# RADIO AIDS TO MARINE NAVIGATION

*Following upon the important International Meeting on Radio Aids to Marine Navigation held at London from 7th to 27th May 1946 under the auspices of the British Ministry of Transport, the detailed Minutes of Meetings, Reports and Papers concerning the different questions submitted have been distributed to the representatives of the different nations and to the organizations invited to the Conference.*

*Twenty-three nations were represented, the total number of delegates being about 117 coming from the under-mentioned countries :—*

*Great Britain (United Kingdom), Australia, Canada, India, Eire, Newfoundland, New Zealand, South Africa, Belgium, Denmark, France, Finland, Greece, Italy, Netherlands, Norway, Poland, Portugal, Spain, Sweden, U.S.A., U.S.S.R., Yugoslavia.*

*The Report of Proceedings of the various meetings is incorporated in the publication entitled:* International Meeting on Radio Aids to Marine Navigation, *May,* 1946, *Vol. I, which gives a summary of the conclusions adopted and the recommendations put forward by this Assembly.*

*A second volume entitled:* Radio Navigation, Radar and Position Fixing Systems for Use in Marine Navigation *is published by the Ministry of Transport (H.M. Stationery Office, London* 1946) *in which use has been made of the scientific documents presented during the Conference and in the drawing up of which assistance was lent by the following departments:—*

*Admiralty Signal Establishment; Admiralty Hydrographic Department; General Post Office; Telecommunications Research Establishment; Royal Aircraft Establishment; Admiralty Research Laboratory; Admiralty Compass Observatory; National Physical Laboratory.*

*Volume XXIII of the* International Hydrographic Review, *Monaco,* 1946, *pp.* 9 *to* 76 *contains a first series of extracts concerning the Loran, Gee, Decca, Consol and POPI instruments employed in Radio Navigation.*

*Hereunder follows a further series of articles which complete the information already given, relating to primary and secondary Radar, to ship's Radar for navigation, to the Decca Navigator instrument together with a few details concerning the propagation of radio waves in relation to the use of radio navigational aids.*

*The above information has been provided by the International Meeting on Radio Aids to Marine Navigation, London, (May* 1946), *and is reproduced by kind permission of the Marine Safety Division, Ministry of Transport. New material and papers for publication concerning progress and development in the field of Radio Aids to Marine Navigation and Radio advance to Marine Navigation problems are expected to be received and should be forwarded to the Ministry of Transport (International News Letters) Berkeley Square House, London, W.* 1.

# PRIMARY AND SECONDARY RADAR APPLICATION TO MARINE NAVIGATION

by H. E. HOGBEN, B. Sc. Admiralty Signal Establishment.

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1° Primary radar may be defined as a radio method of determining the position of a distant target relative to that of the radar set by irradiating the target with a beam of radio waves and detecting that part of the radiation which is reflected back from the target to the aerial of the radar set. This paper is concerned only with pulse radar, in which pulses of energy are emitted from the radar transmitter, the time-interval between successive pulses being longer than the time taken for radio waves to travel to and from the most distant target which is detected.

2° In secondary radar, similar radar equipment called an interrogator is used, but the target contains a radar (responder) beacon, which receives and amplifies each pulse from the radar set, and retransmits a pulse group which may be coded in frequency, duration, number, etc. With this system the interrogating radar set can determine not only the position, but also the identity of any target fitted with a suitable beacon. Moreover two radar beacons in known positions enable an interrogating radar set within the service area to get very accurate position fixes, because of the great accuracy with which range can be measured.

3° It has been realised for more than ten years that primary radar could be of unique value to Marine Navigation, but because of certain characteristics of the wavelength bands which were first used for equipment of military value, the full potentialities of radar in this application could not be realised.

4° For example, during the war a very large number of small craft of the Royal Navy used a radar set working on a wavelength of 1 1/2 metres for surface warning and as an aid to navigation. This set had a directive aerial array of dipoles and reflectors, with an aperture of about 2 m. giving a horizontal beam width of about 40°. The aerial was rotated by hand, and the display was of the ordinary range-amplitude type on the screen of a cathode ray tube of 12.5 cm. diameter. With this set a skilled operator could determine the range and approximate bearing of isolated targets, the bearing being measured by observing the variation of echo amplitude as the aerial was swung through the position of maximum deflection. The bearing accuracy on ships, which give a fluctuating echo, was not better than about ± 5°. When a number of ships was in the vicinity, the operator passed range and bearing of each to the plot, and in this way an appreciation of the situation was obtained, though the process was slow.

With a set of this kind, good ranges on large ships and high land were obtained, but ranges on small ships, buoys, and low land were rather small. Because of this, the wide aerial beam-width, and the method of display and use, very little use could be made of land echoes as an aid to navigation. In order to obtain approximate position fixes, use was made of radar beacons which had originally been set up at various coastal positions for the use of aircraft.

5° Equipment on the same frequency but with a very much larger aerial system was also at first used on shore for ship detection. Its application was similarly limited to determining the range and bearing of ships, the information being plotted by another member of the operating team on a chart.

6° The development of efficient sets on a wavelength of 10 cm., and the application of Plan Position Indicator (P.P.I.) technique completely changed the situation. In P.P.I. radar, the indicator trace is radial on the screen of the cathode-ray tube, and its direction corresponds to the direction of the aerial beam. As the aerial rotates, the trace also rotates correspondingly. The echo from any target detected "paints" a bright arc on the screen, and the position of the arc on the screen with respect to the centre of the rotation of the trace corresponds to the position of the target with respect to the radar set. A phosphorescent (afterglow) screen is used, so that the arcs remain visible for a time. Hence, as the aerial is rotated continuously a map-like display is produced, which shows at once the relative positions of all targets in the vicinity which are detected by the radar set. The advantages for navigation of a display of this type are obvious, but it can be used with advantage only with radar sets of narrow beam-width of aerial.

A ten centimetre set with an aerial of 4 metres aperture giving a beam-width of about 2°, which was installed at Dover at a height of nearly 200 metres, gave a clear map-like picture of the French coast line on the after-glow screen. The positions of all ships over a large area of the Straits of Dover could be seen at once, and under conditions of abnormal propagation even the navigational buoys outside Boulogne harbour could be located.

7° It was clear that sets of this type could give information for harbour supervision and control of ship movements which could be provided in no other way. It was also clear that P.P.I. radar of similar discrimination and ability to give a map-like reproduction of coastlines would be of great value for ship navigation, since it could be used for navigation along the coast and in narrow waters.

8° On a ship, however, the size of aerial which can be used, and the height at which it can be mounted, are very much less than on shore, and 10 cm. P.P.I. radar gave coastline pictures which were frequently difficult to correlate with the map, while the bearing discrimination was inadequate for navigation in congested waters. A satisfactory display, which could be used directly by the Navigator was not obtained until 3 cm. equipment was introduced.

## 2. **Propagation of centimetre waves.**

1° The nature and extent of the service which radar can give depends so much on the wavelength, aerial size, and height of aerial, because of the manner in which radio waves in the centimetric and adjacent bands are propagated over the sea and reflected from ships, land, etc.

2° Electromagnetic waves in this part of the spectrum travel in straight lines in a uniform medium; the attenuation in the diffraction region beyond the horizon is high, and increases rapidly as the wavelength decreases. Thus the service area of the radar set is normally limited to those areas optically visible from the aerial position, and the screening effect of large obstacles to the radar beam is virtually complete. The radio horizon differs from the optical horizon when certain meteorological conditions exist, and is sometimes extended in a remarkable manner, but is in general fixed by the height of the radar aerial.

3° By means of a suitably designed aerial array or reflector system, the waves can be focussed into a beam system; most of the energy is concentrated into a main lobe, but in addition there are subsidiary lobes, called "side lobes". The width of the main lobe is inversely proportional to the size of the aerial or reflector in units of wavelength. Since the width of the beam in azimuth determines the bearing discrimination of the radar set and causes distortion of the P.P.I. coast line map, the determination of an acceptable limit for various applications is very important. For ship borne navigational radar it is found that the azimuth beam width should be less than 3°. In the case of shore radar for harbour supervision the beam width required may vary from 0.5° to 3°. What this means in the terms of aerial size is indicated by the table.

| Beamwidth | Mirror Width metres | | |
|---|---|---|---|
| | 10 cm. | 3 cm. | 1 cm. |
| 3° | 3.3 | 1.0 | .33 |
| 0.5° | 20 | 6 | 2.0 |

Echoes from side lobes can give false bearings and confuse the picture, and it is important to reduce them as much as possible. In practice it is found difficult to reduce them to much more than 50 db. below the echo from the main beam, and this at present is one of the factors which set a limit to the use of centimetric radar in very narrow waters where there are many targets of different sizes to be viewed at the same time.

Because of the effects of roll and pitch the aerial beam of a ship navigational radar set must be fanned out in the vertical plane to a width of about 20°, unless the aerial system is stabilised. For shore radar the vertical beamwidth should be similar to the horizontal beamwidth, in order to minimise interference from rain and wave echoes.

4° When the radar beams is directed over the sea, any target receives a direct ray and a ray reflected from the surface of the sea. The effect of the reflected ray is to set up an interference pattern in the vertical plane with alternate maxima and minima of field strength. The vertical pattern of the radiation fields is broken up into numerous lobes, as illustrated in fig. 1, and the lowest lobe, which is important for the detection of targets at maximum range is directed upwards, away from the surface of the sea. The height $h_2$ of the first maximum

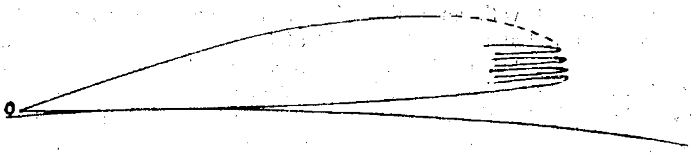

**Fig. 1**
Vertical lobe-structure produced by sea-reflection.

at Range R for a radar set of aerial height $h_1$ is given approximately (neglecting earth curvature) by the formula.

$h_2 = \frac{R}{4h_1}$ i.e. it is inversely proportional to the radar aerial height in wavelengths.

Values of $h_2$ at a range of 10 km. are given in the table.

| $h_1$ metres | $h_2$ metres | | | |
|---|---|---|---|---|
| | 1 m. | 10 cm. | 3 cm. | 1 cm. |
| 20 | 125 | 12.5 | 3.75 | 1.25 |
| 100 | 25 | 2.5 | .75 | .25 |

The advantage to be gained in the detection of low targets by the use of short wavelengths is clear, as is also the effect of increasing the height of the radar aerial.

5° Fig. 2 illustrates the effect of sea reflection and earth curvature on the detection of land.

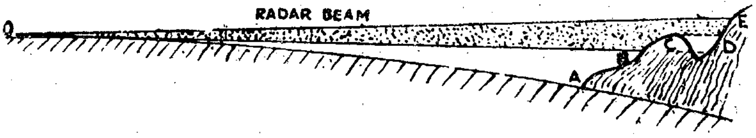

**Fig. 2**
Effect of sea-reflection and Earth Curvature.
A B : Low Land not detected.
B C : Detected.
C D : In shadow of B C, not detected.
D E : Detected.
Radar Beam.

Measurements of the echo power received from ships have shown that the incident radiation is not scattered uniformly but that there is a re-radiation pattern made up of numerous sharp lobes, which causes characteristic fluctuations in echo amplitude as the aspect of the ship varies. There is some evidence, however, that in the region called the " near zone " where the ship is illuminated by one or more of the lobes of the vertical radiation pattern, the echo power varies with range approximately according to a fourth power law and the mean echo power received from a ship is proportional to the silhouette area. At ranges beyond that at which the highest part of the superstructure falls below the maximum of the lowest lobe the echo amplitude decreases much more rapidly with range. In this region, called the " far zone ", the echo amplitude is approximately proportional to the eighth power of the range, and also to the fifth power of the height of the superstructure.

For this reason craft with low freeboard such as motor fishing boats, are very poor radar targets.

6° Navigational buoys are of such diverse shapes and sizes that they differ widely in echoing properties. The most efficient shape for echoing is probably that of the pillar buoy — an irregular vertical cylinder. Certainly the worst shape is the cone, since the inclined surface tends to reflect the incident beam upwards, and some conical buoys, in which the geometry is particularly good, might well have been designed to prevent detection by radar.

The improvement which can be effected in the echoing properties of the buoys by fitting special radar reflectors is described elsewhere. In view of the importance of buoys to

A. 9 CMS.

B. 3 CMS

**Fig. 4**

Effect of Wavelength on P.P.I. Picture.

The lower photograph, taken from the same position with the equipment converted to 3 cm., shows a marked improvement. The coasts of Portsea Island and Hayling Island are clearly shown, with the entrances to Langstone Harbour and Chichester Harbour. Selsey Bill shows very clearly, but the very low land is still not showing, because of the low height (5 metres) of the radar aerial.

### 3. **Absorption and scattering in the atmosphere.**

1° As the wavelength decreases, absorption due to atmospheric gases, rain, increases, as does also the scattering due to rain drops, and these effects limit the choice of wavelength.

The effects of attenuation due to absorption and scattering are illustrated in fig. 5. At wavelengths greater than 5 cm. the effects are negligible, even under cloudburst conditions. At 3 cm. the reduction in maximum range on an average merchant ship is significant, but not serious, in heavy rain. At 1 cm. the reduction in performance on large targets due to heavy rain is very serious indeed.

2° The scattering back towards the radar set of energy by rain drops causes echoes; a patch of rain giving a characteristic patch of echoes which has the appearance of coarse-grained receiver noise. The amount of scattering from a rain drop depends on the diameter of the rain drop in terms of wavelength and is proportional to the sixth power of this quantity for small drops. Hence the effect increases very rapidly as the wavelength decreases. For larger drops and shorter wavelengths, the proportion of the energy scattered back towards the source decreases.

It has been calculated that for a typical 3 cm. ship radar the echo from a patch of heavy rain 1 km. thick at a range of 10 km. could obscure the echo from a merchant ship,

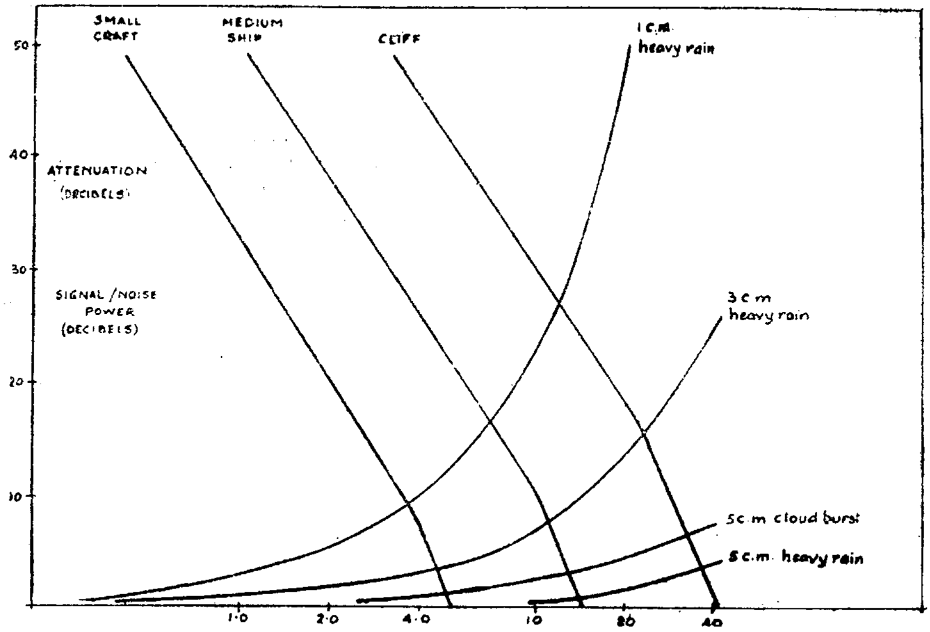

**Fig. 5**
Attenuation due to Rain—Effect on Radar Range.

while at 10 cm. the ship echo would be several times greater than that from the rain at this range.

Meteorological data indicates that such heavy rain occurs only in patches of limited area and short duration, and such experience as has been gained in these latitudes suggests that the operation of 3 cm. navigational sets is unlikely to be prejudiced by this effect, provided that adequate precautions are taken in the design of the set to prevent receiver saturation and paralysis (by the use of narrow pulse, wide band-width etc.). More information is required however, about operation in areas where tropical rains or wet snow are frequent.

## 4. Choice of operating wavelengths.

1° Part 2. indicated that the operating wavelength should be as short as possible, for radar intended to detect ships and coastlines. Part 3. indicated that the shortest wavelengths which could be used in all weather conditions lie approximately between 3 and 5 centimetres. For general purpose application in ships a 3 cm. band has been chosen, since satisfactory bearing discrimination can be obtained at this wavelength with aerials of moderate dimensions. For shore applications, where much larger aerial systems can be mounted at a much greater height, a somewhat longer wavelength could be used, and might indeed be found necessary in places where adverse climatic conditions (heavy rain or snow) are of frequent occurrence.

Pulse modulation involves the transmission of a spectrum in which most of the energy is contained in a frequency band of 2/pulse width i.e. 8 mc/s for a 0.25 microsecond pulse.

Because of the low duty cycle (on off ratio) of the transmitter and the narrow aerial beam, a large number of navigational radar sets can work in the area on the same nominal frequency without serious mutual interference, and the frequency band requirements are determined by other factors. The fixed frequency magnetrons used for transmission at 3 cm. have a natural spread of frequency in production of 2-3%; this can be reduced by adjustments during manufacture, but the percentage of rejects increases rapidly as the acceptance frequency band is narrowed. On the other hand, some R.F. components used in the equipment work efficiently over a narrow band of frequencies only. In particular, it is found that the magnitude of aerial sidelobes increases rapidly at frequencies outside a band of ± 1% about the optimum frequency, with aerial systems of the type commonly used.

Moreover the difficulty of designing an efficient radar beacon system increases rapidly as the radar frequency band increases.

Consequently the frequency band allocated to ship board navigational radar should be restricted to what is a reasonable compromise between the difficulties of magnetron production and the limitations of component performance. In the case of the 3 cm. band this appears to be 150-200 mc/s at the present time.

### 5. Sea Clutter.

1° " Sea clutter " is the name given to radar echoes from waves on the sea. These echoes may have a detrimental effect on the operation of both ship and shore radar, and special care is necessary in equipment design to mitigate the effect.

2° The appearance of sea clutter on the radar display is similar to that of increased receiver noise, the chief difference being

(1) The mean level of sea-clutter decreases rapidly as the range increases ;

(2) There is correlation from scan to scan, a peak persisting at the same range for about 0.02 sec. at 9 cm. and about 0.1 sec. at 3 cm.

3° It is good approximation to say that the mean power level at any range, which depends on the state of the sea, is proportional to the transmitter power, the square of the aerial gain, and the horizontal beam width, while the rate of decrease with range depends only on the wavelength and height of radar aerial.

The decay with range is approximately exponential, of the form.

$$W = W_0 \varepsilon - bR.$$

Numerical values of the rate of decay for different aerial heights and wavelengths of 9 cm. and 3 cm. from measurements made on the English coast are given in the following table.

| Aerial height in metres | Attenuation db/1000 yds. | |
|---|---|---|
| | 9 cm. | 3 cm. |
| 40 | 6.5 | 5.5 |
| 24 | 10.5 | 7 |
| 14 | 17 | 12 |

4° Sea clutter inevitably obscures echoes of smaller power, and modifications to increase the echoing power of navigational buoys may be desirable in many cases. The disturbing effect on a P.P.I., which has very small amplitude discrimination, may however, be more serious, and quite large echoes obscured at close range unless either the receiver gain control is manipulated in an expert manner, or special circuits are incorporated to avoid the necessity for skilled operation. These special circuits are described elsewhere.

5° Although sea-clutter power increases rapidly with frequency, the echoing power of buoys and ships increases similarly, so that there is little difference in the detectability of small targets in clutter over the range of wavelengths between 9 cm and 3 cm. It is found, however, that the sea-clutter level is substantially higher with vertically polarised radiation, than with horizontally polarised radiation, and for this reason horizontal polarisation is preferred for navigational sets.

### 6. Special display arrangements.

1° A requirement for the best possible method of correlating the P.P.I. map with the navigational chart becomes evident as soon as P.P.I. radar was applied to coastal navigation.

There are two alternatives; either the image of a special chart can be projected onto the P.P.I. map, or the image of the P.P.I. map can be projected onto the chart.

2° The first method is very much easier than the second because of the low brightness level of the P.P.I. map, and was originally used both in the R.N. and in the U.S.N., a half silvered mirror being employed to enable simultaneous viewing of P.P.I. and special chart to be effected.

