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Clifford Paterson Lecture

Radar: new techniques and applications

By Sir Eric Eastwood, F.R.S.

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[Plates 1–10]

I was greatly honoured to be invited by the Council of the Royal Society to give the first Clifford Paterson Lecture, for I respect greatly the engineering achievements of Sir Clifford Paterson and admire his work as an outstanding pioneer of industrial research.

Paterson was trained as an electrical engineer and his first investigations were concerned with the techniques of a.c. measurement. His years of service with the National Physical Laboratory, however, coincided with the introduction and rapid extension of electrical illumination and he devoted great effort to the problems of photometry and the creation of international standards. But Paterson was an applied scientist of great versatility, and during World War I he applied himself with equal vigour to a number of military problems including the improvement of aircraft altitude measuring devices for use with anti-aircraft guns.

It was in late 1918 that Sir Clifford Paterson was invited to set up an industrial research laboratory, initially to help the Osram Lamp Works, but the project was soon widened so that in 1923 his personal creation – the Wembley Research Laboratory of the whole General Electric Company Limited was opened by Lord Cecil and Sir Joseph Thomson. Under Sir Clifford Paterson's direction the Hirst Research Centre, as the Wembley Laboratory is now called, was accorded international recognition as a centre of research in electrical and electronic engineering. Outstanding among its achievements was the wartime development of special thermionic valves for the generation of high power radar pulses; this work included valuable contributions to the engineering and production of the magnetron.

Sir Clifford Paterson believed that a broadly based laboratory leavened with an element of fundamental research could contribute to the success of a large electrical manufacturing company; by his integrity and leadership he translated that belief into a reality and so served not only his own company but the community of British industry.

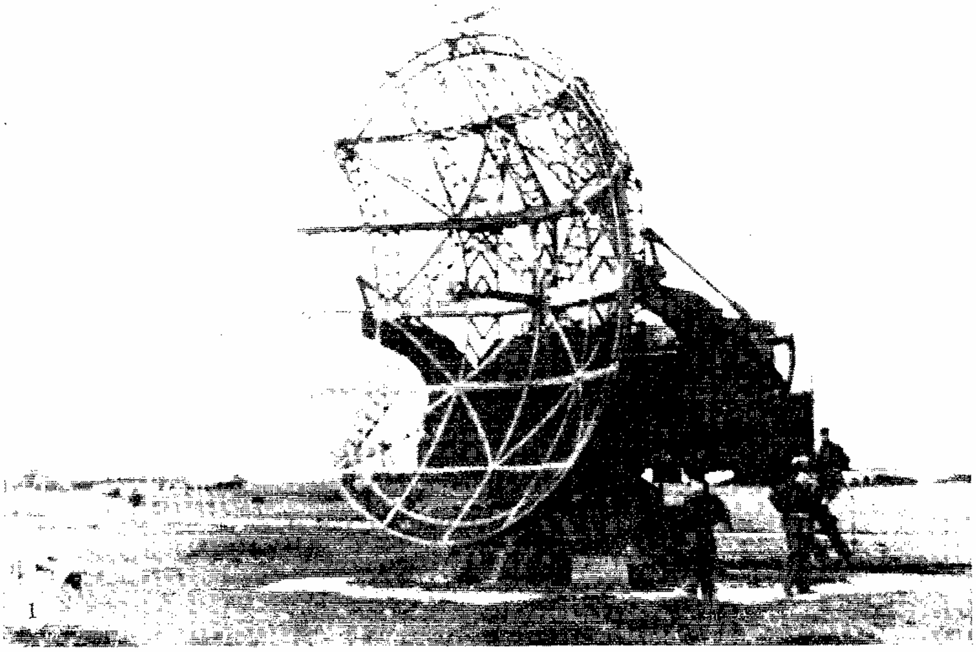
Radar in World War II

By the early 1930s, all the great powers had realized that developments in aeronautics since World War I had made the aircraft a major threat in any future war and that former methods of defending against them were inadequate. But the developments in radio techniques during that same period for communication, broadcasting and television had also provided components and equipment that might lead to a radio method of acquiring early warning of the approach of enemy aircraft. It was therefore not surprising to find at the close of World War II that most of the combatants had been pursuing secret research programmes in the 1930s which were designed to achieve radar solutions to the air defence problem.

Thus by 1938 Germany had in production and ready for deployment the Freya radar which operated on 126 MHz and provided early warning information to two Wurzburgs, the three radars forming an operational 'box' for the control of searchlights and anti-aircraft guns. The Wurzburg used a wavelength of about 50 cm (570 MHz) and so a 3 m parabolic reflector yielded a 12° beam which could be steered in elevation and azimuth to acquire a target. When the control of interceptor fighters later became important the Wurzburg was converted into a 'Giant Wurzburg' by increasing the aperture of the reflector to 8 m (figure 1, plate 1).

In Britain successful demonstration of radio echoes from aircraft was made in 1935 and by 1937 a number of early warning stations were operating round the south and east coasts; this Home Chain was soon extended to form a closed radar fence round the whole country. These stations operated in the 20–30 and 40–60 MHz bands and were of the bistatic floodlighting type. Such a station provided accurate range but less accurate information on azimuthal bearing and altitude. However, association of plot data from a number of stations feeding into the Fighter Group Operations Centre permitted quite good tracks of enemy raids to be 'filtered' out for the guidance of the defending fighters. Surveillance information supplied by the Home Chain was soon supplemented by more accurate range/bearing data from a secondary chain of coastal stations equipped with 200 MHz rotating beam equipments. These low cover stations were known as C.H.L. stations (Chain Home Low) and employed a single rotating aerial for both transmission and reception together with a p.p.i. display (plan position indicator). Similar equipment was used to form the inland G.C.I. stations (Ground Controlled Interception) whose function was to control the night fighters and vector them onto the enemy bombers (figure 2, plate 1). These three types of stations formed the ground radar control and reporting arm of the Royal Air Force during the Battle of Britain and the subsequent German night bombing campaign.

As in all warfare both sides developed new tactical equipment in response to the changing strategic situation. Germany laid emphasis on improved early warning radars and so the Mammut and Wasserman equipments were produced but no new frequency bands were exploited. In Britain the cavity magnetron was invented by Randal & Boot in 1940 and this generator of centimetric radiation in the 10 and 3 cm bands (S and X) was soon in production to power a whole range of new radars for airborne, shipborne and ground use. I will mention only the mobile S-band raid reporting and fighter control radar (figure 3, plate 2). An S-band magnetron provided 2 μs pulses at the 500 kW level and 500 pulses/s to an antenna of 25 ft aperture in the form of a parabolic cylinder with a slotted waveguide feed. A fan beam of radiation was produced with a horizontal width of about $1\frac{1}{2}°$. Since the



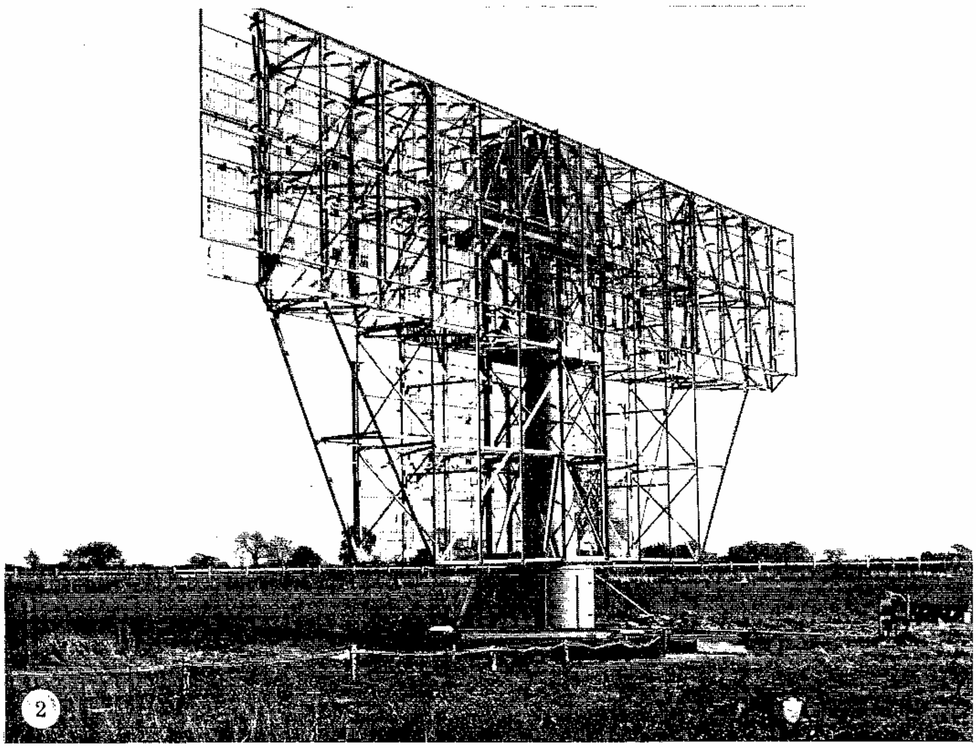


FIGURE 1. Giant Wurzburg: German 50 cm radar used for the pointing of A.A. guns and for fighter control.

FIGURE 2. British 1.5 m radar for the control of night fighter interception aircraft.

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Germans had no centimetric equipment the active jamming of these radars did not occur; by contrast, the German equipments were heavily jammed and, as an additional precaution against German jamming, British radars were built to operate in the same 50 cm bands as the Wurzburgs. Figure 4, plate 2, shows the 50 cm mobile control and reporting radar by which Doppler moving target indication was developed.

