RESTRICTED

B.R.2435

TECHNICAL STAFF MONOGRAPHS

1939-1945

RADAR

1954

TECHNICAL STAFF MONOGRAPHS
1939-1945

RADAR

1954

Admiralty, S.W.1 .
30 January 1954

R.E. 0695/49
B.R. 2435
C.B. 3213 *Technical Staff Monographs 1939-1945--Radar,*

having been approved by My Lords Commissioners of the Admiralty, is hereby promulgated for information and guidance.

By Command of Their Lordships

CONTENTS

ILLUSTRATIONS

CHAPTER I
TECHNICAL DEVELOPMENT AND PRODUCTION
AN INTRODUCTION TO RADAR
ITS CAPABILITIES AND LIMITATIONS

RADAR is a system by means of which objects situated on the direct optical path can be detected irrespective of visibility, use being made of the fact that electromagnetic energy directed at an object is reflected from it.

The radar system can be put to various uses, but any particular radar equipment can be used efficiently only for the specific function for which it was designed. In this book only shipborne radar is considered, and airborne radar is not covered except for ancillary developments which function in conjunction with shipborne equipment.

Initially radar was designed for the sole purpose of giving long-range warning of the approach of aircraft. It was not long, however, before it was recognised that radar would be of value for other purposes, e.g., to provide the accurate range necessary for gunfire and for giving warning of the approach of surface craft, and sets were designed for such specialised functions.

Types of Radar Sets

Radar sets are classified according to the function they are designed to perform. The general capabilities of each class are described below.

WA (WARNING OF AIRCRAFT) SETS

These sets operate on metre wavelengths and give general long-range warning against aircraft. They give good results against medium and high aircraft, but poor results against low aircraft and surface vessels. Ranges of about 120 miles (about 200 miles with the latest sets) can be obtained against high-flying aircraft. A bearing accuracy of about two degrees is obtainable with the more modern equipments. The range and bearing discrimination are not good though usually adequate for general warning purposes.

A drawback to all sets of this category is that continuous radar coverage is not possible owing to unavoidable gaps in the vertical coverage; because of these gaps the echo from an aircraft varies in amplitude and sometimes fades completely. Some advantage, however, can be gained from this characteristic because the approximate height of approaching aircraft can be estimated by observing the variation of echo amplitude.

WS (WARNING OF SURFACE CRAFT) SETS

These operate on centimetre wavelengths and are designed to give the maximum possible range of detection against surface targets. Good results are obtained against low aircraft, but high aircraft cannot be detected. With the most up-to-date sets ranges against large ships can be obtained up to, and sometimes slightly beyond, the optical horizon. Thus, for best performance, it is advantageous to site the aerial as high as possible.

In general WS sets give better range and bearing discrimination than WA sets due to the shorter pulse length and narrower beam than the former normally have.

The bearing accuracy of WS sets is usually of the order of 1°-2°.

A high power WS set (Type 277) has been used to determine the height of aircraft within a range of about 25 miles. When the aerial is elevated the beam subtends a small angle in both vertical and horizontal planes, and thus angle of elevation of the aircraft can be determined in addition to azimuth bearing and range.

WC (WARNING COMBINED OF AIRCRAFT AND SURFACE CRAFT) SETS

These are designed to detect both surface craft and aircraft at all heights. In the design of these sets fair all-round performance has been achieved by sacrificing the optimum performances obtainable by WS and WA sets in their respective spheres. The following two frequencies have been used for these sets.

(a) One and a half metres (Type 291). This set was designed primarily for small ships. Compared with WA and WS sets, ranges are much reduced. As with the WA sets there are gaps in the vertical coverage, but at this frequency they are more numerous. Bearing accuracy is about 5°. Maximum range against aircraft is about 35 miles, and against a battleship about 17,000 yards.

(b) Ten centimetres (Type 293). This set was designed primarily as a target indicating set, i.e., to display all targets in the immediate vicinity. The latest equipment gives warning of aircraft at all heights from 200 to 20,000 feet up to a range of about 25,000 yards. The performance against surface craft approaches that of WS sets. Discrimination and bearing accuracy are likewise comparable with those of WS sets.

GUNNERY RADAR SETS

These are normally designed to form an integral part of their associated fire-control equipment. To be of value a gunnery set must be able to range on targets beyond the maximum range of the guns with which it is associated, and it must have good accuracy and discrimination in both range and bearing. Range accuracy depends largely on the design of the display unit. Bearing accuracy depends largely on aerial design, and, owing to topweight considerations in ships, better bearing accuracy is obtained at the higher frequencies.

The original gunnery sets operated on a wavelength of 50 centimetres. At this wavelength bearing discrimination was poor and it was not practicable to use an aerial giving the narrow beam in the vertical plane necessary to determine angle of elevation. In the later sets operating on the shorter wavelengths (10 and 3 centimetres) the bearing discrimination is far superior, and azimuth and elevation bearings can be determined to an accuracy of about +/-5 minutes.

Gunnery sets fall into the four following main categories.

(a) GS (Gunnery Surface) sets which are used for the control of main armament in battleships and cruisers, supplying range and azimuth bearing. The most recent development is an auxiliary set giving complete plan display of fall of shot round the target so that quantitative spotting for both range and line can be carried out in blind fire.

(b) GA (Gunnery Aircraft) sets are used for control of long-range H.A. armament in large ships and for control of both H.A. and L.A. armament in small ships. The early sets supplied only range and azimuth bearing; later sets supplied in addition angle of elevation.

(c) GC (Gunnery Close Range) sets are used for control of close range H.A. armament. Such sets are only required to range on targets out to about 8,000 yards. The original set, Type 282 operating on 50 cm., supplied only range and azimuth bearing. The later set, Type 262 operating on 3 cm., searches automatically for a target in a preselected space; when a target is picked up in the space thus searched the aerial ' locks on ' to the target and the set provides automatically all the necessary data.

(d) GB (Gunnery Barrage) sets are used for control of barrage fire of the main armament in cruisers and secondary armament in battleships, one set being fitted for each turret to be controlled. The present Type 283 is similar to Type 282.

Radar Displays

Two basic types of radar display were used during the Second World War, the ' A ' display and Plan Position Indicator (P.P.I.). From time to time variations of these two basic types were introduced.

The ' A' display was the original type used with British radar. In this display a trace, usually horizontal, was used on which echoes caused vertical deflections. The characteristics of echoes from different objects vary, and so the appearance of the echo on the ' A ' display could be used to a certain extent to classify the type of target. Thus, with a WA set the echo can give the operator an indication of the number of aircraft in a raid, and by noting the amplitude, an estimate of their height can be made.

In warning sets the ' A ' display has two main disadvantages: firstly the aerial must be stopped to read the bearing of any target, and secondly, if the radar has a narrow beam, there is a possibility that an operator may fail to detect for several sweeps the echo from a fresh target. For these reasons the ' A ' display is obsolete as the main warning display, being displaced for this purpose by the P.P.I.

The advantages of the P.P.I. over the ' A ' display are that the relative positions of all targets can be readily seen and that the aerials do not have to be stopped to make a report of the target. The use of the P.P.I. enables a higher rate of reporting to be maintained and there is greater reliability in the detection of fresh targets. On the other hand, as the echoes on the P.P.I. are uniform in brightness, it is not possible to classify targets from the appearance of the echo as can be done with the ' A ' display, although land can usually be recognised by its irregular shape.

A development of the P.P.I., the Skiatron, is often fitted with WA sets. The skiatron presents a picture similar to that of the P.P.I. except that the picture is much magnified and is projected on to a screen, the screen itself being suitable for plotting.

Modern warning sets whose main operational display is the P.P.I. are often fitted with an auxiliary type of display called the Sector display (or, sometimes erroneously ' R ' display). The Sector display has the advantages of the ' A ' display without the disadvantage of having to stop the aerial to observe a target. By means of a Sector Selector the echoes on any one bearing can be displayed momentarily on an ' A ' display as the aerials sweep through the selected bearing, giving as it were a " photographic still " which lasts for about 6 seconds. The Sector display has many applications such as height-finding, classification of target and accurate ranging, for the echo characteristics can now be examined while the set continues to carry out all-round searching.

As gunnery sets are normally required to give accurate range and bearing of a target whose approximate position is already known, the ' A ' display, or some modification of the ' A' display, is generally all that is required with these sets. An exception is the ' B ' display which is used for splash-spotting for L.A. firing. The ' B ' display gives a plan display of a small pre-selected area, say, 2,000 yards long by 20° wide.

Accuracy of Radar

The accuracy of radar range depends largely on the accuracy with which the operator can read off the range of the echo on the display. This in turn depends on the steepness with which the front edge of the pulse rises (the steeper the rise of the pulse the more clearly defined is the leading edge of the echo, and therefore its range), and what is of greater importance, on the amount by which the trace itself is expanded or magnified (the greater the expansion of the trace the more easily can the operator compare the echo with the range scale). In modern equipments it is usual to expand only a short portion of the trace, the operator being able to select the portion that is to be expanded. The range accuracy of displays varies from about 1 mile for WA sets to about 10 yards for the latest gunnery sets.

The bearing accuracy, on the other hand, is largely dependent on the aerial design; in general, the narrower the beam of radiation the more accurate is the reading of bearing. The most accurate bearing is obtained, however, by the use of the beam-switching system, in which case an ' A ' display or meter display must be used. If there is no beam-switching, then the bearing can be read from either an ' A ' display or P.P.I., the latter giving a slightly more accurate reading.

Factors Affecting Performance of Radar

A number of factors affecting the performance of radar are explained below, and they must always be borne in mind.

GROUND WAVE

This obscures the early part of the trace so that no echoes from targets within a certain distance of the radar can be detected. The extent of the ground wave is a function of the pulse length; in general, the shorter the pulse length, the closer can targets be followed by radar.

MAXIMUM RANGE OF DETECTION

Under normal conditions radar cannot detect objects much beyond the optical horizon and this limits the detection range against ships and low-flying aircraft. The range of detection of aircraft above the optical horizon is a function of the power output and overall sensitivity of the set.

The range of detection is also affected by the inclination of the target, a better response being received from a beam-on target than from an end-on target.

IRREGULARITY OF THE PLOT OF A TARGET

This arises from the combined inaccuracies of range and bearing. When the plot is irregular several readings of range and bearing are required before the target's course and speed can be accurately deduced. Gunnery sets giving a very accurate range and bearing give a good plot more quickly than warning sets.

DISCRIMINATION

The range discrimination and bearing discrimination jointly largely determine to what extent it is possible to distinguish between adjacent targets; in the extreme, the echo from one target will obscure the echo from another. The best discrimination is obtained by a set which has a narrow beam and a short pulse length. On the display the short range scale gives better range discrimination than the long range scale.

UNWANTED ECHOES

These are obtained from time to time, and they may confuse the radar display and impede reporting. The principal unwanted echoes are described below.

(a) Side echoes, which are caused by subsidiary beams of radiation. A large target at close range may give rise to several echoes on different bearings due to such subsidiary beams. Aerial siting may affect these subsidiary beams though they are usually unavoidable except at very high frequencies and using large aerials.

(b) False bearing echoes, which are caused by reflections off own ship's superstructure or rigging and are worse with high-power centimetre sets.

(c) Land echoes, which tend to obscure echoes from other targets. Land echoes are particularly troublesome in the case of sets having either a wide beam or subsidiary beams of radiation.

(d) Double reflection, which is most likely to occur at close ranges using a high-power centimetre set; a single target gives rise to two echoes, one at twice the range of the other.

(e) Rainclouds and cold fronts, which sometimes give echoes rather like large land masses.

(f) Birds, which can give echoes of a weak and fluctuating nature.

(g) Wave-clutter, which is caused by reflections from waves. The resulting confused echoes, or clutter, can extend out to several miles on the trace on a rough day in the case of a high-power centimetre set. The presence of clutter makes difficult the detection of nearby targets.

ROUGH WEATHER

The performance of radar, especially of WS sets, may be adversely affected by rough weather.

(a) The roll and pitch of the ship tend to lift the radar beam clear of the horizon and thus reduce the performance against surface craft. This is countered either by designing the aerial to give a broad vertical beam or by stabilising the aerial.

(b) Heavy swell makes the detection of small targets difficult due both to the excessive clutter on the trace and to the fact that the swell may at times actually obscure the optical line of sight. This can be alleviated by the use of a device to reduce the clutter on the trace.

ATMOSPHERIC CONDITIONS

The performance of radar sets, especially the centimetre sets, may differ markedly from normal under certain atmospheric conditions. Such conditions give rise to the phenomenon of anomalous propagation. When anomalous propagation occurs the range of detection against surface craft may be greatly increased or, less commonly, reduced. With the present state of knowledge it is not possible to do more than to say in what regions and at what seasons of the year anomalous propagation is likely to occur.

Interference by W/T and Voice Transmissions

W/T and voice transmissions, especially in the higher frequencies, in own ship or in the vicinity, may cause serious interference to the radar. This trouble can be alleviated by choosing a suitable communication frequency and, occasionally, by resiting the communication aerials; sometimes special filters in the radar aerials feeder have proved efficacious. Equally, radar can cause serious interference with communications in own ship. To reduce such interference a device known as a radio interference suppressor is fitted to most communication receivers.

Interception of Radar Transmissions

Radar transmissions can be intercepted, and D/F'ed in the same way as W/T. It is, however, much less 'dangerous' than W/T because of the very short wavelengths employed and the fact that the energy is concentrated into a directional beam instead of being an all-round transmission.

Radar Countermeasures

Certain countermeasures can be adopted against radar. The principal countermeasure is jamming, i.e., deliberate radio interference by the enemy; this confuses the radar display making it difficult to detect echoes through the jamming signals. Jamming only occurs when the radar aerial is trained in the direction of the jamming transmitter. "Window" is produced by a 'cloud' of strips of metal foil, cut to a length corresponding to the wavelength of radar set; this 'cloud' obscures a portion of the radar trace on the particular bearing. Various Radar Decoy devices have been used, the echoes from which are intended to distract the attention of the operator from more important targets or to obscure the target echo completely.

Maintenance of Radar Equipment

The radar set is a complicated instrument, and as such it is important to realise it requires regular inspection and servicing. If full confidence is to be placed in radar the possibility of complete breakdown, or even a deterioration in performance, must be reduced to a minimum. And this can be achieved only if the services of specially trained maintenance staff are constantly available.

Radar should not be considered purely as an automatic device. To obtain the best results operators must be thoroughly familiar with the sets they have to operate; this can be achieved only by making the operators use their sets at regular and frequent intervals. If the best use is to be made of all the radar fitted it is essential that the users of radar information should be well acquainted with the capabilities of radar and the various factors that influence performance.

WARNING RADAR

Naval warning radar sets can be divided into two groups, sets operating in the frequency range 40 to 200 Mc/s, and sets operating in the frequency range 3,000 to 10,000 Mc/s. During the Second World War there was a sharp division between the two groups in the development of aerial, transmitter and R/F receiver techniques, though to a considerable extent the development of modulator, receiver I/F and display techniques was common to both groups. The information provided by the two types of sets was complementary; sets in the 40 to 200 Mc/s band, known as the metre wave sets, provided early warning of aircraft, while sets in the 3,000 to 10,000 Mc/s group, known as centimetre sets, were put to a variety of uses which embraced warning of low-flying aircraft, surface warning, accurate height-finding and target indication.

Metre Wave Development

Development of radar before the Second World War was concerned with the one object of providing some means of detecting aircraft at a range which would give from 10 to 20 minutes warning of their approach. It was known that high-frequency radio waves are reflected from aircraft, and though it was not known what frequency actually gave the best reflection it was believed that the longer wavelengths were more efficient. The choice of frequency was, however, largely determined by consideration of the type of aerial required. It was necessary to determine the bearing of the aircraft and it was decided to use a directive beam from a rotatable aerial array. As the size of the aerial array which could be mounted in a ship was limited by considerations of weight and windage, a frequency of 39 Mc/s was considered to be the lowest frequency compatible with a suitable design of aerial. Also, transmitter and receiver valves for this frequency had already been developed, making possible the high peak-power pulse transmitter and the sensitive receiver necessary for radar.

The characteristics of the first naval warning radar, Type 79, were as follows:

> The peak power output was 70kW with a pulse length variable between 8 and 30 microseconds.
>
> The echoes were displayed on a range-amplitude display, on which the range of the target was read off against a scale calibrated in miles.
>
> Bearing was determined by rotating the aerials and setting them in the direction which gave maximum echo amplitude; the target bearing could then be read off an aerial bearing indicator.
>
> A more accurate estimation of bearing could be obtained by noting the bearings for zero signal on each side of the echo bearing and taking a mean of these two bearings, and this process was known as bracketing

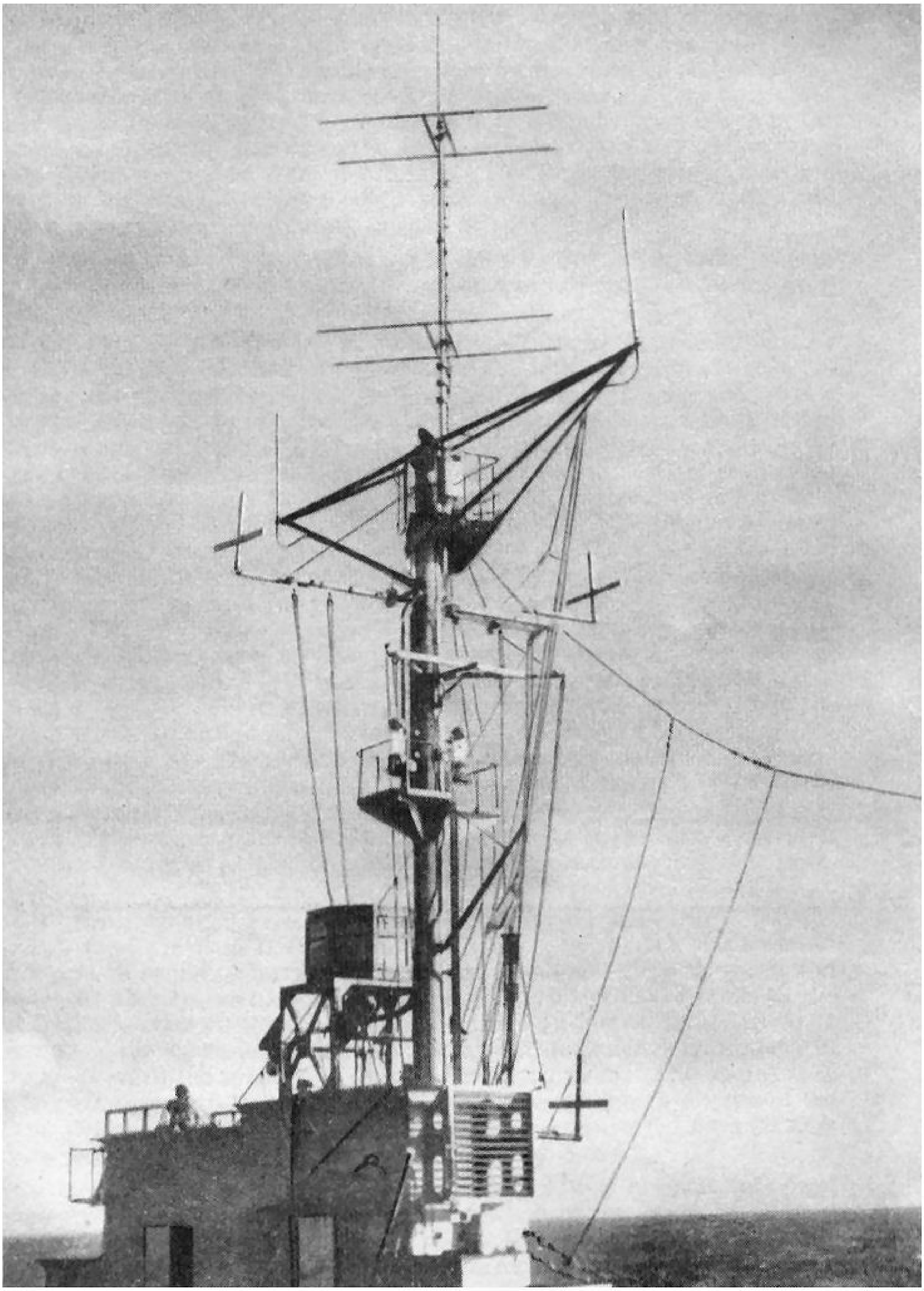

Figure 1. Type 79 aerial

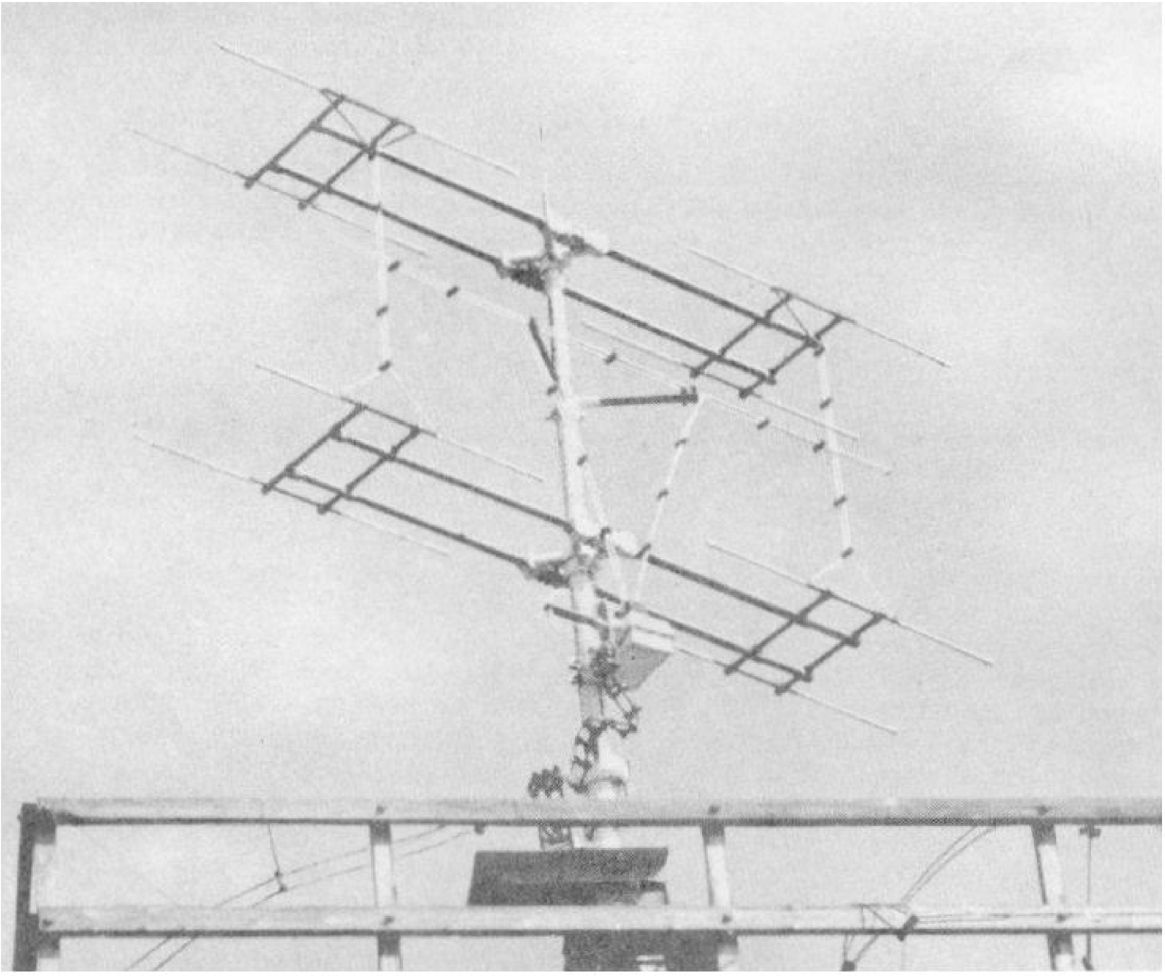

Figure 2. Type 281 aerial

The aerial developed for this set was of importance because it served as a pattern for other metre wave aerials. A photograph of the aerial is shown in *Fig. 1*. The aerial dipoles were mounted on a pole-mast which could be rotated. This array was eminently suitable for shipborne use since it could be conveniently mounted at the masthead, thus giving a clear field of view in all directions. It was also of a light type of construction and had small wind resistance. Separate identical aerials were used for transmission and reception, one being mounted at each masthead. A selsyn transmission system was used to rotate the aerials, both being driven from a hand-turned selsyn in the radar office. Open-wire feeders to the aerials were used, the last section being flexible giving the aerials 400° of rotation. The aerial horizontal radiation pattern, which was broad by modern standards was, however, sufficiently directive to give a bearing accuracy of some 5° on a target.

Only three of these sets were fitted in the Navy by September 1939. One of them was fitted in H.M.S. Curlew, a cruiser specially adapted as an anti-aircraft ship.

Though Type 79 achieved the prime objective of detecting enemy aircraft in time to warn the fleet, the further possibilities of radar were quickly realised. The next stage of development was the provision of accurate range and bearing of the target in order to direct the fire of anti-aircraft guns at targets within some seven miles of the fleet. Accurate ranging was fairly easily achieved by the addition of a special ranging display to the Type 79, the set then being known as Type 279. It was considered, however, that accurate bearing could not be achieved on this frequency with a shipborne set. The use of a switched beam technique was considered essential to obtain the necessary bearing accuracy without appreciably increasing the aerial size, and this could only be achieved by developing a set on a much higher frequency. The frequency chosen, 90 Mc/s, was considered to be the lowest frequency for which a satisfactory aerial incorporating a switched beam could be developed. The new set was known as Type 281 and its aerial, which was similar to the Type 79 aerial, is shown in Fig. 2. The transmitting aerial was fed symmetrically, but the receiving aerial had beam-switching applied. By this means a bearing accuracy of +/- 1/2 degree was obtained. The use of this higher frequency resulted in an inherently narrower azimuth beam width, which in turn increased the gain of the aerial system. This reduction in azimuth beam width was of advantage since it increased the discrimination of the set against targets at the same range, but of different bearings. It also improved the bearing accuracy without beam-switching to 2 degrees.

One very important characteristic of metre wave radar is the vertical coverage diagram. It was realised at the inception of radar development that an interference pattern would be formed by reflection of radiation from the surface of the sea. At 43 Mc/s, and with the radar aerials 110 feet above sea level the path difference between the direct path and the path formed by reflection at the surface of the sea varied from practically zero at maximum range to about 10 wavelengths when the target was directly above the radar. This meant that with aircraft closing the set the received signal passed through a series of ten maxima and minima. A vertical coverage diagram, constructed for a 90 Mc/s set with an aerial height of 120 feet, is shown in *Fig. 3* overleaf.

