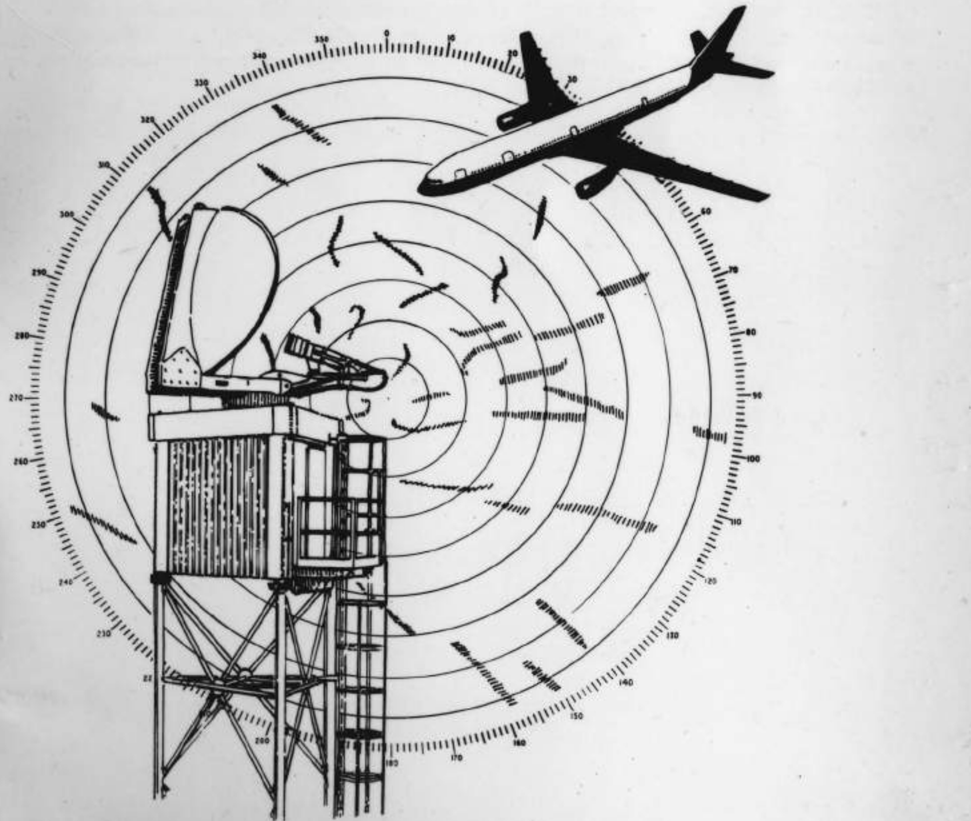
Marconi
Radar Systems

Marconi Radar Systems Limited
Writtle Road
Chelmsford CM1 3BN, England
Telephone: 0245 267111 Telex: 99108
Facsimile: 0245 357927

Marconi
Radar Systems

PRINCIPLES OF RADAR

Sir Eric Eastwood



To mark the inaugural Eastwood lecture in March 1984, Marconi Radar has published this volume on The Principles of Radar.

This work is not new, in fact it dates from the mid 1960s and is taken almost unaltered from Sir Eric Eastwood's work 'Radar Ornithology'.

The basic principles of radar have changed little in the intervening 20 years, but the techniques used have changed considerably, especially with the introduction of computers, digital circuitry and, more recently, the micro-chip.

Sir Eric Eastwood, born in 1910, obtained a doctorate in 1935 at Christ's College, Cambridge, before joining the Royal Air Force, becoming a Squadron Leader and working throughout the war on technical problems associated with the use of radar by the Fighter Defences.

After the war Dr Eastwood joined the Nelson Research Laboratory of the English Electric Company and was transferred to the Marconi Research Laboratory, Great Baddow, after English Electric acquired the Marconi Company. When he retired in 1973 he held the positions of Director of Research of the General Electric Company and Chief Scientist of The Marconi Company, and up until his death in 1981 he acted as Consultant to the Company.

Dr Eastwood's contribution to the military uses of radar was recognised by the award of the CBE in 1962 and his Knighthood in 1972. His work on radar for civil aviation gained him the Wakefield Gold Medal of the Royal Aeronautical Society in 1961. He was elected a Fellow of the Royal Society in March 1967, awarded the Glazebrook Medal by the Institute of Physics in 1970, and held office as President of the IEE in 1972–73.

First printed in this form 1984

Marconi Radar wish to thank Methuen & Co.
for their kind permission to publish this
abstract from Radar Ornithology

Printed in Great Britain by Spottiswoode Ballantyne Ltd,
Colchester and London

The principles of radar

Sound location

Any physically vibrating body such as the skin of a drum, the vocal chords of a human being, the string of a cello, or the column of air in an organ pipe, causes local pressure changes in the adjacent air. We may call such a pulsating source an 'acoustic transmitter', and the pressure changes it produces travel outwards through the air at a velocity of about 1,100 ft/s. When such a sound wave reaches the ear, the pressure fluctuations cause the eardrum to vibrate in sympathy; these movements are linked through the bones of the middle ear to the inner ear and ultimately excite the acoustic nerve. The ear constitutes an 'acoustic receiver'.

Sound waves are reflected from solid surfaces, and when an observer listens to the echo of his voice from a distant rock face he is operating a simple sound location system. A short cry or clap of the hands causes the emission or radiation of a short pulse of sound from his 'transmitter'. This pulse travels to the cliffs and is reflected back to the observer, whose ears form the acoustic receiver which records the return of the reflected signal or 'echo'. If he estimates the delay time of the echo as one second, for example, he will conclude that the signal has travelled 1,100 ft, and that the range of the cliff is 550 ft (Fig. 1.1).

The following three processes are fundamental to any echo ranging system:

(1) Transmission of a pulse or packet of waves.

(2) Reception of the reflected signal.

(3) Measurement of the delay time, which is the total propagation time for the round trip.

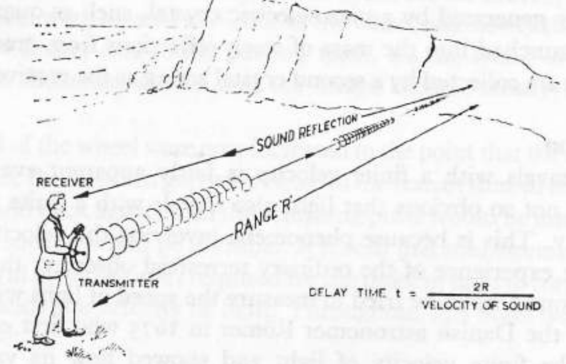


FIG. 1.1. Distance measurement by estimation of the time delay of a sound echo

In addition, the observer can derive information about the direction of arrival of the echo signal. This he normally does by turning his head until he is 'looking at the source of sound'; he is then reacting in response to the binaural effect, which states that the sound signals received by the ears separately are judged to be identical when the source is positioned in the direction at right angles to the line joining the ears. The student of bird song commonly makes use of a plastic or metal reflector in the form of a parabolic dish which he similarly 'points' at the bird whose song he wishes to record. Such a reflector constitutes an 'aerial' for sound waves and the observer adjusts the direction of the dish until the received

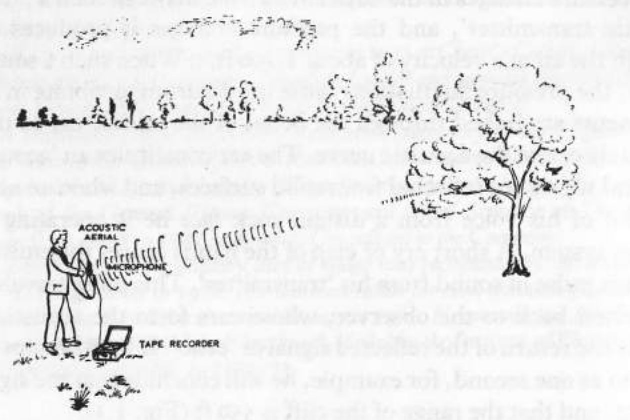


FIG. 1.2. Acoustic direction finding as used to record the songs of birds

signal is a maximum; the bird or sound source then lies on the axis of the dish (Fig. 1.2).

These familiar methods of locating a source of sound or an acoustic echo illustrate the basic principles of radar. Sound-radar or 'Sonar' techniques are widely employed in the steel industry to test for cracks in large forgings. Supersonic waves are generated by a piezo-electric crystal, such as quartz or barium titanate, and launched into the mass of steel; reflections from cracks and other discontinuities are collected by a second crystal acting as the receiver.

Optical location

That sound travels with a finite velocity is fairly apparent even to a casual observer; it is not so obvious that light also travels with a finite though much greater velocity. This is because phenomena involving the velocity of light are not within the experience of the ordinary terrestrial observer; this is what the great Galileo found when he tried to measure the speed of light with flashing oil lamps! It was the Danish astronomer Römer in 1675 who first enunciated the principle of the finite velocity of light and showed how its value could be estimated by measurements of the eclipse times of the satellites of Jupiter. This work was neglected until Bradley, the English Astronomer Royal, discovered the

phenomenon of aberration in 1926. The positions of the so-called fixed stars were found to undergo small angular displacements or aberrations, whose value depended upon the position of the earth in its orbit. Bradley explained this effect in terms of the interaction between the velocity of the earth in its orbit and the finite velocity of light.

These astronomers had ingeniously made use of the vast dimensions of the solar system in order to reveal the fact that light does not travel at an infinite speed. Their measuring techniques, however, could not give an accurate value to this important universal constant of nature c, the velocity of light, since they were dependent upon the value of the solar parallax, or the angle subtended at the sun by the earth's radius, and this is still one of the most difficult measurements to make in practical astronomy.

