

Radar: new techniques and applications

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RADAR: NEW TECHNIQUES AND APPLICATIONS

Sir Eric Eastwood

Although radar was conceived as a military aid its methods and techniques have found applications as diverse as civil air-traffic control, behavioural research with birds, bats and insects and studying plasma drift in the ionosphere. One of the pioneers in radar research looks at some of the new techniques that are available to radar engineers and how they can be applied

The central problem in radar is to recognize and extract the desired radio or microwave echo signal from a mass of interfering signals from noise, back-scattered radiation and, in times of hostility, enemy signals produced with the intent of 'jamming' the receiver. The solution is to design an electrical filter which will execute the separation process.

Progress towards this objective has been greatly assisted in recent times by devices which have stemmed from solid-state physics, such as surface-acoustic-wave filters, charge-coupled devices and, especially, integrated electronic circuits which permit a computer-like approach to the filtering problem.

Early developments in radar

There is not sufficient space here to go fully into the wartime and postwar development of radar (the reader is referred to the full text of the Clifford Paterson lecture) but several landmarks are worthy of note.

Most significant was the invention by Randal and Boot in Britain in 1940 of the cavity magnetron which opened up the 3 and 10 cm (X and S) bands, giving a technological lead which ensured freedom from enemy jamming at these wavelengths up to the end of the second world war.

Vital contributions to the development of the magnetron, as to other special thermionic valves for radar, were made at the Wembley Research Laboratory of the General Electric Company, which was Sir Clifford Paterson's personal creation.

The provision of electronic countermeasures (active jamming) and electronic counter-countermeasures occupied the thoughts of the early radar designers, who realized that the best way to avoid jamming was to incorporate a high degree of frequency flexibility in the transmitter and use broad-band aerials. It was also realized that the transparency of the array to incident jamming power could be reduced by using a very narrow primary beam together with low side lobes at all other angles.

A way had also been found round the passive jamming technique of dropping resonant reflectors – thin strips of metal foil – to obscure the path of a bomber force from surveillance radars. To cope

This is a shortened version of the Clifford Paterson memorial lecture given by Sir Eric Eastwood CBE, FRS to the Royal Society on 11 November 1976. The full text is to be published in the *Proceedings of the Royal Society*, to whom we are grateful for permission to publish. Sir Eric is Chief Scientist at the GEC-Marconi Research Laboratories, Chelmsford.

with this, radars had to have a narrow beam and short pulse length, and had to be capable of using velocity discrimination by taking advantage of the difference in Doppler frequency shift between signals scattered from the aircraft and those reflected by the strips.

More pertinent to the development of modern civil (and defence) radars were the techniques developed to reduce 'clutter' – the unwanted echoes from extended scatterers such as the ground, rain clouds and flocks of birds. This obscuration can be reduced by appropriately shaping the radiation pattern of the antenna and 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.

Another technique developed in wartime which had implications for modern civil aircraft radars was the 'friend or foe' identification. Pulses transmitted from the ground triggered a receiver-transmitter in 'friendly' aircraft which radiated an additional coded signal to be superimposed on the radar echo. In modern equipment, interrogation takes place on an independent channel at about 1100 MHz, known as secondary surveillance radar (SSR) and yields information on range, bearing, call sign and altitude. The aircraft transponder has thus become a communications beacon and an essential component of civil air-traffic control, while primary radar fulfils an airspace monitoring function. In the military case, however, aircraft must be regarded as non-cooperative and SSR is inappropriate.

The microwave antenna

The need for an antenna that will minimize both clutter and jamming (i.e. covering a broad band to

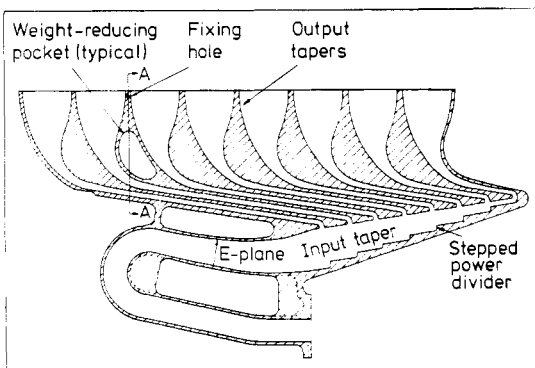
permit frequency agility, with a narrow main beam, low side lobes, reduction of ground illumination combined with comprehensive cover in elevation) has prompted many design approaches. The operational requirement defines the far-field radiation pattern from which may be derived the amplitude and phase 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.