With metre wave sets, first detection of an aircraft is normally obtained somewhere on the contour representing the bottom of the first lobe. *Fig. 3* has plotted on it this lowest contour for the 43 Mc/s set with an aerial height of 120 feet. Comparison of the lowest contours for the two sets shows that the increase in frequency from 43 to 90 Mc/s affected the range of the air warning in some respects. The detection range on aircraft flying at heights less than the height of the tip of the first lobe was improved but high cover was sacrificed,

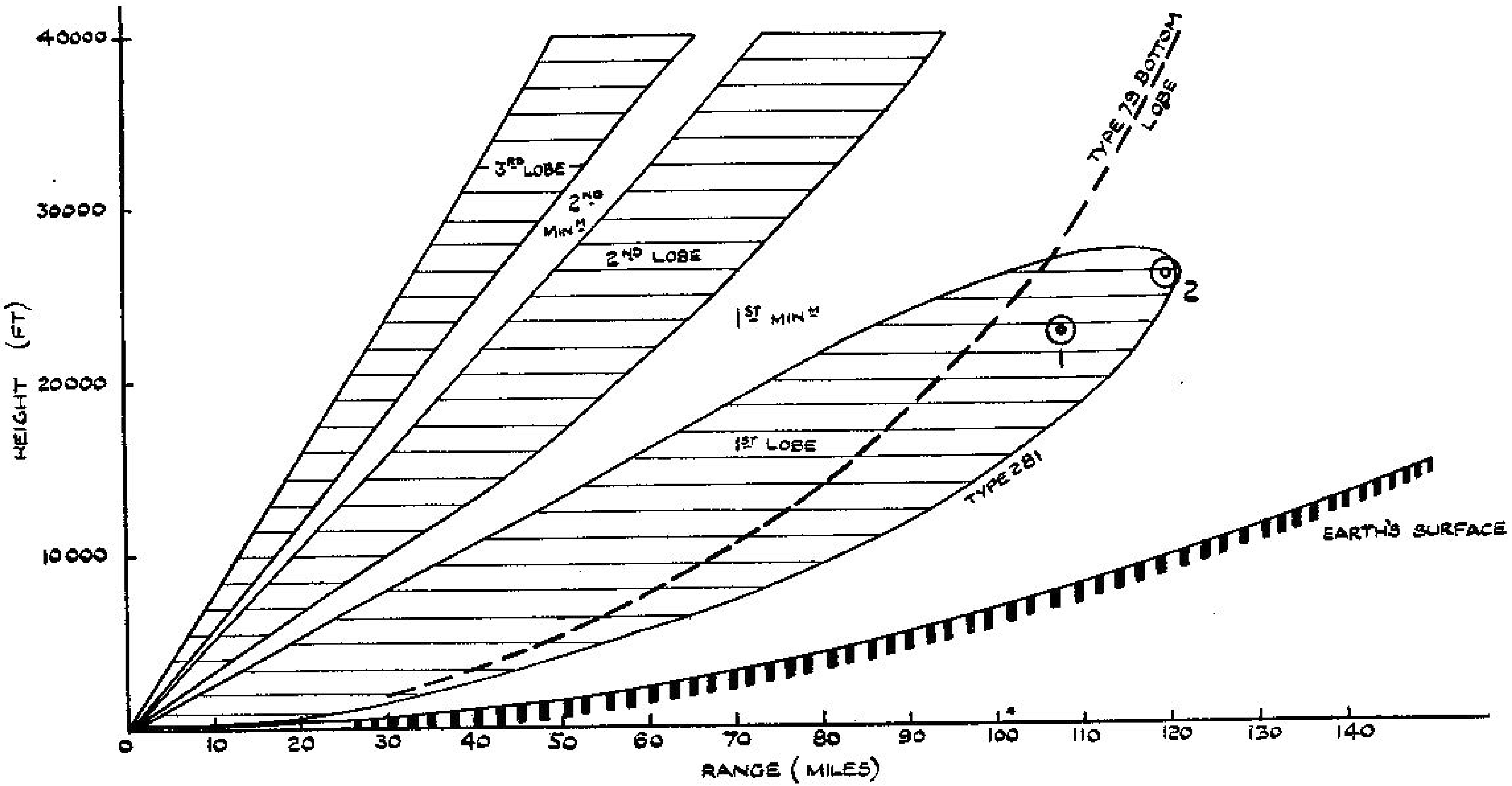

Fig. 3. Type 281—coverage diagram

and aircraft could fairly easily fly over the top of the first lobe, not being detected until reaching the second lobe at a very much reduced range. This situation was further aggravated by the use of beam-switching which reduced the effective sensitivity of the receiver aerial. With the introduction of the 600 Mc/s series of sets for fire control which made the provision of fire-control facilities on early warning radar redundant, the beam-switching facility on the 90 Mc/s aerial was removed.

Both of the air warning sets described so far were only suitable for installation in large ships, of the size of cruiser or larger. They required transmitting and receiving offices of some size. In their original design both these sets required two masts to carry the aerials; later, common T and R switching was introduced so that one aerial could be used both for transmission and reception. This modification permitted the fitting of two air warning sets in some of the larger ships: It was, however, necessary to provide air warning for small ships. Sets had to be developed with lighter aerials and utilising considerably less offlce space. Equipments were developed on 214 Mc/s for this work. An early aerial is shown in Fig. 4, in which the aerial was not rotatable but the ship was swung to face the direction which it was required to search. This set, Type 286, employed beam-switching on the receiving aerial. Type 286 was later replaced by Type 291, having an aerial which was simply a scaled down version of the 90 Mc/s aerial. In order to reduce topweight, common aerial working was developed for these sets.

Surface Warning Equipment

Although the main purpose in view for radar development up to and during 1940 had been the provision of adequate air warning, the value of being able to detect surface vessels had not been forgotten. Now the 43 Mc/s set did not yield any useful range on surface craft, but the 90 Mc/s set with its higher frequency and greatly increased transmitter power -- 350kW peak as compared with 70kW peak -- did provide useful ranges. At 90 Mc/s, however, the performance decreased rapidly as the target size decreased, a range of about 10 miles being possible on a cruiser whereas the range on a trawler was only about four miles. It can be shown that, in general, the shorter the wavelength of the radar the greater is the field strength near the surface of the sea.

In the autumn of 1940 the problem of detecting small surface targets became acute. Very high priority was therefore given to the production of a radar set which would give warning of approach of a surfaced submarine. The sets already developed on the metre-wave band were not suitable for the detection of very small targets on the surface and it was considered that the best solution would be obtained by use of the highest possible frequency. Because development had to be completed as quickly as possible a frequency of 3,000 Mc/s, which had recently been made available for radar owing to the development of the resonant cavity magnetron, was chosen.

Two development programmes were taken in hand simultaneously. The first, a short-term programme, utilising all existing information, was to develop and produce within six months a 3,000 Mc/s set which could be fitted on convoy escort ships. The second, a long-term programme, aimed at developing valves, aerials and a modulator capable of giving a high-power set in the centimetre waveband.

The set produced under the short-term programme (Type 271), used the original type of resonant cavity magnetron as the transmitting valve, which, with 1 1/4 microsecond pulse, gave a peak power output of 5kW. The use of this very high frequency made it possible for an aerial to be designed giving a very directive beam. It was, however, necessary to develop an aerial system with a wide beam in elevation to compensate for the roll or pitch of the vessel, but with a narrow beam in azimuth to give accurate bearings and good bearing discrimination. The form of aerial chosen was a dipole fed, metal parabolic reflector of the "cheese" type. To ensure that the maximum energy was " focused " by the parabolic cheese, a small dipole reflector was fitted in fronts of the radiating dipole. A photograph of such an aerial is shown in *Fig. 5*. In Type 271, separate, identical, aerial systems were used for transmission and reception, the two cheese aerials being mounted one above the other.

In order not to sacrifice too much performance due to the losses in the coupling cables, the attenuation at this frequency even in the best cables available being high, it was necessary to mount the transmitter and the early stages of the receiver immediately behind the aerial *(see Figs. 6 and 7)*. In order to make the whole aerial system, with transmitter and receiver, weatherproof, the whole assembly was placed inside a lantern fitted with perspex windows.

Although the transmitter power available in this set was low compared with that of the metre-wave-band sets, the trials of the first set proved it capable of detecting submarines at useful ranges. The low transmitter power was to a large extent offset by the very large aerial gain obtainable by the use of parabolic reflectors.

A demand arose for the installation of a set in the larger fleet units to provide general surface warning as well as anti-submarine protection. Because the roll and pitch of the large ship is not so serious as in escort vessels. it was decided to use an aerial system with a higher gain for this application. Instead of "cheese" type aerials, two 3-foot diameter paraboloids placed side by side were used. The performance of the set, known as Type 273, was further improved because it was possible to mount it higher above the water than in escort vessels.

While the development of a new surface warning set on 3,000 Mc/s was under consideration a new magnetron became available. In this valve the efficiency had been increased by strapping of the segments. This new magnetron made possible the design of a transmitter of some 90kW peak power.

As the new set, Type 271Q for small ships and Type 273Q for large ships, was wanted as a direct replacement for the original set it was necessary to design it to occupy the same space. The aerials were identical with those used previously; a front view of the Type 273Q aerial is shown in *Fig. 8*. Owing to the increased transmitter power, however, the use of a cable feed to the transmitting aerial became impracticable. The transmitting aerial was therefore altered to a waveguide feed with a horn acting as radiator at the focus of the mirror. This was the first use of waveguide technique in naval radar.

The final model of the new surface warning set, using the same size of aerials, was capable of ranges on surface targets 50 per cent greater than the set it was replacing. Operational experience had shown, however, that even in large ships the roll of the ship could significantly diminish the performance of the set. It was therefore decided to fit a simple form of stabiliser to the paraboloid aerials to stabilise them in elevation along the line of sight.

Low Air Cover

Controlled interception of fighters, using radar to give an instantaneous position of both the enemy and friendly aircraft, was an operational technique that had been firmly established both on shore and at sea by 1943. There was, however, one fundamental weakness in the radar cover provided by the metre-wave air-warning sets: insufficient warning of approach of low-flying aircraft.

As shipborne radar is limited to a maximum aerial height of about 150 feet no appreciable improvement in detection ranges of low-flying aircraft could be obtained using metre-wave equipment. Attention was therefore directed to centimetre waves. Some trials of the 90kW 3,000 Mc/s surface warning set had shown that it was possible to detect large low-flying aircraft at useful

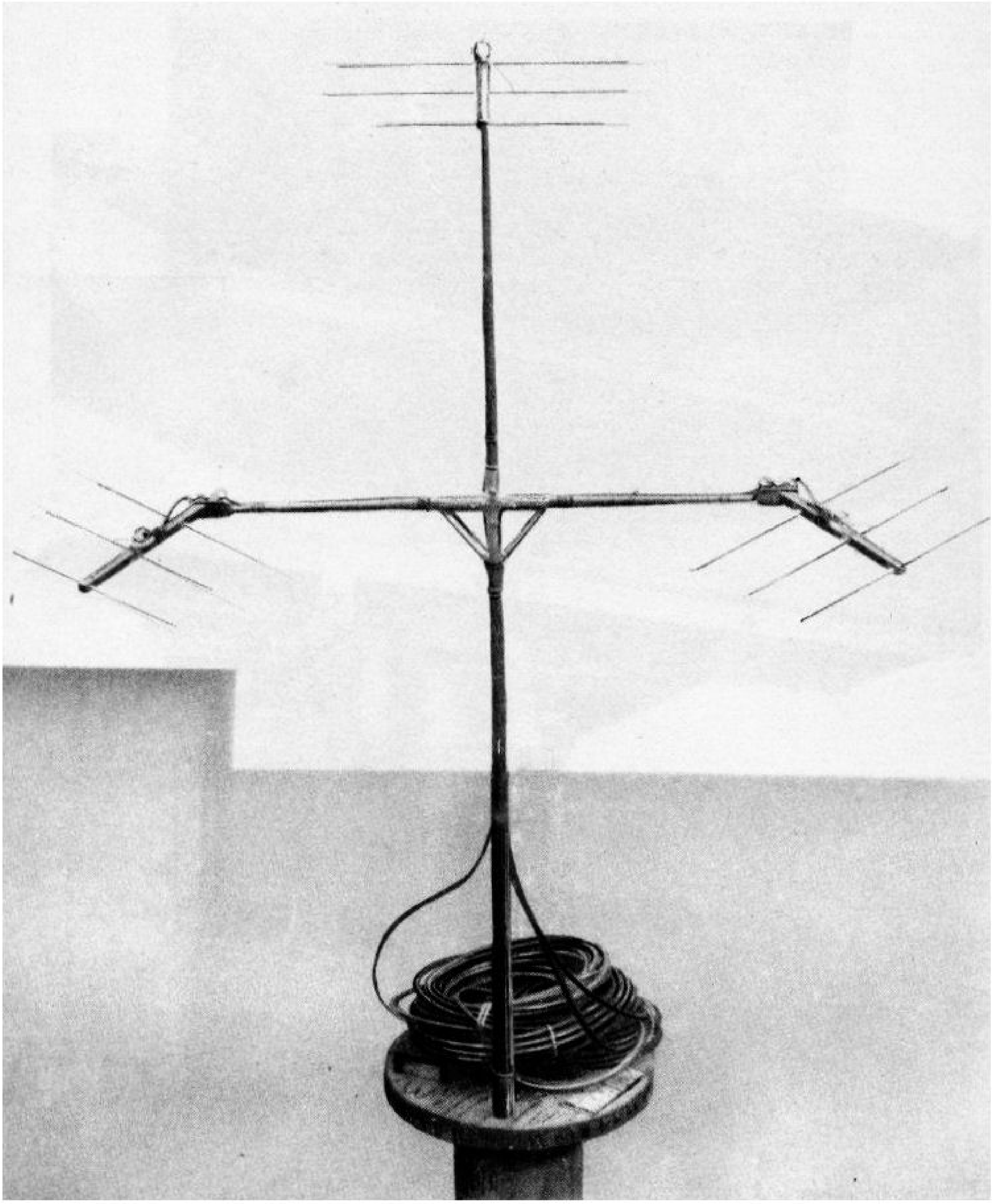

Figure 4. Type 286 aerial

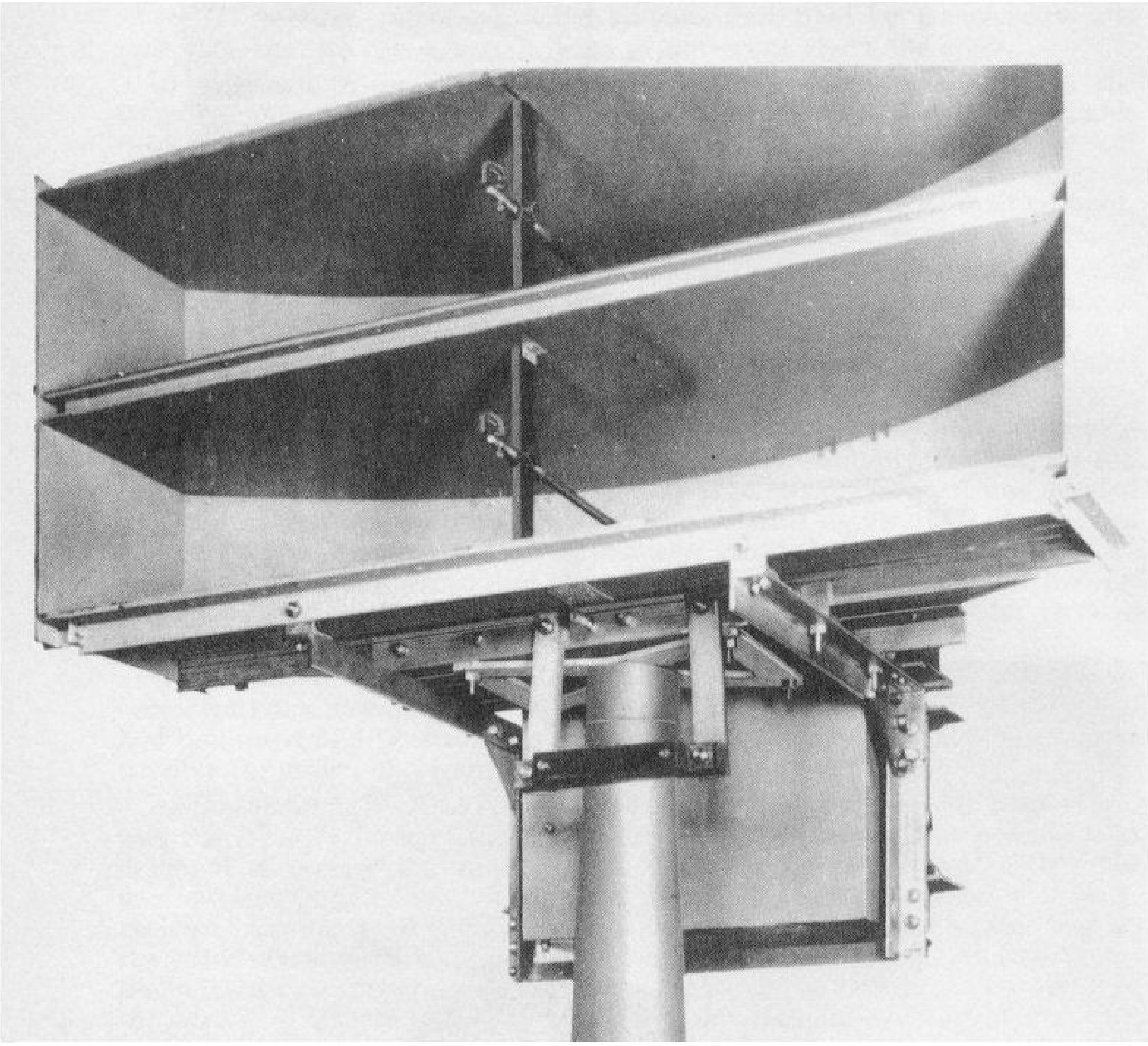

Figure 5. Type 271 aerial

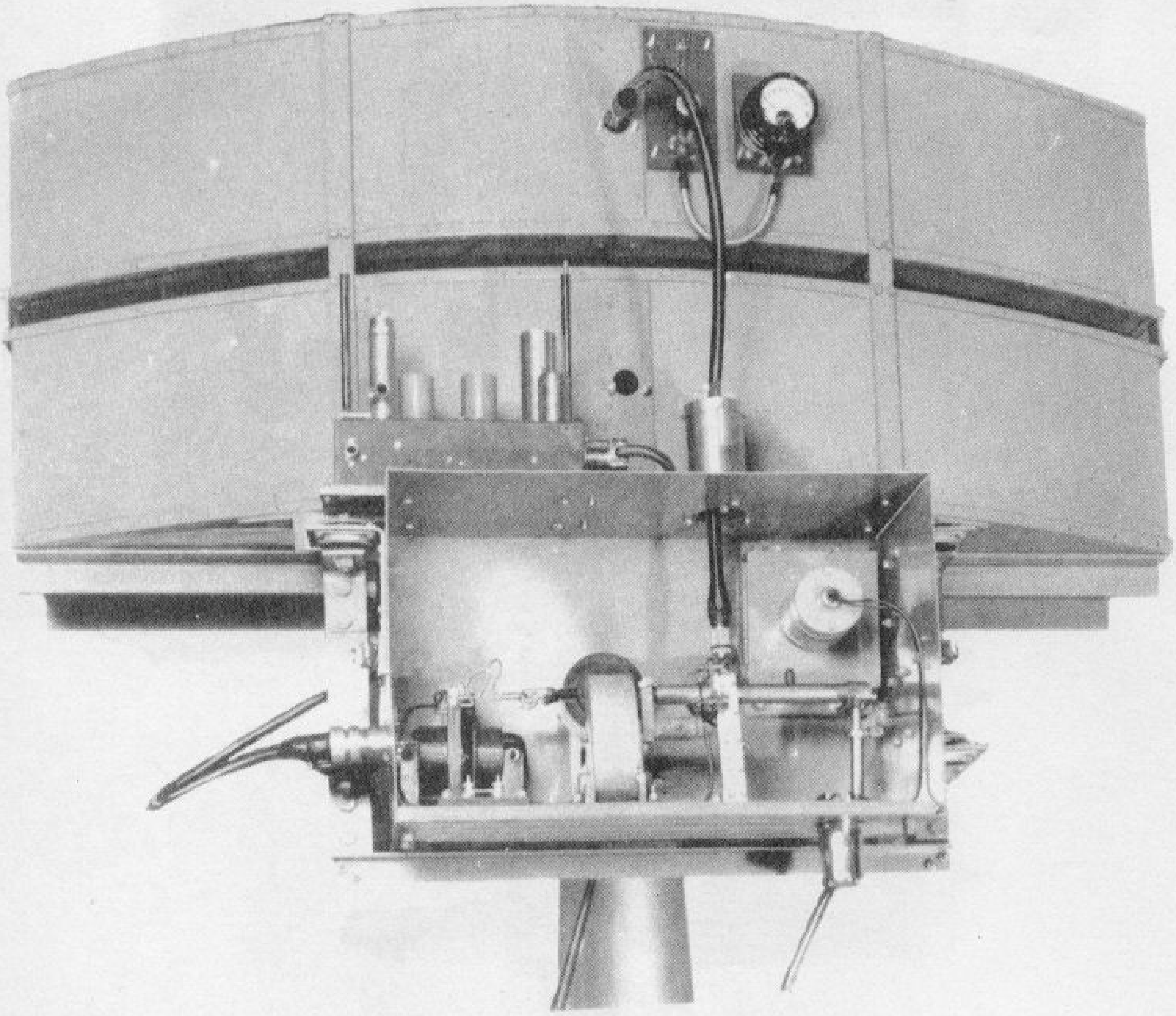

Figure 7. Type 271 transmitter

Figure 8. Type 273Q aerial

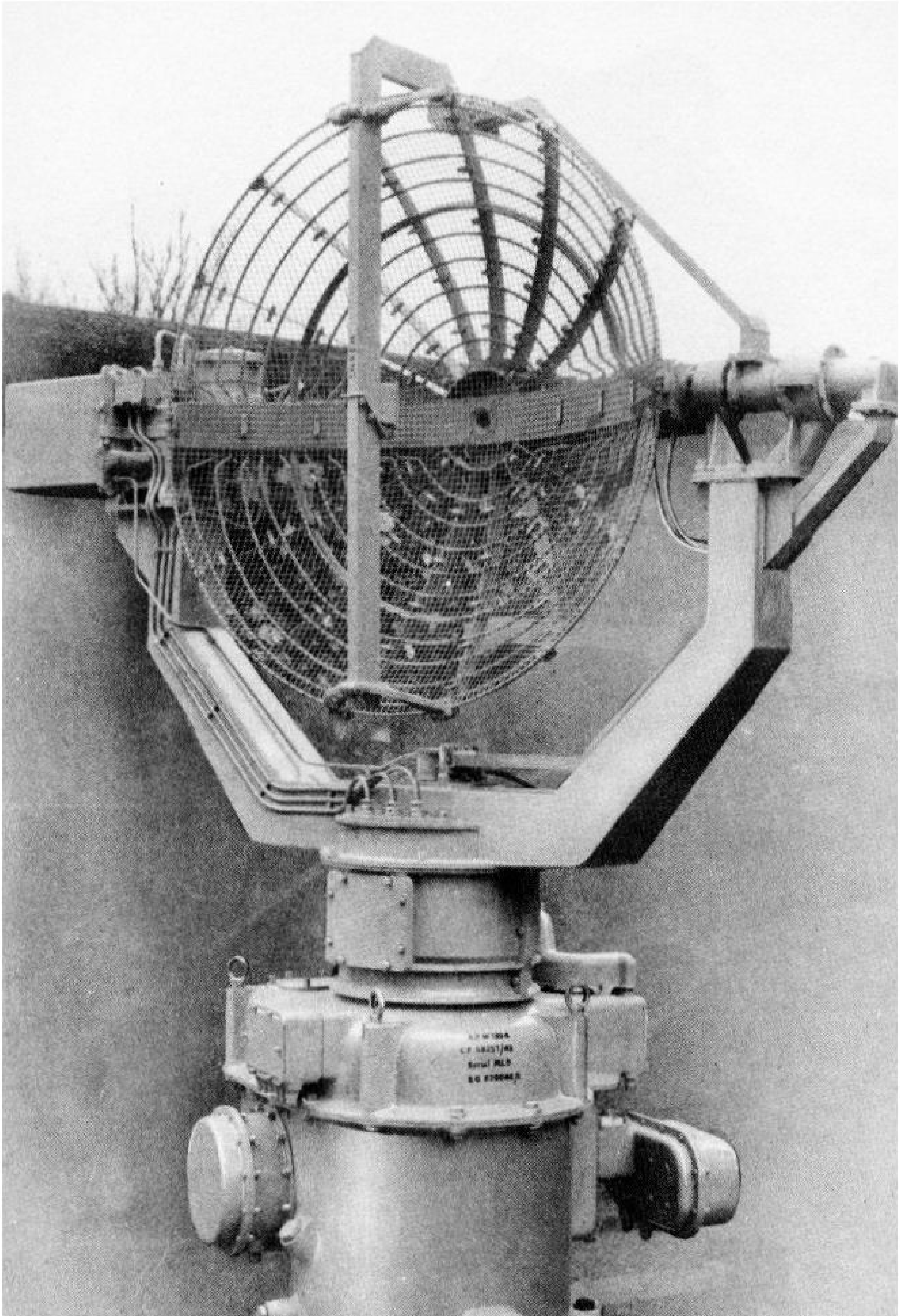

Figure 9. Type 277 aerial

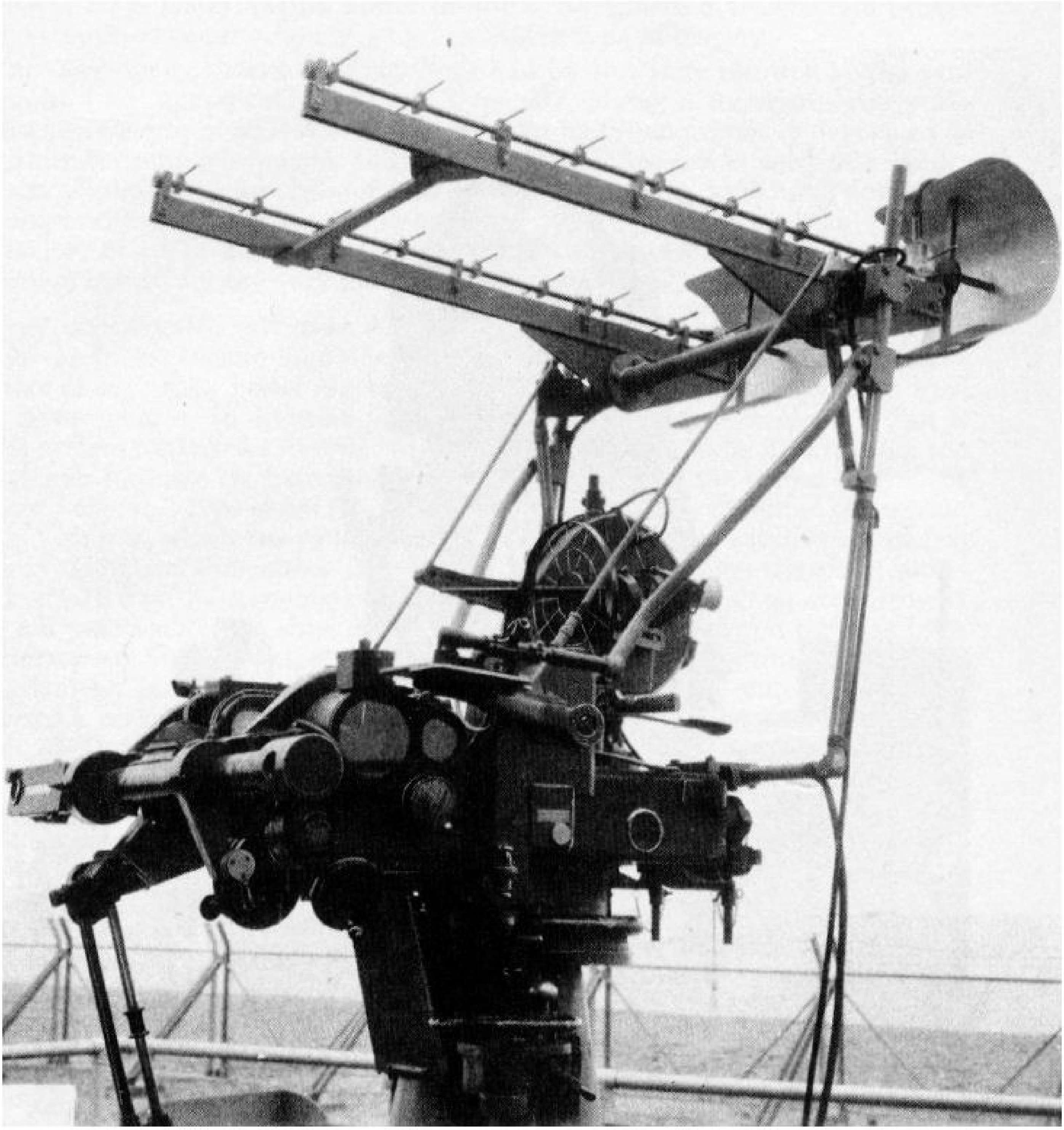

Figure 10. Type 282 aerial

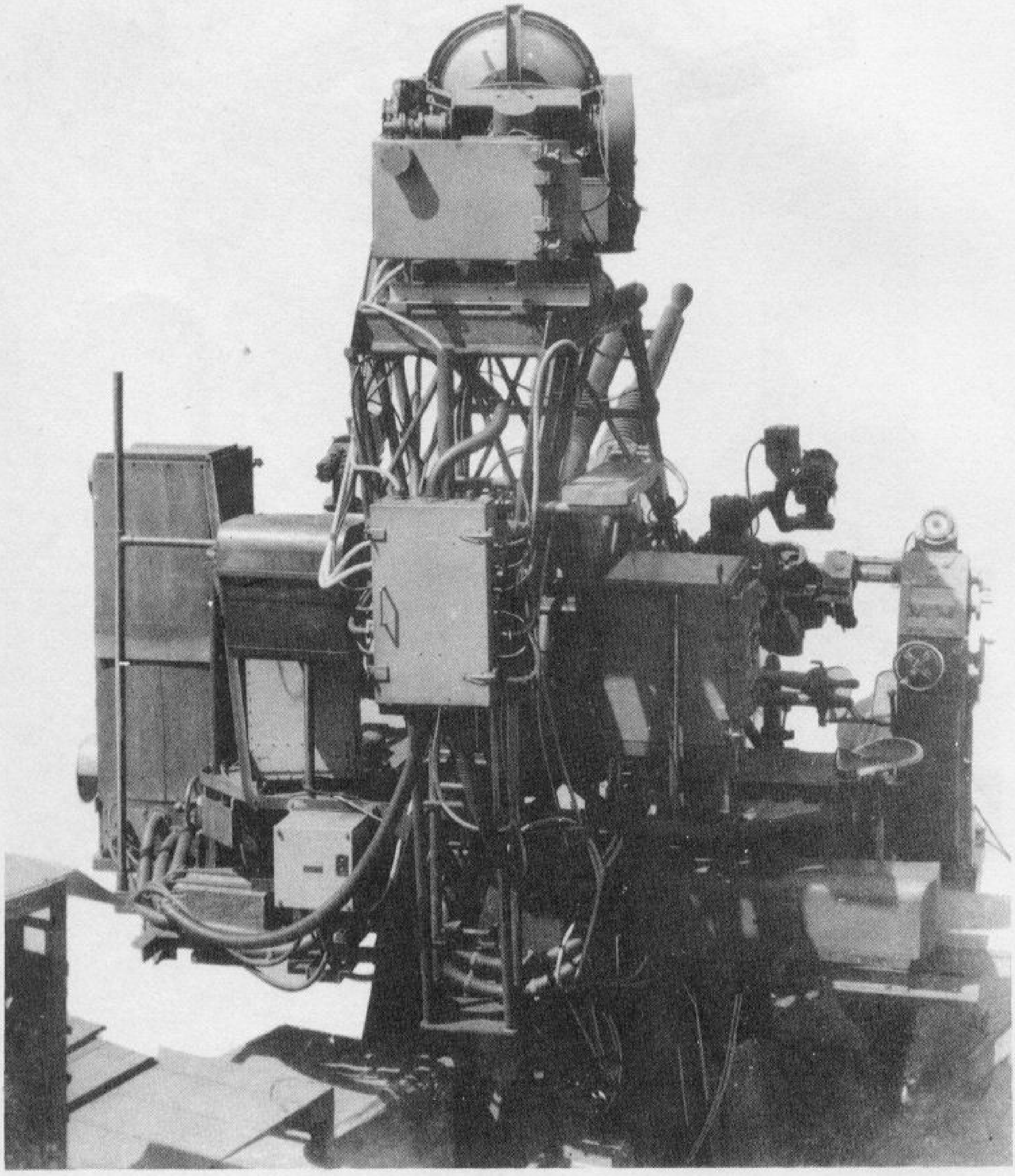

Figure 11. Type 262

ranges. It was, however, very difficult to locate the aircraft using the range-amplitude type of display unless the bearing of the aircraft was known. These trials showed that two improvements were necessary to give a satisfactory low-air-cover set; firstly, higher power in order to improve first-detection ranges and, secondly, the provision of a more suitable type of display.

