B.R.1600A
Code No.1563
A.P.1093E(2)

INTRODUCTION

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INTRODUCTION

1. GENERAL IDEAS

(1) The term 'RADAR' is derived by telescoping the phrase "RAdio Detection And Ranging", retaining the letters indicated by capitals. It is properly applied to those systems and equipments which seek to locate objects by virtue of the radio-waves they emit when irradiated by a controlled source of radio-waves. Such reradiation may derive from the simple scattering by an object of a proportion of the primary radiation which it intercepts, in which case we have an example of a "PRIMARY RADAR SYSTEM", or this elementary response may be reinforced by secondary radiation, produced from within the object and released under the impact of the primary radiation, in which case we are dealing with a "SECONDARY RADAR SYSTEM". Other systems exist to which the description "radar" has been applied, particularly in the field of radio-navigation, and which do not conform with the definition given; a situation due largely to the use of many common techniques in the two fields. The radar art is closely associated with radio direction-finding and radio ionosphere-sounding, and the germ of many radar techniques may be traced back to these older arts; at the same time it should be pointed out that much of modern radar technique has been derived from specific radar research enterprises, and it is quite certain that the prolific developments in this field are now finding, and will continue to find, many diverse applications in other branches of radio and electronic engineering.

(2) The location of an object, or objects, may arise as a radar problem in a variety of ways. In the simplest problems we may be concerned to discover when an object intrudes into the radar field of view, and be satisfied with very approximate information as to its relative position. At this level we are dealing with comparatively crude anti-collision devices, cloud detectors, proximity fuzes and so on. In more complex problems we may be required to give continuous and precise information as to the relative position of an object, as, for example, where accuracy and smoothness of data must provide an adequate basis for prediction and fire-control. Thus, position is a quantity which may be variously specified in different radar problems. For some purposes there will be a need to measure position relative to an observer (actual or hypothetical) situated in a moving aircraft, ship, or other vehicle, whilst for others position will be required as a map reference. In some cases complete information will be needed, whilst elsewhere information incomplete in itself, through lack of one or other co-ordinate of position, will not necessarily be disadvantageous. In all cases the accuracy of the information gained will be subject to limitations, to be ascribed partly to the design of the radar equipment, and partly to external circumstances, such as siting, weather and interference. To assess the adequacy of any equipment it will be necessary to compare its performance with that degree of accuracy actually required to perform the assigned tasks.

(3) In establishing position, equipment may be required either to report whether there is any material object at an indicated position, or alternatively to provide signals which will give guidance as to how to proceed towards, or how to avoid, a selected position. Here arises a primary division of radar roles into searching and guiding.

(4) A search may be carried out systematically by examination of radar information brought in repeatedly over a whole zone, this process being generally known as "scanning" when it is done automatically, or equipment may be allocated to the task of following up the movements of a selected object (the "target"), a process known as "following" or "tracking". In both cases the amount of manual dexterity required and the work allocated to machines and to automatic control devices may vary widely from one type of equipment to another. A mobile search equipment may also be used in a navigational role, either by virtue of receiving a coded signal from a known source, or by making use of a scanning system giving such profuse information of objects on the ground as to render practicable identification with maps.

(5) Guidance may be given in such a way as to facilitate movement towards a position where radar equipment may or may not be situated: in the former case the equipment being approached is known as a "beacon", and in the latter case the equipment serves as a navigation device of wider application. Beacons may also be fitted to friendly aircraft, ships or vehicles so as to allow their identification when it may be necessary to distinguish friendly from hostile radar targets.

(6) Many radar equipments are arranged to fulfil a number of different roles, this being not only economical, but often necessary where saving of space and weight assume vital importance. On the other hand, where radar applications of the highest precision are encountered this view cannot logically be sustained.

2. RADIO DIRECTION-FINDING

(1) Simple direction-finding systems have been widely used as an aid to navigation by ships and aircraft for both civil and military purposes. The majority of these installations work with vertical polarisation at much lower frequencies than those used for radar purposes, and they determine the direction from which any wanted signal proceeds by the use of simple types of directional aerial systems; usually a screened loop or Adcock array. With such a system directivity is low, and is often best exploited by seeking a minimum, rather than a maximum signal. In addition to determining direction, these equipments can usually be made to give the sense (in front or behind) associated with the direction found, by means of a second manipulation. Under these conditions direction-finding is a fairly leisurely process. Apart from navigational requirements, military applications of this type of direction-finding are encountered in intercept receivers used for intelligence work, and examples of similar practice may be found amongst early radar receivers operating at low radar frequencies. These may survive in the field of long-range radar warning, provided time to observe and report is adequate, and if precise location is not required.

(2) In order to determine position by means of a direction-finding equipment it is necessary to establish the bearings of two or more transmitting stations whose geographical locations are known, and this is a very common practice, special transmitters being allocated for this purpose, which send out signals at standard times. Clearly the two or more measurements required should be completed within a time short enough to ensure that any change of position which may have occurred is insignificant in relation to the expected accuracy of determined position. Alternatively two or more direction-finding receivers occupying fixed stations may be used to locate the source of a particular transmission, if the information obtained is passed to a common control-room. This method has also been used to assist navigators (by passing the information on to them by radio) as well as for intelligence purposes.

(3) Both these systems involve co-operation between the users of the transmitters and receivers and thus differ fundamentally from radar detection systems, which depend only on the involuntary co-operation of "targets". It is this involuntary co-operation which has prompted the development of radar camouflage, and other counter-measures for use by or on behalf of potential "targets" which hope to evade location.

3. RANGE-FINDING

(1) Determination of position on a map by the direction-finding technique described is equivalent to solving a triangle from a knowledge of one side and two angles, and this is a special case of the triangulation used for more general survey purposes, with the difference that optical equipment is replaced by radio equipment. It should be noted that in such systems distance to the position which is being located is derived, and not directly measured. Even in the specific instance of the optical "range-finder", an instrument widely used for military purposes, range is really derived from angular measurements. In Fig.A, D represents the "base" of the range-finder

and R the range to be measured. The instrument is adjusted by altering the angle θ so that the same target is viewed in both telescopes. Here $R = D \cot \theta \doteqdot D/\theta$ where θ is the usual small angle. In this case the importance of possible errors can be estimated from:-

$$\frac{DR}{DD} = \cot \theta = \frac{R}{D}$$

$$\frac{DR}{D\theta} = -D \operatorname{cosec}^2\theta = -D\left(1 + \frac{R^2}{D^2}\right) \doteqdot -\frac{R^2}{D}$$

Thus an error in the length of the base D introduces a range error proportional to R whilst an error in estimating θ introduces a range error proportional to R^2. D is at most a few feet, and θ a matter of minutes and seconds of arc, so that the precision required of such instruments taxes the skill and ingenuity of the designer.

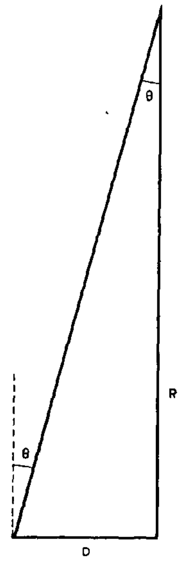


Fig.A: Principle of optical range-finder

(2) The unique factor in radar search systems, which distinguishes them most markedly from direction finders, lies in the use of the "echo principle" for range measurement. If electromagnetic radiation falls upon any material body the body will itself become, for the time being, a centre of reradiation, a phenomenon also known as reflection and as scattering. But waves take time to travel, thus if we can 'label' a particular bit of radiation as it leaves its source (a radar transmitter) with a view to identifying it, after the double journey to and from the material object (a radar target), by means of a suitable detector (a radar receiver), we can infer the length of the double path from a measurement of the time interval which separates these two events. This presumes that we know in advance the velocity with which these waves travel, and further, if the corresponding calculated distance is to be of much use, that the propagation has been substantially rectilinear. For most practical radar purposes these assumptions can be granted, and range errors can be reduced to negligible proportions for all save the most exacting radar roles. The "labelling" is most simply effected by transmitting from time to time short bursts of radiation, which are known as "pulses", and by this means it is usually possible to observe the two events (original disturbance and echo) quite independently.

(3) The original development of such pulse-technique was directed towards the measurement of the height of the ionosphere. Radar may be said to have emerged from the blending of the pulse-techniques and display-systems used in sounding the ionosphere with the aerial techniques of direction-finding.

4. RADAR

(1) The radar detection problem is much the same as the visual detection problem. It is primarily to ascertain the position of a radar target, and secondarily to identify it as being hostile or friendly, and if possible to give whatever information can be gathered as to its precise nature. To specify position completely three independent measurements (or co-ordinates) are required. For radar detection systems these are generally, and most naturally, the slant-range and the angles of elevation (or sight) and though for some purposes it is more convenient to use ground range, bearing and height (or depression). Not all radar detection systems are designed to give complete information, however, some giving slant-range and bearing only, others slant-range and angle-of-sight, or slant-range and clock-angle direction, or slant-range alone, or mere direction. Further, all measurements of position are in the first place relative to the situation of the radar equipment, whether this be mounted on a static site or in a mobile craft or vehicle.

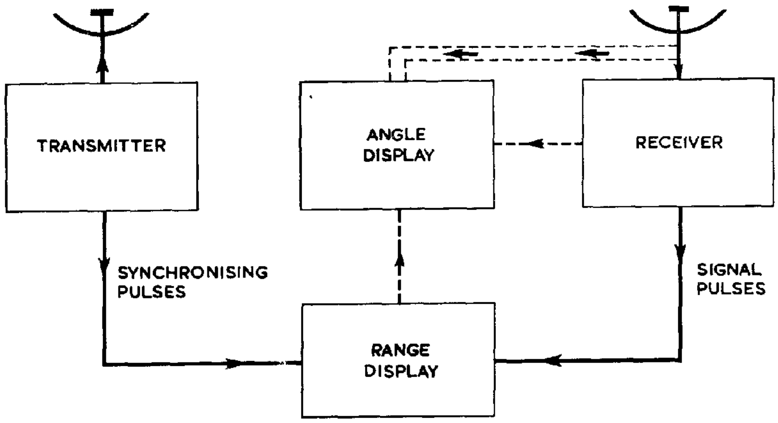


Fig.B: Elements of pulse-modulated radar system

(2) Wherever slant-range is required to be measured by a single detection equipment it is almost essential to use a pulse-modulated transmitter. This necessity arises not only in order to enable us to distinguish an echo from the original impulse, but also to differentiate from each other the several echoes which may be aroused by the same impulse. In other words pulse-modulation confers upon radar equipment the capacity for discriminating between targets at various ranges; it gives us the power of resolving irradiated targets in depth. Resolution does not in itself constitute a measurement of range, however, and to secure this for any individual echo it is further required to measure the time-interval elapsing between pulse-transmission and reception of the appropriate echo. For this purpose the radar receiver must incorporate suitable time-measuring devices, preferably calibrated to give a direct reading of range for any echo under observation. (Fig.B).

