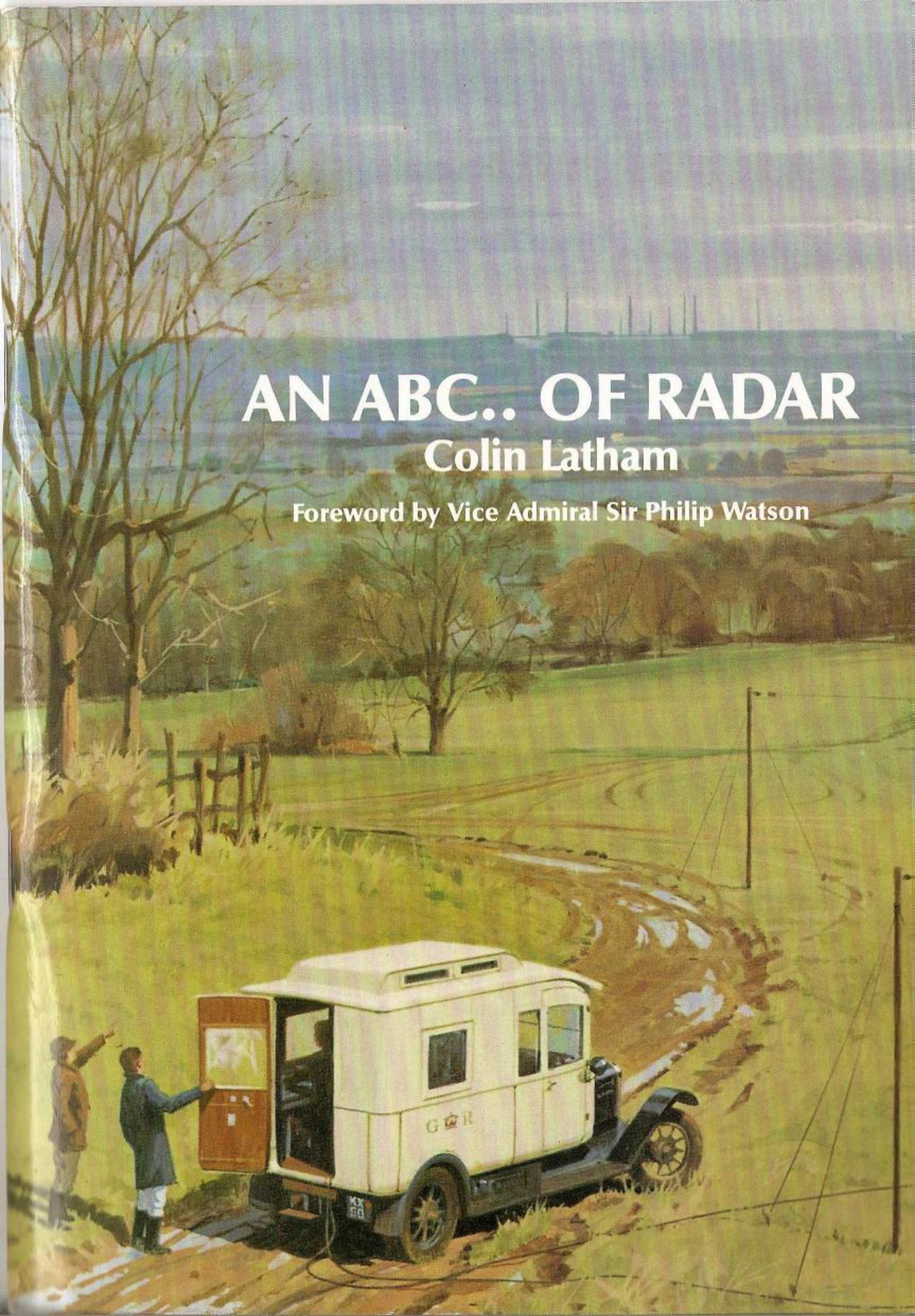
AN ABC.. OF RADAR

Colin Latham

Foreword by Vice Admiral Sir Philip Watson



Dedication

I hope this compilation may be taken as a small tribute to the British radar pioneers of the 'thirties' and 'forties' by whose vision and determination the dream of early-warning by radio came true.

CL

COVER PICTURE

The scene depicted on the front cover is an artist's impression of radar pioneers Wilkins and Watson Watt about to perform their historic experiment on 26th February 1935 (see page 58)

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by Colin Latham

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O P Q R S T U V W X Y Z A B C D F G H I J K L M N

An
ABC… of Radar

by

COLIN LATHAM

Editor's Note

Spread over a period of six years Colin Latham has written this series of short articles, for each letter of the alphabet. They were published in the bimonthly company newspaper, "News and Views". I have done little editing to the original articles. Colin mentions items topical on days they were written. I have not edited out those references and consequently in a few places have had to add a note to indicate the date the item was current.

May I add what a pleasure it has been producing this work, especially working alongside Colin. I would like to say a special thank you to Colin's wife, Vera, and to all my colleagues who have assisted in this venture.

J.P.
Chelmsford
April '89

Foreword by

Vice Admiral Sir Philip Watson,

KBE., LVO., CEng., FIEE., CBIM.
(Sometime Director General of Weapons for the Royal Navy and Chairman of Marconi Radar Systems Limited)

Colin Latham's involvement in the technology of radar has occupied nearly the whole of his working life, which has been contemporary with the development of the technology itself.

Starting when radar was newly available to the Royal Air Force in 1941, Colin has been concerned with it almost continuously as a teacher and as a radar engineer responsible for the design and production of air traffic control and air defence systems.

His knowledge of the subject is encyclopaedic, and it is typical of Colin that he should have perceived an opportunity and written this veritable encyclopaedia for those concerned with the subject but less embroiled in the technology.

Colin's "Alphabet" was a very popular feature of "News and Views" and I welcome this initiative to bring the whole alphabet together in this permanent form.

P.A.W.
Banbury
April 1989

Preface

Those of us present at a general manager's meeting in 1982 were urged to consider what form a new company newspaper might take and to suggest topics for articles and features. Without having thought about it previously I heard myself suggesting a 'popular' non-technical series explaining technical and key historical subjects for those employees who, while not themselves engineers or scientists, would often hear mysterious terms being bandied about. We could, for example, start with the letter A and work through the alphabet.....

So much for making suggestions! When asked to prepare the first article I little thought I would still be at it when retiring (between K and L), let alone carrying on to Z in the years beyond. All along the way I have much appreciated help from good friends, especially Bruce Neale, radar historian par excellence, and Gerry Taylor, authority on air traffic control.

I am very grateful for the company's action in publishing the complete series in such a handsome single volume and hope that the various topics may continue to be of interest

C.L.
Beaumaris
April '89

A stands for Aerial or Antenna

AERIAL or ANTENNA are words that mean the same thing, ANTENNA being the American version. 'A' also stands for Arguments – about whether more than one antenna should be antennas or antennae! In Marconi Radar, however, we use the word antennas, – antennae being reserved for insects.

Radar, like the parent science of radio, relies on aerials to receive and send signals. When Guglielmo Marconi made history by sending signals across the Atlantic, his receiving aerial in Newfoundland was a wire held aloft by a kite while the transmitting aerial in Cornwall was strung from high towers.

Common examples of aerials in everyday use are the whip types on cars and some transistor radios.

Such aerials are mainly for receiving only although Citizen Band aerials are used for transmitting also. Whip type aerials give roughly equal performance all round (omnidirectional) but other very common types, the 'fishbone' or 'Yagi', (after the man believed to have been the originator) as used for TV, favour a particular direction, give improved reception and help to ignore unwanted signals and interference.

A radar has a very high power transmitter and a very sensitive receiver. Very early radars, as used in Great Britain before and during the 1939–45 war, had separate transmitting and receiving aerials mounted on tall towers similar to the one still existing on the Marconi Research site at Great Baddow. (See fig. R1, page 43 and fig. M4, page 35). Later wartime and modern radars usually have a common aerial switched between the separate functions of transmitting and receiving, at rates up to thousands of times a second.

For radar, accurately shaped beams of radiation are essential. These are often produced by a specially shaped reflector which acts as the radiation source when transmitting and the collector when receiving.

For some applications, such as tracking radars which deal with only one target at a time, a 'pencil' type beam is required and this is produced by a circular 'dish' reflector – somewhat similar to the reflectors used in some car headlights (fig. A1).

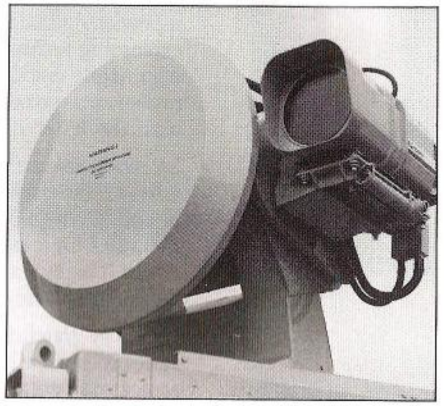


Figure A1. Marconi tracker antenna ('Pencil' beam — 3cm wavelength) with co-mounted TV camera.