The development work on 3,000 Mc/s had by this time resulted in the production of an equipment, known as Type 277, giving a 2-microsecond pulse with a peak power of 500kW. This equipment had been primarily developed as a surface-warning equipment and, in the first instance, was used in a trailer installation intended for harbour guard duties. Later, an aerial was developed for shipborne use. Trials of this equipment showed that the Plan Position Indicator, fitted to a naval set for the first time, overcame the difficulty of detection caused by the very narrow beam.

Very considerable advances in waveguide technique were also stimulated by the problems encountered during the development of this set. With transmitters of such high power the only type of aerial feeder which could be used was a waveguide. In addition, it was decided to develop a common T and R aerial system for this set in order to enable larger aerials to be fitted within the limitations imposed by space and weight in a ship. For the trailer equipment a large "cheese" type aerial was designed. The aerial was mounted on the roof of the cabin in which the radar set was fitted. The whole cabin was rotated, thus avoiding any difficulties in providing a means of rotating the aerial waveguide relative to the standing portion of the waveguide. Such an arrangement was not practicable in a ship, and it was necessary to develop a rotating joint for the waveguide so that the aerial above could be rotated continuously. A 4ft. 6in. diameter paraboloid was chosen as the reflector for the ship aerial as this required a very much smaller circular space in which to rotate than a "cheese" type aerial of comparable gain. The paraboloid reflector was fed at the focal point by a flare. The aerial was power-driven and the waveguide rotating joint was designed to give continuous uni-directional rotation. This was of considerable advantage for use with a P.P.I. as it gave a smoothly painted display. The aerial was also stabilised along the line of sight as had been the large ship version of the previous set. A further advantage of waveguide feed to the aerials was the low transmission losses. This enabled the transmitter and receiver to be installed some distance from the aerial and made unnecessary the use of an aerial lantern. As a surface-warning and low-air-cover set this equipment was fitted to both escort ships and the larger fleet units early in 1944. A photograph ol the aerial is shown in Fig. 9.

Fighter Direction--Height-Finding

The requirement for the direction of fighter interceptions from ships resulted in demands for radar information in a new form. The most important aspect of this operational technique was the establishment in a ship of an information organisation of which radar formed an integral part. Originally, radar displays were installed in the radar offices with the sets, but to meet the needs of fighter direction the displays had now to be centralised, being fed from the distant radar set.

In the large ships three sets were directly concerned in the fighter direction organisation, Type 79, Type 281 and Type 277. Two metre-wave sets were fitted because it could be arranged that the gaps between the lobes of one set could be filled by the lobes of the other, thus ensuring continuous long-range air-warning. In order to allow for the installation of both these sets in one ship they were modified for common T and R working. Type 277 provided warning of low-flying aircraft and filled the gap below the bottom lobe of Type 281.

The P.P.I. display was the display used for warning purposes; several displays could be fed from one set and were located wherever the information was required. In order to obtain a good P.P.I. picture with Type 281, this set was fitted with a slip-ring feeder system allowing for continuous rotation. Owing to its broad horizontal beam it was not considered practicable to use a P.P.I. display with Type 79. In this case it was necessary to continue with the old method of passing reports from the radar office to the Aircraft Direction Room. For interception purposes a skiatron was installed in the Aircraft Direction Room; this was usually fed from the Type 281. Sector displays were also fitted, usually in the Radar Display Room, and were used to provide the information that could only be obtained from the range-amplitude type of display, i.e., estimation of number of aircraft in a group, interrogation and echo-amplitude for height estimation.

Two sources of height information were available. A rough estimate of height could be obtained using the metre-wave sets, by observation of the variation of echo-amplitude with range; and secondly, at close ranges only, an accurate height could be obtained by elevating the aerial of Type 277.

Accurate height-finding by Type 277 was troublesome because it was difficult to search for a target both in azimuth and in elevation using a narrow beam aerial system. In order to provide target-bearing information at the Type 277, a P.P.I. was modified to have an additional cursor in front. This cursor was driven in bearing by the aerial of Type 277. The P.P.I. was fed from Type 281. The Type 277 was trained until the cursor on the P.P.I. coincided with the target, then the operators were able to search in elevation in the knowledge that the set was trained on the right bearing.

GUNNERY RADAR

In the early stages of the Second World War, the only radar sets fitted were WA sets, in battleships and cruisers. These sets were Type 279 working on 7 metres and Type 281 on 3 1/2 - 4 metres. For aircraft-warning accurate range was not required, and therefore to provide accurate range for fire-control the GL Mark 1 ranging equipment, developed for the Army, was added to the Naval WA sets.

The use of WA sets for fire-control suffered from three serious disadvantages:

(1) When the WA set was used for fire-control the ship was left without air warning.

(2) Only one target could be engaged at a time.

(3) WA sets were too curnbersome for fitting in destroyers.

Type 280 working on 3 1/2 metres was fitted in H.M.S. *Carlisle* and a few special anti-aircraft ships. Type 280 consisted of a modified GL Mark 1 with a special aerial system mounted at the masthead.

Because of the number of directors in a modern warship it was evident before the war that it would be necessary for each director to carry the aerial for its own radar. Further, in view of the probability of multiple targets and of the necessity for ensuring that the radar is ranging on the same target that the layer and trainer are tracking, a narrow beam is clearly required. Therefore, it was recognised that for gunnery purposes the shortest possible wavelength must be used.

50 cm. Gunnery Radars

By 1940 the successful development of a new valve for pulsed transmitters, giving a peak output power of 25kW on a wavelength of 50 cm., made possible the design of a gunnery ranging set whose aerials were sufficiently compact to be fitted on a director.

Type 282, the first of the sets working on a wavelength of 50 cm., had an aerial that could be fitted on the lightweight director used for close range weapons. The Yagi type of aerial was used, and, initially, separate aerials were used for transmission and reception. With this set a range accuracy of +/-50 yards was possible and aircraft could be picked up at distances of from 6,000 to 7,000 yards. A photograph of the aerial is shown in Fig. 10.

In November 1940 trials were conducted on a long range A.A. fire-control set, Type 285, which also worked on 50 cm. Type 285 had a larger aerial array than Type 282, and was designed to fit on the H.A. director. As in Type 282, the aerial array was designed to elevate with the line of sight of the director so as to point at the target. Type 285 could provide ranges on aircraft out to about 17,000 yards to an accuracy of +/-150 yards.

In June 1940 trials were carried out on a low angle fire-control set, Type 284, which also worked on a wavelength of 50 cm. The aerial array of this set consisted of two 24-dipole broadside arrays, one for reception and one for transmission, each fitted with a 21-foot long parabolic cylindrical mirror (the length of the mirror corresponded to the length of the visual range finder also fitted on the director control tower). Type 284 could range on a battleship at about 20,000 yards to an accuracy of +/-120 yards.

The first 50 cm. radar range finders were fitted at the end of 1940 and these produced a very marked improvement in the accuracy of surface fire. Against aircraft, however, the improvement was not so marked, because the prediction equipment fitted at that time could not take full advantage of the great increase in accuracy and continuity of the range data available. Another important factor that gave rise to the inaccuracy of anti-aircraft fire at that time was the "dead-time" interval.

Auto-Barrage Unit

In order to reduce the prediction errors and to overcome the difficulty of "dead-time" it was decided to introduce a system of barrage fire in which the fuses were set to a predetermined time-of-flight corresponding to some chosen range between 1,000 and 5,000 yards. The range and range-rate of the target were determined by radar and the guns were fired automatically when the target arrived at the correct range. Bearing and elevation still had to be determined visually.

The Auto-Barrage Unit, which controlled this type of barrage fire, consisted of a radar display mounted on top of, and operated in conjunction with, a prediction unit. The A.B.U. could be fitted in addition to the normal ranging panel of Type 285 enabling the Control Officer of the H.A. director to select either controlled or barrage fire; it could also be fitted as an independent radar set with separate aerials mounted on a special Barrage director, to control the barrage fire of low angle guns. In the latter case the complete set was known as Type 283.

Trials of this method proved most satisfactory, showing that at 2,000 yards range a hit could be obtained for every two four-gun salvos, but, at sea, barrage fire was not liked because it meant that fire had to be withheld until the target was very close and then there was only one chance of destroying it.

Improvements to 50 cm. Equipment

All the 50 cm. sets, Types 282, 283, 284 and 285, underwent progressive improvement. Such improvements were the increase of transmitter output power, increase of receiver sensitivity, improvement of displays and ranging accuracy and the application of the principle of common aerial working; this last improvement gave rise to an increase in aerial gain and better bearing discrimination and was an indispensable step towards the later fitting of beam-switching.

Remote Displays from WS Radar

By the middle of 1941, a 10 cm. set, Type 271, had been fitted in most battleships and cruisers for surface warning. This set was found to outrange Type 284 on surface targets and so a remote display fed from Type 271 was fitted in the transmitting station. The range from this equipment could be plotted on the fire-control table and, by this means, a solution could often be obtained at maximum gun range, which was not possible with Type 284. Since the use of Type 271 for fire-control prevented its use for surface warning, the range from Type 284 was normally used when available.

Beam-Switching

The experience of the Fleet in using radar led, in 1941, to an urgent requirement for a radar adequate for purposes of blind-fire; for this, in addition to range determination, the bearing of surface targets and the bearing and elevation of air targets had to be determined to an accuracy of a few minutes of arc.

With this in view the WA set Type 281 was fitted with beam-switching, and, though the beam of this set was very wide, ships and aircraft could be tracked in bearing with an accuracy of +/- 1/2 degree. This, however, suffered from the disadvantages mentioned previously, and was therefore not much used for gunnery purposes.

Up till 1941, in the fitting of the 50 cm. sets provision had been made to bring the director to the bearing for maximum signal by means of a remote indicator system, but this was really inadequate for fire-control purposes. At this stage, because the 10 cm. sets were as yet unable to give adequate ranges against aircraft, the 50 cm. sets were converted for beam-switching, in bearing only; it was not considered practicable to convert these sets to give angle of elevation as well owing to the size of the aerials they would require.

When fitted with beam-switching, Type 284 gave a bearing accuracy of from +/-3 to +/-5 minutes of arc against surface targets compared with the +/- 15 minutes of Type 285 against aircraft. Type 284 proved a great success in blind-fire against surface targets, but Type 285, so far as blind-fire was concerned, was only of value against low-flying torpedo bombers. Above all, beam-switching was of value in assisting the operator to determine which echo, of the several that were usually present on the radar display, corresponded to the target being engaged by the director.

Radar Training Sight

To facilitate training in blind-fire, Types 284 and 285 were equipped with a remote indicator unit; with the Type 285 this unit was invariably fitted in the H.A. director, but with Type 284 it was usually fitted in the TS. Owing to the bulk of this remote indicator unit it was often impossible to find a position for it in the director convenient for the trainer; for this reason development of a Radar Training Sight to replace the original remote indicator unit was undertaken.

The Radar training sight, besides being of much smaller size, had the added advantage that the trainer could view an image of the radar display in one eyepiece of the binoculars, with normal vision in the other (the radar image could be quickly switched in or out of the field of vision by means of a simple lever mechanism).

10 cm. Gunnery Radars

It was clear that the only way to attain a useful accuracy in the measurement of elevation was to use a shorter wavelength. It was not, however, possible to design a 10 cm. equipment with the size of aerial which could be fitted on existing H.A. directors and which would at the same time give adequate range performance. Accordingly, the design of a new 10 cm. radar set, Type 275, and the design of a new H.A. director for it were put in hand; the development of the latter, however, of necessity took several years and it was not until early in 1945 that a Type 275 was fitted in a destroyer for trials. This set was the first in which the conical scanning technique was used. The requirement for this set was that it should be capable of picking up a target at 36,000 yards and be able to track it accurately below 30,000 yards. Owing to the limitation on the size of the aerial mirrors, under certain conditions tracking was possible only under 25,000 yards. As time was insufficient to develop a conical scanning system for the very high voltages involved in transmissiori (400kW peak power output) a separate aerial had to be used for reception.

For ranging against surface targets too, everything was in favour of the 10 cm. rather than the 50 cm. wavelength. For the same aerial size a greater range and a better bearing accuracy could be obtained by using a wavelength of 10 cm. instead of 50 cm. As the existing director control towers were suitable for carrying the new 10 cm. aerials, the new 10 cm. surface ranging equipment, Type 274, was developed.

Type 274 was designed to ensure adequate signals from destroyer targets at maximum gun range. It was also hoped that shell splashes would give adequate signals at maximum gun range so that spotting corrections could be applied in blind-fire. To obtain accurate "blind" bearings, beam-switching in azimuth was incorporated. The bearing accuracy against small targets was better than +/-3 minutes, but on large targets such an accuracy was not obtainable. The peak power output of the transmitter was 500kW, and, because of the difficulties of switching this high power, separate aerials were used for transmission and reception, beam-switching being applied to the receiving aerial only.

Radar for Spotting Fall of Shot

For the purpose of spotting fall of shot, Type 274 was fitted with a special display showing 2,000 yards about the target range. By means of this display the operator could estimate fairly accurately the distance between the target and the Mean Point of Impact (M.P.I.). This device did not, however, permit the operator to measure the amount of "error for line" of the M.P.I., it being possible only to estimate roughly whether the M.P.I. was to the ' right ' or ' left,' or ' on ' the line of sight.

The " error for line " of the M.P.I. can only be measured accurately on some form of plan position indicator. In order to provide this facility the development of a new equipment (Type 931) was undertaken in Canada but was not completed by the end of the war.

Type 931 was designed for the observation of fall of shot as part of the main armament radar fire-control system in cruisers and battleships. The general performance of the set was such that it could be used to provide the primary fire-control data in an emergency. Type 931 worked on a frequency of 1.25 cm. wavelength at a peak power output of 40kW; " B " display presentation was used.

TYPE 262

A 3 cm. wavelength set, Type 262, was developed to provide for blind-fire with a twin Bofors gun-mounting; this mounting was self-contained, *i.e.* all the equipment, guns, predictor and radar were on the mounting. Type 262 was not available for fitting until after the war. A photograph of this mounting with the Type 262 equipment is shown in *Fig. 11*.

The peak power output of Type 262 was 30kW. A single aerial was used for transmission and reception. Conical scanning was used and achieved by rotating the mirror itself, the mirror axis being skewed from the axis of rotation.

The requirement for Type 262 was that it should pick up a target at 7,000 yards range and be able to track it in all three co-ordinates, sufficiently accurately for fire-control purposes, by the time the target has reached 5,000 yards.

As Type 262 is essentially a close-range set it was essential that a target should be picked up within a few seconds, and because the bearing and range indications of a target may be in error by as much as 5O and 500 yards, respectively, and because of the narrow pencil beam of this set, it was decided that it would be necessary to provide for searching a volume of sky mechanically. In order to do this with the certainty of picking up the target in the shortest possible time, it was considered that the " search and lock on " must be entirely automatic, the normal manual search procedure used with earlier sets being too slow and unreliable.

Type 262 works as follows. When a target has been indicated to the Type 262 it scans 30° in azimuth, the aerial being elevated 3° at the end of each sweep; at the same time the set explores the space to a depth of 750 yards either side of the indicated range. Once the target has been picked up the aerial automatically "locks on" to the target and the predictor runs into alignment with the mirror axis; the guns then automatically follow the predictor.

Target Indication

The introduction of narrow beam gunnery radar sets, *i.e.* Types 275 and 262, stressed the necessity for an efficient Target Indication system. Because of their narrow beams these sets were quite unsuitable for the purpose of searching for a target and they had to be provided with up-to-date and accurate indications before they could find the target.

Ideally, the indications required are range, bearing and angle of elevation. Hitherto, it has not been possible to design a Target Indication set capable of providing angle of elevation in addition to range and bearing.

The target indication set, Type 293, was first introduced into the Fleet in 1944. The set was designed to detect both air and surface targets in the immediate vicinity, to give the Target Indication Officer an up-to-date picture of the tactical situation and to provide facilities for the rapid indication, by instrument, of range and bearing of targets to the various fire-control positions.

Type 293 worked on a wavelength of 10 cm. at a peak power output of 500kW. The main display consisted of a Plan Position Indicator mounted in a Target Indication Unit (T.I.U.); in conjunction with the T.I.U. were fitted Sector Selector panels. The T.I.U. was used to transmit bearing and the Sector Selector panels were used to transmit range to the various fire-control positions.

In its later, modified, form Type 293 gave warning of aircraft flying at heights of from 200 to 20,000 feet, up to a range of about 25,000 yards; its performance against surface targets approached that of Type 277. Range and bearing could be passed with an accuracy of +/-500 yards and +/-2° respectively.

DISPLAYS

As the simplest type of display is one in which the amplitude of the signal is displayed against time or range, a tube for use in an oscillograph is fairly suitable. Commercial tubes of this type were used in the first radar sets. As radar sets became more elaborate, the demands on the tube became greater, and special tubes had to be designed, because Plan Position Indicators (P.P.I.) demand long-afterglow screens. Tubes used in fire-control display units are required to have a fine focus, and in addition they must be suitable for certain very special types of intensity modulation.

The first display unit, designed in 1939, contained a C.R. Tube using about 1kV h.t. The need for good focus and high brightness in tubes used in precision fire-control equipment resulted in the h.t. being raised to 5kV, at which figure it has remained for that type of tube. P.P.I.s initially used 5kV, but with the introduction of the electrostatically focused model the h.t. was raised to 7.5kV and the tendency is to use still higher voltages.

In naval equipment it has been the rule to run the tube with the third anode at earth potential. This complicates the design, but allows the operator to touch the face of the screen with impunity.

C.R.T.s are often located in compartments where a high level of illumination is necessary. This results in a demand for tubes which can be viewed under such conditions. Most of the non-afterglow tubes are provided with screens giving green traces, and it is customary to view these traces through a green filter. This reduces the effect of external lighting, as light which causes reflections from the screen has to pass through the filter before it gets to the observer's eye. Afterglow screens are also viewed through suitably coloured filters, in which case the filter reduces the effect not only of external light but also of "flash" if a two layered screen is used.

Where no great precision is required, measurements can be made on the tube face. When, however, high accuracy is demanded it is more satisfactory to use the tube as a means of comparing two voltages or currents. This technique is almost always adopted in precision equipments.

In naval radar every effort is made to keep the number of types of displays to a minimum. This policy eases the stores problem and makes for satisfactory manufacturing conditions.

Range-Amplitude Presentations

RANGE-AMPLITUDE DISPLAYS

The range-amplitude display is a display in which range is presented parallel with one axis of the C.R. Tube, usually the X-axis, and amplitude of the received signal is presented parallel with the other, usually the Y-axis This type of display, which was the first type to be developed and was the sole display of the first naval radar set, is always fitted in naval equipments because it is necessary for tuning the set and also acts as a standby in case of damage to the more elaborate systems.

The range-amplitude display provides much useful information which cannot be presented on other types of display. For example, the appearance of the echo returned from a group of aircraft can sometimes be used to estimate the number of aircraft in the group; also, when used with metre-wave radar, observation of the variation of echo-amplitude with range can sometimes be used for the purpose of estimating the height of an aircraft.

When the simple type of range-amplitude display is the only type of display fitted with a radar set, the direction of a target can be determined, but only approximately, by rotating the aerial until the signal-amplitude is a maximum.

In the first naval radar set the C.R. Tube was of the gas-focused type. The time-base was produced by applying the alternating supply voltage, which also was supplied to the transmitter, to a deflection coil which provided the horizontal deflection on the C.R. Tube. This system, although simple, suffered from the disadvantage that the picture on the tube drifted to and fro to an extent that was troublesome. In this early set this defect in the display system was overcome by replacement of the existing X-deflection by a conventional, triggered, valve, time-base. This latter system is now standard practice for all range-amplitude displays.

Since 1941 the range-amplitude display unit has remained virtually unchanged and has been fitted in almost all warning radar equipments built since that date. It consists of a 6-inch C.R. Tube electrostatically focused. In early naval fire-control equipment a 12-inch tube, also electrostatically focused, was employed with a cursor mounted in front which could be moved mechanically to cut the leading edge of the echo. The range obtained was transmitted automatically by a data transmission system. This scheme using a cursor suffers from many drawbacks, and was abandoned in favour of a properly designed precision system.

PRECISION RANGING SYSTEM

A considerable amount of thought was given in 1941 to the development of a system that would give very accurate ranges, and would at the same time be simple and easy to manufacture. For this reason it was important that a conventional type of tube should be employed. Such a system was developed, the basic ideas of which have been embodied in all subsequent British naval precision ranging equipment. In this system two traces, a few millimetres apart, are displayed. The upper trace shows the ground wave and echoes as in the conventional range-amplitude display, except that a small portion is considerably speeded up. The lower trace is identical with the top trace, but in place of signals it shows calibration pips. The unit is so designed that the expanded portion of the trace can be readily selected and at the same time the same calibration pip remains in the centre of the expanded portion at all times. The setting of that calibration pip against the echo results in the correct range of the target being given. A feature that is of considerable operational importance is that the range taker can see the whole picture from zero to maximum range.

As fire-control equipment grew more complicated it became necessary to adapt the ranging system to meet new requirements. The new precision ranging display differed from the old type in that the lower trace was renewed and that the calibration pip was replaced by a bright spot on the actual trace. When used for ranging this bright spot is set on the leading edge of the echo.

PRECISION BEARING AND ELEVATION DISPLAYS

In precision equipment the accuracy is usually obtained by swinging or switching the aerial beam at high speed and comparing the amplitude of the signals obtained with the beam in two different positions. In naval equipment the "side-by-side" or "switched" display is usually used. This display is a range-amplitude presentation on which the two echoes, side by side, represent the responses from the target in the two positions of the aerial beam.

Plan Displays

PLAN POSITION INDICATORS

It soon became apparent that range-amplitude displays do not make full use of all the data available from warning radar sets. The year 1942 saw the introduction to the navy of P.P.I.s. In a P.P.I. a radial time-base is employed, range being measured from the centre outwards, the time-base being so arranged that it rotates in synchronism with the aerials. In the absence of signals the trace is invisible, echoes being made to brighten the trace. The P.P.I thus builds up a radar map of the neighbourhood. A C.R. Tube with an afterglow screen is used.

The extensive use of P.P.I.s on board ship brought to light the need for careful magnetic screening of the tube. It is necessary to guard against deflection of the spot caused by the degaussing coils in the ship, and against changes in the local magnetic field when the ship alters its position in the earth's magnetic field. The amount of screening required varies greatly, depending on the position of the instrument.

Early models of naval P.P.I.s used electro-magnetically focused C.R. Tubes, the deflecting system being also electro-magnetic. The design of existing tubes is such that careful lining up of the focusing coil, the deflecting coil and the tube is necessary if a well-focused spot is to be obtained. Under

Service conditions it is difficult to ensure that this is done properly. This has resulted in a change-over to the electrostatically focused tube, in which the responsibility for accurate alignment of the electrode system in the C.R. Tube is undertaken by the tube-maker, and the radio mechanic is relieved of the responsibility of carrying out one set of adjustments.

SKIATRONS

The Skiatron is a type of C.R. Tube in which the usual screen is replaced by one of potassium chloride. This type of tube renders possible an episcopic type of projection, and pictures of at least 2 ft. diameter are quite practicable.

The great benefit that can be obtained from a skiatron equipment is that a large picture is possible and plotting can take place direct on the screen on to which the picture is projected. This system enables a greatly increased speed of plotting to be attained, a feature which is of immense value operationally.

If an echo is allowed to paint once on a particular spot on the screen it very rapidly fades out and disappears. If, however, it is allowed to paint many times on the same spot it is found that when the signal is removed the stain remains on the tube and only fades away very slowly. This feature is most objectionable, especially when the ship is steaming close to land and picking up many land echoes. Special steps have to be taken to clear the screen of permanent echoes from time to time.

For plots of surface craft, or under conditions where the movement of one's own ship has to be taken into account, a variant of the skiatron was produced. In this equipment the plotting surface is moved in accordance with the course and speed of the ship. The technique of moving the surface rather than the projected plan display was dictated by mechanical considerations. A complete plot of own ship's movement combined with the true movement of all targets picked up by the radar set is thus obtained.

RANGE-REARING DISPLAYS

In the range-bearing system of presentation, range is on one axis of the C.R. Tube and bearing on the other, signals being applied as intensity modulations

There are two types of this display. The first is used in conjunction with a continuously rotating aerial, the second with an aerial that swings to and fro about a selected bearing.

If a P.P.I. is used with a radar set that has a narrow beam and a short pulse-length, the limit of the resolving power of the radar equipment is usually set by the size of the spot of the P.P.I. The use of one or more range-bearing displays in conjunction with a P.P.I. can allow the full resolving power of the equipment to be used, as the range-bearing display can be used to show a few miles about any selected range between two selected bearings.

The second type of display, in which the aerial beam swings over a limited arc, is used in the case of low-angle fire-control equipment for spotting fall of shot relative to the target.

Sector-Selected Displays

With the general introduction of continuously rotating aerials necessary for satisfactory P.P.I. operation the value of the normal range-amplitude display became small. A presentation which shows the shape and size of an echo is of great value, however, and a series of displays known as "sector-selected displays" were developed for this purpose. In this type of display a range-amplitude trace is automatically switched on to the tube as the aerial passes through the selected bearing. The C.R. Tube screen is of the afterglow type, so that the picture persists from one excitation to the next, each excitation occurring as the aerial passes the selected bearing.