This method has been elaborated in the U.S. In one system, a magnified image of a microfilm transparency of the required chart is projected onto the face of the P.P.I. In another, a transparency of the chart is interposed between a rotating line of light and a photocell, so that a picture of the chart can be produced on the normal P.P.I. at the same time as the radar map.

These systems are ingenious, but open to the objection that they cannot be used directly by the Navigator, who must use his ordinary chart for plotting and correlating all the navigational information (soundings, D/F, etc.).

3° Development in the U.K. has accordingly been concentrated on the second method, the technique used and the success which can be achieved are described elsewhere and have been demonstrated on H.M.S. *Fleetwood.*

4° The ordinary navigational chart does not present information about the character of land surfaces in a manner which is most useful for radar navigation. Progress has been made in the development of a modified chart, which retains all the information required for visual navigation, but has the land contoured and coloured in a way which makes it easy to correlate with the P.P.I. pictures. It is hoped that a new standard chart will be developed, equally useful for both visual and radar navigation.

5° For shore radar, there is also a requirement for correlating the radar map with the chart; in this case there is no objection to the use of specially prepared charts, and there is wide scope for elaboration of apparatus. Some of the possible technical solutions to the problem are discussed elsewhere.

6° An important limitation at present is the lack of brilliance of the P.P.I. map when a large scale is used, and the limited field of view. In the case of shore radar, there is a reasonable prospect of a solution to the problem in terms of known techniques. For ship borne radar the prospects are not so good because increased brilliance is obtained by increasing the operating voltage of the cathode-ray tube, and the cost and complexity increase rapidly as this is done. However, the technical effort directed towards producing a large bright picture for home television may ultimately bring important benefits to navigational radar for ships.

## 7. The place of secondary radar.

1° The main purpose of Radar for Marine Navigation whether on ship or on shore is to detect and display in their correct relative positions all targets of navigational importance in the coverage area. It is clearly of the utmost importance that any navigational hazards such as drifting wrecks or icebergs should be located with certainty. This is possible only with primary radar.

2° In the case of shore radar primary radar of high discrimination is obviously required. If a suitable radar beacon were fitted in every ship — and maintained in working order — the problem of identification to shore radar would be solved. It is thought, however, that a less expensive solution to this particular problem can be found, using equipment fitted in ships for harbour communication, and thus more likely to be kept in a state of efficiency.

3° In the case of ship radar it has been suggested that a primary radar of "collision warning" type, used in conjuction with a system of radar beacons to form a secondary radar system, could give an economical and satisfactory service, as is the case for air navigation.

The conditions of marine navigation, however, are very different from those in the air. A ship radar for navigation in congested waters, must have not only high discrimination, but also good performance and adequate display. The additional facility which could be given to "collision-warning" radar by a radar beacon chain would not extend beyond position fixing in coastal navigation, as described in 1.-4°, this service would in most cases be given more economically by one of the low-frequency hyperbolic position-fixing systems, which would also give fixes at long range.

4° Radar beacons form a valuable adjunct to ship navigational radar when mounted in selected positions ashore, and in lightships, where power supplies and adequate maintenance facilities are available, since they enable the radar to get position fixes and positive identification of important navigational marks in the most convenient manner i.e. the beacon position is marked directly on the radar display. Now that ship radar giving an identifiable coastline picture in the majority of situations is available, the requirement for radar beacons is much less than would otherwise be the case.

For channel marking, and in other positions where power supplies and maintenance facilities are difficult to provide or not available, patterns of corner reflectors are preferred to radar beacons, as described elsewhere.

5° It is therefore concluded that secondary radar as a system of navigation has no important application to Marine problems, on the other hand there are likely to be many situations where radar beacons form a convenient and economical method of providing position-fixing and identification facilities to high-discrimination primary radar systems. Existing and possible types of beacon are discussed in a previous paper.

## 8. Radar and other navigational aids.

1° The position fixing systems described in other papers are complementary in ships to primary radar, which alone can display the positions of other ships, etc. in the vicinity, but has coverage area limited by the radio horizon, and does not, except in the special circumstances already described, give its own position on the earth's surface.

2° An automatic method of positioning the radar map correctly on a navigational chart has already been developed in the form of a unit called the auto-radar plot. In this unit the radar display is projected onto a transparent chart mounted on rollers, the movement of the chart being controlled by information fed from the automatic dead-reckoning plot. It is to be expected that in the future large ships will carry apparatus for the same purpose, but with the position of the display on the chart controlled by more accurate information from a suitable radio position-fixing system.

## 9. Short-range radar.

While wavelengths shorter than 3 cm. are too much affected by atmospheric conditions for use in shore radar or general-purpose ship radar, a somewhat shorter wavelength might well be used for a short range high discrimination system for small merchant ships. Although suitable R.F. components do not at present exist, the basis techniques are known and it is possible to visualise a compact self-contained equipment, with a small aerial but beam-width of a degree or less, and a minimum range of not more than ten yards. Equipment of this kind may, in the future, enable the navigator to bring his ship right into a small harbour on radar alone.

## 10. Maintenance.

1° During the war naval radar equipment was kept in a high state of efficiency only by the strenuous efforts of a very large maintenance organization.

2° In view of the great improvements in component design which have been made during the war, it is to be expected that radar equipment for peace time application will achieve a standard of reliability at least as high as that of ordinary W/T equipment. Nevertheless, since a ship-borne radar set contains not only rotary machinery needing periodic maintenance, but many radio valves of finite life in circuits of some complexity, the problem of ordinary maintenance will be an important one, and the efficiency of service given by radar will depend to a considerable extent on the adequacy and efficiency of the maintenance service. It is probable that maintenance and stores depots, with adequate test equipment, will be found necessary at most or all of the major ports.

3° The setting up of a large number of different maintenance organizations would probably lead to inefficiency and waste; in particular, efficient technical man-power and special test equipment are both in short supply, and the best method of securing an efficient and adequate service without waste is an important problem for early consideration.

4° Maintenance is unnecessarily complicated by an excessive variety of types and designs of components, particularly valves, and there appears to be a strong case for attempting to get international standardisation of the performance ratings and external design of as wide a range of components as possible.

## 11. Conclusion.

1° During the war radar technical effort was concentrated on the development of weapons of war, and the effect on naval strategy and tactics is said to have been comparable only with the effect of the change from sail to steam.

2° Only a small fraction of the total effort was applied to problems of marine application, but this application represents probably the most important and beneficial contribution which radar can make to the arts of peace.

3° The developments referred to in this paper have already indicated that radar can affect marine navigation as profoundly as it has already affected naval warfare, and now that a substantial effort can be applied to the development of suitable apparatus, we can look forward to a future in which some of the major hazards to life at sea will be reduced to unimportance.

# SHIP-BORNE RADAR

## Factors in the design of Navigational Radar for Marine Transport

Extracts from a paper read by H. E. HOGBEN, B. Sc. and R. F. HANSFORD,
at the International Meeting on Radio Aids to Marine Navigation,
LONDON, 1946.

## I.—HISTORICAL SURVEY OF DEVELOPMENTS IN U.K.

### 1° Preparing for the invasion of Europe

Although during the war navigators in H.M. Ships had made increasing use of information given by the various radar sets, particularly after the general introduction to the Fleet of centimetric warning sets in 1941, the first Admiralty Signal Establishment commitment to study the particular problems which arise in the application of radar to the navigation of ships did not come until 1943 in connection with the preparations for the Invasion of Europe.

It was necessary for the vast invasion Fleet of special assault craft to cross the channel to the Normandy beaches in darkness. Each assault craft must maintain its course, formation and position with respect to other groups during the passage and be able to recognise its designated landing point on arrival at the beaches. It was clearly imperative that this operation must succeed no matter what conditions of visibility might obtain at the time.

To assist in this difficult operation it was planned to use various radio navigational aids, in particular a very high priority was given to the fitting of craft in each assault group with centimetric radar.

Centimetric radar development for the Navy had been concentrated on high power warning and gunnery sets and no suitable small navigational set was available. It was, therefore, decided to adapt an Air Ministry's set, developed as a navigational radar for aircraft. At this time the only equipment available was the 9 cm. *version*.

Some sets of this type had already been fitted in rocket craft and used purely for bombardment control during the invasion of Sicily. Although little experience had been gained of its use for navigation and for station-keeping, some defects of its use for coastline navigation had already become apparent. Medium power 9 cm. equipment of this kind gave very poor detection ranges on low land as compared with high. Because of this, a smearing of the picture due to the wide azimuth beam-width and distortion due to non-linearity of the P.P.I. trace, the P.P.I. picture of a piece of coast-line was difficult to correlate with that shown on the chart or map. In order to overcome these deficiences of the radar set, a technique of making so-called P.P.I. predictions was developed and elaborated during the period before the Invasion. A prediction is a transparency representing what should be seen on the P.P.I. of a radar set of known characteristics with its aerial at a given height at a certain position off the coast. The prediction is marked with navigational information including intended track-lines and the position of radar land-marks easy to correlate with the chart from which accurate range fixes can be taken. An optical device known as a " reflectoscope " was developed and fitted to the sets to enable an operator to view a virtual image of the prediction superimposed on the P.P.I. picture, and thus aid recognition of his land-marks and determination of his position and course.

A series of trials in preparation for D—day began with exercise " Pirate "—a large scale invasion exercise off the South coast—in which the first four radar fitted landing craft took part in Oct. 1943. This exercise showed that the sets could not be used in navigational leaders without substantial modifications. The difficulties were partly technical and partly operational. The technical difficulties were mainly due to the wide azimuth beam-width and the excessive side lobes of the aerial system and also high minimum range of the set (1500 metres) which made it impossible to keep track of craft in close company. The main operational difficulty was due to the fact that no remote display was available to the navigator or commanding officer.

These difficulties were partially overcome by developing and fitting a new aerial with a small beam-width and very small side lobes and by circuit modifications to improve the minimum range to a value of about 200 yards; a remote P.P.I. was also provided.

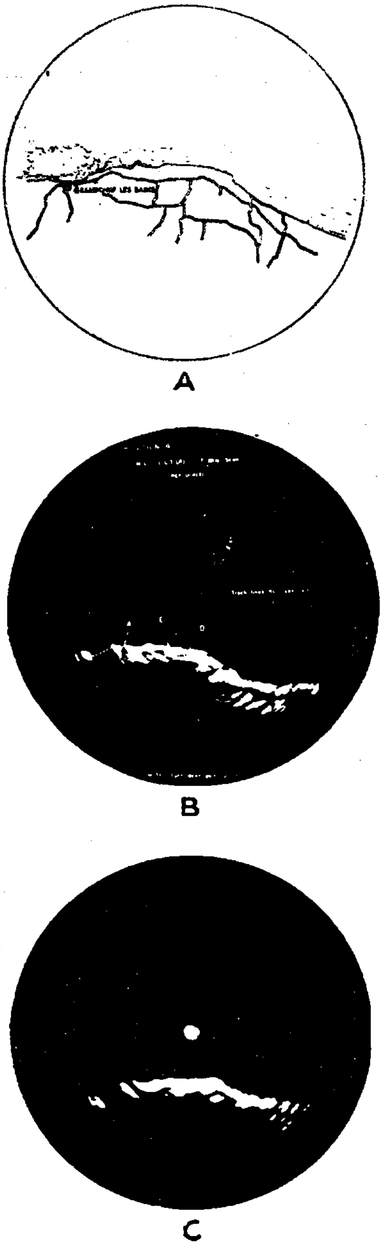

Fig. 1
Radar Predictions
A : Chart showing part of the Normandy Coastline.
B : Prediction of P.P.I. Picture.
C : Photograph of P.P.I.

Assault forces trained assiduously with the improved equipment, very large numbers of predictions for the Normandy beaches were made and supplied and the sets were used successfully during the invasion. Shortly after D-day, a craft was made available to allow a radar survey to be made of the Normandy beach area so that the correctness of the predictions could be investigated. The mathematical prediction of what radar echoes should show on the P.P.I. is a process fraught with many difficulties and uncertainties and it is not surprising if the results obtained at that time look disappointing, particularly to anyone accustomed to the high discrimination picture given by a modern set. At that time, however, the results were thought to be highly encouraging and are illustrated in figure 1. Fig. 1 A shows a reproduction of the chart, figure 1 B the radar prediction supplied and figure 1 C a photograph of the P.P.I. taken during this experimental survey; it will be seen that the P.P.I. bears a much closer resemblance to the prediction than it does to the chart and recognition is therefore considerably aided.

### 2° Subsequent improvements

It was clear from the experience already obtained that a major improvement in the usefulness of the equipment was to be expected by conversion to 3 cm. operation. During the Summer of 1944 conversion equipment was made available by the Air Ministry and trials carried out off the South coast verified the expectation, there was a striking improvement in the coast-line picture as well as a substantial increase in bearing discrimination. Subsequently, it was decided to produce a new aerial in order to reduce side lobes and this aerial still further improved the bearing discrimination.

### 3° The Scheldt scheme

In the Autumn of 1944, consideration was given to the method of maintaining the flow of supplies to Antwerp after the clearing of the Scheldt in spite of the fog which sometimes veils the estuary of this river for days at a time during the winter. The navigation of the tortuous channels of the Scheldt was clearly a far more difficult problem than the navigation of coastal waters involved in the Normandy landings and would, in fact, have been quite impossible with the equipment used at that time. Trials of the newer 3 cm. equipment had, however, *given confidence* that a craft fitted with this could navigate such difficult waters in any conditions of visibility. It was decided to fit six craft as navigational leaders in the expectation that with trained navigators and radar operators they would be able to lead convoys up the Scheldt to Antwerp.

In order to perfect the navigational technique required for this operation, the experimental craft sailed to the Scheldt in November 1944 and two months were spent in trials. The technique developed involved the use of a transparency resembling a prediction, but which was in this case based upon an actual photographic record of radar results obtained in the estuary.

Photographs of the P.P.I. taken during the course of this survey have been pieced together to form a mosaic and the result is shown in figure 2 below a copy of the chart of the Scheldt estuary.

On February 19th a passage was made from Antwerp to Flushing in conditions of very dense fog, navigation being by radar throughout; it is probable that this is the first time that such difficult waters have ever been navigated in conditions of such extremely poor visibility. Owing to the rapid progress of the western offensive it was not necessary to take the Scheldt scheme any further. However, the experience gained during the trials has been of the utmost value in laying the foundation for later development.

### 4° The drafting of a performance specification

With the war beginning to draw to its close, some thought was given to the question of applying modern radio navigational aids to the use of the Merchant Navy and in the Summer of 1944 a Government body known as the United Kingdom Conference on Radio for Marine Transport was set up to investigate this matter. After reviewing the various aids to navigation which had been developed during the war, the Committee came to the conclusion that radar would be of great value to the Merchant Service and asked the Admiralty Signal Establishment to collaborate in preparing a specification for a set suitable for the average merchant ship. As a result of the experience gained in over a year of trials with sets of varying characteristics, the Admiralty Signal Establishment was in a position to prepare such a specification and one was drafted in January 1945. Discussion with various shipping interests confirmed that there was in fact a requirement for a radar set for navigation and pilotage as distinct from a collision warning set, which would, of course, be a much simpler and cheaper device. With agreement reached on this fundamental point, the performance specification was issued by the Ministry of War Transport to ship owners and to the radio industry.

### 5° Thames Estuary project

During 1945 the Admiralty was asked to commence work on an extensive scheme known as the Thames Estuary Project. This project was one embodying a variety of new ideas all designed to assist in the navigation and pilotage of difficult waters by means of radar informa-

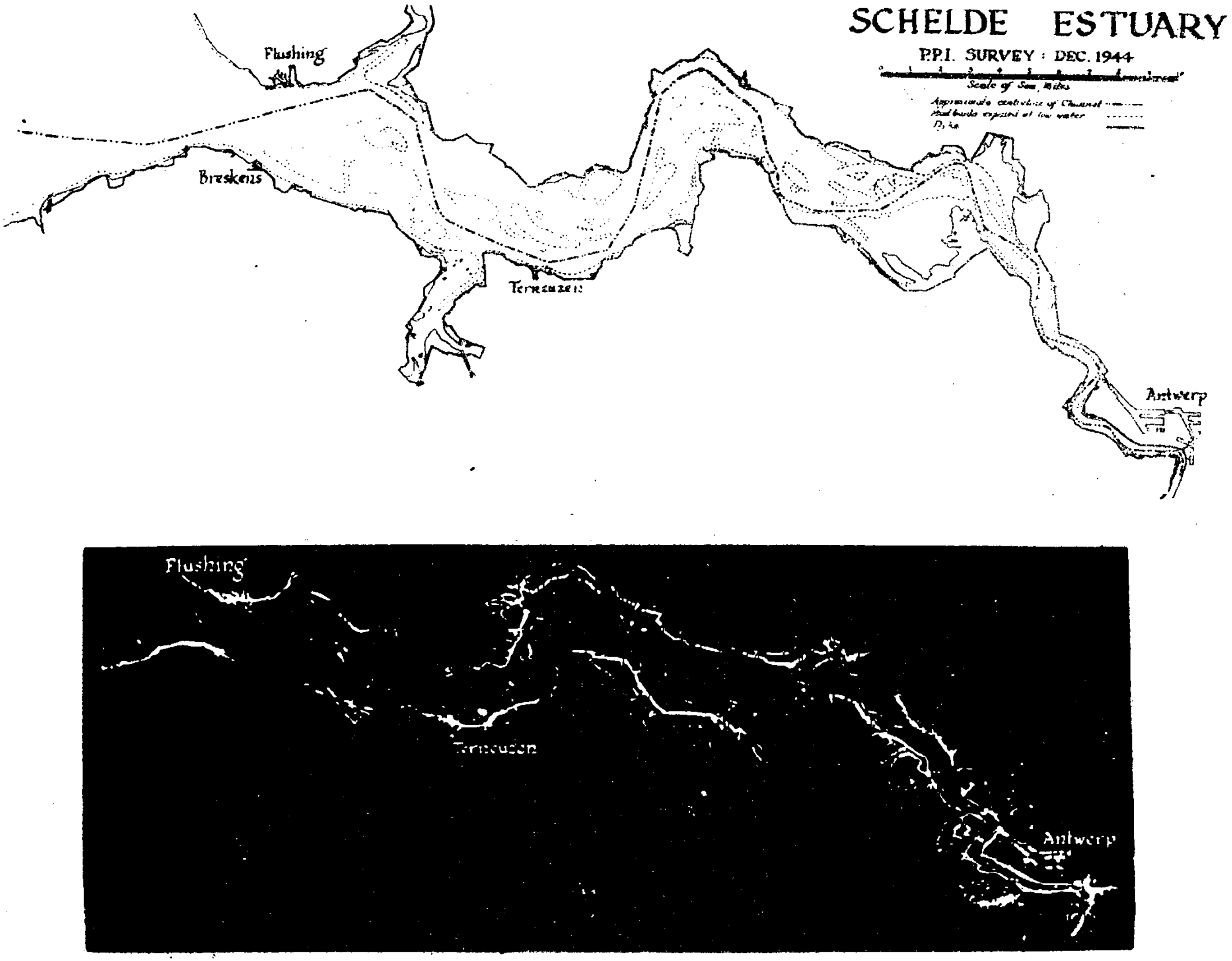

Fig. 2

A chart of the Scheldt Estuary, and below, a Mosaic of P.P.I. photographs.

tion. Foremost among these ideas was a proposal to make full radar use of navigational buoys. Generally, the detection range of navigational buoys is small (about 4 km.) and the liability of confusing their echoes with those from small ships is considerable; it was suggested that if the response of buoys could be increased by adding to them a device known as a "corner reflector", and if groups of buoys were laid in clearly recognisable geometrical patterns, then one of the greatest difficulties in the navigation of narrow channels far from land would be removed.

These corner reflector buoys were suggested as an alternative to radar beacons for several reasons. Radar beacons for various sets have been developed and were successfully used during the Scheldt trials; their use would, however, involve problems both of maintenance and of international agreement on types and on frequencies of operation. It was felt that an alternative scheme was required which would be both simpler and would avoid the delay of awaiting international agreement and for this reason, emphasis was placed upon corner reflectors. A fuller treatment of the subject of beacons and corner reflectors is given in the paper by Mr. Bogle.

A short trial was carried out to determine the optimum design of corner reflector and, subsequently, while these were being put into production, a radar survey of the Thames estuary itself was carried out. This survey was made with the latest type of Naval 3 cm. equipment, which had a very high bearing discrimination (beam-width 1° 1/4). The coast-line pictures which this set presented were far in advance of any which had been obtained previously and were of remarkably clear definition. A number of photographs of the P.P.I. were taken and susbsequently pieced together in the form of a mosaic showing the whole coast-line of the estuary from Felixstowe to Tilbury on the Northern shore and from Gravesend to Deal on the Southern shore. This mosaic is shown in figure 3 along-side a reproduction of the chart. The improvement in the results of new radar equipment can clearly be seen by comparing this mosaic with the one of the Scheldt, figure 2.