A parabolic, cylindrical reflector with a slotted waveguide feed, for instance, has the advantages of 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 azimuthal displacement of the beam (known as 'squint'). For a fixed-frequency radar such as the 50 cm surveillance radar used by the British Civil Aviation Authority it is ideal; a chain of these monitors 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 features in the defence radar for avoiding jamming. 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 1 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 horizontal radiation pattern measured on an antenna composed of eight such 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 four minutes of arc. Computer aided design and digitally controlled machining methods must be used to obtain the required accuracy and are now 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 alternative technique is to employ intermediate-frequency scanning of the received beam only – a type of 'array signal processing' as it

Figure 1 To achieve the characteristics of broad bandwidth, freedom from azimuthal displacement (squint) and very low sidelobes which are desirable in defence radars, linear arrays are fabricated to give an equal path length and similar dispersion characteristics from the transmitter to each of the radiating horns. The geometry of the module is arranged to give both squintless feed and a tapered power distribution across the antenna



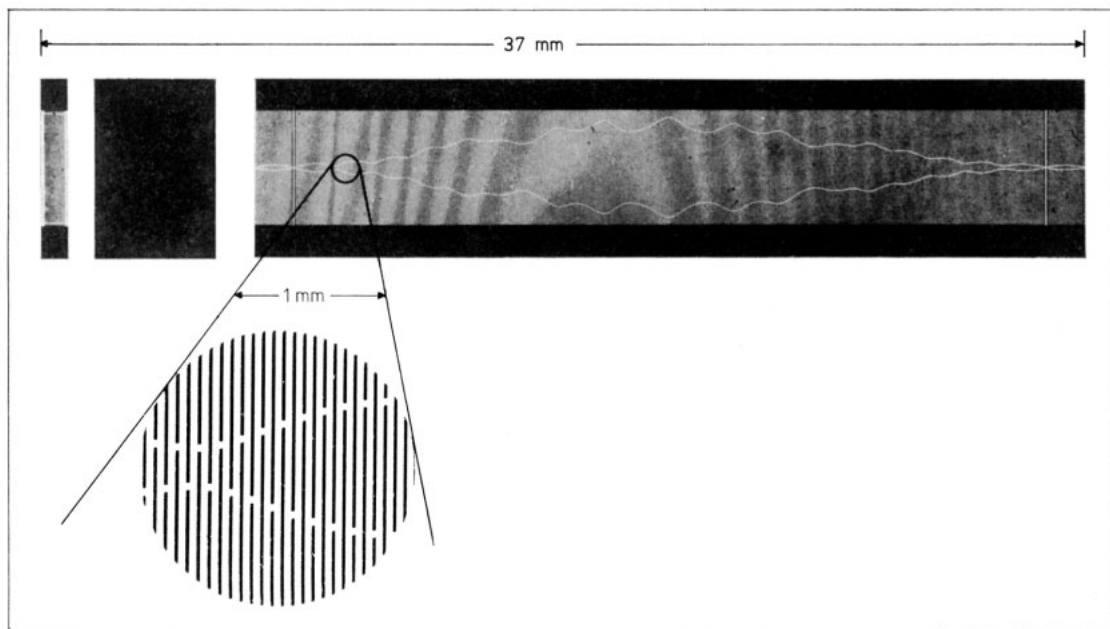


Figure 2 A pulse-compression filter which uses a surface acoustic wave transducer to obtain time compression of a frequency-swept pulse. A microscope picture of 1 mm of the launcher section is included to show the aluminium finger pattern

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 second world war this valve should be further extended to give increased power and improved stability of frequency. Available S-band (10 cm) pulse power was soon raised from 500 kW to 2 MW and L-band (~ 30 cm) 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 role, to produce a so-called cross-field amplifier (where magnetic field is 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.