The first accurate determination of the velocity of light by a terrestrial method was made by Fizeau in 1849 and this classic experiment is worth pausing over for a moment since it illustrates so neatly the basic principles of radar ranging. Fizeau's experimental arrangement is shown in Fig. 1.3. Light from a source

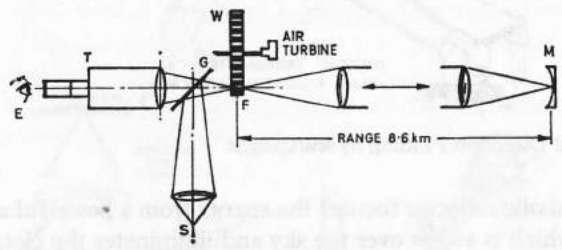


FIG. 1.3. Measurement of the velocity of light by Fizeau's pulse method

S was focused at a point F in the plane of the toothed wheel W before passing through the lens system to the distant concave mirro M 8·6 km away. The light was reflected from M back through the same optical system and through the inclined glass sheet G to the telescope. The observer could see the source, provided that a gap of the wheel were located at F, but as the wheel was slowly rotated the image was caused to flicker due to the passing teeth. As the speed of the wheel was increased this flickering ceased and the image became steady but of reduced intensity.

If the speed of the wheel were now increased to the point that the time taken for a tooth to replace the adjacent gap were equal to the transit time of the pulse of light from F to M and back again, then the returning pulse would be intercepted by the tooth and the source would be invisible. It is seen that measurement of the speed of the wheel will give the time t required for the pulse of light to travel the distance $2R$, and so yields the velocity of light. Throughout this book we shall take the value of c to be:

$$c = 3 \times 10^{10} \text{ cm/s or } 186{,}000 \text{ miles/s}$$

Notice that the source and the toothed wheel together form a generator and transmitter of optical pulses; similarly, the eye and the telescope together form an optical receiver, while the turbine and its tachometer form a timing system that permits the delay time *t* of the reflected echo pulse to be measured. The range *R* of the reflection point then follows from the relation, $R = \frac{1}{2} ct$. These principles of optical echo ranging apply in radar.

In order to determine direction in an optical location system, use is made of a lens or mirror, and the most obvious example of such a system is provided by the human eye. A single eye serves to provide direction, but the combination of the two eyes gives stereoscopic vision, i.e. actual location in space. The optical analogue to the radar case is provided by the old style military searchlight, in

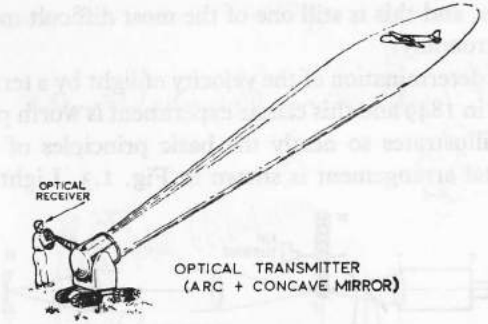


FIG. 1.4. Optical Direction Finding by searchlight

which the parabolic reflector focuses the energy from a powerful arc lamp into a sharp beam, which is swept over the sky and illuminates the clouds or aircraft, thus permitting the direction of a target to be found (Fig. 1.4).

Radiolocation

The close similarity between the acoustic and optical methods of echo location will be apparent, but neither of these techniques was capable of being developed into an aircraft detection and warning system that would possess military significance. It was the substitution of radio waves for the optical or acoustic waves that transformed the situation and so created the new technology of radar. Radiolocation, or radar, is the name given to the system which utilizes the reflection of radio waves in order to detect the presence of aircraft and, by providing measurements of both range and direction, serves to locate their positions.

It is rather a pleasing thought that a presentation of the simple principles of radar, intended to serve as an introduction to the contribution which radar studies have made to the understanding of bird flight behaviour, should really commence with another biological experiment, that of Galvani in 1792 when, in his famous 'frog's leg' experiment, he first stumbled upon the electric current. The sequence of electrical discoveries that led from Galvani to the present use of radar as a tool in ornithological research is graphically traced in Fig. 1.5.

Volta quickly invented his electric cell based upon Galvani's observation and

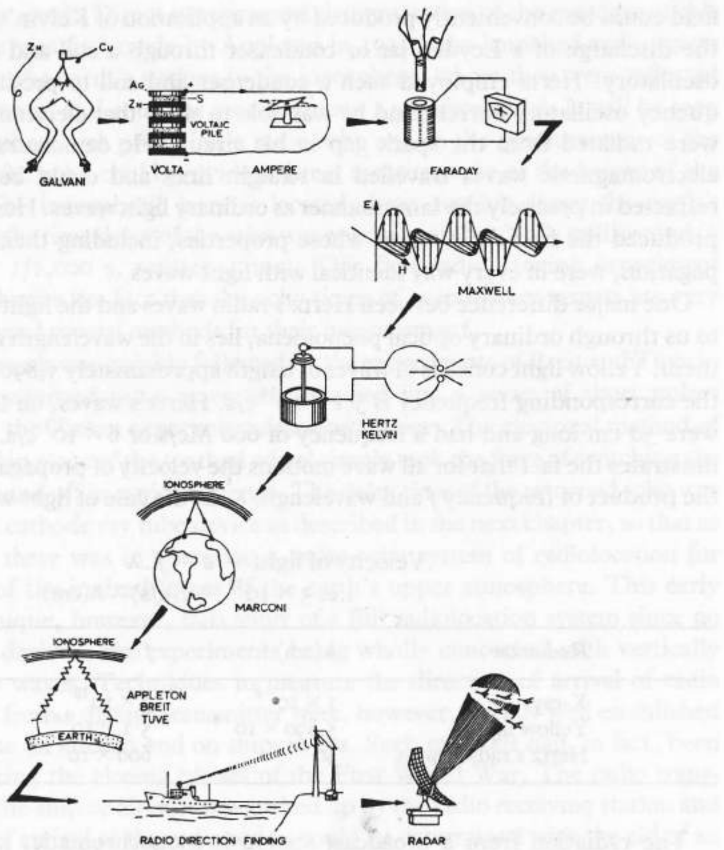


FIG. 1.5. The path of discovery from Galvani's 'frog leg' experiment to Radar Ornithology

Ampère showed that the electric current produced by a 'voltaic' cell produced a magnetic effect. The importance of this interrelation between electric and magnetic effects was recognized by Faraday and was embodied by him in his theories of electric and magnetic fields. His classic experiment of 1831 led him to the discovery of electromagnetic induction, i.e. the principle that a moving or changing magnetic field produces an associated electric field, which can most simply be detected as an electric current induced in a coil of wire. This is, of course, the principle of the dynamo, from which device modern electrical technology proceeds.

The mathematical investigation of Faraday's concept of the interrelated magnetic and electric fields was undertaken by Clerk-Maxwell, whose studies culminated in the electromagnetic theory of light which bears his name. According to this theory, light waves consist of associated oscillating electric and magnetic fields which are propagated through space with the finite velocity we have designated as *c*. Hertz immediately perceived that such an oscillating electric field could be conveniently produced by an application of Kelvin's discovery that the discharge of a Leyden jar or condenser through a coil and spark gap was oscillatory. Hertz employed such a condenser and coil to produce a high frequency oscillatory current and he was able to show that electromagnetic waves were radiated from the spark gap in his circuit. He demonstrated that these electromagnetic waves travelled in straight lines and could be reflected and refracted in precisely the same manner as ordinary light waves. Hertz had, in fact, produced the first radio waves whose properties, including their speed of propagation, were in every way identical with light waves.

One major difference between Hertz's radio waves and the light waves familiar to us through ordinary optical phenomena, lies in the wavelength associated with them. Yellow light consists of waves of length approximately $5{,}890 \times 10^{-8}$ cm and the corresponding frequency is $5 \cdot 1 \times 10^{14}$ c/s. Hertz's waves, on the other hand, were 50 cm long and had a frequency of 600 Mc/s or 6×10^{8} c/s. This example illustrates the fact that for all wave motions the velocity of propagation is equal to the product of frequency f and wavelength λ. In the case of light waves we have:

$$\text{Velocity of light} = c = f.\lambda$$
$$\text{i.e. } 3 \times 10^{10} = f(\text{c/s}) \times \lambda(cm)$$

Radiation	λ (cm)	f(c/s)	c(cm/s)
X-rays	1×10^{-8}	3×10^{18}	3×10^{10}
Yellow light	$5{,}890 \times 10^{-8}$	$5 \cdot 1 \times 10^{14}$	3×10^{10}
Hertz's radio waves	50	600×10^{6}	3×10^{10}

The radiation from a broadcast station is monochromatic, i.e. it is of one wavelength only, as contrasted to the many colours, each of a different wavelength, contained in a beam of white light, and which are separated by refraction in a prism.

It was the recognition that these Hertzian radio waves offered a means of achieving communication between remote stations without the use of connecting wires that prompted the great upsurge of radio experiments which marked the close of the nineteenth century. Many famous scientists worked on radio phenomena during this period. Lodge, Campbell-Walker, Popoff, and many others made substantial contributions, but to Marconi belongs the distinction of being the first to achieve significant long-distance communication. Marconi's bridging of the Atlantic in 1907 marked the real commencement of the radio age, which has culminated in the wonder of television transmitted between remote points on the earth's surface via a communication satellite.

Marconi used long waves of frequency 20,000 c/s (λ = 1,500 m) in his Newfoundland–Cornwall experiment and it was the unexpected success of this work that led to the recognition that the earth's atmosphere must contain a layer, now termed the 'ionosphere', which was capable of reflecting the radio waves around

the bulge of the earth. Direct experimental demonstration of the presence of this reflecting layer was first made by Appleton in 1925, who launched radio waves vertically from the earth's surface to the ionosphere, where they were reflected back to the ground and could be received upon a separate aerial. It will be seen that the ionosphere was providing a radio echo and so the measurement of the time delay of the echo could provide a direct measurement of the height of the ionosphere. The ionospheric layer is located about 100 km above the earth's surface so that the time delay of the echo was approximately 2/3 of a millisecond (1 millisecond = 1/1,000 s, written 1 ms). This first radio ranging experiment serves to emphasize the fact that the echo times of even distant targets are very small and demand special methods for their measurement.

