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## Radar engineering: progress and prospect

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Indexing terms: Radar antennas, Radar displays, Radar receivers, Radar transmitter, Signal processing ABSTRACT

The progress of ground radar from the early British experiments of 1934 to the close of the Second World War is briefly reviewed. The disturbed political situation of the post war world ensured that substantial resources were still applied to defence research, and progress in radar engineering was correspondingly rapid. Developments achieved during this period in methods of generating and receiving microwave signals are considered. Special interest attaches to the plan-position indicator (p.p.i.) as the interface between the controller and the radar 'machine'; the evolution is traced of p.p.i.-based methods of displaying radar data and the associated procedural information. In recent years, substantial advances in electronic units have been made possible by the use of solid-state integrated circuits stemming from the transistor invented by the Bell Laboratories in 1948. Solid-state devices have greatly influenced the design of radar transmitters and receivers, and have also permitted a new approach to the electronically scanned aerial; but it is in the field of digital processing of radar signals that integrated circuits have revolutionised both the function and form of radar equipment. The address discusses these developments and assesses the prospect for future progress in radar engineering as a whole.

### INTRODUCTION

In the course of evolution, various forms of life, both fauna and flora, have developed means of probing an unfriendly environment to ensure their survival, whether to avoid a predator or to secure food for themselves. Such probing devices are appropriately termed 'sensors'. They may be responsive to mechanical pressure, as in the mimosa leaf, or chemical, as when the lion scents its prey. Animals in the wild are sensitive to sound; they are responsive to heat (as the French proverb assures us: 'chat echaude a peur du feu'); and light from the rising Sun disperses starlings from their roosts.

We note that these sensors are mostly passive, i.e. they accept energy from the stimulus in order to produce the protective reaction, but, in some species, nature provides an active signalling system whereby a member becomes a transmitter of energy as well as a receiver, for in this way the survival of the individual or the species may be better secured. Examples of optical signallers are the glow-worm and the firefly; acoustic signalling is used by dogs and dolphins. Smell is used actively in the musk deer, and identification of bees in a hive is achieved by an ephemeron, or chemical secretion, of the queen.

Clearly, success in the evolutionary race is likely for any organism that possesses high mobility guided by a useful armoury of active and passive sensors. Ancient man knew nothing of the theory of evolution, but he was interested in augmenting his natural senses by aids which would help him in the eternal struggle with the environment. It was for this reason that the Greeks were grateful to Prometheus, who stole the heavenly fire and placed it at the service of man.

This ability to produce artificial light was a powerful increase of man's capability, but emission of energy involves risks as well as conferring advantages!

We know that much bird song is for the purpose of preserving a breeding territory, or for a warning to predators. It was not primarily intended to stimulate a Shelley or a Keats to a lyrical outpouring. But the bird employs song to its own peril, for an overenthusiastic response to the trills of Papageno's pipe may lead it into the confines of his cage. Among nature's creatures, the bat species is the one that seems to have mastered best the technique of emitting sounds of a very special type, to use the echo for avoiding obstacles in its flight path or for locating the moths or other insects on which it preys. Although man discovered long ago how to produce light, it is only recently that he has developed sources that enable objects to be located in range as well as in bearing, as does the bat by its acoustic transmitter and receiver.

We have, in fact, to move to the end of the sixteenth century before man gave thought to the possibility that light did not pass from place to place instantaneously, but had a finite velocity. You will remember that Puck was able to put a girdle round the earth in 40 min, but Galileo was more of an experimentalist than Shakespeare, and even tried to measure the speed of light. This he did by signalling with a bull's-eye lantern to a second observer on a local hilltop, who, on receipt of the flash, opened his own lantern, thus permitting Galileo to measure, with his newly discovered pendulum, the lapsed time for the double journey. Galileo had a genius for simple experiment, but, on this occasion, his instruments were just not good enough to achieve the success he obtained in the weight-dropping test he performed at Pisa (repeated even more

spectacularly on the Moon by the Apollo 15 crew).

Galileo is commemorated by a very simple cryptographic plaque in Santa Croce Church in Florence, but this memorial reminds us of the elegant method used by the Danish astronomer Römer 80 years later to measure the velocity of light. He had the ingenious idea of using as his clock the circulation of Jupiter's satellites, while the racetrack was the diameter of the Earth's orbit. He obtained a value surprisingly close to the modern accepted figure of 300 000 km/s. The velocity of light  $c$  is one of the basic constants of the universe, and much effort has been devoted to its accurate determination. The first successful terrestrial measurement of  $c$  was made by Fizeau in 1849, and his method illustrates the principles of location by means of radiation, which is my real theme in this address

Fizeau used a rotating toothed wheel to chop a light beam into a sequence of short pulses which travelled over a distance of 8.6 km to a mirror to be reflected back to the wheel (Fig. 1). The image of the source could be observed through an eyepiece. It will be seen that, if the wheel were speeded up so that the reflected pulse met a tooth instead of the aperture through which it passed on its outward journey, the image of the source would disappear. We know that the light has travelled twice the distance of the mirror, and, by measuring the speed of rotation of the wheel, we obtain the time taken for the pulse to make the round trip.

Knowing the velocity of light, we may deduce the distance of an object by measuring the time taken for a pulse of light to travel from the source to the object in space and back again to the observer. To build such a light-ranging system, it is necessary to develop methods of generating short intense pulses of light, as well as techniques for receiving and detecting such pulses and measuring the very small intervals of time taken for the round trip. It should be remembered that an object 150 km away will return a signal to the source in  $(2 \times 150)/300\,000$  s, i.e. 1 ms. It was not until the development of radio in the first quarter of the present century, and the electronic techniques that stemmed from it, that instruments could be produced capable of measuring these small intervals of time, or of receiving and amplifying the extremely feeble optical signals scattered from a distant object.

### LIGHT DETECTION AND RANGING (LIDAR)

Modern studies in solid-state physics have replaced Galileo's lantern with an extremely powerful source of light in the form of the laser. The ruby laser permits us to produce short pulses of light of only a few nanoseconds duration, which, as shown in Fig. 2, travel from the tube as a rod of light only a few feet in length. Because the light is coherent, it can be focused into a very narrow beam which is almost perfectly parallel. In the Apollo Moon-ranging experiment, the focusing of the light was performed by the Lick telescope, and this produced a circle of illumination on the Moon's surface less than 16 km in diameter, within which lay the reflector left by the first astronauts. This device was made up of an array of 'cats' eyes' or corner reflectors similar to those used on roads. The beam of light from the ruby laser was reflected back to the Earth to be collected by a telescope and detected using a very sensitive photomultiplier similar to that which forms the basis of a modern television camera.

Since the firing of the laser was controlled by a pulse, as in Fig. 2, and the received signal could similarly be observed as a pulse some  $2\frac{1}{2}$  s later, it was possible, by means of modern electronic timing instruments, to measure the total transit time of the signal within one part in  $2.5 \times 10^9$ . This meant that the one-way distance from the Earth to the Moon could be measured within 15 cm in a total distance of  $3.7 \times 10^{10}$  cm.

This precise measurement of the Moon's distance and the study of its minute variations are leading to a more accurate dynamical formulation of the Earth/Sun/Moon system, and forms the most spectacular application which has been made so far of lidar techniques. Other interesting examples are to be found in geophysics, where lidar equipment is being used to measure the rate of separation of the American and European tectonic plates at their point of contact in Iceland.

Fig. 2 indicates that the essential elements of such a lidar ranging system are precisely those contained in Fizeau's experiment and consist of:

- (a) a transmitter to generate short, intense optical pulses
- (b) a mirror or lens to focus the light on a target, as in the searchlight of lighthouse—this also provides direction
- (c) a mirror system to collect the scattered signal
- (d) a very sensitive photoelectronic amplifier coupled to the receiver telescope
- (e) an accurate means of measuring the round-trip transit time of the signal to derive the range.