After this survey had been completed, the positions of three experimental groups of corner reflector buoy patterns was decided and Trinity House undertook to fit these buoys and lay them in the required positions.

At the same time, Admiralty Signal Establishment started to make an experimental radar set which would conform closely to the major electrical features of the performance specification issued by the Ministry of War Transport. Chief emphasis in this design was laid upon producing a set of high definition, giving a good minimum range and relatively simple to handle.

One important feature of this set was that it included a completely new type of P.P.I. Experience in the past had shown that one of the major difficulties in pilotage waters was the quick transference of a radar fix on to the navigational chart. It was realised that if the picture could be viewed in coincidence with the chart, then not only would the central spot of the P.P.I. indicate the ship's own position directly on the chart, but all other objects would be shown in their correct position on the chart itself. The Chart Comparison Unit used with this set was an attempt to develop such an indicator.

It had already long been realised that the existing form of navigational chart was not well suited for use with radar. Firstly, the charts were difficult to see in dim lighting such as that usually employed when a radar set is being used; secondly in radar navigation much use is made of the land picture and emphasis falls on depicting the landward information in the best possible form. In existing charts hill masses are shown in a purely representative form by hachures and not by actual contours. The Admiralty's Hydrographic Department agreed to produce an experimental chart of the Thames estuary in which the land was distinctively coloured and in which hill masses were shown by contours with the height clearly indicated by colouring; in addition, a number of other points making for ease of reading and ease of correlation with the P.P.I. were attended to without in any way detracting from the usefulness of the chart from the point of view of the visual navigator. A fuller treatment of the chart requirements is given in the paper by the Director of Navigation.

In January 1946 comprehensive trials in the Thames estuary commenced. These trials showed that the corner reflectors increased the detection range of buoys from their usual 4 km. to 12 km., and that the geometrical grouping of buoys made them easily recognisable on the P.P.I. without risk of confusing them with other shipping. The results obtained from the experimental set adequately proved the main clauses of the performance specification and in particular the chart comparison unit proved to be an extremely valuable aid to pilotage, transforming radar navigation of restricted waters from its previous difficult and skilled task

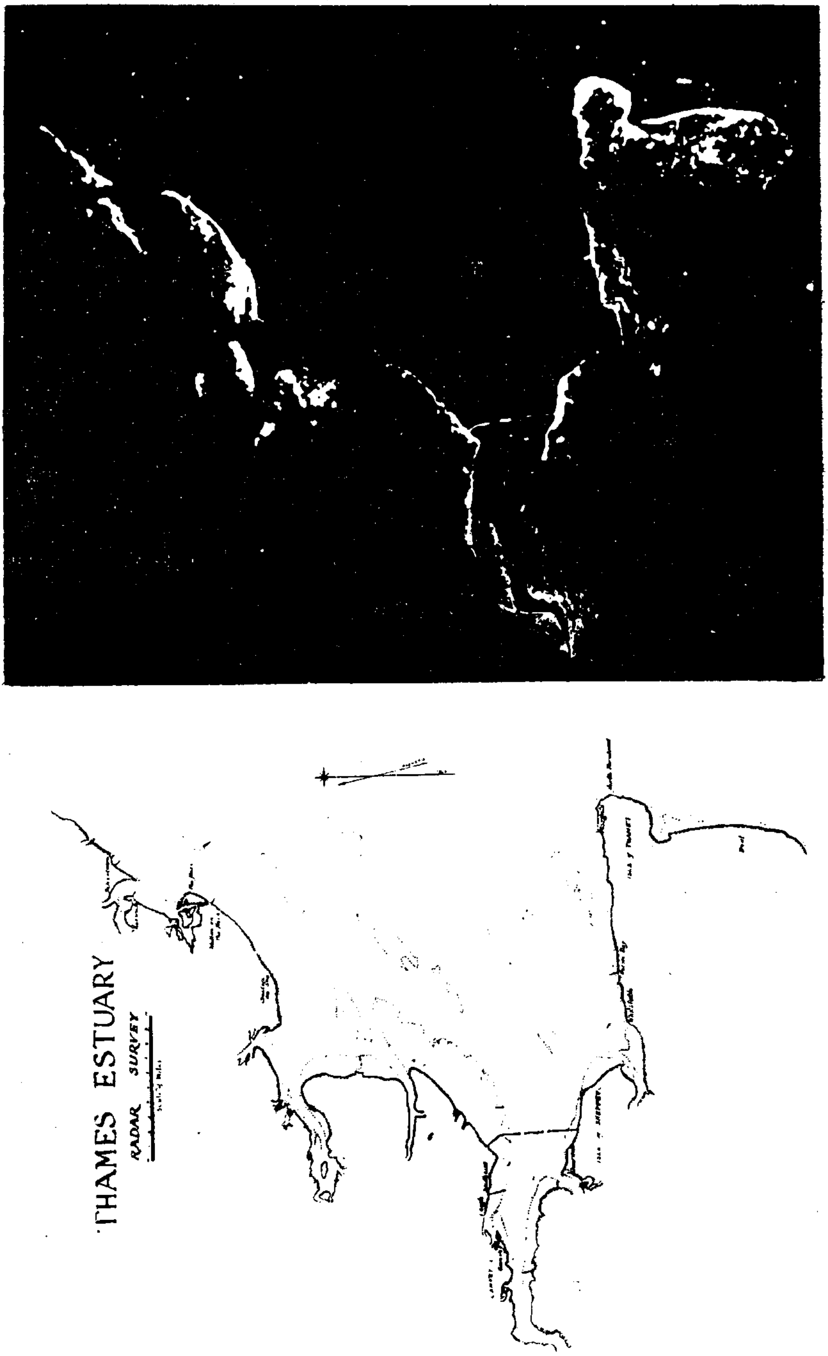

**Fig. 3**

A chart of the Thames Estuary and, to the right, a Mosaic of P.P.I. photographs.

to one of ease and reliability. The special charts were found to be more convenient and useful than their predecessors and information was gathered as to what further improvements are advisable.

After detailed technical information had been gathered, a number of navigational runs throughout the estuary was made on radar information and it was found that even in busy shipping lanes, the ship could be handled on radar with ease and safety; this is perhaps the salient difference between the present state of the art and that of a year ago when good results could be obtained, but only when the equipment was in the hands of highly trained personnel. The Thames project concluded with demonstrations at sea given to some 200 representatives of the shipping world and radio industry.

### 6° Present development

A further radar set has been developed at the Admiralty Signal Establishment designed entirely to meet the Ministry of War Transport performance specification and to embody the latest ideas in navigational radar with particular reference to the needs of the Merchant Service. This set has been fitted in H.M.S. *Fleetwood* and is, at the time of writing, undergoing sea trials. It will be demonstrated to delegates of the present International Meeting.

## II.—REQUIREMENTS

### 1° Navigational

INTRODUCTION.—A full appreciation of the outlook of a navigating officer is essential to the appreciation of the navigational requirements of a radar set for his use. A Navigator's whole training and primary outlook is devoted to the safety of his ship. This means that when a ship enters fog a navigator immediately thinks whether or not he can take his ship through this fog with complete and absolute safety; if he has any doubt whatsoever in his mind about the safety of his ship, he will invariably anchor. This was made abundantly clear in many of the early radar navigation trials when the anchoring of the ship at the onset of fog was a frequent occurrence; only subsequently with improved equipment has this source of continued discouragement been fully overcome.

There are three main tasks which the radar set will be called upon to perform :—

(a) To provide warning of the approach of ships, ice-bergs and other navigational dangers and allow collisions to be avoided. This feature is of equal importance in restricted waters or in open sea ;

(b) To assist in the navigation of coastal waters ;

(c) As an aid to the pilotage of restricted waters.

The following statement of the requirements for a set which is to fulfil the above functions is based upon the experience which was gained in the work set out in Part I.

DEFINITION OF PICTURE.—The most important feature of a radar set which is to instill confidence into a navigator, is that it shall present him with a picture of high definition about whose interpretation he feels he can make no mistake. The definition of the picture is determined chiefly by two factors, the azimuth beam-width and the pulse length. The importance of beam-width can best be seen by reference to figure 4, which shows the polar diagram of an equipment having a beam-width of some 10° and below it, a photograph of a P.P.I. driven from this equipment when a ship was in the middle of the Solent. It will be seen that the coast-lines of both the Northern and the Southern shores are very poorly defined and the shipping anchored in the Solent appears as an extremely confused mass. It will be apparent that no navigator would take his ship along the Solent if this picure were his only source of information. Figure 5 shows the polar diagram of an equipment having approximately a 3° beam-width and below it the corresponding radar photograph taken at the same time and in the same position as figure 4. It will be seen that the picture of the coast-line is now very much clearer and the shipping is more clearly defined. However, there is still a tendency for echoes of individual ships to merge together and a navigator might well feel some reluctance to proceed in bad visibility. Figure 6 shows the polar diagram of a Naval 3 cm. equipment having a beam-width of about 1° and below it, the corresponding radar photograph taken in a similar area. In this picture every ship and buoy is clearly and sharply defined and a remarkable example is that of the boom defences seen across the river in which individual trestles supporting the submerged defences can clearly be picked out; the definition of the coast-line is sharp beyond doubt. In this case the bearing discrimination of the set is so good that the navigator would have no doubt about proceeding and feeling completely safe.

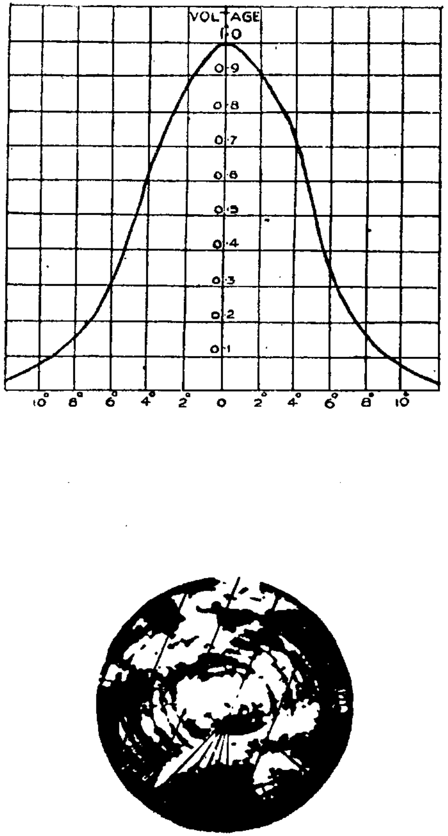

Fig 4.

Polar diagram showing 10° Beamwidth and below, a P.P.I. photograph taken in the Solent.

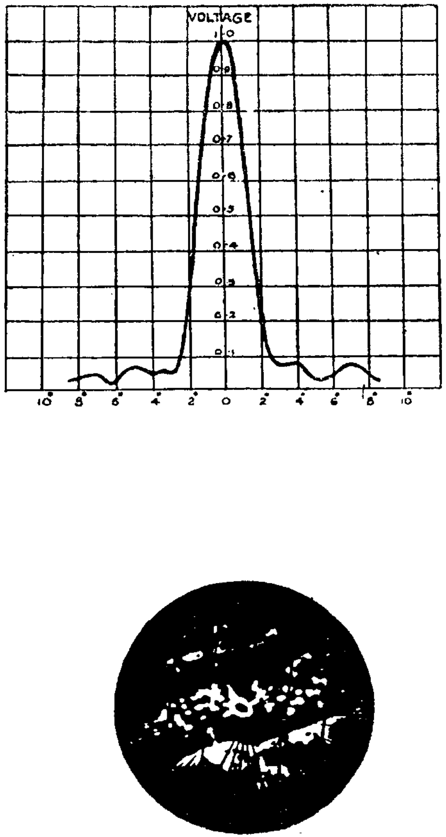

Fig.5.

Polar diagram showing 3° Beamwidth and below, a P.P.I. photograph taken in the Solent.

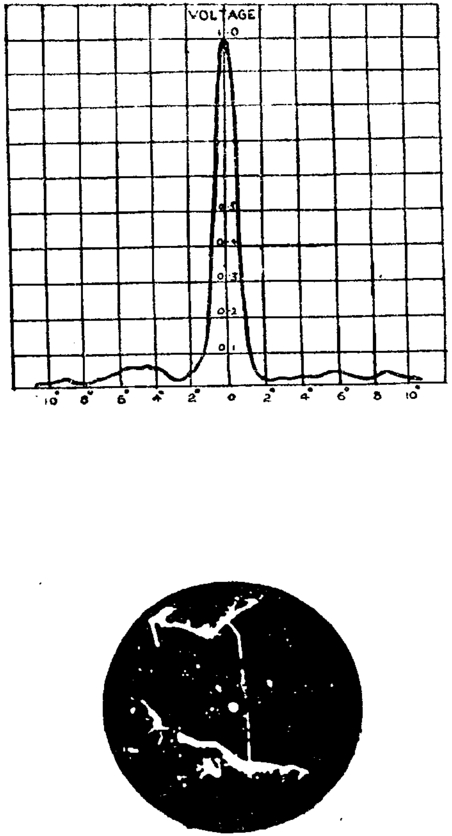

Fig. 6.

Polar diagram showing 1¼° Beamwidth and below, a P.P.I. photograph taken in the Thames.

The pulse length has a similar effect upon the definition of the picture in that if a number of objects on the same bearing are lying close together, then an excessive pulse length will cause their echoes to merge together. This effect is particularly unwelcome in areas of crowded shipping and sea experience has shown the desirability of choosing a pulse length such that two targets can be separated when their range interval is 50 metres.

Form of Picture.—It is of equal importance from the point of view of clarity of the picture that its presentation should not suffer appreciably from any form of distortion. Two forms of distortion are common, firstly a bearing distortion such that targets are displayed on the P.P.I. at incorrect bearings, secondly range non-linearity can also occur, such that the distance from the centre of the P.P.I. to the echo is not proportional to the range of the object from the ship. Both these forms of distortion will mean that any ranges or bearings

Fig. 7
Two stages in a turn with relative display.

read directly off the P.P.I. will be incorrect and in the case of severe distortion the picture of coast-lines can look so different from the shape shown on the chart that recognition becomes extremely difficult.

The correct orientation of the picture is also one which requires careful thought; two alternative arrangements are possible. In the first of these the top of the P.P.I. picture can be made to represent the direction of ship's head; this arrangement, known as a relative display, then shows all targets in their position relative to ship's head, which has the disadvantage that when the ship alters her course the position of all other targets shown on the P.P.I. change through an angle equal to the alteration of course. This is particularly undesirable in the case of land echoes where for example, a 180° alteration of course would cause the land picture to invert and thus render recognition and correlation with the chart extremely difficult. Two stages of such a turn are illustrated in figure 7.

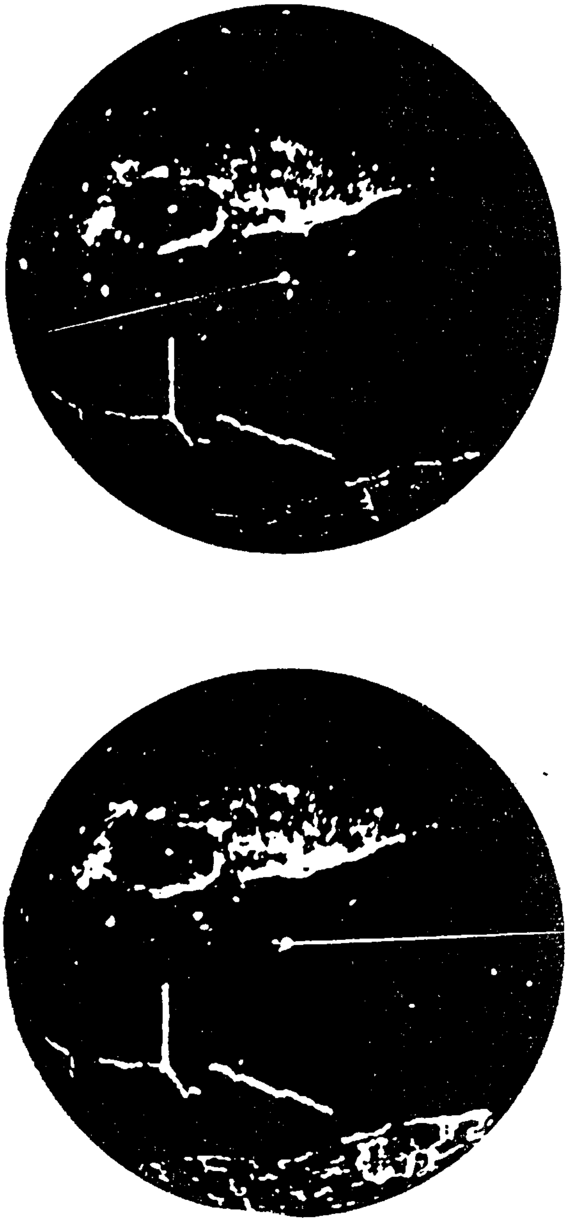

Fig. 8

Two stages in a turn with a true display including a heading marker.

The alternative system known as a true display shows the picture with the top of the tube representing true North, the picture being stabilised by the output from a transmitting compass. The picture then remains the same way up as the chart no matter what alterations of course the ship may make; when navigating near land this is obviously highly desirable. If this system is adopted, then it is necessary for the navigator to have a clear idea of the direction of ship's head; this is usually provided in the form of a bright line on the P.P.I. This ship's head marker is invaluable not only in giving a direct reading of the compass bearing of ship's head, but also in showing at a glance the direction of ship's head relative to any target being approached. Two stages in a turn with a compass stabilised picture are illustrated in figure 8.

In practice, more than one scale is desirable for the P.P.I. display. When the ship is navigating some distance off land or when the set is being used primarily for anti-collision purposes, a scale is required showing a maximum range of 50 km. or more. If such a maximum range is displayed on a practical cathode ray tube (effective diameter about 20 cm.) then a distance of one km. is represented by 2 mm. and it is clear that this scale is much too small to allow the ship to be handled in congested waters with a number of targets at close range. In such a case the ship may well need to be taken within 100 metres of other vessels or navigational marks and therefore 100 metres should be represented by an easily observable distance on the P.P.I.; in practice 4 mm. is an adequate distance and this gives us a natural scale of approximately $\frac{1}{25,000}$ which also compares favourably with the usual scale of pilotage charts. It may, therefore, be said that the scale of the P.P.I. should be variable between limits of the order of $\frac{1}{20,000}$ and $\frac{1}{800,000}$. It may be electrically convenient to switch the scale in steps rather than by continuous adjustment and when this is done a number of different scales should be chosen such that the ratios between them are not excessive; a factor of about 3 between successive scales is found to be convenient.

Detection Range.—If the set is to be used as an effective navigational aid in coastal waters then it should aim to provide a good picture of the land up to ranges of at least 20 km. off shore. It is difficult to lay down a precise figure for the maximum detection range of land, since so much depends upon the character of the land itself; a low lying, gently rising coast-line will yield a much smaller radar response than high cliffs and consequently the detection range of such low land will be poorer. Quite apart from any considerations of radar performance the maximum detection range of land will, of course, be limited by the range at which it disappears below the horizon. In practice, it is considered that if low lying land (say about 10 m.) can reliably be detected at a range of about 14 or 15 km. and high ground (say 100 m. cliffs) can be detected at a range of 40 km., then this provides a satisfactory compromise.

The basic requirement for detection range of shipping is the warning time necessary to allow a collision to be avoided. It is considered that the decision to alter course to avoid collision should be made five minutes before the two ships would meet; assuming a relative speed of 80 km. per hour this entails a range about 7 km. However, it will have been necessary to have had the approaching ship under observation for two or three kilometres before this to determine whether an alteration of course is in fact necessary; a detection range of 10 km. is therefore required. Again, the maximum detection range of shipping must be considered in relation to the size of the target ship, and it is felt that a performance giving warning of a small fishing vessel at about 6 km. and a 5,000 ton vessel at 14 km. would be a reasonable compromise.

In restricted waters navigational buoys are usually laid at distances not exceeding some 4-6 km; for pilotage of such waters it is advisable to be able to detect the next buoy ahead shortly after passing the last one and if, therefore, the radar gives a detection range on buoys of some 4 km., this should be quite adequate for all normal needs.

Minimum Range.—A feature of a navigational radar set which is of far greater importance than the maximum detection range is the shortest range to which a target remains visible. In restricted waters it is often necessary to take the ship either between close lying pairs of buoys or close to other shipping and this means that satisfactory minimum range performance is of paramount importance.