Appleton's work was quickly followed by the experiments of Breit and Tuve in which the transmitted radio wave was chopped into a series of short pulses precisely as in the Fizeau experiment described above. The electrical method of chopping used in place of the toothed wheel simply took the form of switching the transmitter on and off in rapid sequence. The delay time of the returned echo was measured by a cathode ray tube device as described in the next chapter, so that as early as 1925 there was in operation a pulse echo system of radiolocation for investigation of the ionized layers of the earth's upper atmosphere. This early research technique, however, falls short of a full radiolocation system since no direction was derived, the experiments being wholly concerned with vertically incident radio waves. Techniques to measure the direction of arrival of radio waves coming from a distant transmitter were, however, already well established and were in use on aircraft and on ships at sea. Such methods had, in fact, been developed during the closing phases of the First World War. The radio transmission from the ship or aircraft was picked up by the radio receiving station and the direction of arrival of the radio waves could be determined with the aid of an aerial having spaced elements capable of sampling the wave front at two points. In the case of medium frequencies, i.e. about 200 kc/s such as are used in ship communications, the normal form of directional aerial is a loop of wire which can be rotated about a diametral and vertical axis lying in the plane of the loop. The aerial is rotated for minimum signal. This occurs when its plane corresponds to the plane of the advancing radio-wave front, i.e. the direction of the source is at right angles to this plane.

Similar direction-finding techniques were applied in the early 1930s by Sir Robert Watson-Watt and his team to study the rate of occurrence and the direction of location of lightning discharges. Such a discharge of electricity from cloud to cloud or cloud to ground produces a short burst of radio noise that may be heard as an atmospheric in an ordinary sound radio. Since the discharge was of very short duration it was necessary that the direction-finding process should be accomplished within a very short space of time. The piece of apparatus developed to do this was a form of cathode ray tube display such as is now used in a television set. The same method could also be applied to determine the direction of arrival of any short duration radio signal so that, by 1932, the stage was set for bringing together the techniques of radio echo-ranging and radio direction-finding in order to form the new technique of radiolocation.

The early workers in radiolocation were aware that radio waves could be reflected from aeroplanes as well as from the ionosphere but the radio echoes were very weak and difficult to detect. Nevertheless, it was clearly realized that if the echoes produced by a powerful pulse transmitter could be received and amplified then the range of the reflecting aircraft and its direction could be measured. It was also realized that such a perfected, non-co-operative method of detecting the presence of any aircraft in the air space and of radiolocating its position could be of vital importance in combating the air attacks that would inevitably be a major feature of any future war. The development and perfecting of radiolocation techniques were, therefore, undertaken with great vigour and in complete secrecy; the military success of the new weapon in the Second World War is well known.

Radiolocation has become a specialized and highly developed branch of modern radio engineering and so it was probably a happy idea of the Americans to give a new name 'Radar' to the new technology. The new word 'Radar' derives from the essential parts of the radiolocation process, i.e. *Ra*dio *D*etection *a*nd *R*anging, and it is used either as a noun or as an adjective. Thus we use a radar to observe migrating birds and we employ radar techniques to measure the density, altitude, and direction of flight of a stream of birds.

A modern radar station

It is not the purpose of this book to describe in detail the developments in radar technique which have taken place over the last thirty years; we may simply note that the aims of research over this period were to increase the detection range and to improve the accuracy of measurement. The military need to achieve these objectives has resulted in a progressive improvement in the power of the transmitter, in the sensitivity of the receiver and in the gain and resolution of the aerial systems that have been employed.

In the case of the transmitter a thousand-fold increase in pulse power has been obtained since 1939; the pulse powers of a few kilowatts only in 1939 have been converted to megawatts in the 1960s. The requirements for improved target resolution, coupled with high azimuthal accuracy, led to a movement away from the comparatively long radio wavelengths which were used in the first radar stations. Thus, in 1939, a wavelength of about 13 m (23 Mc/s) was employed for the Chain Home radars of the Royal Air Force, which existed as a belt of 'C.H.' stations round the coast of Britain. This wavelength was reduced to 1½ m for the second chain of coastal stations, and radars with wavelengths of 50 cm, 10 cm and 3 cm respectively were later developed and brought into use with the Services. Modern equipments employ wavelengths in the band 50 cm–8 mm, the precise wavelength selected being dependent upon the operational role the radar is intended to fulfil. Thus, a 23-cm radar is commonly employed for long range warning or surveillance (up to 300 miles) but 3 cm or less is used

for airborne radars. Radars operating in the waveband below 50 cm are usually termed 'microwave radars' and are characterized by the use of quasi-optical aerials, usually in the form of reflecting dishes. We shall be concerned exclusively with microwave radars in this book.

The requirement for good target resolution in range led to the use of shorter and shorter pulse lengths. Clearly, if the pulse length is 16 microseconds (16 millionths of a second, written 16 μs), the radio pulse packet occupies a length of approximately 3 miles. If two aircraft lying on the same radius from the radar are separated by less than half this length, they will not be recognized as two distinct targets because they will be contained within the same 'pulse packet'. For this reason radar pulse lengths were reduced progressively and it is now usual for a modern surveillance equipment to use a pulse length of 5μs. Short range sets commonly use 1 μs and in some ship applications even 0·1 μs is called for. Short though these pulses are, they are long compared to the time intervals of nano-

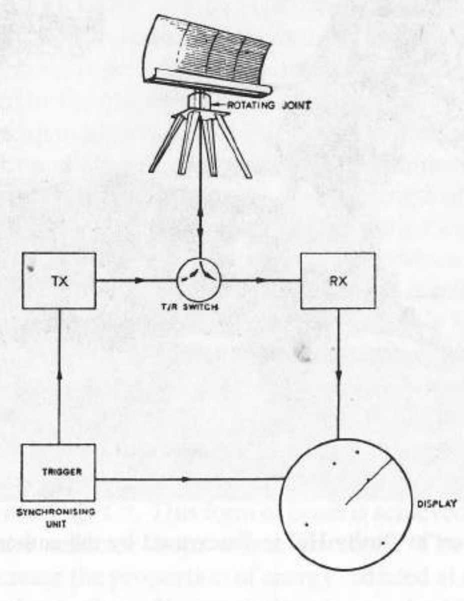


FIG. 1.6. The elements of a microwave radar

seconds encountered in modern computers. (1 nanosecond = 1 thousandth of 1 μs = 10^{-9}s).

The essential elements of a modern microwave radar station, as used for long-range observations of civil aircraft moving along airways may be described by reference to the Marconi experimental station located on Bushy Hill in Essex, England.

The radar consists of the following component sub-systems, shown diagrammatically in Fig. 1.6:

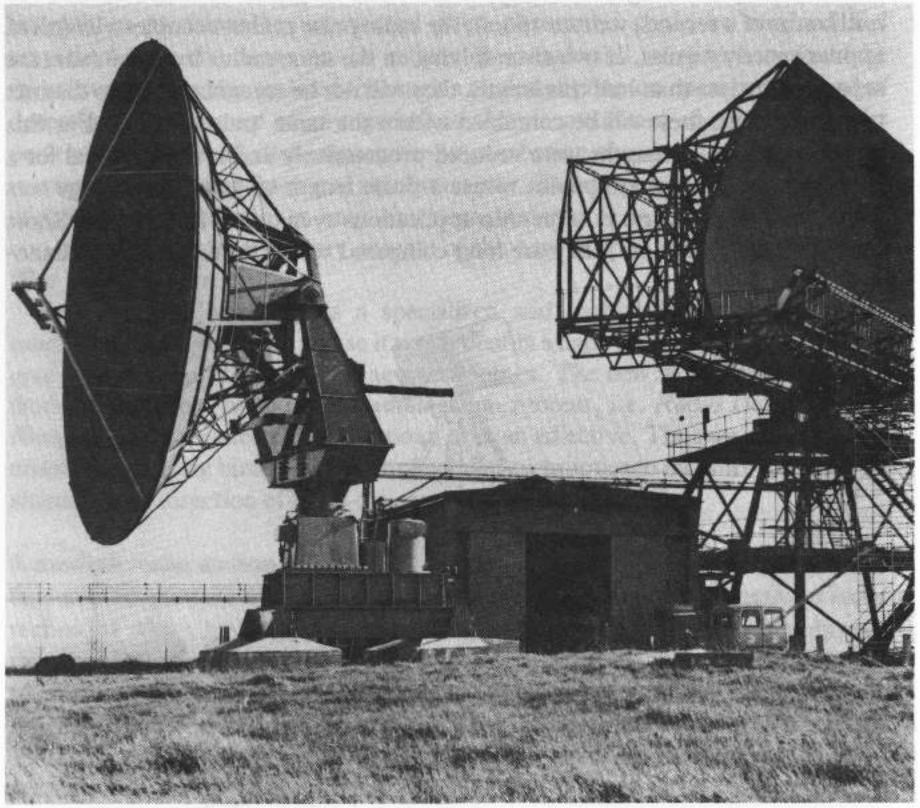


PLATE I. The radars at Bushy Hill in Essex used by the author and described in the adjacent pages.

(1) Aerial – used both to transmit and receive.

(2) Transmitter (TX) – to produce a continuous succession of high powered, short duration pulses.

(3) Receiver (RX) – a very sensitive radio receiver to detect the feeble echoes.

(4) T-R Switch – An automatic device for isolating the receiver from the aerial during the transmission of the pulse.

(5) Display – a cathode ray tube device to measure both the delay time of the echo pulse and its direction of arrival.

(6) Synchronizing Unit or Trigger – to initiate the pulse train from the transmitter, and to trigger the time measuring circuits in the Display System.