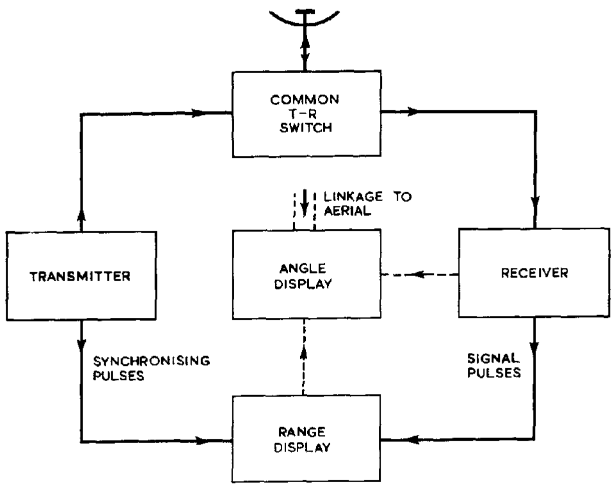


Fig.C: Elements of a radar system using a common transmitting and receiving aerial

(3) A natural consequence of this division of time between an active transmitter and an active receiver is the use of a common aerial system for transmission and reception, as such an aerial can be used alternately to transmit and receive. Such systems are described as "Common T and R" or "duplex", and have important advantages, particularly where space is at a premium. (Fig.C).

(4) To determine angles we must rely on the discretional properties of aerial systems. These properties could be mainly provided in the transmitter (which would be most unusual), or mainly in the receiver, (as is occasionally done), or present more or less equally in both, (as is the usual practice, and a natural consequence where a common aerial system is used for transmission and reception). The directivity is required to be mobile so that it can be brought to bear on any selected target, which means that the aerial system must be capable of performing suitable mechanical movements, or that an equivalent movement of directivity must be achieved by indirect electrical methods, or possibly that a combination of both methods must be employed. In any case a mechanical or electrical indicating device is of necessity associated with these aerial adjustments to permit measurement of the required angles.

(5) Better directivity in a radar system increases its discrimation between targets occupying the selected direction and any which may be adjacent to it, which is to say that in radar practice angular resolution is improved mainly by diminishing the field of view available for each pulse. Improvement in accuracy of angle information is thus obtained by accepting a proportionate increase in blindness (a condition closely paralleled in theodilites and in searchlights). This problem can, however, be met by the use of a subsidiary radar equipment (sometimes called a "putter-on") provided with no more directivity than is essential to help the more powerful instrument to find its target, or alternatively by conducting a systematic search with the latter equipment (a process of scanning).

(6) The problem of identification cannot be tackled by pure radar detection methods. This is because the resolving power of present radar equipments is in general far below that required for any examination of the fine structure of a target. To overcome this difficulty friendly targets can be equipped with an auxiliary radar transceiver equipment called a "transponder" and belonging to the class of equipment known as "radar beacons". Such an equipment is sensitive to radar transmitter pulses received over a restricted frequency-band, and these cause it to transmit a radar pulse of its own synchronised with the arriving radar signals. The responses can, however, be suitably coded to give a distinctive signal in the radar receiver concerned with making the identification.

5. RADAR TARGETS

(1) As already indicated, radar search systems are dependent for their success upon reradiation from radar-illuminated targets, a criterion which is equally applicable to searchlights in the appropriate part of the spectrum. In comparison with optical wave-lengths most material bodies are sufficiently large to have a characteristic appearance which leads to their easy recognition by observation from any angle; or in other words the tiny waves of light permit the resolution of fine detail. It is well-known that in the microscopic field all distinctive features gradually disappear as the size of objects under examination become progressively smaller. In the radar field, on the other hand, the wave-length of the radiation employed lies somewhere between a few centimeters and a few metres, and is quite comparable with the size of many radar targets. This considerably complicates the nature of the radar response. But first we shall consider limiting cases in which behaviour can be described in simple terms.

(2) For a small object, i.e., one whose dimensions are small compared with a wave-length of the radar illumination, the incident waves flow around the object, hardly noticing its presence; the disturbance in the wave structure due to the presence of the object is comparatively trivial. From the small

scale of this disturbance it is fair to conclude that the wave is not only insensitive to the presence of the object, but also to its shape. For such an object it would appear that the most significant linear dimension which it possesses for radar purposes is given by the maximum length (l) which it can project on the wave front of the incident wave in the direction of its polarisation (Fig.D), and that such limited reradiation as occurs would be comparable with that which would be produced by a short conducting rod of this length (l) placed at the same position, normal to the direction of propagation and in line with the electric field. For radar targets complying with this specification the response will be equally simple, and will, in particular, be largely independent of any relative motions between various parts of the target provided that these make no significant difference to its silhouette. In this example simplicity of response is a direct consequence of the ignorance of the target shown by the incident wave, and is realised at a heavy price, this being the low sensitivity of radar equipment to this type of target, for which the echo power actually depends on l^4.

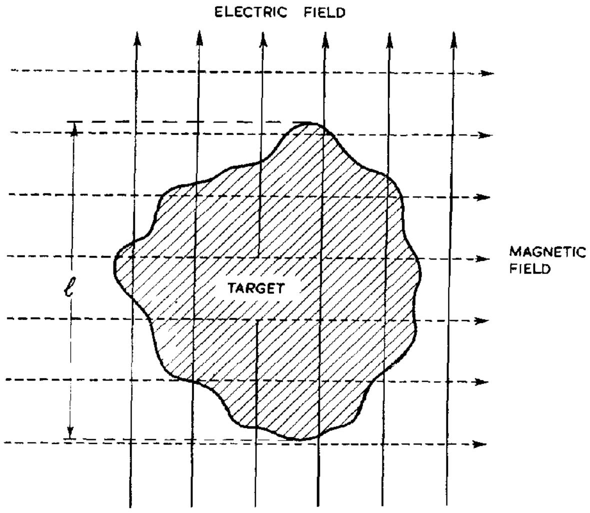


Fig.D: Significant dimension of small radar target.

(3) In the other extreme case, which is that of the object whose significant dimensions (including those of details) vastly exceed the wave-length employed, the radar problem resembles to some extent that of viewing common objects. (To make the parallel closer, monochromatic polarised light should be specified in the optical case, whilst the radar target should be free of details likely to resonate under the influence of the incident radiation.) In both cases the reradiated signal bears the imprint of the structure of the object, i.e., shape and details are clearly defined. Optical viewing systems are able to present this definition in the ultimate form of a two-dimensional image upon a sensitive mosaic, usually the retina of the eye, the extent to which the details are distinguishable being further dependent upon the optical properties of the lens system employed, and the fineness of the mosaic. Too small an aperture results in an inability to make use of all the definition in the incoming radiation, with the result that confusion masks the finer details. An adequate aperture will serve to allow full utilisation of the individual cells of the mosaic, whilst a still larger aperture confers no increase in resolution owing to the limitations of the mosaic. In radar viewing circumstances are usually very different in that there is commonly only one channel through which all information must pass (and even in elaborate radar systems, a very limited number), corresponding to a "mosaic" of a single element only. The construction of analogous "radar images" is thus only possible by the successive utilisation of this channel for different directions, i.e., by the employment of scanning

techniques. Where we are endeavouring to obtain a picture of a large radar target, such as the surface of the ground, the amount of detail which can be built up in the image will increase appreciably with increase in aerial aperture (wave-length being unaltered), and in practicable system sufficiently large apertures to utilise the bulk of the definition present in the incoming signal cannot usually be provided. Returning to the small radar target case, increase in aperture is primarily useful as a means of increasing discrimination between nearby targets and improving angular accuracy. For the very large object the size of the silhouette is a very significant factor, particularly where the surface has a rough structure (in terms of wave-length), though where the surface exhibits a smooth structure (again in terms of wave-length) specular reflections may complicate the response to such an extent as to mask this factor for certain aspects.

(4) So far we have not considered such practical radar targets as aircraft, small ships, etc. For the majority of these the overall dimensions and main features may be measured in a reasonably small, or at any rate not a very large number of wave-lengths, and the radar response will accordingly lie intermediately between the two special and extreme cases so far considered and will be additionally complicated by resonance effects. In particular, for any one angle of incidence, the reradiated signal will be distributed in direction in a markedly non-uniform fashion. Consequently the echo-signal received by a typical radar equipment is found to fluctuate appreciably in amplitude and polarisation from pulse to pulse due to changes in the aspect of the typical target, an effect described as "aspect-modulation" of the received signal. Moreoever changes in the spatial distribution of the reradiated signal may be brought about by relative movements of parts of the target, as, for instance, by the rotation of an airscrew. Fluctuation arising from this particular cause are described as "propellor-modulation" Again, conditions may arise where reradiation from one or more comparatively large and smooth surfaces approaches the case of specular reflection, in which case uncommonly large signals will arrive from those aspects where the receiver lies within the virtually reflected beam, a phenomenon known as "scintillation" or "glittering". Thus the increase in target visibility which arises from the use of shorter wave-lengths must be to some extent offset by the disadvantages of the various forms of aspect-modulation, these troublesome variations being properly regarded, however, as nothing more than the primitive attempt of the target to be seen in detail as something more than a shapeless speck.

6. PULSE RADAR SYSTEMS

(1) Although there is now considerable diversity of types amonst radar equipments, primary development was directed towards the pulse-radar search equipment, and this provides a convenient example on which to base a discussion of the main constituents of a radar system. Radar equipments designed for other roles may, of course, involve additional or alternative items. A pulse-radar search equipment can be divided in principle into two major parts, the radar transmitter and the radar receiver, though in an actual equipment there may be no physical division of units corresponding exactly with the transmitter and receiver, and further, there may be units which serve both, such as power supplies and aerials. Nevertheless this division is one of fundamental importance (Fig.G).

(2) The main object of the radar transmitter is to emit short bursts of radiation in rapid recurrence, and to direct the bulk of this energy into a more or less restricted beam. These transmissions are described as "radio-frequency pulses", each pulse consisting of a similar train of oscillations at the same radio frequency. From some points of view the ideal radio-frequency pulse would be one in which all the individual cycles were of the same amplitude (rectangular RF pulse), and although no actual pulses conform exactly to this description it provides a useful standard of reference. The main difference between an actual pulse and this ideal is that with the former it always takes an appreciable time for the oscillations to rise to their maximum amplitude, and similarly for them to decay to zero. For many purposes the actual waveform of the radio-frequency pulse need not be studied

in detail, and it is sufficient to examine the way in which the maximum value of the individual cycles of oscillation vary throughout the pulsing period; the form of this variation is known as the "pulse-envelope".

(3) The interval separating the times at which successive pulses are initiated in the transmitter (T_r) is known as the time or period of recurrence, whilst the reciprocal of this quantity ($F_r=1/T_r$) is called the recurrence-frequency. In the majority of radar equipments the recurrence-frequency is constant and fixed, though in some cases there may be provision for selection from a number of discrete values, or from within a range of values, whilst in other rhythmical variation of recurrence-frequency may be possible. Such facilities are usually restricted to those equipments using the longer radar waves, where they may be useful in helping to counteract mutual intereference, this being much more of a problem on these wave-lengths owing to the much lower directivity of the aerial systems employed.

(4) The effective duration of an individual pulse (T_p) is known as the "pulse-time", but this term has to be defined in an arbitrary manner (Fig.E). No difficulty arises in the case of the ideal rectangular pulse already mentioned, but with practical pulses it is not possible to state exactly when a particular pulse started or finished, nor would such information be especially useful unless supported by further detailed information as to the shape of the pulse-envelope. For our purposes "equivalent pulse-time" will be defined as the period during which the pulse envelope exceeds $1/\sqrt{2}$ of its maximum value, i.e., it will be the time occupied by those cycles whose energy is not less than half of the energy of a cycle occurring at the maximum (or the largest maximum, if there is more than one) of the pulse-envelope. In similar fashion, the "equivalent pulse" will be a rectangular RF pulse of the same frequency containing the same energy as the original pulse and of duration equal to the equivalent pulse-time; the "equivalent pulse-amplitude" will be the amplitude of the equivalent pulse, and the "equivalent pulse-power" will be the mean power of a continuous oscillation having this amplitude. It should be noted, however, that these definitions are not universally accepted.