These components are also required in the system of detection and ranging using radio waves instead of optical waves.

### RADIOLOCATION (RADAR)

The method of optical detection and ranging which I have outlined was not available in the 1930s when the rise of Hitler to power posed such a threat to the peace of Europe that the British Government decided to modernise the country's defences, particularly against air attack. Sound-ranging devices had been used to locate guns in the First World War, and acoustic techniques had been further developed in the 1920s for the detection of aircraft, and for the pointing of searchlights as a preliminary to engagement with antiaircraft guns. By the 1930s, it had been realised that developments in aeronautics since the First World War had made the bomber a major military threat, and that former methods of dealing with them were inadequate.

It should be remembered that the work of Maxwell in 1865 and Hertz in 1887 has shown that light and radio are composed of electromagnetic waves which travel through space with the same velocity  $c$ , but which possess different wavelengths. Radio waves were developed into practical signalling systems at the turn of the century by men such as Sir Oliver Lodge and Marconi, and, following the perfecting of the thermionic valve derived from the Fleming diode of 1904 and the deForest triode of 1906, commercial broadcasting and radiocommunication were in everyday use all over the world by the 1920s. In 1922, the British Broadcasting Company was born, and two years later Appleton and Barnett measured the height of the ionosphere using the reflection of f.m. radio waves; in the same year, Breit and Tuve used radio pulses for the same purpose. The British Empire communication service became operational in 1927, and in 1936 the television service transmitting at 45 MHz was set up in the UK.

Fig 1

Fizeau's method for measuring the velocity of a light pulse

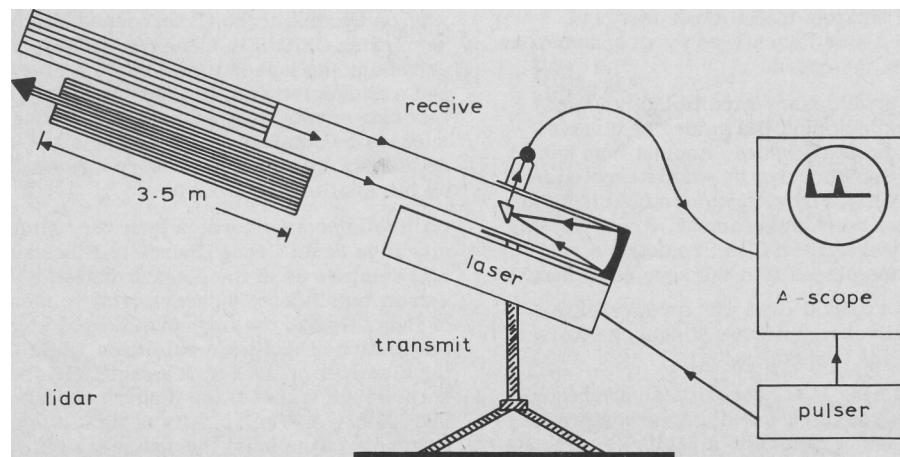
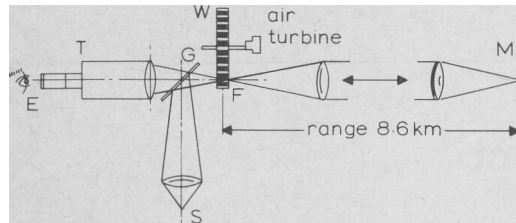


Fig. 2

Measuring the distance to the Moon by lidar

These developments in high-power radio suggested that it might be possible to launch very powerful radio beams against enemy aircraft, possibly to interfere with the electrical ignition system. This proposal was examined by Sir Robert Watson-Watt and his colleagues in 1934, but they decided that, although 'radio death rays' were not yet with us, there was a real possibility that a distant aeroplane could be detected by illuminating it with a radio beam and receiving the waves scattered from it.

It was soon established, in 1935, that radio waves emitted from the Daventry station were, indeed, reflected from aircraft and produced a radio echo which, after amplification, could be presented on a cathode-ray oscilloscope. Intensive development of practical radiolocation systems for British air defence then commenced under a heavy cloak of military secrecy.

Progress was rapid, and in 1937 a series of radio sentinels were deployed around the coast of Great Britain to form the Home Chain. These stations operated in the 20-30 MHz band. The transmitter aerial consisted of a stack of dipoles on towers 110 m high, the purpose of which was to concentrate the radiation to angles of elevation below  $10^\circ$ , while providing azimuth coverage over an arc of  $150^\circ$  which extended out to sea. An aircraft within this floodlit region, when struck by the radio pulse from the transmitter, produced a scattered train of waves which were collected by the receiver aerial mounted on a 73 m wooden tower.

Fig. 3 indicates how the receiver fed the amplified signal to a cathode-ray tube. The timebase of this 'A-scope' was triggered in synchronism with the transmitter, so that the time taken for a signal to travel from the transmitter aerial to the aircraft and back to the receiver could be measured. Such a station provided accurate information on range, but rather inaccurate information on bearing and altitude because of the use of the goniometer method of comparing the signals picked up by the dipoles.

It will be seen that the whole system formed a radio direction-finding device, and, for this reason, the stations termed 'r.d.f. stations'. At a later date, the British name was dropped and the American acronym RADAR was adopted as more indicative of the true function of radar, i.e. radio detection and ranging.

Among the information passed by the operator at a radar station to the central operations room was included an identification of the target as friend or foe (i.f.f.). The signal from the ground transmitter received in a friendly aircraft was amplified and retransmitted so that an identification signal was superimposed on the skin echo from the aircraft. This system of identification worked quite well during the Battle of Britain, but more elaborate methods were needed for radars operating at higher frequencies; in fact, only a partial solution to the identification problem was obtained during the Second World War, and we have still not obtained the perfect method. Interrogation for identification is now

performed on a radio channel separate from the primary radar. This system is referred to as 'secondary surveillance radar'. It is, in fact, a beacon system which can also be used as a digital data link to relay altimeter information to the ground, and now forms an essential component of the civil air-traffic-control system.

Fig 3

A home chain (CH) radar station with separate transmit and receive aerials

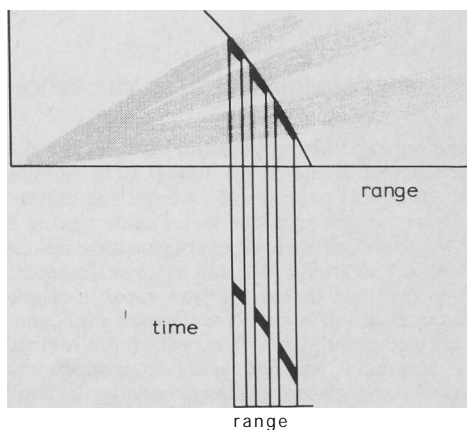
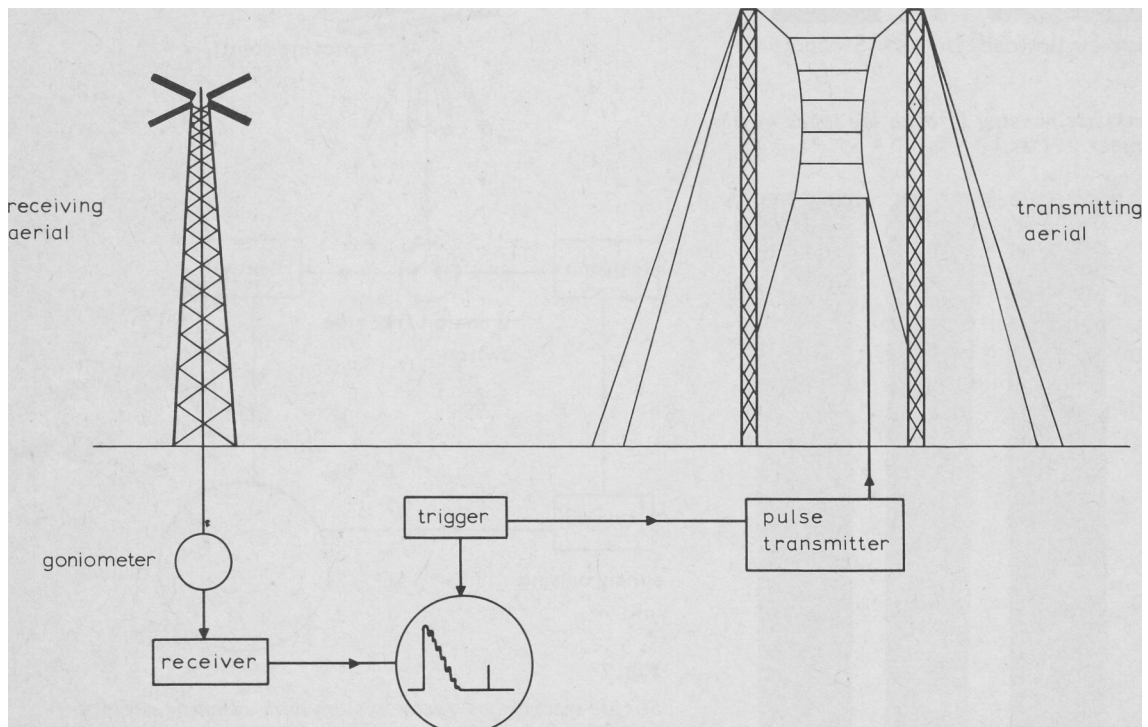