Radar aerials

The prime purpose of the lens of a lighthouse lantern or the reflector of a motor-car headlamp is to bunch the optical energy of the lamp into a narrow beam in order to secure greater penetrating power. The radar aerial similarly serves to focus the radio energy delivered by the transmitter into a beam suitable for the illumination of aircraft at altitudes up to 50,000 ft. The Bushy Hill Surveillance aerial consists of a reflector in the form of a parabolic cylinder, rather similar to an electric fire, and measuring 75 ft × 25 ft. The radio energy at a wavelength of 23 cm is led from the transmitter via a copper tube or waveguide to a rotating joint which permits loss-free transmission of the energy to another waveguide which is attached to and revolves with the aerial on the gantry. This second guide is coupled to the aerial primary feed which is a slotted waveguide running the whole length of the array and occupying a position relative to the reflector identical to that of the heater element in an electric fire, i.e. it is located at the focus of the parabola which is the cross-section of the reflector (Fig. 1.7). The radiation pours from the slots of the feed guide and interacts with the reflector to form a beam whose width in the horizontal plane is only 0·8°. The shape of the beam in the vertical plane is asymmetric, as shown in Fig. 1.7. This form of beam is achieved by distorting the vertical section of the reflector from a true parabola. The purpose of this arrangement is to increase the proportion of energy radiated at angles lower than 10° of elevation, relative to the radiation at elevation angles higher than 30°; in this way the sensitivity of the radar is increased on distant aircraft flying below 50,000 ft.

The aerial is rotated on top of the ganty at 4 r.p.m. and so a fan beam of radio energy is swept like a lighthouse beam through 360° once every 15 s. Any object in the airspace, be it aircraft, cloud, or bird, is illuminated by this radio beam and scatters energy back to the radio aerial. In the case of an aircraft, at a range of 186 miles, the transit time for the double journey is 2 ms, and thus the returning pulse will find the bearing of the aerial substantially unchanged; actually it will be displaced about 3′. This received energy passes through the rotating joint and is routed to the receiver via the switch labelled 'T.R. Switch'.

The first radars employed two separate, static aerials in order to fulfil the transmit and receive functions respectively. Even the early 1½-m radars mentioned above, although of the rotating-beam type, still employed separate *T* and *R* arrays. The problem of ensuring that the receiver array (*R*) was suitably oriented to receive echoes from a target illuminated by the transmit aerial (*T*) was a difficult one, however, and was only ultimately overcome by combining the two aerials into one array – called a 'common *T* and *R* array'. This may seem an obvious solution to the alignment problem but it could only be applied if a method could be found for isolating the receiver from the aerial during the short transmission interval. Now the magnitude of the transmitted pulse from Bushy Hill radar is 2 MW, while the received echo pulse is in the order of 2×10^{-14} W. In order to employ a common *T* and *R* array, it is necessary to ensure that the receiver, so sensitive as to respond to an echo signal of 2×10^{-14} W, shall be completely isolated from the full blast of the outgoing transmitter pulse of 2×10^{6} W. The ratio of these two pulses is about 10^{20}! The device which makes this possible is the *T-R* switch; it is an arrangement of gas discharge tubes which automatically conduct when the transmitter pulse occurs and so screen the entrance of the waveguide which leads to the receiver. When the echo pulse returns it is too feeble to re-strike the gas tubes, for these are no longer conducting due to the cessation of the transmitter pulse, and so the echo pulse passes straight to the receiver without attenuation. The *T-R* switch and the common aerial principle of radar which it makes possible were indeed wonderfully conceived.

Although the azimuthal beam width of the Bushy Hill radar is very narrow (0·8°), its spatial extent is obviously much greater than the aircraft or birds which it illumines, and so a number of echoes will be received from such objects during the transit of the beam over them. The radar emits 250 pulses per second and usually provides echo signals composed of eleven successive 'strikes' on the target. The narrowness of the beam, however, is more than adequate to ensure an accurate measurement of the bearing of the target. An electrical device, either a 'magslip' or 'selsyn', is geared to the array and relays the instantaneous bearing of the aerial to the radar display.

Although the aerial described provides a form of radiation pattern well suited to the surveillance role in civil or military operations, other forms of aerial radiation diagram are also needed and these special aerials can be extremely useful in certain forms of ornithological research. Such an aerial is a steerable tracker which has been used to observe the movements of artificial satellites. This aerial consists of a 30-ft parabolic reflector set in an altazimuth mounting; it is fitted with two rotating joints to permit rotation of the dish about vertical and horizontal axes respectively.

At Bushy Hill the radio energy from the transmitter can be switched into the tracker as an alternative to the surveillance aerial and, after passage through the pair of rotating joints, is finally sprayed on to the reflector through a horn feed. The beam produced by the aerial is symmetrical about the dish axis and has an angular width of 1·8°. This type of radar aerial is the complete radio analogue of

the optical searchlight mentioned earlier and has to be steered to the correct azimuth and elevation so that the target lies on the axis of the reflector. Such an aerial is not suitable for monitoring the general movements of aircraft or birds, but it is extremely useful for the detailed examination of a single target and of the time variation of its echo.

It is interesting to note how fashion can operate even in such an unlikely subject as aerials for radar. In Britain there has been a tendency to design large surveillance aerials in the linear array form described above. In the U.S.A., on the other hand, designers have favoured the elliptical paraboloid which can be caused to produce an identical diagram by the use of a feed in the form of a stack of horns (see Fig. 1.7). The two types of aerial are completely equivalent but whatever

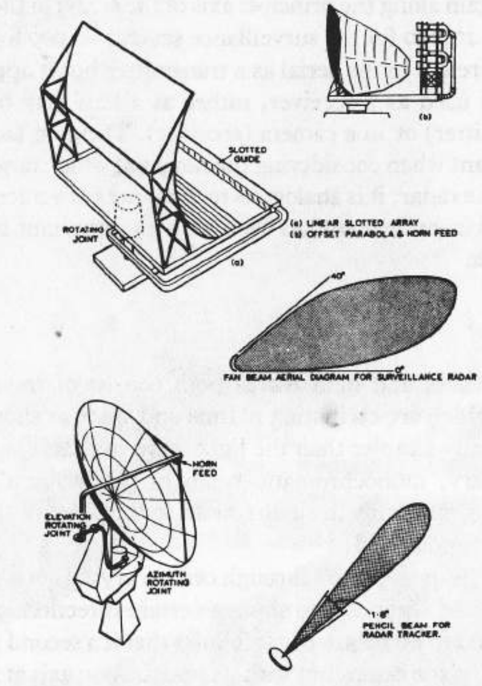


FIG. 1.7. Radar aerials and the radiation patterns which they produce

kind of radar aerial is employed it is necessary to have detailed knowledge of the characteristics of the radio beam which it is producing and of the position of the beam in relation to the aerial structure. This kind of information is calculable from the known geometry of the array and the wavelength of the radiation employed, but it is also desirable to check the results by measuring the magnitude of the signals picked up by the aerial from a remote transmitter of known power. In the case of the Bushy Hill aerials the most convenient source of radiation is the sun itself. The sun is a strong emitter of radio waves; it is also a source of small angular size (30′) whose elevation and azimuth are accurately known at all times and so it is an ideal test source.

Aerial gain

The ability of an aerial to concentrate its radiation into a narrow beam is measured by a factor termed the aerial gain *G*. The gain of an aerial in a certain direction measures the ratio of the power per unit solid angle in that direction, compared to the power that would have been present if the same total power had been fed to a completely non-directional or 'isotropic' aerial. Clearly the gain must be less than unity in some directions, for example to the rear of the array, to make up for the concentration of energy in the forward direction. Usually we are most interested in the maximum gain along the principle axis of the array; in the case of the Bushy Hill aerials this is 20,000 for the surveillance set and 10,000 for the tracker. This definition of gain refers to the aerial as a transmitter but it applies equally to the same aerial when used as a receiver, rather as a lens may be used either in a projector (transmitter) or in a camera (receiver). The gain factor of the array is extremely important when considering the ranges at which targets of various sizes can be 'seen' by the radar; it is analogous to the power of a microscope, a quantity whose continuous improvement has been such an important factor in furthering biological research.

Polarization

Although radio waves and light waves both consist of travelling electric and magnetic fields, which are oscillating in time and space as shown in Fig. 1.5, the radio wave is usually simpler than the light wave in that it is 'Polarized'. In the case of an ordinary, monochromatic beam of yellow light, the electric field vector is oscillating randomly in all directions in the plane of the wavefront; such light is said to be unpolarized.

When the light beam is passed through certain crystals or a piece of 'polaroid', only the electric field components along a certain direction are transmitted and the light is now said to be polarized. It follows that if a second piece of polaroid is placed in the path of the beam, but with its polarization axis at right angles to that of the first polaroid, then no light will be transmitted even though the polaroids are separately transparent.

The field pattern shown in Fig. 1.5 corresponds to a plane polarized wave, because the electric field vector lies wholly in the wavefront and also in a plane through the axis of propagation which is itself at right angles to the wavefront. A high frequency oscillatory current in a straight wire produces such a radio wave, and the ordinary television aerial is a familiar example of a conductor picking up radio energy from the polarized electric field which is parallel to its length.

In the case of the C.H. stations the aerials consisted of horizontal wires which produced horizontally polarized waves. This polarization was selected because it

PLATE 2. A modern military surveillance radar, the Marconi Martello at Bushy Hill. A mobile radar which not only detects aircraft in range and bearing but also finds the height, of all the aircraft in 4 million cubic miles of air space every 12 seconds.

was considered that the metal wings and fusilages of aeroplanes would reflect horizontally polarized waves better than if vertically polarized radiation were employed. In this way a convention of using horizontal polarization was established which was carried over into the microwave era. Surveillance radars are usually horizontally polarized, although there is little difference in the microwave reflectivity of an aircraft to either polarization and, in fact, height finding radars usually employ vertical polarization as a simple consequence of the change of the axis of the aerial through 90°.

If the target is symmetrical no change in reflectivity occurs when the polarization is changed, and so a metal sphere shows no polarization effect. An asymmetric target, however, such as a length of metal rod, will reflect most strongly the radiation for which the polarization of the electric field corresponds to the long axis of the target. During the war use was made of this principle in order to interfere with enemy radars. False targets were produced by dropping strips of tinfoil – called 'Window' or 'Chaff'.

Advantage can also be taken of the polarization effect to reduce the strength of echoes from rain. Falling rain drops assume a spherical shape and so reflect vertically or horizontally polarized waves equally well. A device called a circular polarizer is fitted to the radar aerial which causes the echoes from rain to be reduced greatly in intensity compared to the echoes from polarization sensitive targets such as aircraft.