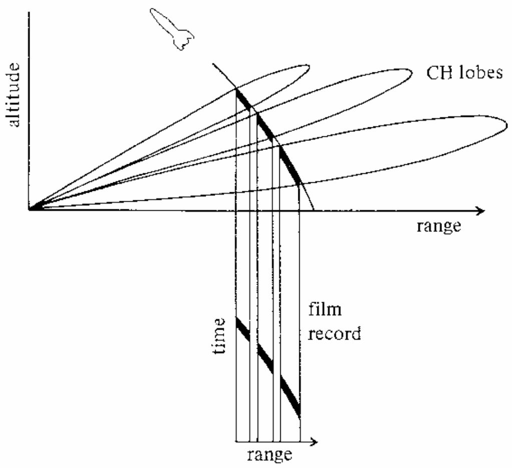


FIGURE 5. Generation of a time-range film record of the passage of a German V2 missile through the lobes of a C.H. radar.

Two later applications of the C.H. station possess special interest. During the V2 rocket attacks on London during 1944/45 immediate warning of a launch could be given by the signal scattered by the rocket as it climbed through the lobes of the C.H. radar (figure 5 and figure 6, plate 3). 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.

During the final stages of the war a major weakness of the German defence was the lack of forward air cover over the North Sea. An ingenious proposal to overcome this deficiency was to site a station on the Dutch coast to receive the radar energy scattered from the approaching aircraft when irradiated by the British C.H. stations. Rather vague information on this possibility was supplied by the British Intelligence to HQ 60 Group which was the ground radar group of Fighter Command. It was decided to test the feasibility of the scheme by an operational test in which I happened to be one of the participants. A small transportable type of C.H. station, but without transmitter, was set up on a hill at St Nic near Brest and the radar illumination was derived from the C.H. station at Ringstead (figure 7, plate 3). The synchronizing pulse for the display time base was the primary radar pulse received direct from Ringstead, while the secondary pulses scattered from aircraft were displayed as usual on the A-scope.

This geometry provides a system of ellipses each corresponding to a constant delay time. Intersection of the identified ellipse with the bearing line supplied by the goniometer gave the location of the aircraft and good tracks were secured. This 'Kleine Heidelberg' scheme, as the Germans named the proposal, was never operational. It is a possible form of 'multi static radar' not without interest at the present time since a number of passive receiving stations can be operated in association with only one transmitter.

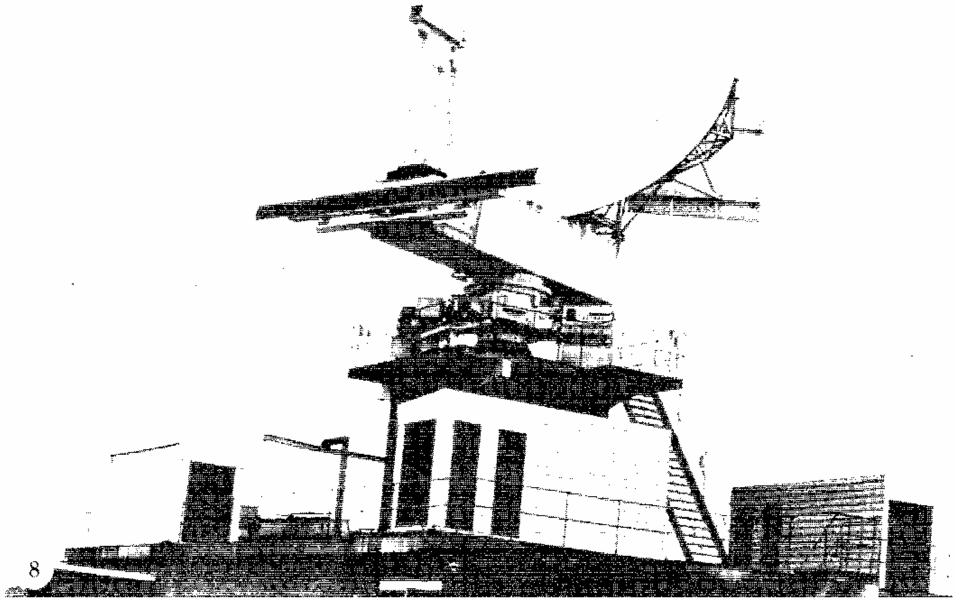
Postwar developments in ground radar

Owing to the pressure of the war it was not possible to find immediate technical answers to all the operational radar problems encountered; the search for solutions still continues but modern radar engineers have many new techniques and components to assist them in their task. Increased range and more comprehensive cover in the vertical plane were obvious needs to be satisfied in the early postwar radars. These needs were met by developing magnetrons of increased power (2–10 MW), producing receivers of improved sensitivity and designing antennae of increased gain and azimuthal resolving power.

When the C.H. system was designed in 1935/36 considerable thought was given to the provision of what are now termed e.c.c.m. devices (electronic counter counter measures – an important aspect of e.w. or electronic warfare). The objective was to anticipate and negative any jamming that an enemy might direct at the stations, i.e. to counter his e.c.m. (electronic counter measures). Thus the frequencies of the stations were distributed over a band and four switchable frequencies were planned for every station together with appropriate T and R arrays, i.e. some measure of 'frequency agility' was provided. Although microwave radars suffered no active jamming during the war it was clearly essential that good e.c.c.m. capability should be incorporated in such radars in the future. To achieve this objective would require frequency agility in the transmitter together with broad band aerials. Reduced transparency of the array to incident jamming power was equally important, which meant a very narrow primary beam together with low side lobes at all other angles.

Passive jamming of surveillance radars by means of resonant reflectors dropped from aircraft so as to obscure the path of a bomber force was early and independently invented by all three combatants and masses of the required thin strips of metal foil were stockpiled. Known as Window in Britain, Duppel in Germany and Chaff in U.S.A., this simple method of jamming was not used until the British 1000 bomber raid on Hamburg when it was decided that revelation of the 'secret' was more than outweighed by the reduced wastage of aircraft. To cope with Window requires that a radar should have a narrow beam and short pulse length, i.e. a small resolution cell, also the capability to use velocity discrimination by taking advantage of the difference in doppler frequency between signals scattered from the aircraft and those returned from the resonant metal strips of the Window cloud.

Detection and tracking with a surveillance radar were also impeded by echoes



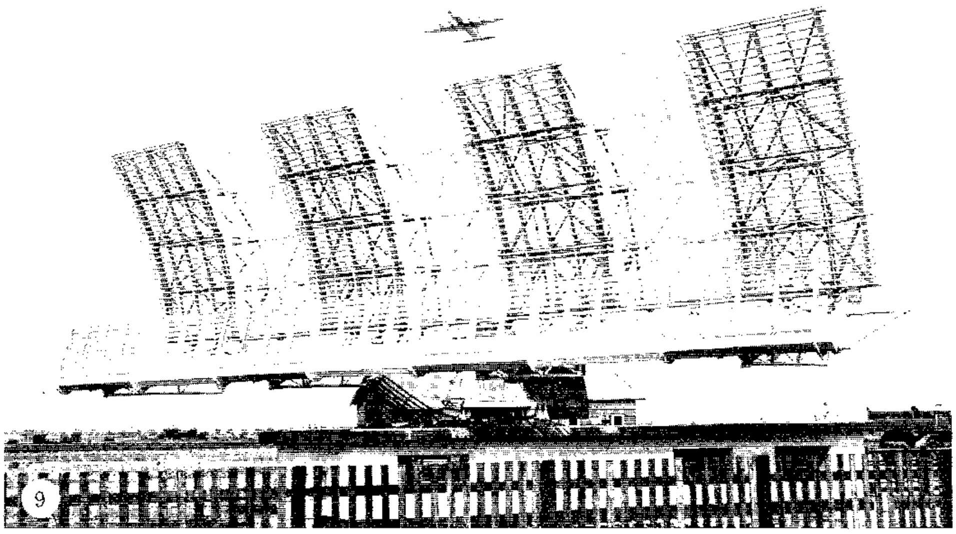


FIGURE 8. S-band radar with 40 ft × 50 ft antenna fed by a pile of horns to produce a stack of 12 beams. (Marconi Radar Systems Ltd.)

FIGURE 9. 50 cm surveillance radar for civil Air Traffic Control – parabolic cylindrical reflector fed by a slotted linear array. (Marconi Radar Systems Ltd.)

which arose from extended scatterers such as the ground, rain clouds and even flocks of birds ('angels'). Obscuration of aircraft by 'clutter' of this type can be reduced by appropriately shaping the radiation pattern of the antenna, also by using circular polarization to discriminate against rain echoes, but the visibility of a target in residual clutter can only be enhanced by using doppler frequency filters with very carefully shaped characteristics.

A surveillance radar may be regarded as a communication system with a few megahertz bandwidth which feeds a prodigious amount of information to the controller only a fraction of which is essential for his task of airspace management. The human operator applied eye and brain to the interpretation of the data presented on his p.p.i. and achieved wonders, but to trace systematically the histories of many targets simultaneously, which is what modern air traffic control demands, required that aids to signal processing and video data processing should be devised. Real progress towards satisfying this long recognized need had to await the arrival of the technology of semiconductors, large scale integrated circuits etc., and the 'digital revolution' which they ushered in. The most important advance in radar technique during the past fifteen years has been the development of digital signal processing and computerized handling of video data – these techniques have made radar data more accessible to the controller and more accurate for his task.

Included with the information on a target passed by the C.H. radar operator to the Group Operations Centre was the identification as friend or foe (i.f.f.) which was derived from the behaviour of the echo. The pulse from the ground transmitter triggered a receiver/transmitter in a friendly aircraft to radiate a coded additional signal which was superimposed on the radar echo from the aircraft. A similar though more elaborate system was used with the metric beam radars (C.H.L., G.C.I.) but the later centimetric radars required that this interrogation process for identification should take place on an independent 200 MHz radio channel. In modern equipment interrogation takes place at about 1100 MHz and this so-called secondary surveillance radar system (s.s.r.) supplies not only range and bearing but also the identification (aircraft call sign in the civil case) and the altitude from the aircraft's altimeter. Thus the aircraft transponder has become a communication beacon. Clearly this interrogation process supplies a signal which greatly exceeds the primary radar echo from the skin of the aircraft; also, the s.s.r. signals will be completely free from radar clutter so that automatic detection and tracking are facilitated accordingly. Thus the s.s.r. system has become an essential component of the civil air traffic control system at most major airports with primary radar fulfilling an airspace monitoring function. Civil aircraft cooperate with the ground control and so the s.s.r. system works well but it is an arrangement which cannot obtain in the military case.

