PRINCIPLES AND PRACTICE
OF
RADAR

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WITH 574 *DIAGRAMS*
and
8 *HALF-TONE PLATES*

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PREFACE

THIS book assembles and co-ordinates the principles upon which radar systems have been developed, so that the reader is given a rapid understanding of the subject. The principles upon which radar depends are presented in three stages :—

(1) Principles directly connected with established radio practice.

(2) Principles connected with the modification to, or extension of, established radio practice.

(3) Principles associated with entirely new technique.

In this thoroughly revised edition, the first stage of this treatment (basic principles of radio practice, forming Chapters II–V of former editions) has been summarised and now forms Chapter II. The space so saved has been used to amplify those parts of the book which experience has shown to be of most practical use to students, operators and technicians.

Chapter XXIV, dealing with actual equipments, has been greatly enlarged ; in addition to the B.T.H., Sperry, Kelvin-Hughes and Liverpool Harbour radars, sections on the Decca, Cossor and Marconi marine radars are now included, and a section dealing with airfield control radar will be found especially interesting. In addition, a new chapter on radar test gear has been added.

The exacting requirements which modern radar installations are called upon to meet are reflected in the use of higher and higher frequencies, and the revisions of this book have taken this trend into account. Those parts dealing with microwave radar have been emphasised and enlarged, and those dealing with longer wavelengths, now rapidly becoming obsolete, curtailed where necessary. The chapter dealing with feeder systems has been entirely re-written, giving greater prominence to coaxial feeders and waveguides than to open wire feeders, since the latter are little used nowadays. In the chapter on duplexing methods, attention has been focused on microwaves and the special problems met with at these wavelengths. A few additional circuits for special purposes have been added, and some later developments such as lenses, slot aerials, etc., have been described.

The information contained in this volume is the outcome entirely of the work of that large body of scientists, British and American, who laboured to perfect the radar systems which played such a conspicuous part in World War II. Some electrical symbols used in this book differ from those employed in the United States, for example, E_a instead of E_P, I_a instead of I_P, but the meaning of each should be clear from the explanation given in the text.

The authors wish in particular to record their indebtedness to *Radar System Fundamentals* and *Radar Electronic Fundamentals* published by the U.S. Army and Navy.

It is desired to thank the following companies for providing much of the information on which Chapter XXIV is based, and for their courtesy in allowing illustrations of their equipment to be reproduced : The British Thomson-Houston Co. Ltd. ; The Sperry Gyroscope Co. Ltd. ; Kelvin and Hughes, Ltd. ; A. C. Cossor Ltd. ; Decca Radar Ltd. ; The Marconi International Marine Communication Co. Ltd.

H. E. P.
R. S. H. B.

NOTE TO SIXTH EDITION

In this edition sections have been added dealing with " True Motion Radar Displays " for marine installations, the cosecant squared aerial, and the use of circular polarisation as a means of minimising the effect of rain interference on airfield radar displays. Opportunity has also been taken to make a number of other revisions.

It is with much regret that we record the death, in January, 1956, of Mr. H. Penrose.

INTRODUCTION

RADAR—by which is meant Radio Direction and Ranging—is not just an invention by a single person. Its development is due to work by many thousands of people, directed in Great Britain and the United States by eminent scientists, who have drawn upon established telecommunication practice, modified it, and added much new technique in course of development.

It has been known for many years that energy in the form of radio waves at radio frequency is reflected by objects in the wave path, but it required the stimulus of dire necessity to bring about the concentration of thought and effort which has resulted in the evolution of modern radar systems from knowledge of this phenomenon.

Basic Principle

Basically all pulse radar systems operate on the principle of emitting a short R.F. signal (usually referred to as a pulse) and measuring the time elapsing between the emission of this signal and the reception of an echo from a target.

Since the velocity of radio waves is known, the information so obtained enables the range of the target to be calculated. The calculation is performed automatically and the final result, in miles or yards, is shown on a Display Unit in a form most convenient for the particular purpose in view.