A radar producing a polarized beam can also be used to study the changes in symmetry of a target by examining the fluctuation in amplitude of the echo signal consequent upon the changed reflectivity of the target with respect to a polarized wave. An example of this phenomenon is the so-called 'propeller modulation' effect encountered with radar echoes from propeller aircraft. The amplitude of the signal is found to vary in synchronism with the rotation of the propellers, since a blade reflects the horizontally polarized radar wave better when it is in the horizontal position than when it is vertical. A similar effect can happen with birds due to the change in shape of the body from near spherical to ellipsoidal during wing flapping.

Radar transmitters

The function of the radar transmitter is to produce a short duration burst of radio frequency oscillations. The Bushy Hill transmitter operates at a frequency of 1,305 Mc/s and a wavelength of 23 cm. The duration of a single pulse is 5 μs, so that during this time 6,525 complete waves are emitted from the aerial. Radar visibility of a distant object can only be secured by using strong illumination, i.e. by using pulses of high energy. In the case of Bushy Hill, this packet of energy is 10 J per pulse so that, to find the equivalent radio power of the transmitter, we must divide the pulse energy by the duration of the pulse and so the equivalent power appears as 2 MW. This radar power may be compared with the 40 kw of a television station.

In the early days of radar it was a difficult engineering task to produce high pulse power. Nevertheless, the C.H. stations were able to achieve 400 kw by the

use of conventional valves. At microwave frequencies the problem of power development is complicated by the fact that the transit time of electrons between the electrodes in the tube begins to be comparable with the time of one cycle of the electrical oscillation. It was necessary to devote much research and ingenuity to overcome this fundamental difficulty both during the war and in the decade that followed. Two completely new types of radio transmitting valves emerged from this work and have been developed to a remarkable level of perfection. First the 'Magnetron' – this is a self oscillating device which, when fed with a high-voltage d.c. pulse, bursts into electrical oscillation of a frequency determined by the geometry of the valve. A substantial proportion of the Bushy Hill bird migration records have been taken with a 2 MW cavity magnetron of this type. A completely different principle of operation is used in the second type of high power microwave valve known as a 'Klystron'. This is a driven valve which accepts a radio-frequency pulse at the kilowatt level and amplifies it to the megawatt range. Its frequency is determined by the low level drive circuits and so it is a coherent radio system which may be held to a predetermined frequency. It is for this reason that the klystron is now finding wide application in ultra high-frequency television. The klystron has been used in certain forms of observation at Bushy Hill concerned with the velocities of aircraft and birds.

It will be appreciated that the magnetron or klystron generator must be fed with d.c. power from a modulator source which is then converted by the action of the tube into high frequency radio power. The engineering of the modulator is a very involved matter which it is not the purpose of this book to describe; the modulator functions as a precision switch which delivers 250 pulses of d.c. energy per second to the magnetron upon receipt of synchronizing pulses supplied from the trigger unit. The same pulse train is also supplied to the Display System described in the next chapter and initiates the range measuring process.

The receiver

High performance radio receivers are now commonplace 'pieces of furniture' in most homes, whether for television or sound radio. In principle, the radar receiver does not differ from these domestic units but, since it is required to respond to the very small signal power received as an echo by reflection from a distant target, it is necessary that the receiver shall be very sensitive. Now every radio receiver creates noise – this fact can readily be appreciated by turning up the volume control on a domestic set which has been detuned from any station and detached from an aerial; a loud hissing noise is produced which is an amplified version of the electrical noise developed in the first circuit of the receiver. Radio noise, in general, is partly received from the outside world via the aerial and is partly produced by the electronic components in the first circuit of the receiver. The purpose of a receiver is to amplify the signals received without distortion and without introducing additional radio noise for this will only confuse the signal detection process. A good receiver, therefore, is one which produces as little extra noise as possible and 'goodness' in this connexion is

PLATE 3. This modern low cost air traffic control radar, a Marconi S511 at Newcastle airport, uses a high accuracy carbon fibre double curvature antenna (see page 13 about fashion in antenna design).

measured by the so-called Noise Figure. In radar work great effort has been devoted to producing receivers of low noise figure – a very difficult problem at microwave frequencies. It was first solved by reverting to the form of crystal receiver familiar in the early days of broadcasting. Crystal receivers are still employed in radar, especially in the modern form known as parametric amplifiers. Special valve receivers are also used and the Bushy Hill equipment employs such a receiver in the form of a low-noise travelling wave tube. This gives a noise figure of 6–9 db as compared to the 15–18 db of 1945. The search for better receiving techniques is well worth while since reduced noise figure in the receiver is just as effective as increased power from the transmitter in improving the radar performance; but the receiver method is much less expensive to achieve in terms of both apparatus and running costs.

The radar equation and the target 'echoing area'

The original purpose of a radar was to detect the presence of aircraft in the airspace and to give the earliest possible warning of their approach. In order to increase the warning time, and to have the defences in a state of readiness, the radar must detect the target at the greatest possible range. It is, therefore, necessary to understand how the maximum range of the radar is dependent upon the characteristics of the aerial and the transmitting and receiving equipment we have reviewed above. But the range is also affected by the size and nature of the target itself; in other words, it is much easier to see aircraft than birds. We will now examine, in a simple way, the relationship between the maximum range and the quantities which determine it, i.e. the power of the transmitter, sensitivity of the receiver, and the gain of the aerial.

We wish to calculate the power of the pulse finally presented to the receiver for recognition as an echo – let this quantity be P_r W.

If the pulse from the transmitter possesses a power P W, then the effective power of the pulse radiated from the aerial is PG, where G is the gain of the array.

Let the target be at a range r, then as the radio waves travel from the aerial they will be spread out over a greater and greater area and the power density will be attenuated according to the usual inverse square law. This law states that the power density at a range r is derived from that at the source by dividing by the area of the sphere – $4\pi r^2$.

We thus have an incident power density at the target of:

$$\frac{PG}{4\pi r^2}\,\text{W/sq m}$$

Now a certain multiple A of this incident energy per unit area will be re-radiated or scattered by the target back to the radar, i.e. the total power scattered by the target is

$$A\,\frac{PG}{4\pi r^2}\,\text{W}$$

This re-radiated wave will again be attenuated by $4\pi r^2$ in its return to the aerial,

$$\text{i.e. Power of echo pulse at the aerial} = \frac{1}{4\pi r^2} \cdot A \cdot \frac{PG}{4\pi r^2} \text{W}$$

Aerial theory shows that the fraction of this incident power which is made available to the receiver is

$$\frac{G\lambda^2}{4\pi}$$

where λ is the wavelength of the radiation employed.
∴ Power in the pulse presented to the receiver

$$= P_r = \frac{G\lambda^2}{4\pi} \cdot \frac{1}{4\pi r^2} \cdot A \cdot \frac{PG}{4\pi r^2} \text{W}$$

$$P_r = \frac{PG^2\lambda^2 A}{64\pi^3 r^4} \text{W}$$

Now a target is at the limit of visibility when this power presented to the receiver is equal to a certain minimum, P_{min}, which is the power necessary to produce a detectable signal on the display. P_{min} is dependent upon the noise figure of the receiver and also upon the video bandwidth, the spot size of the cathode ray tube and the afterglow characteristic of the phosphor.

The maximum range, r_{max}, will be achieved by setting

$$P_r = P_{min}$$

$$\text{i.e.} \quad P_{min} = \frac{PG^2\lambda^2 A}{64\pi^3 r^4_{max}} \text{W}.$$

$$\text{i.e.} \quad r_{max} = \sqrt[4]{\frac{PG^2\lambda^2 A}{64\pi^3 P_{min}}}$$

This expression, which is termed 'the Radar Equation', is of fundamental importance in the study of radar operations and shows how the maximum range varies, not only with the radar system parameters but also with the factor *A* which we have used to describe the scattering of energy from the target. The factor *A* is called the 'Echoing Area' of the target, or the 'Radar Cross Section' and is defined as follows:

The echoing area of a target is the area of the incident wave front which must be intercepted in order to yield the power which, if radiated uniformly in all directions, would produce the same signal at the aerial as is produced by the actual radio wave reflected from the target.

Echoing area is usually measured in square metres and has a value of 11 m² for a Canberra aircraft. The echoing areas of birds are quite small, as is to be expected

from their small size; for comparison it may be noted that *A* for a starling is 0·0002 m² in head aspect! The ratio of the echoing area of a Canberra aircraft to that of a starling is, therefore, 55,000 : 1 but, surprisingly, the ratio of the ranges is only 15 : 1 – this is a consequence of the fourth power law!

The radar performance diagram

Although the radar equation is essential to a precise discussion of the design or performance of a radar system, its implications can be appreciated more readily when it is presented in graphical form. We notice that the radar equation tells us

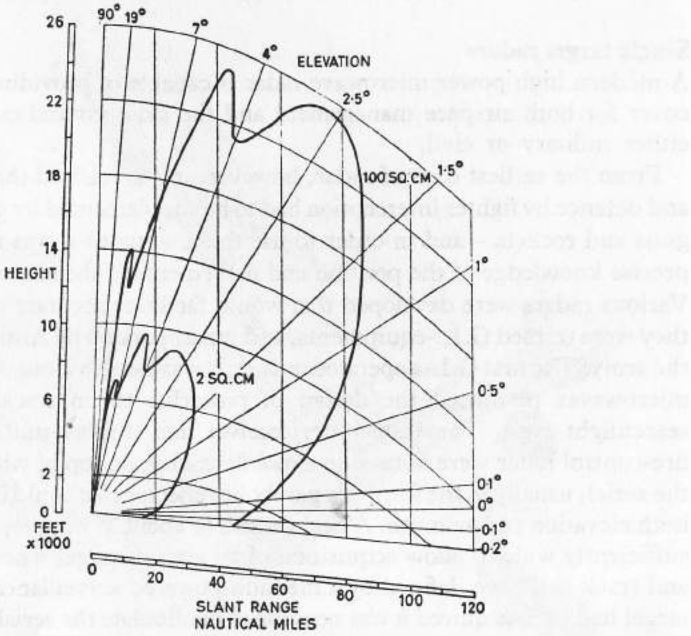


FIG. 1.8. Vertical Performance Diagram of the Bushy Hill surveillance radar against targets of echoing area 2 cm² and 100 cm² respectively

the maximum range at which a target of known echoing area will be seen by the radar whose characteristics *P*, λ, and P_{min} are fixed. The gain factor *G* of the array is also known but it is not a constant, being a function of the angle of elevation, i.e. the maximum range of the radar changes with the elevation. If the maximum range is plotted in polar co-ordinates against the angle of elevation then a closed curve of the form shown in Fig. 1.8 is obtained.