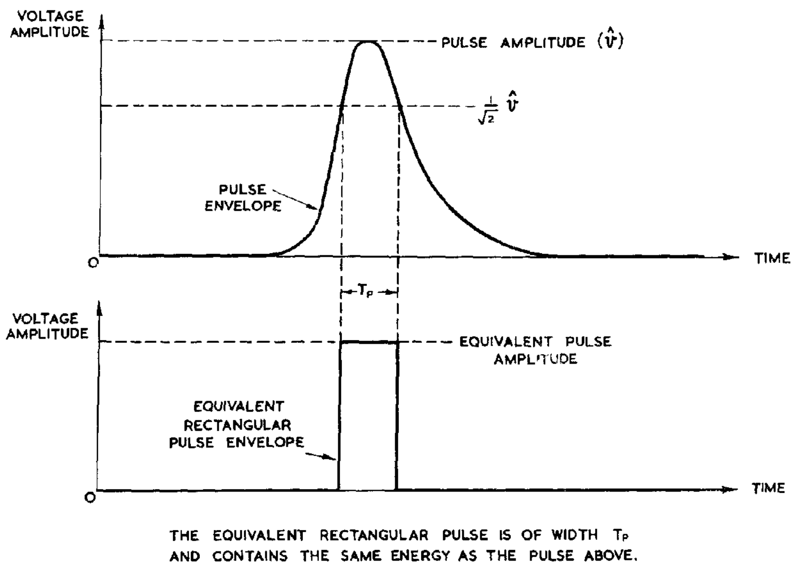


Fig.E: Pulse-amplitude, pulse-time, equivalent pulse, and equivalent pulse-amplitude

(5) In the majority of radar equipments the pulse-time is constant and fixed, though in some cases there is provision for choosing a particular value from two or three discrete values. The shape of the pulse-envelope is not usually intended to be subject to variation, and should be the best attainable from the equipment provided. any falling away from this standard is generally an indication of faulty adjustment or failing components.

(6) Another important quantity associated with the transmitter is the equivalent pulse-power (P_T). (Fig.F). This quantity has already been defined, and it follows that the energy content of a single transmitted pulse (W_p) is given by the product of equivalent pulse-time and equivalent pulse-power ($W_p = P_T \cdot T_p$). The average transmitter power ($\overline{P_T}$) is thus given by:-

$$\overline{P_T} = W_p \cdot f_r = P_T \cdot T_p \cdot f_r = P_T (T_p/T_r)$$

and the ratio of average to pulse-power is known as the duty-cycle (d). Thus the duty-cycle is given by:-

$$d = \overline{P_T}/P_T = T_p/T_r$$

For example, if T_p is one microsecond and T_r is two milliseconds, d is 0.005, or 1/200, which is usually read as one in two hundred. The "pulse-power envelope" shows how the power radiated varies throughout the duration of the pulse (ignoring the oscillating component of instantaneous power at twice the signal frequency). Its shape can be obtained by squaring the ordinates of the pulse-envelope, and its largest value is known as the "peak pulse-power" ($\hat{P}_T$).

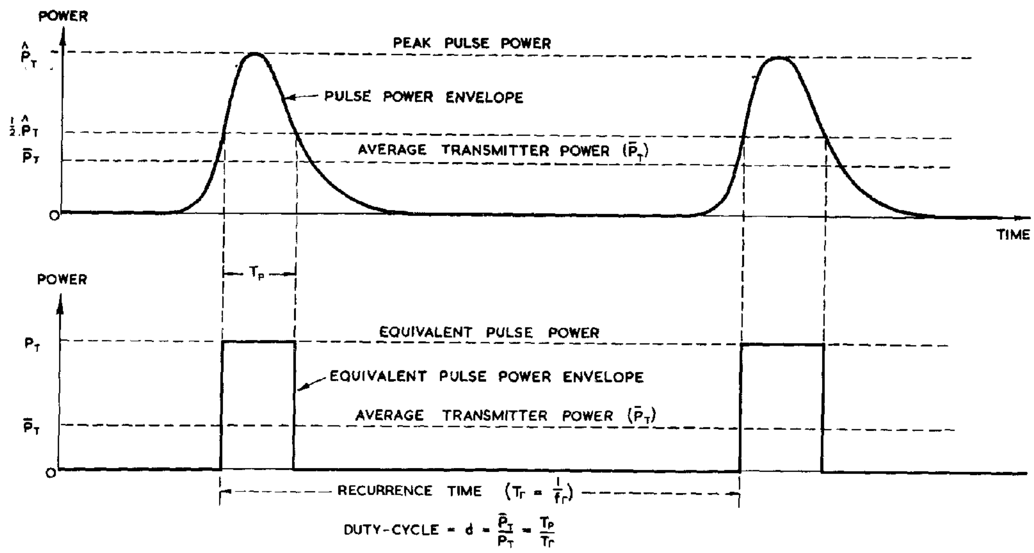


Fig.F: Pulse-power envelope, peak-pulse power, average transmitter power, and duty-cycle.

(7) In order to produce the type of signal described the transmitter must contain a generator of oscillations at the appropriate radio-frequency, in association with a pulse-modulator, which may be described as a device for switching the oscillator on and off at the appropriate times. Whereas in radio-telephony modulation is a continuous process, in radar, as in radio-telegraphy, it is a discontinuous process, i.e. pulse-modulation is closely allied to keying, although in the former case we are dealing with very much smaller times than in the latter, and with a very much smaller duty-cycle. Further, in radio-communication it is customary to generate oscillations continuously at a low power level, the modulating or keying process being performed in a subsequent modulated amplifier. In radar practice, on the other hand, it is customary to develop oscillations at a high level of pulse-power, subsequent power-amplification being provided in relatively few cases.

Such radar oscillators are always modulated, usually by an external modulator, though sometimes they are arranged to be self-modulating; any other arrangement would involve excessive waste of power in the oscillator during the quiescent inter-pulse periods, owing to the very small duty-cycle, and would almost certainly cause interference with the adjacent radar receiver. Power amplification is in any case only practicable for the longer radar waves, and is not very efficient, whilst introducing additional tuning adjustments; for centimetre wave radars there is little possibility of providing such amplification. So the pulse-radar transmitter usually has an essentially simple high-power oscillator, preceded by a pulse-modulator, and feeding the aerial system directly. When the oscillator uses triode-valves modulations may be performed in the grid circuit at low power, or in the anode circuit at high power, but where magnetrons are used high-power modulation is essential.

(8) The other main feature of the transmitter is the aerial system; this may be shared with the receiver, or may be a separate radiator. Where a common aerial is used special devices are needed to ensure that the receiver is protected from the outgoing pulses, and to enable it to extract the maximum available power from the radar echoes during the quiescent interval between pulses. These devices take the form of gas-valve switches which automatically route the outgoing or incoming energy through the appropriate channels, and which are operated by the high-power transmitter pulse. The transmitter aerial determines the spatial distribution of the radiated signals whilst the receiver aerial similarly determines how the receiver sensitivity to echo signals is distributed in direction; for most common aerial systems these directional characteristics are the same for transmitter and receiver, and take the form of a beam. Beams of different widths are encountered in different radar applications, as are beams which differ in other respects, such as cross-section. The majority of beams conform to one or other of the two basic types known as the "pencil-beam" and the "fan-beam". For most applications it is also required to be able to give these beams a degree of mobility in direction so as to allow them to be steered, such steering being carried out manually in some cases, and automatically according to a systematic programme in others, this latter process being known as scanning.

(9) Another feature of the transmitter is its co-ordinate link with the receiver, known as a "synchronizing" device. This may provide the receiver with a synchronizing pulse whenever the transmitter begins to radiate, or may in some cases work in the other direction, in which case a synchronizing pulse produced in the timing-circuits of the receiver is used to initiate modulation in the transmitter.

(10) Auxiliary parts of the transmitter include cables and couplings, power-supplies and power-packs, contactor-panels with protective devices, cooling systems, aerial-turning drives and transmitter monitoring and test gear. Some of these devices may be common to transmitter and receiver when these are, as is usual, in close proximity.

(11) The object of the radar receiver is to detect and to distinguish between the echo-responses to the transmitted pulses, and in so doing to supply more or less complete information as to the location of the source of each echo investigated. To accomplish this task the radar receiver requires four principal devices, a radio-receiver, a steerable-aerial, a time-measuring device and a display-system.

(12) The usual receiver embodies the superheterodyne principle, though it differs very markedly from the common communication receiver. In the vast majority of cases it is designed to operate over a very restricted frequency-band, corresponding with the associated transmitter. In practice this means that, apart from the case of the longer-wave radars, all circuits handling modulated signals (RF, as well as IF) can be pre-tuned, leaving fine-tuning adjustments to be made by control of the local-oscillator frequency, either by hand, or, in some cases, automatically. Within the receiver incoming signals must be examined to provide, as we have seen, two kinds of information concerning the selected radar target or targets.

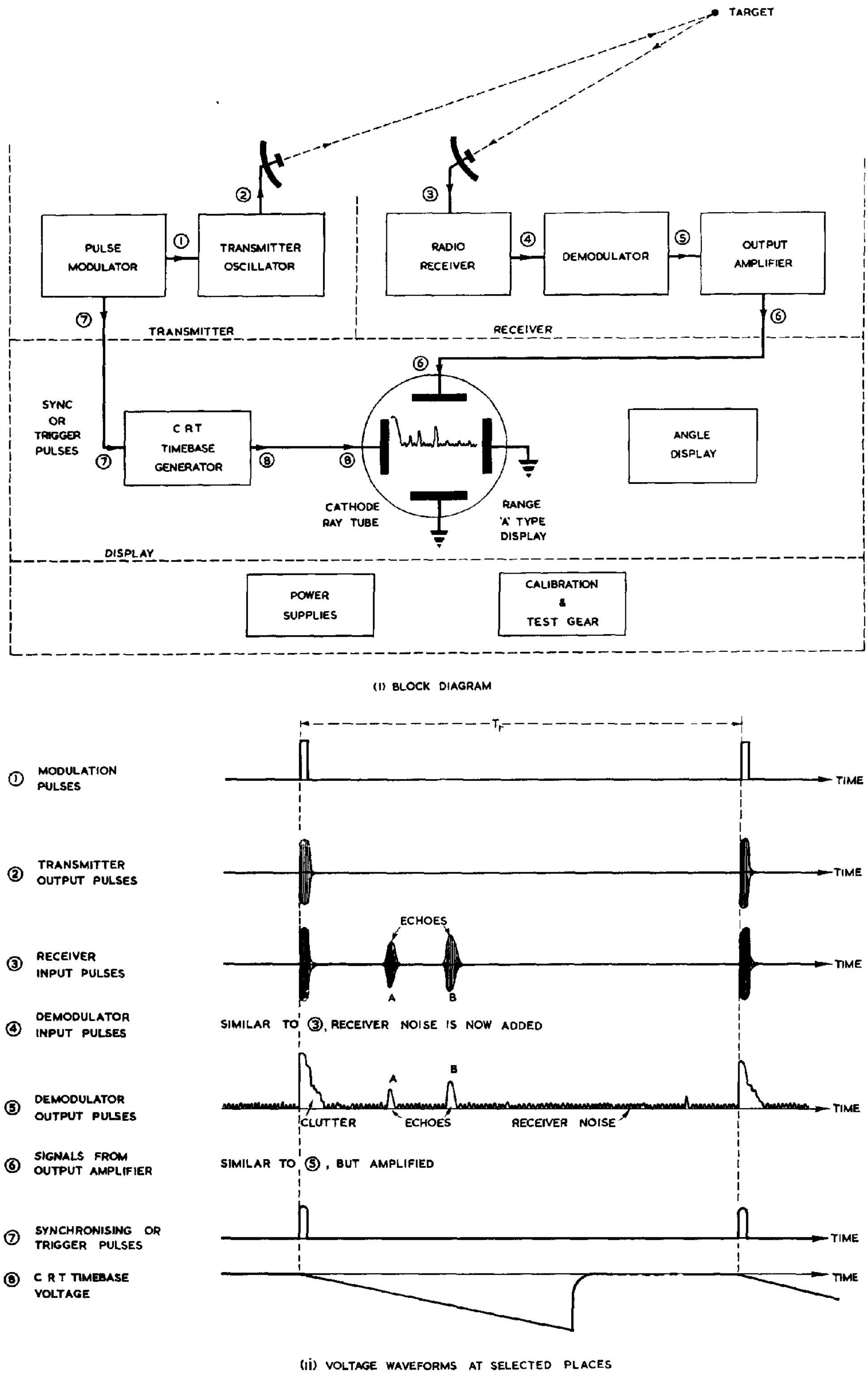
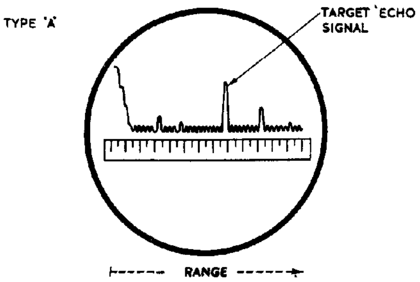
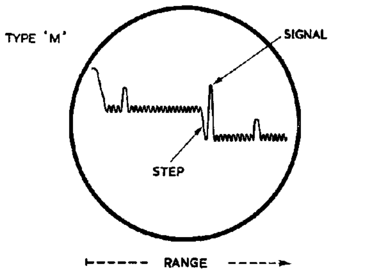