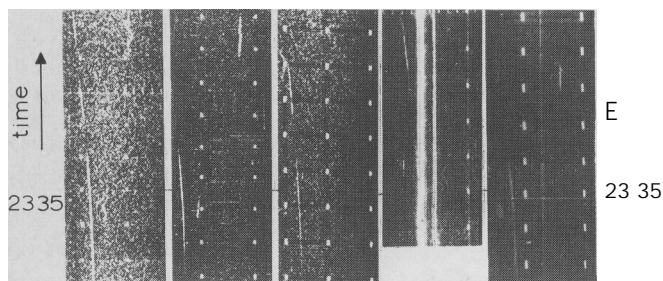
Fig. 4

Aerial lobes of CH station with trajectory of V2 missile

Although the first radar chain will always be remembered for its vital role in the Battle of Britain, it also made a major contribution during the V2 rocket attacks on London during late 1944 and early 1945. Immediate warning of the launch of a V2 rocket from a remote Continental site was provided on a special display, and, by photographic recording, it was possible to determine the point of projection of the rocket (Figs. 4 and 5). One interesting by product of this technique was the discovery that the radar was also recording the arrival of meteors into the Earth's atmosphere

(Fig. 6). Such meteoric particles are volatilised by the intense heat created when they enter the atmosphere; radio reflection takes place from the line of ions and electrons thus created. This process also occurs on re-entry of the Apollo vehicles, when communication is interrupted because the radio aerial is shielded by the conducting sheath of gas boiled off from the heat shield.

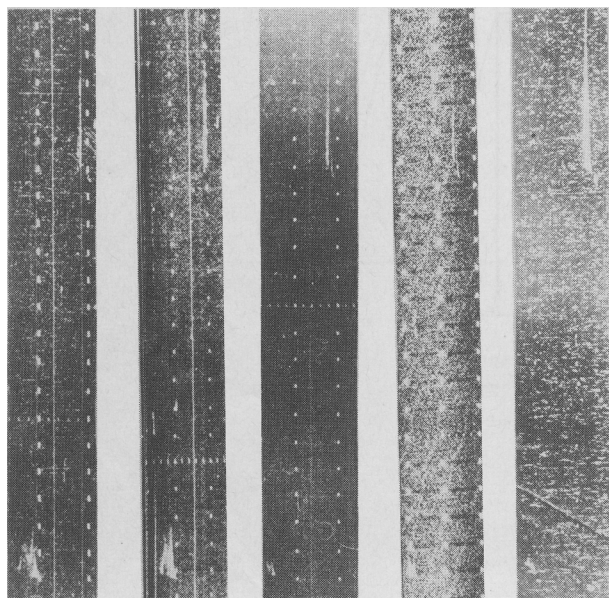




High Street Bromley Bawdsey Dunkirk Swingate

Fig. 5

*Radar record of V2 missile passing through the lobes of five radar stations (November 1944)*



High Street Bromley Bawdsey

Dunkirk Swingate

Fig. 6

*Radar reflections from meteor trails as recorded simultaneously at five CH stations*

## RADAR DEVELOPMENTS DURING THE SECOND WORLD WAR

It seems appropriate to give the story of the development and deployment of the 'chain home' (CH) radars in some detail, but time will permit only a brief indication of the many other radar advances which were made during the Second World War to cope with an ever-changing operational situation. The c.h. stations fulfilled a surveillance role, but it was soon realised that radar was capable of providing tactical support to anti-aircraft and naval guns, and also to the detection and acquisition of targets from aircraft. To fulfil these functions, it was necessary to produce equipment that possessed the necessary power, sensitivity and resolution, but in mobile form. Clearly, high angular resolution can only be obtained if the probing beam is very narrow, and this requires the use of a wavelength very short in relation to the available aperture. The story of radar during the Second World War is therefore concerned with the development of radio-frequency generators that would produce high pulse power at wavelengths considerably shorter than the 13 m of the c.h. radar.

Conventional triodes were soon developed to produce power at wavelengths of 1.5 m, and later at 50 cm, but the most significant advance was the development of the cavity magnetron which delivered pulses of 500 kW at a wavelength of 10 cm. Such short wavelengths permitted aerials to be built that were, indeed, radio searchlights, in that a very sharp beam could be produced which could be swept over the sky in lighthouse fashion. As the beam illuminated an aircraft, the echo signal was received by the same antenna; in other words, by an ingenious switching arrangement, the same aerial could be connected to the transmitter and receiver in succession. When it is remembered that a transmitter may be radiating in the order of  $10^6$  W and the receiver is sensitive to  $10^{-14}$  W i.e. a ratio of  $10^{20}$ , it will be seen that the protective duty which the transmit/receive switch has to fulfil is very onerous indeed (Fig. 7).

Fig. 7

*Simple microwave radar system with common aerial for transmit and receive*

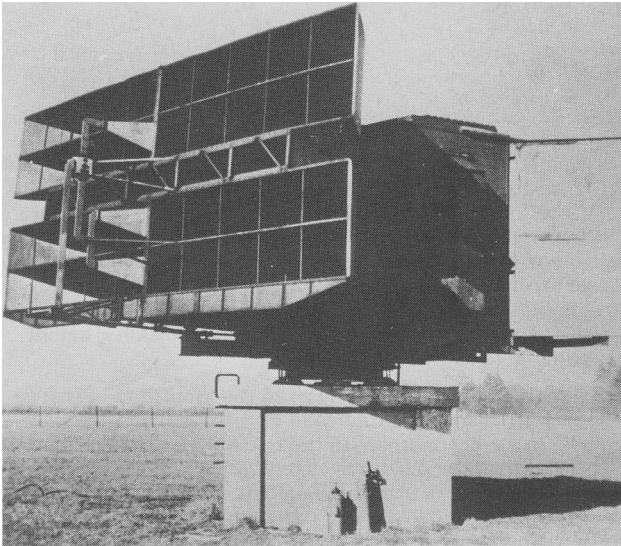
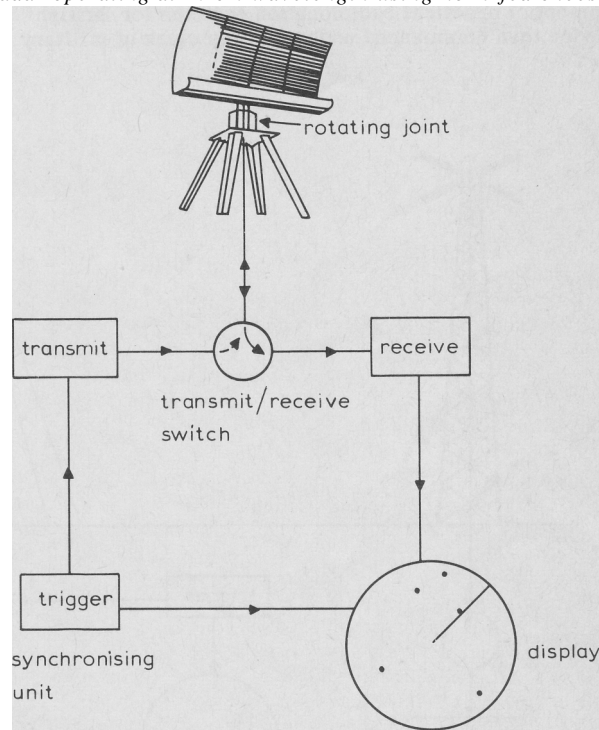