I.F.F. AND BEACONS

The ability of radar to "see" through darkness, rain and fog opened up enormous tactical opportunities. How well and how speedily those opportunities were taken can be realised from the vital part which radar played in the war. Like most new inventions, however, radar brought its own peculiar problems, not the least of which was the need to distinguish between friend and foe when detected by radar.

Early Methods of Identification

In the early stages of the war, when radar was used mainly for warning purposes, distinction between friend and foe was attempted by carefully controlling the disposition and movements of all friendly forces so that any such forces could be identified as soon as they were detected by our own radars. This placed an unacceptable restriction on operations, particularly in the air where the speed of aircraft and last-minute changes in routeing and urgent missions often made it impossible to keep radar stations fully informed of the situation. Full advantage of the early warning given by radar could not be taken if any doubt existed as to the friendly or hostile nature of echoes.

The first step towards a solution of the problem was made by fitting a small transmitter-receiver, known as a transponder, in friendly aircraft. The trans-ponder was designed to receive the signals from the locating radar and to re-transmit them so that the amplitude of the echoes on the radar display increased perceptibly whenever the transponder made a reply. This system, known as I.F.F. Mark 1, was only fitted on a limited scale. It was superseded by I.F.F. Mark 2, which was much more widely fitted.

The number of types of radar sets at that time was small, and they all operated within narrow frequency bands so that it was possible to design the transponder to respond to the transmissions of all radar sets then in use. Designed and produced to meet an urgent requirement I.F.F. Mark 2 was crude and unreliable when judged by present-day standards. Nevertheless, it provided a temporary answer to the aircraft identification problem and on many occasions established the friendly identity of echoes when no other means were available. Its usefulness in aircraft led to its being fitted in ships, but it was never satisfactory owing to its poor sensitivity, low transmitter power, and inability to withstand mechanical shock and vibration.

The rapid development of new radar sets operating on frequencies far outside the bands previously used rendered I.F.F. Mark 2 obsolete. This scattering of frequencies, while highly satisfactory from the radar point of view, made the identification problem all the more difficult because it became impossible to design a reliable transponder which could reply on all the frequencies coming into use. It was also quite impossible to foresee what new frequencies would be used in the future. The only possible solution was to develop a new identification system which could be made independent of the frequencies used by the main radars. As transponders could no longer be designed to receive signals from all the radar sets coming into use it was decided to use a frequency band for the new I.F.F. system as clear as possible of radar signals, and to build special transmitter-receivers known as interrogator-responders which would be tunable to any frequency in this band, and to design the transponders to receive signals and transmit replies on any frequency in the band, this being generally known as " A ' band. "

Identification Friend or Foe Mark 3

The introduction of the new system, known as I.F.F. Mark 3, was clearly a far greater undertaking than that of I.F.F. Mark 2. Not only had the numbers of ships and aircraft to be fitted with transponders increased enormously, but the design, production and fitting of interrogators constituted an additional major commitment.

The interrogator-responders, which were in effect low-powered radar sets, were designed to operate in conjunction with main warning radar sets, so that the transmitted pulses were synchronised and the received signals displayed on the same tube as the radar echoes. A separate aerial, and usually separate power supplies, were also required with each interrogator. With the limited mast and office space available in ships the introduction of I.F.F. Mark 3 therefore involved heavy new commitments, particularly for the Navy, at a time when all available effort was fully extended in fitting the Fleet with radar.

In spite of every effort having been made to change over to the new system as smoothly as possible, the task proved too great for the resources available. Although the introduction was carried out in stages, by changing over in one area at a time, it was quite impossible to ensure that all operational ships, aircraft and ground stations in a given area were fitted with the necessary equipment by the date agreed upon for that area. The ensuing period was generally one of great confusion, particularly in the Western and Central Mediterranean where the change-over coincided with a number of important operations. The uncertainty of radar identification caused particular anxiety at this time when the enemy's air effort was on a considerable scale. As the fitting of I.F.F. Mark 3 became more complete, and as operators and mechanics became more familiar with the new equipment, the situation gradually improved.

Although I.F.F. Mark 3 was known to have technical limitations it was unfortunate that so few of the reports submitted could give any concrete evidence as to the extent or nature of these limitations. Most of the failures occurred when ships failed to identify land-based aircraft, making it extremely difficult to investigate the causes. It was regrettable also that the time and effort could not be spared to carry out a detailed investigation into the causes of failures. As it was, an undue amount of secrecy prevented sufficient knowledge being imparted to the wide range of personnel concerned in its use. It came to be regarded as a "magic box" which must not be opened or interfered with.

Teething troubles with I.F.F. proved to be no exception to the general rule for new systems. The remedial measures were slow to take effect, largely owing to the peculiar nature of an I.F.F. system as compared with normal radar equipment. In particular, unlike a radar set, I.F.F. depended for its success upon:--

(a) fitting transponders in all friendly operational craft;

(b) fitting interrogators in conjunction with all warning radar sets;

(c) the failure of the enemy to simulate our I.F.F. (adequate security);

(d) the correct functioning of all transponders (the breakdown of one radar set in one ship did not reduce the fighting efficiency of other ships, but every single I.F.F. failure reduced confidence in the system as a whole by causing false alarms, etc.);

(e) the automatic indication of breakdowns, enabling appropriate action to be taken in time to avoid the unwanted effects of I.F.F. failures;

(f) the proper correlation of target echo with I.F.F. responses.

OTHER USES OF I.F.F. MARK 3 AND ITS VARIANTS

I.F.F. Mark 3 was capable of performing other functions than that of mere identification of friend or foe. Although these functions were subsidiary to the main purpose, they made, nevertheless, an important contribution to the part played by radar in the war and gave added emphasis to the need for full I.F.F. efficiency in peace time as well as in war.

Identification in Aircraft Direction

Early attempts to carry out interceptions using radar control were handicapped by the difficulty of distinguishing the aircraft being controlled. I.F.F. Mark 2 then in use provided some assistance but the development of plan displays and the introduction of I.F.F. Mark 3 created a need for a special form of I.F.F. suitable for plan display.

To meet this need I.F.F. Mark 3 transponders fitted in fighter aircraft were modified so that in addition to their normal function they could, when required, reply to interrogations on a fixed frequency outside the I.F.F. Mark 3 band. The frequency chosen, commonly known as " G ' band," was that of the R.A.F. ground radar stations which had been specially designed for control of interceptions. The modified I.F.F. equipment was known as I.F.F. Mark 3G.

I.F.F. Mark 3G transponders normally operated in the conventional manner, but whenever the pilot was directed to identify himself, he simply pressed a button which caused the set to operate alternately on the A band and G band for as long as the button was held down, and for a period of 10 to 20 seconds after it was released. As the G band operated on a fixed frequency, responses were continuous. The time-sharing action with the A band caused the G band responses to appear " chopped " on a P.P.I., i.e. as a series of dots instead of a solid arc.

To enable ships to interrogate I.F.F. Mark 3G special interrogators, known as Type 941, were designed and were fitted with Type 281. In order to keep the plan displays as free from clutter as possible it was essential that G band I.F.F. should only be used when absolutely necessary.

The I.F.F. transponders could be varied by using different combinations of narrow and wide pulses or blanks. The various code settings gave four pulses in a 12-second cycle. There was, in addition, a code setting consisting of very wide pulses for use in emergency. The different codes were given various tactical roles during the war and were, in general, most effective.

Indication of Distress and Air/Sea Rescue

The very wide pulses transmitted when the switch on the transformer control box was thrown to "Emergency" gave an immediate and unmistakable signal to any interrogators operating within range. Furthermore, the position of the ship or aircraft in distress could be accurately plotted so that immediate assistance could be given. This was of particular value in aircraft because the signals were automatic once the switch was made, thus requiring no further attention from the pilot.

Increasing Detection Range of Warning Radar

The interrogator aerials fitted in ships had a wide horizontal and vertical coverage, which, although a disadvantage in many ways, was sometimes useful in locating friendly aircraft outside the coverage of the radar set by means of their I.F.F. Good use of this method of plotting friendly aircraft was made by ships such as anti-submarine escort vessels and M.A.C. ships which were fitted with surface warning radar sets only. I.F.F. was also useful in helping to fill the gaps in the vertical coverage of air warning sets.

Rooster

Homing by one aircraft, or by a group of aircraft, on to one or more other aircraft is possible with the aid of I.F.F. The intermittent responses of normal I.F.F. were not ideal for this purpose and a further modification was incorporated in airborne transponders to enable continuous responses on a fixed frequency in the A band to be transmitted. The continuous responses provided the greater bearing accuracy required for homing purposes. The rooster facility, which was alternative to the G band function, did not affect the normal A band operation. Transponders capable of either G band or rooster operation were known as

I.F.F. Mark 3G.R. in R.A.F. aircraft and as AN/APX-l or AN/APX-2 in Naval aircraft.

To Indicate Individual Ships by Name

As a means of providing greater security of inter-ship identification the coding facilities of shipborne transponders were extended by a modified coding unit sufficient to allow each ship to use a different code. The modified transponder, known as Type 253P, had a Code Selection Unit with:--

(a) three Operation Buttons, I, A, and B, and

(b) nine Identity Code switches, each having three positions, to select either a Wide Pulse, a Narrow Pulse, or a Blank, i.e. no pulse.at all.

Beacons

A radar beacon was designed primarily for homing purposes and usually had the following characteristics:--

(a) it responded on one frequency only (not necessarily that on which it was interrogated);

(b) it had greater power than an I.F.F. transponder, in order to give it maximum range;

(c) it was able to transmit a distinctive coded signal which enabled it to be identified from other beacons of the same type.

The principal use of radar beacons was to provide a homing aid to aircraft fitted with radar. Although other radio homing aids existed a radar beacon was the only one which provided simultaneous range and azimuth information. Its use was, however, restricted to those aircraft which carried radar equipment capable of operating it.

The requirement for a Naval radar beacon first arose with the fitting of A.S.V. Mark 2 and was met by the introduction, in 1941, of Type 251, a makeshift equipment, battery-operated and of very low power, which was hurriedly fitted in ships. This was later replaced by 251M, a mains-operated equipment of much higher power which was capable of extremely good results with A.S.V. Mark 2. Being designed and produced to meet an urgent requirement, it was unreliable because there had not been time to include the requirements necessary to make it more stable in operation. Furthermore, unlike an I.F.F. set, it operated on a fixed frequency so that tuning errors in the beacon or in the aircraft's radar were sufficient to cause failures, even though both equipments were otherwise in perfect working order.

With the introduction of Lucero, an airborne interrogator, difficulty was experienced in obtaining satisfactory performance with Type 251M, which had been designed to respond to the more powerful transmissions of A.S.V. Mark 2. Investigation showed that the performance of Type 251M could be improved by modifications to the transmitter and receiver. When these modifications were carried out the set was known as Type 251P.

Type 251M/P beacons were fitted in aircraft carriers and certain other ships requiring co-operation with aircraft and at Naval air stations, and a separate code group was allocated to each.

As with I.F.F. the development of radar beacons did not keep pace with the rapid development of airborne radar equipments, in fact Type 251M/P was still the only equipment at the end of the war available for use in ships, although only those aircraft fitted with A.S.V. Mark 2 or Lucero could use it. For the many aircraft fitted with modern centimetre radar but without interrogation facilities, there was a pressing need for a centimetre radar beacon; the only suitable beacon in existence was of American design and manufacture, known as AN/CPN-6. A few models were available and these were fitted at Naval air stations.

Radar Beacons for Use by Ships

Radar beacons were installed at various places for use as navigational aids for shipping. Their success was limited by the following:--

(1) The fact that most of the sites where navigational aids are most required were remote from maintenance bases and power supplies.

(2) The only equipment available was of a makeshift nature, unsuitable for long periods of operation without regular maintenance, of low power and poor bearing accuracy.

(3) Lack of resources prevented the development of equipment suitable for the conditions in (1) above and capable of giving adequate range and a high degree of bearing accuracy.

(4) The development of high-definition radar sets made navigation by radar possible without the use of beacons.

The first radar beacons for use by ships, known as Type 256, operated on 214 Mc/s and could only be interrogated by Types 286 or 291. They were subsequently dismantled, apart from a small number which were retained for use by coastal craft fitted with Type 291U.

The limited use which could be made of Type 256 led to the introduction of Type 253S, which consisted of an I.F.F. Mark 3 transponder modified to sweep from 177 to 187 Mc/s. The restricted sweep covered the frequencies used by ship's interrogators, 179 or 182 Mc/s, but prevented aircraft from receiving unwanted responses.

Type 253S was installed in lighthouses, lightships, at radar stations and other convenient sites. Two other beacons, developed for special purposes, are described below.

TYPE 255

This was developed for use as a navigational aid for ships fitted with Types 286 or 291 taking part in assault operations. Operating on 214 Mc/s, it was housed in a buoy container, and when dropped in the sea it automatically set up its own aerial, switched itself on and dropped an anchor; it was designed for launching from a motor launch or similar craft and would operate continuously for a predetermined period, after which it blew itself up. A similar beacon, known as Type 255M, was capable of being launched from a container fitted on the hull of a submarine, but owing to delay in completion it was never used operationally.

TYPE 952

The introduction of centimetre radar in all classes of ships raised a requirement for a special type of beacon suitable for fitting in navigational leaders, or for being carried ashore and set up on the beach as a marker beacon for assault craft fitted with S or X band radar.

Produced to meet this requirement, it differed from other types of radar beacon which receive and reply on the same or similar frequencies in that it could be triggered by radar signals on S band or X band and reply on any pre-selected frequency in the I.F.F. Mark 3 band (157-187 Mc/s).

In addition to the function described above, Type 952 could be used as a marker beacon for ships carrying out shore bombardments. If the position of the beacon in relation to the target to be bombarded was known, ships could open accurate fire even though the target was invisible. Range accuracy was equal to that of the radar set being used up to the maximum working range; beyond this and up to the limiting range the error increased with range. Up to the maximum working range, beacon responses appeared 400 yards in excess of the radar range.

Development of I.F.F. at the End of the War

To conclude this brief war history, the I.F.F. sets in use at the end of the war, though by no means ideal, proved to be of very great assistance to the Allies.

The rapid advance in radar research made it clear, however, that I.F.F. Mark 3 was out of date, both technically and operationally, even at the time of its introduction. The staff requirements for a new I.F.F. set (Mark 5) were drawn up to include as many improvements over I.F.F. Mark 3 as could be introduced without requiring too much research effort or too complex equipment. The urgent need for a better system of radar identification gave the project a high degree of priority, but even so, by August 1945 development was barely complete.

Much thought was given to the possibility of introducing improvements to the existing equipment to overcome its limitations. Although minor modifications were introduced from time to time any major improvements proposed were rejected as they invariably involved such re-design of equipment that their introduction would have involved almost as much effort as that of a completely new system.

The application of the I.F.F. principle to radar beacons for aircraft and ship navigational aids, and for bombardments and identification, also made great progress, though, as in other fields of radar, there is vast scope and need for improvement.

PRODUCTION

Before the war the Production Department of the Admiralty Signal Establishment was responsible for the production of all wireless and allied equipment; and with the invention of radar and the need for the production of other miscellaneous radio equipment these too became the responsibility of the Production Department. Because radar and wireless equipments follow the same general technique their requirements and problems in connection with production are the same. The approximate sums expended in the production of radar during the war years are shown graphically in Fig. 12.

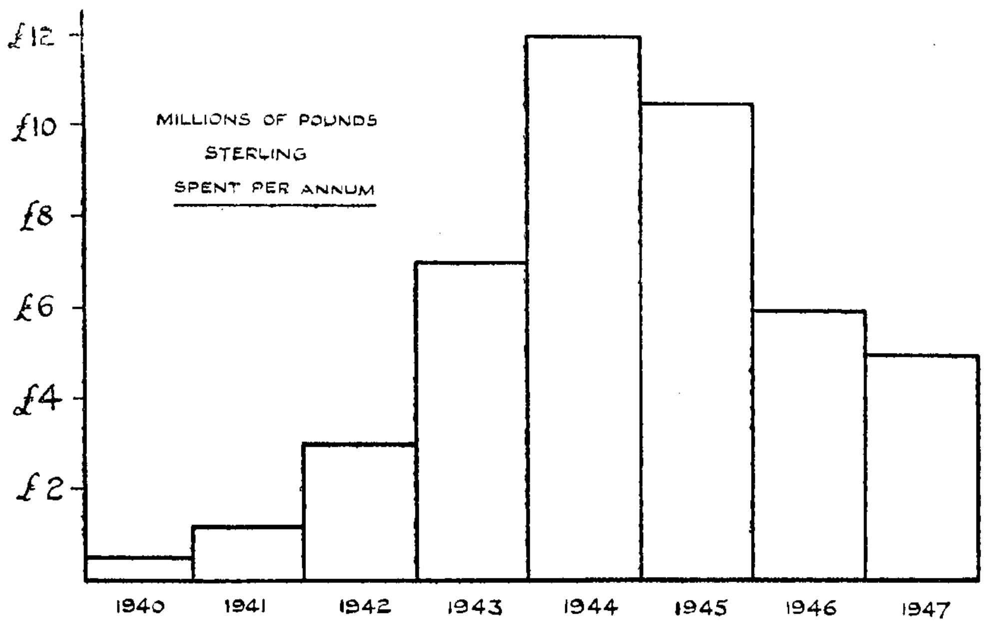

Fig. 12. Expenditure on production of radar, 1940-1947
The monies quoted are based on deliveries of apparatus and are approximate only, and take no account of the devaluation (in value) of the pound sterling.

The increase of production naturally necessitated a considerable expansion of the Production Department, which was itself responsible for such matters as initiating contract action, dealing with technical difficulties in manufacture, progressing and inspecting, etc. etc. The technical staff, which consisted of less than 50 people at the outbreak of war, was ultimately increased to about 1,000 of whom a large proportion were in the Test and Inspection Division.

Placing Contracts

Until the outbreak of war the general method for quantity production of H.M. Signal School's designs was to place with manufacturers contracts to comply with a rigid technical specification (which included a complete set of checked drawings whose accuracy had been assured by compliance with a proved prototype equipment). Even for proprietary designs a full and detailed "performance" specification was prepared. For both categories of design, subject matter regarding processes of prime importance to satisfactory production, requirements concerning quality of materials, a complete test schedule and an established list of Naval Stores for free issue to the contractor, were included. Nornnally, several contractors were invited to tender and, generally, the contract was placed against the lowest tender. Unfortunately the urgent need for equipments and lack of the necessary technical staff precluded the continuance in time of war of the established and ideal procedure; the Production Department was, in fact, faced with finding a large increase of capacity for the manufacture of apparatus which had to be undertaken, at the best, with the provision only of emergency specifications and drawings often unchecked and incomplete, and sometimes only of models or sketches.

Other drawbacks engendered by the urgent requirements for equipment were that production had frequently to be put in hand without bulk supplies of components being readily available, and often even before the development and designs were finally completed, which usually led to changes having to be made during production with consequent loss of production time; and, finally, contractors of certain apparatus, usually of a complex and secret nature, had to be denied information regarding the nature of that apparatus.

The first radar set designed to detect U-boats affords an interesting example of how urgent quantity requirements had to be met. Contract action was taken, in mid-March 1941, to produce 250 sets of equipments from an incomplete model which had been made in A.S.E. workshops from meagre and incomplete drawings; the model was delivered to the contractor in mid-April and a successful copy was produced by mid-June, a total of 250 sets being delivered during the ensuing 12 months.

Means of Production

In peace-time there had always been a steady, if relatively small, flow of contracts to certain firms for the production of wireless equipment, and with the expansion of the Navy for war it was relatively easy to place contracts for increased quantities of equipments of fully specified types. For radar however the position was different as, the science being new, there were no complete specifications available.

The first two experimental radar sets, both Type 79Y, were produced in the workshops of A.S.E. and fitted in ships in 1938. Later three more sets, of an improved design known as Type 79, were put in hand, and one of these was installed in H.M.S. Curlew in September 1939. In 1939, the first major contract for radar equipment was placed, being for 50 sets of Type 279. These sets were estimated to cost £5,000 each and to entail the employment of about 6,000 people (direct labour). The major part of this radar set consisted of new production items and also called for new testing techniques.

The quantities, complexity and number of different types of equipments for which the Production Department was responsible increased enormously. These equipments were destined for use in all types of ships and for shore stations and they ranged from W/T, Voice, visual-signalling apparatus generally, and D/F, to Radar, Radio Countermeasures, Radio-navigational aids and Infra-red apparatus.

New equipments gave rise to the introduction of items not previously manufactured; at one time new items were being introduced at the rate of 500 per month, and during the course of the war a total of some 30,000 new design items of varying complexity was produced. In particular, about 60 different main types of radar equipment were produced between 1939 and 1945.

An idea of the increase of manufacturing capacity that was necessary to satisfy the requirements of the Production Department can be gained from the following data:--

> The advance estimated expenditure at the contractors for 1939 was about £1,000,000, a sum which was in point of fact exceeded owing to the outbreak of war in that year; during 1944 the expenditure reached a peak of over £35,000,000.
>
> At the outbreak of war the number of contractors employed in Radio Construction (all engineering firms from the largest to the smallest), was about 350. By the end of 1944 the number of firms engaged had risen to over 1,000 and included some which previously manufactured such items as sports gear, artificial flowers, jewellery, cathedral organs, dart boards, stained-glass windows, cardboard toys, knitting needles, looms, etc.

Prefabrication

As the production of radio equipment increased, so the facilities of the ship-building yards for fitting this and other electrical equipment became increasingly strained. Efforts were made to ease the burden on the yards by the production of prefabricated radar offices, which were complete in every detail and ready for instant installation. As the most urgent requirement was for large numbers of centimetre surface warning radar to combat the U-boat, these equipments were the first to be prefabricated. Prefabrication was started in 1942 and in the first twelve months 255 complete assemblies were produced and installed; this rate of production was subsequently improved upon.

Labour

There was always a shortage of labour, particularly of skilled labour. The lack of skilled workers had to be overcome by recruiting of and training unskilled labour; this necessarily involved some loss of production time as existing skilled personnel had to be diverted to the task of training. Subsequently, however, much of the work was undertaken by unskilled labour.

The number of persons directly employed on Admiralty (and Allied) radio production increased roughly in proportion to the expenditure, rising to a peak of 40,000 in 1944. Had it not been for the Essential Works Order it would not have been possible to obtain the necessary labour, much of which consisted of women workers. A.S.E. had frequently to negotiate with Regional Labour Controls in order to provide additional directed labour for priority projects, and also to prevent loss of essential labour, particularly to the Forces. The necessity for placing contracts with contractors working in those regions where the labour position was less difficult often guided the decision as to who should make the articles.

A.S.E. itself suffered from shortage of labour, not only in numbers but also in skill. The employment of much labour initially untrained in the processes necessary for placing contracts, testing and inspecting also presented difficulties.

Machine Tools

The expansion programme called for large numbers of machines and tools; a range of nearly 50 types of production machines had to be considered. Negotiations for about half a million pounds worth of machines and tools were effected by A.S.E. under various Government-sponsored schemes.

Materials

The supply of materials caused some difficulties in the early stages, but this was finally eased by the introduction of Government Control Boards. A.S.E. regularly provided these control boards with quantitative estimates of various materials needed by their contractors.

Co-ordination of Production

Any one type of equipment comprises a variety of completed items of differing manufacturing techniques, and therefore many contracts are usually involved in the production of one equipment. For this reason it was essential to co-ordinate production rates of all stores to ensure delivery of individual items. To meet this need the minimum rate of production was determined for each item, and a progress system was evolved comprising contract delivery data and contractors' works planning schedules which were compiled in personal collaboration with firms' executives to ensure that the contractors were fully aware of the minimum requirements and that the total load thus conceived was within the contractors' total capacity. Equipment Production Reports and Contractors' Programmes were published regularly; also, Production Progress meetings were held regularly for the purpose of reporting progress and any difficulties that might have arisen.

The value of H.M. Signal School's pre-war established system of recommending purchase for known commitments and additional quantities for minimum stock of common components was proved to be of inestimable value, as it ensured the econon1ical production of items which were used in more than one type of equipment. This practice is being followed by other Services and will be continued.

To overcome difficulties which might be expected in regard to sharing the country's total production capacity there was originally prepared for use by all supply departments of the country a Capacity Registry indicating the share of the various production departments in the various firms throughout the country. In 1941, however, for radio only, an inter-service executive, known as the Radio Production Executive, was formed. This authority was set up to deal with such matters as the co-ordination of production, expansion of capacity, and co-ordination of the requirements of all Services, and ostensibly to ensure that manufacturing potential was used in the most economical way. Committees were also established to bring about inter-Service standardisation wherever possible; inter-Service standardisation was found to be more readily applicable to components and valves than to equipments.

In consequence of rationalisation the variety of components was reduced to the extent that fixed resistors were reduced from 10,000 varieties to 1,300 preferred types, fixed capacitors from 8,000 to 750, laminations from 700 to 32 and relays from 17,000 to 200. As an example of the effect on production by the choice of preferred types, the delivery period of some components, which was quoted at 26 weeks in 1943, was reduced to 10 weeks in 1945 without a corresponding increase in production capacity.

Inter-Service standardisation of equipments was not carried out to any great extent because those used by the different Services were not sufficiently similar. Each Service, however, used the existing equipment of another Service when this was practicable.

SHIP FITTING

At the outbreak of hostilities the responsibility for testing and tuning wireless equipment in new construction ships, and in those undergoing large repair, was the responsibility of A9 Section, which formed part of the Experimental Section of H.M. Signal School at Portsmouth. For ships in commission this function was carried out by the Port Wireless Officer (P.W./T.O.) stationed in the Royal yards and bases.

Installation specifications were produced by H.M. Signal School and issued through the Admiralty in the 9,000 series and these, together with guidance layout drawings, where necessary, were used by the dockyards and shipbuilders for guidance in installation. Equipment for specific services was provisioned annually and the programme of building and large refits was such that requirements could be worked out well in advance.

At the beginning of the war a few long-range warning sets were fitted, and the production of these sets and others, notably Gunnery Radar, was envisaged. The production and fitting programme was speeded up and A9 Section was expanded to deal with the situation. Temporary experimental officers and assistants were recruited and given a short course of training and sent into the field.

Towards the end of 1940 a quantity of Air Ministry A.S.V. sets were obtained and a number of these sets (renamed Type 286) were fitted in ships, principally those in Western Approaches Command. A special party was formed in the Signal School to deal with this commitment.

Early in 1941 the fitting of Type 286 was rapidly expanded; more officers were attached to the Signal School to deal with its fitting and a number were lent to the Home ports to advise dockyards on layout problems and to carry out maintenance in ships.

Stores were taken over from the Air Ministry, held in bulk at Flowerdown W/T Station, and issued on charge to fitting-out officers. This was not a very satisfactory arrangement from the accounting point of view, but was the simplest way of dealing rapidly with installations in ships which became available at short notice. As the numbers of ships being fitted with radar equipment increased, the problem of maintenance became serious. Fitting out parties were strengthened, but even so, many hours were spent in travelling to and from operational bases, often only to fit a new valve or minor component. This situation improved when officers were attached to operational bases to deal with the problem.

By August 1941 the experimental section of H.M. Signal School had moved to Lythe Hill, Haslemere, and become the Admiralty Signal Establishment. A9 Section and the Type286 fitting-out Section amalgamated and became known as the M Section.

From then progress was rapid; by the end of 1941 the country had been divided into well-defined areas and it was possible to keep in touch with every phase of ship-fitting in any part of the United Kingdom. As the tempo of production and fitting increased, the staffs at fitting-out bases were strengthened and more accommodation was required. These fitting-out staffs were still nominally under the control of the M Section at Haslemere and had no official status in the Command organisation. Authority suddenly became aware of these mushroom growths and steps were quickly taken to place them on a proper basis. The result was the Port R.D.F. Officer on the staff of the Flag Officer in whose area they were based.

The M Section at Haslemere continued to function as a headquarters for all information on fitting problems and was a clearing house for all enquiries concerning layouts, stores and technical advice. Bulletins were issued on every conceivable item of information which would be of help to the Port R.D.F. Officer. If "A" discovered that the reason for trigger units in "X" set breaking down was due to an incorrectly rated resistor, he reported it to M Section who, after confirmation with the technical department concerned, sent the information out to all bases by the next mail. An "A message" or A.F.O. generally followed, but the Port R.D.F. Officer was thus always kept up-to-date and able to take prompt action with the ships in his area.