Recent advances in radar techniques

The microwave antenna

The need for an antenna that will minimize both clutter and jamming, i.e. broad banding to permit frequency agility, narrow main beam, low side lobes, reduction of ground illumination combined with comprehensive cover in elevation has prompted many design approaches. The operational requirement defines the far field radiation pattern from which may be derived the amplitude and phase distribution over the aperture of the antenna by use of Fourier transform methods. Whether to use a reflector or a lens, a point feed such as a horn or a distributed array of slots, for example, are open questions which the designer has to resolve in the light of the proposed use of the radar. Figure 8, plate 4, shows a high powered S-band radar with a double curvature reflector fed by a stack of horns while figure 9, plate 4, illustrates a parabolic, cylindrical reflector with a slotted waveguide feed. Advantages of the latter system are the relative cheapness and ease of construction of the single curvature reflector and the accuracy with which the aperture distribution can be controlled; disadvantages are the narrow frequency bandwidth of the simple slotted waveguide and the fact that a shift in frequency with a series fed sequence of slots produces 'squint' or azimuthal displacement of the beam. For a fixed frequency radar such as the 50 cm unit of figure 9 it is ideal; a chain of these radars is operated by the British Civil Aviation Authority to monitor the movement of aircraft along the airways, the long wavelength ensuring minimum interference from rain echoes.

Advances in workshop machining techniques have now permitted linear arrays to be built which provide broad bandwidth, freedom from squint and very low sidelobes – all desirable e.c.c.m. features in the defence radar. For a linear array to possess these properties it is essential that for any frequency within the band to be covered, all the radiators should be fed in phase. This requires that all the waveguide paths from the transmitter to each of the radiators shall be of equal length and possess the same dispersion characteristics. Figure 10 shows the geometrical arrangement whereby this equality may be obtained and also indicates the means for producing the required power taper across the antenna. A number of such modules are combined to form the complete linear array. The only way of making to the required accuracy the feed modules and the waveguide manifolds which interconnect them was to machine them from a solid slab of aluminium using a numerically controlled mill. The module was machined in two halves, each the mirror image of the other, so that when joined together the labyrinth of waveguides was enclosed within the block; negligible electrical effect was produced by the dividing plane. A fully machined module is shown in figure 11, plate 5. The horizontal radiation pattern measured on an antenna composed of eight modules yields 40 db suppression of the main sidelobes relative to the main beam. An operational bandwidth of 400 MHz centred on 3000 MHz was obtained and the total beam displacement across the band was 4′. These test results on production aerials illustrate how modern computer aided design and digitally controlled machining methods are improving the operational capability of radars.

Azimuthal squint of a series fed linear array can be employed to scan a radar beam by controlled change of frequency of the transmitter. Extension of the scheme to a planar array of radiators in which the phase of each element is controlled individually allows a pencil beam to be steered in both azimuth and elevation. An

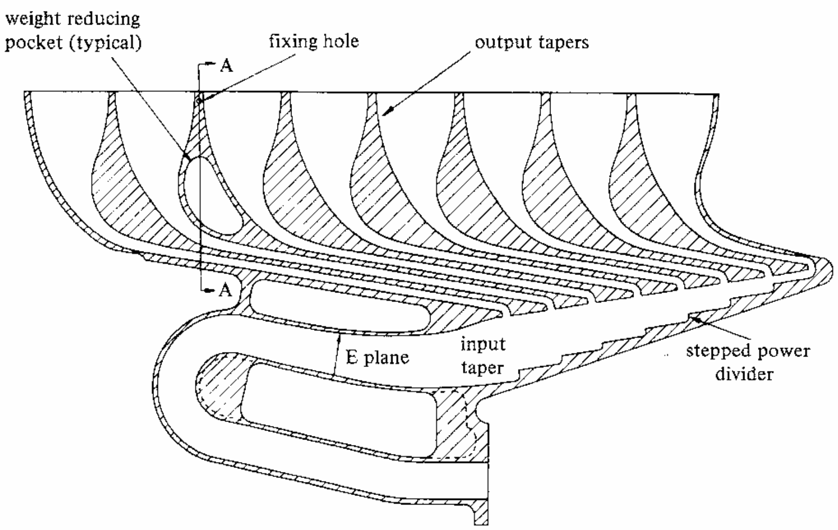


FIGURE 10. Module for squintless feed showing equal path length distribution network to the sequence of radiating horns, also the stepped power dividers. (Marconi Radar Systems Ltd.)

alternative technique is to employ intermediate frequency scanning of the received beam only – a type of 'Array Signal Processing' as it is now termed; this is economically very attractive and is under investigation in many laboratories.

The high power microwave radar transmitter

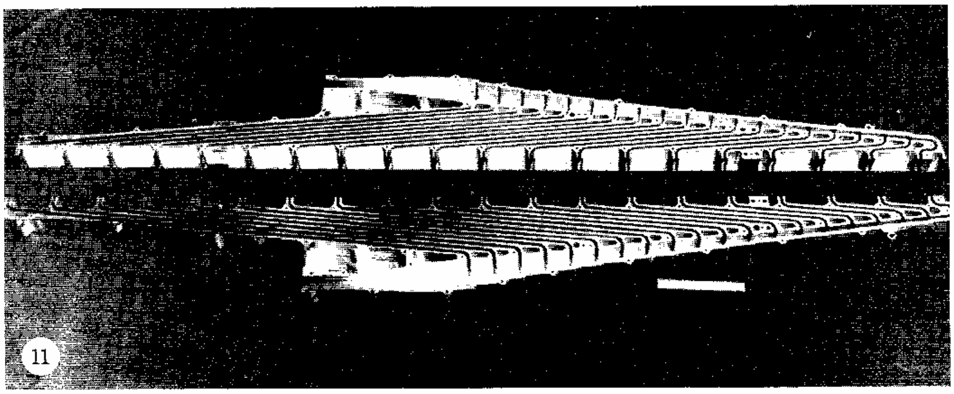
The magnetron is a very efficient generator of microwave power and so it was logical that in the first phase of radar development after the war this valve should be further extended to give increased power and improved stability of frequency. Available S-band pulse power was soon raised from 500 kW to 2 MW and L-band magnetrons were built to supply 10 MW. Performance of ground radars was improved accordingly but clutter from clouds and weather was also increased and significant interference from bird echoes was encountered for the first time. Elimination of such clutter signals depends mainly upon the use of the doppler principle and this can be most effectively applied when a coherent amplifier is employed; such a transmitter also meets the need for wide band frequency agility and the ability to apply frequency modulation for pulse compression purposes.

Although it seemed attractive to adapt the magnetron to an amplifier rôle, to produce a so-called cross-field amplifier (magnetic field orthogonal to the applied electric field) the tubes which have emerged have never been wholly successful. In any case a strong competitor was immediately to hand in the klystron which is a linear beam tube with the magnetic field directed axially along the path of the electron beam and parallel to the electric field. Figure 12, plate 5, shows the 50 cm klystron transmitter used for coherent m.t.i. at Heathrow in association with the antenna of figure 9, plate 4.

A major disadvantage of the klystron is its limited bandwidth ($< 3\%$). The power travelling wave tube however is also a linear beam tube and can provide a 10% bandwidth which is adequate for the required military frequency agility. The solution to the modern microwave transmitter problem would appear to be a combination of the virtues of the klystron and the TWT – this is just what the 'Twystron' provides, for it may best be described as a klystron injected TWT and provides high gain with large bandwidth. In figure 13, plate 6, is shown the modern Marconi L-band radar transmitter whose power tube is the E.M.I.–Varian Twystron. This transmitter provides a pulse power of 4 MW and a mean power of 10 kW over a band of 100 MHz centred on 1300 MHz. Overall gain is 70 dB so that the drive from the solid state frequency synthesizer is only at the 1 W level. With this equipment, frequency change from pulse to pulse may be programmed. If the transmitter were serving a civil A.T.C. function then within a single modulator pulse two r.f. pulses on different frequencies could be radiated consecutively, a short pulse for close monitoring of air movements in the terminal area and a long pulse for airways surveillance.