Fig.G: Typical pulse radar system



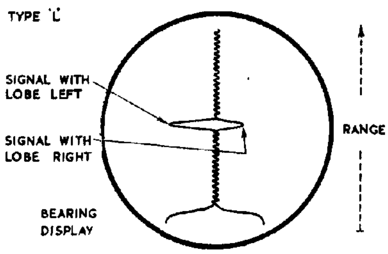
NORMAL RANGE DISPLAY
TIMEBASE HORIZONTAL DEFLECTION PLATES
SIGNALS VERTICAL DEFLECTION PLATES

(i)



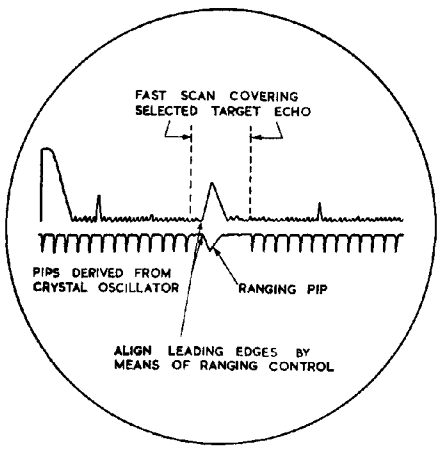
MODIFICATION OF TYPE 'A' WITH MOVABLE STEP MARKER FOR ACCURATE RANGING. STEP GENERATOR CONTROLLED BY RANGE MECHANISM TO GIVE DIRECT RANGE READING WHEN SIGNAL IS AT FOOT OF STEP

(ii)



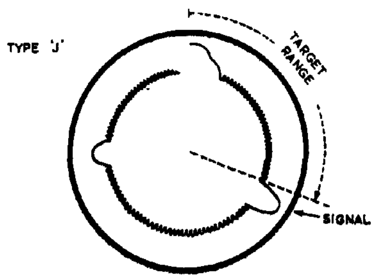
ELEVATION DISPLAY IS SIMILAR BUT WITH HORIZONTAL TIMEBASE
MODIFIED TYPE 'A' DISPLAY FOR AIMING DOUBLE LOBE AERIAL SYSTEM IN BEARING OR ELEVATION. SIGNALS FROM LOBES DISPLAYED BACK TO BACK INSTEAD OF SIDE BY SIDE AS IN (vi)

(iii)



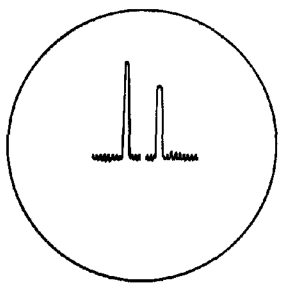
MODIFIED TYPE 'A' DISPLAY COMBINING LONG RANGE AND ACCURATE RANGING

(iv)



MODIFICATION OF TYPE 'A' EMPLOYING CIRCULAR RANGE SWEEP, PRODUCED BY APPLYING EQUAL AMPLITUDE QUADRATURE SINE WAVES TO HORIZONTAL AND VERTICAL PLATES. SIGNAL APPEARS AS INWARD OR OUTWARD DEFLECTION PRODUCED BY ELECTRODE AT CENTRE OF C R T SCREEN.

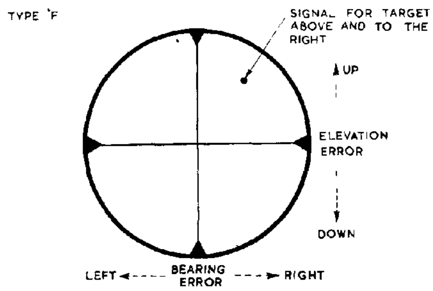
(v)



'PIP-MATCHING' DISPLAY FOR AIMING SWITCHED LOBE OR CONICALLY SCANNING AERIAL SYSTEM IN BEARING OR ELEVATION THE SIDE-BY-SIDE ECHOES CORRESPOND TO SIGNALS RECEIVED FROM A SELECTED TARGET, STROBED ON THE RANGE DISPLAY, AND MAY BE BEARING LEFT AND RIGHT SIGNALS, OR ELEVATION UP AND DOWN SIGNALS.

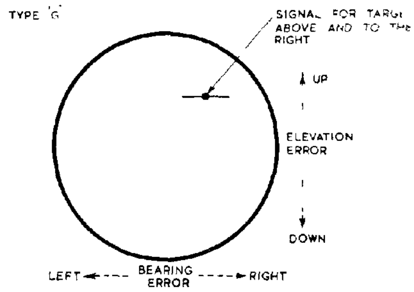
(vi)

<u>Fig.H: Typical radar displays.</u>



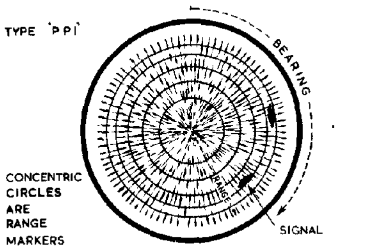
DISPLAY OF BEARING ERROR AND ELEVATION ERROR FOR SINGLE TARGET
D C ERROR VOLTAGES ARE APPLIED TO C R T PLATES TO DEFLECT SPOT FROM TUBE CENTRE WHEN OFF TARGET

(vii)



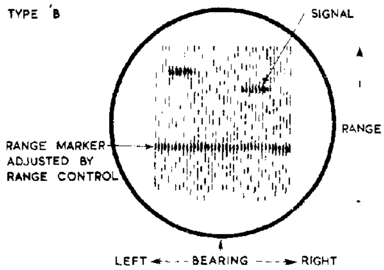
SIMILAR TO TYPE 'F' BUT WITH WINGS ON EACH SIDE OF SPOT WINGS INCREASE AS RANGE DECREASES GIVING ROUGH INDICATION OF RANGE

(viii)



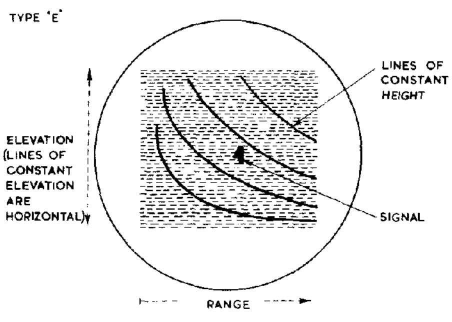
PLAN POSITION INDICATOR (PPI) DISPLAY
SIGNAL INTENSITY MODULATION
RANGE MEASURED RADIALLY DIRECTION OF SWEEP GIVING BEARING INDICATION SWEEP APPLIED BY EXTERNAL MAGNETIC COILS ROTATED BY AERIAL SYSTEM OR ELECTROSTATICALLY FROM WINDINGS OF AERIAL SELSYN

(ix)



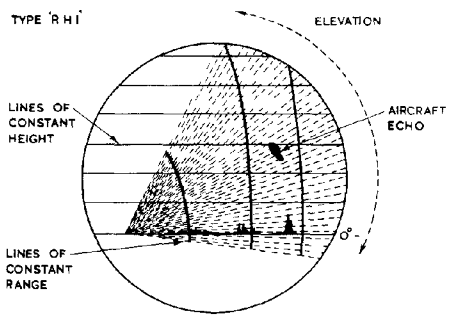
LINES OF CONSTANT BEARING ARE VERTICAL
DISPLAY OF RANGE AND BEARING
RANGE TIMEBASE VERTICAL
BEARING SCAN HORIZONTAL
SIGNALS INTENSITY MODULATION

(x)



DISPLAY OF RANGE AND ELEVATION (COMPARE WITH (X))
RANGE TIMEBASE HORIZONTAL
ELEVATION SCAN VERTICAL
SIGNALS INTENSITY MODULATION

(xi)



RANGE-HEIGHT DISPLAY INDICATES TARGETS IN AN ELEVATION SECTOR, CONTINUOUSLY SCANNED BY A HORIZONTAL FAN BEAM
IT IS A STRETCHED VIEW OF A SECTOR IN ELEVATION

(xii)

Fig. H: Typical radar displays.

Firstly there is data concerning range, which is entirely a matter of timing, and is not primarily related to signal-amplitude, providing this is adequate; secondly there is data concerning direction, which is entirely bound up with the direction in which the aerial beam is pointing, and which is functionally related related to signal-amplitudes. Where accurate range-finding is a prime requirement all signal-handling circuits must have adequate bandwidth to ensure reasonable reproduction of the transmitted pulse, which should itself have as steep a leading-edge as practicable, but where range accuracy requirements can be relaxed, a smaller bandwidth will prove more satisfactory for the circuits concerned with angular measurements. This state of affairs exists in consequence of the effects of receiver noise, which set an ultimate limit to the performance of all radar equipment. The practice of providing separate channels for range and angle data from an early stage in the receiver is, however, restricted to the most elaborate radars, and the usual practice is to provide a common channel for signals right up to the display.

Where the receiver has its own aerial it is, of course, necessary to ensure that the transmitter aerial is linked to it in such a way as to ensure that targets under investigation are properly illuminated (in direction and polarisation). A further requirement is to provide from the aerial mounting an accurate indication of the angle, or angles, being measured. These indications form part of the signal-display, and are the counterpart of the range-indications which come from the time-measuring unit.

(13) The time-measuring device is required to provide a frame of reference (in time) commencing anew with each successive transmitter pulse, and against which the time of arrival of any echo-pulse under investigation can be determined. Many techniques have been exploited in finding alternative solutions of this problem, where accuracy, flexibility and the provision of smooth output-data may vary in importance from one type of radar to another. Associated with the timing-circuits are devices known as "strobes" which are essentially time-filtering elements. Such a strobe, according to its setting, will indicate a particular brief period of time occuring at a prescribed interval after each outgoing pulse, and will permit signals arriving during such successive periods to be isolated from all others, wherever the facility is required. Thus the association of a narrow aerial beam with a correspondingly "narrow" strobe serves to isolate a particular small pocket of space from the remainder and facilitates examination of its radar significance.