Fig. 8

*Wartime fixed-location scanning radar operating at 10 cm wavelength using horn-fed cheese aerials for surveillance*



The signals from such a microwave ground radar were displayed on the 'plan position indicator', which was a cathode-ray tube in which a radial time base was rotated about the centre of the tube in synchronism with the rotation of the aerial; in this way, the aircraft echoes were shown in their correct relative plan positions. The common transmit and receive principle, the plan position indicator and the cavity magnetron were probably the most significant advances in radar techniques made during the whole of the war.

It is a curious fact that the invention of the magnetron as a high-power generator of centimetre waves was not matched by a receiver tube. It was necessary to resort to a method of reception used in the early days of broadcasting; i.e. the signal was applied through a 'cat's whisker' to a germanium or silicon crystal, together with a signal from a klystron oscillator. The nonlinear characteristic of the crystal produced a heterodyne or difference frequency, usually at 45 MHz; this signal was amplified and ultimately detected to provide the video drive to the p.p.i. Receivers for this frequency had been produced for the television service started in 1936.

The operational triumph of centimetric radar was complete; here I would only comment that such compact radars added further power to the air-interception capability of the night fighters and to the ground equipment that controlled them (Fig. 8).

## RADAR PROBLEMS, 1945

Although the engineers and physicists of both Government and industrial laboratories could take pride in their wartime achievements, they were also well aware of the deficiencies in performance of the various radar systems they had created. There was need to extend the detection range by increasing the transmitter power and reducing the receiver noise factor. Accurate tracking required improved azimuthal resolving power, i.e. better mechanical design of wide-aperture aerials.

Detection and tracking with a surveillance ground radar are both impeded by the echoes which arise from extended scatterers such as the ground, rain clouds or flocks of birds ('angels'). Clutter obscuration of this type can be reduced by appropriate shaping of the antenna beam and control of sidelobes. The visibility of a target in residual clutter, however, can only be enhanced by application of the Doppler principle, which required the development of moving-target indicating systems and components such as 'delay lines'. Better display of radar data was required, as was the provision of aids which would help the operator with the tracking of targets and the controller in the execution of his airspace- management function.

Even this short list of operational deficiencies presented the radar designer of 1945 with a formidable challenge. The resources to execute the required research and development programme would hardly have been forthcoming from the civil authorities interested only in radar for air-traffic control or commercial maritime purposes. In the event, it was the onset of the 'cold war' that caused even greater resources to be applied to radar than had been available during the war to create and control the radars, guided missiles and, ultimately, satellites, which were regarded as necessary to contain the nuclear threat so starkly revealed by the abrupt ending of the Japanese war.

Perhaps the military scientists of the early postwar world were too optimistic in assuming that radars could be developed which would be impervious to enemy jamming and yet provide comprehensive cover, so that no aircraft could escape detection. During the Second World War, time did not permit deep theoretical studies to be made of the radar process, but, in the 1950s, very careful analysis was made of the factors which influenced the detection of reflected signals from a target, whether that signal was of the pulse type or of continuous waveform. Dr. Woodward's theoretical group at the UK Royal Radar Establishment were among the leaders in this kind of study, and they have provided very valuable guides to those responsible for the development of radar equipments to satisfy military objectives. The work of the theoreticians has emphasised the statistical nature of the receiving process, and has shown how a compromise has to be struck between the possibility of failing to detect targets in noise and clutter and the other possibility of creating equipment so sensitive that too many false alarms are caused because the statistical grouping of the noise peaks can cause transient simulation of a real target.

This work has drawn attention to the important part which the transmitted waveform can play in the total performance of the radar system. The simple detection of the target can best be performed by a continuous waveform which can lead to a clear unambiguous Doppler signal, but this method does not yield range information unless some type of modulation is imposed on the wave; neither is it applicable to a large number of targets. The simple pulse system as used in the original CH is ideal for multiple targets, and supplies range information, but no use is made of the Doppler-frequency change produced by the velocity of the target. The compromise at present made is to use a mix, as it were, of the two states, with the pulse providing range and the Doppler effect permitting rejection of fixed clutter, together with information about the nature of the target.

It almost appeared at one stage as if it might be possible to adjust the waveform transmitted so that the maximum probability of detection of a target could be secured in any region of clutter, whether produced by the ground or produced from precipitation. This hope has not materialised; neither can it be claimed that this theoretical work has revolutionised the aims of radar development, but it has certainly provided a background of understanding which has permitted such developments to take place more intelligently. It has also performed the very useful function of preventing wasted effort directed towards the achievement of technical objectives incompatible with the basic physics of the situation.

A rough analysis of the distribution of costs between the various parts of a radar system suggests that the transmitter/receiver section accounts for some 40% of the total. What is more, this is the part of the equipment which absorbs the electrical energy from the public supply, and there is therefore a need that it should be efficient in its utilisation of that power. It also contains the very expensive r.f. valve which calls for replacement from time to time. It is thus not unreasonable that the bulk of the development effort devoted to radar since the Second World War should have been applied to improving the existing r.f. generators and devising new ones. The objective has been to create tubes capable of producing very high pulse power free from noise and jitter which would be electrically efficient and possess long life.

## THE MAGNETRON

It is interesting to recall that, even in 1924, research was in progress in a number of countries on devices making use of the electron-transit-time effect for the generation of high- frequency energy. It was well known that energy exchange could take place between an electron beam and successive r.f. fields produced by a multigap anode of a magnetron diode oscillator. Understanding of this process was greatly helped by the travelling-wave hypothesis of Postumus, and led Megaw and Gutton to the idea that a multigap system, with a cathode of diameter about half that of the enveloping anode, could be the basis for a high-power pulse valve for short wavelengths. The chief limitation of this form of r.f. generator was the low power dissipation of the multigap circuit, which had developed from the split-anode arrangement used successfully at longer wavelengths. This limitation was removed by Randall and Boot in 1940 by the invention of the block anode containing many high-Q factor resonators, which immediately produced 400 W at 10 cm wavelength, using only a small-diameter tungsten cathode.

By improved constructional technology and the embodiment of the large oxide cathode, established by earlier French work, the valve engineers of 1940 raised the power to 100 kW. Subsequent addition of Sayers's straps to ensure correct relative phasing of the gap voltages, produced by the separate resonators, resulted in further improvement in power, efficiency and stability of operation. The production version of the 10 cm valve was the CV 76, shown in Fig.9, which produced about 500 kW of S band power at a pulse duration of 2  $\mu$ s. It was this valve that was used in the various wartime ground radars.