This point is best illustrated by reference to figure 9, in which the large central spot representing the ship's own position has an effective diameter of some 500 m. whilst to the South-east of the ship can be seen a series of close lying pairs of buoys marking the channel in towards Sheerness. If the navigator looking at this central blob as the position of his own

Fig. 9

The effect of bad minimum range is here seen in which the large central spot indicates own ship's position and the channel in towards Sheerness is marked by the three pairs of buoys to the Southwest.

ship were asked to take it in between these pairs of buoys, he might well feel reluctant to do so. In the case of the set from which this photograph was taken, the minimum range is limited not only by the size of this central spot, but by an area of paralysis surrounding it making the minimum range performance of the set about 400 m. The effect of this paralysis is clearly shown in figure 10 taken with the same set in the narrower reaches of the Thames estuary; whilst the Western bank of the river can clearly be seen, the Eastern bank near to the ship has a large " bite " taken out of it due to this paralysis. This effect would be most undesirable when the ship was being taken in towards a berth in fog, when the effect of the berth disappearing from the radar screen as the ship approached would be highly distressing.

Fig. 10

The effect of bad paralysis causing the near shore of the estuary to disappear.

The foregoing figures can be compared with figure 11, which shows the performance of a set having a minimum range of 50 yards and in which nearby targets are clearly visible; the two ships nearby to the south are at ranges of 60 m. and 100 m., the large ship to the west is at 300 m.

Whilst it is clearly important to keep this minimum range performance as good as possible, there is a limit to what can economically be achieved in the present stage of the art. A figure of 50 yards is suggested as a compromise satisfactory from the operational point of view and achievable with existing known techniques. It may be added that if the target can be held by the radar down to 50 m., then it will be under only the very worst conditions of visibility that the target will not by this time be visible by normal means.

A further minimum range consideration is that when the ship is coming up to two close lying buoys, then these will appear on the screen as two spots of light lying very close together each side of the heading marker and the navigator is faced with the problem of assessing whether the bearing of each buoy is sufficiently open from ship's head for safety,

**Fig. 11**
Good minimum range allowing the two ships, 60 yards and 100 yards to the South, to be clearly seen.

while having in effect only a very minute picture to look at. This problem can be eased by purposely introducing a form of distortion into the picture, by means of which, the central spot is expanded to a circle of about 3 cm. diameter; when this is done the buoys will appear to be opened out by a corresponding amount and observation of bearing is rendered very much easier. Use of this expanded centre will introduce distortion into the general shape of the picture and therefore cannot be tolerated permanently; if, however, this effect is brought into play only when required by means of a spring-loaded switch, then there are times when it will be found extremely valuable not only when passing between buoys, but also when passing close to other shipping. Figures 12 A and B illustrate what would be seen when approaching two buoys without and with the use of the expanded centre.

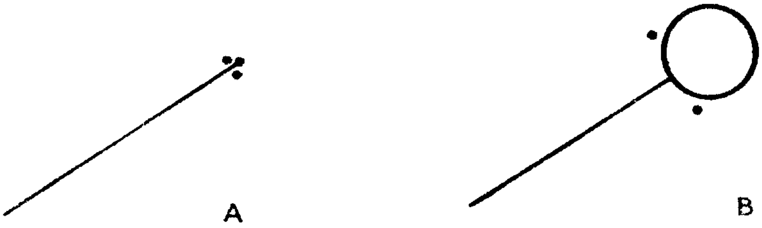

**Fig. 12**
The effect of approaching two buoys.
A—Without, and B—With the use of expanded centre.

Obtaining a Navigational Fix.—When the set is used for navigation, its primary function is to allow the navigator to determine the position of his ship. While a rough idea of a ship's position can be obtained simply by inspection of the radar picture, this is by no means sufficiently accurate, particularly when the ship may be in a narrow channel some distance from land. There are two main methods by which such a navigational fix may be obtained.

Measurement of the compass bearings of two or more navigational marks or land features may be measured off the P.P.I. and laid off on the chart, their intersection then giving ship's position. A consideration of the factors affecting the accuracy of such a fix is of importance. Clearly, any error between the position of the radar aerial and the position of the scan at that instant on the P.P.I. will introduce an error into the bearing with which any object is measured; in order to keep this error to a minimum the transmission system employed between the aerial and the P.P.I. must have a good accuracy. The effect of aerial beam-width is to show any target as an arc on the P.P.I., in the case of an isolated target this is of secondary importance since the centre of the arc will be the correct bearing of that target; however, when looking at the complex picture of a coast-line the centre of the arc can no longer be discerned and an error may therefore be introduced into the reading. It is, therefore, important that the aerial beam-width should be kept as small as possible in order to reduce this source of error to a minimum. In practice, it is considered that if the set is to provide effective navigational assistance the total effect of the above errors should not be allowed to exceed 2°.

An alternative method of obtaining a navigational fix is to measure the range of a number of navigational marks or land features and to plot these off on the chart with a pair of compasses. This process is rather longer than fixing by bearings, but it is preferred where accuracy is important, since a radar set is inherently a more accurate ranging than bearing device. Ranges may be measured on the P.P.I. either by superimposing electronically a number of calibration rings at a known range interval and interpolating between them, or, by arranging a single "strobe" circle whose diameter can be changed by means of a control calibrated directly in units of range. The former system is the quicker to use, but the latter is essential where high accuracy is required; both are desirable under different circumstances and it is usual to include the two systems. Since quick reading is the salient advantage of the calibration ring system, it is undesirable to display more than five rings on the P.P.I. and it may, therefore, be seen that, assuming an interpolation accuracy of 1/10, the range

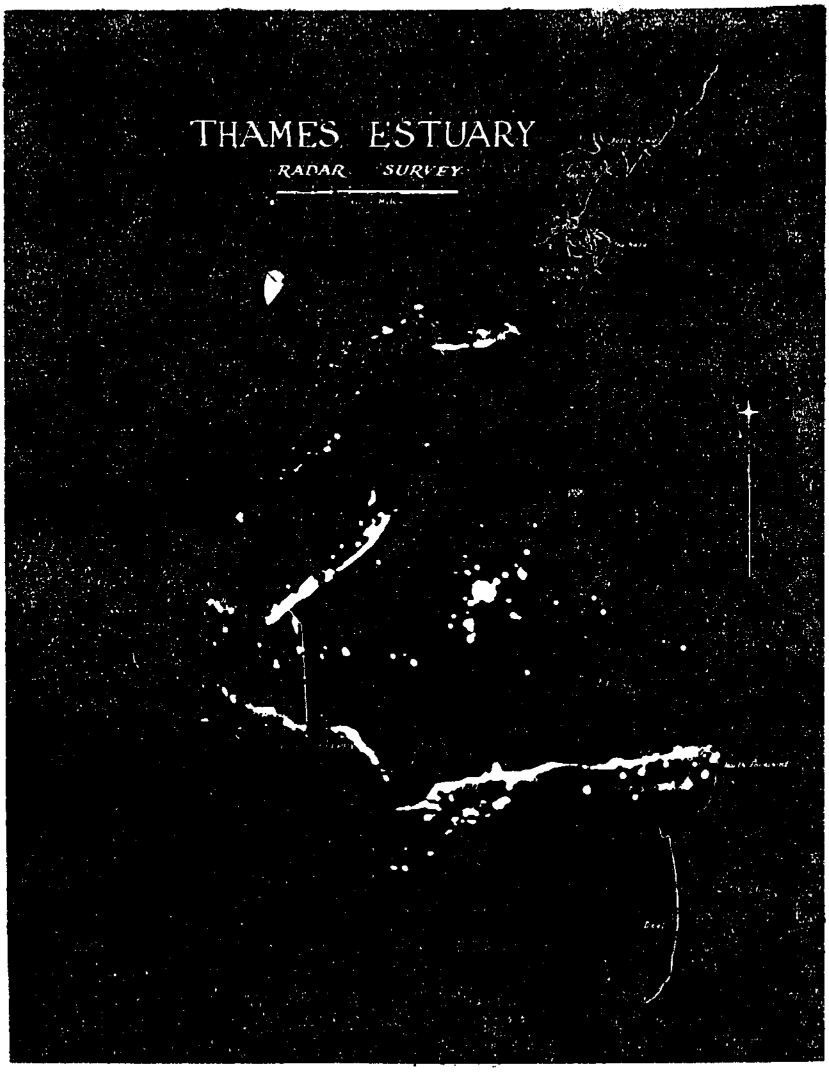

Fig. 13

A single Radar Photograph superimposed on a chart. The position of the ship can be fixed simply by noting the position of the central spot relative to the chart.

accuracy obtainable by this system is of the order of 1/5 times 1/10 or 2% of the maximum range of the display. In the alternative system, accuracy is the governing requirement and an accuracy of the order of .25% of the range scale should be aimed at; this would mean an accuracy of range measurement of 50 m. when 20 km. off shore, adequate for all normal needs.

Both the foregoing methods are adequate for coastal work, but are far too lengthy when the ship is in restricted waters where a continuous appreciation of the ship's movements is a prime essential and some alternative method is necessary. Figure 13 shows a P.P.I. picture superimposed on a chart and suggests the basis of such a method, since the ship's position may now be seen on the chart by direct inspection of the position of the central spot. Further, all other targets in the neighbourhood are now shown at a glance in their right position on the chart. An optical system which allows the P.P.I. picture to be viewed in coincidence with the chart therefore provides a rapid and simple fix coupled with instantaneous appreciation of the surrounding situation and puts pilotage, as distinct from open sea navigation, on a practical basis. For this system to be satisfactory the P.P.I. must have a variable scale in order to match the navigational chart in use and adequate reduction of all forms of distortion is essential. The practical value obtained from such a system is found adequately to repay the additional trouble taken in indicator design.

Automatic Performance Check.—When considering the use of the radar set as an anti-collision device in poor visibility, it is imperative that an automatic indication be given of any serious decrease in the performance of the equipment. Automatic circuits should, therefore, be included in the equipment such that if the performance should fall off the navigator is immediately notified either by the sounding of a warning signal or, alternatively, by an automatic closing down of the equipment.

It is safe to say if some such arrangement is not included the radar set, far from adding to the safety of life at sea, will be a danger to shipping.

Operation in rough weather.—In rough weather the ship carrying the radar equipment may be rolling severely and attention must be paid to the design of the equipment such that this will not cause serious deterioration of the results obtained. Rolling of the ship will cause the radar beam to swing through a vertical angle which may occasionally be as large as ± 20° from the horizontal. If this beam is to continue to illuminate a target, then either the vertical beam-width must be large or alternatively the aerial system must be gyro-stabilised against roll; the gyro-stabilisation of an aerial is a complicated and an expensive matter and is thought to be sufficiently undesirable to make the former method the better alternative. In severe rolling some missing of the target can be tolerated at extremes of the roll provided that it is certain that the target will not be missed for a prolonged period.

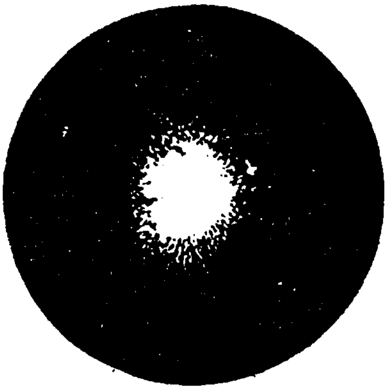

Fig. 14

Photograph of a P.P.I. with Sea Clutter extending to nearly two miles.

A further complication arises in rough weather in that the waves now yield echoes which show up as bright area (perhaps several kilometres in radius) at the centre of the picture. These signals are probably saturating the P.P.I. and therefore even a very much stronger signal from a large target within this area of " sea clutter ", as it is called, may not show up on the P.P.I. Figure 14 is a photograph of a P.P.I. under such conditions with " sea clutter " extending to almost two miles.

Whilst a strong signal within this region could be detected by turning down the gain of the radar receiver until the " sea clutter " at the range of this target had disappeared, such a procedure would mean that in rough weather the navigator would be required to be continually adjusting his gain control. It is highly desirable that some automatic arrangement be included in the set, such that the effect of " sea clutter " is removed from the P.P.I. and allows any signal of greater amplitude to be shown. Figures 15 were taken within a few seconds of figure 14 with successive adjus'ments of such a device. In figure 15 C a number of targets previously obscured can clearly be seen. (The device in use was a " swept gain " circuit).

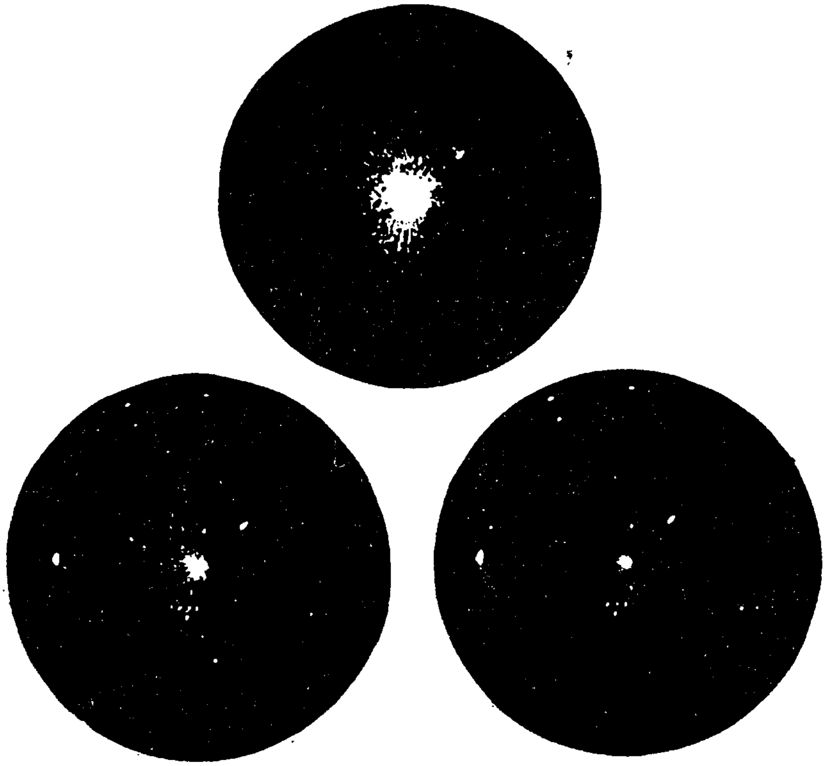

Fig. 15
Photograph of a P.P.I. with successive adjustments of an anti-clutter device.

Ease of Operation.—The fact should never be lost sight of that a navigator's job is to handle his ship on a variety of different sources of information of which radar may be one; particularly when a ship is running in thick fog the navigator is a harassed and a busy man and needs to be able to get the maximum use from his radar set, while devoting the minimum amount of time to operating it.

Fullest possible consideration should, therefore, be given to designing an equipment which can be operated simply by the minimum number of controls readily and conveniently accessible.

### 2° Electrical requirements

Whilst it is beyond the scope of this paper to detail all the electrical requirements which the equipment should fulfil, it may be of value briefly to mention some of the more important factors.

Freedom from Interference.—Particular care should be taken to ensure that the operation of the radar set does not cause any form of interference with the ship's W/T or radio telephone equipment. Such interference is not likely to be caused by the 3 cm. radiation, but it has been found that the modulator circuits are very prone to radiate serious interference over a wide frequency band. Careful design of the modulator circuits with particular reference to adequate screening is the usual method of combating this trouble. Adequate suppression of any electric motors, contactors etc., is also a consideration.

It is of equal importance to ensure that the ship's communication equipment does not interfere with the operation of the radar. Careful screening is again the key-note.

POWER AVAILABLE.—In most cases the only electrical power which will be available for the set will be the ship's mains, commonly 110 or 220 volts direct current. Power available in a small ship may be strictly limited and the set should consume certainly not more than 5 kw., preferably much less. The mains voltage is liable to fluctuations sometimes by as much as ± 10% and it is important to ensure that the equipment continues to perform satisfactorily under these conditions.

RELIABILITY.—The complex nature of a radar set means that if it is to give satisfactory service over a prolonged period, particular care must be taken to ensure freedom from breakdown. The ship may well carry no trained maintenance personnel and under these circumstances, it is a very sound policy to run all components of the set well below their full rating.

EASE OF MAINTENANCE.—The whole question of maintenance is one which it is difficult to generalise upon, since the requirements cannot be divorced from knowledge of the size of ship and the nature of the run which she normally makes.

In the case of a large ship which may be away from her home port for many months, maintenance at sea must be envisaged under the care of personnel who have had at least some training in electronics. It can be expected in many cases that such training will have been of an elementary nature and the equipment should, therefore, be designed to make the tasks of maintenance as simple as possible. Automatic monitoring to localise a fault to one unit and the carrying of spare, easily replaceable units is one suggested solution. In this class of vessel, maintenance will almost invariably be carried out on a unit in situ and accessibility of components is important, particularly when it is remembered that working space around the set may be almost non-existent.

In the case of small ships either coasting in home waters or on a regular run between two ports, it may be economically unadvisable to carry any maintenance staff and maintenance may have to await arrival in the home port. In this case particularly, speed of repair may be all important and here again the unit replacement principle seems to offer the best solution, the faulty unit being replaced by a spare held ashore and serviced at leisure after the ship has sailed.

### 3° Mechanical requirements

Here again it is beyond the scope of the paper to launch into a complete survey of desirable mechanical features, but some mention may profitably be made of the points which have been found in Naval experience to be of particular importance for sea-going radio equipment.

ROBUSTNESS.—Sea-going equipment is subject to much rough usage and to severe vibration. Experience has shown that rough handling, particularly during installation, is to be expected.

CLIMATIC CONDITIONS.—The equipment should perform satisfactorily when subjected to the severe extremes of Arctic and Tropical conditions. In conditions of high humidity particular care must be devoted to keeping the inside surface of any waveguides clean and dry.

Finishes and insulating surfaces should be considered in relation to problems of smoke deposit and salt spray.

SUB-DIVISION OF EQUIPMENT.—In siting a radar set a number of conflicting requirements arise. The aerial should be mounted in a position such that it has the clearest possible all-round view without blanking by superstructure, masts etc. The indicator and control position should be on the bridge. The transmitter and receiver circuits should not be allowed to take up bridge space and in addition should not be too far away from the aerial, thus avoiding an excessive length of waveguide.

These requirements are best met by sub-dividing the set into three units, aerial, display and control unit and main console. The main console should be arranged as a unit which can run unattended so that it may be mounted in any available position within easy reach of the aerial (say 20-35 m.). The main console should also be a robust unit with all its units and pre-set controls under locked covers to prevent them being tampered with.

Size and Weight.—All units should be made of such a size that they can be passed through a ship's hatch or, alternatively, that they can be broken down into sub-units which may be passed through. Any sub-unit which may need withdrawal for maintenance should be of a weight such that it can be lifted out by one man, bearing in mind that the ship may be in a sea-way and rolling badly.

Attention should be paid to reducing so far as possible the weight of the aerial assembly, since excessive weight might preclude it being fitted in a desired position at a mast-head.

Ease of Installation.—The majority of radar sets are likely to be fitted in existing ships and this may have to take place while the ship is in port for only a short period. In addition, the cost of installation can become an appreciable part of the cost of the radar set and for this and the foregoing reason, the set should be designed such that installation is as simple as possible. In this connection, the important features have been shown by experience to be that the set should not be subdivided more than necessary, and that interconnecting cable runs should be made straight-forward and without the use of too many junction boxes.

Storage and Transit.—Both in the case of new equipment being sent overseas for fitting and in the case of spares being carried at ports abroad, equipment may be subject to rough handling in transit and to severe climatic conditions in store. Very careful attention to adequate crating and waterproofing has been proved in the past to be of paramount importance. In the case of transport by air, the effect of high altitude on any oil filled components needs careful thought.

## CONCLUSION

**Example of an existing equipment.**— The set is not intended as a design prototype ready to go into production but rather as a model, which can be used to demonstrate the latest results to the shipping industry and as a guide to such radio manufacturers as may wish to take advantage of it.

**Lay-out of equipment.**— The set is divided into four major units—the main console and aerial unit, a display and control unit and an auxiliary display unit for chart comparison use.

**Main Console.**— This is a unit of dimensions approximately 55 cms wide by 70 cms deep by 170 cms high, total weight 350 kg.; the general form of the unit may be seen from fig. 16 which shows it in its normal running form with a locked steel shutter drawn over all the preset controls.

The unit is built on the drawer system for ease of maintenance and in fig. 17 the console may be seen with two units partially withdrawn for maintenance.

The console consists of four main units. In the bottom drawer are the 500 cycle motor alternator and hydrogen thyratron modulator. In the next drawer up is the R.F. head containing the transmitter, crystal mixer, local oscillator and A.F.C. unit and also the Intermediate Frequency head amplifier. In the next drawer are the H.T. power pack for the whole equipment and also the main Intermediate Frequency amplifier with its Swept Gain and Instantaneous Automatic Gain Control circuits.