For surveillance or search type radars a precisely shaped beam is required. It must be narrow in width for fine discrimination between targets at close bearings but broad in height to detect those at greatly differing heights (fig. A2).

If this beam is swung in a circle by rotating the aerial, full all-round cover is achieved. The angular position of the aerial, together with the indicated range, giving the plan position of the target.

If the vertical beam of a surveillance radar is divided into a number of narrow, slightly overlapping beams, it is also possible to obtain the height of each radar return by using the known beam angle and the target distance. This type of radar, able to define a target's position in space, is known as "three dimensional" (e.g. Martello).

Even when extreme care is taken to produce a radar beam which has 'clean' or 'sharp' edges, some radiation inevitably spills over in unwanted directions.

This unwanted radiation causes 'sidelobes' or 'backlobes' and can be of great disadvantage to military radars in jamming conditions.

Such side or backlobes can be reduced significantly by using a 'planar' type of aerial, as in Martello (fig. A3).

In the planar aerial, a very large number of small aerial elements (typically several thousand) are arranged over a flat surface. When care is taken to ensure that all elements operate in the correct phase relationship, the resulting radiation from them combines to form a beam (or beams) of the required shape.

The techniques of radar aerial design have much in common with optics. Similar principles are used in the design of astronomical telescopes but with much smaller dimensions for the shorter wavelengths involved.

Radar aerials require sophisticated design, precision manufacture and careful testing, all of which are very much within the province of Marconi Radar.

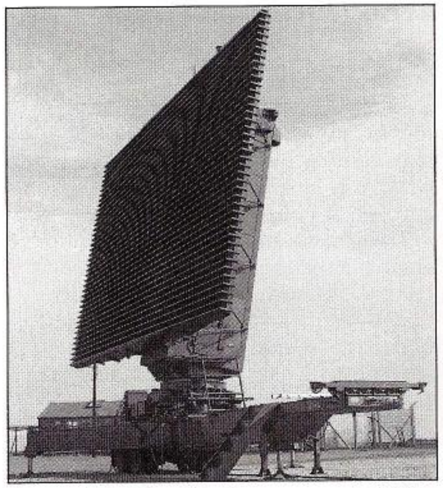


Figure A3. Martello planar array of 2560 elements (23cm wavelength).

Figure A2. Marconi air traffic control antenna (10cm wavelength) produces a beam narrow in horizontal plane, broad in the vertical.

B for Beamwidth, Bandwidth and Bistatic

BEAMWIDTH

A surveillance or search radar beam rotates continuously, seeking targets in all directions. The power, and hence the sensitivity, of the radar are maximum at the centre of the beam when it is looking directly at the target and less at either side.

The beamwidth is the measured angle between the sides of the beam at the points where the power has fallen to half the value at the centre. Typical horizontal beamwidths (fig. B1) for surveillance radars range from less than a degree to several degrees.

For a given wavelength, the wider the antenna the narrower the beamwidth and designers have to consider many conflicting factors before settling on a practicable compromise.

For example, a large antenna gives a narrow beam and good angular discrimination but can be expensive to manufacture. Also it may require considerable power to rotate it, especially in high winds (figs. B2, B3, B4).

Shorter wavelengths give narrower beams for a given antenna size but the radar performance may be affected adversely by weather conditions such as heavy rain.

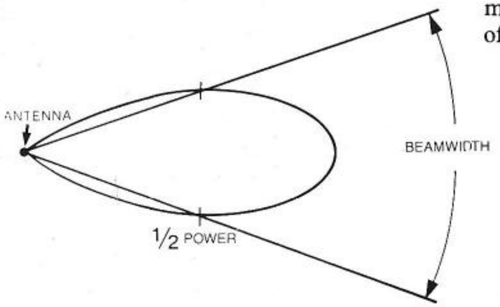


Figure B1. Plan view of surveillance radar beam.

BANDWIDTH

This is a term with many applications. In radio and radar engineering it is used to describe the range of frequencies to which a system can respond instantaneously without adjustment or tuning.

For example, a radio set is tunable so that it may, for instance, pick up stations on the medium, long or VHF wavebands but it is its bandwidth that enables it to respond to the variations of frequency contained in each programme – and is a factor controlling the quality of sound produced.

Bandwidth is also used to describe the range of radio frequencies over which a radar can operate. Simple radars work at a fixed frequency but more sophisticated equipments may operate over a band for various reasons, such as improvement in target detection and, in the case of defence radars, improved resistance to enemy jamming.

A bandwidth of 10-20 per cent of the centre frequency is common and for such 'wideband' or 'frequency-agile' radars the bandwidths of many parts of the system have to be matched, (e.g. transmitter, receiver, antenna and the entire radio-frequency transmission system between these elements).

Successful wideband design calls for much patience and skill and nowadays is often aided by computer models.

BISTATIC

The majority of radars incorporate the transmitter and receiver on the same site, generally sharing the same antenna. This is called monostatic.

However, there are advantages, particularly from the air defence point of view, in installing the transmitter and receiver, together with their associated antennas, at separate sites which can be many miles apart. Such a radar is said to be bistatic.

Because the transmission and reception paths are different, determination of target position is more difficult, requiring calculations for every radar plot. With modern high-speed on-line computers this problem can be overcome and we may expect to see an increasing use of bistatic radar installations in the future.

In fact, many receiving and transmitting stations may work together with suitable computer control and correlation of signals. Such a system would be 'multistatic'.

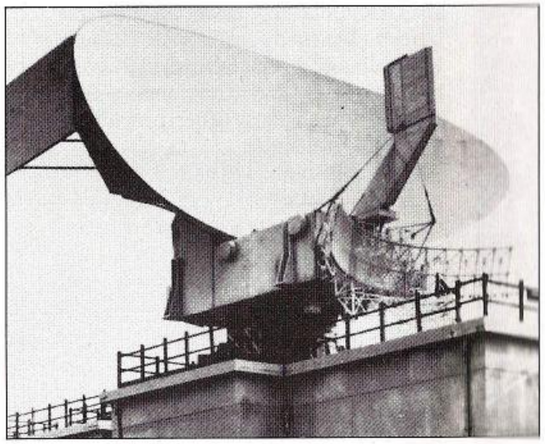
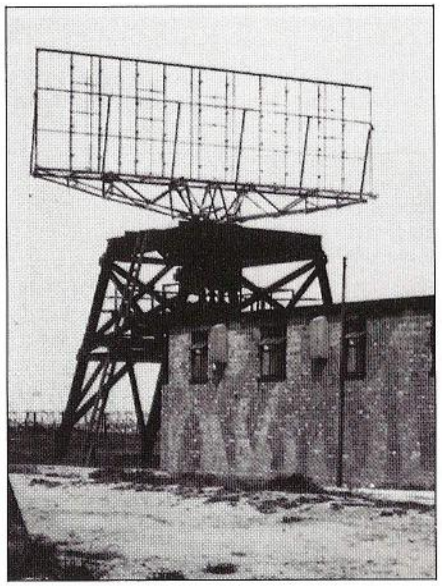


Figure B3. Large horizontal dimension gives beamwidth under half-degree because of short wavelength (10cm).



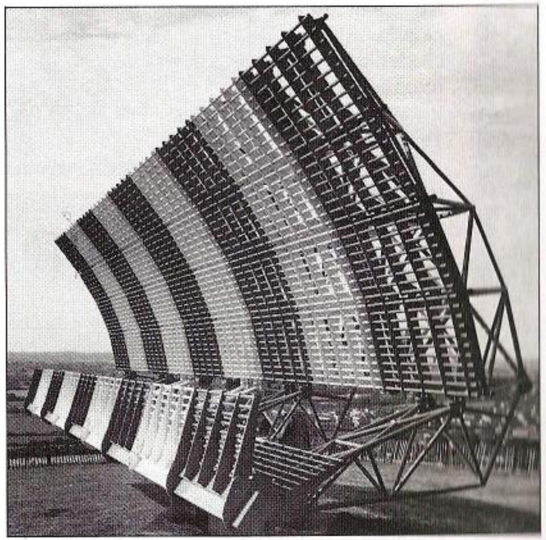


Figure B4. A large Marconi ATC antenna. Horizontal beamwidth nearly 3° despite size because of longish wavelength (50cm).

Figure B2. Wartime radars of this type (Chain Home Low) had poor angular discrimination. Beamwidths approached 10° because of long wavelength (1½ m).

C for Clutter

IN CHOOSING a radar word for the letter C I picked CLUTTER because it has probably been the cause of more hard work and heartache among radar engineers than most other problems in the history of radar.

Clutter in radar has much the same meaning as in everyday life – something unwanted that gets in the way of the job in hand – and is applied to the effects caused on a radar picture by returns from unwanted targets.

A surveillance radar is employed to detect and monitor the changing positions of aircraft but its ability to do so is often hampered by responses from fixed objects (towers, buildings, mountains etc). This is 'ground clutter' but clutter also arises from reflections from moving objects such as birds and clouds. Also, in wartime, man-made clutter may be produced by the intentional dropping of metal foil known as 'chaff' (or 'window' in the 1939/45 war).