This figure presents the performance diagram of the Bushy Hill radar. The outer curve represents the limit of visibility of a target having an echoing area of 0·01 sq m, i.e. 100 cm² which is roughly the target that would be presented by a flock of about five lapwings. It will be noted that the curve of limiting visibility continues to negative angles of elevation; this is a consequence of the fact that the site height of the station is 250 ft above sea level and so many birds are visible at depression angles from the radar.

Another feature of the diagram to which reference will frequently be made in later chapters is the inclusion of lines of constant altitude. These curves have been calculated to take account both of the curvature of the earth and also of the bending of radio waves due to refraction in the earth's atmosphere. This diagram permits us to read off the range of disappearance of any target of known echoing area which has been flying at constant altitude, radially away from the station. Conversely, it marks the point of first appearance of such a target.

Single target radars

A modern high power microwave radar is capable of providing comprehensive cover for both airspace management and the close ground control of aircraft, either military or civil.

From the earliest days of radar, however, it was realized that 'early warning' and defence by fighter interception had to be supplemented by ground defences – guns and rockets – and in order to use these weapons it was necessary to have precise knowledge of the position and movements of the aircraft to be engaged. Various radars were developed that would facilitate accurate gun laying and so they were termed G.L.-equipments, and were operated by Anti-Aircraft Units of the army. The first G.L.s operated on metric wavelengths, but the introduction of microwaves permitted the design of powerful 10-cm trackers of the radar searchlight type. The transmitter/receiver and display units of this type of fire-control radar were housed in a mobile trailer, on top of which was mounted the aerial, usually in the form of a parabolic reflector that could be moved freely in both elevation and azimuth. A beam width of about 4° was employed, which was sufficiently wide to allow acquisition of an aircraft target whose initial position and track had been defined by a medium-powered surveillance radar. After the target had been acquired it was possible to manipulate the aerial so that the target was held in the beam, no matter how it might manoeuvre to avoid attack. More sophisticated radars were equipped with a 'lock follow device' which performed the tracking function automatically and supplied very accurate range, bearing, and elevation information. A short pulse length was employed so that good range resolution could be obtained. Target tracking radars of this type are very useful for the examination of single bird targets.

Other forms of very short pulse, high resolution radars have also been used to study the behaviour of individual bird targets at ranges less than 10,000 ft, e.g. to measure altitudes, rates of climb, and speeds of flight. These equipments operate on a wavelength of 3 cm and include Air Interception Radars (AI) as used in military aircraft or as Weather Radars in civil airliners; the Precision Approach Radars of Civil Air Traffic Control Units and various adaptations of ship radiolocators.

It will be seen that there exists quite a variety of radars which the ornithologist

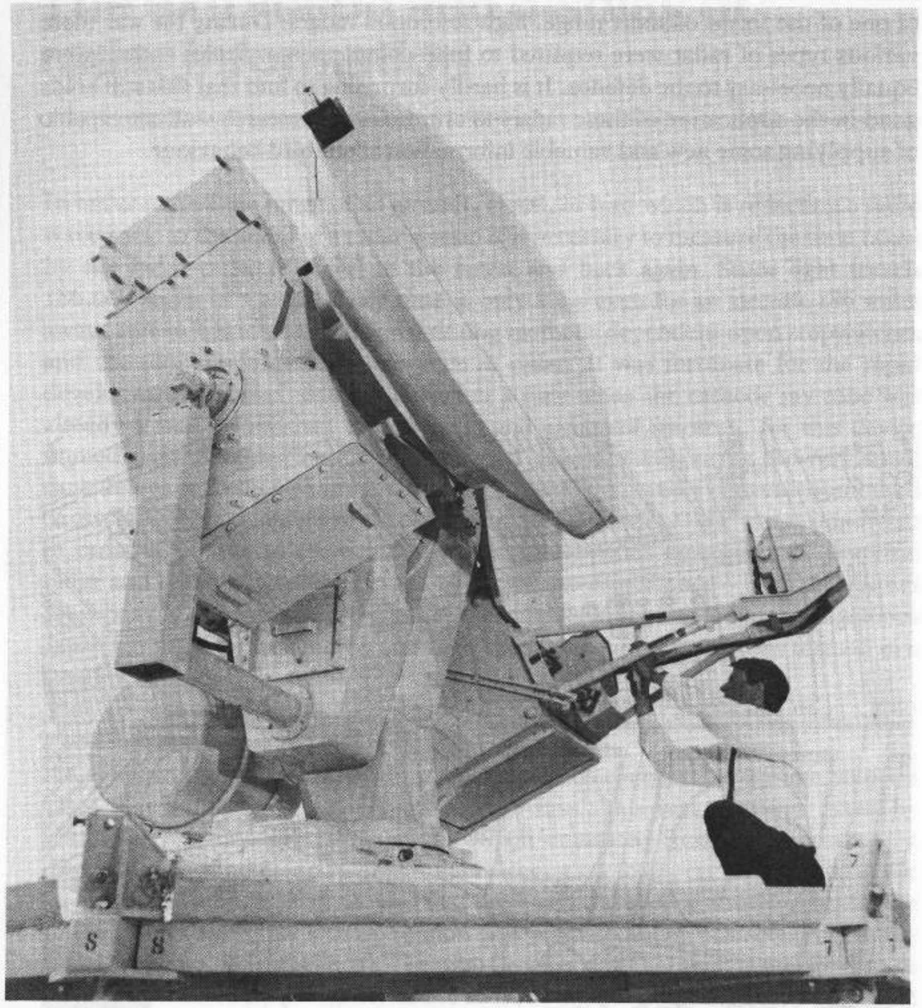


PLATE 4. Radar antenna for control and direction of the Sea Wolf missile. One of a family of modern 'Single Target Radars' discussed on the opposite page.

could use with advantage in various types of research. To observe the progress of large scale migratory movements requires access to a high power surveillance radar. The flight behaviour of a single bird, however, is best studied with the aid of one of the forms of short range, high resolution radars. During the war these various types of radar were required to fulfil complementary roles and all were equally necessary to the defence. It is hardly surprising to find that this still holds good in the application of these radars to ornithological research – all are capable of supplying some new and valuable information about bird behaviour.

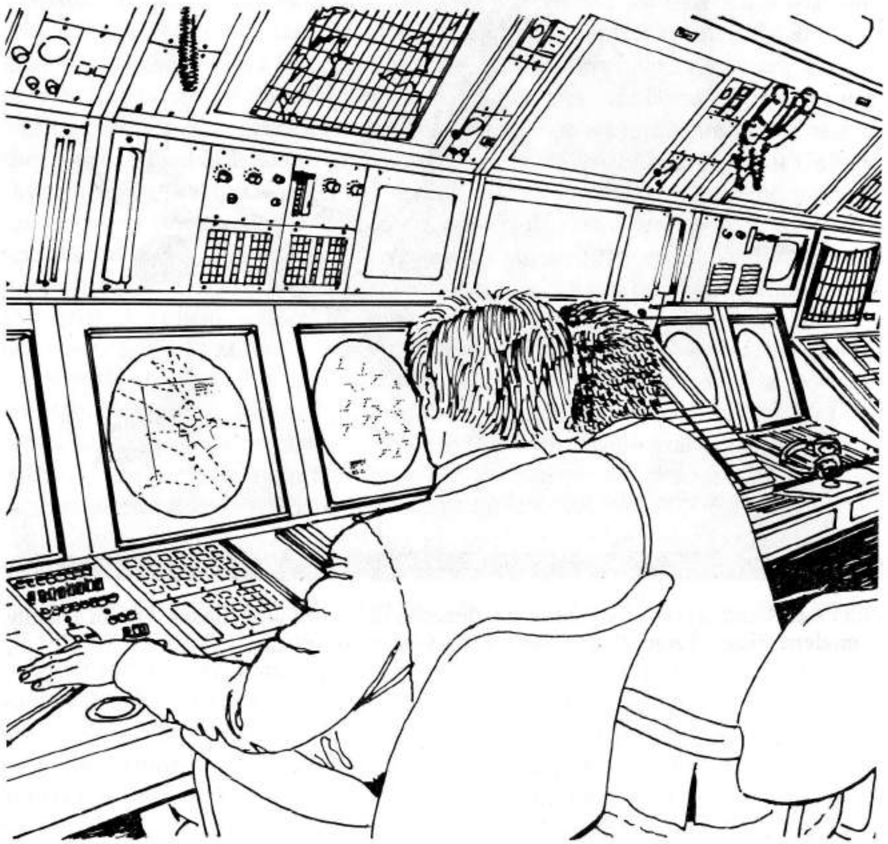


FIG. 1.9. Marconi display consoles in the Scottish Air Traffic Control Centre at Prestwick.

The extraction and display of radar information

In order to find the range of an aircraft, cloud, or bird which is reflecting a radio wave back to the aerial of a radar station it is necessary to measure the time taken by the radar pulse to travel to the target and back again. Since light travels 186,000 miles in 1 s this delay time is only 2 ms even for an aircraft 186 miles away, and so it is clear that normal timing methods dependent upon stopwatches and the like can have little relevance in radar. It was fortunate for the rapid development of radar that it occurred at a time when the cathode ray tube was already a well established tool in radio and electrical research, for this device immediately provided not only a perfected means of measuring the very small time delays encountered in radar ranging, but also offered a convenient method of displaying radar signals to the observer. The cathode ray tube was as important to radar as it was to television and the simultaneous emergence of practical radar and television systems in the 1930s was no coincidence – both techniques drew heavily upon the long and patient researches which had led to this ingenious exploitation of the low inertia and high speed of beams of electrons formed in a vacuum tube.