(14) Display-systems form the output end of radar equipments, where the data collected from targets is collected together and presented in order to permit appropriate action to be taken (Fig.H). A large variety of display-systems have been evolved to meet the requirements of particular radar problems, some to provide facilities for accurate measurement of the individual position-coordinates of a single target on separate displays, and others to provide composite information on a single display; when associated with a scanning radar other displays aim to present a radar picture of all targets within the zone under examination. Throughout this field the cathode-ray tube provides a most versatile basis for the vast majority of systems, and has no serious competitor where the compact presentation of easily accessible data is a prime requirement. With the tendency to supersede human operators by automatic mechanisms, however, as in the field of automatic-following radar, display-systems as such become redundant to the extent that they can be replaced by instruments designed to interpret radar-data and produce not only the desired output information, but also to provide suitable signals to fit the input requirements of the associated servo-mechanisms. Even here it is usual to retain an elementary display in order to assist in the process of target-selection, or to allow the operator to ensure that the appropriate target is being followed whenever there is confusion, as, for example, with targets crossing, or when bombs are dropped. In the case of many radar equipments which provide information for use elsewhere, the display-system is associated with a reporting-system, which may vary, according to circumstances from a telephone to elaborate data-transmission systems, or to display-relaying systems.

(15) Auxiliary parts of the receiver include miscellaneous devices of the types already listed for the transmitter, and, in addition, a common feature is the range-calibrator. This device is usually provided when the ranging-circuits do not themselves embody a primary frequency standard, and serves as a check on the performance of these circuits. Other accessories may be provided to give a simple overall test of the transmitter-receiver ensemble without recourse to actual targets, from the standpoint of power and noise, or to provide such a test by the use of standard targets. External tests of range and angle may also be conducted by the use of special targets at known points, and these additionally check radar-bearing with compass-bearing.

7. TABLE OF TYPICAL RADAR EQUIPMENT PARAMETERS

A few typical figures are quoted in order to give an idea of the kind of magnitudes involved. The four equipments concerned all operate in the 10cm. band and are briefly described as follows:-

A. An airborne gun-laying radar equipment to control blind fire from the rear turrets of heavy bombers.
B. A Naval radar equipment for anti-aircraft armament control used in destroyers and larger ships.
C. Army Heavy Anti-Aircraft Fire-Control equipment; light-weight and mobile giving automatic-following in elevation and azimuth, and optionally automatic or manual-following in range.
D. Army mobile Early-Warning or "Putter-on" equipment, to be used in conjunction with a H.A.A. Fire-Control set, such as Equipment C.

	Equipment A	B	C	D
Frequencies				
Radiating	'S' band	'S' band	'S' band	'S' band
Pulse Recurrence	660 p.p.s.	500 p.p.s.	1500 p.p.s.	690 p.p.s.
Intermediate	45 Mc/s	60 Mc/s	60 Mc/s	30 Mc/s.
Performance				
Peak power	30 kW	500 kW	200 kW	600 kW
Pulse width	0.5 sec.	0.5 sec.	0.5 sec.	1 sec.
Receiver Band-width	4 Mc/s	4 Mc/s	5 Mc/s	3 Mc/s.
Detection Range	restricted to 1400 yd.	30,000 yd.	30,000 yd. for medium bomber	50,000 yd. for medium bomber
Accuracy				
Range	± 20 yd.	± 25 yd.	± 35 yd.	
Elevation	± 15 min.	± 10 min.	± 8 min.	
Bearing	± 15 min.	± 10 min.	± 8 min.	
Target Discrimination				
Range		100 yd.	200 yd.	500 yd.
Bearing		5 deg.	4 deg.	5 deg.
Elevation		5 deg.	4 deg.	

8. Radar Roles

(1) Radar methods have found application in a wide range of service problems, and in this section we shall attempt a broad classification of the main field. In the more direct applications of radar to warfare obvious limitations affecting the design of ground-based, sea-based and air-based radar systems should be examined. Considering first those limitations inherent in the nature of the base, ground-based systems generally suffer least from space and weight restrictions, but usually lack mobility (when in operation), whereas air-based systems are subject to severe space and weight limitations, whilst enjoying considerable mobility. Sea-based systems obviously occupy an intermediate position. The second factor to be considered is the nature of the role: a significant classification relates the nature of the base to that of the target, thus:-

(a) - Ground-air

(b) - Ground-sea

(c) - Ground-ground

(d) - Sea-air

(e) - Sea-sea

(f) - Sea-ground

(g) - Air-air

(h) - Air-sea

(i) - Air-ground

(2) In any introductory chapter an exhaustive classification cannot be attempted, and it should be borne in mind throughout that the mobility of the radar target as compared with that of the radar-base may be a factor of considerable signifance in particular cases. Thus manoeuvrability of a fighter in relation to its targets has a profound bearing on the design of an air-borne radar aid to interception to which there is at present no parallel in any ground-based systems, whilst for sea-borne systems, manoeuvrability is significant in relation to sea-borne targets, but has much less significance in relation to air-borne targets. Should radar systems be developed for active employment in vehicles on the move, these will occupy a position somewhat similar to sea-borne systems in this respect, but with many difficulties even more acutely emphasised.

(3) The ensuing outline of radar roles will be based primarily on other characteristics, however, being concerned with the following problems:-

8.1 Detection

8.2 Searching

8.3 Tracking

8.4 Beacon

8.5 Guidance and Navigation

8.6 Survey

8.7 Miscellaneous

8.1 Detection

(1) The detection of objects which intrude into the field of view, and the provision of crude position data concerning them, is one of the less

complicated problems in which radar may offer a solution. Simple radar systems have been envolved to meet requirements of this character in such applications as anti-collision devices for aircraft and ships, iceberg detectors, and cloud detectors. The corresponding detection problem for vehicles presents considerable difficulties due to the profusion of unwanted signals (known as "clutter") which usually arise from the landscape, and which serve either to mask the wanted signal or to render it unidentifiable. Where the landscape is amenable, however, radar detection systems may still find useful employment, as, for instance, within the confines of an airfield. Another field of application occurs in proximity-devices for projectiles and bombs, and here the problem is usually a short-range one. In such cases pulse-radar solutions are usually impracticable and alternative radar methods employing continuously-radiated waves offer an easier solution.

(2) Also in the detection class may be placed radar devices designed to indicate movement. These rely on the Doppler-shift of frequency of the received signals in relation to those transmitted, which is proportional to the radial velocity of the moving object in relation to the radar transmitter-receiver, thus affording a basis for the isolation of signals from such moving objects from a background of other signals corresponding to static objects (Fig.I). Such discrimination falls off as the radial velocity becomes smaller, and if sensitivity is increased to deal with very slowly-moving objects unwanted interference may arise from such factors as the swaying of trees in a wind.

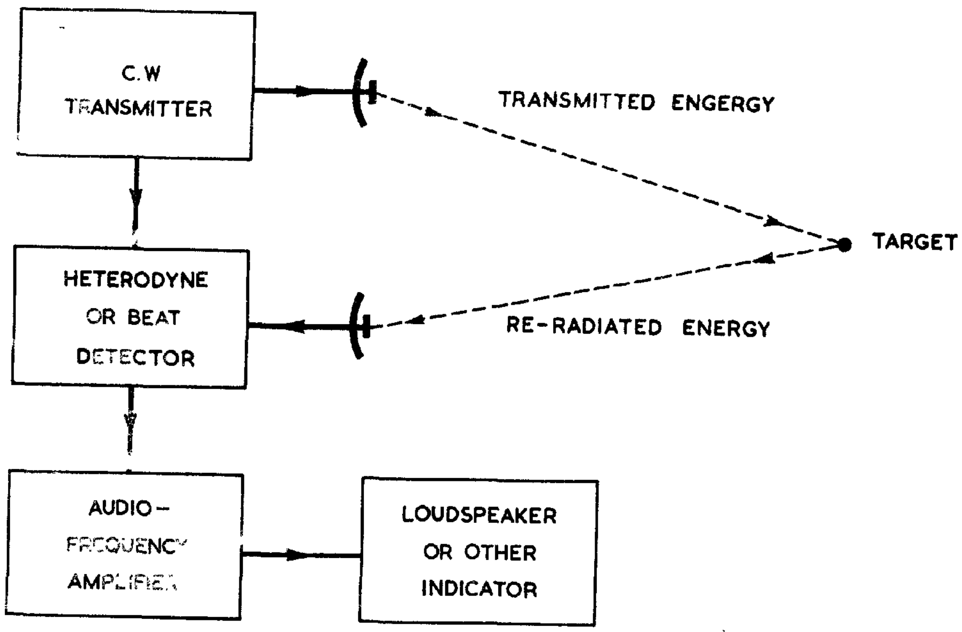


Fig.I: Block diagram of C.W. radar system using doppler technique for moving target detection

8.2 Searching

(1) Here we are concerned with radar systems which are required to subject an allotted zone of space to radar investigation with the object of finding any radar targets which may exist within the zone, and of reporting upon their position. In each case the degree of accuracy needed in the information derived will exert a substantial influence upon the detailed design of the system. Generally speaking, these systems aim at flexibility rather than precision; they are encountered under such names as "early-warning", "tactical-control", "putter-on", "reporting", "surveillance", etc. Usually such systems employ scanning methods and present the information gained from a completed scan in such a way that all can be seen at once. In many cases a complete scan involves the full rotation of a fan-beam

about a vertical axis, giving complete coverage in bearing and partial coverage in elevation (Fig.J). The object in using a fan-beam with narrow

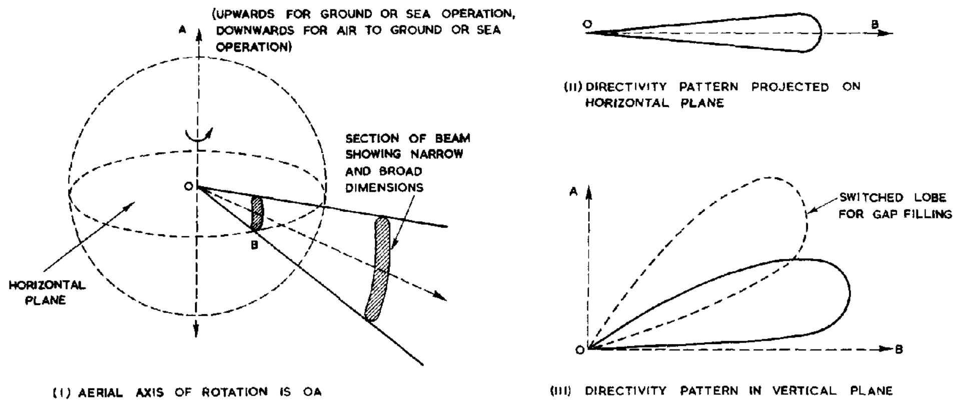


Fig. J: Scanning using vertical fan beam

bearing and broad elevation-cover is to increase the bearing-discrimination of the equipment and improve the accuracy of bearing measurements as compared with the performance of a broader beam; at the same time broad elevation-cover is required in order to reduce the time for a complete scan. Deficiencies in elevation-coverage may be reduced by lifting the beam in alternate rotations (or by more elaborate operations), at the cost of increasing the total scanning time. Systems of this nature usually present their output by means of a "Plan-Position Indicator" (P.P.I.) in which targets appear as bright patches on a cathode-ray tube, the distances of such patches from the electrical centre of the tube being characteristic of the slant-ranges to the corresponding targets, and the directions (from the centre), of their bearings (Fig.H(ix)). The use of long after-glow tubes