During the war tremendous advances took place in radar so that by the end the defence chain was extensive, well organised and reliable. Airborne, naval and army radar too was well established. Probably the greatest outstanding radar problem confronting all three services was clutter rejection and little real progress was made until the early 1950s, notably with Marconi experimental equipment set up at Bushy Hill.

MTI (Moving Target Indicator) systems were developed which, by employing frequency-stable transmitters and receivers, examined the very small frequency changes contained within returning signals in order to assess target velocity (another application of the well-known 'Doppler' effect). Fixed targets were then separable from moving targets and could be eliminated from the radar picture. However, there were limitations in that aircraft flying on a course around a radar at constant range might also be rejected; also the first MTI systems suffered from 'blind speeds', so that targets moving at certain discrete velocities were eliminated as if they were ground clutter.

Blind speeds are related to the radio frequency itself and to the interval between pulses. Blindness was overcome by changing the interval rapidly by the use of 'staggered PRF' (PRF – Pulse Recurrence Frequency).

Some of the earlier MTI systems installed 20 or more years ago gave an excellent improvement but had the disadvantage that they required frequent re-adjustment to keep at peak performance, not always an easy matter on radars at remote sites where specialist engineers are not always at hand.

More recently, numerous technical advances in signal processing have enabled both fixed and moving clutter to be suppressed and blind speeds virtually eliminated, but probably the biggest improvement is in circuit reliability and freedom from the need for adjustment by the user. This is the result of solid-state digital circuits using suitable computer-like techniques which are vastly superior in stability to the older generations of analogue valve circuits.

In addition to complex circuit techniques for sorting wanted from unwanted signals, antenna design – previously mentioned in this series – can assist in clutter reduction by providing beams with a 'sharp bottom cut off' to minimise radar illumination of the ground.

Although technically the battle for clutter rejection is largely won, operational radar performance specifications continue to call for better visibility of small targets against large clutter backgrounds. So the work goes on, with emphasis on designs that compete commercially and which, despite their complexity, are reliable and easy to maintain.

Finally, because the purpose of most surveillance radars is to see aircraft for air traffic control or defence they are designed to reject rainclouds as clutter.

On the other hand designers of storm warning meteorological radars would have a different objective! One man's meat...

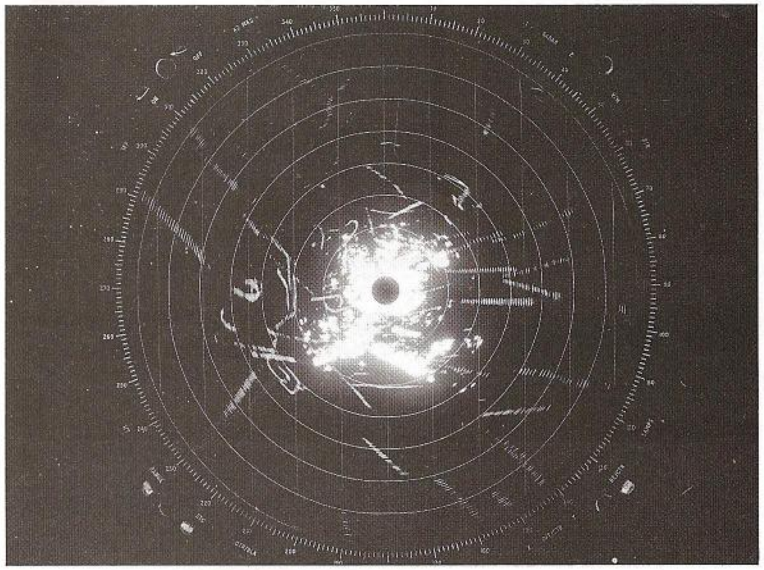


Figure C1
Unprocessed radar display. The clutter is the white area in the centre.

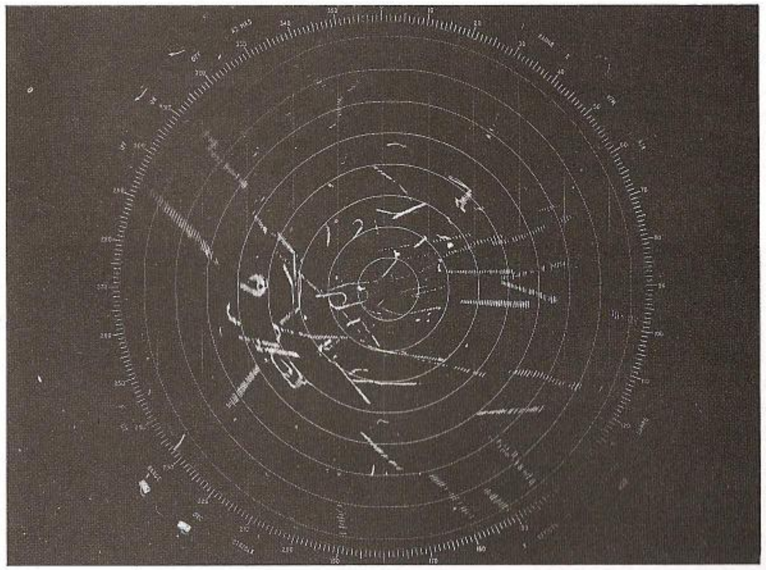


Figure C2
Processed radar display, with clutter removed.

D for Display

THE essential equipment for a surveillance radar comprises a transmitter, an aerial (usually common to transmitter and receiver), a receiver, some form of signal processor and finally a display on which the radar information is presented to the operator. The display is thus the final link in a chain of electronic equipment and to use fashionable jargon is the main 'man/machine interface'.

Figure D1 shows an early range display as used on the pre-war CH stations where radar echoes were presented as downward vertical deflections from a horizontal trace calibrated in miles. Such displays were based on the already established circuit techniques for using cathode ray tubes in television (remember, in 1936 we were the very first country in the world to have a public high-definition television service).

Although it was necessary to view the CH radar screens under dim lighting the trace was very finely focused and permitted experienced operators to assess the number of aircraft flying in a formation – a feature which is hardly possible even with modern radar. However, bearings had to be found for each echo by manual operation of a direction finding control (goniometer) so the overall process was somewhat slow (see page 20).

In the early war years the first plan position indicators (PPIs) went into service; these, as the name implies, give a total presentation of the area surveyed by a radar (see fig. C2, page 13). Echoes appeared as bright-up marks on a trace rotated about the centre (like the hand of a clock) by deflection coils behind the screen, placed around the neck of the cathode ray tube and mechanically driven from the rotating radar aerial. Later the deflecting coils were rotated by electro-mechanical links (old hands will recall the 'Selsyn' system) until, in the early 1950s, work commenced in Marconi Research on development of the so-called 'fixed coil' display.

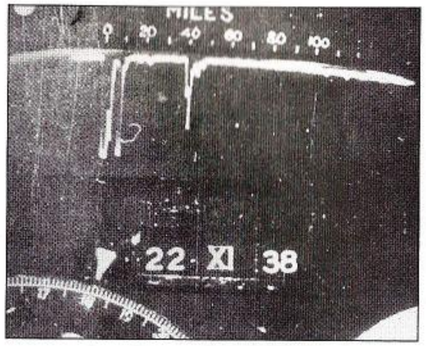


Figure D1. Range display in operation at experimental CH station just before the war.

This enabled a rotating trace to be produced by suitable electrical waveforms applied to non-rotating coils and opened the way for the presentation of additional information and symbols on the radar screen such as identification markers, area maps, etc.

From that moment radar displays became altogether more effective for air defence and ATC operations: it became easier to link together several displays and to improve co-operative working between a team of operators.

In the early fixed coil display installations the 'back-up' equipment which generated deflection waveforms and symbols used valve circuits and far exceeded in bulk the displays themselves. In recent years advances in transistor technology and miniaturised circuits have enabled much, if not all, of the 'back-up' to be built inside a tabletop display, such units being known as 'autonomous displays'.

Despite many improvements, the principal component is still the cathode ray tube and although there have been ideas for other forms of display (e.g. plasma and electro-luminescent) it still reigns supreme and appears likely to do so for the rest of this century at least. A lonely thermionic survivor in a solid-state age!

Most radar displays, whether they operate directly from received radar signals or from synthetic digital signals formed by plot extractors (see fig. D2) are 'stroke written' i.e. the electronic beam is moved directly to trace out the shape to be presented to the viewer. Nevertheless there is now increasing interest in 'raster' displays where, as in television, the spot traces out a standard background of lines on which the picture is imposed. This system has some advantages, particularly where a colour display is required under conditions of high ambient lighting. The essential problems of storing vast quantities of picture elements (pixels) are being overcome by employing modern digital computer techniques. No doubt we shall see an increase in the use of raster displays for radar in the next few years.

Stroke and raster displays are available in monochrome or colour but, somewhat surprisingly, both civilian and military authorities have not shown themselves to be quick in exploring the possible operational advantages of colour.