The fitting-out staffs worked long hours and their hardest work began when fitting of sets was completed and testing and tuning began. Allnight sessions were commonplace, and although in most cases ships would sail with sets complete and working, the time allowed for tuning and testing was wholly inadequate. As a result ships would arrive at Scapa Flow with 50 per cent or more of their equipment out of action. To cope with this a small group of officers was based at Scapa Flow, their main job being to tidy up loose ends and ensure that ships got good value out of their working-up period. In addition, M Section had a "Flying Squad" of experienced Naval and Civilian technical officers whose job it was to join certain ships before completion to assist with tuning and testing, sail with the ship to her working-up base and not leave until she was a satisfied customer.

By the beginning of 1943 the Port R.D.F. Officer was as firmly established and recognised as the P.W./T.O., and it was part of the routine that all ships should be visited immediately on arrival in harbour.

A very close liaison grew up between the radar officers in ships and the Port R.D.F. Officer; it persisted throughout the rest of the war and was responsible for a great deal of the success with which equipment was fitted, maintained and operated in the Fleet.

CHAPTER II

PERSONNEL AND TRAINING

OFFICERS

Technical Officers

WHEN air warning sets were being fitted in ships towards the end of 1939, R.N.V.R. officers from the ships concerned were detailed to take charge of the radar and were given brief instruction at the Signal School's experimental station at Southsea. These officers were responsible for the general supervision of the radar and the operators; they had to organise watches, arrange plotting and reporting procedure, and advise their Commanding Officers on the correct use of the equipment. The maintenance was undertaken largely by the Telegraphist Branch. Similar *ad hoc* arrangements were made to provide officers to take charge of the Scapa Flow radar stations.

It was soon realised that it would be essential to have officers with special knowledge of radio engineering, and trained in radar, if the best results were to be obtained from radar, or indeed if any reliable performance at sea was to be expected.

The first aim was to produce one such radar officer for each battleship, carrier and cruiser fitted, but for some time this was not easy to achieve. As radar officers became more numerous they were also appointed to flotillas, repair bases and fitting-out ports. At a later stage newly trained officers were sent to large ships to assist a senior radar officer. Eventually, it was usual for qualified radar officers to join, and specialise in, one of the following categories:--

(a) large ships (usually starting as Second Radar Officer);
(b) ship-fitting;
(c) escort groups;
(d) coastal forces;
(e) submarines;
(f) shore stations.

In small ships not carrying a qualified radar officer it was the practice to detail an executive officer to act as radar officer.

When radar equipment first came to be generally fitted a qualified Signal Communication Officer was appointed to fleets and certain squadrons as Fleet (or Squadron) Radar Officer. Such an officer's duties were to co-ordinate radar policy, the use of radar, and radar exercises. Initially, it was thought that a knowledge of the Royal Navy was preferable in such appointments to a technical knowledge of the apparatus. Ultimately these appointments came to be held by senior qualified radar officers who had, from their Naval experiences during the war, been able to supplement their higher technical knowledge by an understanding of Naval needs and Naval staff work.

The training of officers with specialised radio knowledge started in H.M. Signal School, Portsmouth, in mid-1940, the trainees being Canadians; these were entered as Sub-Lieutenant (Special Branch) R.N.V.R., as were most of those who subsequently took the course. With the exception of a very few R.N. Emergency, R.N.R. officers, and permanent members of the Volunteer and Volunteer Wireless Reserves, radar officers held temporary commissions in the Special Branch of the R.N.V.R. There were also some Electrical Officers, R.N.V.R., with professional or amateur radio experience, who were sub-sequently given the option of transferring to the Special Branch or remaining Electrical Officers.

Radar officers were originally trained and appointed to supervise the operation and maintenance of the radar equipment. In fact, especially during the first three years of war and before the radio mechanics were available in any numbers, radar officers had to do all the maintenance themselves, but were sometimes assisted by such operators as had an aptitude for the work.

Owing to the widespread lack of knowledge in the Fleet, radar officers afloat were, initially, the only officers aboard ship in a position to advise on the operational use of the equipment. As knowledge and experience of radar spread, other specialist executive officers (G, F, N, T & A/S) gradually became capable of taking over the operational control of the radar equipment with which they were concerned; this was because radar is not itself a weapon, but rather an important adjunct to nearly all weapons. At the same time these specialist officers began to take over the application and development of radar in their own particular spheres. This shift of operational responsibility away from the radar officer to the specialist executive officer only started to become a reality in 1944, and the transition was certainly not complete by the end of the war.

During the transition period the responsibility of the radar officer as between "operational" and "technical" duties varied in different ships and depended upon personalities and the extent to which the specialist officers could incorporate radar in their own departments. The ultimate object was that the Gunnery Branch should be responsible for the operational use of Gunnery radar and the Navigational Direction Branch for the operational use of Warning radar whilst the newly formed Electrical Branch would be responsible for the maintenance of all radar equipment. This plan has now of course been put into effect.

General Service Officers

By 1941 a considerable number of radar sets had been fitted in the Fleet and the great importance of this new instrument was becoming generally recognised. It was realised that, if the fullest benefit was to be gained from its use basic information about radar would have to be disseminated amongst executive officers generally. To this end, a series of weekly courses was started at H.M. Signal School, Portsmouth, covering the general capabilities of radar sets normally fitted and their tactical applications. Originally, the courses lasted 2 1/2 days, but were lengthened to 5 days towards the end of 1944. It is of interest to note that up to the end of March 1946 a total of nearly 7,500 officers had attended these courses. In addition, all other regular executive officers' qualifying courses, such as that for Sub-Lieutenant R.N. or R.N.V.R. qualifying for Lieutenant, now include periods of radar training.

Specialist Executive Officers

In order to equip the specialist executive officers to take over full operational control of the equipment, all short, long and refresher ' G' and ' N ' courses after 1944 included periods varying from two to eight weeks' training in basic radar theory and in the technical equipments.

Recruitment of Technical Officers

As radar became available for fitting, the problem arose of finding officers suitable to supervise the operation and maintenance of the equipment. This task fell to H.M. Signal School.

Initially, one officer from each ship to be fitted with radar was selected and sent to Portsmouth for brief instruction. It was, however, soon realised that it was essential that these " R.D.F. Officers," as they were then called, should have a sound knowledge of radio.

Meanwhile there was keen competition for the nation's radio and electrical manpower from the other Services, in particular from the R.A.F. The Navy, while itself having many competing interests, also suffered from the disadvantage of having started to look for suitable men some time after the other Services, and so in order to recruit the required numbers, the Navy had to lower its standards progressively and generally did not obtain such well-qualified personnel as did the R.A.F.

Until February 1945 prospective candidates were interviewed and their various qualifications considered in the Department of Scientific Research and

Experiment, Admiralty. After February 1945 all candidates were interviewed by a properly constituted Admiralty selection board in H.M.S. *Collingwood*.

In order to meet the rapidly increasing requirements for radar officers in face of the growing competition for suitable candidates, the Navy tapped various sources. When it was first decided to recruit radar officers with technical qualifications, efforts were made to find, and transfer to radar, officers who were already in the Navy and who had a knowledge of radio. These officers usually retained their executive status. The supply of such officers was rapidly exhausted.

At this stage it became necessary to widen the field of selection. The physical standard of fitness normally required for executive officers was relaxed, and the normal period of executive training was greatly reduced. Most officers joining under the new conditions were usually granted temporary commissions in the Special Branch of the R.N.V.R. The four main sources of candidates for commissions in the Special Branch as radar officers are discussed below in the order of importance.

DIRECT ENTRY FROM OUTSIDE SOURCES

Various outside sources provided suitable candidates. These men were usually direct entries to the Navy, and they were granted commissions immediately on joining. Efforts were made to recruit men with degrees, particularly with scientific or engineering degrees, and men with a knowledge of radio. Men were seconded from industry, especially from the cinema trade. Certain civilians who had some experience in fitting wireless equipment were accepted without further training and appointed for fitting-out duties. To meet special requirements, a few Scientific Officers from A.S.E. were given protective commissions in the R.N.V.R.

CANDIDATES FROM THE LOWER DECK

Commissions were granted to suitable candidates from the lower deck. Originally, the majority of candidates were operators who had been enthusiastic wireless amateurs; later the main supply consisted of radio mechanics.

UNIVERSITY CANDIDATES

In the spring of 1941 arrangements were made to secure the early release of selected candidates from the universities. At the same time special university radio courses, with a bursary scheme, were instituted by the Hankey Skilled Radio Personnel Committee. These candidates were direct entries.

DIRECT ENTRY FROM THE DOMINIONS

At the beginning of the war a request had been made to the Canadian Government for the loan of engineering physicists for various duties, including radar. In response to this the National Research Council of Canada, together with the Canadian universities, compiled a register of trained men. The first batch of Canadians started their radar training in the United Kingdom in May 1940. It was only the timely arrival of these Canadians that saved the Navy from facing a truly disastrous position in regard to radar personnel. As in Great Britain, many of the Canadian universities modified their courses to suit the work that lay ahead and subsequently supplied further contingents, all of whom were of a high standard. Similar aid came later from Australia, New Zealand, South Africa, and India. Many of these officers returned later for service with their own Navies. All such candidates were direct entries.

In addition, from 1943 onwards a few W.R.N.S. officers were recruited, did a part of the course, and were appointed generally for maintenance duties to shore establishments.

Between May 1940, when organised courses were started, and May 1941, a total of 52 radar officers had been trained. By November 1942 the total of trained radar officers had reached 380; by the end of the war they numbered 720 and were being accepted in batches of 12 a month.

At the end of the war the total number of radar officers, including some who had not received Naval radar training, was just over 800; of these, about 100 were from the Dominions. The officers from the Dominions at one time numbered nearly 150, but from time to time some were recalled to serve with their own navies.

Training of Technical Officers .

In the early days of the war no particular efforts were made to organise special courses for officers appointed to look after radar, nor was this feasible, because these officers were arriving in H.M. Signal School in twos and threes; all that was possible was to give them brief instruction and show them the equipment.

With the arrival of the first batch of Canadians, about 20 strong, in mid-1940, an attempt was made to organise some sort of training programme for them and for the subsequent batches of officers that were anticipated. The training was for an indefinite period, lasting usually until the officers concerned were appointed to ships; it included one week's instruction in plotting and sea-going terminology, brief instruction in the equipment by the designer, and a period at Fort Wallington where there was a Type 79 installed, forming part of the CH network. The first course in 1941 was of 3 weeks' duration plus one week's divisional training in R.N. Barracks, Portsmouth, supplemented by an indefinite period at Fort Wallington, either while awaiting course or while awaiting appointment. Theoretical training in Type 79, and an introduction to the sets Type 281 and Type 285, were given by an Instructor Officer, and a few lectures on operational matters were given by a Signal Officer. Outline training on the equipments was given in A.S.E. Research Establishment at Eastney Fort East, and at Onslow Road, Portsmouth. Training continued on these lines until May 1941.

By May 1941 the classes had gradually become better organised. At this time, too, the system of giving each class a distinguishing letter was started, the class then going through being allocated the letter " A." The last class started during the war was Class " XX," and the last normal H.O. Long Radar Course was Class " ZZ " which completed training in July 1946.

In May 1941 the training was more or less on the following lines: five weeks theoretical and practical instruction in radar at H.M. Signal School, three days in H.M.S. *Excellent* for fire-control, one week at Allen West's factory at Brighton, and about one week at Fort Wallington to obtain practical experience in operating. At the same time some of the sets installed in Radex House, Southsea, were becoming available for demonstration and practical instruction.

In July 1941 a proper staff of instructors, consisting of two radar officers and one Instructor Lieutenant, was appointed; these three were responsible for the instruction of all classes up to December 1943, when a much bigger staff was enrolled.

In August 1941 the instruction at H.M. Signal School was extended to eight weeks in order to include preliminary instruction on basic radio theory.

By the end of 1942 the instruction at H.M. Signal School had been increased to about 10 weeks and, in addition, five weeks were spent in H.M.S. *Valkyrie,* in the Isle of Man, for practical training. In 1943 the visit to H.M.S. *Valkyrie* was replaced by a penod of three weeks in the Radar Training Flotilla operating in the Clyde.

At the end of 1943 the training syllabus was completely overhauled and the course extended to about six months. The new course was designed to give a thorough grounding in basic radio principles, all types of Naval radar equipment in general use, and a certain amount of instruction regarding the operational use of radar. For this extended course it was necessary to increase the staff of instructors considerably and radar officers with sea experience were appointed. The basic radio course by now had been extended to about five weeks and for this some additional Instructor Lieutenants were appointed. During 1945 the courses were gradually extended to nine months.

In 1944 much new radar equipment was becoming available for fitting in the Fleet and it was realised that many of the radar officers who had qualified earlier in the war would be handicapped by their lack of knowledge of this new equipment. Accordingly a refresher course lasting three weeks was organised and efforts were made to enable radar officers to attend. The course was started in the autumn of 1944 and continued for about a year, during which time about 200 radar officers received instruction. Early in 1945 the officers' training was transferred to, H.M.S. *Collingwood* at Fareham.

RADIO MECHANICS

Evolution of Radio Mechanic Branch

Although the institution of a new branch to maintain wireless equipment had been mooted as far back as 1930, the decision to create the new Wireless Mechanic Branch was not made until May 1941. By this time the issue had become urgent owing to the ever-increasing number of radar sets being fitted and to maintenance having become a full-time occupation for radar officers.

Originally, it was intended that wireless mechanics should be able to maintain both W/T and radar equipment, but, as telegraphists were accustomed to servicing W/T equipment, and the demand for maintenance personnel for radar was so great, it was some time before mechanics could be drafted for other than purely radar duties. The first wireless mechanics for radar maintenance were drafted towards the end of 1941.

At the end of 1941 it was clear that, although the final objective was to train all wireless mechanics to service W/T and radar equipment, if sufficient mechanics were to be trained to meet immediate requirements a certain specialisation in the Naval technical training would be essential. Mechanics were accordingly divided into two categories after completing the Civil Technical College course, Wireless Mechanics (R) being given a 6 weeks' course on radar, and Wireless Mechanics (W) 2 1/2 weeks on W/T and 3 1/2 weeks on radar.

In May 1942 the Wireless Mechanic Branch was transformed into the Radio Mechanic Branch. Mechanics were now divided into the following categories:--

Radio Mechanic (R)--general service; maintenance of radar only.

Radio Mechanic (W)--general service; maintenance of radar and W/T in small ships.

Radio Mechanic (S)--maintenance of shore W/T.

A radio mechanic was an artisan and, on successfully completing his training he was advanced to Leading rate. After one year in the Leading rate, and if recommended, he could be advanced to Acting Petty Officer and confirmed after a further year.

In mid-1943 the original intention of training all radio mechanics to service both W/T and radar equipment was finally abandoned and it was decided that only Chief Petty Officers would have to be so qualified. A start was made in withdrawing Radio Mechanics (R) and (W) from sea and these were given a two months' course to qualify them professionally for Chief Petty Officer. Mechanics thus qualified became P.O. Radio Mechanic (C) until advanced to Chief Petty Officer. For this course P.O. Radio Mechanics (R) were instructed in W/T, and P.O. Radio Mechanics (W) were instructed in radar.

In mid-1944 the C.P.O. course was reorganised. In this new course ratings could specialise in either W/T or radar, although it was not until April 1945 that an A.F.O. was published stating specifically that C.P.O.s would not be responsible for the maintenance of both W/T and radar equipment.

The last stage in the evolution of the branch in war-time was the institution early in 1945 of three new categories of general service radio mechanics:--

Radio Mechanic (W/T)--for maintenance of W/T.

Radio Mechanic (R)--for maintenance of radar.

Radio Mechanic (WR)--for maintenance of all types of small ship radar and W/T.

Shortage of Radio Mechanics

At no time during the war were there sufficient radio mechanics to meet requirements, and this was one of the major factors contributing to the all too frequent cases of breakdown and inefficient performance of radar equipment which occurred in the Fleet. As a further result of the persistent shortage there was always difficulty in making mechanics available for the refresher courses which are so necessary when equipment is undergoing continual modification.

The grave shortage of radio mechanics was due primarily to two causes: first, the lack of foresight in delaying the decision to provide mechanics until 1941, and, second, the failure after this decision had been made to visualise the large numbers that would be necessary to ensure efficient maintenance.

To alleviate the shortages of radio mechanics it was decided in 1943 to train W.R.N.S. Radio Mechanics for servicing both W/T and radar equipment at shore stations, in ships in port, and at coastal force bases. The use of W.R.N.S. for this purpose was generally successful and it enabled numbers of general service radio mechanics to be released for sea service. By mid-1945 the total of W.R.N.S. mechanics had reached about 650.

An illustration of the lack of a decisive policy for radio mechanics is afforded by the fact that it was not until the autumn of 1944 that a firm figure of the requirement of radio mechanics was received by the Director of Manning. This requirement was for 5,635, and at that time only 3,754 including 320 W.R.N.S. were borne. Every effort was then made to increase the number, although the man-power situation at that time made the task extremely difficult, and it was not until mid-1945 that the total borne of 5,650 including 650 W.R.N.S. approached the total requirement.

Selection and Training

The limited supply of civilians whose qualifications made it possible to absorb them immediately in the Radio Mechanic Branch was soon exhausted; these men were given a few weeks' training on radar equipment at H.M. Signal School and then drafted. It soon became clear that there was no alternative to putting men, usually with no previous radio experience, through a long and intensive training to fit them for the job of maintaining radar and W/T equipment, and special courses were started in July 1941.

The men selected for this intensive training had to be up to School Certificate standard educationally, and to have an interest in, but not necessarily a knowledge of, radio. These men were sent first to Civil Technical Colleges under a scheme sponsored by the Hankey Skilled Radio Personnel Committee; here they were given a course in basic electricity and basic radio, and instruction in special radar circuits and fault-finding technique, and the course included theoretical instruction and practical work. Initially the course lasted 17 weeks. After doing the Technical College course the men were sent to a Naval establishment to undergo training on the actual equipments they would have to maintain at sea. In 1942 this Naval Training Course lasted about 10 weeks and comprised training of Radio Mechanics (R) in all types of radar equipment, and training of Radio Mechanics (W) in small ship radar and small ship W/T equipment.

The products of this training programme were not uniformly successful. Reports received from sea indicated that many of the mechanics lacked the necessary practical ability for handling tools and instruments. Consideration was given to this matter during 1943 and it was decided that the poor quality of a number of the mechanics was due to two causes:--

(1) the training programme laid too much emphasis on theoretical instruction and too little on practical work, and it was said that the course produced a low grade radio engineer instead of the radio Serviceman required;

(2) some men were being accepted for the course who, although up to the required educational standard, lacked the necessary aptitude for manual dexterity.

In 1944, after a certain amount of delay, the training syllabus was recast to devote more time to practical work and less to theoretical instruction. Also, an attempt was made to improve the standard of training at the technical colleges by remedying the following restrictions:--

for reasons of security adequate information on radar had not been passed to the colleges, and without such information it was impossible to plan the syllabus of instruction properly;

insufficient apparatus had been allocated to the colleges, and without this apparatus it was impossible to give the necessary training in practical work.

With this reorganisation of training its duration had to be increased, and so the Technical College course was increased to 20 weeks, and the training in Naval establishments was increased, first to 18 weeks and later, towards the end of the war, to 22 weeks.

At about the same time the procedure for selecting candidates was improved. Before starting the course they were all interviewed by a Personnel Selection Officer, their suitability being based on the results of a biographical questionnaire prepared by the Admiralty Psychologist.

The biographical questionnaire was designed to obtain information on the man's educational and occupational record, his hobbies, and responsibilities, etc. The questionnaire was then considered in conjunction with results obtained from certain standard tests; in addition, the candidate was required to be above average in intelligence and 'practical' ability, to have reached university entrance standard educationally, to be interested in electricity or radio, and to be steady, persistent and conscientious in his approach to the training and the job. The standard required was necessarily high in view of the intensity and content of the course.

From mid-1944 considerable attention was paid to the provision of adequate refresher courses on radar equipments, both for Petty Officers and Leading rates. In due course the reforms in the selection and training of mechanics bore fruit in that the standard of maintenance at sea was improved.

No special qualifying course for P.O. Radio Mechanic was initiated during the war, the qualification for advancement to P.O. being one year as Leading rate and a recommendation. In mid-1943 a course of a few weeks was started to qualify P.O. Radio Mechanics for advancement to C.P.O. Radio Mechanics; in mid-1944 the standard of the course was raised and its duration increased to 17 weeks plus a preliminary refresher course intended to bring all participants to roughly the same level of knowledge.

RADAR OPERATORS

Radar Operators (1939-1943)

At the outbreak of war only two ships were fitted with a radar set and no special provision had been made to provide trained personnel to operate them. Operators for these sets were selected from the Telegraphist ratings serving in each ship, and the ships were left to work out their own operating and reporting routines.

As the radar equipment had been provided by H.M. Signal School, it was natural that the operators should also come under the aegis of the same establishment. From late in 1939 the ratings selected as radar operators were given a few weeks' training at H.M. Signal School, Portsmouth. At first only small numbers of operators were required, but during 1940 the number of sets fitted increased rapidly and difficulties were encountered in providing and training sufficient ratings.

In the autumn of 1940 it was decided to meet the requirements by instituting a specialised section of the Seaman branch for radar operating duties. Only Ord. Seamen (H.O.), mainly new entries, were selected and they were transferred to a special roster of Radar Operators, or R.D.F. Operators as they were then called. These ratings were required to have completed only Part I Seamanship training, they did not necessarily have to be up to the physical standard normally required of seamen, ordinary sea service qualifications were not required for advancement, and they were not required to perform the normal duties of seamen. They were advanced on a time basis with recommendation, no professional qualifications being required. By these measures it was hoped to meet the ever increasing demands for radar operators.

In spite of the steps taken to provide them quickly the large number of operators required were not always available. Where deficiencies in the radar complement existed, ships were allowed to employ, as Acting Radar Operators for watch-keeping duties, any suitable ratings whose normal duties were not interfered with by watch-keeping on the radar.

The numbers of operators borne in ships continued to increase. In 1942 it became generally realised that these operators could not be kept fully employed on radar duties, while at the same time they occupied a significant proportion of the available ship accommodation. For these reasons there came a growing demand from sea that the radar operators should be qualified substantively as seamen and made available for the normal duties of seamen when not required for radar. Proposals on these lines were put forward by H.M. Signal School.

In December 1942 an A.F.O. was issued in which it was stated that the Radar branch was to be reorganised as a non-substantive rate for the Seaman branch. The details of the reorganisation were still under discussion, but preparatory steps were taken to facilitate the eventual reorganisation. It was laid down that all new entries, and all ratings transferring to radar, had to be fit in all respects for the Seaman branch. Also, the qualifications for substantive advancement for all radar ratings whose date of qualification in the radar branch was later than 1st February 1943 had to be those for the Seaman branch.

Two big problems of manning which involved radar came to the fore in 1943. The first was that of manning the Aircraft Plot, which was shortly to combine with the Surface Plot and the Target Indication System, etc., to form the Action Information Organisation. It was considered desirable that the plot ratings for the Aircraft Plot, and for its successor the Action Information Centre, should have some knowledge of radar, and conversely that the Radar operators of warning sets should be acquainted with the duties of the plot ratings.

The second problem arose from the need for non-substantively qualified ratings to operate fire-control instruments because radar had come to play such a large part in fire-control that it was realised that the fire-control problem was analogous to that of the Aircraft Plot and that it would therefore be desirable to man the fire-control instruments with ratings conversant with the operation of gunnery radar.

Finally, there appeared to be a clear-cut demarcation between these two requirements, and out of these considerations sprang the scheme of organisation of the new R.C. and R.P. branches.

RC/RP Scheme

In February 1944 the RC/RP scheme was introduced, the main features of which will now be described.

The selection and entry to the R.C. and R.P. branches was to be similar to that for any other Seaman's non-substantive branch. The duties of the two categories of rating are given below.

> *Radar Control Ratings* (R.C. ratings). To man all gunnery and target indication sets and to carry out certain important fire-control duties in the T.S. and/or calculating positions.
>
> *Radar Plot Ratings* (R.P. ratings). To man all warning sets and to carry out plotting duties in the Action In-formation Centre and relative positions.

Upon entry to these branches, Seaman ratings first had to qualify for the non-substantive 3rd class rate of either R.C.3 or R.P.3. They were advanced substantively like other Seamen, i.e. by passing professionally, and they could qualify for advancement non-substantively, through R.C.2 or R.P.2, to R.C.I or R.P.l. Passing a non-substantive rate, however, did not qualify them for substantive advancement, though it still did in the case of the obsolescent Seaman (Radar) ratings. Later it was decided that RC/RP ratings should have the opportunity of promotion to the commissioned ranks of Gunner or Boatswain (P.R.), through the non-substantive rates of Gunner's Mate or Plotting and Radar Instructor (P.R.I.).

The R.C. ratings came under the control of the Gunnery Officer, and the R.P. ratings were put under the control of the Navigating Officer because the latter had been made responsible for the Action Inforrnation Organisation.

All ratings in the now obsolescent Seaman (Radar) branch were encouraged to qualify professionally in the Seaman branch and to transfer to the RC/RP branches. It was inevitable, however, that some H.O. ratings would be unable to transfer, generally because they were not up to the physical standard of fitness required for the Seaman branch.

In general the RC/RP scheme worked well and solved the problem of what to do with so many radar operators when they were not required for operating, and it is interesting to note that, at the end of the war, in a light fleet carrier, over half the ratings available for upper deck work were RC/RP ratings.

Although there were usually sufficient Ordinary Seamen (Radar) and Able Seamen (Radar), grave shortages were experienced in the higher rates, and in the early years also in operators with sea experience. Shortages of Leading Seamen (Radar) existed up to mid-1943, and there were never sufficient Petty Officers (Radar) available. The lack of operators with sea experience resulted initially in many ships being sent, on commissioning, a draft of operators all or most of whom were quite inexperienced, but this position was mitigated in 1942 by the introduction of a dilution scheme. Under this scheme a proportion of experienced operators in commissioned ships were relieved from time to time by inexperienced operators, the experienced operators thus relieved then becoming available for drafting to newly commissioned ships.

Situation at the End of the War

By early 1945, when the RC/RP scheme had become well established the total of RC3/RP3 ratings approximately equalled the total required, though at one time there had been an excess of RP3 and a shortage of RC3 ratings; this state of unbalance was rectified by converting RP3 ratings to RC3. At no time were there sufficient RC2/RP2 and RCl/RPl ratings, and the lack of instructors was very marked.

In July 1945 a special temporary scheme of advancement was introduced in an attempt to alleviate the shortage of higher rates. Under this scheme RC/RP ratings could be trained and examined at sea to qualify for the first or second class rates. If such ratings satisfied the ships' officers who examined them they were rated up on a ' U,' or unqualified basis. Successful candidates retained their new rating until an opportunity arose for them to be sent to a shore training establishment where they were confirmed in their new rates, or otherwise.

By mid-1945 the RC/RP branches had reached a peak total of about 16,500 ratings. Demobilisation, which began at the end of May 1945, had the effect of worsening the manning situation, and an analysis of the age groups revealed that both 1st and 2nd class ratings could be expected to leave the Navy at a faster rate than replacements would cover, even at the maximum possible training rate; the shortage of 3rd class ratings, however, was not so serious. In view of this situation the policy decided in May 1945 for the RC/RP branches was as follows:--

> to fill all the courses as far as possible; to include the highest possible proportion of continuous service ratings;
>
> to increase facilities for training all 2nd class rates, if necessary reducing 3rd class training;
>
> to introduce emergency measures for obtaining higher rates, particularly instructors; for the RC branch the transfer of other higher gunnery rates was considered feasible, but for the RP branch the only possible course was by depleting the Fleet of many of its best higher rates.

Generally, it may be said that the greatest need was that of attracting the Continuous Service rating, of whom there was at the end of the war a very serious shortage. For the first four years of the war such ratings were debarred from becoming radar operators and it was therefore a branch little known by influential ratings on the lower deck.

Training Early in the War

Before the war no organisation existed, or had been planned, to train radar operators. The two ships then fitted with radar carried out their own training of the ratings detailed to operate the equipment. From this humble beginning the training of operators progressed throughout the war in consonance with the development of radar equipment.

Soon after the outbreak of war it became necessary to train operators for the WA sets that were to be fitted in cruisers and above. The ratings selected were sent to H.M. Signal School Portsmouth for a few weeks' instruction. In 1940 this course was extended to five weeks, and arrangements were made to use for training during the night A.S.E.'s experimental Type 79 fitted in Eastney Fort East.

In anticipation of the general fitting of the gunnery sets Types 282/4/5, the classes were increased. To meet the pressure of training requirements it was decided early in 1940 to build Radex House, near Eastney Fort East.

Up to mid-1940 the training programme had proceeded more or less according to plan.