Direction finding is achieved, at least in the case of the longer wavelength equipments, by methods bearing considerable resemblance to conventional radio direction finding. On the shorter wavelengths the principle is even simpler, amounting fundamentally to little more than determining the direction in which a radar beam must be pointed in order to hit a target and so produce an echo. The method is analogous to illuminating a target with a searchlight beam.

Radar Applications

Radar was intensively developed under the threat of war, its first purpose being to serve as a means of warning of the approach of hostile aircraft.

As techniques developed and increasing accuracy became attainable, development tended to diverge along two separate lines. One was the continued development of warning radar, the other being directed towards the attainment of higher accuracies, although at shorter ranges, with a view to obtaining data of sufficient accuracy for laying and ranging anti-aircraft guns against unseen hostile aircraft.

Along with this, there was also the obvious development of radar sets fulfilling similar roles with respect to ships at sea. In some ways this problem was easier, since all surface ships are at sea level, and the problem of locating was reduced from one of three dimensions to two. On the other hand, the fact that the target was so near the sea surface introduced complications due to reflection of radar waves from the sea, as well as from the target.

The earliest radar equipments were land installations, but sets for use on board ship and in aircraft were soon developed and used for purposes roughly similar to their land counterparts, with various obvious differences.

When the war was over it was natural that the effort that had been put into the development of radar for military uses should be turned to account for peacetime purposes. Since the function of a radar set is to determine the position of an object in space, without the active co-operation of that object, the system is neither inherently warlike nor peaceful, but can be used for both purposes, with certain necessary differences in the actual equipments owing to differences in the uses made of the results.

At the present time one of the most widely used civilian applications is that for merchant ships, and several commercial designs have been produced for this purpose. A ship fitted with radar can " see " the neighbouring coastline (if within range) and also other ships and buoys in the vicinity.

Another application of growing importance is the harbour control radar, a shore-based installation enabling harbour authorities to " see " at a glance the positions of all ships in the approaches to the port, even in thick fog. The information so obtained can be communicated to pilot boats, and any other interested ship by radio.

On the air side, peacetime developments have followed in a roughly similar manner, but considerations of size and weight have prevented radar being adopted by civil aircraft to the same extent as in the case of the merchant ship.

The counterpart of the harbour control radar is to be found in the airfield control radar which enables the officer in the control tower to determine the positions of all planes within a range of several miles of the airfield. An interesting development in connection with this equipment is the means whereby moving objects can be distinguished from fixed ones.

Technical Development

Apart from improvements in accuracy, reliability, range performance, and similar things normally expected as development progresses, one of the most important points to be noted is the continual tendency to work at shorter and shorter wavelengths. The earliest radars operated on wavelengths of several metres. The figure was soon reduced to from 5 to 10 metres, after which followed wavelengths of the order of a metre, and so on down to the most commonly used 10 and 3 centimetre waves which are a feature of practically all new radar equipments.

The shorter wavelengths have the advantage of behaving more like light waves, thus facilitating the design of aerials giving highly directional beams. The advantage of a narrow beam is that the available energy is more concentrated, and there is also a considerable reduction of complication due to reflections from the ground, since for the most part the beam can be pointed so that little or no energy strikes the ground.

The transition to centimetre waves was initially retarded by the absence of any really satisfactory high power oscillator for these frequencies, but this difficulty was resolved by the invention, early in the war, of the high power resonant cavity magnetron. After this, centimetric radar development proceeded rapidly.

Differences between Radar and Radiocommunications

Although both radar and conventional radiocommunication systems employ radio waves which are, of course, intrinsically of the same nature, there are many differences in the techniques employed.

On the R.F. side, the techniques are very similar, except in so far as they necessarily differ in detail due to the fact that in general, but by no means always, conventional radio systems work on wavelengths which are considerably longer than those used in radar.