Our company has a long history of radar display design and an excellent reputation for reliability and performance. Figure D3 shows one of our large multiple display installations in the Scottish air traffic control centre. At the present time (early 1983 - Ed.) development work is in hand to complete the design of the very successful Astrid display system which has been on demonstration at Rivenhall throughout the past year; it has been ordered in quantity by the Ministry of Defence, and will be the principal display system to be offered with the new S511 airfield surveillance radar.

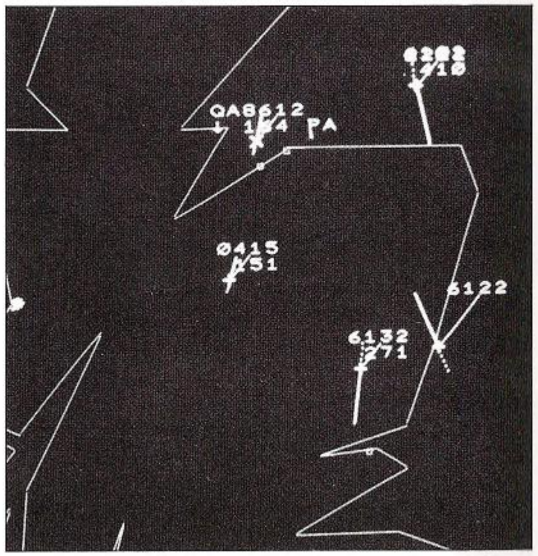


Figure D2. Part of a modern display showing the east coast of Scotland.

Figure D3. The Scottish air traffic control centre.

D F G H I J K L M N O P Q R S T U V W X Y Z A B C

E is for Echo

CONTINUING our way through the alphabet of radar terms, we arrive at the letter E and I can think of no better candidate than ECHO, the essential ingredient of radar.

All sorts of objects, in a very wide range of materials, can produce radar echoes by reflecting energy radiated from a radar antenna, the best reflectors being, in general, electrical conductors. The most obvious targets are aircraft but we also get echoes from clouds, snow and rain storms, land masses, buildings, birds, etc.

The distance at which we can detect objects by radar depends on many factors including the ability of the object itself to reflect. It is easy to appreciate that targets vary enormously in their reflective ability if one considers the obvious differences between a warship made mainly of metal and a bird made mainly of bone, feathers and water.

The size of expected targets and their ability to reflect have a bearing on the design of radars for specific jobs. For example, navigational radars for ships can be quite low-powered with compact antennas because they are required to detect objects with large echoing areas e.g. other ships and land masses. On the other hand, a ground-based radar for air defence looking for small missiles at very long ranges needs to have a powerful transmitter, sensitive receiver and a large antenna because missiles produce only very small echoes.

Even in detecting ordinary aeroplanes the matter is complicated because the echoing ability of an aircraft depends very much upon its attitude in relation to the radar station; as the aircraft moves about in the sky so different parts of the fuselage and wing structure give their own individual echoes and the total signal strength received by the radar varies considerably. This effect, which is similar to the visual glinting of diamonds in ordinary light, gives rise to great difficulty when trying to specify the range detection capability of a radar, as anyone who has been involved in performance trials will know.

To permit sensible calculations and comparisons a concept of 'equivalent echoing areas' has been introduced in which targets are considered as if they were perfectly reflecting metal spheres which appear the same when viewed from any angle.

The result of this approach is that, for example, a medium sized fighter aircraft might present a 'target echoing area' or 'radar cross section' of between say 2 and 10 square metres, depending on the angle from which it is viewed. But again there is a complication in that the value of radar cross section varies with the frequency of the radar. At one extreme, warships have echoing areas of tens of thousands of square metres, while at the other, missiles present only about a tenth of a square metre.

One interesting practical application is the use of devices known as 'corner reflectors' on the masts of small vessels, like many to be seen on the River Blackwater, to enhance greatly the otherwise poor echoing abilty of a small craft. Other ships' navigational radars then have a much better chance of detecting these small craft, almost as if they were large ones, so safety at sea is improved (fig. E4).

Figure E2. Targets like this may have echoing areas of several tens of thousands of square metres.

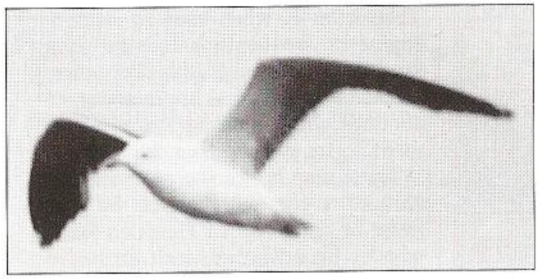


Figure E3. This chap may have an echoing area of only about a hundredth of a square metre but if he brings a lot of pals along they can cause significant radar clutter.

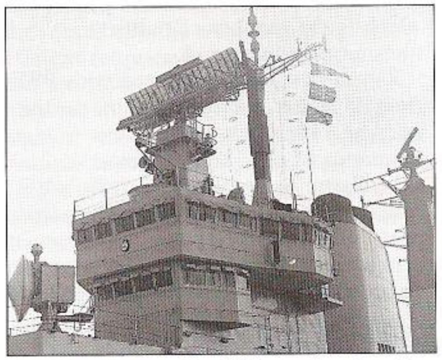
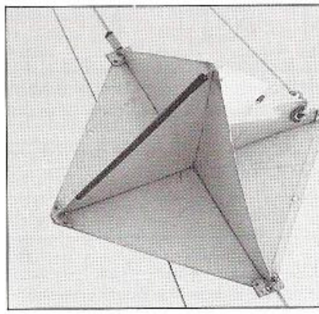


Figure E1. Note the difference in size of the tracker, surveillance and navigational radars on HMS Invincible. (Nav. radar just above right hand end of surveillance.)

Figure E4. Yachts on the Blackwater at Tollesbury



Inset: A Corner reflector on the mast.

F is for Frequency

THE letter F, when used by radar engineers, frequently stands for some kind of frequency! Radar, like other branches of electrical engineering, abounds with repetitive events which recur so many times per second.

These may be known as 'cycles per second' or commemoratively by the name of the physicist Heinrich Hertz, who by his advanced work in the nineteenth century laid the theoretical foundations of radio and paved the way for Marconi.

So, one repetitive event in a second equals 1 Hz; a thousand = 1 KiloHertz (kHz); a million = 1 MegaHertz (MHz) and a thousand million = 1 GigaHertz (GHz).

One of the lowest electrical frequencies we meet in our everyday lives is that of the alternating current mains electricity supply; 50 Hz here and in Europe and 60 Hz in North America. By comparison, the highest frequencies normally encountered at home are the colour TV signals at around 400 to 800 MHz, and microwave ovens at 2.45 GHz.

Generally speaking, most radars employ radio frequencies around 1200, 3000, 5000 or 9000 MHz (1.2, 3.0, 5.0, 9 GHz if you prefer), although there are some special radars on much lower frequencies and some quite a bit higher. Some of the most commonly mentioned frequencies in radar are those radio frequencies (RF) which are used for transmission and reception and the 'pulse recurrence frequency' (PRF) which is the number of pulses transmitted in a second.

Radars have been produced with PRFs from 25 pulses per second (pps) on the wartime CH radars, up to some thousands of pps; however, most surveillance radars with which we are concerned have PRFs of a few hundred pps.

In a complex radar many frequencies are needed for a variety of functions and these are usually provided from a central source known as the frequency synthesiser.

In dealing with radar signals it is often useful to extract all the frequencies contained within a complex response (e.g. saw-tooth, square-wave, or whatever). This process can be aided by using modern integrated circuits in what has become known as FFT, which stands for Fast Fourier Transform, after the French mathematical physicist Jean Baptiste Fourier (1768 – 1830). It was he who gained enduring fame by exploring mathematically the relationships of the different frequencies embodied in a complex waveform. I wonder if he ever imagined that his methods would find practical real-time application a couple of centuries later? Come to that, Hertz (1857 – 1895), surely never anticipated the far-reaching results of his work nor how his name would become a household word. To both of them we owe much.

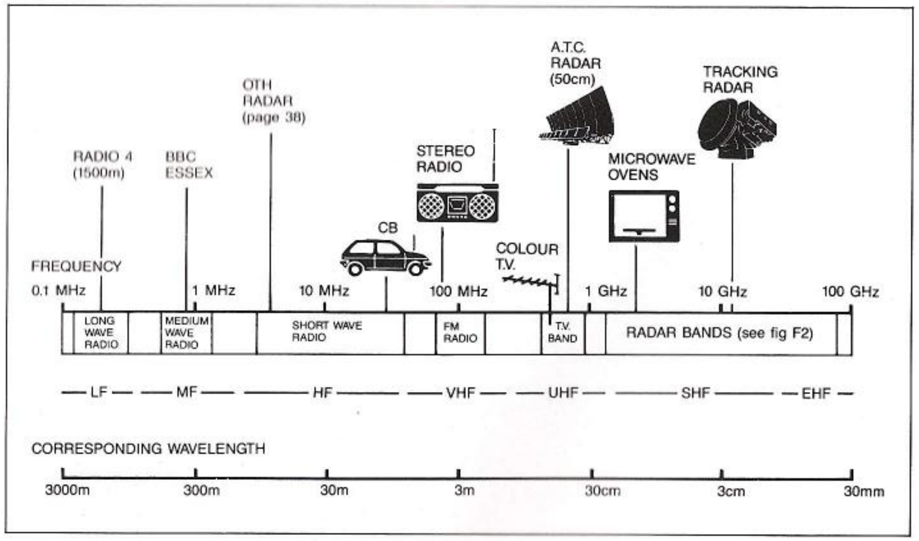


Figure F1. Part of the electromagnetic frequency spectrum showing the relative position of the radar bands.