Pulse compression

A pulse compression radar radiates a frequency modulated pulse which, after reception and i.f. amplification, is passed into a dispersive filter whose effect is to bring the various Fourier components of the f.m. signal into phase coincidence. In this way the original long pulse is compressed into a short pulse which increases the resolution of the radar but retains the target detection capability of the long pulse. This principle was first suggested nearly thirty years ago, but utilization in microwave radars had to await the arrival of stable amplifier transmitters such as that described above. Dispersive networks made up from lumped capacitors and inductors were first employed for the i.f. filter, but they were difficult to design and construct for stable operation. Acoustic dispersive lines followed, but the most convenient form of pulse compression filter is the surface acoustic wave device shown in figure 14, plate 6. This modern application of the Rayleigh surface wave uses a piezoelectric substrate of crystalline quartz or lithium niobate on which is laid down a sequence of interdigital aluminium fingers. The array of electrodes on the right launch the incoming chirp signal as a Rayleigh wave and the electrodes at the left extremity collect the output; in between is a metallized screen to reduce direct electrical coupling. By grading the finger lengths of successive elements in a calculable manner a dispersive characteristic is given to the line so that a long



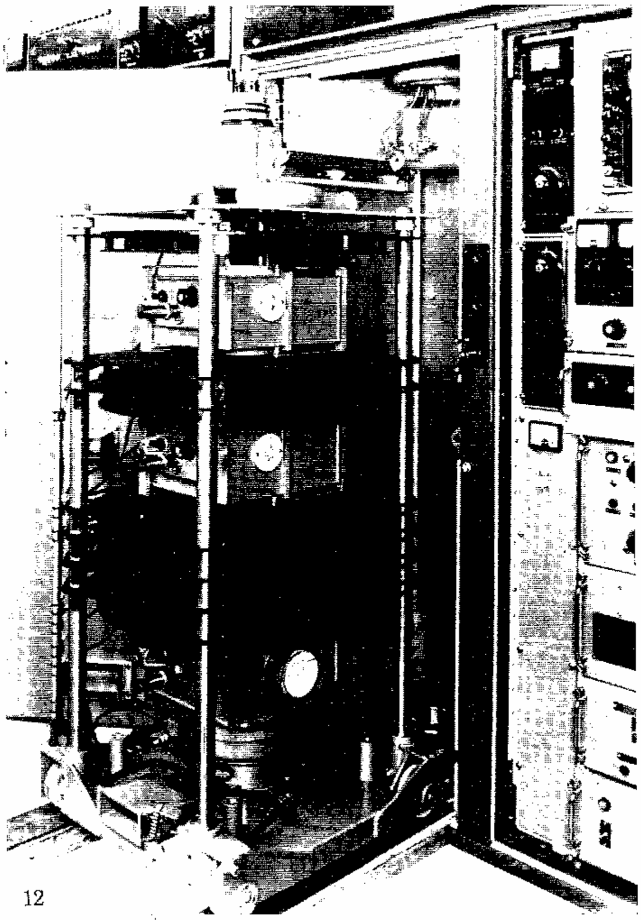


FIGURE 11. Fully machined module which is produced by a numerically controlled machine. (Marconi Radar Systems Ltd.)

FIGURE 12. Klystron amplifier for the radar of figure 9. (English Electric Valve Co.)

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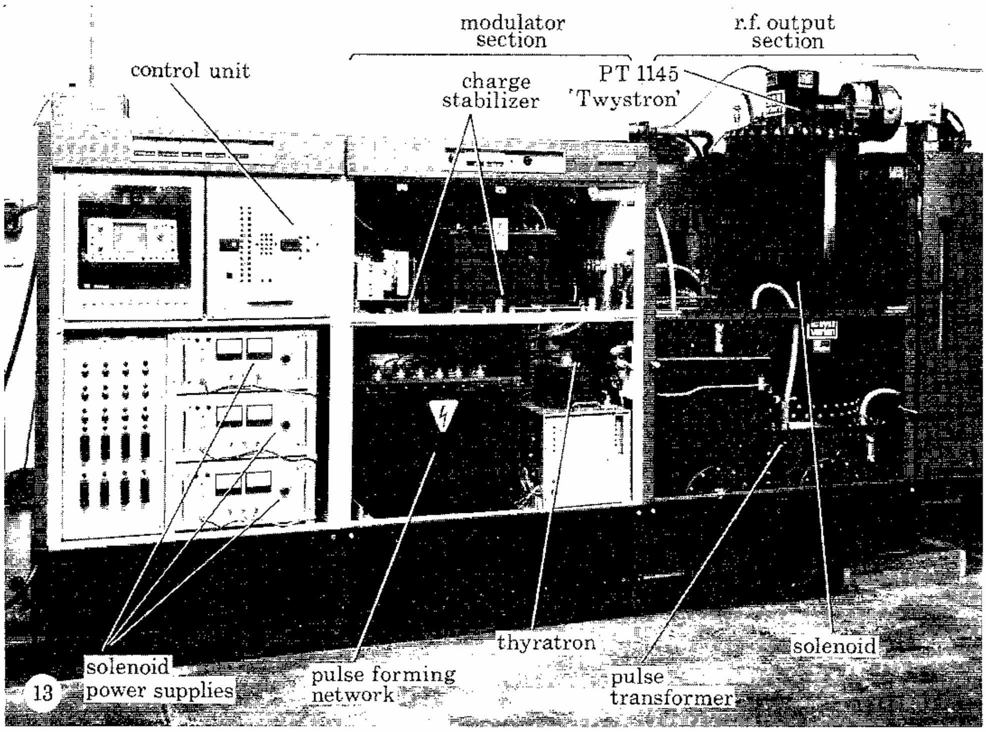


FIGURE 13. High power radar transmitter using the Twystron amplifier valve. (Marconi Radar Systems Ltd.)

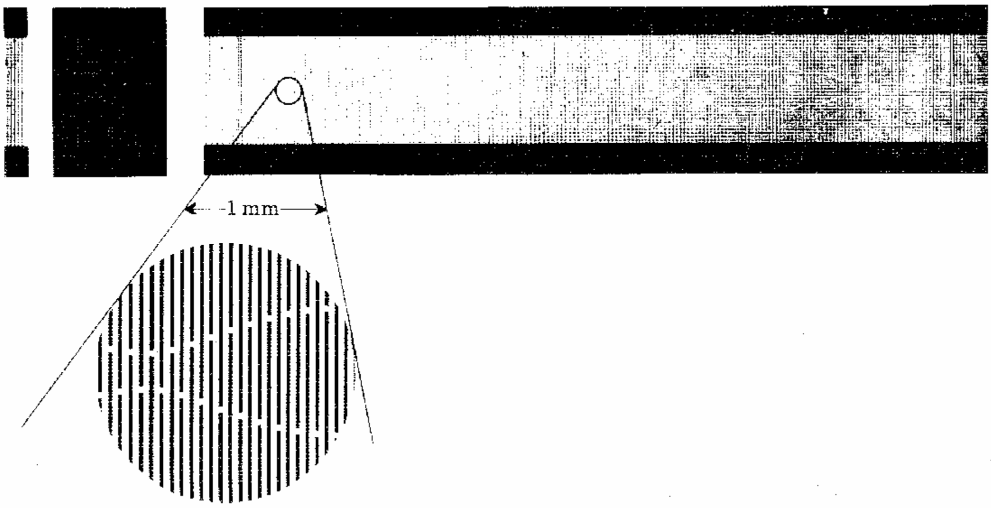


FIGURE 14. Pulse compression filter which uses a surface acoustic wave transducer to obtain time compression of a frequency swept pulse. (A microscope picture of 1 mm of the launcher section is included to show the aluminium finger pattern.) (Marconi Research Laboratory.)

frequency modulated pulse at the input appears as a compressed pulse at the output of width $1/\Delta f$, where Δf is the frequency sweep of the transmitted pulse. Figure 15, plate 7 shows an input pulse of 1.6 μsec with 60 MHz carrier; $\Delta f = 20$ MHz and the output is 60 ns wide at 3 dB corresponding to a compression ratio of 27. This unit was supplied to the University of Denmark for an airborne radar experiment to measure the thickness of ice layers.

The microwave receiver

The S-band radar shown in figure 3, plate 2, used a superheterodyne receiver with the signal from the aerial fed into a germanium diode mixer together with the output from the klystron local oscillator. A noise factor of about 18 dB was obtained.

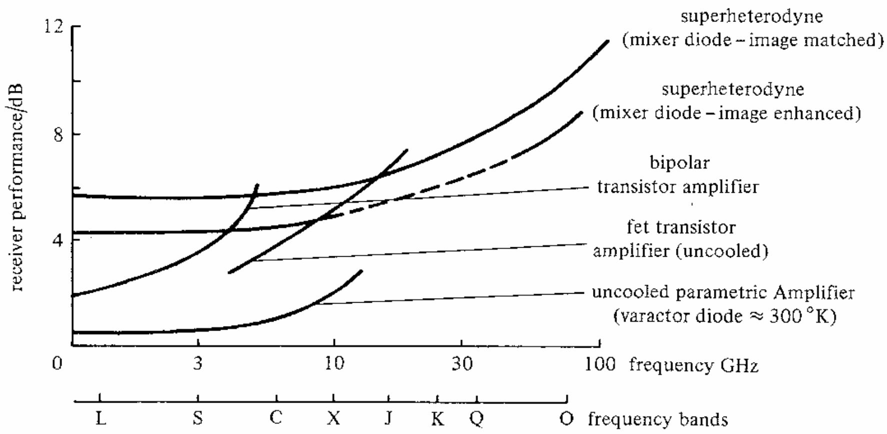


FIGURE 16. Microwave receiver noise figure performance as a function of frequency. (G.E.C. Hirst Research Centre.)

Although the travelling wave tube r.f. amplifier was used with many postwar radars, improved duplexers and crystals have made such an expensive unit unnecessary. Modern superheterodyne receivers using Schottky-barrier mixer diodes have noise factors of 4.5 dB at S or L band. Figure 16 illustrates the variation of noise figure with frequency for various types of semiconductor microwave receivers. The L-band radar of figure 13, plate 6, is fitted with a four port ferrite duplexer and the transistor receiver provides a noise factor of 2.5 dB. If the complexity of a parametric amplifier based on a varactor diode can be accepted then a noise figure as low as 1 dB may be obtained at L-band.

Clearly, radar has benefited greatly from advances in solid state physics. This is well illustrated by figure 17, plate 7, which shows how integrated microwave circuits can provide the essential units of a complete radar head small enough to be carried by one man, and yet capable of detecting a moving man at a range of nearly 1 km. A pulse doppler system with r.f. of 17 GHz is employed with doppler tone detection of the target made through headphones. The microwave receiver and automatic frequency control circuit are integrated onto one alumina substrate; Gunn diode transmitter and local oscillator are contained in similar units. A design of a microwave integrated circuit assembly for an earlier radar was completed in 1973 and is shown for comparison. The reduction in size emphasizes the rapid progress in this field.

