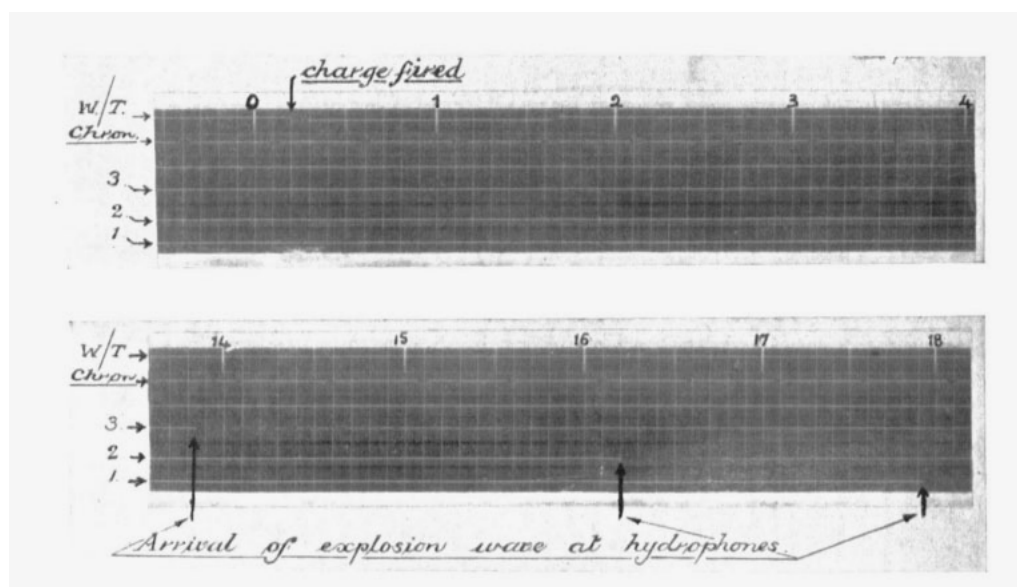


FIG. 2.—RECORD OF CHARGE No. 54.

Charge  $2\frac{1}{4}$  lbs. G.C., 40 feet deep.  
 Rapid R/A.—Charge 1: 15 Nautical miles.  
 Charge 3:  $11\frac{1}{2}$  "  
 Bearing 1-2:  $124\frac{3}{4}^{\circ}$ .  
 Bearing 2-3:  $109\frac{1}{2}^{\circ}$ .

Whence position  $51^{\circ} 14' 15''$  N.,  $1^{\circ} 54' 30''$  E., as compared with  $51^{\circ} 14' 12''$  N.,  $1^{\circ} 54' 18''$  E., estimated by "Thruster."



position, the divergence being much greater than the possible error in the destroyer's estimate. These observations led the authors to suspect that the light vessel was not in her charted position. Consequently further R/A observations were made in the neighbourhood of other light vessels, with the results shown in the following table :—

TABLE III.

Light Vessel.	Charted Position.	R/A Position.	Error in charted position.
" West Hinder " ...	51° 22' 30" N. 2° 26' 20" E.	51° 23' 16" N. 2° 27' 50" E.	1½ naut. miles N.E.
" Sandettie " ...	51° 13' 24" N. 1° 53' 42" E.	51° 13' 25" N. 1° 53' 43" E.	Nil.
" Ruytingen " ...	51° 14' 28" N. 2° 12' 58" E.	51° 14' 38" N. 2° 13' 59" E.	0·7 naut. mile 78° true.

Later observations of " Sandettie " light vessel, after a period of rough weather showed her to have moved about half-a-mile from her charted position. Further observation showed that she remained fixed in this position throughout the remainder of the winter. The R/A position of " Ruytingen " light vessel was checked by Lt.-Comdr. Archer by accurate bearing observations of the light vessel and Dunkerque. The R/A position required the bearing to be 156·5° true, whilst the charted position indicates 154° true. Direct observation gave 157° true—in good agreement with the R/A prediction. This was subsequently confirmed by the French hydrographer, in response to inquiries, who gave the position of the " Ruytingen " light vessel as 51° 14' 50" N., 2° 13' 52" E., which closely agrees with the R/A location quoted in the above table. " West Hinder " light vessel was driven from her moorings in a storm soon after she had been located by R/A ; no comparison of positions has therefore been possible.