Intense development of the magnetron has taken place since the Second World War, the first objective being increased

power output. The second tube, shown in Fig. 9 for comparison with the CV 76, is capable of 2 MW of peak power at 0.1% duty cycle at the same wavelength of 10 cm. In all the early applications of the magnetron, it was used as a fixed-frequency self oscillator, but many radar operations now require a tunable generator (Fig. 10). One method of tuning uses multiple plungers operated electromechanically. Frequency stability is secured by careful temperature control through vapour cooling, and this also removes microphony effects; in consequence, good moving-target indication (m.t.i.) performance is possible, and so the magnetron remains the preferred tube for mobile radar equipment.

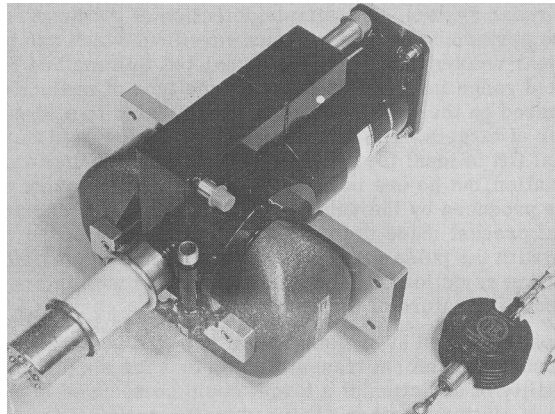


Fig. 9

[English Electric Valve Co.]

*S band magnetron CV 76 as used in wartime ground radars and modern magnetron for the same waveband*

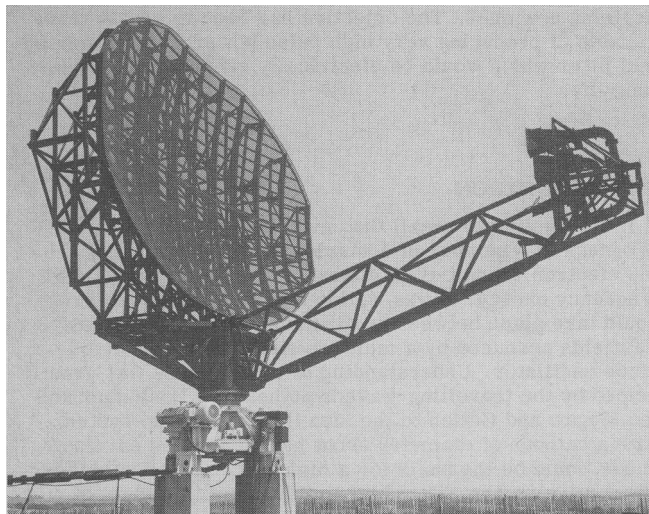


Fig. 10

*Modern L band radar for air-traffic control using tunable magnetron and digital m.t.i.*

#### THE CROSSED-FIELD AMPLIFIER

The magnetron is a crossed-field device, in that the magnetic field is orthogonal to the applied electric field. The interaction between the electron beam and the r.f. wave provides high power with high efficiency in a relatively small volume, and so it is attractive to apply the same process in an amplifier.

There are now a number of variants of such devices known collectively as crossed-field amplifiers, but so far the gain has been less than 20 dB, while the self-generated noise is high, which is not good in a coherent amplifier intended for use in a Doppler radar. The crossed-field amplifier is subject to spurious semicoherent noise arising from fast-wave interactions, and methods of reducing this noise are being investigated. Typical performance of an S band tube is 1 MW of peak power with an efficiency of 50%, but the gain is unlikely to match that provided by linear-beam tubes.

#### LINEAR-BEAM TUBES

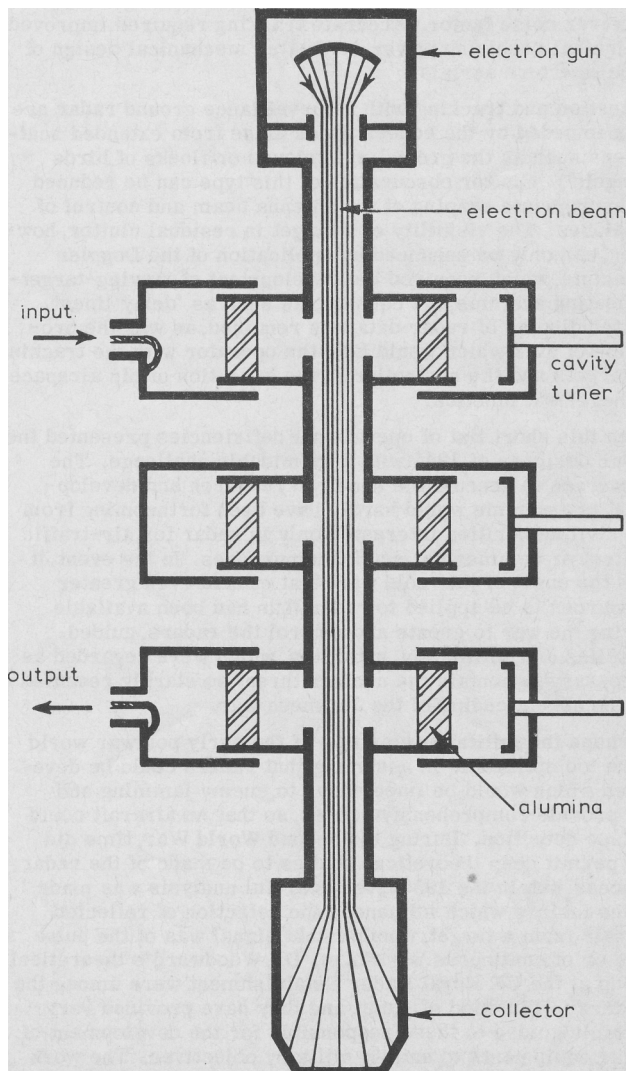
There is a second family of r.f. generators described as 'linear-beam tubes', in which the magnetic field is directed axially along the path of the electron beam and parallel to the electric field. Members of this family are the klystron and the travelling-wave tube. The electrons acquire full energy from the d.c. field before entering the interaction region where the r.f. field from the input signal produces velocity modulation of the beam. The bunched electrons pass down the drift tube, and the bunches give energy to the output circuit in the form of an amplified version of the input signal. In this process, the electrons are slowed down and finally gathered by a collector (Fig. 11).

The first successful generator of microwave power was the low-power reflex klystron, which found widespread application as the local oscillator in microwave radars. A high-power version of the klystron was not developed during the war

because of the success of the magnetron, but, after 1945, there was a need for a power amplifier at microwave frequencies for use not only in coherent radar but also for other purposes. Indeed, the first successful tube was that produced by the Stanford Research Institute for use in a linear accelerator.

The great advantage of the klystron is that the high power output is coherent with the low-level drive signal. This means that the frequencies of all returned echoes may be compared with the crystal-controlled frequency of the drive,

Fig. 11 Arrangement of cavities in a klystron radar amplifier



and those echoes which do not show a Doppler displacement of frequency can be rejected. In this way, the echoes from fixed targets are prevented from cluttering the display and obscuring the moving aircraft targets (m.t.i.). Equally important is the application of the coherent amplifier to pulse compression. If a frequency-modulated drive pulse is employed, the passage of the echo pulse through a dispersive line produces compression. In this way, short-pulse range resolution may be obtained from a long transmitter pulse, which eases the peak-power-handling problem.

Magnetically focused multicavity klystrons have now been developed which have gains of 50 dB or more and pulse outputs of many megawatts. The bandwidth is of the order of 1-3%, dependent on power levels, and efficiencies of about 40% are achievable at S band. In view of the high gain of this tube, it is now possible to employ a solid-state source as the drive. Future development will seek to reduce noise, especially that caused by positive ions trapped in the beam, and to improve the linearity of response to input modulation



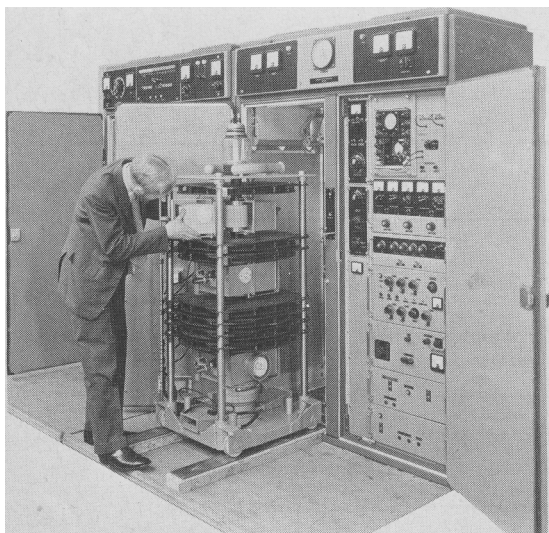
**Fig. 12**

[English Electric Valve Co.]