Moving target indication and the doppler filter

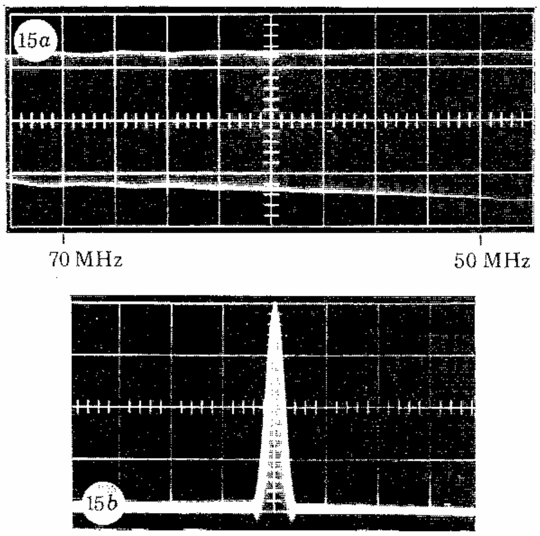
The detection and tracking of aircraft in the presence of clutter signals returned by extended scatterers occupying the same range cells, e.g. echoes from hills, rain or even birds, has proved to be a major difficulty, whether the radar is used for military purpose or in civil air traffic control. It is true that A.T.C. at major airports now relies upon s.s.r. but primary radar has still an important civil monitoring rôle to fulfil and this requires that the clutter limitation to performance shall be removed.

Careful antenna design can reduce the problem, and use of circular polarization provides a useful 15 dB of protection against rain, but substantial elimination of clutter requires use of the doppler effect. A target having velocity v relative to the radar when illuminated by pulses of frequency f returns an echo of frequency $f \pm f_d$, where f_d is the doppler frequency (+ refers to an approaching target) and $f_d = (2v/c)f$ or $(2v/\lambda)$ (where c is the velocity of light and λ is the radiated wavelength).

The early method of achieving moving target indication (m.t.i.) was by means of a delay line canceller which eliminated the echoes from stationary targets (figure 18). Echo pulses are heterodyned to the intermediate frequency for amplification, then applied to a phase detector for comparison with the signal from a coherent i.f. oscillator. The output is a bipolar video pulse which fluctuates in amplitude at the doppler frequency. If the target is stationary the doppler frequency is zero and consecutive pulses are of equal magnitude and give zero output on subtraction. Consecutive pulses from a moving target are not equal and after subtraction provide a difference signal which is also a bipolar video pulse fluctuating sinusoidally at the doppler frequency f_d. Full wave rectification of this signal from the canceller yields a video drive signal for application to the p.p.i.

In a klystron amplifier radar the coho (coherent i.f. oscillator) is a crystal controlled oscillator, but in a magnetron m.t.i. radar the magnetron is incoherent from pulse to pulse so a locked 'coho' is employed to remember the phase of the outgoing pulse. A modern tunable magnetron locked to a crystal stabilized local oscillator (stalo) gives an m.t.i. performance little inferior to that of a fully coherent system, except that second trace clutter cannot be rejected. In both radars the essential component is the delay line which stores the sequence of signals at various ranges for comparison with the corresponding signals occurring at the same ranges but arising from the following transmitter pulse. It is essential that the time delay should exactly match the interpulse period of the transmitter and so it was usual for the trigger pulse of the radar to be generated by a 'run-round' sustaining circuit linked with the same delay line.

Now the amplitude of the difference signal from the canceller varies as $\sin \pi f_d T$



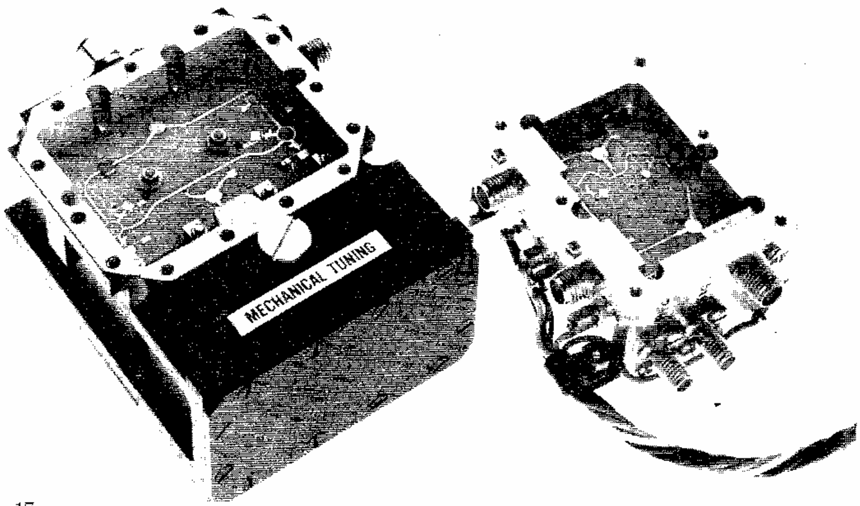


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FIGURE 15. Pulse compression by s.a.w. dispersive filter. (*a*) Input signal, sweeping in frequency from 70 MHz to 50 MHz in 1.6 μs. Time scale 0.2 μs/cm (and *b*). (*b*) Output signal, compressed pulse width is 60 ns at 3 dB. (Marconi Research Laboratory.)

FIGURE 17. Two generations of J-band microwave integrated circuit radar receivers. (G.E.C. Hirst Research Centre.)

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which is a function of the doppler frequency of the particular target and the pulse recurrence frequency $f_r = 1/T$ (T is the interpulse period). Thus the delay line canceller functions as a simple filter which rejects the d.c. component of the clutter and has the frequency characteristic of figure 19. It will be noticed that the output is zero whenever $\pi f_d T = n\pi$, i.e. $f_d = n/T = nfr$. Such speeds are called 'blind speeds' and correspond to the displacement of the target through a multiple of

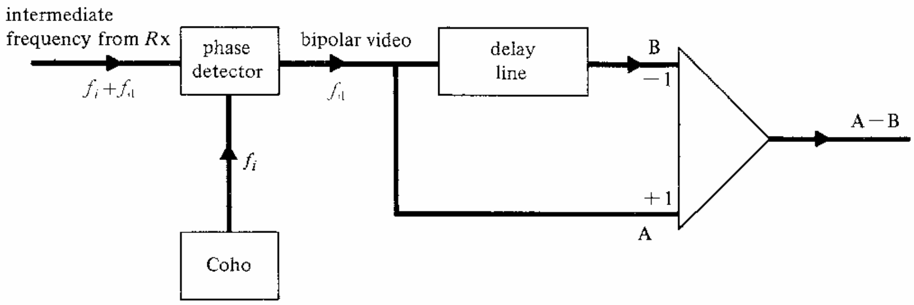


FIGURE 18. Moving target indicator radar: two pulse single delay canceller.

$\frac{1}{2}\lambda$ during the interpulse period T. This frequency characteristic would be more acceptable operationally if the nulls were broader so as to reject more near zero doppler echoes; some improvement can be obtained by passing the output from a single delay canceller through a second identical stage (figure 20) when the $\sin \pi f_d T$ characteristic becomes $\sin^2 \pi f_d T$ as in figure 19. It is possible to add further cancellation stages to extract the third or fourth difference but such additions make matching of the delays progressively more difficult, neither does the resultant characteristic possess increased operational advantage. What is required is an adaptive filter which removes not only zero doppler ground returns but also the clutter from rain, angels and chaff (in the military case).

Examination of figure 20 suggests that an alternative approach to the design of a double delay canceller is to regard it as a transversal filter with appropriate multipliers or weights being applied to the tapping points. Implementation of this approach demands a method of achieving the required delays more conveniently and precisely than the supersonic delay lines which were formerly employed. In the first generation of m.t.i. radars the delay line consisted of a tube of water through which was passed an acoustic pulse derived from the video output of the phase detector. Mercury soon replaced water and this form of ultrasonic delay line was also used as a store in early digital computers. Liquid lines gave place to quartz, and quite complex radar multi-line cancellers were built with such units. But recent advances in semiconductor integrated circuits have now allowed such acoustic delay lines to be abandoned in favour of wholly digital signal processing systems. This digital treatment of radar signals applies not only to the doppler filter process but to the subsequent automatic extraction of aircraft plots.

In such a radar signal processing system a crystal controlled oscillator (about

1 MHz) provides a range sampling waveform which gates the output from the phase detector into a sequence of range increments during each of which the bipolar video is digitized by an analogue to digital converter to 8 bit accuracy (256 discrete

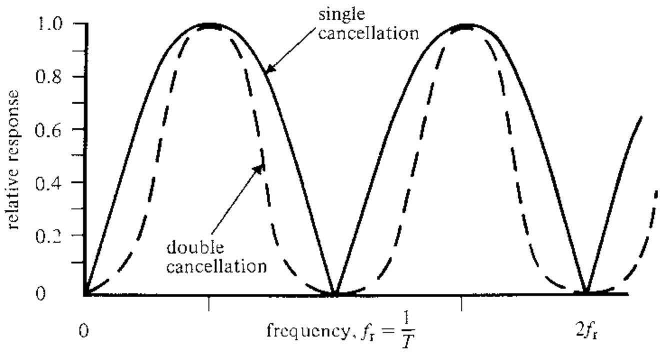
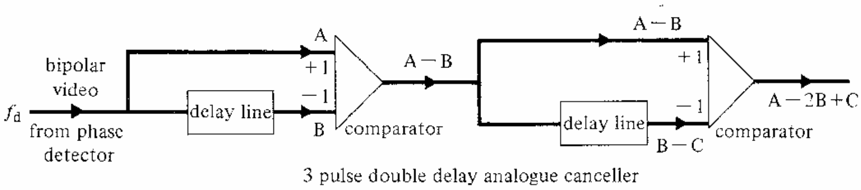


FIGURE 19. Frequency response of single delay line canceller (solid curve) and double delay line canceller (dashed curve).