The above illustrations serve to show how the R/A method might be applied to the location of buoys, light-vessels, &c., in hydrography. It is simple, direct and time saving. An accurate " survey " location of a buoy can be worked out in about two hours by the R/A method, whereas long and laborious observations and calculations are required in other methods of survey.

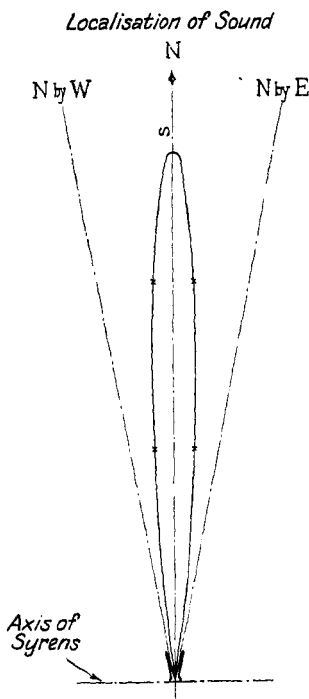
Suggestions have been laid before the Admiralty for a simple form of portable R/A set to be carried by survey ships as part of their equipment, and set up wherever required for the purpose of a particular survey.

It was considered possible that temperature differences in a horizontal plane in the sea under winter conditions might conceivably affect the R/A locations, since temperature differences of as much as 2°C. (corresponding to about 20 ft./sec. change of velocity) were known to occur. Under such conditions the wavefront of an explosion wave would to some extent be refracted, with consequent errors in range and bearings deduced from the records. Experience has shown, however, that such errors are too small to be of any importance in navigational locations, but may possibly be not entirely negligible in hydrographical survey work where greater accuracy is required. For this reason it is recommended that surveys should preferably be carried out in settled weather when temperature fluctuations are a minimum.

## DISCUSSION.

Col. H. F. TOWLER said there was no doubt as to the great need for aids to navigation in foggy weather. The method might find a further application in the prevention of collisions by a ship's emitting simultaneous fog-horn and wireless signals for observation by other ships. The direction could be got by wireless D/F, as the sound might be subject to refraction in the conditions mentioned. This arrangement would have two great advantages over that in which the locations are given by a shore station, viz., that the navigator would feel more confidence in the observations if they were taken by himself, and there would be no risk of jamming when a number of ships simultaneously required locations in a sudden fog. The speaker considered that for navigation near the shore the wireless D/F shore stations can hold their own against the R/A stations, as the errors ascribed to the former are not usually manifested at the ranges considered, viz. 30 to 40 miles. D/F stations can give a location in as good time as that claimed for R/A (10 minutes), they already exist in considerable numbers, and they are useful for other than marine purposes, e.g., for air-raft.

Mr. F. TWYMAN said it might not be irrelevant to mention an acoustic directional transmitting system\* which he had devised, but had not yet constructed. It comprises a row of synchronised



Number of Syrens 11. Vibrations per second 224. Distance apart 2 ft. 6 in.

syrens the total length of which is great compared with the wave length, and emits sound which is practically confined to the plane bisecting the row at right angles. The distribution of intensity has been worked out by Dr. Silberstein on the basis of the ideas put forward by Lord Rayleigh.†

\* British Patent Specification 4797/14 (Twyman and Another).

† Theory of Sound, 1896, Vol. 2, p. 103.

It might be expected that a beam of sound thus produced would be of more stable intensity in windy weather than a spherical wave from a point source, and that its intensity would fall off less with distance. A directional receiving apparatus might perhaps be designed on analogous lines.

Dr. C. V. DRYSDALE said that the R/A method would be an invaluable aid to navigation, but he agreed that seamen would be disinclined to rely on observations taken by other persons. The solution seemed to be that the lightships should be fitted as transmitting stations and the ships as receiving stations. For direction finding it would be preferable to use subaqueous sounds, detected by hydrophone, rather than those emitted by a foghorn, which are liable to changes of direction by refraction or reflection.