Comparison showing K347 radar amplifier klystron (50 cm) and K300 and K302 oscillator klystrons (X band)

Coherent amplification is also obtained in the power travelling-wave tube (t.w.t.), which differs from the klystron in that the resonant cavities are replaced by a wave-guiding structure which is continuous from the input to the output terminals, except for one or two short attenuator sections or 'severs'. Such a slow-wave structure provides a wider bandwidth than the klystron. Perhaps the largest t.w.t. yet built was the VX 526 designed by SERL for the RRE/Marconi antiballistic-missile radar; this transmitter produced 100 MW of pulse power at a frequency of 450 MHz, and, by frequency modulation of a  $4\mu\text{s}$  pulse, it was possible to achieve compression to  $0.1\mu\text{s}$ .

It will be seen that the radar designer has no lack of r.f. generators from which to choose. The increasing emphasis placed on the removal of clutter from the system has caused the coherent amplifier to be favoured in many operational



**Fig. 13**

[Marconi Co.]

Klystron transmitter for coherent 50 cm m.t.i. radar at Heathrow Airport

situations. The British airways, for example, are monitored by a chain of 50 cm scanning radars which utilise a high-power klystron as a power unit (Figs. 12 and 13). Such a radar is of little value to the military authorities, since a beamwidth of  $2^\circ$  makes it vulnerable to jamming, but as a civil equipment it is almost ideal. Its advantages are reliability and long tube life; full coherence facilitates Doppler elimination of ground clutter, and long wavelength reduces rain returns and provides consistent aircraft echoes ideally suited for automatic extraction and tracking by a digital processor (Fig. 14).



**Fig. 14**

#### **SOLID-STATE DEVICES IN TRANSMITTERS/RECEIVERS**

The most important event of the postwar period of radar development was the invention of the transistor by the Bell Laboratories in 1948, and the creation of the semiconductor industry to provide the devices on which modern electronics is based.

The contribution which modern solid-state devices make to the radar receiver is very great. Second World War S band radars used a superheterodyne receiver having a noise factor of about 18 dB; present equipment using a Schottky-barrier mixer diode has a noise factor of 5.3 dB at S or L band. Fig. 16 illustrates the progress over all wavebands which has been made in the noise factors of such mixers during the last 20 years. It now appears likely that application of the image-recovery technique will permit effective noise factors of 3.5 dB, thus lowering the theoretical limit from 4.5 dB for the image-matched condition shown.

A transistor receiver can yield 25 dB at L band, and approximates, in performance, to a parametric amplifier based on a varactor diode, a device which is more complicated in its supporting circuitry.

Although solid-state devices found ready acceptance in the receiver, their limited power-handling capacity seemed to preclude their use in the transmitter. Improvement in materials and processing techniques have now produced silicon controlled rectifiers (thyristors) that permit wholly solid-state modulators to be built for magnetron transmitters—with corresponding advantages of compactness and lightness for mobile radars.

1 kW is possible from a single L band device so that it is now feasible to design active-aerial radars in which the transmitted beam is produced from a matrix of radiators each driven by a solid-state source. An assembly of 1000 such elements could yield 1 MW of pulse power at L band, comparable with an ordinary single-tube generator, and such an active array offers the advantage of beam steering by electronic scanning. In this way, dwell time on a particular target can be increased, height finding is facilitated and catastrophic failure of the radar by loss of a single r.f. tube can be avoided. A new type of solid-state power amplifier may soon be available if present experiments on hybrid electron-beam/semiconductor devices are successful.

#### **ADVANCES IN TECHNIQUES FOR DISPLAY AND PROCESSING OF RADAR SIGNALS**

The p.p.i. was primarily intended to show aircraft in their geographic locations, but this device also contributes to the target-detection process. An operator has to associate the successive 'paints' from a target to form a track. He is assisted in this process by the use of a phosphor whose light emission decays gradually after excitation, in contrast to a television tube where instantaneous decay is required to avoid 'sticking images'. Thus the p.p.i. phosphor functions as an energy store, and integration occurs of the successive pulses received from a target during the passage of the aerial beam over it. In this way, the probability of detecting the target is increased—at the expense of confusing the two functions of signal storage and display!

In the 1950s, the p.p.i. was greatly improved by the introduction of magnesium fluoride as a phosphor possessing good integration capability. The electron optics were simultaneously refined so that a spot size of 0.25 mm was produced to match the aerial beamwidths of less than 1° which characterised the new ground radars. At the same time, the rotating-coil method of

turning the p.p.i. timebase in synchronism with the aerial was replaced by fixed coils fed with appropriately varying currents, an engineering development which not only facilitated the coupling of large numbers of displays to a single aerial, but also allowed tracking aids for the operator to be provided on the p.p.i.

These marker signals were written during the intertrace period, and could be used by the operator to track particular echoes or to mark such echoes on other displays. 'Cunning' circuitry was developed so that a marker followed a target automatically, giving a so-called 'track-while-scan' facility. This freed the operator to watch for new targets. Alternatively, the marker could be 'rate-aided', i.e. given a velocity across the tube to match that of the echo. Elaboration of these analogue-circuit techniques resulted in the 'labelled plan display' in which selected targets could have associated with them labels of defining symbols which accompanied the targets in their passage across the tube. In other words, gradual improvement in the electronics associated with the p.p.i. had made it a very flexible tool to help the controller. Unfortunately, the data which could be displayed in this manner were limited by the small time available between the end of the radar trace and the next pulse of the transmitter. Buying time by the expedient of stealing radar traces at random was only a partial solution to the symbol-writing problem.

It will be seen that the p.p.i. is a vital interface between the man and the machine which is the radar system as a whole. We wish to present both radar and flight plan information to the controller, so that efficient management of the airspace can be possible, but it can be questioned whether the p.p.i. is ideal for the simultaneous display of both classes of data. The confusion between display and storage which I have already commented on is aggravated by the fact that the sequence of echo signals offered to the p.p.i. is locked in time to the initiation of the radar pulse itself and to its physical translation through space.

If the interlocking of these functions of display, storage and real-time sequencing could be avoided, a form of display could be devised which would match more truly the needs of the operator. The solution to this problem was to devise an electronic buffer store for the radar signals; this is just what modern transistors and integrated circuits have made possible. By means of extraction processors, we are able to detect the presence of an aircraft target and to encode the parameters of the radar signal, i.e. amplitude, range and bearing, into digital form for immediate storage and subsequent display or processing. Active semiconductor elements of the m.o.s. type assembled into compact, addressable stores, hold these packages of binary bits, so that it is no longer necessary to present in real time the sequence of signals that compose a 'raw radar' trace on the p.p.i. Instead, the extracted plots may be displayed on a synthetic display at a rate and time which is most convenient. The intermediate electronic store confers flexibility; e.g. high brightness may be obtained by repetitive scanning, or, as for a short-range marine radar, by presenting the radar trace at reduced speed.