On the video side the differences are much more marked. When radio is used to convey speech or music, or even telegraph signals, the aim of the designer is normally to produce circuits which pass the signals with a minimum of distortion. In radar on the other hand controlled distortion is the rule rather than the exception. This arises from the need to produce pulses which are of certain required lengths and shapes, generally rectangular. So much is this so, that it can be said that ordinary sinusoidal A.C. circuit theory has but little application to radar problems.

The radar transmitter is required to emit a pulse at regular intervals, and these pulses are required to be as nearly rectangular as possible. The receiver must " note " the time at which a pulse is emitted, and must measure the time which elapses before the return of an echo. This involves the use of some form of time base circuit, roughly akin to those used in oscilloscopes. The answer must be presented to the operator in a suitable form, generally by aid of a cathode ray tube. The exact form of presentation depends on the purpose for which the installation is to be used.

Layout and Treatment of the Subject

It is not practicable to cover, in a single volume, the whole field of conventional radio practice as well as radar, and it is therefore assumed that the reader is already familiar with the more usual radio circuits, tubes, superheterodyne receiver, and so on, or if not so familiar, that he will obtain the necessary knowledge from standard radio textbooks.

Treatment of these subjects has therefore been condensed into a single chapter (II) ; this may be regarded as intended mainly to refresh the reader's memory. Cathode ray tubes are dealt with in Chapter III, and this is followed by a chapter on the basic radar system. The next eight chapters deal mainly with special circuit techniques. Chapters XIII and XIV deal with thermionic tubes and the magnetron respectively.

Eight chapters are then devoted to a consideration of the various parts of the radar installation, after which there is a chapter on test gear. The final chapter gives examples of actual radar installations.

The theory of transmission lines, waveguides and cavity resonators as applied to radar is treated in Appendices I, II and III respectively.

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CHAPTER I

FUNDAMENTAL PRINCIPLES OF MEASUREMENT OF RANGE, BEARING AND ELEVATION

VELOCITY is defined as the distance travelled by a moving object or wave in a unit of time. If the distance is measured in feet and the time in seconds, then the velocity is expressed in feet per second. If the distance is measured in miles and the time in seconds, then the velocity is expressed in miles per second. For instance, a ray of light and a radio wave both travel through space at a velocity of 186,000 miles per second. If the metre is taken as the unit of distance, then the velocity is expressed in metres per second. In one second radio waves (and also light waves) travel a distance of 300,000,000 metres. This fundamental fact forms the basis of the whole science of Radio Detection and Ranging.

A radio impulse sent out from a suitable transmitter is reflected back when it meets a metallic or other suitable obstruction in its path. This reflected wave is received back by the transmitting station a fraction of a second after it has been sent out. The time interval between the sending out of the impulse and the reception of the reflected wave provides an exact measurement of the distance which the wave has travelled. It has already been mentioned that radio waves travel at a speed of 300,000,000 metres per second. This speed may be expressed more conveniently for our present purpose as 328 yds. per microsecond. Thus if there is a suitable object 328 yds. from the radar transmitter the radar impulse will travel to the object and be reflected back in a time of exactly 2 microseconds.

It can be seen from the above brief introduction that the underlying principle of radar is extremely simple, but it will also be realised that the application of this theory requires the use of apparatus capable of measuring time intervals accurately to within a fraction of a millionth of a second. Fortunately for the science of radar, this property is possessed by the cathode ray tube.

Measurement of Range by the Echo

Since the time taken by the echo to travel from the target to the receiver must be equal to the time taken for the transmitted wave to travel from the transmitter to the target, the time interval between the start of the echo from the target and its receipt at the transmitting-receiving site must be half the time interval between the start of the transmitted wave and the receipt of the echo. Consequently the range of the target must be $\frac{328 \times t}{2}$, or 164t yds. approx., where t measured in microseconds is the time interval between the instant of transmission and the instant of receipt of the echo.