The cathode ray tube

It was the study, during last century, of electrical discharges through low pressure gases that led to the discovery of 'cathode rays'; this was the name given by Hittorf to the mysterious radiations which emanated from the cathode of a discharge tube and caused a green, fluorescent glow to appear on the glass at the far end of the tube. Hittorf showed that these rays travelled in straight lines by the simple observation that a sharp shadow was produced of an obstacle lying in the path of the rays, as in Fig. 2.1(*a*). In 1879 Crookes demonstrated that cathode rays could be deflected by a magnet, and so must be regarded as composed of negative electricity in motion (Fig. 2.1(*b*)). The story was completed by Thomson in 1897 when he proved that cathode rays were streams of swiftly moving negatively charged particles emitted by the cathode. These particles we now call 'electrons'. Thomson employed crossed electric and magnetic fields in his experiment shown in Fig. 2.1(*c*), in order to exert opposing forces on the moving electrons. The electric field deflected the cathode ray beam from its equilibrium position at O to the point A – the point of impact of the electrons being rendered visible by coating the end of the tube with a phosphor such as zinc sulphide in order to enhance the natural fluorescence of the glass. By adjustment of the magnetic field the deflected beam could be returned to O and comparison of the two fields

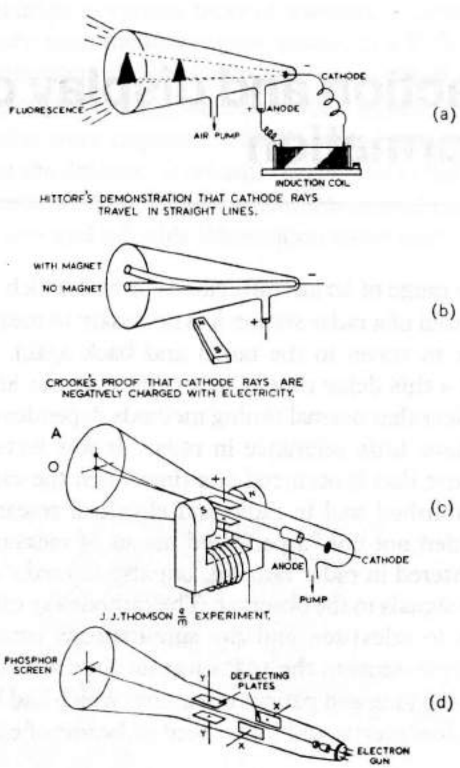


FIG. 2.1. The development of the cathode ray tube
(*a*) Cathode rays travel in straight lines
(*b*) Cathode rays are negative electrical charges in motion
(*c*) Thomson's experiment to prove that cathode rays are swift moving electrons
(*d*) An electrostatically deflected cathode ray tube

in this balanced state permitted Thomson to measure the ratio of the charge of an electron to its mass. The constancy of this ratio led to the recognition that the electron is a fundamental particle in atom building.

Thomson's experiment was a crucial one for the progress of atomic physics but its importance for the subjects of television and radar which developed forty years later was that it showed how the deflexion of high velocity electrons could be used to measure changes in electric and magnetic fields. Electrons possess very small mass, which means that they can be easily accelerated to velocities near the velocity of light, their low inertia also permits them to respond to rapid fluctuations in the deflecting fields applied to them. Fig. 2.1(*d*) represents a modern electrostatically deflected cathode ray tube and shows how little it has changed from Thomson's apparatus. The electrons are no longer derived from an electrical gas discharge but are produced thermionically from a heated cathode in an evacuated bulb. Acceleration and focusing of the electrons into a fine beam takes place in the 'electron gun', while deflexions in two directions at right angles

are produced by the two pairs of deflexion plates. In a modern television set the deflexion of the electron beam is achieved magnetically, i.e., changing electric currents are passed through two orthogonal pairs of coils which are placed externally round the neck of the cathode ray viewing tube. The crossed coil technique of television is cheaper to apply and so is appropriate to a commercial industry, particularly as it allows brighter pictures to be produced. Electrostatic deflexion, on the other hand, in which varying voltages are applied to the two pairs of plates, requires a more expensive tube but is superior for measurement work. This superiority arises from the fact that higher rates of change of voltage than current can be observed, due to the limitation imposed by the self-inductance of the deflexion coils.

The cathode ray oscilloscope

In order to convert the cathode ray tube from the field-balancing device used by Thomson into an instrument for measuring rapidly fluctuating electrical voltages or currents, it is necessary to provide not only calibration of beam deflexion in terms of voltage applied, but also to arrange for a movement or sweep of the beam along the x-direction in a prescribed manner. It is usual to provide a voltage for application to the X-plate of the tube which increases in a linear fashion and so causes a steady, straight line progress of the spot of light across the phosphor screen of the tube. Special electronic circuits have been devised to provide the required uniformly increasing voltages and such circuits are usually termed 'time-base circuits' since they provide the basis of time measurement in a C.R.T. (cathode ray tube) instrument. Linear time bases are most commonly employed and controls are provided in the circuit which permit different speeds of sweep to be employed, i.e. to change the rate of motion of the spot across the tube. In addition, the time base is caused to deliver its sweep voltage in a cyclic or repetitive fashion. The rate of repetition of the sweep, or time base recurrence frequency as it is called, can be adjusted, and if this frequency is caused to coincide with the repetition rate of the phenomenon under observation on the Y-plates then a steady or locked pattern may be observed upon the screen. This is the manner in which a C.R.T. and its time base are used to examine repetitive events, such as an alternating current waveform in an electrical power circuit, or an electrical oscillation in radio engineering. When used in this way the C.R.T., together with its time bases and the associated X- and Y-input amplifiers, is known as a 'C.R.T. oscilloscope'. It was the C.R.T. in this form which played such a vital part in the early development of radar; it was used, not only as a test instrument, but also as the first radar display device for the measurement of range. When used in this way the C.R.T. oscilloscope is known as a 'Radar A-scope'.

The radar A-scope display

The arrangement of an A-scope, when used to measure the time delay of a radar echo, is shown in diagrammatic form in Fig. 2.2.

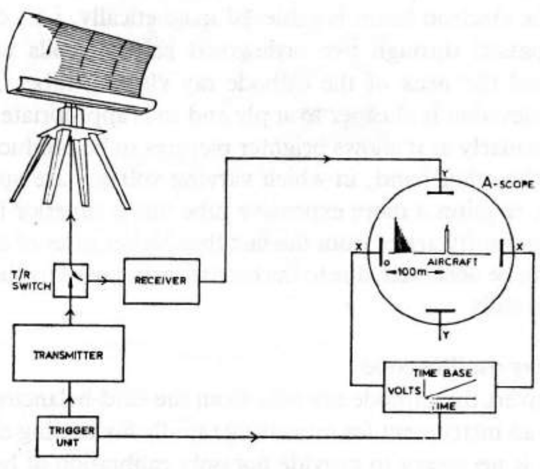


FIG. 2.2. The measurement of radar range using an A-scope

The trigger unit produces a continuous sequence of very short pulses (1 μs duration) which, in the case of Bushy Hill, are separated by intervals of 4 ms, i.e. the pulse recurrence frequency is 250 pulses per second. When such a synchronizing pulse is received by the time-base circuit, a steadily increasing voltage commences to be generated and is applied to the X-plates of the A-scope, and the spot begins to move steadily from left to right across the tube.

The same synchronizing pulse is applied to the transmitter, which is caused to fire, and so produces the radar pulse, which is immediately radiated from the aerial. Ground and other objects close to the aerial are illuminated by the radar pulse and scatter energy back to the aerial, so producing short-range echoes which are detected by the receiver, and the signals are applied to the Y-plates of the A-scope. These echo signal voltages cause vertical deflexion of the cathode ray beam simultaneously with its horizontal motion under the influence of the time base, and so the clutter of permanent echoes near zero range are produced, as shown in Fig. 2.2. Suppose a single aircraft at a range of 100 miles lies in the path of the radar beam, then a radar echo signal will be received 1·07 ms after the trigger pulse, and will produce the single vertical deflexion indicated. Clearly, it is more convenient to mark the x-deflexion axis of the tube in terms of miles of range rather than milliseconds of delay time, and the A-scope becomes a convenient device both to display echoes and to measure their ranges.

When the aerial rotates so that the radar beam sweeps over the target, the echo signal increases to a maximum and then decreases to zero until the next revolution.

The plan position indicator

A rotating beam radar can provide both the range and bearing of a target. If an A-scope is used to measure the ranges of the echoes, however, it is necessary

to use also an angle measuring device to give the bearings of the targets before their positions can be plotted upon a map of the area. It would be more convenient if a combined range and bearing measure device could be employed that would immediately locate a target in its correct position relative to the radar station. Such a device is the plan position indicator.

The main features of the plan position indicator display (p.p.i.) are shown in Fig. 2.3. The signal from the radar receiver is applied to the grid of the electron gun in order to produce an intensity modulated trace.