In the top drawer are contained chiefly the starter for the motor alternator, the voltage regulator, the magnetron H.T. delay unit, and the differential for mixing in the output of the ships compass.

**Aerial unit.**— The aerial unit, illustrated in fig. 18 includes 150 × 7.5 cm. "cheese" type mirror and its driving pedestal. The total weight is approximately 100 kg. The unit is completely waterproof, suitable for mounting, without any aerial housing, at the mast head: it may be sited any distance from the main console within a maximum wave guide run distance of 20 to 35 m.

On top of the pedestal is mounted the mirror which is capable of being driven at speeds up to 100 R.P.M. the speed of rotation will later be fixed after the optimum speed has been determined from sea trials. The mirror is excited by a fog-horn type of feed with a wave guide passing down through the centre of the pedestal and through a rotating joint mounted at the bottom. The pedestal also contains a d.c. driving motor, the magslip for repeating aerial position to the displays and a set of contacts for producing the heading marker.

Mounted near the aerial is a watertight box containing part of the performance monitor. A wave guide horn type of aerial picks up the radiation from the main aerial and applies it to a crystal which is used to measure transmitter power: this crystal also provides a triggering

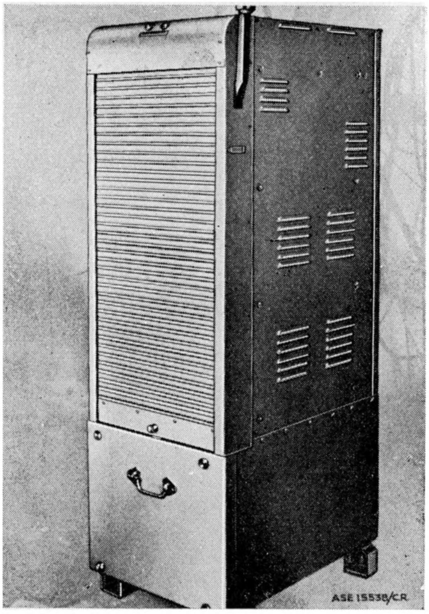

**Fig. 16**
Main Radar Console with the front locked down for normal unattended operation.

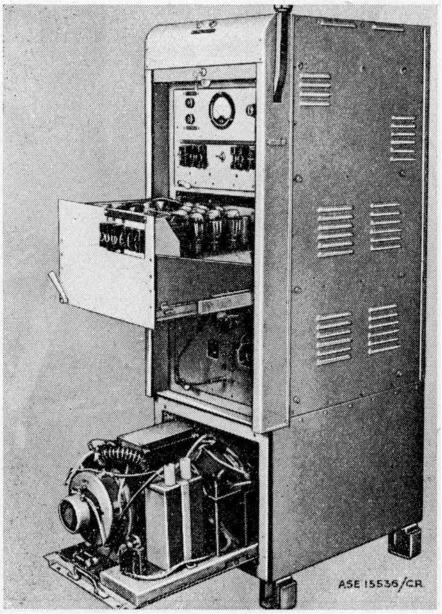

**Fig. 17**
Main Radar Console with two units withdrawn for maintenance.

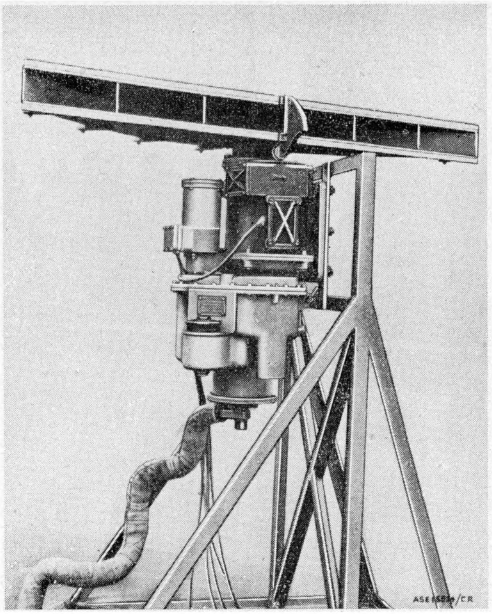

**Fig. 18**

Weatherproof aerial unit comprising "Cheese" type mirror and feed, and its driving pedestal.

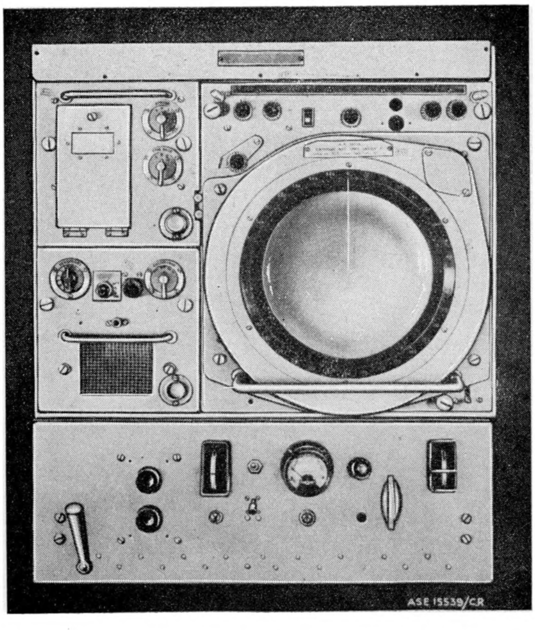

**Fig. 19**

Main display and Control Unit in its experimental form.

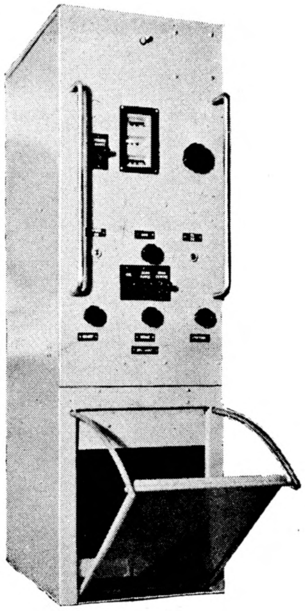

**Fig. 20**

Chart Comparison Unit with its partially reflecting mirror withdrawn for operation. Through the mirror, the chart may be viewed with a virtual image of the P.P.I. in coincidence.

voltage to a modulator firing off the spark gap in a resonant cavity producing a 3 cm. pulse which is fed back out of the horn aerial, this is picked up by the main aerial and receiver and used for checking receiver performance.

**Display and control unit.**— This unit is 55 cms wide by 55 cms deep by 70 cms high, approximate weight 140 kg. The unit which may be seen in fig. 19 is intended to be mounted on the bridge and forms the main display and also includes all the controls necessary for complete operation of the set, (for experimental purposes rather more controls than necessary have been brought out to the front panel; after trials some of these will be changed to internal presets). This unit may be operated up to 200' away from the main console.

In the top section of the unit are three withdrawable sub-units. The right hand unit contains the cathode ray tube and scanning coil and coil driving mechanism. The lower of the two left hand units consists of the final stages of the I.F. amplifier, detector and video stages, also the calibrator and brightening pulse generator. The upper of the two left hand units contains the initial multi-vibrator stages and the time base generator. The bottom unit contains the controls for operating the main console, the E.H.T. power pack for the cathode ray tube and also the final stages of the performance monitor (which multiply the transmitter power and receiver sensitivity components of performance) and the relay circuits for disabling the display when the performance has fallen seriously.

**Chart comparison unit.**— The chart comparison indicator is similar to the main indicator except that it includes an optical system allowing this picture to be viewed in coincidence with the chart. The unit has approximate dimensions of 28 cm. wide by 32 cm. deep by 90 cm. high and a weight of approximately 60 kg. The unit is shown in fig. 20.

The unit contains the cathode ray tube, scan coil and coil driving mechanism and also the controls for operating it.

The circuits associated with the unit are contained in a separate unit (not illustrated) approximately 50 cm. cube. This unit has drawer type sub-units containing the I.F., video, calibrator and brightening pulse circuits and also a power pack.

**Performance data.**— Briefly the electrical characteristics of the set are as follows :—

Wavelength 3 cm. band ;
Peak power 40 kw;
Pulse length 0.25 microseconds ;
Pulse repetition frequency 1,000 P.P.S. :
Azimuth beam-width 2° ;
Elevation beam-width 40° ;
Aerial rotation speed 20 to 100 R.P.M. (to be fixed later) ;
Band width 8 megacycles ;
Display 9" P.P.I.
    Scale varying from 1 : 20 000 to 1 : 800 000.
    Range non-linearity less than 5%.

Actual performance figures for this set are not at present available but trials of previous similar equipments give confidence that the requirements laid down in Section 2 will be met.

It is desired to point out that the work described in this paper has been shared among a number of organizations. The authors wish to acknowledge the help that has been given them both by their colleagues within the Admiralty Signal Establishment and by the members of other Government Establishments.

# RADIO WAVE PROPAGATION IN RELATION TO MARINE NAVIGATIONAL AIDS

by R. L. SMITH-ROSE, D. Sc., Ph. D., M.I.E,E,
*(National Physical Laboratory, England, April,* 1946).

## ABSTRACT

This paper presents a survey of the various methods now available for the application of radio wave technique to marine navigation, and of the manner in which these methods depend on a close and detailed understanding of the propagation of radio waves. Much of the success of the marine type of radio direction finder depends upon the stability of radio waves transmitted along the earth's surface, and the extent to which this transmission is confined to the great circle plane through the beacon transmitting station and the direction finder on board ship. When, at increasing distances and mainly at night, radio waves are also received from the beacon after traversing the conducting regions of the upper atmosphere, the reliability of the bearings obtained on the direction finder is seriously impaired. On the wavelengths already in use for such ships' direction finders, this effect limits the range of usefulness of the bearings obtained at night. This limitation has, however, been largely overcome by the development of improved direction finding systems, the use of which is so far practically confined to shore stations.

In recent years, radio navigational systems have been developed based upon a measurement of the difference in time of transmission of radio waves from two or more sending stations to the receiving station on board ship. The successful application of such systems involves a precise knowledge of the speed with which the radio waves travel, and of the actual path which they pursue between sender and receiver. In this sphere, the tendency is to confine the application to ground wave transmission, and the use of long waves is being exploited in order to gain the greatest reliable range possible.

Radar technique is also being explored, particularly for the purpose of short range navigation and pilotage; and the success of this depends upon a knowledge of the mode of transmission of very short waves, and of the effects on such transmission of various atmospheric conditions likely to be encountered in different parts of the world.

The results of this survey show in what directions there is a need for continued research on the propagation of radio waves, if full and adequate use is to be made of the various types of radio navigational aids now under consideration.

### 1. **Introductory.**

Marine navigation unaided by any electrical, radio or acoustic techniques is carried out by taking directional bearings with the human eye, assisted by an optical instrument, on fixed sources of light of a primary or secondary nature. The primary sources are the sun, stars, lighthouses, buoys and lightships; while the secondary sources are usually prominent landmarks in towns or the country landscape which are illuminated by sunlight. Position fixing is usually effected by taking cross-bearings from the ship on two or more such objects; or by using a range-finding instrument which, in effect, enables one observer to take simultaneously two bearings of an object from the ends of a short, but known, base-line. All this technique is based upon the assumption that the light waves travel in straight lines between the source and the observer, and long experience and adequate scientific observation have confirmed this assumption as a general rule. There are, however, occasions on which, when the line of sight is practically horizontal, the rays of light are bent or refracted in the vertical plane, by their passage through the earth's atmosphere. This phenomenon is well known to mariners in the form of a depression of the horizon, and becomes evident by the apparent flattening of the disc of the moon or sun when this is rising or setting. As a result of this bending of the light waves around the curved surface of the earth, objects are sometimes visible at distances appreciably in excess of the geometrical horizon. Cases are on record in which under certain favourable weather conditions, the range of visibility has become several times that normally possible. This is due to the existence of a suitable vertical temperature and density gradient in the atmosphere and a resulting horizontal stratification which produces the bending of the light waves in the vertical plane causing a change in apparent elevation of the object observed. It is conceivable that in other circumstances the required atmospheric gradients might occur in a horizontal direction, and that as a result there would be a lateral deviation or change in azimuth of the light waves, but it is thought that for such occurrences to be of practical importance is comparatively rare.

There are three major limitations to the use of such visible light methods of obtaining bearings and positions. In the first place, the reliable range of observation of objects on land or sea is, under clear weather conditions, limited to the geometrical horizon distance surrounding the observer. Secondly, under conditions of darkness, the observations can only be made on primary sources of light, and during periods of cloud or overcast sky, these may be limited to the sources on land or sea. In the third place, even in daylight the incidence of fog or bad weather conditions generally may limit the range of observation to below that which is practically useful. It is on account of these limitations that mariners have for the past forty years or more looked to other means of assistance, of which it may be said with confidence that radio technique in one or other of its now various forms has undoubtedly proved the most successful. The radio methods evolved make use of electromagnetic waves similar to those of light but differing in the matter of length. The length of the waves used for radio communication and navigation purposes nowadays ranges from a few thousand metres down to a few centimetres, while the spectrum of light waves which are visible to the human eye extends only from 40 to 80 millionths of a centimetre. It is on account of this large difference in wavelength, with a consequent difference in the characteristics of the transmission of such waves, that radio wave technique offers such great advantages, albeit with some limitations, over those relying upon the use of visible light waves. The main advantage is that the longer the wave, the more is it bent or diffracted round the curved surface of the earth. Thus for a given radiated power, the strength of signal received at distances beyond the geometrical horizon becomes increasingly greater, as the wavelength is increased up to the longest at present used in radio technique. This refers to transmission along the earth's surface only, and as will be seen later, other modes of transmission may be superimposed on this for particular bands of wavelength.

## 2. Radio Direction Finding.

The conception of the possibilites of directional methods in the transmission and reception of radio waves is literally as old as the application of such waves to practical communication; and it is now over a quarter of a century since ships began to be fitted with radio direction finders, an instrument enabling an operator or navigator in the ship to take bearings on signals from transmitting stations located either on shore or on other craft. The principle of the radio direction finder is based upon the rotation of a plane vertical loop or its equivalent aerial system about a vertical axis. The strength of signal induced in such a loop or aerial by an arriving stream of electromagnetic waves from the distant transmitter is proportional, in the simplest case, to the cosine of the angle between the plane of the loop and the direction of the arriving waves. Thus as the loop is rotated about a vertical axis, the strength of the received signal varies from a maximum to a minimum or zero, in accordance with the well-known figure-of-eight diagram. A consideration of this diagram shows that the rate of change of signal strength with rotation is greatest at the minimum position, which is therefore always used in direction finding, either directly, or by a comparison of signal strength positions of the aerial symmetrically disposed about the minimum position. The method of indication of this position may be aural by a signal in head telephones, or visual by the aid of an indicating instrument or cathode ray tube; in all cases, the result is the same. The ideal and perfect direction finding instrument will thus indicate the direction of arrival of the radio waves in the great-circle vertical plane through the receiver; and if this plane also passes through the transmitter, the bearing of this transmitter is thus known to the observer. Some twenty years' research on the mode of propagation of radio waves conducted simultaneously with a study of the performance of direction finders under a variety of conditions, has brought to light a detailed knowledge of the circumstances in which this ideal state of affairs can be approached.

## 3. Ground-Wave Transmission and Direction Finding.

The loop direction finder as used on board ship gives its best results when the radio waves reaching it are travelling horizontally along the earth's surface. It is subject to certain errors in indication due to the reception of secondary waves radiated by the metallic parts of the ship's structure, or by neighbouring ships, cranes and other structures, if the ship is reasonably close to these, such as when lying in dock. The errors arising from the ship's own structure can be partially compensated for by design features, and the residual deviations in the observed bearings can be corrected for after the whole installation has been calibrated over the range of wavelengths on which it is intended to be used. Such a quadrantal error, as it is termed, may vary from zero in the fore-and-aft and thwartships directions to a maximum on the quarters, this maximum error being anything from 6° or 8° to 20° in typical cases. The calibration may need to take account of the effect of variation in loading of the ship.

If the ground waves arriving from the distant transmitter cross a coastal boundary at a grazing angle, they may be deviated from the great circle path by a few degrees as they pass from land to sea. The direction finder will still indicate the true direction of arrival of the waves, but this is not now the great circle bearing of the sending station which is what is required. Such a coastal refraction error is not easy to compensate for in practice. Its value will be greatest when the waves cross the coast from a dry sandy desert, but the observed values are even then only 3° or 4°, the waves being bent towards the coast-line as they pass from land to sea, and vice-versa. The occurrence of such an error is best avoided by ensuring either that there is an all-sea path between the sending station and the direction finder or that the path of the waves intersects the coast line at a sharp angle. It was at one time the practice to mark on charts the "arcs of good bearings" centred on those stations used as radio beacons, the limiting directions of these arcs being such as to avoid the possibility of coastal deviation errors.

These beacons have been installed to an increasing extent during the past twenty-five years or so, and are used in the manner of radio lighthouses, an easily recognised signal and identifiable call-sign being transmitted at specified intervals so that ships with radio direction finders may determine their position as frequently as desired. As navigational aids particularly for the use of the mercantile marine, such beacons usually operate on the medium wavelength band between 600 and 1,200 metres (frequencies 250 and 500 kc/s.). Similar results could be obtained on the short wave band centred on, say, 60 metres (5,000 kc/s.), so long as ground wave reception is used, but the range thus attainable is much less than at medium wavelengths. For example, for equal radiated powers, the same signal strength is obtained at some three times the distance over sea on a wavelength of 1,000 metres (300 kc/s.) as on 50 metres (6,000 kc/s.). For transmission over land the advantage is even more in favour of the longer waves, which produce the same signal strength at about ten times the distance as the shorter wavelength referred to above. Such comparisons emphasise the importance of using long waves and over-sea transmission paths, when it is desired to take advantage of the stability of ground wave propagation.

## 4. Ionospheric or Sky-Wave Transmission and Direction Finding.

### (a) *Medium Wavelengths.*

It is now well known that radio waves, in addition to travelling along the ground are also transmitted through the ionised regions of the atmosphere, or the ionosphere as it is termed. On the medium band of wavelengths, such ionospheric or sky-wave transmission takes place chiefly at night, the signals received by the sky-wave in the daytime being comparatively weak. The effect of such sky-wave transmission at night becomes evident in the form of fading or fluctuation in the strength of signals, and of erratic variations in the bearings observed on a loop direction finder. The nature and extent of these variations depends upon the relative strengths of the sky-wave and ground-wave signals, since the former is continually varying in amplitude and polarisation, while the latter remains sensibly constant. Since the sky-wave has been reflected from an ionospheric layer, termed the E region, about 100 km. (60 miles) above the earth, it arrives at the direction finder at a steep downcoming angle, and is thus in a position to produce the maximum disturbing effect. As the distance between the sending station and the direction finder increases, the effect of the sky-wave conditions at night increases rapidly, in the presence of the rapidly diminishing strength of the ground wave. After the ground wave has become so weak as to be negligible, however, further increase in distance has a decreasing effect since the sky-waves then arrive at a steadily diminishing angle of elevation above the earth's surface. At sufficiently great distances, the direction of arrival of the sky-waves approaches the horizontal, and in these circumstances the effect of their characteristic variations on the loop type of direction finder is relatively small.

From the above explanation, it will be appreciated that when the distance between a beacon transmitter and a ship using a direction finder thereon exceeds a certain minimum value, the bearings observed at night will be subject to a variable error due to the superposition of the sky-wave upon the ground waves normally received alone in the daytime. For a transmission path entirely over land this minimum distance will be about 40 km. (25 miles) and somewhat greater than this value over sea. As the distance becomes greater these variable errors increase considerably in magnitude, and at distances of the order of 130 km. (80 miles) over land or 400 km. (250 miles) over sea, the effects will be at their worst on medium waves. In these circumstances the bearings may occasionally fluctuate over an arc exceeding 60°, and at times the normal signal minimum conditions may be entirely absent. In spite of such effects, however, experience has shown that it is not often that more than ten per cent of the night observations give an error exceeding 10°; and furthermore, since the deviations in bearings usually show no systematic error, the mean of a number of observations taken in succession over a few minutes gives a reasonably close approximation to the true bearing.

We thus see that for the moderate distances and medium wavelengths discussed above, the stable and fairly accurate bearings obtained on the ground wave in daylight, become disturbed by the incidence of the sky-waves at night, these effects being moderately well confined in time between about one hour before sunset and one hour after sunrise along the path of transmission. As the wavelength is increased above 1,000 metres (300 kc/s.) the sky-wave effects begin to overlap more and more into the daytime conditions particularly in the winter and extreme northern and southern latitudes.