Mr. F. E. SMITH said that the captain of a vessel would certainly want to make the observations himself. It might not be generally known that, backward as the wireless equipment of this country may be, some thousands of locations are given annually to ships by the D/F shore stations. In spite of the greater accuracy of R/A, the D/F stations will probably hold the field in this service on account of their relatively small cost. Their accuracy is greatest where it is most needed, namely, in the proximity of the stations themselves. The speaker paid a tribute to the naval officers and ratings who had worked at the method and had shown great keenness as to both its scientific and its technical aspects.

Mr. T. SMITH, referring to the question of the distribution of sound intensity raised by Mr. Twyman, said that on general physical grounds one would assume that air and water are not dispersive media for sound. If, however, on a closer approximation to the facts they should be regarded as dispersive, could the existence of "silent zones" be explained on such lines?

Major W. S. TUCKER said that there are two kinds of silent zones. The first is of the type exemplified in the recent explosion experiment in Holland. The other type is really illusory, and is due simply to screening by acoustic clouds. The illusion arises from the fact that the observations have been made upon foghorn blasts emitted at one-minute intervals. If during such an interval the cloud has moved, the observing vessel having meanwhile also moved along its course, an impression is created that the vessel has steamed out of a silent zone. In reply to a question by Dr. Rayner, the speaker said that an acoustic cloud consists in the surface of separation between two bodies of air in different physical states.

Dr. A. RUSSELL pointed out that the parabolic formula given by the authors for the variation of the velocity of subaqueous sound with temperature showed a maximum. Was the formula a purely empirical one?

Mr. R. S. H. BOULDING (communicated): The authors are to be congratulated on having carried out some very interesting experiments which should prove extremely useful to the Mercantile Marine. In regard to recording, would it not be preferable, if possible, to operate the galvanometer by the W.T. signals without the aid of a Brown microphone relay and a Weston relay? The statement that a rough position can be given in ten minutes seems to suggest that there is room for improvement. Admittedly, accurate determinations require careful calculation, but rough locations could, one would think, be worked out graphically or instrumentally in a negligible time. I should very much like to have any information the authors can give as to the time lag introduced by a sound wave passing round the edge of a sand bank. I gather that this rarely occurs; but if it does, it constitutes a somewhat serious objection to the R/A method, unless it is possible for the observer to ascertain without doubt exactly what is happening. Although quite a small explosive charge is sufficient, it is feared that the use of an explosive of any sort may be objected to in connection with the Mercantile Marine. I have obtained satisfactory results with a submarine bell up to distances of 10 to 15 miles. The comparison between the R/A position of the Ruytingen L/V and that given by the French hydrographer is interesting. The difference between these two positions appears to be some 500 yards. What degree of accuracy is claimed for the R/A method? I should like to ask whether any allowance has been made for tidal streams which, in the Straits of Dover, reach at times velocities 8 ft. to 10 ft. per second.

REPLY to the Discussion by Dr. A. B. WOOD: The method mentioned by Col. Fowler for the prevention of collisions at sea by the simultaneous emission of foghorn and W/T signals has already received attention by the authors. On account of the great variability of atmospheric conditions, however, it is considered more satisfactory for the lightship to emit simultaneous *under-water acoustic signals* and W/T signals. A proposal on these lines has already been

submitted to the Admiralty by the authors\* in which the light-vessel emits a series of W/T dots (the first of which is accompanied by the acoustic signal) at intervals corresponding to half a mile distance from the light-vessel (*i.e.*, every  $3/5$  second app.). A ship can thus obtain her distance from the light-vessel by counting the number of W/T dots received up to the arrival of the acoustic signal. The direction can, of course, be obtained by W/T.

Light-vessels are liable to shift position in stormy weather, however, and this might have serious consequences under certain conditions.

The R/A method has one great advantage over the directional W/T method in that it gives not only bearings, but also ranges. An error of 2 or 3 deg. in bearing might result in an error of several miles in range of location, especially so when the position of the vessel lies on a line making only a small angle with the base-line (the transmitters in W/T and receiving hydrophones in R/A). A knowledge of the range as well as the bearing is essential under such circumstances.