A major disadvantage of the klystron is its limited bandwidth ($< 3\%$); the power travelling-wave tube

(TWT) 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, and this is just what the 'Twystron' provides. This may best be described as a klystron-injected TWT, which gives high gain with large bandwidth. A modern Marconi L-band radar transmitter using an EMI-Varian Twystron power tube, for instance, can provide 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 need only be 1W. With this equipment, frequency change from pulse to pulse may be programmed. If the transmitter were serving a civil air-traffic control function, then within a single modulator pulse two RF 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 intermediate frequency (IF) amplification, is passed into a dispersive filter whose effect is to bring the various Fourier components of the frequency modulated (FM) 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

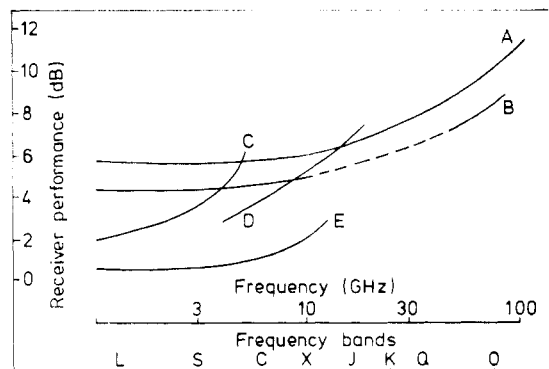
retains the target detection capability of the long pulse. This principle was first suggested nearly thirty years ago but utilization in microwave radars had to await the arrival of stable amplifier transmitters such as that described above. Dispersive networks made up from lumped capacitors and inductors were first employed for the IF 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 2. 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 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. Such a system giving a pulse-compression ratio of 27 has been supplied to the Technical University of Denmark for an airborne radar experiment to measure the thickness of ice layers.

The microwave receiver

Although the travelling wave tube RF amplifier was used with many post-war 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 in the S- or L-bands compared to around 18 dB in early receivers. Figure 3 illustrates

Figure 3 Variation of receiver noise figure performance as a function of frequency for various types of semiconductor microwave receivers.

A: Superheterodyne (mixer diode, image matched), B: Superheterodyne (mixer diode, image enhanced), C: Bipolar transistor amplifier, D: FET transistor amplifier (uncooled), E: Uncooled parametric amplifier (varactor diode ~ 300 K)



the variation of noise figure with frequency for various types of semiconductor microwave receivers. The Marconi L-band Twyston radar described earlier 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 in the L-band.

Clearly, radar has benefited greatly from advances in solid-state physics. Integrated microwave circuits have been significantly reduced in size so that, for instance, the essential units of a complete radar head are now small enough to be carried by one man, and yet are capable of detecting a moving man at a range of nearly one kilometre. This is done by using a pulse Doppler system (RF at 17 GHz) with Doppler tone detection of the target made through headphones. The microwave receiver and automatic frequency-control circuit are integrated onto one alumina substrate; while a Gunn diode transmitter and local oscillator are contained in similar units.

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

Figure 4 Moving-target indicator (MTI) using a two-pulse single-delay canceller to eliminate echoes from stationary targets. COHO stands for coherent IF oscillator; f_i is the intermediate frequency and f_D the Doppler frequency

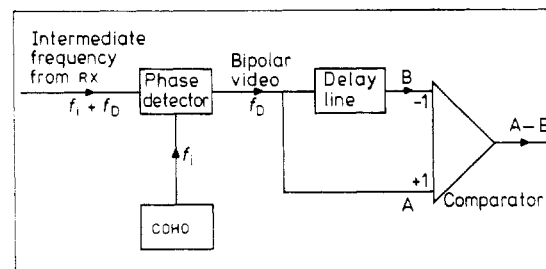
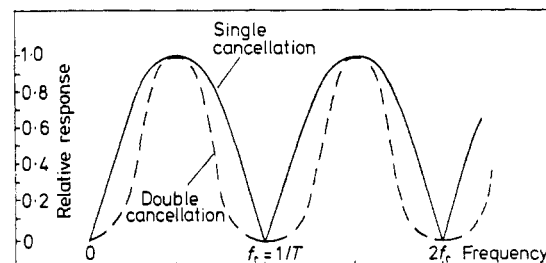


Figure 5 Frequency response of a single-delay-line canceller (solid curve) and a double-delay-line canceller



ATC at major airports now relies upon SSR but primary radar still has an important civil monitoring role 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 $f_D = \frac{2v_r}{c}$ or $\frac{2v}{\lambda}$ (where c is the velocity of light and λ is the radiated wavelength).