The time base of a p.p.i. is of the linear growth-of-current type, a process which is initiated by a synchronizing pulse from the trigger unit. The time-base

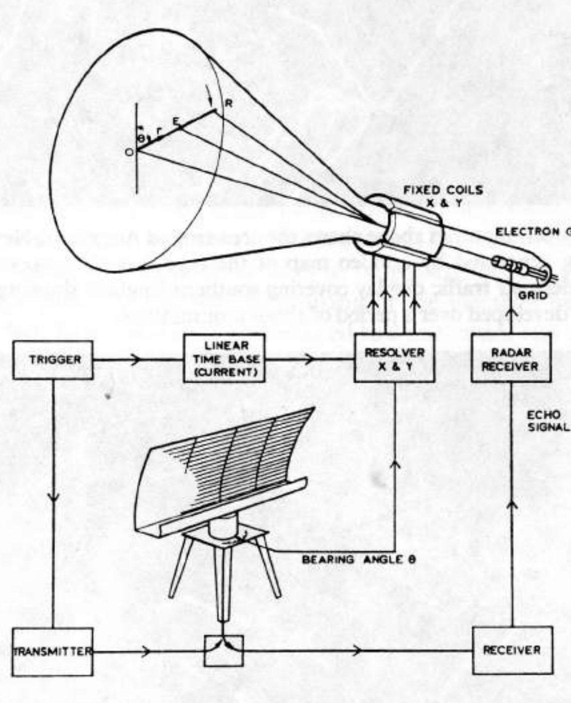


FIG. 2.3. The C.R.T. used as a Plan Position Indicator

current waveform is fed to the rotating coil of the resolver unit and induces currents in two pairs of coils at right angles. The central coil is linked to the aerial and rotates in synchronism with it. The currents derived from the crossed coils are applied to a corresponding pair of orthogonal fixed coils which envelop the neck of the tube and produce deflexions of the cathode ray beam such that the trace *OR* revolves about *O* like the spoke of a wheel, but in exact time and angle synchronism with the aerial. This method of applying brightness modulation to the scanning electron beam is identical to that used in television, as is also the magnetic method of moving the trace over the face of the tube. In television

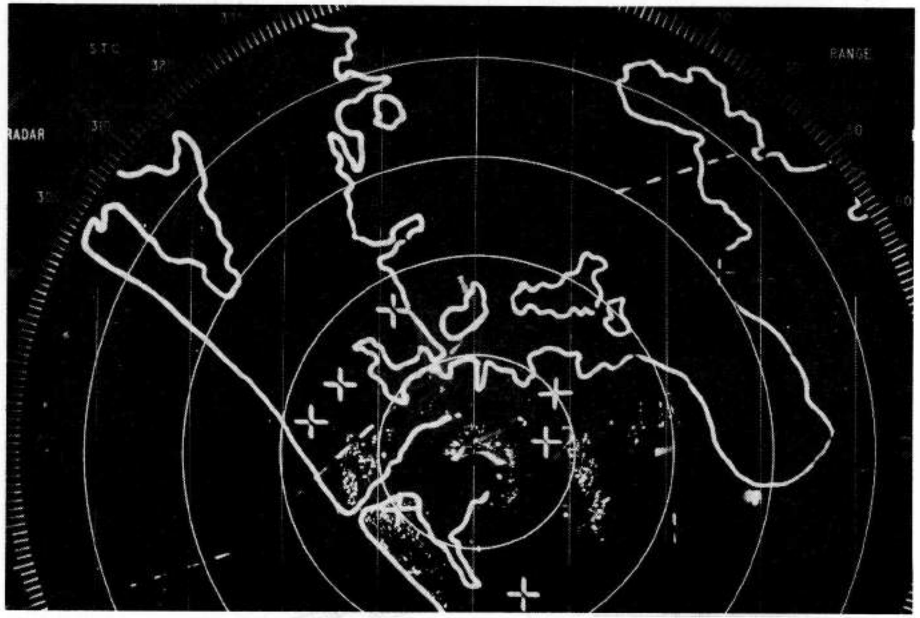
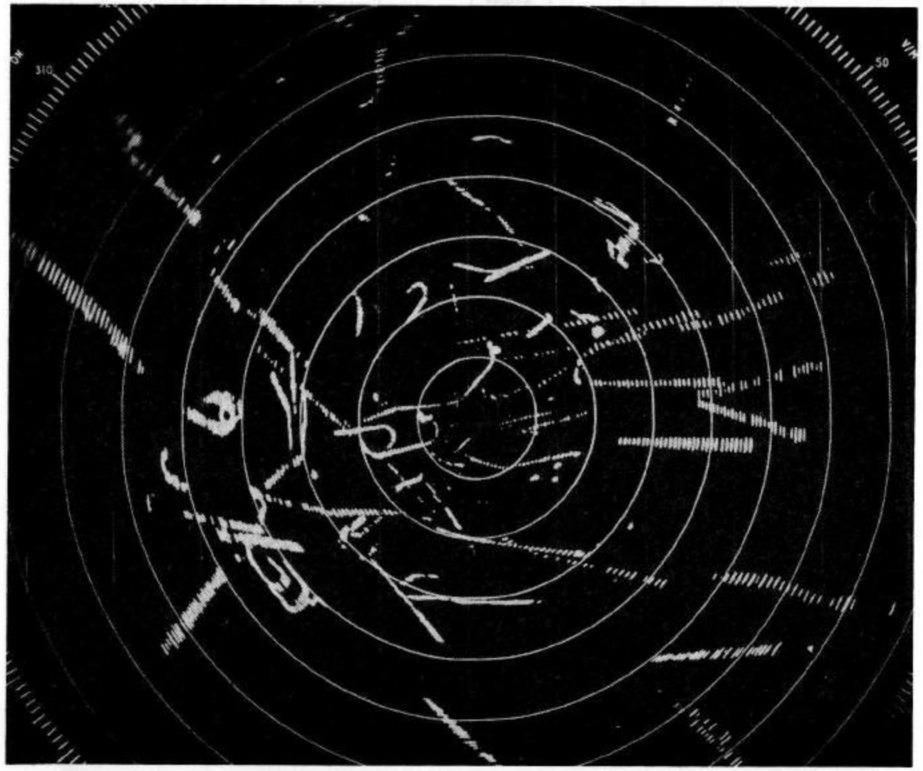


PLATE 6. The p.p.i. pictured above shows the area around Auckland, New Zealand. The coastlines being generated by a video map of the type described opposite. The lower picture is a modern air traffic display covering southern England showing tracks of more than 50 aircraft developed over a period of about four minutes.



the time base trace moves parallel to itself, up and down the tube, during a single frame of the picture, but in the p.p.i. the range trace rotates about its zero range end, in sympathy with the aerial's motion. As a consequence of the simultaneous presentation of both range OE, and the bearing angle θ, the position of the target at E is shown in its correct plan position. If a graticule of the map of the area is made on perspex and caused to overlay the p.p.i., then map references of targets such as E can immediately be read from the tube.

One curious feature of the p.p.i. display deserves special mention – the apparent lack of correlation between the size and brilliance of an echo 'paint', as it is termed, and the physical size of the target reflecting the radio wave. When the p.p.i. was developed it was realized that the signal power available from a target to drive the C.R.T. would depend upon the echoing area of the target and upon its range. This relationship is expressed by the Radar Equation. Expected variations in available power, in fact, could easily extend over a range of $10^{11}:1$, a range so wide that it seemed at first impossible to design a display which could simultaneously present weak signals from small, remote targets, and strong signals from large aircraft close to the radar station. The trick which overcame these difficulties was to use a 'limiter'. This is a circuit device which allows a signal of up to about three times the noise level to be passed, but cuts all larger signals to just this level. In this way defocusing of the electron beam on strong signals is avoided, halation effects are reduced to a minimum and burning of the phosphor is prevented. But the price paid is substantial loss of information about the amplitudes of the echoes; however, this information can be found in other ways when it is required.

The video map

So convenient and realistic did the p.p.i. prove for observing the movements of aircraft, that it was considered necessary to extend its usefulness still further by developing a device that would permit the direct presentation of fixed map features, such as the coastline, upon the face of the C.R.T. The device now employed for this purpose is called the video map; it is a flying spot scanner similar in principle to the film scanner used in television studios.

A slide is prepared which is a photographic negative of the lines of latitude and longitude, coast outline or airway boundaries which it is required to show as bright lines upon the p.p.i. This slide is illuminated by a radial time-base trace formed on the face of a small projection-type C.R.T. of high brilliance (Fig. 2.4). The time base is rotated in synchronism with the similar time base of the p.p.i. As the bright spot tracing the radial range line crosses each of the transparent lines on the slide, a light impulse is transmitted into a photocell, and so produces an electrical signal. This video signal is mixed with the radar signal applied to the grid of the p.p.i. Video signals corresponding to map details are thus produced simultaneously with the journeyings of the radar pulse through space and are also impressed upon the grid of the p.p.i., so that the rotating time base will paint the map lines of the area at the same time as the radar signals are painting the

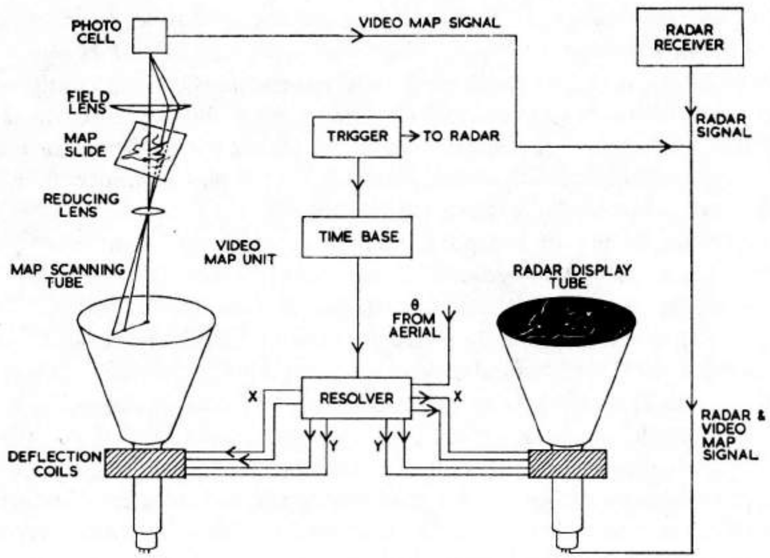


FIG. 2.4. The Video Map Unit which supplies mapping signals to the p.p.i.

targets themselves. It will be appreciated that a large number of p.p.i.'s may be supplied with synchronized map signals from one video-map unit.

The measurement of speed and direction of flight by radar

The p.p.i. is an ideal form of radar display, not only for the measurement of range and bearing of targets, but also for the extraction of speed and direction of flight. Two plots of an aircraft echo on the p.p.i., as produced by consecutive scans of the aerial, are sufficient to estimate roughly the speed and direction of flight of a fast target. For a jet airliner, travelling at a speed of 500 knots, the distance travelled in the 15-s interval which separates two successive sweeps of the aerial is about 2 miles and this quantity can easily be measured on the p.p.i.

The preceding text originally appeared as the first chapters of Sir Eric Eastwood's book 'Radar Ornithology' printed and published in 1967 by Methuen & Co, which contains further details of basic radar design but concentrates on the study of bird migration using radar techniques.