While, as will be seen below, research into these phenomena has resulted in the development of direction finders with special aerial systems which are relatively immune to the deleterious effects of sky-wave transmission, the production of suitable instruments for use in ships has not so far proved very practical, particularly for moderate range working.

(b) *Short Wave Working.*

In considering the effect of sky-wave reception with the short radio waves in the band 10 to 100 metres (3 to 30 Mc/s.), two points are to be noted. First, as already mentioned, the decrease in strength of the ground wave signal with distance, is much more rapid than on medium waves, while in addition the transmission of short waves by way of the ionosphere is more efficient, and their effect is experienced in the daytime as well as at night. These short waves are reflected from one or two, and at times three, ionised regions designated E, $F_1$ and $F_2$ respectively, in the atmosphere at heights varying from 100 to 250 km. (60 to 150 miles). As a result, at all distances exceeding some 40 km. (25 miles) the sky-wave plays a dominant part in the received signal, and radio direction finders using loop aerials are so erratic in their indications as to be almost useless for navigational purposes.

With the understanding of the cause of these undesirable effects, a spaced aerial system, originally invented by Adcock, has been developed, which gives bearings on sky-waves of comparable accuracy with those obtainable on a loop set using the ground wave only. While such aerial systems can conveniently be provided at shore direction finding stations, it has not proved very practicable so far to provide them on ships except in special circumstances. The Adcock type direction finder has, however, been extensively developed for shore station use; and it is available for observing bearings equally on transmissions from ships and aircraft, where it is not essential that the bearings should actually be taken by the operator or navigator on board the craft. The application of such a technique assumes the existence of radio communication between ground and the ship or aeroplane.

In recent years, various improved systems of spaced aerial direction finding have been developed. Among these are the spaced loop direction finder which is a very accurate instrument, more suited as a research tool for studying wave propagation than as a practical instrument for navigational purposes. There have also been developed for shore station use, instruments using very wide aerial spacing and intended to give a great discrimination of bearings within a narrow arc of the order of 20° or so.

### 5. **Direction Finding on Ultra Short Waves.**

The instrumental technique of radio direction finding has been developed for several purposes at successively shorter wavelengths from 10 metres (30 Mc/s.) down to less than 0.5 metres (600 Mc/s.). The main application has been its use at ground stations for position fixing of aircraft and of meteorological balloons carrying radio transmitters. At wavelengths shorter than about 4 or 5 metres, it is known that the ionosphere plays no part in the propagation of the waves; and the range obtainable is thus virtually limited to the geometrical horizon, beyond which the waves are transmitted with a rapidly diminishing intensity as a result of slight bending round the curved surface of the earth. Following the trend already described, these very short waves are rapidly attenuated when transmitted along the ground; but if either the transmitter or receiver is elevated, the distance of the direct ray transmission can be increased with advantage, in the same way that the ordinary visible horizon distance increases with the height at which the observer places himself. It will thus be appreciated that a direction finder with its aerial system only a few feet off the ground or sea will have a rather limited range on signals from a sending station also near to the ground, but on signals from a transmitter in an aircraft or balloon, the effective range will be considerably extended. It will, for example, be increased from 20 km. (12 miles) to 250 km. (160 miles) as the transmitter is raised from 30 to 6,000 metres (100 to 20,000 feet). Radio direction finding on very short waves in the metre wavelength band has thus experienced considerable development in connection with aircraft navigation and control, but for the above reasons it would appear to have only a limited application to marine navigation. This limitation is quite apart from the serious difficulties which are encountered due to instrumental errors and their calibration, when a very short wave direction finder is installed on board a ship.

## 6. **Rotating Radio Beacons.**

As an alternative to the use of a special radio receiving instrument in the form of a direction finder on board ship, the directional property can be transferred to the sending station on shore, so that its bearing can be determined at a distant receiver by the aid of some characteristic of the emitted radiation. The use of directional transmitting systems is very old, since in his experimental researches Hertz used reflectors to concentrate the radiation from a straight rod aerial, and also loops whose sending or receiving properties depend upon the orientation of the loop. Investigations on the possibilities of rotating beacon transmitters using wavelengths between 6 and 10 metres were conducted over twenty years ago, and two experimental beacons were at that time in use in Scotland and the South of England respectively. Owing to the lack of practical development of receivers suitable for these wavelengths, the use of these beacons by ships did not become very widespread. In view of modern developments, however, these beacons were obviously the forerunner of the short-wave " radio-lighthouse " which is likely to be developed in the future.

### (a) *The Rotating-Loop Beacon.*

Various other means of securing directional transmission as a navigational aid were suggested or developed before 1930 and some, at least, of these have been applied to aircraft navigation. The counterpart of the ship's direction finder is the rotating loop beacon, one of which has been in operation in England since 1929 for the use of ships, although experimental stations were used in conjuction with aircraft some years previously. In this installation, a vertical closed-loop transmitter operating on a wavelength in the region of 500 or 1,000 metres (frequencies of 300 and 600 kc/s.) rotates about a vertical axis at a uniform speed of one revolution per minute. The polar radiation diagram of such a loop is of the same figure-of-eight form as that of a receiving loop. Thus as the loop rotates the field radiated in any given direction in the horizontal plane varies according to a cosine law, passing through successive maxima and minima at intervals of fifteen seconds. When the plane of the coil is perpendicular to the geographical meridian, a characteristic signal is emitted by the beacon, termed the N point. An observer at a distant receiving station notes with a stop-watch or chronograph the time taken by the signal from this N point to pass through its zero or minimum value, at which instant it is known that the plane of the transmitting loop is at right angles to the great circle joining sending and receiving stations. From the stop-watch or chronograph reading observed at this instant of minimum signal strength, it is evident that the bearing of the receiving point from the transmitting beacon can be obtained by a simple calculation. To provide for the case in which the observer is due north or south of the beacon, when the N signal would probably be inaudible, another characteristic signal is emitted after a ninety degree rotation to the corresponding E point. Since the radiation from the coil is symmetrical about its plane a second minimum is obtained after a rotation of one hundred and eight degrees from the first, and so a bearing observation can be made every half-minute.

### (b) *Ground-Wave Range with Rotating Beacon.*

So long as the point of reception is within the range at which the ground-waves predominante over any sky-waves, the effects observed with a rotating loop beacon will in general be comparable with those already noted for a rotating loop direction finder, and experience has confirmed this deduction. An important difference lies, however, in the fact that with the beacon system, the effect of re-radiation from currents induced in the ship and its superstructure is negligible; and if, as is usually the case, the rotating beacon can be erected on a good site on land, no correction is applicable to the bearing calculated on the assumption of a cosine law of radiation. The ground-waves from the beacon transmitter travel along the great circle path to the receiver, but if this path crosses a coast line, at a grazing angle a deviation is observed, which may be of the order of 2° or 3° in the wavelength range 600 to 1,000 metres. This experience is identical with the corresponding phenomena observed in using direction finders on the signals from a fixed beacon transmitter.

(c) *Sky-Wave Reception from Rotating Beacons.*

As the distance between the beacon and a receiver is increased, the ground-wave signal becomes gradually weaker, and the receiver becomes increasingly susceptible to any sky-wave radiation from the beacon transmitted through the ionosphere. This sky-wave reception causes errors and variations in the observed bearings in the same way and under the same conditions as those experienced with direction finders on the same range of wavelengths. This is readily realised when it is pointed out that, although when the sending loop is at right angles to the great circle plane through the receiving station no ground wave signal is obtained, the loop is still sending radiation in the above plane in an upward direction towards the ionosphere. This sky-wave radiation ultimately reaches the receiver and so spoils what should have been a position of zero signal. With the sending loop in a direction to one side or the other of this, some ground-wave as well as the sky-wave signal is received, and if the phase and amplitude relationships are appropriate, the resulting signal may be zero. The displaced position of the loop at this instant thus represents the error in bearing; in general, however, this will not remain constant owing to the variations in amplitude and polarisation of the sky-waves.

These phenomena have been experienced both in the practical use of the beacon and in comprehensive experimental investigations conducted with rotating loop beacon transmitters. As in the case of the use of the loop direction finder, the results of sky-wave reception are observed under night conditions only for ranges in excess of about 40 km. (25 miles). All the effects observed are analogous to those described in 4 (a) above, and the closeness of this analogy has been verified by many experiments in ships in which the bearings were observed simultaneously by the rotating beacon system and by the ship's direction finder.

If the medium-wave rotating beacon system described above is to be developed as an aid to marine navigation, it would be desirable to make use of a spaced aerial system in place of a closed loop. Such an arrangement has been explored theoretically, but direct experimental development of the system was abandoned in this country some years ago. In the interval a considerable amount has been learnt about the design and performance of spaced aerial direction finding systems, the results of which could be applied to the corresponding transmission problem. It is possible that in this way the rotating beacon could offer considerable advantages over the direction finder for marine use. These advantages include the freedom from sky-wave errors or night effects and the consequent increase in range for reliable bearings, and the fact that with the beacon systems, no special apparatus is necessary in the ship itself. The latter point may be of some considerable importance in the case of small ships in which the installation and accurate operation of a direction finder is not always easy.

This whole subject of medium wave direction and position finding must, however, be considered in relation to the systems and possibilities brought to light in the past five years or so, some of which are referred to below.

## 7. **Position Finding by Time Difference Observation.**

Well over twenty years ago the heights of the ionised regions in the atmosphere were determined by measuring the time taken for radio waves to travel from a sending station on the ground up to the reflecting region and back to a receiving station also on the ground. Both frequency and pulse modulation techniques have been used for this purpose, and this type of measurement conducted regularly at many stations in the world forms the basis of our present knowledge of the ionosphere and its effect on the propagation of radio waves as applied to communication and other purposes.

More recently this principle of measuring the time of transit of a pulse of radio-waves from a sending station to a reflecting target and back again to a receiver where the measurement is made, has been applied extensively for radiolocation purposes. Under the stimulus of war, prodigious progress has been made during the past few years in the development of this technique in a wide variety of directions, not least important of which are new radio methods of navigation.

### (a) *Pulse-Modulated Navigation Systems.*

These methods are known as the Gee system, which was developed in the United Kingdom for aircraft navigation at distances up to 500 km., and Loran, developed in the United States of America, for the navigation of both ships and aircraft at appreciably greater ranges.

Both Gee and Loran depend upon the same fundamental principle of determining the difference in time of arrival of pulses of radio-waves emitted simultaneously, or with a known delay, from two sending stations A and B, located on the ground at the ends of a suitable base-line. Assuming that the speed at which the waves travel is known to the requisite accuracy, the observer at the receiving station can then deduce the difference in his distance from the two stations A and B. Now, the locus of a point having a fixed difference in distance from two fixed points is a hyperbola; and so the above measurement places the position of the observer on one of a series of confocal hyperbolae. If the measurement is repeated on the signals from one of the stations A and B, and on those from a third synchronised sending station C, the position is found on one of a series of intersecting hyperbolae, and so a true fix is obtained.

From this brief description of these hyperbolic systems of navigation as they are called, it will be appreciated that their success and accuracy depend upon a knowledge of the exact path along which the radio-waves are propagated and the speed at which they travel between sending and receiving stations. In different circumstances the path of the waves may be a straight line, a smooth curve due to diffraction or refraction, or a pair of lines resulting from reflection of the waves from a region in the ionosphere, all these paths lying however in the great circle planes through the sending and receiving stations. At very great distances we may be concerned with successive reflections from the ionosphere and the earth.

### (b) *The Speed of Radio-Waves.*

Investigations on the velocity of light have been conducted by many workers during the past century, and the most accurate of the results show that electromagnetic waves in the visible part of the spectrum travel in a vacuum at a speed of 299,775 km, per second, a value which differs from the conveniently assumed value of 300,000 km. per second by about 750 parts in a million. The overall accuracy of the above measurements is about fifty parts in a million, and this represents the best knowledge today of the speed of light.

Since for radio purposes we are rarely concerned with wave transmission in a vacuum, the above value must be corrected for the dielectric constant, or refractive index of the air through which the waves travel. For air under normal atmospheric conditions at the earth's surface in England, corresponding to a pressure of 760 mm. mercury, a temperature of 15°C., and a relative humidity of seventy per cent, the corresponding value of the velocity will be reduced to 299,670 km. per second (186,250 miles per sec.).

Various attempts have been made to measure the velocity of radio-waves under various conditions and the results suggest that for medium radio-waves, the velocity lies between 299,000 and 299,500 km. per second for transmission over a clear air path, while for propagation over land, an even lower value has been suggested. It has not so far proved practicable, however, to attain an accuracy in these measurements of better than one or two parts in a thousand (i.e. 1,000 parts in a million), which is comparable with the difference between the value suggested for radio-waves and that known for light-waves. If the best use is to be made of the radio navigational systems depending upon a measurement of the time of transit of the waves, it would appear that there is room for considerable further investigation of the speed of radio-waves under the various conditions met with in practical applications. This is rendered all the more necessary by the suggestion obtained in the use of these navigational systems that a distance discrimination of some forty parts in a million is attainable with the instruments already available.

### (c) *The Path of the Waves - Gee System.*

As developed for the Royal Air Force during the war, Gee operates on a wavelength between 3.75 and 15 metres (frequencies 20 to 80 Mc/s.) and relies upon direct ray transmission to the point of reception. This direct ray path may be a straight line for short distances, but for longer ranges when the path differs by only a fraction of a degree from the horizontal, the waves will be bent in the vertical plane in a curve concave to the earth. This bending is due in the first place, to diffraction round the curved surface of the earth, and secondly, to the variation in the refractive index of the air with height. The extent of this bending under average conditions is fairly well known, and it may be judged from the fact that for aircraft flying at 5,000 metres (15,000 ft) or more, a range of about 500 km. (300 miles) can be achieved, although the geometrical horizon range of the Gee sending stations to such aircraft is only about 300 km. (190 miles). For reception in ships with their much less aerial height, the effective range at which reliable signals could be received would be less than about 120 km. (75 miles), and even this would require that the sending stations could be erected in elevated points at frequent intervals along the coast.

When receiving signals from Gee stations at or near ground level, a second path of transmission sometimes occurs due to re-radiatian of the radio-waves from large metallic obstacles on the ground. Due to the short length of pulse used at the sending stations these secondary waves are usually quite distinct from the primary signals, except when the obstacle is very close to the receiver, when it is of little concern. Reflection from such obstacles as balloon cables and gas-holders at distances of from 1 to 10 km. from the receiver have caused the addition of secondary pulses at the receiving station, and these can at times be confusing to the observer, who may be unaware of the existence of the cause of these unwanted pulses.

(d) *The Path of the Waves - Loran System.*

The Loran system operates on one of several wavelengths between 150 and 170 metres (1,700 to 2,000 kc/s.), and therefore the propagation of the ground and sky-waves depends upon the characteristics of the land or sea and of the ionosphere respectively. The sending stations so far developed give a ground-wave range over sea of about 1,200 km. in the daytime; but over land the effective range is seldom more than 400 km. to surface craft. At night the ground-wave range over sea-water is reduced to about 1,000 km. by the increase in atmospheric noise but sky waves, which are almost completely absorbed by day, become effective and increase the reliable range to some 2,500 km.

The base-line used with the normal Loran system is usually of the order of 300 km., but may be extended to 1,000 km. under exceptionally favourable conditions. With such lengths of operating base, a considerable accuracy is possible in the discrimination of position, of the order ± 0.2 per cent and ± 0.3 per cent of the range for ground and sky-wave transmission respectively. If this discrimination is to be reliably applied to absolute position finding, it will be appreciated that an accurate knowledge is required of the exact path followed by the sky-waves from sending to receiving stations. At first, it was considered that the use of waves which had been transmitted through the ionosphere would be somewhat unreliable; but one of the surprising and interesting phenomena discovered during the experimental work on Loran in the U.S.A. was the high order of stability of the waves reflected from the E region of the ionosphere. This led to the idea of a system using an extremely long base-line of the order of 2,000 km. between the sending stations, the signals from which were synchronised by means of pulses reflected from the E region. The adoption of this system, known as Sky-Wave - Synchronised (S.S.) Loran, increased the minimum average error of position discrimination to less than ± 2 km.

It must be realised, however, that the attainment of such a high accuracy of position-fix must inevitably involve a detailed knowledge of the prevailing conditions in the ionosphere at the time of observation and along the path of transmission. Investigation of these conditions by means of signals from Loran stations has shown that the transmission of the radio-waves through the upper atmosphere is variable, and that the E region comprises one main and two subsidiary regions which are effective in the transmission, and these regions differ in height above the earth from 70 to 110 km. In addition to this variation in height of the reflecting region, the path of the waves may deviate from the great-circle plane between sending and receiving stations, and this departure will increase the time of transmission by an, at present, unknown amount. Experiments suggest that the probable error of a single measurement of the time of transmission may in typical circumstances vary between ± 4 and ± 10 microseconds, and for a distance of transmission up to 2,000 km., this will involve a position line error of between 2 and 5 km., when using a sending station base-line of 500 km.

It is well known that the characteristics of the ionosphere vary with the latitude and longitude, and they are also subject to variations of a diurnal, seasonal and solar cyclic nature. Much further research would appear to be necessary on these conditions at the frequencies in question, and it is likely that observations made on the Loran stations themselves can materially assist in this work. In the meantime, a Low-Frequency Loran system is under development on a wavelength of about 1,500 metres (frequency 200 kc/s.), estimated to give a reliable ground-wave range of some 2,000 km. over land or sea, by day or night. Owing to the lower frequency, it is necessary to use much longer pulses than with the normal system, and it is likely that the average error in the time measurement will be about four times that for Standard Loran. The errors at long distances are not yet well known, but there seems to be evidence that the extreme timing errors are not larger than in the case of S.S. Loran. The added stability of the ground-wave reception offers the possible advantage, however, of being able to utilise a phase measurement of the radio-frequency cycles within the pulse-modulation, and so to acquire some of the advantages of a continuous wave navigation system of the type described below.

### 8. Position Finding by Phase Difference Measurement.

An alternative method of determining the difference in time of transit of waves from two sending stations to a single receiving station is based upon the use of continuous, or modulated continuous waves, and the use of the known radio or audio frequency to make the time determination. Systems based on these principles have already been developed to some extent in this country, one of them, known as Decca, using continuous waves. By measuring the phase-difference between the waves received from two sending stations maintained in exact synchronism, the difference in time of transmission, and so of the path difference between the receiver and the two sending stations, can be measured to a very high order of accuracy. In the Decca case, the frequency at which the phase measurement is made is of the order of 340 kc/s., which is derived by a simple radio technique from the carrier wave frequencies of the sending stations, which may have a combination such as 85, 113.3 and 127.5 kc/s. The phase measuring instrument at the receiver integrates the total number of cycles (360°), and also the odd fraction of a cycle of phase difference between the signals received from each pair of sending stations. As in the case of the methods described in 7, each pair of stations gives rise to a series of confocal hyperbolae representing loci of equal phase-difference from the sending stations. The spacing of the hyperbolae on the charts is appropriate to the wave-length corresponding to the frequency at which the phase is measured.

It will thus be realised that such a system as Decca is really a means of determining position by measuring the difference in time of transit of two sets of continuous wave signals, a simple derivative of the actual carrier frequency being used as the reference standard for the time measurement. Since continuous waves are used, it is necessary to know the phase velocity of the waves in order to translate the time or phase measurement into distance. The accuracy already attainable in daylight is of a very high order, the discrimination of position possible with existing instruments being claimed to be about 40 metres in 320 km. i.e. about 125 parts in a million. At such ranges on the frequencies mentioned above, we are concerned solely with ground-wave propagation and the absolute accuracy of a position fix is thus determined by our knowledge of the velocity of the waves over land or sea as already discussed. It has already been found empirically that it is necessary to assume a speed of propagation about one part in a thousand below the accepted value for light, and this emphasises the need for further investigation of the speed of travel of radio-waves at various frequencies and over different types of terrain.

At night, the maximum range attainable with reliability will be determined by the magnitude of the ground-wave in relation to the sky-wave received from the ionosphere, since the receipt of both sets of waves will be very detrimental to an accurate measurement of phase difference.

It is clearly an advantage with these phase-measuring systems as with the corresponding pulse-modulation methods, to use as low a frequency as possible for the radio carrier waves in order to secure the maximum ground-wave range over sea and land and the consequent adequate stability of signals both day and night. Since the choice of frequency for all radio navigational aids is determined by other considerations as well as those most advantageous to the particular system, it is necessary that an adequate knowledge of the propagation of the waves over the ground and through the ionosphere shall be available for the particular ranges of frequencies which will ultimately be selected. At the present time, our knowledge of this propagation on wavelengths above about 300 metres (below 1,000 kc/s.) is inadequate and considerable further investigation is necessary.