An essential requirement for the measurement of range by this method is identification of the echo with the transmission by which it is produced. This is accomplished by pulsing the transmitter at some convenient but constant rate, the duration of each successive pulse being identical and extremely short.

The transmitter output is therefore a succession of short sharp pulses or bursts of radio frequency energy.

The echo signals returned by a target are identical in shape but greatly reduced in amplitude, and since they are received in the intervals between successive pulses of transmitted energy, they can be automatically identified with the pulse of transmitted energy by which they are produced.

As a result of the above arrangement the instants at which successive pulses commence can be used as a reference from which to measure the time intervals between the transmitter firing and the receipt of echoes from targets at varying ranges. These ranges can then be calculated from the formula :—

$$\text{Range (yards)} = \frac{328 \times \text{interval time (microseconds)}}{2} \text{ (approx.).}$$

Pulse Repetition Rate, Pulse Width, Carrier Frequency and Wavelength

The number of times per second that the transmitter is stopped and started is the pulse repetition rate. The duration of the pulse is commonly referred to as the pulse width. The frequency and wavelength of the R.F. energy transmitted during each pulse is determined by the electrical constants of the R.F. generator as for normal W/T or R/T signalling.

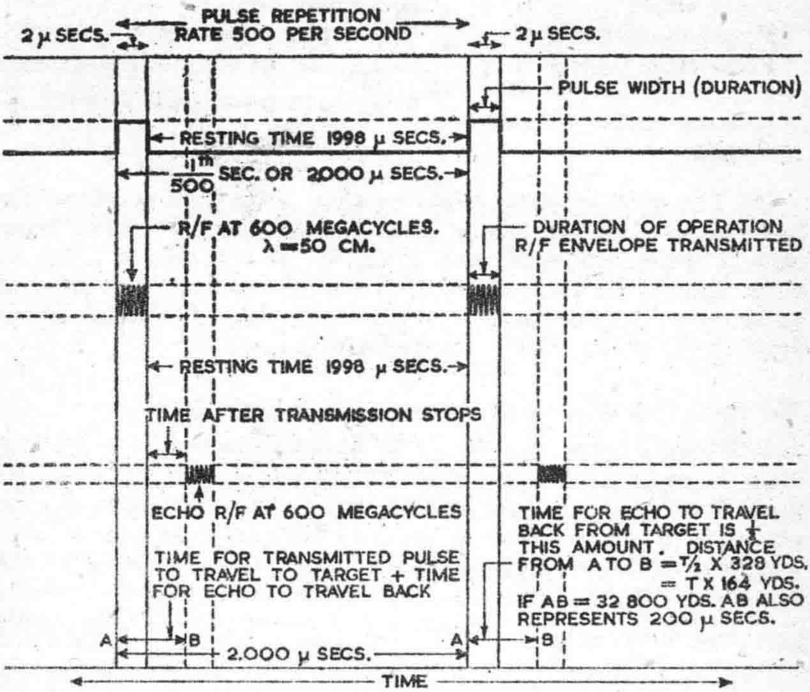

Fig. 1.—ILLUSTRATING RELATIONSHIP IN TIME OF PULSE WIDTH, PULSE REPETITION RATE, R.F. ENVELOPE AND ECHO.

Range is measured from the "leading" edge of the transmitted pulse to the "leading" edge of the echo.

Fig. 1 illustrates the relationship in time of pulse width, pulse repetition rate, carrier or radio frequency and received echo for the following conditions, all of which may vary within comparatively wide limits for different radar systems and conditions.

Pulse width (duration of pulse) = 2 microseconds
Pulse repetition rate = 500 pulses per sec.
Radio frequency = 600 megacycles per sec.
Wavelength = 50 cm.
Range of target = 32,800 yds.