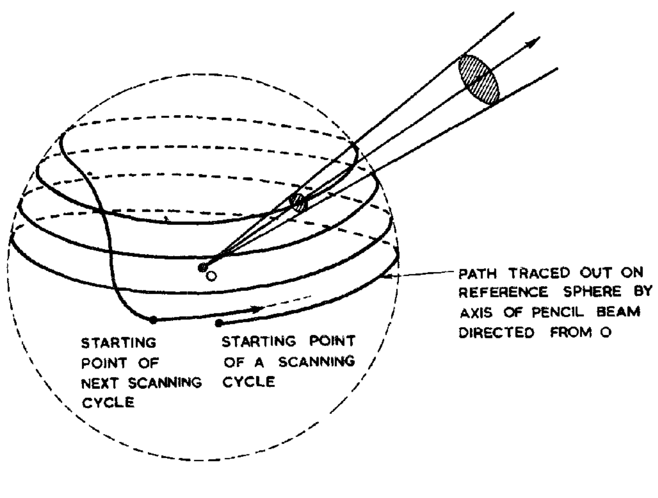


Fig. K: Helical scanning

provides the requisite retention of information throughout the period of a complete scan. It is thus possible to indicate many radar targets existing at the same time in a common display, and this has great advantages wherever an appreciation of the general situation is required. On the other hand, such systems do not usually offer the highest grade of position-data on individual targets, partly because they give only intermittent glimpses of each target, partly because the most accurate methods available for range and bearing measurement do not readily lend themselves to P.P.I. display, and partly because such systems are most commonly designed to afford the maximum visibility for weak target-signals a condition which limits the range-accuracy for all targets. In addition elevation measurement is either ignored, or attemped only in terms of fairly broad angular bands, as attempts to scan by pencil-beams produce intolerably long scanning periods (Fig.K) unless the zone to be scanned by one such beam can be effectively reduced. Where there is a need for accuracy in elevation measurements comparable with that of bearing, this is often met by the use of an auxiliary radar system which specialises in this measurement and which can be steered from one target-bearing to another from the main equipment. Such a height-measuring system may employ a fan beam so arranged as to cut across the fan beam utilised for bearing measurement in the main system (Fig.L). A form of elevation-indicator commonly used to display height information in conjunction with a fan-beam arranged to scan an elevation sector is shown in Fig.H(xii).

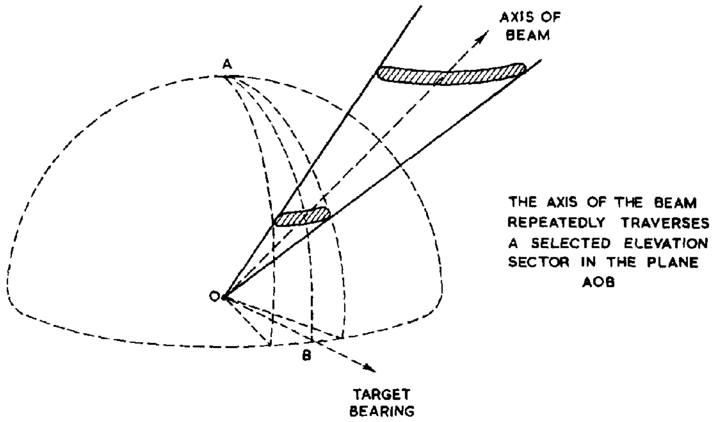


Fig.L: Fan beam system for elevation sector scanning.

(2) Although the foregoing paragraphs would seem to imply that the radar systems under discussion in this section exist on the ground (or sea) no such restriction is intended. Essentially similar systems are employed in airborne roles, as, for example, in searching for surface vessels. This is not unlike the anti-aircraft problem upside-down, apart from one simplifying feature, namely, the sea-surface, which contains all the sought targets and, therefore, renders elevation measurement unnecessary, height (i.e., minimum range to sea) being readily available when required.

(3) The type of system described as fulfilling an anti-surface-vessel role yields interesting results when flown over land, as under this condition the display reveals a primitive map of the terrain beneath, showing clearly such features as coast lines, rivers, mountains, railways, large buildings and towns (Plate 2). This property has led to the development of systems of this character as an aid to navigation and bombing.

(4) Another type of radar system falling into the searching group is involved in the air-air role. This yields two different requirements, one being primarily defensive, in order to give bombers due warning of approaching air-attack, and the other, an offensive requirement to enable fighters to find and engage their airborne targets. The former of these is mainly concerned with rear aspects and the latter with forward aspects. If a bomber has no defensive armament a simple warning-device may suffice, but when guns are carried it may be very helpful to be able to anticipate the angle from which an attack may develop. For both of these systems a novel feature is the interest in radar targets above and below the horizontal, which results in types of scan and presentation specially designed to meet this requirement.

(5) Belonging to this class are certain radar systems from which a higher degree of precision is required than for the majority of search applications. These are well exemplified by a ground-controlled approach system for aircraft. In such a system an aircraft is controlled by instructions from the ground which commence as soon as it has been picked up at a

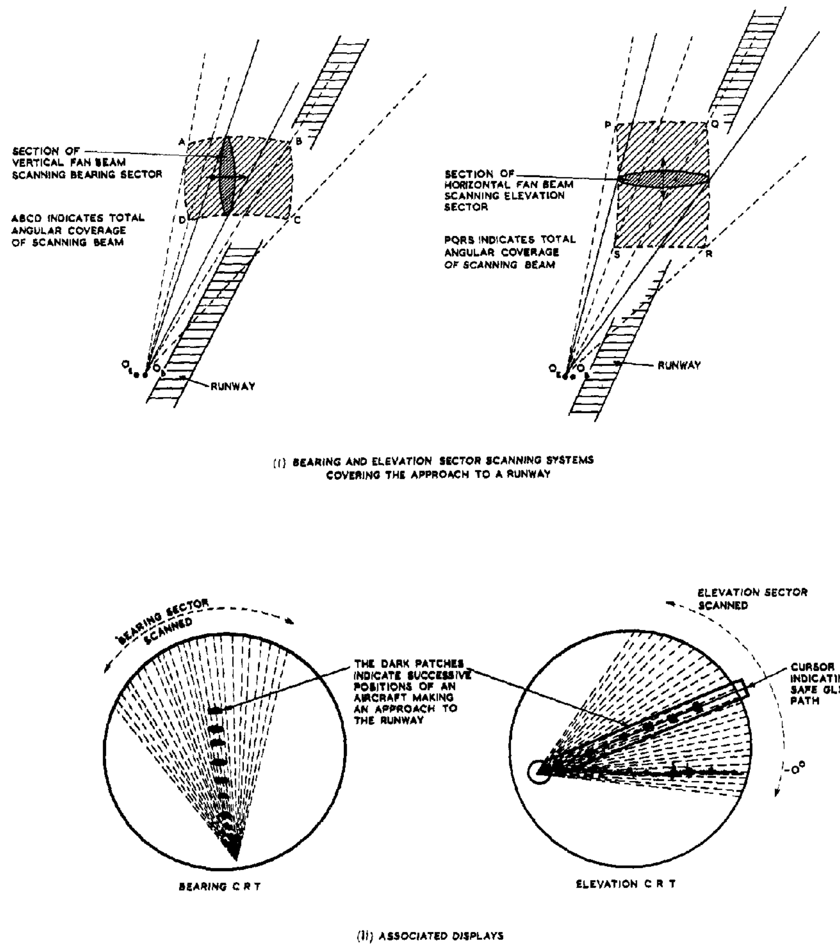


Fig.M: Principles of ground controlled beam approach system

suitable range by all-round search equipment of a common type. Thereafter the pilot follows the instructions received from the controller, and, after spending time on a circuit of the airfield (should this be necessitated by traffic conditions), is guided into and down the special radar approach-beams, until landing has been accomplished. During this latter period a narrow sector embracing the approach-lane is rapidly scanned successively in elevation and bearing by narrow fan beams (Fig.M). The associated radar displays permit the controller to estimate continuously the position and motion of the aircraft, and so to issue appropriate guidance, with the object of procuring a safe landing.

(6) In the radar-search field Doppler techniques have found fruitful application where normal target-discriminating techniques have been insufficient, and have been used to provide additional target-discrimination on a velocity basis. Such conditions arise where there is excessive clutter, as, for instance, with ground or sea-based radars operating at low angles of elevation, or at very short ranges. A number of other techniques have also been developed to meet requirements of this character. At the bottom of Plate 2 is shown the improvement possible by use of "Moving Target Indicator" systems where cancellation of permanent echoes reveals the aircraft echoes.

8.3 Tracking

(1) Radar tracking systems are intended to follow continuously the movements of a selected radar target, usually with the object of providing full and accurate position-data of sufficient smoothness to enable rates of change of range and of elevation and bearing to be reliably determined. This requirement for adequate smoothness is important where predictions are to be based on radar-data, as spurious rates may generate excessive errors even when position-data is otherwise reasonably good. In order to secure a high standard of performance more precise techniques are employed for range and angle measurements than is customary for searching. Systems of the highest accuracy, associated with long-range weapons, utilise fine pencil-beams, which are devoted to the tracking of single targets, this process being accomplished automatically in many cases (Fig.N); and increasingly so where consistent performance against high-speed targets is very much worth-while, even at the cost of the extra complications in equipment necessary to produce a fully-automatic radar fire-control chain. Less accurate solutions can be tolerated where short-range weapons are involved, though any saving due to possible simplification is offset to some extent by the need for higher speed in target-acquisition and for faster turning-rates to deal with crossing targets.

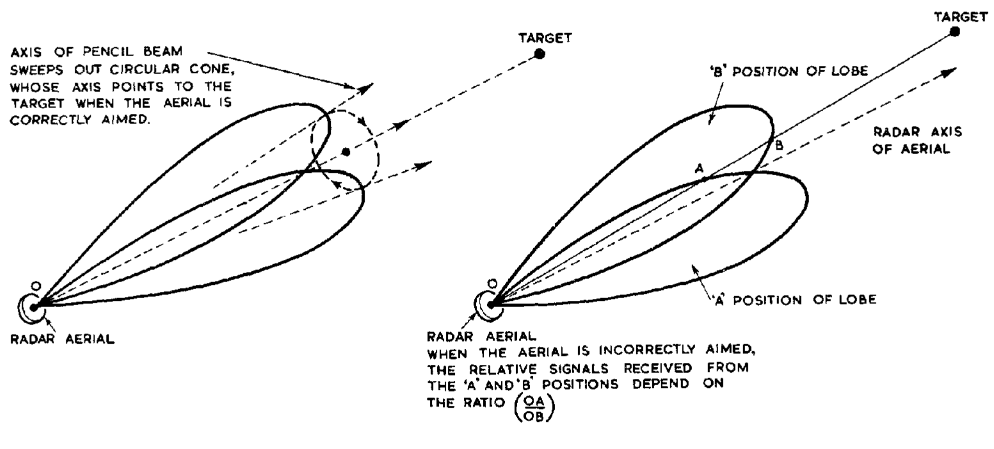


Fig.N: Conical scanning

(2) Somewhat similarly, in air-air systems the need for precision radar-tracking is dependent on the effective range and accuracy of the weapons provided; and thus, for fighters which use short-range barrage-fire radar systems are primarily needed to enable contacts to be made, and the enemy approached from a favourable angle. But where fighters are equipped with longer-range guns of greater accuracy, precision radar techniques are essential if such weapons are to be employed with maximum effect. In connection with the fighter-aircraft problem it should be stated, however, that means of positive identification of radar targets as hostile or friendly is a paramount requirement, and this is a major factor in controlling the actual employment of blind-firing systems. For bomber-defence a flexible fire-control system may be required in order to deal with assault from any angle, and radar-tracking systems are commonly employed for this purpose in heavy bombers.