Below 30 MHz — OTH radar (see letter O, page 38).

20-50 MHz — Chosen for CH. Within the (then) current valve technology; and theory that wavelengths (6-15m) were optimum for aircraft echoes. Targets 'floodlit' by static aerials, hence low PRF of 25pps adequate.

40 MHz and 90 MHz — Early naval radars.

200 MHz — Used on CHL and GCI stations, and today for long-range naval surveillance. Targets illuminated only as beam passes, so higher PRFs (typically 250 minimum) essential.

550-600 MHz — Used by German ground radars, later adopted by us on the grounds that jamming would be unlikely. Became excellent choice for long-range ATC.

1200-1400 MHz — 'L-band', a favourite for long-range naval and ground radars. PRFs typically 250 plus pps.

3000 MHz — 'S-band', greatly-used from the first magnetron onwards.

5500 MHz — 'C-band', a useful compromise between 'S' and 'X'. (for precision height-finders, etc.)

9000 MHz — 'X band', used for the H2S bombing aid. Standard for navigation radars, short-range surveillance and short/medium range trackers.

16 GHz, 35GHz, 95GHz — Specialised compact short-range applications.

For designers the choice of radio frequency and PRF involves compromise and consideration of many conflicting factors. Above is listed some of the frequencies used successfully for radar.

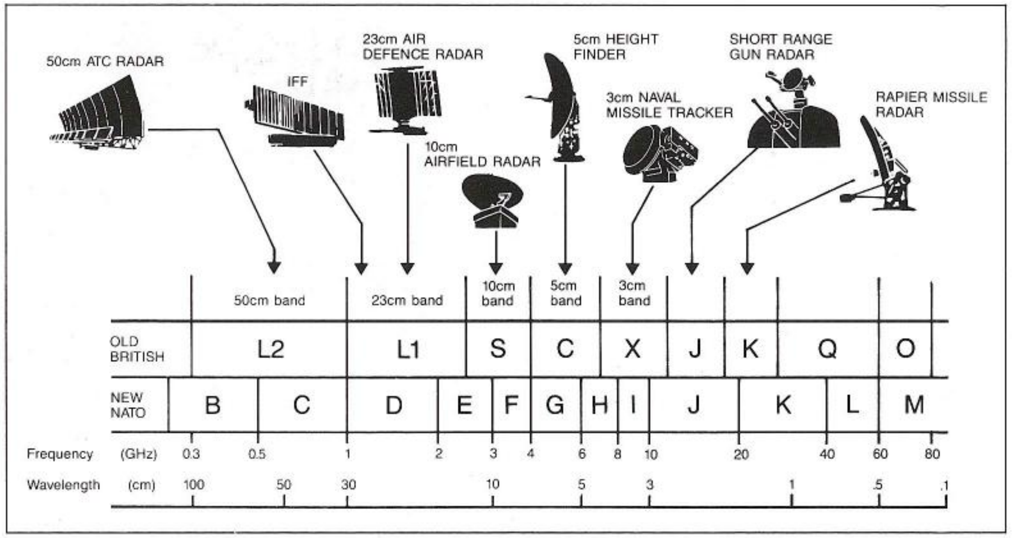


Figure F2. Expanded section of Fig. F1 to show where some common Marconi radars fit into the radar frequency bands.

G is for Goniometer

WITH the first half-century of radar being celebrated so widely, particularly in London by the IEE's international seminar on the History of Radar Development to 1945[1], perhaps I may be allowed to dispense a whiff of nostalgia in this article.

The letter 'G' in the context of wartime radars stands predominantly for the gonio (or radiogoniometer to give it its full name), used in the receivers of the main radar chain erected around the UK, and known as the Chain Home (CH).

The radiogoniometer measures the angle of arrival of radio signals, the gonio bit coming from the Greek word gonia for angle, but more familiar perhaps when it crops up in words like trigonometry and pentagon.

The goniometer was well-known before the war in radio direction finding, and was adapted to CH, the first working radar system. It enabled an operator, sitting in front of a radar receiver, to sense the direction of a target by rotating a large control knob while observing the signal strength of its echo on a cathode ray tube.

Fixed receiving aerials, aloft at some 240 ft on wooden towers, were connected by cables to fixed coils within the gonio. A single rotating pick-up coil, on a shaft carrying a control knob, supplied the input to the radar receiver. As the operator turned it, the effect was as if the aerials themselves were being rotated.

The gonio was a precision instrument, about the size of a car dynamo or alternator, and was mounted at the bottom of the receiver near the floor, with its shaft rising at an angle, allowing the knob to be conveniently close to the operator's left hand.

Operation of the gonio was not restricted to the primary purpose of finding bearings; by pressing appropriate keys, it could be connected to alternative sets of aerials at different heights on the receiving towers, and the readings then obtained were fed into an early form of computer (the GPO calculator) to find the angle of elevation and hence the height of targets. CH was a 3-D radar!

In the very early days at the start of the war, the RDF[2] operators were mostly men, usually engineers and scientists. But as the war went on operators were specially trained and the number of WAAFs increased steadily. These attractive young ladies contributed greatly to the success of CH by their ability to seek out faint echoes on the screen and quickly take bearings and heights with the gonio. The readings were taken from a pointer on a degree scale at the position of minimum signal.

It required some skill to find the correct reading; the technique was to swing the coil back and forth through minimum signal and quickly find the correct null point.

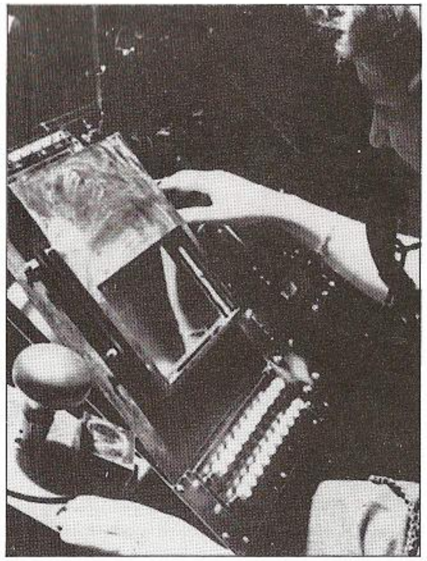


Figure G1. WAAF CH operator with the gonio knob to the left of the display.

There were about 50 CH stations around our coasts, and at each the gonios were in constant use throughout the war, day and night, endlessly swinging to and fro as the operators' attention passed from echo to echo. No wonder that occasionally the connections to the rotating search coil, via slender brushes and slip rings, got a little less than perfect; if so, continuing to work as best she could, the WAAF would call for a mechanic's assistance.

To assess the trouble he would have to come close beside her in the low light of the receiver room to peer into the tube and perhaps overlay his hand on hers. Yes, life was hard in the war for RDF mechanics!

If the slip rings were playing up, he would soon attend to the trouble with a drop of carbontetrachloride mixture; or perhaps it was some other fault, like defocusing of the display or time-base jitter. All the same, he would have to operate the set with her and, under pressure of the real-time war situation, they would be united in a mutual problem until it was solved.

No wonder that many friendships and enduring marriages ensued between WAAF operators and RDF mechanics, and who knows how many lifetimes together started from that physical contact on the gonio knob?

There used to be an old saying among mechanics that exposure to radio frequencies led to impotence. (It was often put rather differently!) However, many had several children, four being a favourite number, so there wasn't much truth in that particular line. I think everyone who used the good old gonio must look back on it with many happy and exciting memories.

If you would like to learn more of the technical side of CH, please see Bruce Neale's paper, **'CH – The First Operational Radar'**, published in the **GEC Journal of Research**, Vol. 3 No. 2 1985.

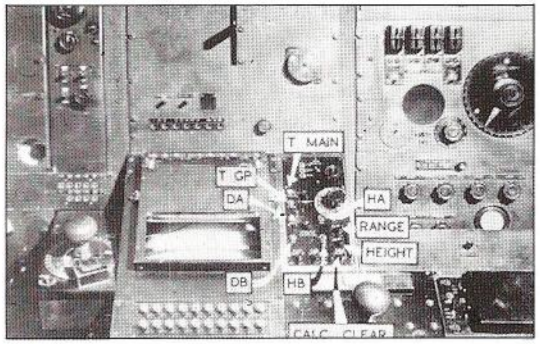


Figure G2. General view of CH receiver controls with gonio knob at left.