(1) *Note* that the resting time of the transmitter (the time elapsing between each stop and start) is long compared with the duration of each pulse, *i.e.* :—

Pulse width = 2 microseconds
Pulse repetition rate = 500 pulses per sec.
Pulse time period = $\frac{1}{500}$ sec. or 2,000 microseconds
Resting time of transmitter $\left\{\begin{array}{l}= 2{,}000 \text{ microseconds} - 2 \text{ microseconds} \\ = 1{,}998 \text{ microseconds}\end{array}\right.$

(2) The resting time between each stop and start of the transmitter must be made long enough for all echoes from targets within the maximum range of the equipment to travel back and to be received without being masked by the next pulse from the transmitter. This requirement sets an upper limit to the permissible pulse repetition rate.

The Basic Unit of Range Measurement and Calibration

Referring to Fig. 1, the time, AB, measured from leading edge to leading edge, is clearly the total time for the outgoing pulse to reach the target plus the time for the reflected echo to travel back to the transmitter-receiver position. Since both outgoing and incoming waves travel the same distance at the same velocity, the time for the return echo must be exactly half the total time, *i.e.* $\frac{AB}{2}$ Consequently the distance of the target from the transmitter in terms of time will be $\frac{AB}{2}$ microseconds. The wave velocity is 328 yds. per microsecond; $\frac{AB}{2}$ microseconds × 328 yds. equals the distance of the target from the transmitter in yards. This is more conveniently expressed as

AB (in microseconds) × 164 = range (in yards) approx.

The above expression forms the general basis for calibrating the screen of a cathode ray tube.

This is accomplished by causing the electron beam of a cathode ray tube to trace a bright line horizontally across the diameter of the screen *each time the transmitter fires*, the *commencement* of each trace being *synchronised* with the *instant of firing* of the transmitter. It is usual to arrange the length of the trace so that it occupies the whole working width of the screen, say, for example, 6 in.

This 6-in. line can be made proportional to any desired time by varying the rate at which it is traced by the electron beam, *i.e.*, by varying the speed at which the electron beam is moved or deflected across the screen. Thus if each trace is completed in say 200 microseconds, the whole length of this 6-in. line is proportional to 200 microseconds. If the trace is made at half that speed, it will take 400 microseconds to complete the same length of trace and the 6-in. line will then be proportional to 400 microseconds.

This means that a line traced in the above manner across the screen of any C.R.T., no matter of what length, can be made proportional to any desired *time* by adjusting the speed at which it is traced.

This line is called the *time base*, and the circuits which control the speed of tracing are the *time base* circuits.

From the foregoing, and from Fig. 2, it is evident that a time base can be calibrated in target range yards, *e.g.*, in Fig. 2 let the length of the time base be proportional to a time of say 366 microseconds. 366 × 164 = approx. 60,000 (target) yards. Therefore, in this case the time base is proportional to 60,000 yds. The whole time base can be divided into equal lengths, marking it by some means at each point of division. The time base (Fig. 2) is calibrated

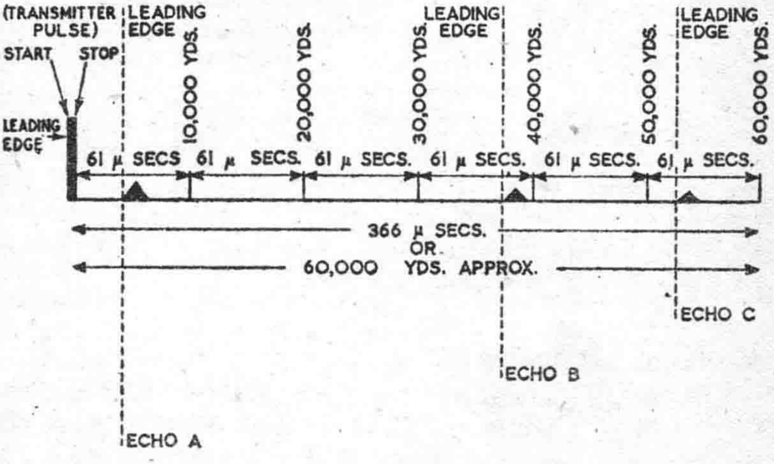

Fig. 2.—CALIBRATION OF A TIME SCALE IN TERMS OF YARDS.