### 9. Radar Navigation Technique.

The modern type of ship's radar equipment forms an admirable means of navigation in harbour entrances, estuaries or marked channels where an effective range of not more than about 30 km. (20 miles) is required: it is particularly suitable where a range discrimination of 50 metres and a bearing discrimination of about 2° suffice for all distances from 50 to 5,000 metres. A typical experimental equipment suitable for mercantile marine purposes has recently been demonstrated by the Admiralty using a radio wavelength of 3 cm. (frequency 10,000 Mc/s.). At short ranges the above performance will be obtained under all conditions, day or night, since the radio-waves then travel in straight lines between the radar equipment and the point of reflection. At the wavelength mentioned above, the range of transmission may be reduced by some twenty-five per cent with the occurrence of thick fog particularly in polar regions, or in the presence of heavy rain such as is experienced in the tropics. In addition, very heavy rain and clouds can on occasions give echoes which may cause some confusion on the viewing screen. On shorter wavelengths, for which radar equipment is already under development, all these phenomena are likely to become more serious, and this subject is now under active investigation.

In certain circumstances, diffraction round the vertical edge of a cliff can cause a deviation of radio-waves in a horizontal plane; and similarly propagation at grazing incidence over the top of a hill or other obstacle can cause a deviation in the vertical plane. Both these effects give rise to a deviation which seldom exceeds a fraction of a degree, but may at times result in the radar observer being able to detect a target, fixed or moving, which is not visible by optical means.

On the wavelength of 3 cm. referred to above, the deviation of the waves in either a vertical or horizontal plane by atmospheric refraction is unlikely to be more than a fraction of a degree; but under certain weather conditions, the waves travelling almost horizontally may be bent to a curvature approximating to that of the earth's surface. In such circumstances, reflections may be obtained from objects considerably beyond the normal field of view, and even beyond the optical horizon. If the distances at which such reflections occur are beyond the range scale of the display tube, they may give rise to the appearance of confusing images at apparently much closer distances. This type of abnormal range of vision is likely to occur chiefly on fine, warm days or during clear nights following such days: the frequency of occurrence is also likely to be much greater in tropical than in temperate latitudes. This phenomenon of abnormal propagation through the lower atmosphere, or troposphere, is now the subject of active scientific research, and more definite statements as to its effect in marine navigation must await the results of this work. It must be emphasised once more, however, that no difficulties are likely to be encountered in using radar for short-distance navigation.

## 10. **Conclusion.**

This review of the various systems of radio aids to marine navigation shows that the success of such systems is directly dependent upon our knowledge of various phases of radio-wave propagation over land, sea and through the ionosphere. In order to obtain the best practical use of the various techniques now available, it is desirable to ensure that some outstanding problems in the propagation of radio-waves are investigated as soon as possible.

There is a conspicuous lack of precise knowledge of the speed at which radio-waves of all frequencies travel over various types of terrain and through the atmosphere, and it is possible that some of the navigational systems under development can be of considerable assistance in investigating this subject. Although a good deal is known about the mode of propagation of radio-waves over land, and to a lesser extent over sea, at medium and high frequencies there is a need for a further detailed investigation of this subject at the lower frequencies, from 1,000 kc. per second downwards, now being exploited for marine navigation. Similar remarks apply to wave propagation through the ionosphere, where the need for understanding the phenomena of efficient transmission to great distances has been largely responsible for work in this field being confined to the frequency bands above 1 Mc/s. At the other end of the radio frequency spectrum, the use of radar techniques for short distance navigation and pilotage, and also the development of very short-wave radio lighthouses, has given rise to a need for understanding the phenomena involved in the transmission of centimetre waves (frequencies of 3,000 Mc/s. and above) through the atmosphere. This involves a precise knowledge of the effects of such conditions as fog, cloud and rain in various parts of the world on the scattering and absorption of such waves, and the scientific investigation of these problems has only just been commenced within the last year or two.

# GENERAL PRINCIPLES AND USE OF THE DECCA NAVIGATOR (*)

The Decca Navigator-Marine - Model Mk III (**).

The Decca Navigator System consists of the following items :—

(a) A Radio Receiver of special design, see photograph (fig. 1) ;

(b) Two (sometimes three) meters known as Decometers which are connected to the output of the Radio Receiver. These are described as the Red Decometer, the Green Decometer and, where a third is supplied, the Purple Decometer. Fig. 2 is a photograph of the three meters ;

(c) A Decca Chart. Usually a standard navigational chart for the area in which the equipment is to be used, with intersecting red and green lattice line overprinted on it. Charts, covering the service area of the three transmitting stations, are gridded with a series of red lines and green lines which are all numbered. At any time when the position of the ship is required, it is merely necessary to read off the number indicated by the Red meter and the number indicated by the Green meter, then look for the correspondingly numbered Red line and Green line on the chart. The point of intersection of the two lines is the position of the ship. Combinations of " Red " " Purple " and " Green " " Purple " are similarly used.

(d) A system of radio stations, generally situated inland and described as follows : Master Station, Red Slave Station, Green Slave Station and sometimes a third Slave, known as the Purple Station. Fig. 3 shows the transmitting mast of one of these stations. The most common arrangement as, for instance, in the English Decca Chain is for the Master Station to be centrally situated with the Three Slaves equally disposed about it at a distance of about 70 miles. A combination of Master and two or three Slaves is known as a Decca Chain. One master and two Slaves are sufficient to fix the position of a ship, but there occur certain areas in which fixing is impossible. Therefore, for the Chain to give all-round coverage over 360 degrees azimuth, it is customary to provide a third Slave, to which reference has already been made. The English Chain at present consists of a Master and two Slaves, illustrated in fig. 4, but a third (Purple) Slave is in course of construction.

## General principle.

The master station transmits a continuous radio wave; a " Red " slave radiates on a different frequency a continuous wave which is automatically locked to the Master. The receiver after converting the Master and Red slave to a common frequency compares their phase on the Red Indicating meter. The indicator reading is a precise determination of the position of the ship on a hyperbola passing through the ship and the base line joining the Master to the Red slave.

At the same time a Green slave is radiating a continuous wave on a third frequency again automatically locked to the Master radiation. In the same manner as with the " Red " signal, the " Green " signal is compared with the Master and the resultant phase difference indicated on the Green indicating meter.

These two readings if taken simultaneously " Fix " the position of the ship. Charts prepared with lattice lines corresponding to the " Red " and " Green " hyperbola and numbered with the same notation as the " Red " and " Green " meters enable the meter readings to be immediately translated to a pin point on a chart.

Examine fig. 4. It will be noted that between the Master and Red Slave are drawn a number of equally spaced red curved hyperbolic lines. In the Decca system two such patterns are arranged to cross each other to form a " Decca Lattice " (the red and green curves on fig. 4). The Decca Indicating meter or " Decometers " integrate their phase readings and accordingly keep constant record of the ship's position at all times.

## Lattice notation and how decometer readings are taken.

The entire area covered by the Master-Red Slave combination is divided up into such zones designated by letters. The zone nearest the Master is denoted A, the next B, and so on towards the slave.

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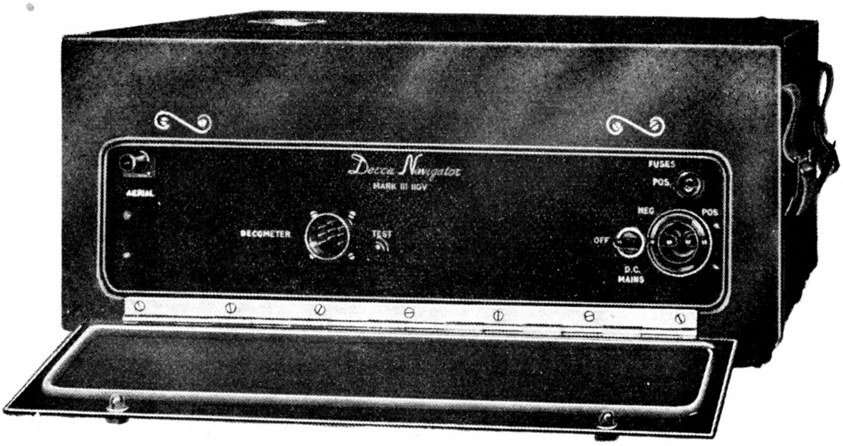
(*) See also « International Hydrographic Review », Vol. XXIII, Monaco 1946, pages 37, 61-65.

(**) The Decca Navigator Company, Limited, 1-3 Brixton Road, London, S.W. 9.

**Fig. 1**

Decca Receiver (Marine MK III).



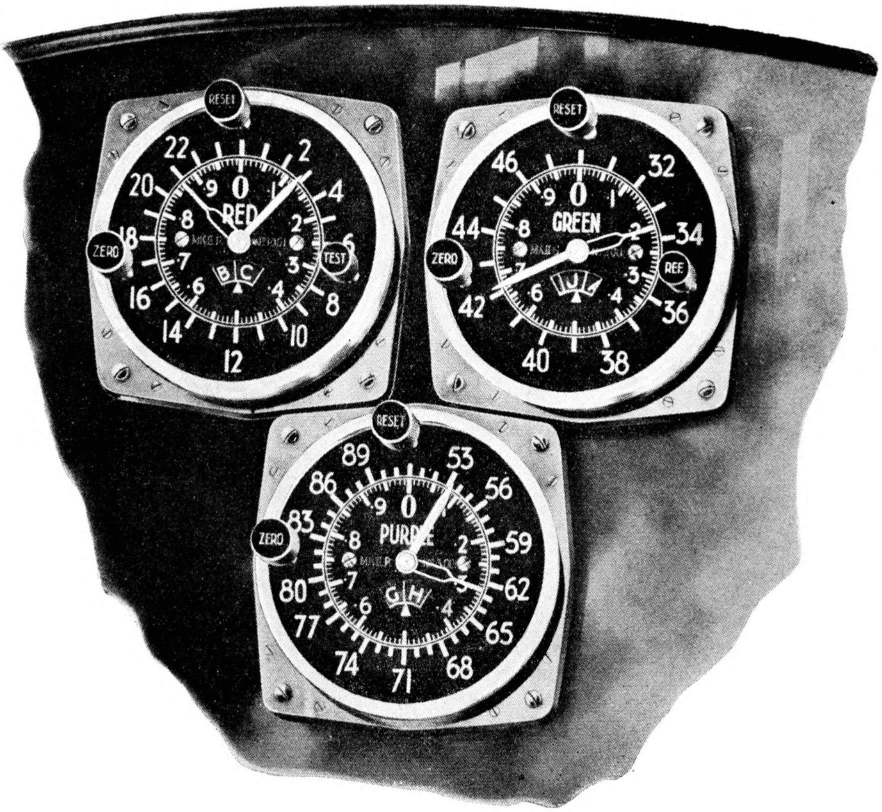


**Fig. 2**

Decometers.

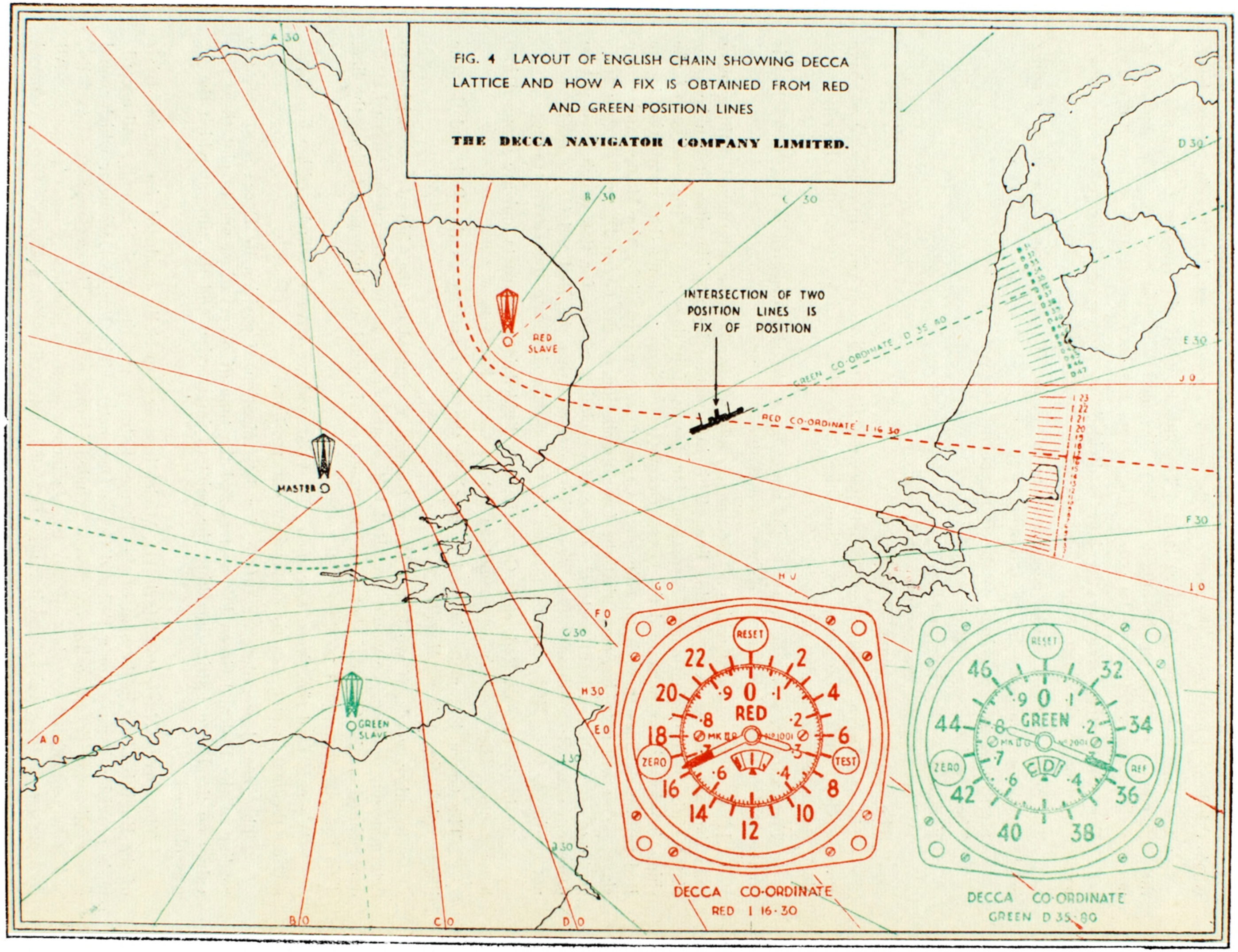


FIG. 4 LAYOUT OF ENGLISH CHAIN SHOWING DECCA LATTICE AND HOW A FIX IS OBTAINED FROM RED AND GREEN POSITION LINES

**THE DECCA NAVIGATOR COMPANY LIMITED.**

The notation of the Decca Pattern will be made clearer by reference to fig. 5, which shows the zone pattern radiating from the master and red slave, and how the pattern is further subdivided.

A position has been chosen in zone H. The letter " H " accordingly appears in the window indicator just below the centre of the meter, above the small triangular arrow head.

The zone is broken up into 24 lanes. The lane in which the position falls is shown by the long pointer reading on the outside scale of the meter—in this case 16. The position is not exactly at the beginning of lane 16 so the pointer lies between the 16th and 17th division.

For still further accuracy the lane is divided into 100 parts, indicated by the small pointer reading on the inner scale. This shows 30 hundredths.

The actual position chosen was therefore H. 16.30. To summarise : the meter reading is obtained at any moment in the following way :—

Firstly, record the colour of the meter being observed, e.g., Red ;
Then read the zone letter, e.g.,H ;
Followed by the lane number, e.g., 16 ;
Followed by the fraction of a lane, e.g., 30 ;
The full reading being, Red. H. 16.30.

This is a Decca Reading, but in itself does not give us a fix. You will note that we have now merely positioned ourselves on a line since the reading Red H. 16.30 may be any point along the hyperbola of that value.

For example, referring again to the map, fig. 4, the ship depicted in the North Sea is on the Red position line I 16.30, shown as a dotted red line.

If we were provided with one Decometer only we would have determined nothing more than the fact that we were on this line. This information is valuable since it can be associated with other navigational information, but by itself it does not fix the position of the ship. To do this we must read the Green Decometer. Figure 4 shows that in addition to the Red pattern of lines there is an equivalent Green pattern produced by the Master and Green slave. You will note, however, that the Lane numbering on the Green Decometer runs from 30 to 48 (see outer scale of meter). There is a technical reason for this which need not be gone into now. In addition it is a precaution to ensure that the Red and Green readings are not confused, since Red reads 0-24 and therefore cannot duplicate the Green reading.

As in the case of Red, each Green Lane is divided into 100 parts and are grouped into letter zones. There are, however, not 24 but 18 Green Lanes to a zone.

The Green Decometer is read in precisely the same manner as the Red, and the one illustrated in fig. 3 is reading D. 35.80.

In other words, if we had a Decca Navigator situated on the ship and we wished to determine our position, we would read Red I 16.30 and mark our position on the Decca Lattice over-printed on the Chart of that area. In practice it is usual to faintly pencil along the line. This has placed us on a position line.

We now read the Green Decometer D. 35.80, and we have a second position line intersecting the first, which exactly determines our position.

The general procedure, therefore, for determination of position by Decca is to note the reading of the Red and Green Decometers and the time of observation, and to plot these two values on the Decca Lattice, marking the point of intersection and the time at which the fix was obtained.

The Decca Navigator Mark III Model has been specially produced for marine trials of the English Chain in the area of the Thames Estuary, and the North Sea only, and accordingly provision is made for a Red and Green Decometer. The Purple Decometer which would ensure all-round coverage has not beeen included in this model. The receiver weighs 75 lbs, and is accommodated in a box of size 21 1/4 inches × 16 1/4 inches × 12 1/4 inches. All controls are on the receiver and it can be located in any convenient position. Meters coloured Red, Green and Purple can be mounted in the chart room and/or bridge.

Although the Decca Navigator gives information of one's position at any moment, it functions in a manner not unlike that of a Ship's Log, since it will only indicate the correct position of a ship if it has been continuously logging the progress of the ship from the commencement of the voyage or from the departure from the last known object.

To understand this it must be realised that the distinguishing features of a Decca

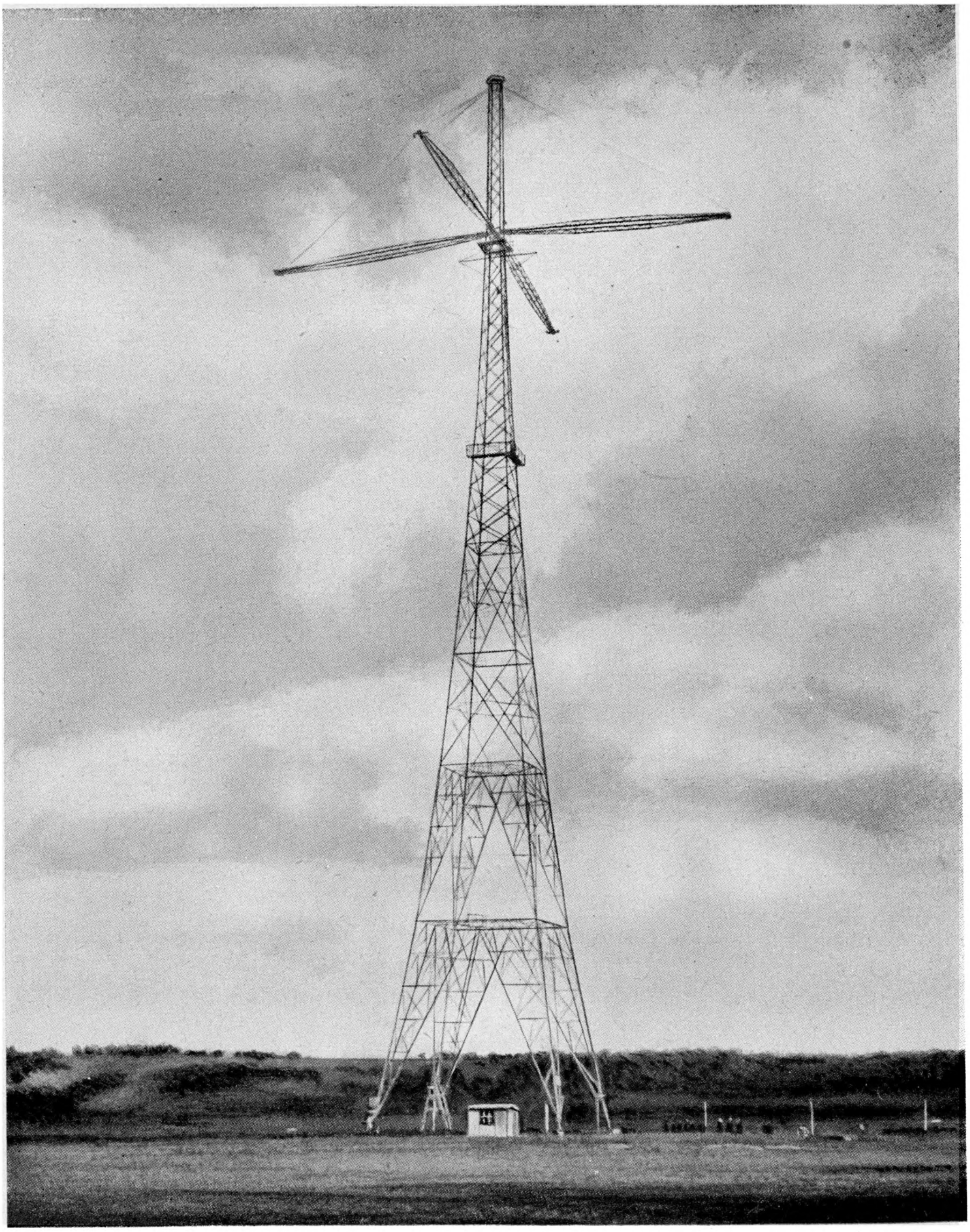


Fig. 3
Decca Navigator Slave Station Mast.