(3) In the field of tracking instruments hybrid radar-optical systems also exist, which give radar range and optical angle-data. By such methods weight and space can be saved whilst retaining sufficient accuracy for the problems they are designed to meet, though such systems are necessarily limited to visual targets.

(4) In certain applications, notably ground-sea and sea-sea roles, tracking-radar systems may be employed for the correction of gun-fire. Such systems consist in principle of highly accurate search-radars using narrow beams, short pulses and restricted scans operated at high rates. Whilst operated in such a way as to give continuous tracking of the target, they also expose to radar view a small zone surrounding the target, and within this area splashes from falling shells give a transient radar-echo which can be interpreted from the radar display in terms of appropriate gun-laying corrections. By this means fire-correction by "bracketing" can be accomplished with unseen targets. Similar results can be obtained in a ground-ground role providing all the conditions are favourable, though circumstances often make this very difficult or quite impossible.

(5) The development of automatic tracking-aids has, as has already been pointed out, helped to safeguard the quality of radar position-data and of its rate of change under conditions of rapid change. Such systems may be operated by radar angle-data (automatic-aiming) or radar range-data (automatic-ranging), or by both (automatic-following). They obviously have special significance in relation to airborne radar targets, whether attacked from ground, sea or air; and also for ground or sea targets subjected to attack from the air, though this presents much more difficult problem for automatic systems owing to clutter.

(6) A radar-tracking system which differs from those already discussed is often used for the control of searchlights to aid in picking-up targets, and to ensure that a beam of light embraces the target whenever it is switched on. The object of the system is thus to provide accurate aiming for the lamp, and to control this automatically in some cases. Such a system is complete in itself and is not normally required to give output data. The angular accuracy required must be compatible with the beam-width of the lamp, and the simple ranging circuits used are provided not in order to ensure range, but to permit target discrimination on a range basis, thus assisting in target selection, and in proving the quality of the angle-data which controls the lamp movements.

8.4 Beacons

(1) The roles available for secondary radar systems (Fig.0) considerably extend the facilities which can be derived from radar equipment. Dealing first, however, with the primary radar roles already discussed it is evident that equivalent secondary radar systems are conceivable, but that their operation would be confined to radar targets provided with beacons: that is to say from a service point of view, such applications would have to be confined to friendly formations. On the other hand wider applications of secondary radar systems may be developed for international use in commercial

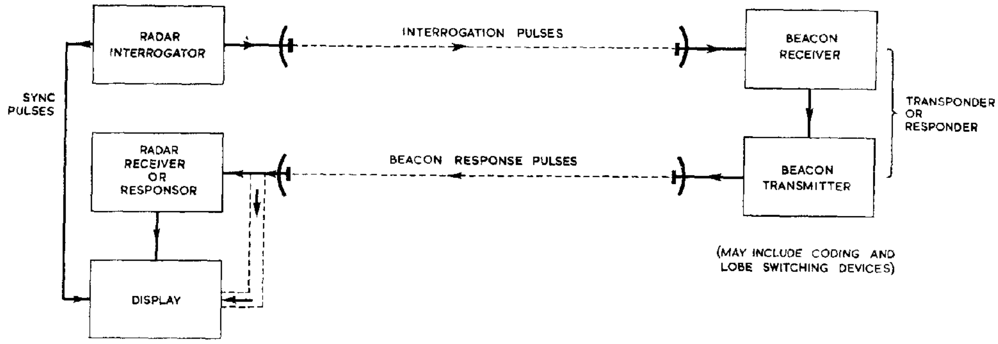


Fig.0: Elements of radar beacon system

air and sea transport. Granted the co-operative target response, which is implicit in all secondary radar systems, the most striking features which emerge are, on the one hand, the enormous saving of power (which mean large ranges for low overall power requirements), and the possibilities of using coded responses to convey more explicit information concerning the target, in addition to the usual radar positional data.

(2) The possibilities of coded response enormously extend the uses of radar beacons, and enable such devices to be used for detailed radar identification. Special terms are often used to distinguish between the main items in a secondary radar system, thus the radar transmitter becomes an "interrogator", the radar beacon in the target a "transponder" or "responder", and the radar-receiver, a "responsor".

(3) Radar beacons fall into two main classes, those which are required to identify a place e.g., an airfield, and others which are required to identify an object which has no specific place e.g., a friendly aircraft. In the latter case the usual object of the system is to identify hostile radar targets and this problem can only be tackled negatively when radar identification is the sole source of information; that is to say that radar targets which do not give the correct secondary response must, by implication, be regarded as hostile, in the absence of further information, whilst those which do, must likewise be regarded as friendly. Occasions arise frequently, however, when the position occupied by the identified friendly target is also directly useful, as when radar control of interception is being organised, or radar control of bombing, in both cases from a relatively remote base or bases. In each of these examples the radar system is used in order to provide guidance, but to deliver the guidance in the form of instructions a communication link is also required, though this may be of a comparatively elementary type if the number of possible instructions is reduced to a minimum, and may possibly be incorporated within the radar system by some additional modulation process.

(4) For the other class of beacons, namely that providing identification of places, a number of alternative roles are met. In one of the simpler applications a beacon is intended to provide a rendezvous, as may be required for aircraft or ships returning to a base, for beach-landing parties, or to mark a dropping-zone for parachute or bombs, the received signal being examined to indicate the direct course to such a rendezvous, as well as the distance to be covered. In a rather similar application, radar beacons may be used to indicate zones to be avoided, e.g., a mined channel, or an

area where hostile submarines have been reported, or an area heavily defended by gunfire.

(5) Other applications make use of beacons in order to offer navigational facilities. A single beacon at a known location would suffice for this purpose in theory, granting sufficiently accurate measurement of absolute (compass) bearing, as well as range. The bearing requirement is not easy to satisfy, however, particularly for aircraft, and much more suitable navigational systems have been devised making use of multiple beacons (Fig.Q(i)). Thus with a pair of identifiable beacons at known locations, position is accurately fixed as soon as the two ranges have been established: strictly with an ambiguity as to whether the position is to one side of the base-line or the other, but this can easily be solved, if troublesome, by the crudest of direction-finding techniques. Furthermore a system of this character not only allows position to be fixed on a map, so permitting more orthodox navigation to ensue, but also provides a direct basis for navigation in terms of the beacon signals themselves, and without recourse to maps, providing that the course to be followed has been translated into the appropriate beacon range-coordinates. Extension of such a system can lead to remote control of bombing.

(6) One rather special application of radar-beacons is in the field of **beam approach** devices where a suitable beacon can be used to guide approaching aircraft. An interesting feature of this system lies in the employment of directional responses by the beacon, in contrast to the all-round radiation usually encountered. Here the beacon radiation alternates between two large patterns which overlap, thereby defining an equi-signal approach-path in bearing (Fig.P). Similar techniques have been used in non-radar **beam approach** systems, which lack, however, the advantage of continuous range-data provided by beacon systems. (This system may be regarded as the counterpart of the precision angle-measuring techniques, employed in most tracking-radars, known as "lobe-switching".) An extension of this technique can be made to further define the approach path in elevation, but this more difficult problem can only be satisfactorily solved by the use of microwave beacons.

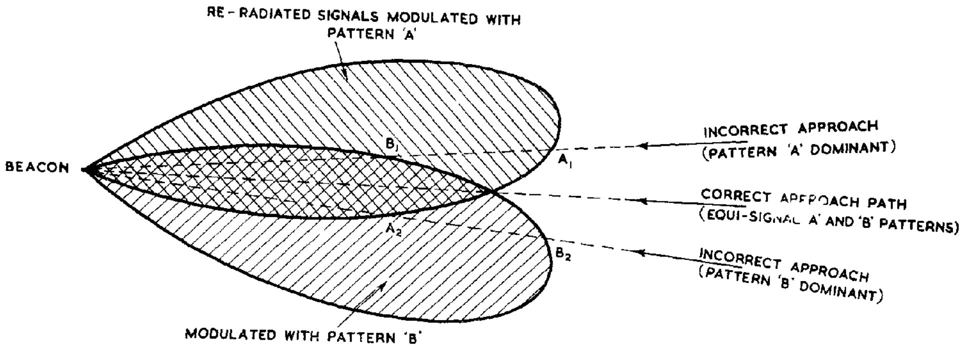


Fig.P: Beacon (employing switched lobe technique) suitable as landing aid.

(7) An intermediate class of applications for beacons is in the field of devices to enable formations to be maintained to an appropriate pattern; such systems may be applied to vehicles in open country, or to ships in open sea. The comparable aircraft problem presents many more difficulties.

(8) Of beacon systems in general it should be stated that, apart from special requirements, they should be sensitive to interrogating signals arriving from all bearings, and should likewise transmit responses on all

bearings. This can be accomplished by employing omni-directional aerials for beacons, or by using continuously rotating fan-beam aerials, providing that the speed of rotation is suitable. Another common requirement is that they should be able to respond to any interrogation within a limited frequency band, to meet which it is necessary for the tuning arrangements to be varied rhythmically in order to sweep the band at regular intervals. It is not essential for the beacon response to be on (or near) the same frequency as the interrogating pulse, though this is a very common arrangement.

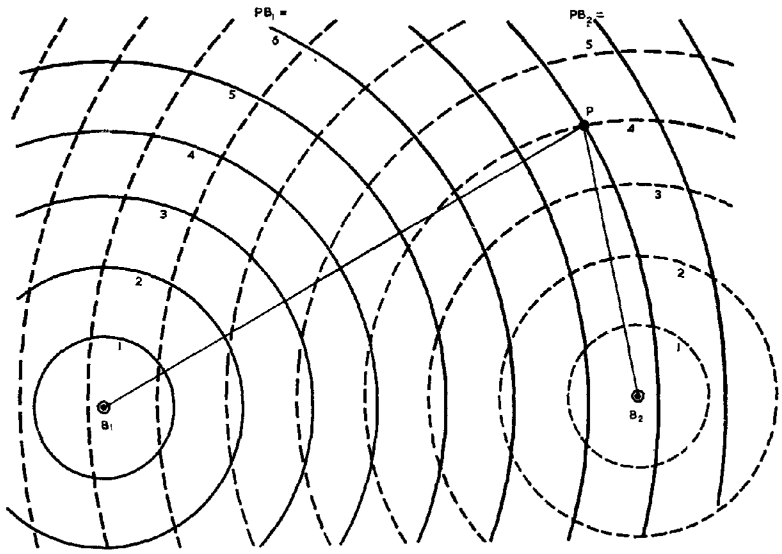
(9) A characteristic property of radar beacons is that they remain mute until interrogated, with consequent saving of mean power and rather better security, though these gains are not very significant. Improved security could be obtained if coded-interrogation were required, but this complication would only be justified for very special purposes. Radar beacons are also limited in the number of interrogations they can handle at one time, i.e., they are subject to traffic saturation. More traffic can be handled by reducing the recurrence-frequencies of interrogators, by cutting down the time devoted to interrogation, by using simpler response codes, and by the use of rotating-beams, always providing that sufficient time remains available to complete each interrogation under operational conditions.