The time of 10 minutes estimated for giving a location is largely occupied by the W/T procedure of calling up, &c., which is common to all systems of this sort and cannot be reduced appreciably. One or two minutes might, however, be gained by the use of more automatic methods of reading off the time-intervals and plotting the positions.

(To Mr. F. Twyman): The method of directional acoustic transmission in air as suggested is certainly very interesting, but experience has shown that the transmission of sound in air over great distances is very unsatisfactory both as regards distortion of wave-front and erratic variation of intensity. Unless extremely powerful sources are employed the range is limited to a few miles only. Under the best conditions it is considered that an accuracy of  $\pm 5$  deg. in direction could hardly be obtained by this method. The consequent errors of location would under such circumstances become very serious. Directional reception of under-water signals has already been considered and abandoned mainly on account of such serious errors in direction-finding.

As we have already stated above, the main feature of the R/A method is that *it gives an accurate value of the range in addition to accurate bearings.*

(To Dr. C. V. Drysdale): There is much to be said in favour of the "converse" R/A method. Owing to the closing down of the St. Margaret's Bay station, however, it was not possible to continue experiments on these lines.

(To Mr. F. E. Smith): It should be noted that in W/T direction-finding the captain of a vessel does not make the observations personally any more than in the R/A method. In the latter case it should be noted the record is taken in permanent form so that locations can be checked, complaints can be investigated and reasons ascertained. This is not possible in the W/T D.F. method. In the R/A method there are no "night-errors" or any such errors corresponding. The difference of cost in the two systems worked on a commercial basis need only be very trifling.

(To Mr. T. Smith and Major W. S. Tucker): The dispersive and distortional effects of a non-homogeneous atmosphere is the most serious objection to the use of acoustic signals in air as a means of direction-finding. The sea is a much more homogeneous medium in which sound waves are propagated for very great distances without serious distortion of wave-front. No "silent zones" have ever been observed in the sea, except perhaps in the very shallow water above a sand-bank such as the Goodwins.

(To Dr. A. Russell): The velocity formula referred to is an empirical one which applies only within the range of temperatures  $6^{\circ}\text{C}$ . and  $17^{\circ}\text{C}$ ., between which limits the velocity measurements were made.

(To Mr. R. S. H. Boulding): In recording W/T signals both methods have been employed, but for certain experimental reasons it was found preferable to use the relay arrangement.

With regard to the time of 10 minutes required to obtain a navigational "fix," *see* reply to Col. Fowler.

On only one occasion has any distortion effect by a sand-bank been observed, and on that occasion the experiment was deliberately arranged to determine the extent of such distortion under extreme conditions. The record obtained was quite normal as regards the three hydrophones clear of the sand-bank, but in the case of the fourth hydrophone the record was only just readable and was obviously different in character from the usual sharp "break" produced by an explosion. Under service conditions such a record would have been rejected

\* *See also Joly, loc. cit.*

without hesitation and the "fix" given to the ship would have been based entirely on the information supplied by the three perfectly readable breaks. In *all* cases the ranges were good, but the bearing obtained by using the fourth record was clearly in error. This point was only mentioned in the Paper as being of academic interest—even under the worst conditions such an effect could certainly not be regarded as serious in the service application of the R/A method.

It has been definitely decided by the Board of Trade that, subject to proper precautions, no objection will be raised to the carrying of the necessary explosive bombs by merchant vessels.

The accuracy of the R/A method as applied to survey purposes is very great. Since the velocity of the explosion wave is known with an accuracy of 1 or 2 ft. per second at all seasons of the year,\* it is considered that the error in range at a distance of 50 miles does not exceed  $\pm 250$  ft. as an outside estimate. The difference in position of the Ruytingen Light Vessel obtained by R/A and by the French Hydrographer might possibly be ascribed to the fact that the observations were made at different times and the light-vessel had shifted in the meantime, or what is more probable, the position given by the French Hydrographer (obtained by ordinary laborious survey methods) is in error by the amount stated.

In accurate survey work it is recommended that all observations be made as far as possible at times of slack water (neaps preferred) when no tide is running. Otherwise a correction for tidal velocity must be applied to the explosion wave-velocity.

\* See Proc. Roy. Soc. loc. cit.