The early method of achieving moving-target indication (MTI) was by means of a delay line canceller which eliminated the echoes from stationary targets (figure 4). Echo pulses are heterodyned to the intermediate frequency for amplification, then applied to a phase detector for comparison with the signal from a coherent IF 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 plan-position indicator (PPI).

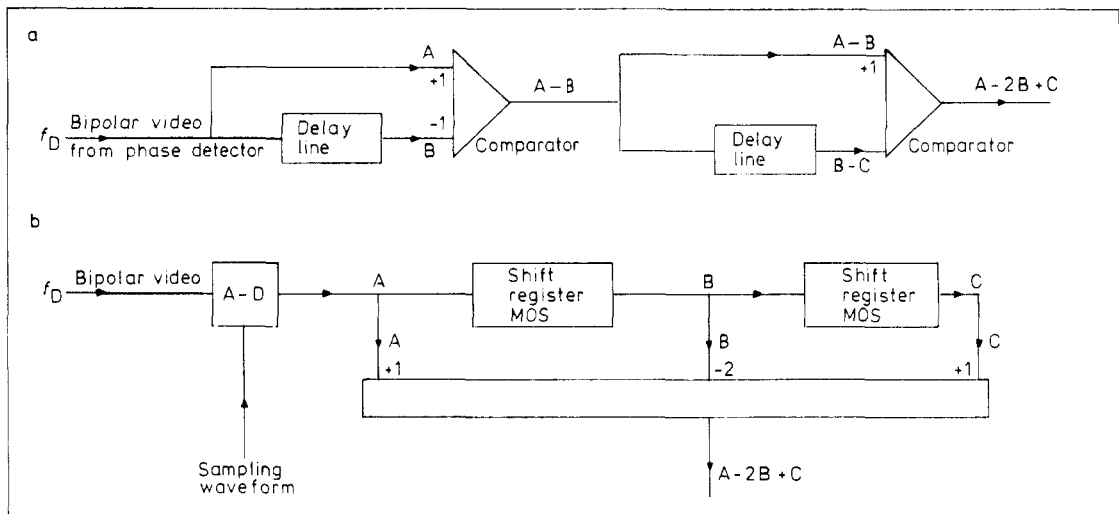
In a klystron amplifier radar the coherent IF oscillator (COHO) is a crystal-controlled oscillator, but in a magnetron MTI radar the magnetron is incoherent from pulse to pulse, so a locked COHO is employed to 'remember' the phase of the outgoing

pulse. A modern tunable magnetron locked to a crystal-stabilized local oscillator (STALO) gives an MTI 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.

The delay-line canceller functions as a simple filter which rejects the DC component of the clutter and has the frequency characteristic shown in figure 5. It will be noticed that the output is zero for certain conditions ($f_D = nf_r$) known as the 'blind speeds' which correspond to the displacement of the target through a multiple of $\lambda/2$ 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 6) when the sinusoidal characteristic becomes squared. 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, and the resultant characteristic does not give increased operational advantage. What is required is an adaptive filter which removes not only zero Doppler ground returns but also the clutter from rain, bird flocks and reflective jamming (in the military case).

Examination of figure 6 suggests that an alternative

Figure 6 Derivation of a three-pulse digital MTI comparator (b) from a three-pulse double-delay analogue comparator (a)



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 MTI 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 way 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 levels) in a period of about $1\ \mu\text{s}$ (figure 6). 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 of the transmitter and this trigger pulse is derived from the clocking sequence which moves the bits through the registers, it is easy to operate the radar on two or more pulse-recurrence frequency values whereby MTI 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’.