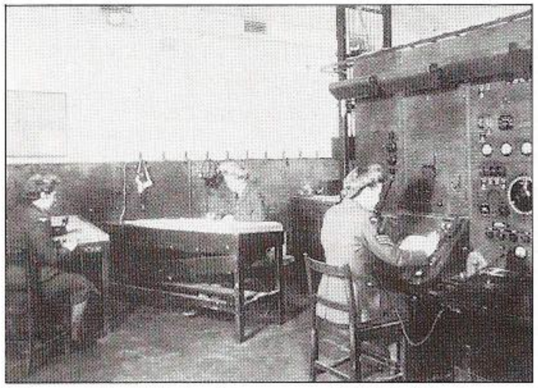


Figure G3. CH Receiver room with WAAF operators.

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[1] 10-12 June 1985.

[2] RDF: Radio Direction Finding, later known as Radar

G I J K L M N O P Q R S T U V W X Y Z A B C D E F

H is for heightfinding

HEIGHTFINDING by radar has two separate meanings: an aircraft may measure its height above the surface, or a ground-based radar station may estimate the height of a distant target (e.g. an aircraft).

Although the former is strictly 'radar', in that a signal is sent to the ground and reflected to the aircraft, the continuous-wave frequency-modulated techniques usually employed differ from those of conventional pulsed radars and the airborne equipment is referred to as a 'radio altimeter'.

It is the second application – finding the height of a distant object – that is of particular interest to us in Marconi Radar.

For many applications, such as simple defence systems and air traffic control (ATC), two dimensions of information – 'range and bearing' – are adequate, and such equipments are termed '2D' radars. However, for more advanced defence requirements, the third dimension – height – is highly desirable: hence, '3D' radars. (For ATC, height is measured by radio altimeters in the aircraft and transmitted to the controller on the ground by 'secondary radar', which I'll cover in another article.)

The first operational radar chain, known as CH, erected around our coasts during the war (and of which you may have heard much in 1985, when half-a-century of radar was celebrated) was a true 3D system, in that height information was readily available for virtually all echoes received. This capability arose naturally from the long wavelengths then used: a vertical beam structure, ideal for heightfinding, was generated from the interference between direct rays from the antenna and reflected rays from the ground.

However, there were two drawbacks to CH; it was unable to see targets at low altitudes and the heightfinding characteristics varied around the compass unless, as was rarely the case, the ground had constant reflecting capability in every direction from the station. Consequently, CH stations were calibrated by flight trails, a time-consuming and tedious activity, which had to be rechecked periodically.

The war had not advanced very far before the need arose for heightfinders that were able to work at lower angles of elevation and which, by avoiding ground reflections and the need for calibration, could be transported and made available for siting as required at short notice.

Both these aims were achieved by moving to much shorter wavelengths and the first centimetric heightfinder (CMH) was produced by BTH at Rugby in June 1941 (fig. H1).

In this early model, which used separate transmitting and receiving antennas, a narrow beam, like an invisible searchlight, was projected into the sky. By measuring the range and angle of elevation of targets, heights could be determined with reasonable accuracy. Allowance was made in the height calculations for the effect of earth curvature at long ranges.

Many variations of this basic design followed during the war and, as radar technology developed, single transmit/receive antennas came into use. This type of heightfinder has been developed and refined over the years and one of the most successful and more recent designs was the C-band (5 cm) heightfinder of the Marconi S600 series of transportable radars. Figure 2 shows one of these supplementing the 2D surveillance radar in the background.

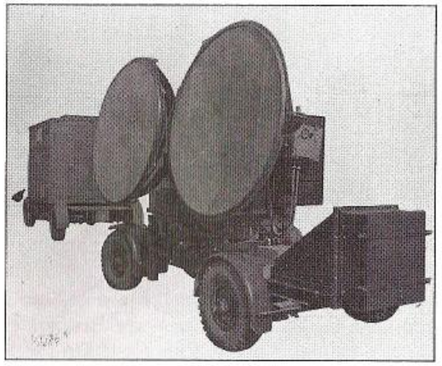


Figure H1. Experimental radar heightfinding equipment (CMH) 1941

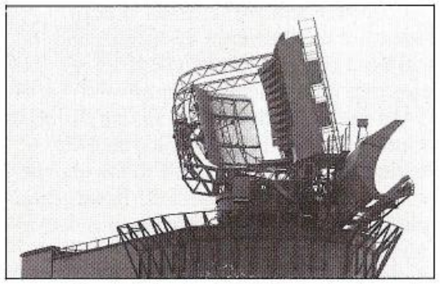


Figure H3. An unusual radar, the RAF type 82 with a multi-beam (heightfinding) receiving system.

This radar had the ability to find the angle of elevation of a target by a simple 'nodding' routine, the extent of the 'nod' being controlled according to the range of the target to which it had been directed by the surveillance radar. As long-range targets are necessarily at low angles of elevation, the minimum time is spent on wasteful 'nodding', allowing the heightfinder to achieve as fast a data rate as possible. This system of '2D plus heightfinder' has found application in many parts of the world.

However, defence specifications are calling more and more for true 3D radars which, like CH, give heights on every echo but which, unlike CH, are both transportable and capable of operating at low angles. This is the role fulfilled by Martello whose vertical coverage is divided up into a number of overlapping but separate beams (see fig. VI, page 57).

A separate signal channel is associated with each of the receiving beams so that the angle of elevation of all responses can be assessed directly. A Martello, looking at an aircraft more than a hundred miles away, can fix its height within a thousand feet, a performance more than adequate for most long-range defence requirements.

Figure H2. C-band heightfinder

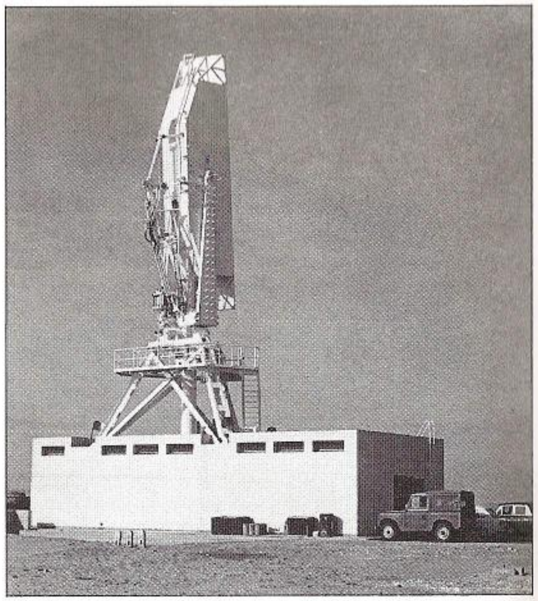


Figure H4. High power S band heightfinder.

I is for Interrogation and Identification

'MAKE your cockerel crow!'. An odd-sounding command perhaps, but an essential one early in the last war from Ground Control to newly airborne aircraft.

That was at the time when the sensitivity of early IFF (identification friend or foe) systems had to be adjusted in flight, because the optimum setting could not be achieved close to the ground. Too little sensitivity, and an aircraft might fail to be identified as 'friendly' by our radar stations; too much, and its transmitter could radiate uncontrollably causing havoc with ground stations and other aircraft. Thus the command to check and adjust the IFF.

To go back to the beginning, the first major development in radar was the setting up of the east coast CH chain of radar stations just before the war. It had been a major achievement to be able, for the first time, to detect aircraft off our coasts but this very success led immediately to another essential requirement – the ability to tell whether aircraft were 'ours' or 'theirs'.

As a result, the development of IFF followed rapidly; in its very earliest forms Allied aircraft carried simple antennas with motor-driven tuners, which became resonant to each of the radar stations in turn. If they were lucky, the ground radar operators would see a regular increase in the responses from 'our' aircraft each time the airborne reflector was tuned to their particular station. Discrimination between friend and foe was becoming possible but improvements were necessary for reliable identification under all conditions.

Those early experimental systems, of which there were many variations, were followed by Mks 1 and 2, in which the aircraft carried an active circuit to re-transmit to the ground when a radar pulse was received. Use was made of 'super-regenerative' circuits which, basically on the verge of oscillation, suffered the added complication of needing adjustment in flight.

As the war progressed, radars on many more wavelengths came into use, including the 10 cm band following the invention of the magnetron. It was then clear that as all radar stations needed to identify friend or foe, the only practicable solution was to have a common IFF channel for all radars, irrespective of their type – CH, CHL, Naval, Army – whatever.