8.5 Guidance and navigation

(1) In effect a system providing guidance issues instructions which are to be blindly followed by the recipient without reference to other information, or alternatively provides signals which act as a frame of reference against which a programme of instructions, otherwise given, can be interpreted. Such guidance may very well proceed without the recipient have any exact knowledge of the geographical significance of the route being followed. On the other hand a navigational system must provide a framework of reference signals which can be positively identified with map references, i.e., a system of coordinates must be defined analogous to (though not necessarily in any way identical with) latitude and longitude.

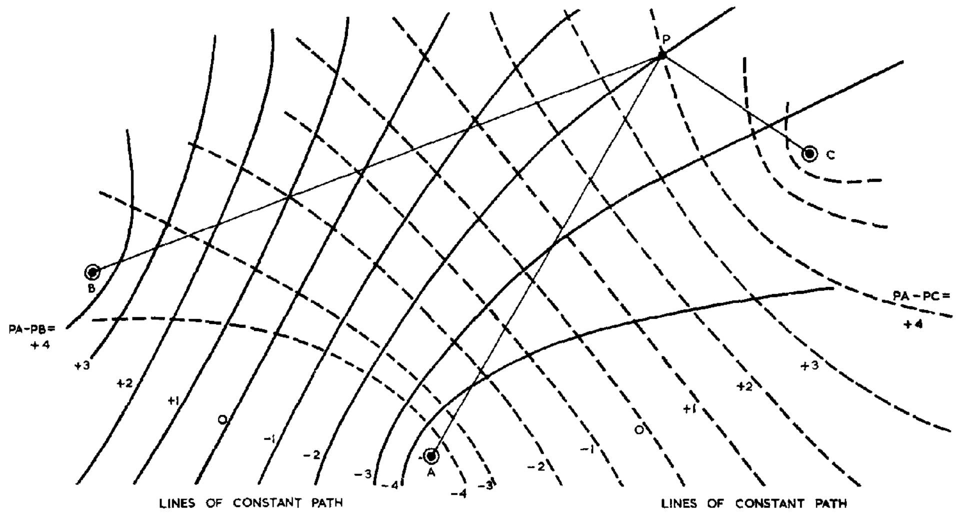
(2) In these fields radio (including radar) devices play a prominent part for sea and air journeys and are finding application on land where conditions are suitable. Some primary and secondary radar systems have already been mentioned which can be used in guidance or navigational roles. Looking at the problem more generally it is evident that where a radar solution is employed for guidance or navigation this involves the provision of radar transmitter and receiver in the craft to be steered, the incoming data being provided either by natural echoes (primary radar) or beacon-echoes (secondary radar), or alternatively the provision of one or more radar transmitters and receivers (with intercommunication in multiple systems) at a base or bases, utilising the natural or (more usually) beacon-echo from the craft to be steered, and with facilities for transmitting instructions.

(3) In the radio-navigation field, in addition to radar systems, there are other systems which do not involve the use of the radar-echo, as, for example, the radio direction-finding systems already mentioned. Other, and more precise, non-radar systems are available, however, which utilise the characteristic speed of radio-waves, though they only depend on one-way propagation. From an engineering standpoint there may be strong resemblances between much of the equipment used for such applications and for true radar systems: this is a natural consequence arising from the employment of similar techniques. One-way systems cannot normally be made to give true range-data directly, but can compare the arrival-time of signals from different sources, so that with synchronised transmission the recipient may infer the difference between the two ranges without being aware of either separately. In effect this information gives him a single position-coordinate corresponding to a line drawn on a map to represent all places having this range-difference from the two transmitters. To complete this system a third synchronised transmitter must be brought in from yet another base to yield a further position-line, thus giving a "fix", which identifies the position more completely. Radio-navigation systems can, when required, be designed to give accuracy of a high order in providing location as a map reference, but are incapable of giving accurate height information under existing practical conditions.



LINES OF CONSTANT RANGE TO EACH OF THE TWO BEACONS, B_1 AND B_2

(i) CIRCULAR SYSTEM



LINES OF CONSTANT PATH DIFFERENCE FOR STATIONS A AND B (HYPERBOLIC)

LINES OF CONSTANT PATH DIFFERENCE FOR STATIONS A AND C

(ii) HYPERBOLIC SYSTEM

Fig.Q: principles of navigation systems

8.6 Survey

(1) The successful development of radar navigational systems has led very naturally to consideration of radar systems for use in surveying. Here it is essential to distinguish between a comprehensive radar-survey system and one which makes use of radar-aids to control and evaluated survey-operations carried out by means of air-photography. The radar-map is not nearly as good as a carefully-made photograph, and can only be recommended when conditions make photography impossible or undesirable, apart from its special value as a training-aid for navigators who will make use of the same system for navigation or bombing. In the other field systematic flight-programmes may be regulated according to radar-data, and accurate position continuously recorded alongside the relevant photographs, with other essential data. For the most accurate work use can be made of multiple beacons to give range to bases already surveyed; this method makes the most effective use of radar data, exploiting the unique value of radar range-finding. With precision equipment, survey of a high order of accuracy can be completed in a fraction of the time required for classical methods, though the very highest accuracy is not attainable. Another survey application lies in the measurement of base-lines; here the radar solution gives a rapid answer satisfactory for all but the most accurate work, and again with enormous saving of time.

8.7 Miscellaneous

(1) A common type of radar system with one special role is the radar altimeter, carried by aircraft in order to measure height above ground or sea. With a simple extended target so favourably situated and with the requirement to measure only a simple coordinate, a fairly simple pulse-system is adequate for most purposes, but will fail below a certain minimum height. More elaborate systems, which will work to within a few feet of ground or sea, have been devised using frequency-modulation techniques: equipment of this character is often called a "Terrain Clearance Indicator".

(2) Other applications of radar systems occur in such fields as Ballistics, Meteorology and Astronomy. In Ballistic work many problems arise in connection with the measurement of position, velocity and spin to which radar solutions can be found. Such systems may differ considerably from the type of systems already considered in that they can be designed to deal with much more specific problems, i.e., they are usually only concerned with one target at a time of known character and with that target in an expected place. These advantages permit radar techniques to be exploited in a fashion which would not be practicable when dealing with many targets moving in unforeseen ways.

(3) Meteorological science can employ radar methods in order to locate clouds, rainstorms and snowstorms and to plot their movements. Radar observations of balloons also gives information of winds. As will be seen in Sect.9, certain atmospheric conditions give rise to peculiar propagation circumstances which markedly affect radar performance at low angles. The existence of these phenomena suggests the possibility of deriving meteorological data from a study of propagation conditions through the medium of radar performance.

(4) Radar measurements have been used to confirm some well-known facts about the moon, and similar measurements may possibly be made in respect of other heavenly bodies, though the number of these which subtend a sufficiently large angle for practicable systems is rather limited. An astronomical field which has been found to yield copious information under radar investigation is that concerned with the study of meteors entering the earth's atmosphere.

9. Propagation

(1) The basic assumptions regarding radar propagation have already been stated. For most radar purposes these can be taken as a tolerable approximation to the truth, though it is evident that radar performance at

long ranges requires a more comprehensible explanation. In an introductory chapter it will not be possible to do more than indicate one or two circumstances affecting the propagation of electromagnetic waves close to the surface of the earth which must be taken into account in considering such questions. Rectilinear propagation is a concept taken over from the field of geometrical optics - in a way, it may be said to represent limiting behaviour as frequency tends to become infinitely large - and this idea gives a useful approximation to natural events under appropriate conditions, but a more exact correspondence is obtained through the study of refraction and diffraction. The notion of the horizon plane (strictly a cone) is very useful, and to a first approximation this divides the visible from the invisible in a radar as well as an optical sense. Coming nearer to the truth we should recognise, however, that the normal process of atmospheric refraction makes the visible region rather more extensive; for radar purposes this is often expressed in the state that to a normally refracted wave close to the earth, the earth appears to have a curvature which is 3/4 of its actual value. Thus the fiction of rectilinear propagation can be made to give more useful results by considering the radius of the earth to be some 4/3 of its actual value over a region embracing the horizon and going some little way beyond, retaining other dimensions at their natural values within this region, of course. It will be seen that this factor increases the distance to the horizon. Radar waves continue to hug the earth beyond the horizon because of diffraction, though this earth-bound component is rapidly attenuated in comparison with the behaviour of unrestricted waves, and the extent to which waves of appreciable amplitude persist beyond the horizon is dependent on frequency, becoming less as frequency rises. Diffraction thus adds very little in the way of working range beyond the horizon for centrimetric radar systems, but gives more assistance to the longest radar waves. It is important to remember that these considerations affect primarily the component of radiation travelling in the immediate neighbourhood of the earth's surface and have little effect on paths which are not so restricted.

(2) Atmospheric refraction is not a stable phenomenon, and its magnitude is highly dependent on meteorological conditions, particularly on temperature and humidity-gradients. These factors may combine to give local conditions under which a glancing ray is refracted by just that amount which is necessary to follow the actual curvature of the earth. This phenomenon is known as "super-refraction", and is associated in optics with the formations of mirages. For this to take place the appropriate conditions must apply throughout an atmospheric belt whose minimum depth is determined for each frequency, and which becomes less for the shorter waves. When the belt is established a "duct" is said to exist and this will permit propagation of waves within the duct under highly favourable conditions provided the waves are short enough to be trapped. The unexpectedly large ranges at which radar targets are sometimes detectable can usually be explained as due to super-refraction. It should be noted that whereas diffraction helps the longer waves, super-refraction favours the shorter waves owing to the fact that ducts become more rare as their depth increases, but that these favours, though handsome, are somewhat fickle in their incidence over large tracts of the earth's surface.

(3) As regards radar-measurements, the most significant effect of the processes considered so far is to make angle of sight determinations rather suspect for extremely small angles, but as these are in any case suspect for other reasons, the additional complication is not very serious for most practical purposes.

(4) Constancy of velocity of propagation should also be considered briefly. Here it is sufficient to say that so far as unrestricted waves are concerned any effects due to atmospheric inhomogeneity may be ignored in practical radar range-computations for comparatively short paths, but that in long-range working with paths close to the ground or sea, a correction can be made to allow for the slightly reduced speed encountered, in addition to making allowance for the curved path. These factors are of practical significance in radio-navigation, particularly at the longer ranges.

(5) The ionosphere plays no significant part in most radar-propagation problems, though the longest radar-waves are not too short to be reflected. If it becomes necessary to increase the range of early-warning radar systems very considerably, then the ionosphere might be expected to play an important part in longer-wave radar systems, as it does in long-wave long-range radio-navigation. On the other hand, atmospheric absorption is quite negligible for the longer radar-waves, but becomes very important in connection with centimetric radar systems owing to the presence of broad absorption-bands (due to oxygen and water vapour, particularly) in this part of the spectrum, and these will seriously impair range-performance if frequencies are chosen without regard to atmospheric transparency. A rather similar effect arises owing to scattering by small particles in the atmosphere such as raindrops. These also drain away energy from a wave passing through and not only weaken the response of radar targets situated in or beyond the raincloud, but in addition complicate the response to a target in the cloud as seen on a radar-display by presenting with it all the associated echoes due to back-scattering which arrive at the same time. Here too the longer radar-waves suffer to a negligible extent whilst the problem becomes more pressing on the shorter centimetric waves. In the region the situation is alleviated by the use of short pulses and narrow beams, which serve to reduce the number of interfering raindrop-echoes arriving at any instant.

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Chapter I

LINEAR CIRCUIT ANALYSIS

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