Cancellation of echoes from targets moving on tangential courses is well illustrated by figure 7 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 IF signal is fed in parallel to a second phase detector whose reference is the COHO signal delayed in phase by $\pi/2$. 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)

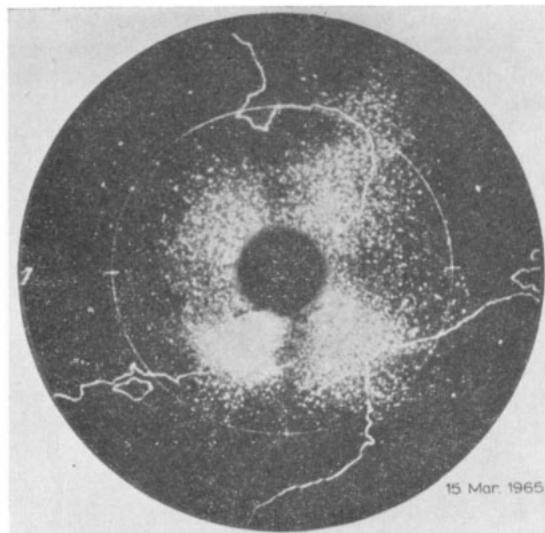


Figure 7 Easterly migration of birds observed by radar. Illustrates ‘MTI wedges’ to the north and south due to cancellation of near-zero Doppler returns from targets moving on tracks tangential to the radar station

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 MTI system can provide a clutter cancellation ratio of 40 dB, the limit being set by the aerial-scanning effect on the clutter spectrum.

Using the digital signal-processing methods outlined above, together with I and Q channels and a sequence of four identical shift-register delay-lines it is possible to design a form of transversal filter which, in effect, covers the Doppler band of the radar (0 to f_r) by four filters whose characteristics are located as shown in figure 8. 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.

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 level of clutter plus thermal noise is averaged over time, the stored result being updated with every

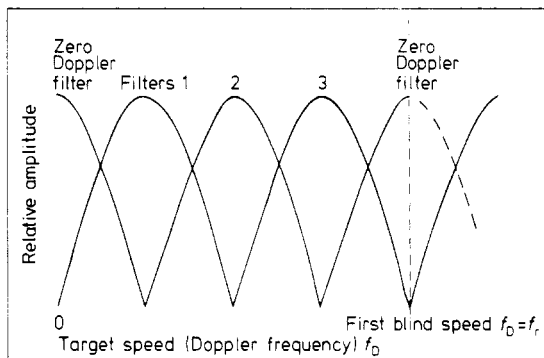


Figure 8 Frequency characteristics of the multifilter, digital MTI system

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 PPI 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 PPI or, more usually, to the plot extractor stage of the signal processing system.

Perhaps, however, 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.

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 CCD. The CCD is a silicon integrated circuit which may be made by well established MOS processing techniques. 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-SiO₂ 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 CCD price competitive with the MOS shift register; when this happens CCD digital delay lines may well be used in the multifilter MTI 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), PPIS 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. The PPI 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 PPI 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 PPI 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 SSR links such as identity, altitude etc, can all be written upon the PPI 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 SSR plots and these tracks presented on the PPI. Such tracks can be used in the computer to anticipate conflicts 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

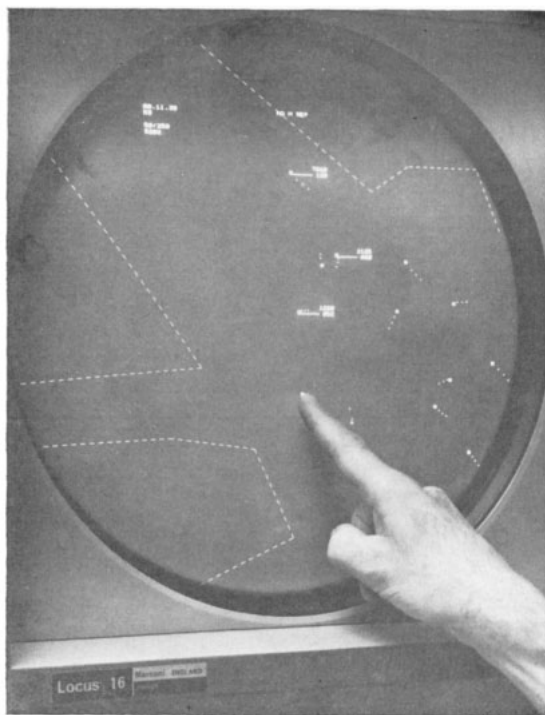
state of the airspace is not to saturate the controller he must be given some means of selecting the information he needs and structuring it for his immediate purpose – this is just what the 'Digilux' form of display supplies.