Recent advances in cathode-ray tubes and solid-state-circuit techniques, coupled with the use of highly reproducible deflection coils of the printed-circuit type, have now substantially reduced, from 100  $\mu$ s to 15  $\mu$ s, the time taken to move the cathode-ray beam across the tube. Similarly, the writing time for a character has been reduced to 5  $\mu$ s. These improvements in display technology mean that characters, maps and other data may be displayed in association with raw radar without loss of radar information. The use of extracted or synthetic radar plots from the store enhances still further the ancillary data which can be presented. In addition, registration on the tube between the different types of data is preserved, since all switching can be performed digitally while constant writing speed is preserved, i.e. constant brightness irrespective of picture expansion.

The fact that the information is held in store in 'bits', and that the input to the c.r.t. brightup and deflection circuits consists of binary bit trains, suggests that the display itself should be digital. Modern digital-compatible displays have a timebase waveform which is of the 'staircase' type, in which the time steps correspond to the successive range intervals within which the automatic plot extractor looks for targets. In an m.t.i. radar, this digitising and electronic storage of the range/amplitude information has the great advantage that comparison of consecutive returns from fixed targets may be achieved even with a varying interpulse period, i.e. the pulse-recurrence frequency need not be constant, so that loss of echoes owing to blind speeds can be largely obviated.

## CHARGING THE STORE

### Automatic target detection, plot extraction and tracking

How is the store charged with radar data? The output from the radar receiver has an amplitude which varies continuously with time. This signal is composed of noise having characteristics determined by the bandwidth of the receiver chain, together with echoes from aircraft which may be described as distorted versions of the r.f. pulse originally radiated by the transmitter, combined with varying amounts of energy reflected from the ground, rain clouds, birds etc., which we loosely describe as clutter (Fig. 19). This mass of signals is normally presented on the p.p.i. to form a pattern by which the operator is able to supplement his initial judgment of which paints are true targets, by noting the subsequent history of the various signals as they appear on the tube with each successive revolution of the aerial. Noise paints come and go, but the aircraft signals gradually build up to form clearly defined tracks. It is this kind of discrimination that we wish our electronic boxes to perform automatically to produce characterisation of the signals which is at least as good as that of the best operator working under ideal conditions and without fatigue; i.e. the boxes have to perform automatically the functions of target recognition, plot extraction and storage, followed by association of plots into tracks.

The sequence of radar signals is first sampled for amplitude during successive short time intervals corresponding to range increments of 250 m. The amplitude above the noise threshold is expressed as a binary number, while the threshold itself is determined by the false-alarm rate measured in an echo free region. For each trace, a cascade of bits relating to possible echoes is poured into the plot extractor, each sample containing amplitude and range, and the problem is to decide which are true targets and which are 'false alarms' produced by noise or clutter. It would obviously be extremely difficult for a decision to be made from one sample only, but, when the radar beam sweeps over an aircraft, each successive pulse from the radar produces a reflected echo, and so the processor has to take into account a group of pulses at the same range whose number and relative amplitudes depend on the horizontal polar diagram of the radar, the speed of rotation of the aerial, the pulse-recurrence frequency and the instantaneous echoing area presented by the target. If, in accordance with the selected criteria, a target is confirmed, the azimuth is calculated and the plot (r,  $\bullet$ ) in digital form is fed into the track computer either locally or via a narrowband link.



This process of automatic recognition, followed by plot extraction, is a very subtle one; the dilemma which faces the operator of balancing 'false alarms' against 'missed targets' also faces the computer, but, remembering the value which the operator derives from his ability to see the time development of a track on the face of the c.r.t., it is better to favour the false alarm rather than the missed target, leaving to the subsequent tracking process the rejection of those plots that fail to return a track. The tracking computer compares this totality of stored plots with existing tracks and assigns plots to them (automated track development) or creates new tracks (automatic track initiation) (Fig. 20).

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#### **CLUTTER VERSUS AUTOMATIC RADAR**

The desirable objective is to eliminate the operator and yet to remain confident that all aircraft have been detected. If we were always dealing with echoes in the clear having high signal/noise ratios, i.e. if we could ensure that clutter were removed from the system, the problem would be easy, but it is the statistical nature of the total radar signal that prevents this essential simplification. The emphasis of modern radar research is on digital processing of this complex radar signal, with the aim of extracting the aircraft echo from the clutter. Variable noise/clutter threshold levels, correlation and other methods applied through the computer are under examination, but equally important is the reduction of clutter by improved m.t.i. systems employing, for example, new approaches such as 'within pulse' electronic scanning by a separate receiver aerial.

In civil air-traffic control, where it is reasonable to assume that the aircraft will be co-operating with the ground stations, the obvious answer to the automatic-tracking problem is to make use of secondary surveillance radar. I have already mentioned this system of identification whereby a pulse from the ground interrogator stimulates a coded reply pulse from a 'beacon' in the aircraft. Clearly, it is possible for this interrogation process to produce a signal which greatly exceeds the radar echo from the aircraft; also, replies will only be received from co-operating aircraft, and the system will be completely free from radar clutter. Automatic recognition and tracking, by such a secondary surveillance system, is then comparatively easy, or would be if the interrogating system did not lead to difficulties of its own. All too often, the system becomes self-jamming because of over interrogation. Nevertheless, the system is steadily being improved and is coming increasingly into use, e.g. in the UK at Heathrow Airport and elsewhere. Since only co-operating aircraft are accommodated by this scheme, the need remains for primary radar to monitor the airspace to take account of those aircraft not fitted with secondary radar or those in which the equipment is defective. This means that there is a problem of checking the responding aircraft against the totality of primary-radar plots before the process of association with the flight plans filed with the air-traffic-control system can be performed by the central computer.

#### **P.P.I. AND ITS COMPETITORS**

We may conclude that, if all the primary- and secondary- radar information were capable of automatic extraction, the p.p.i. might cease to be the preferred way for the controller to interact with the aircraft under his control. Information on tracks contained within the computer, details of aircraft flight plans such as altitude, destination etc., can all be presented to the controller on 'alpha-numeric' displays; so it is conceivable that the whole of the control over the air space could be exercised using such outputs as intermediaries. If all the information to be presented were of this type, there would be little point in thinking in terms of cathode-ray tubes, since progress already achieved with other forms of display, such as light-emitting diodes, electro-luminescent panels, liquid crystals or reflecting displays, could fulfil this function adequately. For example, the distance-to-threshold indicator, which has proved so useful to the airfield controller, using a direct-view storage tube, might well be replaced by a matrix of light-emitting diodes supported by a local store.

Unfortunately, clutter and signal fluctuations have ensured that the complete answer to the automatic recognition and tracking problem has not yet been achieved, and the need for operator monitoring of the radar output still remains a requirement, but employing the close integration with track store and computer which I have described. But how can we display this information? Undoubtedly, the p.p.i. possesses a persuasive appeal because of the close correspondence between paints on the tube and aircraft in the airspace. The visual association of radar tracks with procedural flight-plan details, derived from the central store and computer, means that the modern c.r.t./p.p.i. is by no means outmoded by the various forms of solid-state displays becoming available, nor by the television scan-conversion type of display.

Coloured phosphors provide a useful additional measure of signal characterisation, while 'light-pen' interrogation of p.p.i. signals provides immediate linkage into the computer store, as does the 'touch-wire' method of updating as used with an alpha-numeric display. The modern p.p.i., with its associated digital plot processors and with access to the station's central computer, is likely to be with us for some considerable time.