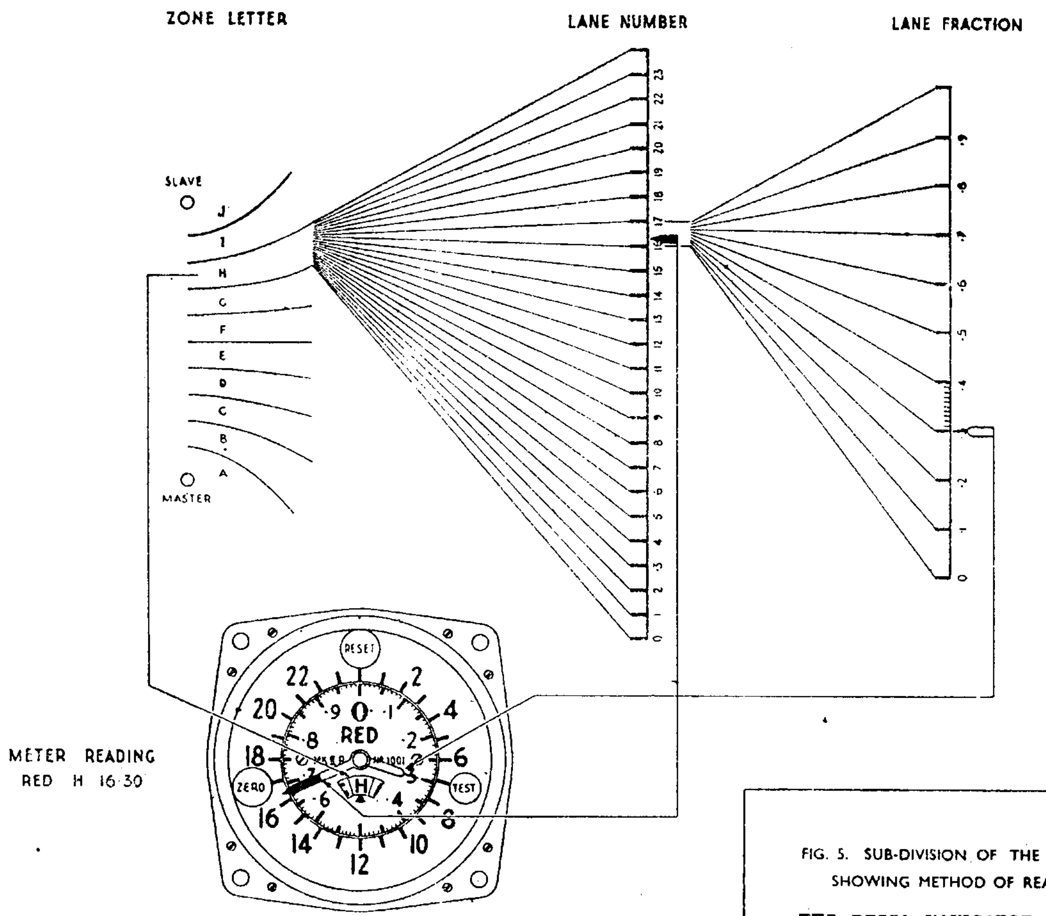


FIG. 5. SUB-DIVISION OF THE RED LATTICE PATTERN SHOWING METHOD OF READING DECOMETERS.

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pattern (which enable the receiver to determine a distance difference) repeat themselves every lane.

Thus receiver can tell with great accuracy what part of a lane it is in, but cannot by itself distinguish which lane of the pattern. A movement from one lane to another is, however, recorded because the fine decometer pointer then crosses the zero mark, and, being geared to the long pointer indicates an increase of one lane. Masters of Ships must, therefore, ensure that before they move away from dock or mooring the Decometer is switched on, and the Decca co-ordinates at the point at which they are docked or moored set up on the meters.

Should the ship go outside the coverage, then before it can re-employ the Navigator, it must establish itself within a zone and lane by other means, set these values up on the Navigator.

There is in hand a further development for the provision of a system known as *Lane Identification* which will completely remove the necessity for such a procedure.

Where, however, a Decca Chart is available, the Master should plot the position of his ship on this chart and then read off the Decca co-ordinates of that point. In doing this he must ensure that he is using a chart of a scale adequate to fix his position within the lane.

### Determining initial co-ordinates.

It is most important to set up the meters to the correct reading at the start since any error made will appear in all subsequent readings.

Wherever possible the co-ordinates should be set up in dock before leaving, as the system is of such accuracy that in part of the coverage half a lane is less than 250 yards, and an error in determining the exact position for setting up can alter the reading of the fraction pointer considerably.

The ships position should be carefully plotted on the chart and the Decca co-ordinates estimated to the nearest tenth of a lane.

If it is quite impossible to do this, the co-ordinates of a number of buoys which the ship will pass close to, should be determined and the meters set up at the first buoy, and subsequently carefully checked against at least three further buoys.

Once set up the set will function automatically, and apart from an infrequent check of " Zero " and " Test ", requires no further attention from the Master or his Officers other than to take readings at desired intervals. As the ship moves, so the Red and Green Decometers will automatically follow. The Red and Green Meters presenting continuously exact information of her position.

### Range, accuracy and coverage.

As the Decca system operates on frequencies between 85-130 kilocycles it is capable of giving signals of workable strength from transmitters of low power up to ranges of 1500 miles.

The following estimated accuracies are based on trials carried out over many weeks during the past two years, and under all kinds of weather and seasonal conditions.

| Distance from transmitter base line | Estimated maximum accuracy from any position lines | |
|---|---|---|
| | Day | Night |
| 50 miles | 10 yards | 20 yards |
| 100 — | 20 — | 50 — |
| 200 — | 40 — | 200 — |
| 300 — | 100 — | 500 — |
| 500 — | 200 — | |
| 1.000 — | 500 — | |

The Decca system provides a highly accurate navigational aid on a 24 hour basis up to a range of 300 miles from the base line. During the hours of day light the range will be increased to 1500 miles.

### Principle of operation of the system.

In the Decca system, the time differences are measured indirectly as phase differences in the waves received from fixed transmitters, which radiate pure unmodulated CW.

The Decca phase indicator is shown schematically in fig. 6. The amplified signal Va from transmitter A is fed in phase opposition to both pairs of diodes connected as phase discriminators. By itself, this signal would give equal and opposite rectified outputs, and the inputs to both DC amplifiers would therefore be zero. The signal from transmitter B is divided into two equal parts, Vb1 and Vb2 in phase quadrature (i.e., at 90 degrees) with one another.

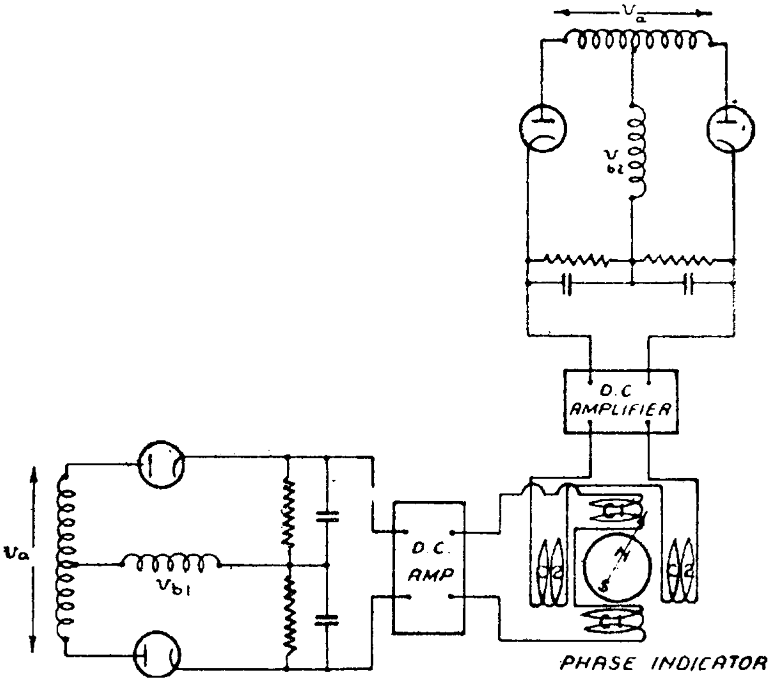

**Fig. 6**
Diagram of the Decca Phase Indicator.

Suppose Vb1 happens to be in phase with one half of Va (and therefore opposes the other half). This upsets the balance and causes DC to flow through coils C1 in the phase indicator. At the same time Vb2, being in phase quadrature with both halves of Va, effects both rectified outputs from the other discriminator equally. Their combined result is still zero and there is no current in coils C2. The moving element in the phase indicator is a magnetized disc which, in the conditions just described, sets itself along the axis of the C1 coils, and the attached pointer indicates O.

If now the ship carrying the receiver moves away from the in-phase position, the in-phase component of Vb1 starts to decrease while an in-phase component of Vb2 appears. The corresponding changes of current in the indicator coils cause the pointer to start rotating. When the phase difference of the B signal reaches 45 degrees, Vb1 and Vb2 are both 45 degrees out of phase with Va. The currents in C1 and C2 are therefore equal, and the pointer sets itself to 45 degrees, or 12 1/2 on the 100-division or lane fraction scale actually fitted. In a similar way, any phase difference from 0 to 360 degrees between the two incoming signals is shown.

To distinguish which lane one is in, the indicator meter is fitted with a train of gears. Every time the decimal pointer moves through 100/100 of a lane the main units pointer (see fig. 2) registers one lane on the outer scale and every time 24 lanes have been registered on the " Red " meter a new zone letter is automatically displayed. The Green meter similarly shows a new zone letter every 18 lanes and the Purple meter every 42 lanes. To prevent confusion Red lanes are always numbered 1-24; Green lanes, 31-48: and Purple lanes, 51-92. The table below shows the range of each indicating meter.

| Meter | Zone letter | Lane number | Lane fraction |
|---|---|---|---|
| Red ........... | A to J | 1 - 24 | 1 to 100 |
| Green ......... | A to J | 31 - 48 | 1 to 100 |
| Purple ........ | A to J | 51 - 92 | 1 to 100 |

The first difficulty in devising a practical realisation of the scheme is that the phase indicators can only work on signals of identical frequency, whereas if the transmitters all work on that frequency it is impossible to separate their signals at the receiver in to the channels necessary for feeding the phase indicators. This difficulty is neatly overcome by making the transmitters forming a pair work on the two different frequencies that have common harmonic frequency. Taking round numbers for the sake of simplicity, suppose A radiates 60 kc/s and B 80 kc/s. These signals are separately amplified in the receiver, and frequency multipliers extract the 4th harmonic of 60 kc/s. and the 3rd harmonic of 80 kc/s., giving 240 kc/s. in each case, for applying to one of the phase indicators. If station C transmits on 90 kc/s. a third amplifier in the receiver can be used to deliver its 2nd harmonic 180 kc/s., while an extra frequency multiplier at the end of the A amplifier supplies the 3rd harmonic of 60 kc/s., also 180 kc/s. to feed the other phase indicator. A block diagram of the whole receiver is shown at fig. 7. A fourth channel would be added for receiver designed for 3 slave system.

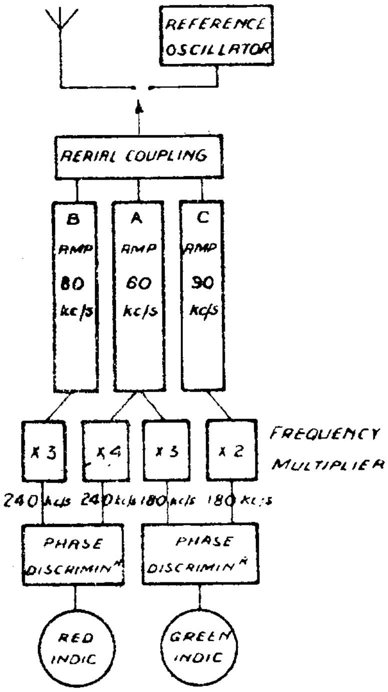

**Fig. 7**

Block diagram of the whole receiver.

The next problem is to ensure that the phase pattern of which fig. 4 is an example, is accurately maintained. This obviously necessitates the output of the two transmitters in any pair not only being the right frequencies at all times, but also invariably in phase within about 1 degree. Obviously this is quite impossible if they transmit independently : so one of them, say A, is the " Master ", and B and C are the " Slaves ". The 80 kc/s. transmitter at A is crystal controlled, and its signal is picked up at B on a receiver feeding a frequency divider, giving 20 kc/s. This frequency is doubled twice to supply a drive for transmitter B. Although its frequency is thereby bound to be 4/3rds that of A, the phase is liable to vary over many degrees due to slight changes in the tuning circuits and aerial. So a receiver, installed near B extracts the common harmonics, 240 kc/s from the signals put out by slave and master, and applies them to a phase discriminator, the DC output from which is used to control a reactor valve associated with the drive to the slave transmitter, on the same principle as automatic tuning correction in broadcast receivers. Transmitter C is similarly locked to 3/2 of the frequency of A.

The actual frequencies of the chain shown in fig. 4 are :—

Master ......... A : 85 kc/s. × 4
Red Slave ...... B : 113.3 kc/s. × 3 — 340 kc/s.

Master ......... A : 85 kc/s. × 3
Green Slave .... C : 127.5 kc/s. × 2 — 255 kc/s.

Purple Slave .... A : 85 kc/s. × 7
Master ......... D : 99.16 kc/s. × 6 — 595 kc/s.

To ensure continuity of service, duplicate transmitters are automatically brought into action in the event of failure.

The master station consists of an unmodulated C.W. transmitter with a standby channel and power supplies. The most suitable aerial is a 300 foot vertical radiator of standard design. A radial earth system is employed.

Each slave station is similar to the master station but contains in addition a loop aerial feeding a receiver. This receiver has a special control system fitted which enables the phase of the slave transmission to be very accurately synchronised to the master signal. By this means the stability and accuracy of the system is maintained locked without the need for employing operating personnel for phase control such as is necessary in the case of the Gee and Loran systems. Additional equipment is provided at master and slaves for lane identification purposes.

### Lane identification.

Two systems of " Lane Identification " are being developed. The first, on which successful trials have been carried out, was primarily intended for marine use and is not ideal for aircraft flying at high speeds close to the transmitting stations because the time required for identification, about 20 seconds, is sufficiently long for the aircraft to have travelled more than a lane. With this system lanes are identified by indications on the Decometers when special transmissions take place at fixed intervals. These indications take the form of two series of 10 " flicks " by the Decometer pointer. All the " flicks " may be in a clockwise direction, all in anti-clockwise direction or some in one direction and the remainder in the other. By noting the direction and counting the number of flicks up to the time they change direction and setting this information up on the simple calculator provided, group identification (actual lane in group of 12) is obtained. For example: 3 flicks clockwise followed on the second series by 5 flicks anti clockwise would, on the " Lane Identifier ", indicate lane No. 5.

The second system of " Lane Identification " which requires a somewhat more elaborate receiver and an additional meter provides direct meter indication of lane number every five minutes. This system has the obvious advantage for aircraft that the indication is instantaneous.

Both the above systems depend on extra transmissions from the ground stations, but no additional frequencies are used. Both provide accuracy to better than .2 of a lane so that positive identification is assured. But neither completely removes all ambiguity. In the first system, in the case of the Red pattern, one must know in which zone or group of 12 lanes one is situated and with the second system, in which group of 24 lanes (approx. 12°).

Additional to either of the above Lane Identification systems a means will be provided for identifying zones or groups of lanes. This is done by means of a frequency shift of the Master Transmitter, which will take place immediately after each series of Lane Identification transmissions. This indication is direct and instantaneous on the Decometers and used in conjunction with the proceeding Lane Identification eliminates all ambiguity enabling the Decometers to be exactly set whenever the instrument is switched on within range of a Decca chain.

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### International New Letters No. 3. The Decca Navigator.

A chain of stations known as the English chain has been erected with transmitter sites in the vicinity of the following localities :—

(a) Hertford " A " (master station on 85 kc/s.) ;
(b) Norwich " B " (slave station on 113.3 kc/s.) ;
(c) Lewes " C " (slave station on 127.5 kc/s.) ;
(d) Warwick " D " (slave station on 70.83 kc/s.).

The A.B. pair give Red readings which are interpreted by means of Red lattice lines on the charts. The A.C. pair give Green readings which are interpreted by means of Green lattice lines on the charts. The A.D. pair give Purple readings which are interpreted by means of

Purple lattice lines on the charts. These stations are now providing a continuous 24-hour service. Transmissions from stations A, B and C are monitored by a government station situated at Sheerness.

The monitor station provides a check on the accuracy of the system and any break in transmission or other failure will be promulgated to shipping through coast W/T and R/T stations.

Special receivers are now in production and available commercially from the Decca Navigator Co., London.

Marine Mark IV : 110 volts D.C., 90 watts; dimensions in inches : 15 1/2 × 15 × 8; weight : 31 1/2 pounds. Receiver operates on AB, AC and AD pairs of the English chain giving red, green and purple readings ;

Marine Mark III : 110 volts D.C., 70 watts; dimensions in inches : 18 × 16 1/2 × 8 ; weight : 27 1/2 pounds. This set operates only on the AB and AC pairs of the English chain giving red and green readings.

The following briefly describes the method of lane identification :—

1° The lane identification meter is shown at the top of figure 8. It will be seen that it has three scales and these are engraved on perspex rings individually illuminated in the colour corresponding to the meter or pattern to which they refer, i.e. Red, Green, Purple. This meter operates only when identification signals are being transmitted. Only one identification takes place at a time, and the other two patterns are temporarily shut down while this identification is in progress. The time taken is sufficiently short to avoid any risk of " lane slipping " on the meters associated with the patterns which are removed. It is intended that the lane identification transmissions will be made at frequent intervals, and a possible time schedule is

| | | |
|---|---|---|
| 8:00 — Red | 8:01 — Green | 8:02 — Purple |
| 8:05 — Red | 8:06 — Green | 8:07 — Purple |
| 8:10 — Red | 8:11 — Green | 8:12 — Purple |

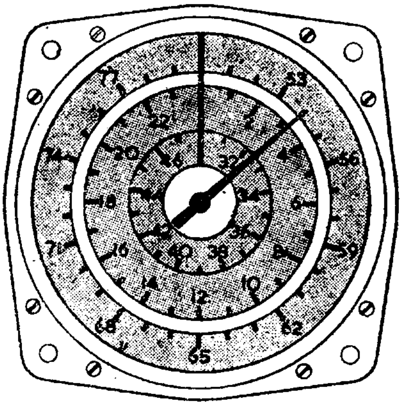

**Fig. 8**
Decca Lane Identification Meter.

2° When an identification transmission takes place, the appropriate scale of the identification meter lights up and the main pointer swings to the correct position on that scale. For example, at 8:00 the middle scale will light up and the pointer will swing to the position to which the units pointer on the red meter should be set ;

3° It is seen, therefore, that this identification is completely automatic and requires no operation on the part of the user except to read off the correct lane number when the meter is illuminated.

Subsequently as a result of scientific tests it has been decided to incorporate a vernier pointer which, operating as an integral part of the lane identification meter, provides a fine reading which has an accuracy six times that of the basic identification.

The British Ministry of Transport has approved the use of the system as an aid to general navigation up to 240 nautical miles from London in areas for which charts have been issued.

The estimated accuracy of the system is :—

| Distance from London | Accuracy | |
|---|---|---|
| | Day | Night |
| 50 nautical miles | 1/2 cable | 1/2 cable |
| 100 — | 1 cable | 2 cables |
| 200 — | 2 cables | 5 cables |

* * *