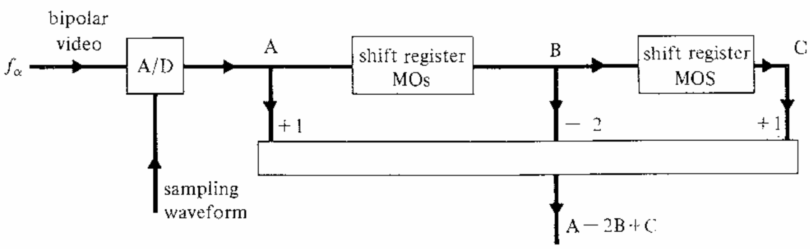
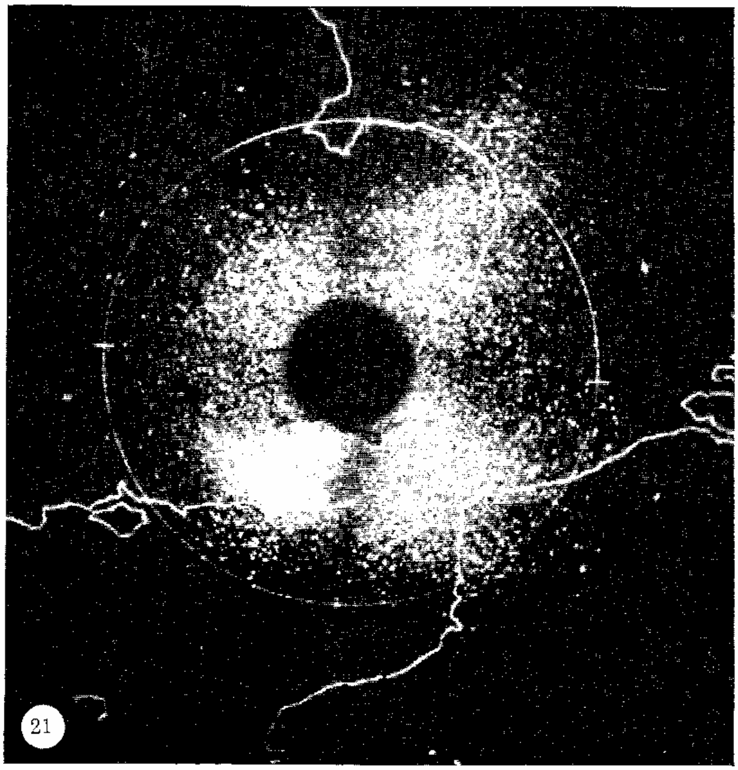


FIGURE 20. Derivation of a three pulse digital m.t.i. comparator system from a three pulse double delay analogue canceller.

levels) in a period of about 1 μs (figure 20). These packets of bits are fed into a MOS active device store (metal oxide silicon field effect transistors) with controlled time delay achieved by clocking the digits through two shift registers in series. The three packets of bits in corresponding range cells, i.e. immediate, once delayed and twice delayed, are weighted with the multipliers +1, −2 and +1 respectively before summing.

Since range cells are determined by time delays after the instant of triggering



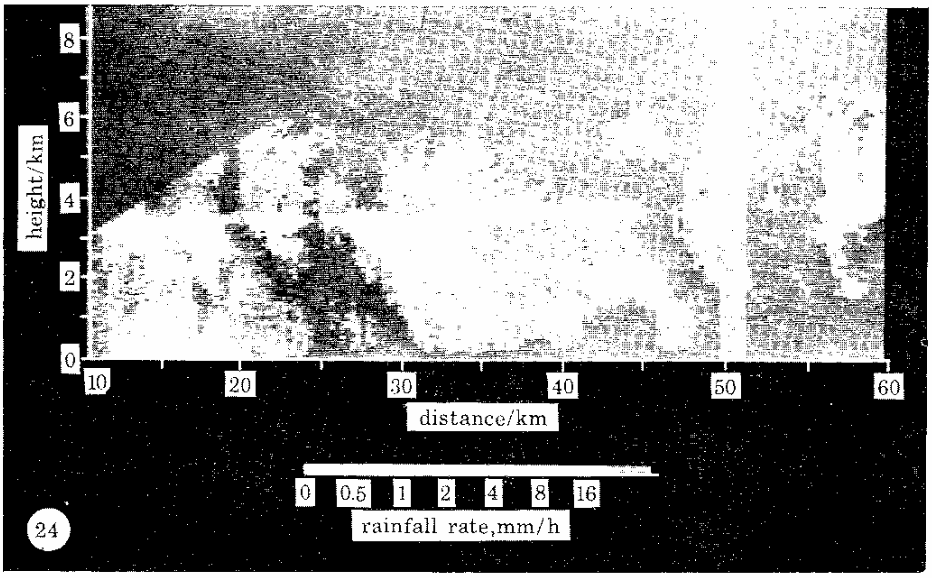


FIGURE 21. Easterly migration of birds observed by radar. Illustrates 'm.t.i. wedges' to the north and south due to cancellation of near zero doppler returns from targets moving on tracks tangential to the radar station (Eastwood 1967).

FIGURE 24. Cross-section through rain cells observed with Chilbolton S-band radar, showing melting layer, also the angle of lean of the cells due to wind sheer. (Appleton Laboratory.)

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of the transmitter and this trigger pulse is derived from the clocking sequence which moves the bits through the registers, then it is easy to operate the radar on two or more pulse recurrence frequency values whereby m.t.i. performance is preserved but the blind speeds can be displaced from the speed bracket of operational interest. Two other cases of signal loss can occur which are not disposed of quite so easily – I refer to the cancellation of the echo from an aircraft moving on a tangential track and loss of signal due to so-called 'blind phases'.

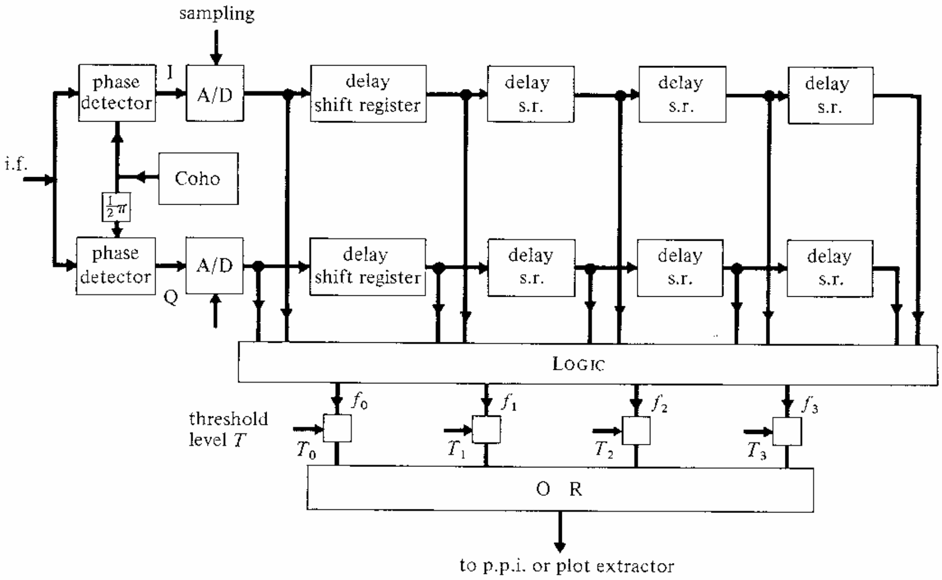


FIGURE 22. Schematic of digital, multifilter, clutter suppressor using five pulse samples and a sequence of four delay line shift registers. (Marconi Radar Systems Ltd.)

Cancellation of echoes from targets moving on tangential courses is well illustrated by figure 21 and prevention of this effect is discussed below. Blind phase signal loss occurs when the bipolar video output from the canceller, whose time variation is harmonic at the doppler frequency, passes through zero. To overcome this effect the original i.f. signal is fed in parallel to a second phase detector whose reference is the coho signal delayed in phase by $\frac{1}{2}\pi$. Thus if $A \sin 2\pi f_d t$ is the output from the in-phase detector I, then the output from the second detector is $A \cos 2\pi f_d t$, i.e. it is in quadrature (Q) with the I output. Both I and Q signals are passed through identical processing chains but are finally combined by a modulus extractor so that any blind phase losses in one channel are compensated by the signals then present in the other channel. Such an m.t.i. system can provide a clutter cancellation ratio of 40 dB, the limit being set by the aerial scanning effect on the clutter spectrum.

By using the digital signal processing methods outlined above, together with I and Q channels and a sequence of four identical shift register delay lines (i.e. five pulse system as in figure 22) it is possible to design a form of transversal filter which, in effect, covers the doppler band of the radar (0 to fr) by four filters whose characteristics are located as shown in figure 23. The effect of the 'Logic' is to free filters 1, 2 and 3 from fixed target echoes and from near zero doppler clutter arising from tree and vegetation covered ground; these signals fall within the pass band of the so-called zero doppler filter. Thus each filter has to deal only with the signals that fall within its own velocity band, so that the signal from a wanted target has then to compete only with the interference contained within the frequency domain of one filter, and the probability of detection is enhanced accordingly. But to exploit this advantage requires that the detection thresholds of the filters shall be separately optimized and varied according to the changing nature of the clutter in both time and space.