In mid-1940 the discovery that the A.S.V. set used by the R.A.F. could be readily converted to Naval use (as Type 286) upset the whole training programme. Because fairly large stocks of A.S.V. equipment were available for adaptation and fitting in ships, there arose an immediate requirement for operators which was difficult to meet. Later the position became yet more difficult with the advent, first of Type 290, and then of Type 271. The rapid expansion of the training programme necessary to meet requirements enforced the specialisation of training; the operators were trained to operate only specific classes of set, *i.e.* WA, WC or Gunnery sets. This specialisation enabled the training to be of minimum duration, but it had the disadvantage of making drafting more complicated.

The expansion of training and the delay in the completion of Radex House through bombing made it necessary to organise a larger training establishment and to locate it away from the danger areas. A suitable site was found in the Isle of Man, where buildings were requisitioned and fitted out for training. Training was started at this school, H.M.S. *Valkyrie,* towards the end of 1941, and the courses were of four or five weeks' duration.

In the meantime courses had been started at H.M. Signal School to qualify operators for advancement to Petty Officer (Radar). These courses included a considerable technical content, as Petty Officers (Radar) were expected to do a good deal of maintenance in addition to assisting in the training and supervision of operators.

During the course of 1942 various steps were taken to supplement the basic radar training received by the operators in H.M.S. *Valkyrie. A* Radar Training Flotilla was formed to give all operators two weeks practical training at sea, and schools were set up at most of the principal ports at home and abroad. The object of these schools was to provide short refresher courses for qualified operators and to train acting radar operators for those ships which did not carry a qualified radar officer. The biggest of these schools was at Sherbrooke House, Glasgow, which catered for the numerous ships in the Clyde area. Refresher courses were of the utmost value, because unfortunately radar operators, on completing their training in H.M.S. *Valkyrie,* were often drafted to depots and kept there for long periods without having anything to do with radar; under such conditions they soon forgot the little they had learnt while under training.

Towards the end of 1942 the training syllabus at H.M.S. *Valkyrie,* for all operators except those destined to operate Type 271 in small ships, was altered to include instruction in elementary fire-control, a Gunnery Officer being appointed to H.M.S. *Valkyrie* to implement this training. From mid-1943 these operators were sent to H.M.S. *Excellent* for one week's instruction in gunnery, in addition to their training in H.M.S. *Valkyrie.*

Meanwhile, at the Fighter Direction Centre at Yeovilton, Plot Control ratings were being trained to man the Aircraft Plot. It was soon appreciated that it would be advantageous to employ ratings for the Aircraft Plot who had some knowledge of radar, and so training of Plot Control ratings was stopped and a certain number of radar operators were sent to Yeovilton for a short course on aircraft plotting immediately after their training in H.M.S. Valkyrie.

At about this time pre-commissioning courses were started for radar operators and others about to join ships. Operators were sent for training as a team to one of the schools, either to the Gunnery Schools or the Fighter Direction Centre at Yeovilton, and later on to H.M.S. *Dryad* (for training in the Action Information Organisation).

Training Under the RC/RP Scheme

The next development came in 1944 with the introduction of the RC/RP scheme. Under this scheme the courses were extended and differed widely for RC and RP ratings. Also, effect was given to the gradually formed conviction that no operators, not even the higher rates, should be concerned with maintenance. By 1944, maintenance was held to be entirely the job of the radio mechanic -- a view completely at variance with that held in the early years of the war.

Early in 1944 the first RC/RP classes went through H.M.S. *Valkyrie,* where they were given about four weeks' general instruction in radar (Part I of the training). After this RC ratings were sent to the Gunnery Schools for Part II training, which up to May 1945 lasted for three weeks. RP ratings were given an intensive two weeks' course in the Radar Training Flotilla, where they were instructed in Group A/S work, warning radar and plotting, before going to Yeovilton for a three weeks' course in Fighter Direction and Aircraft Plotting. After April 1945 RP ratings were given an additional course of one week on Surface Plotting in H.M.S. *Dryad*. The training of RPl and RP2 ratings in surface plotting started in August 1944.

A complete syllabus of RC/RP training was published in July 1945. The durations of the courses were:--

	PART I	PART II
RCl	12 weeks	11 weeks
RC2	6 weeks	6 weeks
RC3	4 weeks	5 weeks
RPl	12 weeks	9 weeks
RP2	8 weeks	6 weeks
RP3	5 weeks	4 weeks

Later in 1945 it became clear from sea experience that the question of maintenance by radar operators needed review again. At the end of 1945 it was generally agreed that the operators should undertake the responsibility for unskilled maintenance work, such as daily routine tests, but that anything more complicated pertained to the radio mechanic.

On 1st November 1945 responsibility for the whole of the training of RC and RP ratings was assumed by H.M.S. *Excellent* and H.M.S. *Dryad* respectively.

The Radar Training Flotilla had, by the summer of 1945, been reduced to one ship, H.M.S. *Isle of Sark,* and in due course she also was returned to her original owners and other arrangements were made for the essential sea training of operators.

Selection of Radar Operators

In the first instance no special machinery existed for selecting ratings. Whenever possible those selected were above the average of intelligence for Ordinary Seaman and were recommended.

In 1942, selection was put on a more scientific basis with a system introduced by the Admiralty Psychologist. Under this scheme ratings were interviewed by a Personnel Selection Officer (P.S.O.). Only those who, as a result of the interview were shown to fulfil certain conditions were selected as radar operators; these conditions were that they must:--

be above the average of intelligence required for Ordinary Seaman (H.O.):

be devoid of neurotic symptoms;

have a sense of responsibility and mental stability.

Owing to an initial lack of Personnel Selection Officers in 1942 the scheme was then limited to about half the new entry intake. As more P.S.O.s became available the scheme was extended, until in 1944 all new entries could be interviewed, and by 1945 a large proportion of ratings transferring could also be interviewed.

Although it is not possible to prove conclusively that this selection procedure improved the standard of operators, such statistics as have been determined do point to this conclusion.

TRAINING FACILITIES

Originally, all radar personnel were trained in the Portsmouth area, under the direction of the Captain, H.M. Signal School. Lectures were given in Portsmouth Barracks. Some practical training was given on Type 79 equipments, one of which was installed at Fort Wallington and formed part of the CH network, and the other which was installed at Eastney for experimental purposes.

It was not long before the need for better facilities for practical training became obvious and it was decided to build Radex House on the foreshore at Eastney. The completion of Radex House was much delayed by bombing, and not until May 1941 could training there be started. The inadequacy of accommodation and facilities at Portsmouth, which was accentuated by the bombing, soon became apparent, and so other arrangements were put in hand.

Early in 1941 a new training school for the basic radar training of operators and mechanics was set up in the Isle of Man, which was relatively free from air attacks. Suitable buildings were requisitioned for the accommodation of personnel, and for the training school H.M.S. *Valkyrie* which was situated on a headland giving an uninterrupted outlook over the sea. To supplement the training at this new school, the Radar Training Flotilla was formed in 1942 to provide practical instruction under sea conditions. This Flotilla was first based for about a year on Douglas, I.O.M., and was then moved to the Clyde area where the conditions were more favourable.

In due course two major drawbacks to H.M.S. *Valkyrie* as a training school became obvious; these were that its distance from the Home ports necessitated considerable travelling on the part of the ratings, and hence much loss of time, and that the accommodation provided for ratings was at some distance from the school, thus causing daily a further loss of training time.

At about the same time a small school for operators and mechanics was started at Sherbrooke House, Glasgow. It provided refresher courses for qualified operators and mechanics and trained acting operators from the numerous ships visiting the Clyde. Similar schools were also set up from time to time at many of the principal ports at home and abroad.

In March 1944 a Captain (Radar Training) was appointed with the responsibility of organising all radar training. With the appointment of the Captain (Radar Training), H.M.S. *Collingwood* was selected as the future centre for all Naval radar training, and it was intended that H.M.S. *Collingwood* should be essentially a Technical Training establishment.

As facilities became available more and more radar training was transferred to H.M.S. *Collingwood*. The first step was to transfer from H.M.S. *Valkyrie* the radio mechanics', and part of the radar operators', training. Radex House was still retained for operational training.

Owing to the ramifications of the RC/RP branches, and to the numbers of ratings involved, the training of RC/RP ratings was not to be solved so simply. The final objective was to make provision for their complete training at each of the Home ports, but owing to lack of facilities, progress in this could only be made by degrees.

By May 1944 the training of RC/RP ratings was proceeding as follows:--

> Part I Training of all RC/RP ratings -- in H.M.S. *Valkyrie*.
> Part II Training of all RC ratings -- at the three Gunnery Schools.
> Part II Training of all RP3 ratings at the Plotting School, H.M.S. Collingwood
> Part II Training of all RP2/RPl ratings first at the F.D.C. Yeovilton, and then at the A.I.T.C., H.M.S. Dryad.

The building difficulties delayed the provision of complete training of RC and RP rates at each of the Home ports and so, in the autumn of 1945, the following interim scheme was adopted:--

> H.M.S. *Valkyrie* was to be retained to carry out Part I training of both RC and RP ratings until the end of 1946.
>
> RP3 Part II training in H.M.S. *Collingwood* was to be retained as long as possible, until H.M.S. *Dryad* and other radar plotting schools were able to take on training.
>
> The new plotting schools were to be located and built as quickly as possible.

Apart from the training schools established in the U.K. the following facilities for training existed abroad:--

> *H.M.A.S. Watson* at Sydney for training of RC3/RC2 and RP3/RP2 ratings.
> Training of RC3/RP3 ratings at Malta.
> Ships at sea carrying suitable officers were authorised to qualify fully RC3 and RP3 ratings, and to qualify 1st and 2nd Class rates on a " U " basis.

These measures were invaluable in alleviating the grave shortages in the Fleet of properly qualified RC/RP ratings.

As these measures for the training of RC and RP ratings came to fruition, H.M.S. *Collingwood* was equipped for her destined role of undertaking all the electrical training of all the Navy's technical personnel.

GENERAL CONCLUSIONS REGARDING RADAR PERSONNEL

Throughout the war Naval radar was handicapped by a lack of properly qualified personnel, including officers, mechanics and operators. This frequently contributed to equipment not being used to full advantage, and unfortunately cases were all too numerous when the equipment was not even functioning correctly through lack of maintenance personnel or adequate facilities for maintenance.

The difficulties encountered in manning equipment, and the makeshifts resorted to for recruiting and training personnel, can be ascribed largely to lack of foresight in gauging the future development and importance of radar. The early lack of a proper appreciation of the situation resulted in undue delay in recruiting suitable personnel, which permitted other competing interests to recruit an undue proportion of the nation's existing suitable manpower. In particular, the ratio of radio mechanics in the Navy to those in the R.A.F. was unduly low, and remained unadjusted long after the discrepancy was realised.

In the matter of training, grave deficiencies existed during the war though improvements were introduced from time to time. Such deficiencies in maintenance personnel were more serious than in operators, because the former naturally required a more specialised and lengthy training. The difficulties arose both from an initial lack of qualified instructors and the continual and pressing need for personnel to man equipment fitted in ships. The initial lack of qualified instructors resulted in a poor standard of training in the early days, and the urgent need for personnel afloat demanded that the periods of training be kept to a minimum. Both these circumstances militated against a high standard of training, and furthermore made the ensuing task of improving general standards throughout the Fleet even more difficult.

Although in war it is inevitable that training must be intensified and speeded up, experience shows that the following points must not be overlooked.

(a) It is essential to have a nucleus of qualified and experienced instructors for training all grades of radio personnel available on the outbreak of war so that there need be no delay in embarking upon expanded training programmes.

(b) The technical training of personnel must be undertaken in anticipation of the shipbuilding and ship-fitting programmes. In general, equipment can be manufactured and fitted more speedily than personnel can be trained, and this must be borne in mind if ships are to commission with full complements.

(c) The priority of new equipment allocated for technical training should be at least on a par with that given to operational fitting. During the war it was generally the policy to allocate equipment to ships before training establishments; consequently, ships were often unable to make the best use of new equipment solely because they lacked the trained personnel to maintain it.

Adoption of these three principles would go a long way towards preventing a recurrence of such circumstances.

The realisation of the importance of radio in modern warfare, apart from its use for communications, only came gradually during the war. By the end of the war radio had assumed an all-important role in many applications, of which radar is but one. There can be no doubt that radio will assume an even more preponderant role in any future conflict, and furthermore, the equipment will probably be even more diverse and complicated and will be used on a far wider scale than at present. It cannot be emphasised too strongly that the basis for the war-time organisation for the operation and maintenance of radio equipment must be laid in days of peace, before the advent of war; and plans for the rapid expansion of the organisation, for the recruitment and training of personnel and for the mobilisation of reserves already having experience in radio, must be laid well in advance if the transition from peace to war is to proceed smoothly and the Fleet is to be provided with radar personnel in adequate numbers.

CHAPTER III
ENEMY RADAR
GERMAN NAVAL RADAR

Pre-War Equipment

GERMAN interest in the possibilities of radar appears to have started in 1934. Telefunken rejected a proposal to develop pulse radar for ship and aircraft detection, and the firm of Gema undertook the development of the "Freya" equipment, which was ready for trials in 1938. "Freya" went into large-scale production and was widely used during the Second World War as a land-based radar for ship and aircraft detection; about 100 equipments were actually in existence at the outbreak of war.

The "Freya" equipment had separate arrays for transmission and reception which were mounted on a rotatable mesh reflector. The beam width of this array was 40°, zero to zero. Lobe switching was possible on the receiving array, giving a bearing accuracy of better than 1°. Range accuracy was better than 1000m. The frequency was about 125 Mc/s at a peak power output of the order of 15kW. Later in the war the frequency range was widened to 115-145 Mc/s, mainly as an anti-jamming measure.

From the naval viewpoint a more important development was the Gema "Seetakt," designed for coastal defence. About a dozen of these were ready at the beginning of the war. The "Seetakt" had a large "mattress" type aerial array, giving a beam width of 15°, zero to zero. The bearing accuracy was about 0.2° and range accuracy was better than 1000 m. The frequency was 370 Mc/s (80 cm.) at a peak power output of 7kW. The p.r.f. of the earlier models was 1000 c/s, but this was later reduced to 500 c/s. With a set sited 250 feet above sea level a range of about 22 miles against a small craft was possible.

The only other set in production at the beginning of the War was the "Wurzburg" which was used mainly for A/A and searchlight control. This set was also adapted for coastal defence in the form of the "Wurzburg Seeriese." The "Wurzburg" used a single paraboloid, of diameter 3 metres, for both transmission and reception. Later, the "Giant Wurzburg" was built using a larger mirror of 7.5 metres diameter. The frequency was 560 Mc/s at a peak power output of 7 to 11kW. Bearing accuracy was +/-1.8° and ranging accuracy +/-150 m. An idea of the performance of the "Wurzburg Seeriese" is given by the following figures: with the set sited 100 feet above sea level a range of about 19 miles could be obtained against a battleship, 15 miles against a destroyer and 6 miles against an M.T.B. With the set sited at 400 feet these figures were increased to 32, 27 and 12½ miles respectively.

War-time Equipment

Examples of the radar fitted in typical German warships are given in the following table.

CRUISERS

Prinz Eugen.	Gema for range-finding; Gema for general warning; Berlin; also one Gema never set up.
Leipzig.	One Gema which was never used operationally.
Nurnberg.	Gema; Hohentwiel.

DESTROYERS

Friedrich Ihr.	Gema; Hohentwiel.
Erik Steinbrink.	Gema; Hohentwiel.
Nans Galspar.	Gema; Hohentwiel.
Theodor Riedel.	Gema; Hohentwiel.

DESTROYERS - continued

Paul Jacobi. Gema; Hohentwiel.
Z25. Gema; Hohentwiel.
Z33. Gema; Hohentwiel.
Hans Lody. Gema; Hohentwiel; Berlin.

TORPEDO BOATS

Elbing Class. No. 22 Gema; Hohentwiel; No. 33 Gema; Hohentwiel
1100 ton Class. No. 14 two Hohentwiels; No. 17 two Hohentwiels; No. 19 one Hohentwiel.

S-BOATS

In general one or two boats per flotilla were fitted with Hohentwiel. Fitting with Berlin was imminent at the end of the war.

U-BOATS

Nearly always one Hohentwiel.

In general German ships used radar only for warning and navigation. There were no facilities for radar plots, repeating presentations, etc.

METRE SETS

In the early part of the war, the only set which was fitted in ships, in particular in the *Graf Spee,* was the Gema Seetakt, modified for use on shipboard. The performance of this set at sea with aerials sited about 50 feet above sea level was as follows: against a battleship the range of detection was about 11 miles, against a destroyer about 8 1/2 miles and against an M.T.B. about 3 miles. To compensate for the low power output of the transmitter, large arrays had to be fitted in order to concentrate the beam and this presented serious difficulties when fitting the set in small ships.

In general Gema Seetakt was fitted in all ships down to destroyers. The installation in *Prinz Eugen is* of particular interest as no less than three of these equipments were fitted. One of these was obsolete and was not set up; another, Fu Mo 25, which was used for general warning, and was fitted at the base of the main mast, had a mesh reflector measuring about 18 ft. X 6 ft. on which were mounted 16 full-wave dipoles. The third set, Fu Mo 26, which was used for accurate ranging, was fixed to the control tower. This set had a mesh reflector measuring 18 ft. x 9 ft. on which were mounted 32 full-wave dipoles. In addition *Prinz Eugen* also carried a "Berlin" *(see below)* in contrast to most other ships of her size which only carried two radar sets.

It was not until 1942 that the U-boat staff found it desirable to fit the Gema Seetakt. There was some difficulty in designing an aerial array suitable for U-boats; about 10 variations of the set appeared at different times, the differences being mainly in aerial design and mounting. The first aerial to be fitted in U-boats was mounted on the bridge. The whole array, which measured 6 ft. X 9 ft., was rotatable through 14˚. This array, however, was vulnerable to depth charge attack and was replaced by a system of fixed dipoles and a phase-shifting attachment which allowed the beam to be swung through 10˚.

In its final form the array consisted of eight vertical dipoles mounted on a mesh reflector of size roughly 4 ft. x 3 ft.; the array was mounted on an extensible pillar beside the conning tower and could be rotated through 180˚. Common T and R working was usually employed for these sets. The beam width of the U-boat aerial was 26˚ to half amplitude, and the bearing accuracy was about +/-3˚.

In June 1942 the Air Force A.S.V. set, known as the "Hohentwiel" or FuG 200 appeared. This set, which was adapted for Naval use in 1943, was fitted extensively in U-boats, and to a certain extent in surface vessels. The aenal of the modified "Hohentwiel" was similar in design and size to that used with the "Seetakt." Besides operating on a higher frequency the "Hohentwiel" had an additional advantage over the "Seetakt" in that its various units were smaller. By the end of the war all operational U-boats had been fitted with the "Hohentwiel," whilst the "Seetakt" was fitted only in one or two training boats. As with the "Seetakt," there were several designs of aerial for the "Hohentwiel." Operators had never been allowed to execute more than very minor repairs to the "Seetakt" and no spares were carried, but they were allowed to do some servicing of the "Hohentwiel" at sea.

The technical details of "Hohentwiel" as fitted in submarines were as follows: frequency 550-580 Mc/s; peak power 30kW; pulse length 4.7 microseconds; p.r.f., 50 c/s; range on surface vessels, 3-7 km.; range on aircraft, 10-40 km.; ranging accuracy, 10 per cent; bearing accuracy 1.5 per cent; horizontal beam width to half amplitude 17°; vertical beam width to half amplitude 24°. Towards the end of the war a common T and R switch was fitted enabling the whole aerial to be used for transmission and reception.

DISCOVERY OF USE BY ALLIES OF CENTIMETRE SETS

During 1943, because of their heavy losses, U-boat Commanders lost much faith in their radar, and the possibility of Allied aircraft fitted with search receivers picking up U-boat radar transmissions seems to have been over-estimated. Other possible reasons for their heavy losses they considered to be that Allied aircraft were using A.S.V. with supersonic p.r.f. which would not be heard on U-boat warning receivers, and that aircraft were detecting and homing on radiations from the local oscillators of the search receivers, and using infra-red detectors for U-boat hunting. It was not until the autumn of 1943 that the German navy heard of Allied centimetre radar, and from then technical development took a new turn. The highest priority in the radar field was then given to projects for the radar camouflage of U-boats, untuned centimetre search receivers for warning, and the production of a German copy of the British 3,000 Mc/s radar.

CENTIMETRE SETS

After the discovery of the British H2S in 1943 immediate steps were taken to produce a German copy. Before this no work had been carried out in this region because the general policy in force during the period 1940-1942 allowed only short term projects owing to confidence in an early German victory; there was scepticism as to the advantages to be gained at centimetre wavelengths, and there were inherent difficulties.

Of the sets eventually produced none was operational before June 1944. The only two Naval sets to come into use were "Berlin" and "Renner."

The "Berlin" was intended for surface warning and for use as a navigational aid. Its performance was not quite so good as that of the British Type 271. In the "Berlin" nearly every unit, and in particular the magnetron, was copied from the British H2S. The main points of difference between the two sets lay in the aerial array and the receiver local oscillator. The aerial was of an original design consisting of four dielectric rods mounted horizontally above a metal plate. This aerial could be rotated at 400 r.p.m. and was used in conjunction with a small P.P.I. display. The local oscillator consisted of a low power tunable magnetron. Several variations of the set existed which were suitable for fitting in aircraft, surface vessels and U-boats, but in the Navy only a few surface vessels were fitted by the end of the war. The U-boat sets existed in two forms: one was a normal search set for use when the boat was surfaced, the other, presumably a late development, was to be used as a radar periscope when the boat was at periscope depth. The characteristics of "Berlin" were as follows:--Wavelength, 8.9-9.1 cm.; peak power, 15-20kW; aerial beam width, 10° to half amplitude; pulse length 1 microsecond; p.r.f., 1500 c/s.

A 3 cm. set for use in U-boats was also envisaged.

The "Renner" was a land-based set used for coast watching. Its performance was probably slightly better than the British Type 271. The aerial was a 3-element dipole assembly at the focus of a parabolic mirror, as used in the small "Wurzburg" set. The mirror was mounted on the top of a rotatable cabin and 360° search was possible. The beam width was about 4° to half amplitude. The frequency, power, etc. were the same as for the " Berlin."

Many of the units used in "Renner" were the same as those used in "Freya," this being an example of the German practice of using the same units in different sets as much as possible.

Sets Under Development in 1945

Reference must be made here to two sets which would have been used in the German navy had the war continued. One of these, the "Lessing," was designed as an air-warning set for U-boats and used the 2-4 metre band; presumably it would have been fitted with "Berlin." The other set, the "Euklid," was a development of the " Wurzburg," but operated on a wavelength of 27 cm. The "Euklid" was fitted with a parabolic mirror of 1.5 metres diameter and would have provided height-finding facilities; a rotating dipole at the focal point of the mirror provided a switched echo giving a bearing accuracy of +/- 0.2° in a horizontal plane and +/- 0.3° in the vertical plane. Other characteristics of the "Euklid" were: range accuracy, +/- 30 metres; peak power, 100kW; pulse length, 2 microseconds; warning range, 30 km.

I.F.F.

German I.F.F. lagged behind Allied technique all through the war. In the latter part of the war all ships were fitted with transponders which were triggered by the "Seetakt" 80 cm. sets. The I.F.F. response, which was radiated on a different frequency, was displayed on the lower trace of the " A " display.

DISPLAYS

The " A" display was usually fitted with all sets. The "Berlin" was an exception and was used with a P.P.I. display, this P.P.I. being a copy of a British unit. When accurate ranging was required, an "A" display with "expanded" trace was used. There is no evidence that the Germans ever attempted any refinements such as the skiatron.

JAPANESE NAVAL RADAR

Nomenclature of Japanese Radar Equipment

It is convenient to summarise, initially, the nomenclature adopted by the Japanese for designation of radar equipment. The standard nomenclature of the Japanese navy involved the use of four indicators, namely the Type, Mark, Model and Modification, which were invariably quoted in the order stated.

The principal classification was established under the Mark Model terminology and was divided as follows:--

Mark I Series--land-based radar, employed for aircraft and auxiliary surface search. Models 1, 2 and 3.

Mark II Series--shipborne radar, employed for aircraft and surface search, surface fire-control and auxiliary anti-aircraft fire-control. Models 1. 2. 3 and 4.

Mark III Series--land-based radar, employed for aircraft warning. Frequency modulated " radar " system, employing one or more receivers remote from the transmitter and Doppler Beat principle of detection.
Mark IV Series--land-based radar and in certain cases shipborne radar, employed for anti-aircraft fire-control and searchlight control. Models 1, 2 and 3.
Mark VI Series--airborne radar, employed for air and surface warning, blind bombing, and torpedo fire-control. Models 1, 2, 3 and 4.

In addition, there existed a series classification, designated by a letter. This latter system referred to Japanese army equipment, and included the following.

C.H.I. Series--land-based radar, employed for aircraft search. Model A employed a fixed transmitter and one or more receivers remote from the transmitter. A continuous wave was transmitted and the Doppler Beat principle of detection was employed. Model B was of conventional design and was produced either as a fixed installation for use in strategic positions, or as a mobile installation for field use.

T.A. Series--land-based radar, employed for anti-aircraft fire-control and auxiliary searchlight control. Models 1, 2, 3 and 4.

Model B--land-based mobile radar, ernployed for surface search.

Model K--land-based radar, employed for air search.

Model U--airborne radar, employed for surface search and blind bombing of land targets.

Equipments of the Mark Model Series were given a type number indicating the year in which such equipment was accepted by the Japanese navy. Two series of type numbers were used:--

(a) Designation based on the Japanese Imperial calendar, in which the year 1940 corresponds to " O." Thus, Types 2, 3 and 4 indicate the year of acceptance by the navy as 1942, 1943, and 1944, respectively.

(b) Designation based on the Showa calendar, in which the year 1940 corresponds to 15. This series was assigned to equipment in the experimental, or pre-production stages. Upon acceptance of the first model a type number was assigned as under (a).

Finally, any equipment of the Mark Model Series may have been assigned a Modification Number which designated a minor change in the basic equipment. Thus an individual equipment of the Mark Model Series, once established, underwent no fundamental or major changes as a result of subsequent type or modification designation.

Listed at the end of this chapter are the operating characteristics, installation, purpose and a brief description of all known types of Japanese radar equipment which were in operation or under development during the Second World War, and reference to it will be useful when reading this chapter.

State of Development of Japanese Radar at the Outbreak of the Japanese War

Records of Japanese research into the possibilities of radar quote the year 1940 as that in which the initial experiments were made. The first technique investigated by the Japanese navy was intended for aircraft detection; it involved the employment of a frequency modulated transmitter operating on a wavelength of about 10 metres, and one or more receivers remote from the transmitter, at ranges of 20 or 30 kilometres. An aircraft was detected by observing the beat frequency between the wave travelling direct from the transmitter to the receiver, and the wave reflected from the aircraft. The method relies on the fact that there is an apparent change of frequency in radio waves reflected from a moving object. It was possible to make the system roughly directional by assigning sector coverage to each receiver station.

Such a system, whilst providing warning of the presence of enemy aircraft and a rough indication of their bearing, was not capable of any absolute measurement of range, or of target elevation. It is believed, however, that the Japanese navy continued development work on this project for some time before realising its obsolescence. The Mark III radar equipment resulting from these efforts never came into any wide operational use with their navy, although the Japanese army developed a similar system (C.H.I. Mark A) for employment as a warning equipment for inner defence areas.

The initial Japanese radar developments were thus somewhat rudimentary in character. The primary requirement was to produce a system capable of detecting airborne and surface targets at the maximum possible range, and of determining the range and bearing of the target. It was evident that a new technique was necessary to provide both these facilities simultaneously. The Japanese knew of the employment of pulse radar technique in the European theatre during the early stages of the war, and in 1941 they began experiments with this system.

The first radar to be developed employing pulse technique was the Mark I Model 1, which operated on a frequency of 100 Mc/s and was intended as a fixed, land-based installation for air search purposes. By October 1941 the Japanese had succeeded in achieving a range performance of 60 kilometres against aircraft with this equipment. The transmission characteristics of the Mark I Model 1 radar illustrated features which were to become common in later radar equipments, *i.e.* low peak transmitted power, high pulse repetition frequency and long pulse. In general terms these characteristics result in low maximum-detection range, poor range-definition and accuracy. Spurred by the relatively greater success of pulse radar technique, however, the Japanese navy supplemented its research on the Mark I Model 1 air search equipment by experiments on two further radars ultimately intended for shipborne installation. Work began in the autumn of 1941 on the Mark II Model 1 radar operating on a frequency of 200 Mc/s, and the Mark II Model 2 radar operating on a frequency of 3000 Mc/s. The Japanese started this research with the idea of producing a radar for shipborne installation which would be capable of detecting both ships and aircraft at ranges of approximately 40 kilometres. It is interesting to note that, even in this early stage of development, an attempt was made to produce a radar system operating on a frequency of 3000 Mc/s. This was possible owing to the availability of suitable ultra-high-frequency magnetron valves -- a natural consequence of Japanese pre-war interest in this type of generator.