The Digilux interactive display

Primary or secondary radar plots held in store are displayed as in figure 9 upon the Digilux PPI 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

Figure 9 *The Digilux system as used with a PPI display to interface the controller with the radar data processing system*



definition since with a 'refreshed' display it is unnecessary to have the long-persistence phosphor required by an ordinary PPI.

A similar touch address system can be employed in an alphanumeric tabular 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 navigation, 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. Space 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, London, 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 nocturnal flights through trees, or into caves, and even to hunt their insect prey. This suggestion was confirmed in 1938 by Pierce and Griffin 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

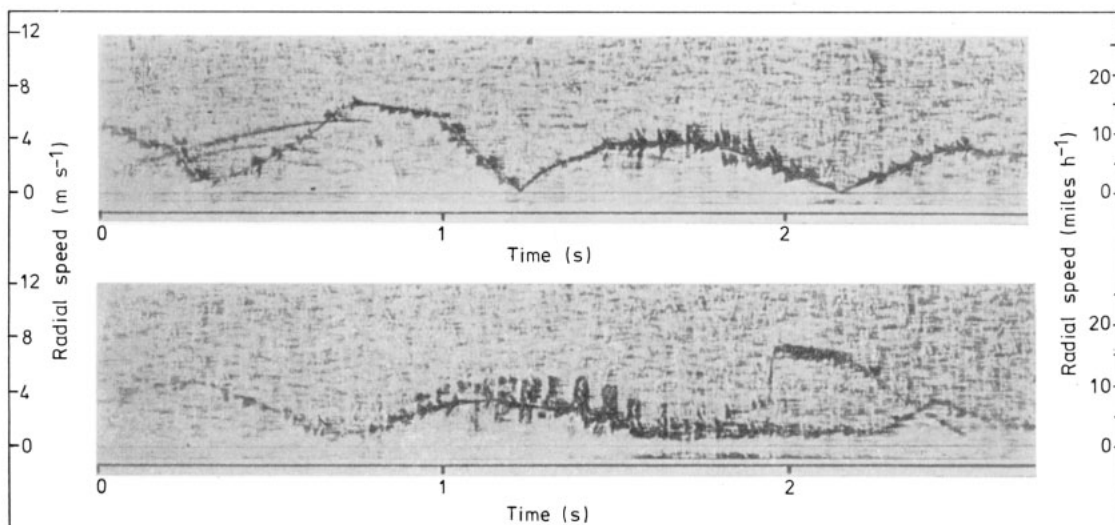


Figure 10 Radial speed record of a pipistrelle bat in flight as derived from the Doppler signal output of a J-band radar

very capable and experienced physicists'.

It is now known that three types of ultrasonic signals are used by various species of bats: (i) sequences of short clicks, each a fraction of a millisecond in duration, (ii) trains of swept frequency pulses with pulse separation varied to suit obstacle avoidance or the manoeuvres that mark the final stages of an interception, (iii) long pulses of constant frequency but with variable interpulse periods. These three modes of sonar may be regarded as roughly analogous to pulse radar, FM 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 FM pulse will tend to favour more accurate range estimation.

The horseshoe 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. This arrangement would tend to optimize the range performance of the sonar but the experiment also suggest 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. Professor 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 is supplied from a Gunn diode to an antenna of 20 cm² 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 10 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 echo location and how adaptive is their choice of transmitted signal.

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