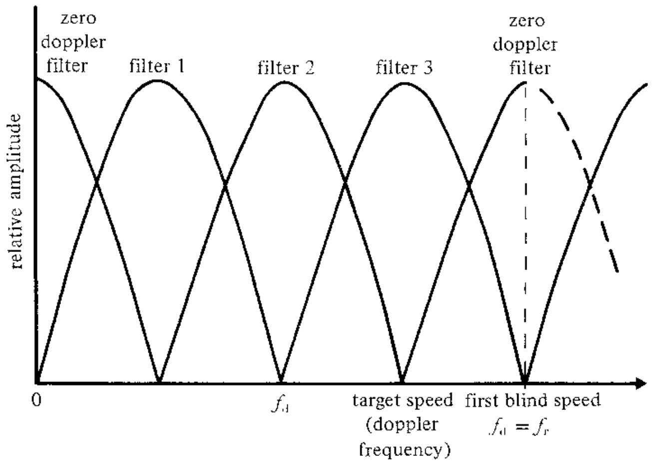


FIGURE 23. Frequency characteristics of the multifilter, digital m.t.i. system. (Marconi Radar Systems Ltd.)

To establish the threshold of the zero doppler filter the whole of the radar coverage is divided into range/azimuth resolution cells, in each of which the clutter plus thermal noise level is averaged over time, the stored result being updated with every revolution of the aerial. Increase of total amplitude within a particular cell relative to the stored time average will be produced temporarily by the presence of an aircraft within the cell and so the tangentially moving aircraft may be detected by its 'supraclutter visibility'. A much coarser graticule suffices for the filters 1, 2 and 3 whose thresholds are determined temporally but with spatial comparison to adjacent cells. In all cases the thresholds are determined by the clutter itself, i.e. the filters are adaptive. Flocks of birds or moving clouds in their progress across the p.p.i. will in effect carry their filter thresholds with them. In addition, the continuity or otherwise of the clutter within a 'cell' is assessed by a 'clutter switch'; in the absence of clutter the signal continues unprocessed with no losses incurred, such signals are combined with the outputs from the four filters and finally transmitted to the p.p.i. or, more usually, to the plot extractor stage of the signal processing system.

The complex variation of the clutter signal from within an extended rain cell is well illustrated by the structure of such a cell as derived by the Appleton Laboratory, using the Chilbolton 40 m steerable antenna and an S band transmitter – perhaps we should not try to remove all such clutter by doppler alone but use, rather, as long a wavelength as possible to reduce the back-scatter (figure 24).

The charge coupled device in radar signal processing

Digital signal processing with its attendant advantages has only become practicable because cheap, yet reliable analogue to digital converters and MOS shift registers have become available. It is curious that at just this time a new semiconductor component should have appeared which can also function as a digital delay line – this is the charge coupled device or c.c.d. The c.c.d. is a silicon integrated circuit which may be made by well established MOS processing techniques (figure 25). In its simplest form the device consists of a linear sequence of control 'elements' laid down on a film of silicon dioxide covering a substrate of silicon. A 'bit' of data may be stored in the form of a charge located at the Si/SiO_2 interface and lying beneath one electrode. This charge may be transferred, shift register fashion, along the chain of elements by application of a three-phase clocking waveform to the trio of aluminium electrodes which constitute the 'element'. Chips have already been produced which can handle thousands of bits with shifting rates up to 10 MHz. It is likely that bulk production will soon make the c.c.d. price competitive with the MOS shift register; when this happens c.c.d. digital delay lines may well be used in the multi-filter m.t.i. system described above.

Automatic plot extraction and data utilization

When the radar beam sweeps across a target, not every pulse from the transmitter yields a detected echo pulse or 'strike'; this is due to interference from noise and residual clutter. The function of the automatic plot extractor is to relate the pattern of such strikes within every range quantum to the possible number of returns as determined by the pulse recurrence frequency, aerial beam width and rate of rotation. As usual with statistical data of this kind it is necessary to balance false alarm rate against the probability of missed targets, so criteria are set up in the extractor which permit 'true' targets to be selected, that is, a 'plot' is formed and its range and bearing derived. Extracted plots are expressed as digital messages (about 30 bits) which can be transmitted over narrow band links to the Radar Operations Centre.

The radar operations centre is a complex of distributed data processors (as opposed to a large central computer), p.p.i.s for raw radar or extracted plots, alphanumeric displays, radio communication terminals etc. whose function is to provide an effective interface between the controller and the total electronic/radar/radio machine which is assisting him in the execution of his airspace management task (figure 26).

The p.p.i. was the simple but effective wartime progenitor of the modern radar display system but editing of the plot information on the tube was completely lacking. Also the p.p.i. as a display instrument was too inflexible because the sequence of echo signals offered to it was locked in time to the initiation of the radar pulse itself and to its physical translation through space. Although strict time sequencing is inevitable in the digital signal processing system the plot messages received and stored in the radar operations centre need no longer be handled in real time. Stored raw radar video or extracted plots can be presented on the p.p.i. display, repetitively if desired, or displayed at fixed brilliance by use of constant writing speed.

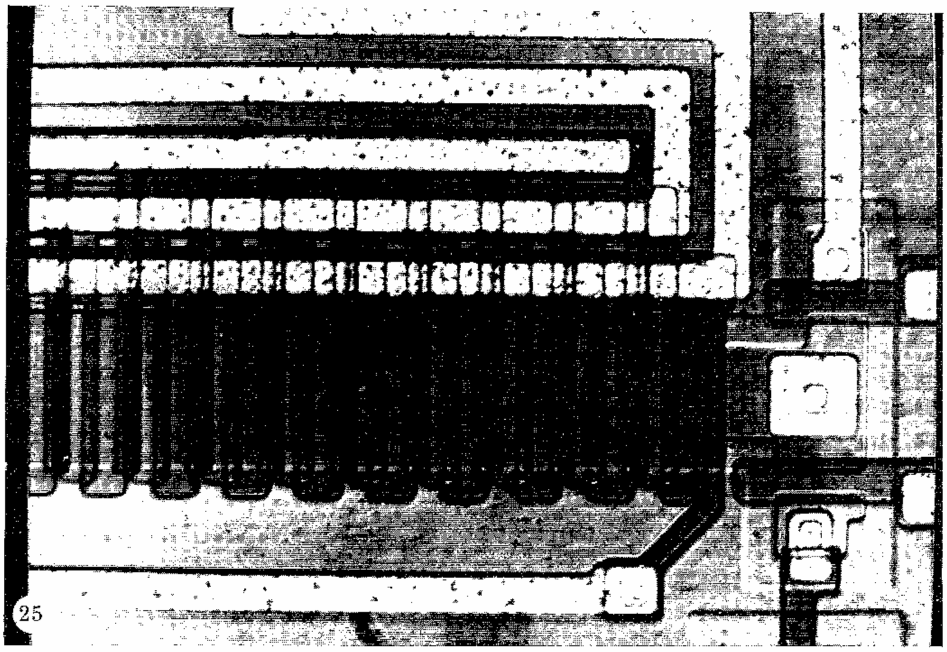
Ancillary procedural data relating to civil aircraft as derived from pilots' flight plans, also information supplied through the s.s.r. links such as identity, altitude etc. can all be written upon the p.p.i. tube face for the immediate information of the controller. Similarly, aircraft tracks can be formed by the tracking computer from the stored radar plots or from the extracted and stored s.s.r. plots and these tracks presented on the p.p.i. Such tracks can be used in the computer to anticipate conflictions and suggest corrective action. Courses to steer may also be immediately extracted and instructions passed to the pilot. But if this wealth of available data on the state of the airspace is not to saturate the controller he must be given some means of selecting the information he needs and structuring it for his immediate purpose – this is just what the 'Digilux' form of display supplies.

The Digilux interactive display

Primary or secondary radar plots held in store are displayed as in figure 27, plate 10 upon the Digilux p.p.i. to the controller. If he wishes to be informed of other flight data relevant to a particular aircraft he must inject its address into the data processing system. This he does by simply placing his finger over the plot of interest when the required data appears as a legend in proximity to the plot. Again, it is the availability of new semiconductor components which have made this convenient system possible.

The face of the cathode ray tube is surrounded by a square frame whose sides house a series of infrared emitting diodes and the corresponding photodiode receivers. Thus the tube face is traversed by a graticule of 64×64 infrared beams. When the controller places his finger over a radar target the intercepted x and y beam serve to generate the store address of the plot. Complicated optics are avoided by the simple expedient of activating the emitter and receiver associated with one beam only, the beams being scanned in sequence by the application of suitable waveforms to the diodes. In this display the phosphor is selected for brilliance and high definition since with a 'refreshed' display it is unnecessary to have the long persistence phosphor required by an ordinary p.p.i.

A similar touch address system can be employed in an alphanumeric tabular



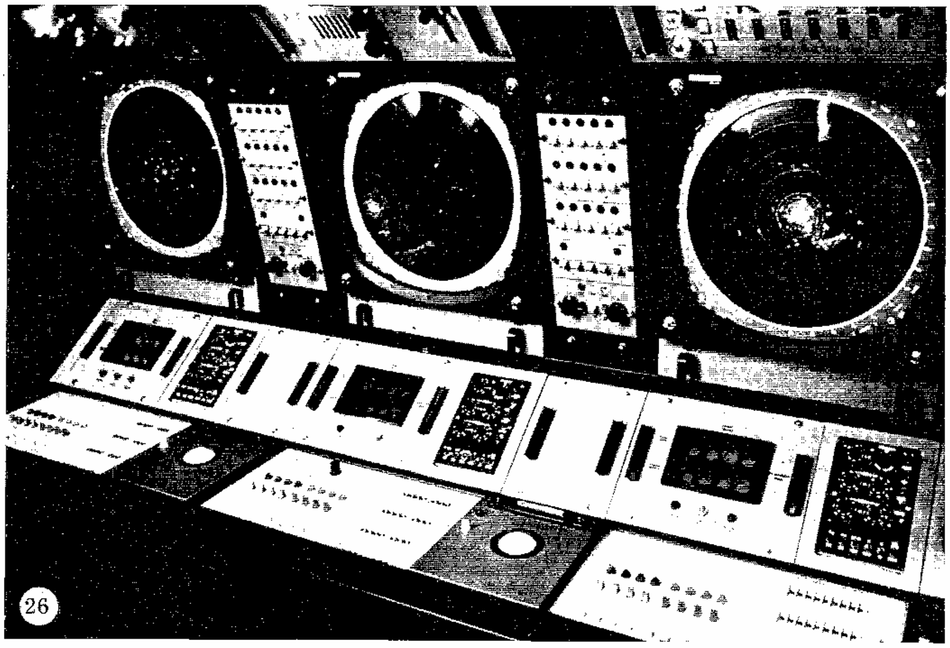


FIGURE 25. Output end of a charge coupled device showing the polysilicon electrode structure and part of the amplifier (magn × 2000). (G.E.C. Hirst Research Centre.)