At Japan's entry into the war her radar development programme was thus in its initial stages. Experiments were being conducted to improve the Mark III system employing the Doppler Beat principle of detection; the Mark I Model 1 land-based radar had given a satisfactory performance in its role of air-search equipment; and finally, the Mark II Model 1 and Mark II Model 2 radars were under development for shipborne applications.

Development of Japanese Radar During the War

NAVAL RADAR (1941--1943)

The Mark II Model 1 radar was completed and installed in the *Ise* for its first trials in March 1942. Its performance during these trials showed that the requirements for detection range could be largely fulfilled. Against surface targets the detection range achieved was 40 km., and against aircraft 30 km. The accuracy of the equipment, roughly 500 yards in range and +/- 5° in bearing, though sufficient for the role of searching, was insufficient for the function of a fire-control radar. This radar was therefore adopted as the first basic naval equipment to be installed in all classes of surface units for providing the facilities for air and surface search.

The Mark II Model 2 radar was ready for trials in April 1942, and was installed in the battleship *Hyuga* for this purpose. The original equipment employed identical aerial systems for the transmitter and receiver, each consisting of a single waveguide fed, flared electro-magnetic horn. The horns were capable of training in azimuth only and had a beam width of the order of 20° in the horizontal and vertical planes. It is not therefore surprising that the Japanese achieved no success in the trials when employing the radar as an air search equipment. Against surface targets, however, a range of 35 km. was achieved. The Mark II Model 2 was, however, still in a relatively early stage of development, and work to improve its performance continued for a lengthy period.

Difficulties were experienced with the transmitter, receiver and aerial system. The capabilities of the magnetron transmitter valve were not fully known, but the power output was increased by stages up to a maximum of 2kW peak. The Japanese also experienced some difficulty in the selection of the type of receiver to employ in this radar and experimented with superhet, regenerative, super-regenerative and finally the autodyne types. As regards the aerial system for the Mark II Model 2, the Japanese evolved a waveguide feed system such that the plane of polarisation of the transmitted waves changed from horizontal to vertical as the transmitting horn rotated through 90 degrees. Taking into account differential phase lags at the bends in the feed system, the output from the horn was elliptically rather than plane polarised. The only improvement effected in the aerial system, however, took place in the receiving element of the system. The single receiving horn was replaced by a twin-horn array, the feed to which was arranged to provide a split lobe polar diagram. This system was adopted in an attempt to provide a more accurate bearing, using the steep-sided minimum of the twin-lobe system, than could be obtained when using the maximum of the single-lobe system.

With the above modifications to the original design the radar appeared as the Mark II Model 2 Modification 2, of which 60 sets had been built by the end of 1943. Few of these equipments operated really satisfactorily and further development work was undertaken.

The system was eventually adopted as surface search equipment for surface units and coastal stations, with the auxiliary function of surface fire-control equipment. A further modi cation, known as Modification 3 and designed to reduce the volume and weight of the equipment, was brought out about this time for submarine installation.

A.A. FIRE-CONTROL AND SEARCHLIGHT CONTROL RADAR

The developments in Japanese radar technique already outlined were relatively straightforward in character, and the principles involved were of the simplest. The Japanese were at this stage apparently not aware of such refinements in radar technique as beam-switching, elevation measurement, P.P.I. presentation, the employment of I.F.F. for recognition, and so on.

Japanese radar development greatly benefited, however, from Japan's swift successes in the opening stages of her war in the Far East, when she captured much Allied radar equipment of relatively advanced design. British and U.S. radar equipment captured in the Malayan, Singapore and Philippine campaigns included British S.L.C., GL. Mark II, CD/CHL and U.S. SCR268, SCR270. These equipments were subjected to an intensive examination by the Japanese radar technicians, and it is considered that the information they gained proved invaluable. The equipments captured included examples of high power, accurate, anti-aircraft fire-control sets -- a type of radar not yet attempted by the Japanese. As the simplest method of producing equipment capable of a performance similar to the Allied equipment, and including the feature of elevation measurement, the Japanese began production of copies of most of the Allied radars. In general the copies were exact, although in some cases slight modifications from the Allied original were incorporated. The series of radars copied or developed from the Allied equipments included the TA Model 1, TA Model 2 and TA Model 3 for army use, and the Mark IV Model 1 and Mark IV Model 3 for naval use.

Of the naval developments from captured Allied equipment, the Mark IV Model 1 fixed ground installation, for anti-aircraft fire-control and search-light-control, was copied from the U.S. SCR268 radar, with the following differences in detail:

> the pulse-repetition frequency was changed from 1,000 to 2,000 per second; the pulse-width was changed from 9 to 3 microseconds;
>
> the bearing and elevation receivers were located at the base of the aerial array instead of actually on the array;
>
> the circuits were re-designed to employ Japanese valves, and to provide easier servicing;
>
> the equipment was produced for a fixed installation.

Both the azimuth and elevation receiving aerial systems of the Mark IV Model 1 radar were lobe-switched to provide higher bearing accuracy. Although the equipment had a relatively good performance it was not placed in mass production as it was rather large.

Their second naval development from captured equipment, the Mark IV Model 3, was produced as a portable equipment for land-based operation, and also as a shipborne installation intended for anti-aircraft fire-control and searchlight-control. This equipment is rather similar in principle to the TA Model 2, copied from the British SLC radar. Its effective range was not great, but the accuracy of measuring range, bearing, and elevation was an improvement over that of previous types.

Of the whole series of radars produced during the war by the Japanese to fulfil the function of anti-aircraft and/or searchlight control, the foregoing discussion on equipments copied from captured Allied radars includes all except two of the series. Of the two remaining equipments, the army TA Model 4 is stated (in a captured document) to be a copy of a U.S. GL radar, although the identity of the U.S. original is a little obscure. The TA Model 4 is probably a further development from the SCR268. The second radar in the fire-control series not accounted for is the naval shore-based Mark IV Model 2 equipment. There is no evidence to account for the origin of this radar, although it seems reasonable to assume that it was a development parallel with that of the Mark IV Model 1 and Mark IV Model 3, particularly in view of the similarity of the operating characteristics. The conclusion is therefore drawn that the entire series of Japanese anti-aircraft fire-control and searchlight control radar equipments, i.e. the army types T.A. Models 1, 2, 3 and 4, and the naval types Mark IV Models 1, 2 and 3, were copied and developed from corresponding Allied equipment captured in the early stages of the war in the Far East. These radars were put into service during 1943, and with subsequent modifications they were in relatively wide use from 1944 onwards.

NAVAL RADAR, 1943--1945

The status of radar equipment produced for the Japanese Navy by the end of 1943 may be summarised as follows:--

(a) Land-based radar, for air and surface search
Mark I Model 1
Mark I Model 2

(b) Shipborne radar
Mark II Model 1 Modification 1 (Surface units, for a* and surface search)
Mark II Model 2 Modification 2 (Surface units, for surface search and fire-control)
Mark II Model 2 Modification 3 (Submarines, for surface search) .

(c) Land-based A.A. Fire-control radar and S.L.C.
Mark IV Model l
Mark IV Model 2
Mark IV Model 3

(d) Airborne radar, for A.S.V. and A.I.
Type 3 Air Mark VI Model 4

There is no doubt whatsoever that these equipments were technically and operationally inferior to corresponding Allied radar equipments. Technical developments had proceeded relatively slowly, and the performance of the equipments was correspondingly poor. Added to this, the operational efficiency of the equipments was considerably reduced owing to a number of poor engineering features. For example, little precaution was taken in the ship-borne radars to prevent shock-damage due to gunfire, or de-tuning of the equipment due to engine vibration. Further, the quality of the components employed was of a low order, and frequent breakdowns due to component failure were experienced. There appears to have been no attempt to produce components to tropicalisation specifications, and this fact must have accounted for a large percentage of the breakdowns. Accessibility for servicing of the equipment was not given much thought, which tended to make things rather difficult. The Japanese were, however, fully conscious of these deficiencies, and made constant efforts to improve the quality and performance of their radar equipments. The results of these efforts are reflected in the production of various Modification types to existing basic equipments.

The great shortcoming of the series of naval equipments available was the lack of a radar whose performance, particularly in regard to accuracy, was sufficiently high to permit of its use as surface fire-control equipment. This situation appears to have created a panic amongst the Naval High Command, for instructions were issued to the fleet to use any radar that happened to be available for fire-control purposes, whatever the purpose for which it was designed.

As noted earlier, the original Japanese development policy was for an equipment which would fulfil the functions of air and surface search, and no consideration was paid to the relative efficiencies in these roles. The Mark II Model 1 radar, one of the first products of this policy, now had to be adapted for anti-aircraft fire-control and surface fire-control in addition to its normal functions. The Mark IV series were also adapted for both anti-aircraft and surface fire-control. This state of affairs was, of course, highly unsatisfactory, and probably contributed very largely to the poor performance of Japanese surface fire-control experienced in naval actions. The operation of the Mark II Model 2 radar, intended for surface search and fire-control, had proved relatively unreliable until the end of 1943. Later, however, its reliability was considerably improved, and this radar became more commonly employed for surface-fire-control, for which role it was more suitable than other available equipments owing to its higher accuracy.

An attempt was made, however, to produce a further shipborne radar whose performance would be sufficiently good for surface fire-control. This radar, the Mark II Model 3, operating on a frequency of 520 Mc/s, was closely modelled on the German "Wurzburg " radar, a sample of which had been made available to the Japanese. The equipment was ready for testing early in 1944, and it is believed to have provided a satisfactory performance. There is, however, no evidence to show that this radar was employed in anything but very limited numbers in the fleet before the end of the war. It is possible that the large-scale U.S. air attacks on Japanese factories producing electronic equipment effectively prevented the production of the Mark II Model 3 in any quantity. Two interesting features of the aerial system may be noted:--

> the polarisation was vertical, whereas every other naval radar, with the exception of the Mark II Model 2, employed horizontal polarisation;
>
> the aerial system consisted of a dipole mounted in a paraboloid reflector, whereas all other naval radars, except the Mark II Model 2, operated on lower frequencies, for which paraboloid reflector technique was not practical.

Experimental work on a further naval radar development was completed in 1944, and the equipment was brought into relatively wide operational use before the end of the war. The original development, known as the Mark I Model 3, was designed as a much improved version of the Mark I Model 2, although it operated on a nominal frequency of 150 Mc/s, instead of the 200 Mc/s of the latter equipment. The Mark I Model 3 was designed as a portable land-based radar intended primarily for air search. A later version of the Mark I Model 3, which was named Mark II Model 4, was designed for installation in all classes of surface units and submarines, and also for air search. This equipment was widely fitted during 1945. It is thought that the intention was for the Mark II Model 4 to act as search equipment, thus releasing the Mark II Model 1 from this role and enabling the latter to be employed as anti-aircraft fire-control radar, in spite of the fact that it was not possible to measure target elevation with this equipment. This is just another example of a compromise to which the Japanese navy were forced owing to the non-availability of suitable fire-control equipment for fitting in ships. Prisoners stated that optical anti-aircraft fire-control was always preferred, although in cases of necessity, such as bad visibility, radar control was employed to direct blind-fire.

The Mark I Model 3 and Mark II Model 4 employed a single aerial for common transmitting and receiving operation, consisting of driven and reflecting dipoles, to eliminate the necessity of using a metal screen reflector. This feature was incorporated to facilitate easy transport of the equipment over rough country. The component units were correspondingly compact, e.g. the indicator was a single unit comprising the monitor, the indicator, and the synchronisation control. The transmitter was designed to operate over a wide frequency band, approximately 150 to 180 Mc/s, to permit the facility of frequency changing to avoid jamming and mutual interference between adjacent transmitters. The Japanese favoured the installation of two similar air warning equipments near one another, although there did not appear to be any regular watchkeeping system arranged between the two. One document states that the reason for this was to increase the coverage of any given radar site, e.g. while one radar is engaged in watching a given direction, the second is free to search other areas. The Mark I Model 3 was effective only as an air search equipment, and its low peak power and aerial gain resulted in a poor performance against surface targets.

As a supplement to the Mark I Model 3 the Japanese also produced a land-based version of the naval airborne search equipment Type 3 Air Mark VI Model 4. The aerial system alone was modified for this application and a simple directive dipole array was designed. The resulting equipment probably fulfilled its purpose as an early warning air search equipment.

The final naval radar development of the war was interesting in its application. The equipment was known as the Tase Model 1; it operated on a frequency of 375 Mc/s and was employed as control equipment in the liaison boat accompanying Japanese suicide craft in night attacks upon Allied shipping. One transmitting and two receiving aerial arrays, which were lobe-switched, were mounted in a fixed frame in the bow of the liaison boat. The indicator contained two presentation units, one for measuring range and the second for measuring bearing. A calibrated range drum was used to shift a selected target echo along the time base, for measuring range. As the aerial array was mounted in a fixed position facing forward the installation could only be employed to provide homing indications. The information deduced from the Tase Model 1 was presumably passed to the suicide craft, by R/T, to enable them to close to a selected target. The maximum range of the equipment was 12,000 metres.

I.F.F. EQUIPMENT

The Japanese are known to have learned of the principle of I.F.F. from interceptions of Allied transmissions. It is very probable that this arose from the triggering of the Allied Mark 3 I.F.F. by the Japanese Type 3 Air Mark VI Model 4 airborne radar. Band A of the Mark 3 equipment covers the range 157 to 187 Mc/s, the Japanese transmitter could operate within the range 140 to 177.5 Mc/s, and the Japanese receiver could tune over the range 135 to 170 Mc/s; it is therefore likely that the Air Mark VI Model 4 triggered the responder of an Allied Mark 3 I.F.F., the responding pulses being received on the Japanese presentation unit.

Early in 1945 the Japanese conducted some experiments with an I.F.F. system for aircraft which operated with an interrogator frequency of 189 Mc/s and a responder frequency of 198 Mc/s. The ground receiver detected the responder pulses and presented the signal on a cathode ray tube. It was intended that the equipment should have an operational range of 200 km., although a captured document reports that a maximum range of 100 km. was achieved. No attempt at coding was made with this equipment, which, it is believed, did not reach the operational stage.

A further development, similar in principle to the German "Benito" ranging system, was produced by the Japanese. This unit, known as the Guide Radar F, was set up near land-based air units, and working in conjunction with the airborne part of the equipment, which was identical with the Japanese I.F.F., it enabled fighter aircraft to be vectored on to attacking aircraft. A pulsed transmitter operating on a frequency of 106 Mc/s interrogated the aircraft I.F.F., and responding pulses were transmitted by the aircraft equipment on a frequency of 100 Mc/s. The delay between transmission and reception of the pulses was measured on a cathode ray tube, thus enabling the range of the fighter aircraft to be determined. The receiving aerial array was lobe-switched, and a second cathode ray tube fitted with separated echoes for pip matching enabled the azimuth of the aircraft from the ground station to be determined. This equipment was essentially an army development.

As far as is known, the Japanese navy did not employ any original I.F.F. system, in either aircraft or ships, during the war. There is, however, evidence to indicate that the Japanese compromised Allied Mark 3 I.F.F. equipment in attempts to deceive radar operators during approach to a target, such as a naval task force. It is possible that in such cases the Japanese were employing actual Allied I.F.F. equipment recovered from crashed aircraft. There were also numerous instances reported in which Japanese aircraft appeared to home on Allied aircraft I.F.F. transmissions. It is considered that the Japanese aircraft employed the Type 3 Air Mark VI Model 4 radar transmitter to trigger the Allied equipment, and then employed the radar receiver to home them on to the I.F.F. responses. This is substantiated by the fact that in some instances the Japanese aircraft lost contact with Allied aircraft which switched off their I.F.F. while being shadowed.

"WINDOW" SHELLS

In September 1944 the Japanese navy issued a type of shell which released a cloud of "window" material on bursting. The tactical employment of the shells was rather obscure, although it seems reasonable to assume that the intention was for the Japanese surface fire-control radar to obtain an echo from the window cloud, and hence a measurement of the range of the shell-burst. Several prisoners reported that it was not possible to obtain an echo from shell-splash with the Japanese fire-control radars, and the production of the window shell appears to have been an attempt to overcome this deficiency and improve the range correction data for gunnery control. There is no evidence detailing the success of the scheme, but it does not appear to have been very widely employed.

Conclusions

Japanese radar technique suffered primarily from late development and lack of originality. Such advances in technique as were made during the war owed their origin to earlier Allied developments. Liaison with Germany was on a comparatively small scale and few developments can be traced to this source

The earliest Japanese appreciation of the possible applications of radar was limited to that of a universal "search equipment." More advanced applications, e.g. fire-control equipment, blind-bombing equipment, etc. were all gleaned from Allied sources.

Actual equipment produced was inferior to equivalent Allied equipment, technically, in production, and in performance. Further, although most refinements in radar technique were known to the Japanese, they did not succeed in incorporating all of them in their own equipment. A notable example of this is the employment of P.P.I. presentation, although extensive experiments were carried out. Until 1943 the operational efficiency of naval radar was impaired by the fact that little or no basic training in the principles, operation and maintenance of radar equipment was provided for operators prior to sea-duty. This training was largely the responsibility of the officer-in-charge afloat, who, on a "learn as you go" basis, was expected to give instruction in operation of radar, target recognition, range estimation, and maintenance. Such a state of affairs was highly unsatisfactory, and from 1943 onwards basic training for operators was provided ashore. The Japanese fully appreciated the superiority of Allied radar equipment -- the capture of Allied Naval radar equipment intact was given the highest priority--and they continually strove to achieve an equal standard.

It is difficult to judge whether the failure to achieve parity was due primarily to a lack of suitable resources, or to the hampering effect achieved by the heavy U.S. air attacks on the Japanese electronic industry. Whatever the reason the Japanese can hardly be judged to have succeeded in their ambition.

DETAILS OF JAPANESE NAVAL RADAR EQUIPMENT 1939 - 1945

Land-Based Radar

TYPE	FREQUENCY (Mc/s)	PEAK POWER (kW)	INSTALLATION AND PURPOSE	ACCURACY		
				RANGE	BEARING	ELEVATION
Mark I Model I	90-110	5	Fixed, ground. Aircraft and auxiliary surface search.	500 metres	+/- 5 degrees	-
Modification I	95-105	5	As Model I	500 metres	+/- 5 degrees	-
Modification 2	100	30	As Model I	2,000 metres	+/- 3 degrees	-
Mark I Model 2	190-210	5	Mobile on trailer chassis. Aircraft and auxiliary surface search.	500 metres	+/- 5 degrees	-
Modification I	190-210		As Model 2			-
Modification 2			As Model 2			-
Mark I Model 3	147-165	10	Portable, ground. Aircraft search.	100 metres	+/- 10 degrees	-
Type 2	150	10	Portable, ground. Aircraft and auxiliary surface search.		+/- 10 degrees	-
Type 3	150		as Type 2	50 metres		-
Mark III	57-61	0.5	Fixed, ground. Aircraft.	-	Non-pulse radar. Frequency modulated. Doppler beat detection.	-
C.H.I. Mark A	60	0.5	Fixed, ground. Aircraft warning.	-	Non-pulse radar. C.W. transmission modulated at 800 cps. Doppler beat principle of detection	-

Shipborne Radar

TYPE	FREQUENCY (Mc/s)	PEAK POWER (kW)	INSTALLATION AND PURPOSE	ACCURACY		
				RANGE	BEARING	ELEVATION
Mark II Model I	190-210	5	Surface ships.. Aircraft and auxiliary surface search. Auxiliary A.A. and surface fire control.	500 metres	+/- 5 degrees	-
Type 2	190-210	5	Surface ships. Aircraft warning and A.A. fire-control.	500 metres	+/- 5 degrees	-
Type 3 Modification 3	200	30	Surface ships. Aircraft and auxiliary surface search. Auxiliary A.A. and surface fire control.	300 metres	+/- 5 degrees	-
Mark II Model 2	3,000 (nominal)	0.5	Surface ships and fixed ground. Surface search and fire-control.	+/- 1.6 per cent	+/- 2.5 degrees	-
Modification 2	2,900	2	As Model 2	50 metres	+/- 0.5 degree	-
Modification 3	2,900	2	Submarine. Surface search and navigation.	50 metres	+/- 0.5 degree	-
Modification 4	2,900	2	As Model 2	100 metres	+/- 1 degree	-
Mark II Model 3	520	3	Surface ships. Air and surface search and fire-control			

A.A. Fire-Control and S.L.C. Radar

TYPE	FREQUENCY (Mc/s)	PEAK POWER (kW)	INSTALLATION AND PURPOSE	ACCURACY		
				RANGE	BEARING	ELEVATION
Mark IV Model I	200	30	Fixed, ground. A.A. Fire-control and S.L.C.	50 metres	+/- 0.5 degrees	+/- 0.5 degree above 15 degrees. +/- 1 degree between 10 and 15 degrees elevation.
Mark IV Model 2	200	30	Fixed, ground. A.A. Fire-control.	50 metres	+/- 0.5 degrees	+/- 0.5 degree above 15 degrees. +/- 1 degree between 10 and 15 degrees elevation.
Modification 2	200	60	Ground A.B. Fire-control.	25 metres	+/- 0.5 degree	+/- 0.5 degree above 15 degrees. +/- 1 degree between 10 and 15 degrees elevation.
Mark IV Model 3	200	20	Transportable, ground, and surface ships. A.A. Fire-control and S.L.C.	50 metres	+/- 1 degree	+/- 1 degree above 15 degrees. +/- 3 degrees below 15 degrees elevation.
Modification I	200	20	Transportable ground and surface ships S.L.C.			
TA Model 1	200	5	Ground. A.A. Fire-control.			
TA Model 2	200	12	Ground. A.A. Fire-control and S.L.C.	100 metres		
TA Model 3	75-86	50	Ground. A.A. Fire-control..	+/- 25 metres	+/- 0.5 degrees	+/- 1 degree in the range 10-55 degrees.
TA Model 4	187-214	50	Ground. A.A. Fire-control.	100 metres	+/- 0.5 degrees	+/- 0.5 degrees.

CHAPTER IV
TACTICAL USE OF RADAR

ACTION INFORMATION ORGANISATION

THE Action Information Organisation, as it became in 1946, was no more than the logical development of the Plotting Organisation which existed at the outbreak of war. There were several reasons for this development, the most important being the introduction of radar into the Service.

In 1939, H.M. ships were equipped with space and facilities for a plotting organisation under the charge of the Navigating Officer, and all ships from destroyers upwards were fitted with an automatic plotting table. The conditions of war were, however, vastly different from those experienced in peacetime exercises. In the early stages most ships operated singly or in small forces and a much larger volume of operational signals and movement summaries were received than had ever been anticipated, particularly during a hunt for surface raiders. It thus became necessary for all ships to man their plots permanently at sea because the information available, and hence the scope, was considerably increased.

In 1940, radar sets (Type 279 in big ships and Type 286 in sloops and destroyers) began to be fitted in the majority of ships. The information obtained by the radar operator was initially passed directly to the bridge or the A.D.P., but this only gave the Command a succession of individual ranges and bearings, and, in order to make full use of the radar, it was essential that reports should be plotted so that a full appreciation of the situation, *i.e.* range, bearing, track and speed, could be passed to the Command.

The introduction of Fighter Direction led naturally to the installation of an air plot, which not only provided for the control of aircraft but also proved of great value to the gunnery control for air defence, as it provided a very elementary form of radar target indication.

The appearance of Surface Warning Radar in 1941, which, like the early radars for air warning, employed an "A" display and manually rotated aerials, formed a new source of information for the original surface plot. It was usual at first to pass surface reports to both the Command and the plot simultaneously, but this method again did not give the Command sufficient information for a full appreciation of the situation.

With both air and surface warning radars (together with other improvements in R/T and plotting arrangements) a great deal of information was thus be-coming available which needed sifting and sorting for presentation to the Command in a fully appreciable form.

The Action Information Organisation did not come into being as a complete unit, however, until 1944 15. It was then that the enormous increase in fitting the Fleet with warning, gunnery and navigational radar sets, together with the advent of the P.P.I., made it essential to have some system for co-ordinating and controlling the mass of information so that the maximum efficiency would result.

For the first time the P.P.I., besides simplifying the radar operator's task in making reports, made possible the direct viewing of radar echoes in positions other than the radar offices. This was of great assistance to the plotting teams when P.P.I.s were fitted at the air and surface plot positions; the Command, too, were able to visualise the situation far more clearly than before, because reports from the plot could be more readily understood when used in conjunction with observations of the P.P.I. Provision was made for such observation by the use of a viewing device which enabled the Command on the compass platform to see both the plot and the P.P.I. in the plotting office.

With the improvements in the bearing and elevation discrimination of gunnery radar sets the verbal methods of target indication from the air (or surface) plots were much too vague to be efficient. To overcome this, Type 293 was fitted as a Target Indication set, and a Target Indication Unit was provided to digest the information and to pass away, electronically, the lookout bearings (with the range) to the gunnery control positions.

The logical step to co-ordinate the various sources of information in order -to present a comprehensive picture was the formation of the Action Information Organisation comprising the Operations Room, the Aircraft Direction Room, the Target Indication Room, and the Radar Display Room, all sited below armour, and the Bridge Plotting Room situated in the bridge structure. Its primary object was to supply the command with a picture of the tactical and strategical situation which was both up to date and intelligible. Its secondary, though equally important, function was the control of the air weapon, surface forces, and the armament.

The main details of the operation of the various compartments of the A.I.O. are given below.

(a) Operations Room (Ops. Room) dealt primarily with the surface situation and contained the Local and General Operational Plots. On the radar side a P.P.I., normally operated from the WS set but switchable to the WC set, was fitted. In larger vessels an Auto Radar Plot, a unit combining an A.R.L. table with a skiatron, was sometimes fitted as a Local Operational Plot. Enemy reports based on radar were made from the Operations Room.

(b) Aircraft Direction Room (A.D.R.) dealt with the air situation and contained the Main Air Display Plot and Interceptor Plots. The latter were skiatrons for use in carrying out actual interception of enemy aircraft, the radar set displayed being switchable between WA (Type 281) and WS (Type 277). One or more P.P.I.s were fitted, switchable either to WA or WS and also in certain cases to WC. The P.P.I. was normally operated on a different set to the skiatron to provide a complete picture for the Fighter Direction Officer.

(c) Target Indication Room (T.I.R.) carried out the function implied by its name. It was either a separate compartment or formed part of the A.D.R. The radar picture was observed on the Target Indicating Unit fed from the WC radar (switchable to the WS radar in the event of a breakdown of the WC radar).

(d) Radar Display Room (R.D.R.) was provided for the following purposes:--

(i) to enable the Radar Officer to exercise technical supervision of all warning radars from a central headquarters;

(ii) to provide a central reporting and control position for all warning radars;

(iii) to provide a centralised height-finding position;

(iv) to provide a centralised interrogating position.

(e) Bridge Plotting Room (B.P.R.) was the compartment in the bridge structure where the filtered picture was presented to the Command and where the Command appreciated the situation and made the necessary decisions. It contained a General Operational Plot, Local Operational Plot, and Air Plot, all of which displayed filtered versions of the equivalent plots in the Action Information Centre, and a P.P.I. switchable either to WS or WC. To enable the Captain to study the plots and P.P.I. a viewing device was fitted between the compass platform and the B.P.R.

With this structure the A.I.O. could largely fulfil its commitments. The raw information was supplied from the radar, visual reports, W/T and Voice, whence it was digested in the Ops. Room, A.D.R. and T.I.R. and so out to the Command (via the B.P.R.), the guns, the aircraft, and the ships in company. The layout just described applied generally to large ships. In small ships the layout was proportionately smaller; a combined chart house and Operations Room was fitted with the T.I. Unit in the adjacent T.I.R., there was no A.D.R., and, as the A.I.C. was sited in the bridge structure, there was no B.P.R. A viewing device was fitted between Bridge and Operations Room.