Echo A appears at about 5,000 yds., or 30·55 μ secs. (approx.) after the transmitted pulse.

Echo B appears at about 38,000 yds., or 231·7 μ secs. (approx.) after the transmitted pulse.

Echo C appears at about 52,000 yds., or 317 μ secs. (approx.) after the transmitted pulse.

in six 10,000-yd. lengths, each of which is proportional to 61 microseconds.

Example of Simple Calibration

In Fig. 2, echoes A, B and C are shown on a time base at ranges of 5,000, 38,000 and 52,000 yds. respectively. (Note that the height of the echo diminishes as the range increases. This is true when the targets at B and C present identical *reflecting surfaces*. If, for example, however, the A target was very small and the B target was very large, it might happen that the B echo was comparable with the A echo.)

The effect, produced on the screen by the arrival of an echo signal, is achieved by the application of the output of the receiver (at video frequency) to the cathode ray tube, in such manner that echo signals deflect, vertically, the time base trace. This means that a " pip " appears on the time base for each echo received, marking by its position on the time base the instant at which it is received relative to the commencement of the time base and to the firing of the transmitter.

The distance measured along the time base from the leading edge of the transmitted pulse to the leading edge of the echo signal, see Fig. 2, is proportional to the time interval between the firing of the transmitter and the receipt of the echo.

Since this length can be physically measured as a fraction of the total length of the time base scale, it has a proportional value in time and range ; consequently, assuming that the time base scale has been calibrated at 164 range yards per microsecond of length, the range of the target can be read from the position of the echo on the time base.

Measurement of Bearing

In order to measure the bearing of a target it is necessary to be able to identify the direction from which a given echo arrives. This requirement means that it is essential to be able to direct the transmitted energy in any given direction at will, and to discriminate between signals received from a given transmission in a given direction and signals arriving from all other directions.

These requirements are met by concentrating the transmitted energy into a narrow beam, which can be directed at will, by rotating the aerial in azimuth,* and since the receiving pattern of an aerial is similar, fortunately, to its transmitting pattern, an aerial which transmits a narrow beam discriminates in favour of all signals received from targets within the beam. The aerial may therefore be pointed in any direction at will, or caused to sweep continuously through all points of the compass.

If the beam is symmetrical about the axis of the radiating system the distribution of R.F. energy in the target area will be maximum when the axis of the radiating system is aimed directly at the target. Since this factor determines the pattern for distribution of the transmitted energy over the target it must also control the collected or received energy. Consequently, maximum energy is received or collected from a target when the target lies along the axis of the radiating system. In other words, the conditions applying to maximum transmission of energy to the target are identical with those for maximum collection of energy by the aerial system from the target.

Beam Width

The beam width is very important. The narrower the beam the greater is the concentration of energy upon the target for any given transmitted signal and, all other things being equal, a larger echo will be returned for any given range and target. Also, the separation (or definition) in the case of bunched targets is better with a narrow beam, and greater accuracy of the bearing reading is also rendered possible. In general, very narrow beams necessitate, for practical reasons, the use of centimetre waves and range is (as will be explained) limited. Hence, there is a line of demarcation between long-range warning sets and sets for precise measurement. Long-range sets generally employ frequencies of the order of 100 to 1,000 megacycles. The beam, with practicable aerials at these frequencies, is generally wide, but since a high degree of accuracy in measurement is not essential, this does not matter very much. Indeed, it may be an advantage for search purposes. Precision sets require to use narrow beams, and in order to obtain them with practicable aerials, ultra-high frequencies must be employed. Range is, however, limited.

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* Azimuth is defined as the angle between the vertical plane containing the line of sight and the true meridian passing through the observer's position. It is measured " clockwise " from the north point of the horizon to the horizon point in the line-of-sight plane as an angle of between 0° and 360°.