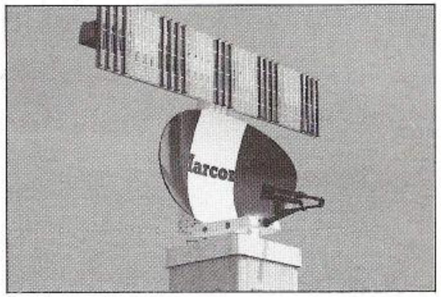
This was a project of major importance to the war effort, and some of the best engineering brains in the country were applied to the development of what became known as IFF Mk 3. It operated in the band 157 – 187 MHz, and remained the standard equipment throughout the war. It had several important new features, including automatic gain stabilization of the receiver, so the 'cockerel' routine could be abandoned, to the relief of all concerned.

The concept and development of the system was British but vast numbers of IFF sets were needed, and the USA made a major contribution through mass production. All Allied aircraft carried IFF transmitter-receivers (transponders) which, on picking up an interrogating signal from the ground, replied on a slightly different frequency with coded pulses. Four codes were in use, plus a distress code, known as 'broad IFF', which could be used by aircraft in difficulties, e.g. ditching in the sea.

The ground station's IFF receiver fed the replies from aircraft on to the radar screens so that the operators could relate them to the radar echoes. Obviously, reliability of the airborne IFF equipment was paramount; failure to respond to interrogation could result in aircraft being assessed as hostile, with tragic consequences!

It was important also that airborne IFF sets should not fall into enemy hands, otherwise the enemy could copy the equipment and make his aircraft appear to be friendly. The airborne IFF sets were constructed with two chassis, mounted back to back, with a detonator in the space between, arranged to explode automatically under the impact of a crash landing. In practice, they were sometimes so sensitive that they could be activated by a hard landing. To avoid this, aircrews were asked to operate a temporary cancellation switch. Who knows how many good IFF sets were lost by jaded crews overlooking this drill when returning after raids! Who can blame them? They had more far important jobs on hand.

One of the most effective radar-assisted functions carried out during the war was that of GCI – ground controlled interception. Special radar stations concentrated on particular enemy aircraft, and by direct ground-to-air RT – radio telephone – directed our fighters against them. For this high-speed, moment-to-moment type of control, it was an advantage to identify friend from foe on the radar screens, directly from the radar transmission. This was achieved by Mk 3G IFF, which had an additional channel at 212 MHz, (the frequency of the GCI stations), in addition to the general 157 – 187 MHz coverage.

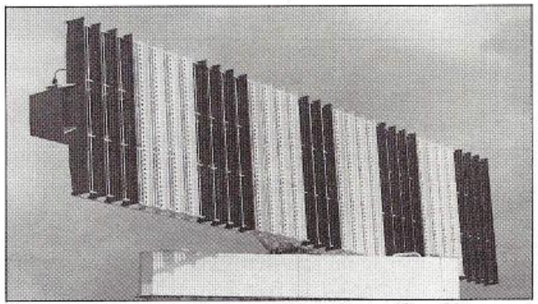


The successful development of Mk 3G IFF led to the introduction of other triggered beacon systems, too numerous to mention here. Older readers will recall Rebecca/Eureka and the 'H' position-fixing system, both of which used IFF-like principles and contributed to aerial navigation.

Other marks of IFF followed for use abroad, and after the war Mk 10 became established as the standard, remaining with little change in its principles to this day. Like Mk 3, this operated with a ground-based interrogator but the frequency was moved up to the band 1030 – 1090 MHz.

Although Mk 10 was developed for the new generation of defence systems following the war, it also became the basis for the SSR – secondary surveillance radar – systems, used for civil air traffic control. It is now used universally by all civil aircraft, and the old system of identification codes, which in the war proved that an aircraft was friendly rather than hostile, is now adapted for peaceful purposes like confirming flight identity and giving the height of the aircraft from its on-board instruments.

Thus, modern SSR is a direct descendant of the vital wartime IFF. In part a radar system, in part a communication system, it is an essential contributor to modern air safety. SSR for both military and civil applications is still under development, and the new Marconi Messenger equipment for which we have already had orders overseas, is all set to be a world leader in the field.



Messenger antenna free standing above (fig. I2) and co-mounted with an S511, left (fig. I1).

J is for jamming

EVER since radio communication found application in warfare, and for the broadcasting of political propaganda, opponents have striven to spoil reception by operating interfering transmitters on the same wavelength.

Such deliberate jamming is applicable also to radar, where the intention is to minimise the extent to which one side can detect the presence and movements of the other's aircraft and ships.

There are many ways of going about it, e.g. different forms of interfering signal, and the whole range of techniques is covered by the term 'electronic counter-measures (ECM). As one might expect, sophisticated radars can to some extent offset the effects of jamming by design features, known as 'electronic counter counter measures' (ECCM)! Together, these technologies with opposing aims form part of the whole gamut of electronic warfare (EW).

In Marconi Radar we have been involved in all aspects but as our business is largely in the field of the radars themselves it is mainly in ECCM that our efforts lie.

Active jammers, i.e. deliberately interfering transmitters, are not the only man-made hazards to radar. In the last war much confusion was caused by a passive measure – the dropping of thousands of strips of metal foil from high-flying aircraft. As the foil – known to the British as 'window' and to the Americans as 'chaff' – slowly floated down, it effectively prevented radar detection of targets over a large area.

The whole subject is extensive and has a fascinating history. I would recommend anyone seeking more information to consult the eminently readable **Instruments of Darkness** by Alfred Price, which is fast becoming the classic treatise on the development of EW.

However, to take a simple overview, there are three fundamental features that a good surveillance radar must have if it is to stand a reasonable chance of combating enemy jamming. Firstly, the radar's beam should be as clearly defined as possible so that it sees mainly where it is supposed to be looking and is not sensitive to radiation coming from other directions.

If a perfect beam were attainable, the radar would only see a jammer when pointing directly at it: in practice, however, there are always 'side-lobes' to the main beam and if a jammer is sufficiently powerful its inteference can be effective over a much wider angle than the normal beamwidth. In the extreme, a poorly designed surveillance radar with excessive side-lobes could be affected over the full circle of its coverage by a very powerful jammer.

It is the constant endeavour of antenna designers to improve main beam performance and reduce side-lobes but there is no easy solution. Most of the progress in recent years has been due to improvements in the methods of calculating the finer details of antenna design – physical dimensions and the phasing of the different elements – and Marconi engineers at Great Baddow have proved themselves to be in the forefront of this computer-aided technology.

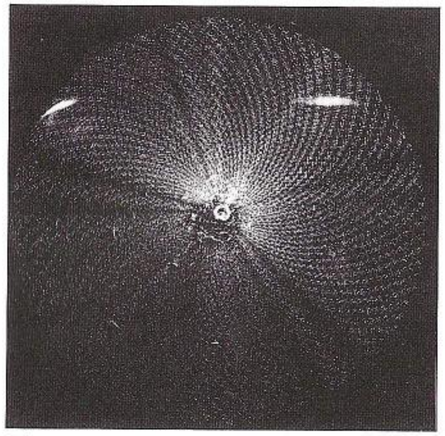


Figure J1. Pulsed interference or jamming

Turning now to the second basic ECCM characteristic, we come to the ability of a radar to change frequency in order to dodge a jammer. There are various grades of effectiveness, from the simple ability to tune to a different part of the waveband to the really 'frequency agile' mode, where a radar can jump about in frequency very quickly – perhaps in a random manner on a pulse-to-pulse basis.

Thirdly, we have to consider the ability of a radar receiver to respond equally to all levels of signal, from very weak to very strong. An ideal receiver, whose job it is to amplify signals, should increase everything that is received (on the chosen frequency) by the same amount. The snag is that radar signals vary enormously in strength, especially in relation to heavy clutter or a powerful jammer.

A power ratio of 1,000,000,000 (one billion) to 1 is not unusual between strong and weak signals (it can be even greater) and yet the receiver has to apply the same amplification to each. The moment the receiver 'limits' and is unable to increase the strong signal by the same factor as the weak one (becoming, as engineers say, 'non-linear'), the two, if they occur simultaneously, become inextricably mixed together by a process known as cross modulation and no further signal processing can separate them.

So, to sum up, the basic ECCM features of a good defence radar are low side-lobes, frequency agility and wide dynamic range. Naturally, our main defence radar, Martello, has these features in good measure, and a few other clever tricks up its sleeve as well!

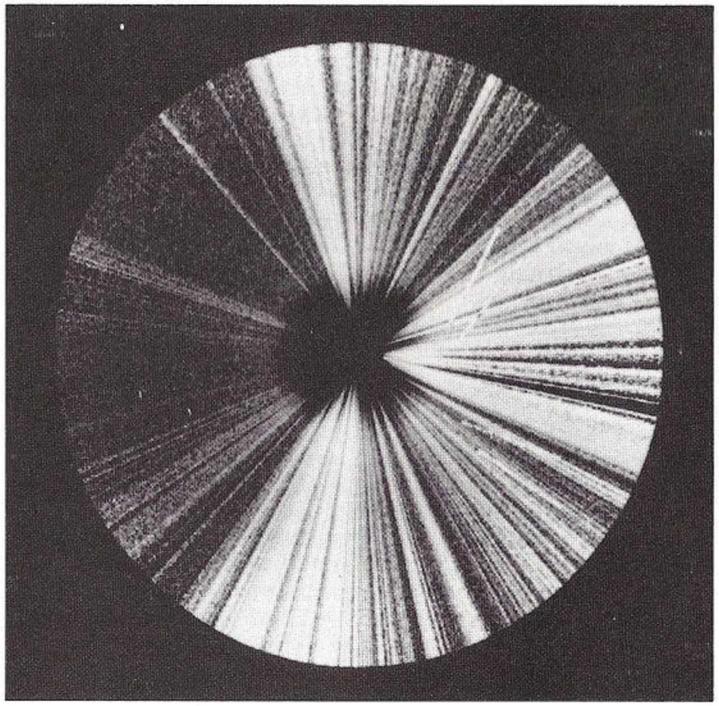


Figure J2. A heavily jammed radar display.