At the end of hostilities in 1945 fully one quarter of the Fleet had an up-to-date A.I.O.; the remainder, having progressed the work to some degree, were operating with some interirn form of A.I.O. It was not easy to fit these new offices retrospectively in ships because of the large increase in space required. In new construction, however, the fullest possible allowance was being made, not only for current requirements but also for those future requirements which were foreseeable at the time.

To sum up there was nothing inherently new in the Action Information Organisation. It set out to unite, under the control of the Command, all the sources of information, the plots, the means of appreciation, and the execution which modern Naval warfare demanded. In addition it provided a meeting ground upon which the navigation, radar, gunnery, torpedo, anti-submarine, communication, and air branches could pool their separate resources for the common good and the greatest efficiency.

AIRCRAFT DIRECTION

The results of six years' war experience and the hard work of radio scientists have given a solution to several of the early fighter direction problems; many difficulties have not been entirely overcome, however, and much work still (1946) remained to be done to improve and perfect the apparatus and methods at present employed. The information required in 1939 was the range and bearing, speed, track height, numbers and identity of aircraft approaching the Fleet, to which there was no answer at that time.

The introduction of radar (Types 79 and 279) and Voice communication in ships made controlled interceptions a practical consideration. No longer was it necessary to maintain a continuous patrol over the Fleet, or to await visual detection before initiating an interception. The radar operator passed reports of range, bearing, and estimated number of aircraft to the Fighter Direction Officer (F.D.O.), who plotted them on a mooring board. When sufficient plots had been obtained the speed and track were deduced, and an intercepting course could be passed to the fighters. Height estimation was inaccurate (nor has the problem of accurate height measurement been solved to any real extent) and in 1939 and 1940 when fighter direction and radar were in their infancy it was usual, rather than accept the rough estimation obtainable from the radar set, to rely on intelligence information on heights. This was based on our knowledge of the type of enemy aircraft likely to be employed in a raid, because the enemy, knowing little of the potentialities of our radar, usually flew at the height best suited to his aircraft.

Early in 1940 the R.A.F. introduced in their aircraft an I.F.F. which, with a small modification, was arranged to work with the Naval Types 79 and 279 as well, thus providing Naval fighter direction with a solution, though not the final one, to the problem of identity.

Because of its manually operated aerials and "A" display, Type 279 could not track more than two or three aircraft at a time, and as the enemy attempted to saturate our radar screens by multiplying the number of formations of attacking aircraft, it was obviously necessary to develop a procedure for combining the efforts of all ships, by passing reports of echoes from one ship to another, so that all echoes might receive adequate attention. A special W/T line was introduced for radar reports, and one ship was deputed to control the radar traffic on the line to see that the most efficient use of the Fleet's radar was obtained. Thus, by 1942, this system gave every ship in the Fleet a fairly complete air picture, whether they were themselves fitted with radar or not, and it was used with considerable success in operations.

Up to 1942 virtually the only ships fitted with Voice equipment for communication with aircraft were carriers, but with the increasing requirement for control of fighters it was decided that cruisers and battleships should also be fitted. The R.A.F. fighters being fitted with VH/F Voice equipment whereas Naval fighters had H/F Voice equipment, it was necessary to fit cruisers and above with both these Voice channels and to provide them with an office arrangement similar to that of carriers, though on a reduced scale, for plotting and fighter direction. These early plotting offices were simple in the extreme and contained only one spider's web horizontal plot and one W/T and two Voice channels, but with the experience gained from these elementary layouts it was possible to visualise the future requirements for an efficient and fully equipped Aircraft Direction Room.

The warning sets used by the Navy up to the end of the war for high cover, Types 279 and 281, presented a fairly accurate air picture out to about 100 miles, and by virtue of the shape of their vertical coverage lobes they gave a means of estimating heights. Until the enemy understood the potentialities of our radar these two sets allowed the Fleet to protect itself fairly effectively. As more losses were incurred by enemy aircraft, however, and as the enemy gained more information about radar, they changed their tactics in an attempt to confuse our Fighter Direction Officers. In this they were for a time successful, but on the introduction of the P.P.I. and skiatron the lot of the F.D.O. was considerably eased, as this enabled him to keep a constant "up-to-the-minute" check of the relative positions of friendly and enemy aircraft by cutting out the time lag inseparable from the system of told plots.

Once again the enemy changed their tactics and attempted to evade our radar by flying low, so that detection range fell to ten miles or so. This move had been anticipated, and in 1944 Type 277 was fitted for surface and low-air warning. Because it operated on 10 cm. it was possible to direct its transmission path very much closer to the optical line of sight. At the same time provision was made with Type 277 to control the aerial in elevation in order to obtain accurately the height of an aircraft; unfortunately, however, the range to which heights could be obtained was only about 20 miles.

The I.F.F. fitted from 1940 until the end of the war was only partly satisfactory. Its drawback was that although it differentiated between friendly and hostile groups, it was so insensitive for bearing that when an interception was in progress it was virtually impossible to distinguish which echoes were showing I.F.F. and which were not. Towards the end of the war the R.A.F. used an improved I.F.F. system on the "G" band to aid fighter direction; it provided a better bearing resolution, but unfortunately it was never used operationally at sea owing to lack of interrogation equipment.

From 1944 until the end of the war no further new sets were introduced into general service for fighter direction, though the existing sets, and the methods of presentation of radar information, were considerably improved. These modifications included a continuously rotating aerial for Type 281, an improved skiatron, greatly modified P.P.I.s and also the inclusion of the Type 293 (Target Indication) set in the air warning organisation to supplement the information provided by Types 279, 281, and 277. To extend the range of air warning, picket vessels were stationed at distances of up to 50 miles from the main body whose defence was the primary object of the disposition. This method, though providing valuable early information, was initially extravagant owing to the casualties suffered by the pickets, but by increasing the strength of a picket and by providing them with fighter direction facilities they were able to protect themselves with a fair degree of success.

For special projects, such as combined operations in which large numbers of R.N. and R.A.F. aircraft were employed, special Fighter Direction Ships were fitted out. These vessels were fitted with R.N., R.A.F. and American radar equipment, together with a large-scale filter plot, and were manned mainly by R.A.F. fighter direction personnel. During operations in which these ships took part they were usually anchored close in shore, thus relieving the Naval escort of the greater part of aircraft control duties so that they might have freedom of action in their support commitments.

It is not intended to describe here the fighter direction procedure but only to outline how the various demands for information were met by radar. In general therefore, it is sufficient to say that when a ship was in the vicinity of enemy airfields or carrier forces it was found convenient to vest the control of the air warning radar in the person of the F.D.O., who could most efficiently co-ordinate the various radar sets and the subsidiary interrogators and displays.

On the reception of an unidentified plot of some new echo, the F.D.O. directed the fighter aircraft so that they might intercept the hostile aircraft as far from the Fleet as was tactically possible. This was usually done on the plotting screen of the skiatron so that any change in the enemy course was instantly noted and a new course passed to the fighters. Requests for height information were passed to the Radar Display Room (or in some ships to the Height Filtering Position) and the estimated height, together with any supplementary information, was reported back to the Aircraft Direction Room. When the plots were within about ten miles of one another the set on which the actual interception was being carried out was usually given the order to sweep backwards and forwards across the target bearing, while other warning radars continued an all round search.

In conclusion, the situation at the end of hostilities was that we had a fighter direction organisation in all cruisers and above, and also in certain smaller ships and headquarters ships, which enabled fighters to be controlled and tracked with radar information of range and bearing, track, speed, numbers, identity and approximate heights. The displays in the Air Direction Position were arranged to give the F.D.O. the complete radar picture, which, together with the W/T radar reports from other ships, formed the basis from which the air situation could be comprehensively appreciated.

War experience indicates, however, that with the increasing performance of aircraft the requirements for Aircraft Direction make the following further demands of future radars:--

> fadeless cover to the limits of the interception zone, i.e. 150 miles with aircraft speeds up to 600 m.p.h.;
> accurate heights of aircraft to the same range;
> low air cover to be extended to at least 60 miles; an I.F.F. system of greatly improved performance and accuracy;
> an automatic plotting system.

DIRECTION OF SMALL CRAFT

Radar was used to a certain extent during the war for the direction of small craft. In the first place use was made of information from shore-based radar stations; later both shipborne radar, and, towards the end of the war, airborne radar equipment, contributed information for the direction of small craft.

In the early days of the war a number of WS radar stations were set up and operated by the Navy to secure the approaches to Naval ports and bases. These radar stations were supplementary to the then incomplete coastal chain of

R.A.F. stations. In due course the R.A.F. undertook the whole responsibility for air and surface warning round the coasts of Britain, although a few WS radar stations still remained under the direct control of the Navy; information from the R.A.F. stations was passed to the local Naval plots. Overseas the Navy operated a few mobile WS radar stations, chiefly in connection with opening up ports in former enemy territory.

As regards the direction of small craft from shore-based stations the various Commands worked out their own systems to suit local conditions. With the progressive improvement of radar the effectiveness of the various systems was likewise improved. The direction of small craft in the principal Commands concerned are discussed briefly here.

NORE COMMAND

In general, and up till the time of the Normandy invasion, most of the actions involving small craft took place on the East Coast. The use of radar for surface warning was distinctly limited owing to two factors:

(a) The low lying nature of the coastline offered no good sites for the radar equipment, and consequently the normal extreme range obtainable against E-boats was 17 to 20 miles, though better ranges were sometimes obtained under conditions of super-refraction.

(b) The War Channel in the Yarmouth and Harwich sub-commands was at a distance of between 7 and 20 miles from the coast, and in the Humber sub-command it lay entirely beyond extreme radar range.

Shore radar stations passed their information to the Naval sub-command plots, which, in turn, passed on the information to the Nore plot where the control of all actions was centralised. There was usually a considerable time lag, up to 12 minutes, between the first detection of the enemy by radar and the receipt of sufficient information to act by patrolling craft.

On the East Coast, patrols were normally maintained; destroyers and corvettes patrolled in the War Channel and units of Coastal Forces (M.T.B.s, M.G.B.s, and M.L.s) were stationed on a line, known as the " Z-line," which ran parallel with the War Channel and some 10 miles seaward of it.

Under normal conditions the enemy always reached the Z-line before being detected, and as the units of Coastal Forces were usually themselves beyond radar horizon it was not possible for the latter to make an interception during the enemy's approach. At times, however, it was possible to pass information to the patrolling destroyers so that these could intercept the enemy before he reached the War Channel. As the enemy retired from the War Channel an estimate of his course was made and units of Coastal Forces ordered to positions on the enemy's general line of retreat in the hope that one or more of these units would make an interception.

The plots of E-boats obtained by radar were of use, not only because this information enabled defensive action to be taken, but also because traffic could be diverted from danger areas and mine-sweeping could be organised without delay.

DOVER COMMAND

There was considerable activity in this area. The height of the radar stations enabled complete radar cover to be maintained in the area up to the enemy's coastline, and for this reason radar could be used both defensively and offensively.

A watch was kept on all enemy movements and these were broadcast to the various units of Coastal Forces on patrol in the area. Coastal Force units were left to work out their own interceptions.

On the whole better results were obtained in this area than on the East Coast.

PORTSMOUTH COMMAND

There was never much activity in this area until the time of the Normandy invasion and then the onus of the direction of small craft was undertaken by frigates lying off the Normandy invasion beaches.

The shore radar stations were all on high sites, but even so, complete radar cover across the Channel could not be maintained except towards the end of the war when using the most modern equipment.

A plot was maintained at Fort Southwick, but there was little development in the direction of small craft because the area was little menaced. Generally, a few destroyers were on patrol. Information was broadcast to the destroyers and sometimes they were ordered to certain promising positions although no attempt was made at making an interception. Coastal Forces units were generally engaged on offensive operations outside the zone of radar cover.

PLYMOUTH COMMAND

There was little activity in this area and conditions were similar to those in the Portsmouth area.

Early in 1943, trials were carried out to determine the possibility of vectoring units of Coastal Forces from shore. This was found to be feasible, but as there was little need for defensive action, and the radar cover was inadequate for offensive action, the matter was not pursued.

The direction of ships using shipborne WS radar first occurred during the Russian convoy operations where there were a few cases of destroyers being vectored from other ships in order to intercept enemy vessels.

It was not until the Normandy invasion that the direction of small craft from ships was undertaken on a large scale. Units of Coastal Forces had the task of protecting the flanks of the assault forces. Although by that time modern WS radar equipment installed on the English coast frequently gave cover to the beaches of the Seine Bay, it was found to be more expedient to control Coastal Forces from certain frigates stationed on the flanks of the assault area. These frigates were fitted with up-to-date WS radar (U.S. type SL) and communication equipment and a small Action Information Centre. They controlled the movements of Coastal Forces and were highly successful; the fact that these frigates were able to keep in the vicinity of an engagement was particularly advantageous.

Later, the group of units of Coastal Forces with their controlling frigates played a more offensive role in the Le Havre area, and with as much success as before.

In the autumn of 1944 the whole group was transferred to the Nore Command to undertake defensive work in connection with the Antwerp convoy operations. In the winter of 1944 the effectiveness of the group was enhanced by the co-operation of A.S.V.-fitted aircraft, which patrolled the Scheldt estuary and passed information to the frigates, thereby materially increasing the radar cover provided by the frigates.

At about the same time as aircraft began to co-operate with the frigates in the Scheldt estuary, A.S.V.-fitted aircraft also began to co-operate with units of Coastal Forces patrolling off the East Coast. In this case, however, in-formation was passed direct from the aircraft to Coastal Forces.

TARGET INDICATION AND BLIND FIRE

Before the Second World War, and before the advent of radar, there was little difficulty in pointing out the selected target to the gunnery control positions because visibility was essential before any information could be obtained as to the direction and range of the target. With the introduction of radar the problem of target indication became more complicated, and it is discussed briefly here under the headings " Surface Gunnery " and " Anti-Aircraft Gunnery."

Surface Gunnery

Before the advent of radar, "bearing" was the only indication required and this was passed by Evershed transmission from the Captain's (visual) sight on the bridge to the Director Control Tower (D.C.T).

When warning radar was fitted, together with the GS set Type 284, the existing system of indication was retained but in a modified form. The modification was that bearing could now be transmitted by Evershed to the D.C.T., either from the Captain's sight on the bridge or from the Type 284 office, and the Warning Radar Office was linked by telephone or voicepipe to the D.C.T. and the GS office. With this arrangement, when visibility was poor, it was possible to pass the approximate bearing of an echo detected by the warning radar both to the D.C.T. and to the gunnery radar operator. The latter would then guide the director in a sweep about the indicated true bearing by means of his Evershed system. Once the echo had been detected by the Type 284 the operator attempted to guide the director to keep its line of sight on the target, by keeping the echo at maximum amplitude.

In 1942 Type 284 was modified to improve its bearing accuracy, and it became possible to train to within about 1/4° of the target. In addition an extra indicator, known as tlle Training Tube, which facilitated training by radar, was fitted either in the D.G.T., or, preferably, in the T.S. When the training tube was fitted in the T.S. the D.C.T. had to be guided remotely as before. These two modifications made accurate blind-fire possible.

So long as the GS set used was the Type 284 no more accurate method of target indication was necessary, because of the wide beam of this set.

In 1944 the 10-centimetre radar, Type 274, was introduced into the Fleet. As the total beam width of this set was no more than 2°, greater accuracy in the indication of bearing became essential.

Hitherto the usual method of target indication for Type 274 had been to use the information from the WS set Type 277 for putting on Type 274, the information either being passed direct from the WS office or through the Operations Room. The required information was passed to the D.C.T. and Type 274, bearing being passed by instrument and range verbally.

As an alternative arrangement in some ships, it was possible to use the Target Indication Unit (described below under "Anti-Aircraft Gunnery") to pass the required information. The Type 293, however, which normally feeds the T.I.U., gives ranges against surface targets inadequate for long-range L.A. gunnery; so that it was still found advantageous to use a separate plot for L.A. target indication rather than the T.I.U. for Damage Control purposes arrangements were made in some ships to feed the T.I.U. from Type 277 instead of from Type 293; the use of Type 277 for this purpose has the disadvantage that radar cover against high aircraft is sacrificed.

Anti-Aircraft Gunnery

Originally, the information required for anti-aircraft gunnery was bearing and elevation. Before the advent of radar, bearing and elevation were passed verbally from the Air Look-outs to the Air Defence Officer (A.D.O.) on the bridge, whence they were relayed to the directors by Evershed transmission. Targets were indicated verbally to the close-range weapons and directors.

Many of the early WA sets were fitted with accurate ranging panels which enabled use to be made of them, in particular Type 281, for A.A. gunnery. The range and bearing of an approaching aircraft could be indicated to the A.D.O. either by instrument or, more normally, by telephone, or through the Air Plot. In some ships arrangements were made to transmit by instrument from the WA set, the bearing to the H.A. director and the accurate range to the T.S. This set-up was employed for barrage firing.

At sea however, the WA set was not often used to obtain accurate ranges because the rotation of the aerials had to be stopped and this interfered with all-round search -- the primary function of the set. In harbour, on the other hand, when warning information was available from the Gun Operations Room ashore, Type 281 was often used for providing range and bearing during air attacks; under these circumstances an estimate of height was available from shore and reasonably accurate blind-fire was possible.

Subsequently, radar sets operating on a wavelength of 50 centimetres were designed and fitted solely for A.A. gunnery (Type 285 for long range and Type 282 for close range). This step emphasised the need for some better form of target indication, but existing gear had to be used. In Type 285, range and bearing were either passed verbally from the WA set to the director, or else the director followed the A.D.O.'S sight, which itself was kept on the latest bearing from the W A. In some ships bearing could be passed directly from the WA set to the H.A. director, but this system was usually only employed in harbour when the WA was not required for all round search. Type 285 had its aerials mounted on the H.A.D.T. Owing to its very wide beam no more than a rough indication of the bearing on which to search was needed, and, owing to the extreme width of the beam in the vertical plane, information regarding elevation was not required.

Two important modifications were carried out to Type 285, one enabling bearings to be obtained to an accuracy of 1/4°, and the other enabling the trainer in the H.A. director to train by radar (this was achieved by fitting a training tube in the director); these modifications improved the possibilities of the set for blind-fire, though it was still not possible to obtain elevation, and these conditions obtained generally in the Fleet for the last three years of the war.

Type 282 aerials were similarly mounted on their corresponding directors. These directors still had to be put on verbally.

Target indication became a real problem with the introduction of the long-range set Type 275 (10 centimetres). This radar, with its narrow conical beam about 10° wide, needs to be put on for bearing and elevation with great accuracy; an indication of range is also of assistance to the operator. Although a target indication system which indicated accurate bearing and range to the Type 275 was introduced there was no method of indicating accurate elevation so that the Type 275 had to be put on for bearing and then sweep in elevation until the target was found.

The same system was used to put on the close-range set Type 262 which had an even narrower beam than Type 275.

As angle of elevation could not be indicated, Type 262 was designed to search automatically in elevation, and also about the indicated bearing and range.

This target indication system comprises:--

WC set Type 293 (10 centimetres). Target Indicating Unit and associated Range Transmission Units.

Type 293 is a set designed to give warning of all targets from surface vessels to high-flying aircraft which are within the immediate vicinity of the ship.

The aerial rotates continuously at a fairly high speed. The display is a P.P.I. which forms part of the Target Indicating Unit (T.I.U.). The T.I.U. was designed to pass bearing, and make alarm call-ups, to five gunnery control positions (three positions only in small ships); indications, bearing of director and "target found" light from these positions are received at the T.I.U. In the large ship model the fifth panel is available for controlling an interrogator as well as the main surface armament. The latter application has not hitherto been generally employed, as the surface warning normally comes from Type 277, as was explained on page 68 under "Surface Gunnery." Associated with the T.I.U. are the range transmission units, by means of which range can be transmitted away at the same time as bearing. This equipment gives the Target Indication Officer a clear picture of all targets in the vicinity and permits the rapid indication of targets to the various gun positions.

The method of indication is as follows. A number of lines of light, one for each position to which bearing is passed, are projected as radial lines on to the face of the P.P.I. tube. Each line of light can be rotated independently by movement of a handwheel, the handwheel at the same time operating a bearing transmitter. To indicate the bearing of a particular target a line of light is made to bisect the corresponding echo, and the alarm callup push-button switch is pressed. A bearing repeater on the T.I.U. indicates the bearing of the director concerned, and when the target has been picked up by that director, or its radar, a light burns on the T.I.U. panel. In association with each bearing indication system there is a range transmission unit by means of which an accurate range of a target can be transmitted at the same time as its bearing is transmitted. The range transmission unit consists of a sector selector panel and a sector selector unit, the latter being directly coupled to the bearing handwheel on the T.I.U.

Present forms of target indication are far from satisfactory, and ideally all three dimensions, bearing, range and elevation, should be indicated.

USE OF RADAR FOR NAVIGATIONAL PURPOSES

From the early days of the war the Navigating Officer made increasing use of information given by radar sets, particularly after the general introduction into the Fleet, in 1941, of centimetre warning sets. There were numerous instances of ships making long voyages at high speed, entering harbour, or making a rendezvous under conditions of poor visibility, when such feats would seldom have been attempted in pre-radar days.

Generally speaking, all radar sets suffer to a greater or lesser extent from certain fundamental limitations. The value to the navigator of the various radar sets depended on the extent to which these limitations were overcome. The principal limitations are discussed below.

RANGE

Reflection from high peaks and bluff headlands is usually better than from gently sloping land; in the latter case it sometimes happens that there is no indication at all on the radar display, this effect being more likely at the lower frequencies. Also, the range discrimination between two targets on the same bearing depends largely on the pulse length; the shorter the pulse the better is the range discrimination.

BEARING

Most radar sets will give a reasonably good bearing on a comparatively small isolated object. When viewing a coast, trouble arises, however, owing to the width of the radar beam in a horizontal plane; as the radar scans the coast an echo is still received even after the centre-line of the radar beam has passed the headland and is pointing out to sea. Under such circumstances it is not possible to determine with accuracy the bearing of any part of the coast. Another effect of the wide beam is to throw a "shadow area" along the coast-line so that not only is the apparent bearing of a headland in error but also the shape, and therefore the apparent range, of the coast is often incorrect.

As the radar beam is made narrower these two inaccuracies become less and the bearing discrimination is improved.

SIDE RADIATION

In almost all sets a certain amount of power is radiated in directions other than that of the main beam. Due to side radiations, false echoes appear on the radar display and are liable to cause confusion and ambiguity with the true echoes.

The earlier warning sets, e.g. Types 286, 291, 79 and 281, which operated on metre wavelengths, were not of great value to the navigator owing to their wide beam, long pulse length and poor echoes from low-lying land. These sets gave only general warning of land, and they were of no value for station-keeping.

In 1941 a low power 10-centimetre set, with a hand-operated aerial which could not be continuously rotated, was widely fitted in the Fleet. Many modifications were made to this set from time to time to increase both its reliability and overall sensitivity. Although its performance for navigational purposes was superior to that of the early warning sets, and with its aid a landfall or sea rendezvous could be effected with fair accuracy, it still suffered from the troubles of too wide a beam, too long a pulse, excessive side radiation and poor ranges.

Early in 1943 the first of the Plan Position Indicator (P.P.I.) displays made the* appearance, and they were used to give supplementary information to that obtained from the normal "A" display. The possibilities of the P.P.I. presentation were quickly appreciated, especially for station-keeping and coast-wise navigation. Nevertheless, a radar set of improved characteristics was required before its potentialities could be fully developed. Ultimately the P.P.I. became the most commonly fitted type of operational display, and displaced the "A" display from this role; also, several P.P.I. displays were driven from one radar, the P.P.I. units being fitted in the various remote positions where there was a requirement for the radar information.

Towards the end of 1943 fitting started of Type 277. Type 277 was a very high power 10-centimetre set, and in designing it steps had been taken to reduce the beam width, reduce side radiation and shorten the pulse. Type 277 was the first radar set to be fitted with power-operated, continuously rotating aerials. Continuously rotating aerials contributed notably to the improvement in the P.P.I. display and were incorporated in the designs of all subsequent radar sets. The performance of Type 277 was markedly superior to that of Type 271, and the P.P.I. picture obtained correspondingly improved. Even though the P.P.I. picture of the coastline obtained by the Type 277 did not correspond perfectly with the chart, the equipment was frequently used to good effect for coast-wise navigation. The set also proved its worth for station-keeping, though the minimum range obtainable (about 200 yards) was still too great.

The principal disadvantages of the Type 277 were, first, that the offshore ranges were not always entirely accurate, and secondly that the equipment was too bulky for light craft (in particular, for vessels used in Combined Operations).

To meet the need for a navigational set for Combined Operations, a medium power 10-centimetre set was produced in 1943. The performance of this set fell midway between that of the Type 271 and Type 277. The P.P.I. picture of the coast lacked sufficient definition for the very accurate navigational requirements of Combined Operations owing to too wide a beam and excessive side radiation.

In 1944 the immediate problem of accurate navigation by radar for Combined Operations was solved. It was found possible to predict what the P.P.I. picture would look like from various offshore distances and bearings, and to produce the corresponding P.P.I. Prediction Charts. The technique involved the comparison of the P.P.I. prediction with the P.P.I. picture; when the two corresponded the exact position of the vessel could be located on the standard chart.

Though P.P.I. predictions proved admirable for the requirements of Combined Operations the labour involved in their production precluded their general adoption in the Fleet. Efforts were therefore directed towards improving the results obtained by radar, the next important development being the production in 1944-45 of the 3-centimetre sets, Types 268 and 972.

By reason of the very high frequency employed, it was possible to design aerials for both Types 268 and 972 with a very narrow main beam and virtually no side radiation. Other improvements incorporated in both sets were a further reduction in length of pulse and a virtually linear P.P.I. trace. Both sets having good range and bearing discrimination, good range-accuracy and linear traces, they produced P.P.I. pictures of the coast which could be readily compared with the standard chart. Furthermore, both sets were compact and suitable for fitting in small craft. The principal disadvantage of these sets was the high frequency employed; certain weather conditions gave rise to abnormal transmission and reception, and thus the performance was liable to fluctuate widely.

Towards the end of hostilities the requirements of a navigational set for the Merchant Navy were investigated and the specification, based on the accumulated experience of A.S.E., was drawn up. The equipment envisaged was a compact 3-centimetre radar having the narrowest beam yet obtained (1.7degrees), virtually no side radiation, a pulse so short that the minimum range would be under 50 yards, and a linear P.P.I. trace. A simple device to enable the navigator to view the P.P.I. picture superimposed on the standard chart and thus obtain directly the ship's position was also developed.

Radar beacons were used throughout the war as an aid to navigation. A number of permanent installations were set up both at home and abroad, temporary beacons were set up on the enemy-occupied coast to guide the oncoming invasion craft, and beacons were also fitted in ships for the purpose of homing aircraft.

Radar beacons radiate a coded response when triggered by the pulse from a radar set operating on the appropriate frequency. A beacon can be positively identified by virtue of its coded response, and an accurate range and bearing be taken of its position, even though the beacon response appears amongst land echoes on the radar display. In general, beacon responses can be detected at ranges somewhat greater than the ranges at which land can be detected by means of radar.

Although radar beacons have always had an important part to play in radio navigation, their general use is hampered by two disadvantages:--

(1) the impracticability of designing a beacon which will respond to all radar frequencies in use, and

(2) the fact that maintenance sets a limit on the number of beacons that can be fitted.

Besides radar and radar beacons other systems of navigation by radio were developed; these other systems come under the general heading of Radio Navigational Aids.

The first of these, the "Gee" system, was introduced in 1943. "Gee," which consists of chains of synchronised pulse transmitters set up on shore, enables ships fitted with the appropriate receiver accurately to obtain position lines up to a range of about 150 miles from the transmitters. A later development of the "Gee" system was "Loran." " Loran" is operated on the same principle as "Gee," but use is made of the reflected skywave as well as of the ground ray. A navigational fix obtained by "Loran" is not quite so accurate as one obtained by "Gee," but the former is sufficiently accurate for ocean navigation.

The Decca system was perfected too late to be utilised in the war although a few equipments were used in the Normandy invasion. This system consists of pairs of synchronised transmitters set up on shore, and a receiver fitted in the vessel by means of which the phase difference of transmission from each of a pair of stations is determined, thus enabling a navigational fix to be made. The range and accuracy of fix obtainable by the system are comparable with those obtained by the "Gee" system.

The chief advantages of such radio navigational aids are that the shipborne receiving equipment is compact and simple to operate and is eminently suitable for use in light craft, and that fixes can be obtained at greater ranges than by the use of radar. Nevertheless, radar still has an important function, because only by radar can a vessel navigate successfully in poor visibility in confined waters, or receive warning of obstacles above water.