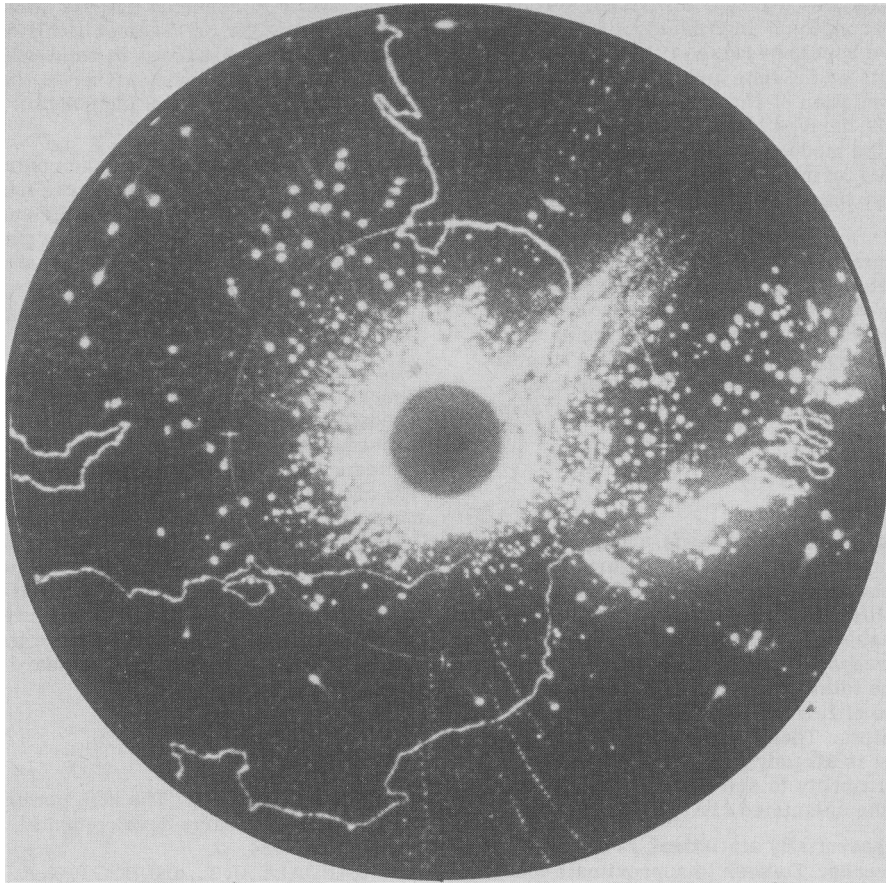


Fig. 19  
*Long-range p.p.i. picture showing aircraft in the presence of clutter from  
angels, clouds, video map and distant ground echoes due to anomalous  
propagation*

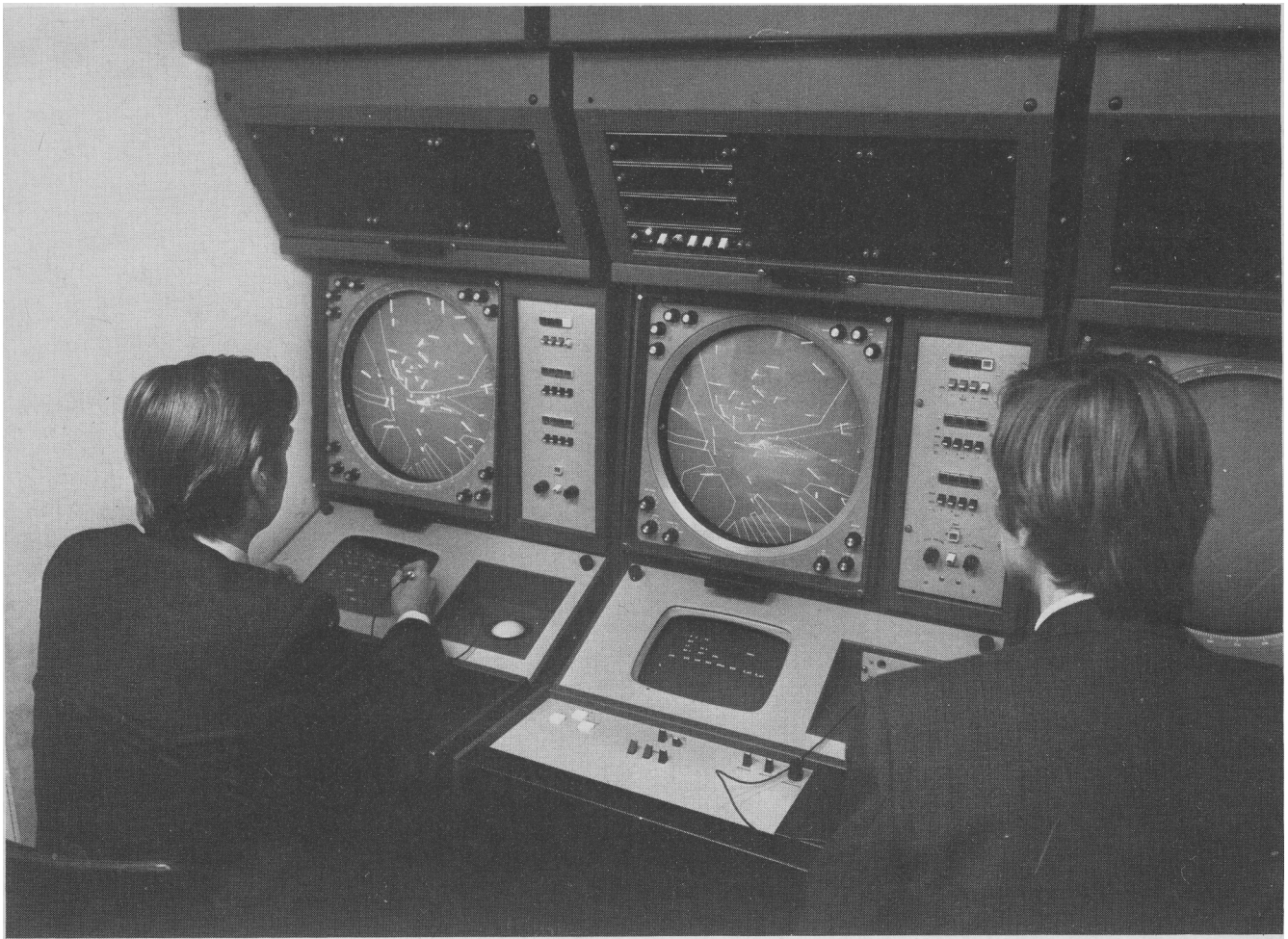


Fig. 20

*Modern radar display suite with inbuilt computer for automatic extraction and tracking*

#### FUTURE PROSPECT

Radar was developed as a wartime weapon, and so might be thought inappropriate as a subject for an inaugural address. I suggest that this is not so, for defence is vital for the maintenance of our way of life. The troubled state of the postwar world ensured that massive resources were devoted to radar, and progress was correspondingly rapid. Similar spectacular developments in the future, however, are less likely to occur, not only because of financial stringency, but by reason of engineering constraints. Thus the Earth is round and the cover of our equipment is already limited by this circumstance rather than by inability to see aircraft at greater distances—at least in the unjammed civil environment.

Again, radar data are essentially statistical, as also are the sources of interference. To seek to approximate too closely to certainty of detection under all conditions of clutter would require research effort on a prohibitive scale; neither is such superlative performance really required operationally. I conclude that the performance of a modern radar transmitter or receiver is already approaching the economic limit. Progress in solid-state devices will continue, and will contribute further to the efficiency of radar equipment, as well as making possible a new approach to the electronically scanned aerial.

Even more important will be the contribution which higher-speed semiconductor-logic devices can make in the digital processing of both radio-frequency and video signals with the aim of extracting the total information contained in the echo signature. Such digital processing will not be confined to the central computer, but will take place in special integrated-circuit units distributed through the reception and display sequence.

The real purpose of radar, however, is to assist aircraft operation, whether military or civil, and research is still needed on the matching of radar data to airspace-control procedures. I do not wish to suggest that radar is a perfected subject, but it is certainly not a speculative science. We can be certain that there is still great scope for contributions from ingenious engineers in accordance with the role forecast for them by Sir Robert Watson-Watt in his opening address to the first IEE symposium on radar in 1946. He quoted Tredgold's definition of the engineer as one who directs 'the great sources of power in nature for the use and convenience of man'. I am sure that the radar engineer has measured up to this high standard in the past, and will continue to do so.

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