FIGURE 26. Display console suite as used in a radar operations centre – with p.p.i., alphanumeric displays, tracker ball and inbuilt digital signal processing and computing facilities. (Marconi Radar Systems Ltd.)

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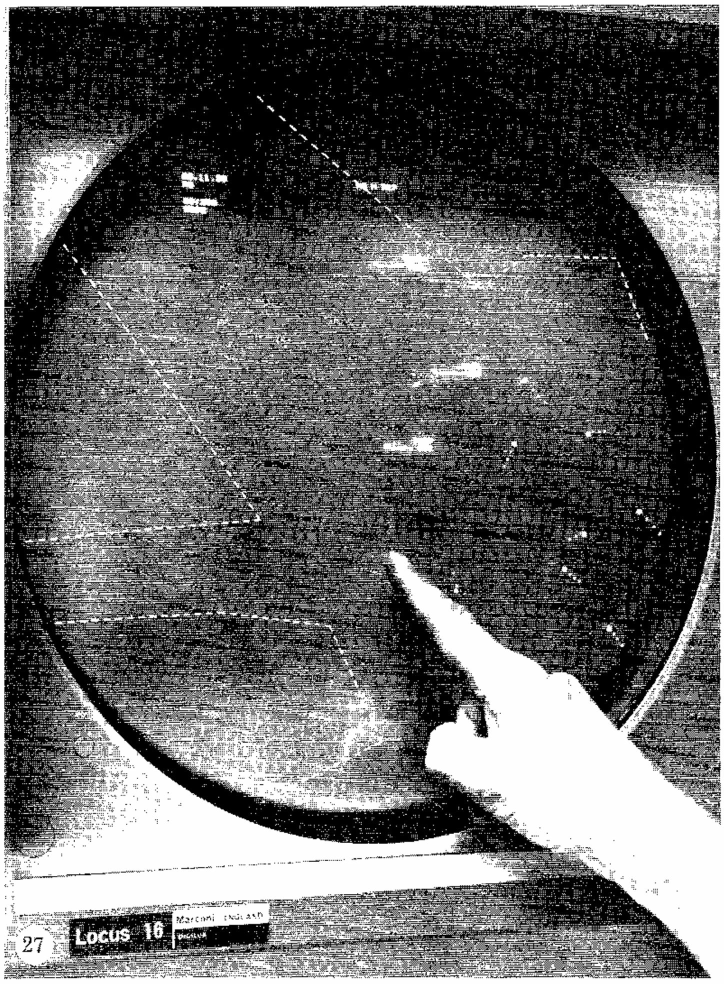

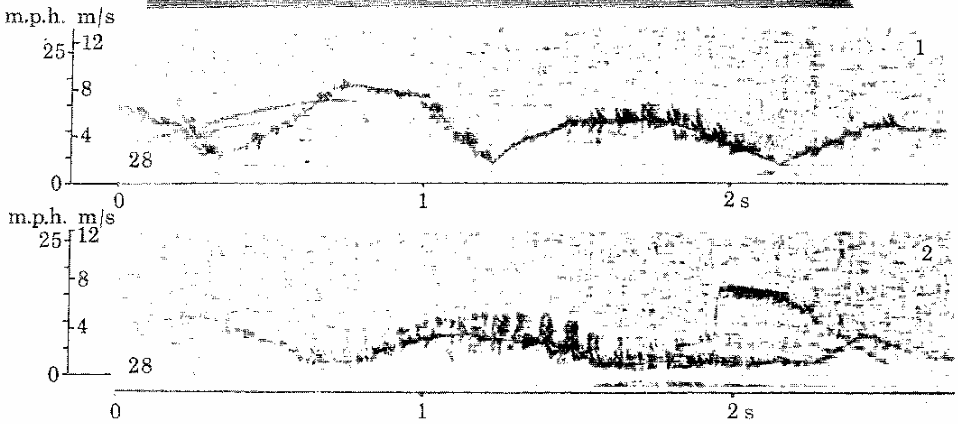

FIGURE 27. The Digilux system as used with a p.p.i. display to interface the controller with the radar data processing system. (Marconi Radar Systems Ltd.)

FIGURE 28. Radial speed record of a pipistrelle bat in flight as derived from the doppler signal output of a J-band radar. (Professor J. D. Pye, Queen Mary College).

display when it functions as a keyboard giving access into the data processor in order to call up or modify the data presented in the columns of the display. Unlike a keyboard however the Digilux presents to the operator only valid options and he has no need to remember the syntax which is structured for him in the software.

Some new applications of radar

Although radar was originally developed as a military aid it has proved to be a very effective sensor and measuring device for use in many civil systems and in many fields of scientific research. It has played an essential part in the development of Air Traffic Control and I have already made frequent reference to the ground radar surveillance component; but radar is equally essential in blind landing, and in the aircraft movement indicator, also in the aircraft itself for cloud and collision warning and in the doppler navigator. Other civil uses include merchant ship navigator, docking radar, road traffic control, security systems, as a monitor to check particle emission from chimney stacks and in engineering metrology using millimetric radiation. Scientific uses include – lunar and planetary studies; measurement of the astronomic unit; in meteorology, particularly cloud and precipitation studies, measurement of ice sheet thickness from an aircraft, satellite surveys of the Earth's surface; ionospheric and magnetospheric investigations with the Thomson scatter technique, also studies on the aurora. Radar is making a major contribution to certain behavioural studies in biology, e.g. studies of bird migration, observations of the swarming of insects and in investigations relating to the acoustic echo location system of bats etc. Time will only permit me to make brief reference to the very recent application of radar to the study of the flight of bats and their use of the sonar doppler effect.

Bats and the doppler effect

In sharp contrast to the 'big radars' of the Military and Air Traffic Control Authorities is the really small, solid state radar used by Professor Pye of Queen Mary College to help resolve certain aspects of a bat's use of sonar. It was in 1920 that Hartridge suggested that many species of bat might employ some form of acoustic echo navigation system to guide their noctural flights through trees, or into caves, and even to hunt their insect prey (Hartridge 1920). This suggestion was confirmed by Pierce & Griffin (1938) with their discovery of the bat's ultrasonic signals. Since that time and with the aid of modern electronics, a great deal has been learnt about the ultrasonic navigation and hunting systems which many bat species have evolved. As Professor Pye has commented 'In echo location bats appear to be very capable and experienced physicists' (Sales & Pye 1974).

It is now known that three types of ultrasonic signals are used by various species of bats, (1) sequences of short clicks, each a fraction of a millisecond in duration, (2) trains of swept frequency pulses with pulse separation varied to suit obstacle avoidance or the manoeuvres that mark the final stages of an interception, (3) long pulses of constant frequency but with variable interpulse periods. These three modes of sonar may be regarded as roughly analogous to pulse radar, f.m. radar and doppler radar respectively. It is tempting to equate the frequency modulated system to pulse compression but this has not been established; certainly, the increased bandwidth of the f.m. pulse will tend to favour more accurate range estimation.

The horsehoe bats (Rhinolophidae) are the most studied exponents of the constant frequency pulse; this frequency characteristic must provide very sensitive doppler detection of prey together with accurate knowledge of relative velocity to guide the subsequent interception. In a series of laboratory experiments performed in 1968 Schnitzler showed that when this bat approaches a target it changes the pitch of its emitted note so that the scattered signal is received at the constant frequency of about 83 kHz to which its ears are selectively tuned (Schnitzler 1968). This arrangement would tend to optimize the range performance of the sonar but the experiment also suggests that when a bat employs a constant frequency it is for the purpose of deriving relative velocity. Some species such as the pipistrelle when hunting in the open add a constant frequency element to a frequency swept pulse. Pye has suggested that the bat might derive some operational advantage from the doppler information supplied by this constant frequency addition. He has also pointed out that this possibility would be greatly strengthened if it were shown that the pipistrelle also applies doppler compensation. To establish this point requires that the bat's velocity relative to the recording microphone shall be measured simultaneously with the determination of the ultrasonic frequency, so that the frequency of the sound as emitted can be calculated. Professor Pye is developing a method of measurement which employs a small J-band radar (14 GHz, $\lambda = 2.14$ cm); 10 mW of power are supplied from a Gunn diode to an antenna of 20 cm^2 aperture (50 dB gain) and sensitivity is improved by a 2 MHz sinusoidal modulation applied to the carrier. Ranges of 50 m are obtained. The radar doppler signal is recorded simultaneously with the sonagram of the cries of the bat as in figure 28, which also shows a target in the form of a pebble thrown to the bat, as well as the movements of the bat's wings.

This work is in progress at the present time and may well establish how flexible bats can be in their use of echolocation and how adaptive is their choice of transmitted signal (Pye 1976).

It is a pleasure to acknowledge the generous assistance which I have received in the preparation of this lecture from my colleagues in the G.E.C. Hirst Research Centre, in the Marconi Research Laboratories and in Marconi Radar Systems Ltd. I am grateful to Professor J. D. Pye of Queen Mary College not only for permission to refer to his current radar studies of bats but also for a fascinating introduction to the ultrasonic navigation system of these amazing creatures. I would also like to thank the Director of the Appleton Laboratories for figure 24 on the structure of a rain cell as recorded at Chilbolton.

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