K is for klystron...and some of its relatives

KLYSTRON is the name of a type of valve (or vacuum tube to North Americans) often used in the output stages of radar transmitters.

Its invention is usually attributed to the Varian brothers in the USA, and it was under development both there and in this country from early on in the second world war. Apart, however, from low power oscillators (known as reflex klystrons, successfully used in radar receivers,) it was not until after the war that it was perfected as a reliable high power microwave amplifier.

The klystron finds its field of application at the higher radio frequencies where conventional valves are dropping off in performance and where, for the pulsed operation needed in radar, it is not yet possible to get sufficiently high powers from semiconductors.

The essential feature of the klystron is an electron beam: electrons emitted from a hot cathode are attracted by a positive anode, called the 'collector', and are constrained en route into a narrow beam by a magnetic or electrostatic focusing system. The whole is contained in a vacuum and in essence is not unlike the focused electron beam behind the screen of a TV set. But there is an important difference between the ways in which the beams of a picture tube and a klystron are modulated. The former is intensity-modulated to produce light and shade on the screen but the latter is velocity-modulated, and to explain that I need to digress.

Let's pretend for a moment that electrons in the beam are like cars travelling on a motorway. You may have noticed how rarely it is that all cars go at the same speed; usually there is a series of overtakings going on all the time, and if these are well spread out the traffic density is about the same all along the road.

At other times, however, a few middle-lane cars will overtake one or two in the nearside lane while simultaneously some in the outside lane are overtaking them all. When that happens there is, temporarily, a high concentration of cars over a short stretch of road that presently may become devoid of traffic for a while. In other words, the traffic density is bunched up rather than being spread out fairly uniformly. Bunching happens more or less at random for cars on motorways but is used in a controlled fashion for electrons in the klystron beam where it is the key to the whole operation.

Shortly after leaving the cathode all electrons in the beam travel at more or less the same velocity until they pass through a cavity to which the input microwave signal is applied. They pass through this cavity, known as the 'buncher', rather like cars going under a bridge over the motorway. It needs only a small amount of input signal power to modulate the velocity of the electrons in the beam; some emerge slightly faster, some slightly slower, according to the polarity of the input signal as they pass through.

The result is that a series of over-takings occur all along the path of the beam at specific points called 'bunching planes'. At one of these another motorway bridge or rather, cavity, is situated. This also carries a microwave signal acting upon the beam trying, as it alternates, to slow down and speed up the electrons as they pass through.

The clever trick lies in the phasing so that when this second cavity, known as the 'catcher', is slowing electrons down a bunch of electrons is passing through, but when it acts to speed them up, there is a dearth!

In slowing the electrons down, energy is transferred from the beam to the microwave circuit and as there are always more to slow down than to speed up (because of the bunching) there is an overall transfer of power from beam to catcher.

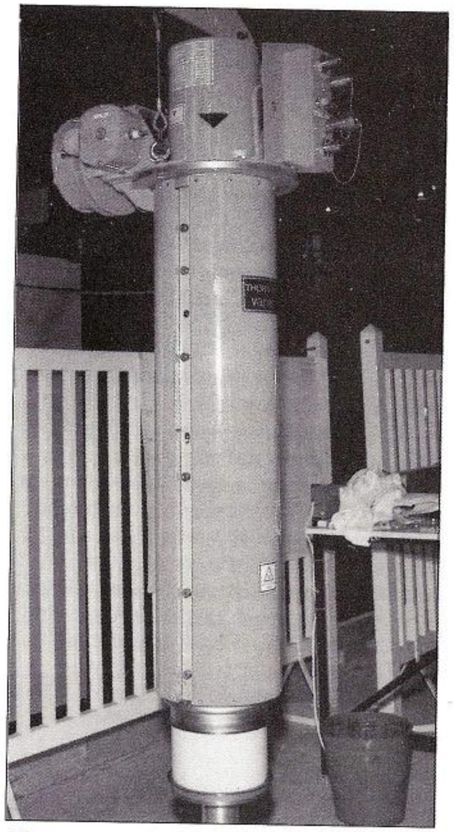


Figure K1. L-band (23cm) hybrid amplifier (Twystron), used in Martello S713 with a peak power output of 3.3 MW

To sum up, the input signal to the klystron is applied to the beam via the buncher and extracted from it by the catcher, the power of the beam (which comes from a direct current power supply) being used to raise the strength of the signal. The amplification can be very significant indeed, perhaps raising a 10 watt input signal to a million watts in a large transmitter klystron.

Klystrons come in a range of sizes, the electron beams varying in length from a few inches to several feet. The largest tubes, complete with focusing and cooling systems, are substantial and expensive pieces of engineering needing mechanical handling aids to fit them into transmitters.

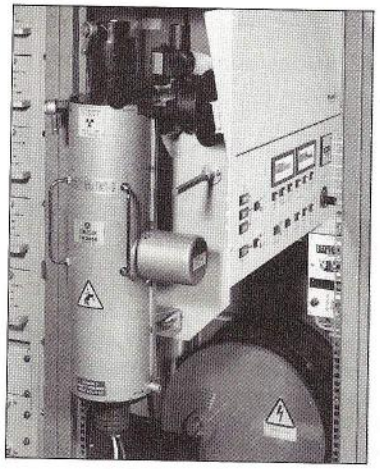


Figure K2. S-Band (10cm) TWT amplifier (left) used in the S711 low level radar. The circular object is the pulse transformer (see page 40).

Because the klystron employs a straight electron beam it is classed as a 'linear beam tube' and in its basic form is characterised by high gain (amplification) and narrow bandwidth – i.e. it operates at a single frequency or at best over a small range.

To some extent, greater bandwidth can be traded for lower gain by using many stagger-tuned cavities; but for really wide bandwidth there is another kind of linear beam tube known as the travelling wave tube. Velocity modulation and bunching is still employed but the 'motorway bridges' are of quite different construction – more like a continuous tunnel that progressively bunches and de-bunches.

Although TWTs are often used in high power form for radar transmitters, they have also been made as low-noise signal amplifiers for radar receivers, but that application is becoming less common with the advent of microwave transistors.

It is for high power that the TWT has the greatest attraction these days. Sometimes, to get the optimum combination of gain, bandwidth and power the electron beam is made to pass through a structure where klystron-like bunching is followed by TWT-like de-bunching, and in that hybrid form the tube is called a Twystron. One such is used in the output stage of the S713 Martello radar. It provides 8 – 10 kW of average power at a peak pulse power of 3 MW (fig. K1).

L is for Long Range, Low Level, LIN/LOG and L-Band

WHEN I first encountered the letter L for this series, I felt that perhaps it stood for LACK of any outstanding major item or subject! Yet, on reflection, it is indeed the initial letter of several terms, such as the following, that crop up quite frequently in radar work.

LONG RANGE

I doubt whether this has been defined accurately, but in our business of ground-based and shipborne radars it is generally applicable to equipment capable of reliable and consistent plots on aircraft at ranges in excess of 200 miles. Martello, for example, with a range well beyond this is clearly in the long range class. On the other hand, an airfield control radar such as the Marconi S511, required to see aircraft out to 60 or 70 miles but capable of rather more under favourable conditions, is in the medium range category.

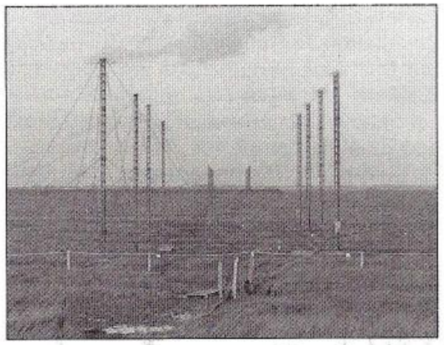


Figure L1. Long range and Low Level — simple OTH radar antennas belie the complex nature of the systems.

LOW LEVEL

Ever since the days of the UK wartime radar chain, the effective detection of aircraft flying at low altitude has been a persistent problem, and even today, in newspaper reports of aerial attacks, one reads such words as, 'The bombers flew at low level, below the radar cover'.

This is a natural phenomenon arising from the generation of lobes in the vertical plane caused by reflection of radio waves from the earth's surface. In general, the effect is minimised when the wavelength is very small by comparison with the height of the radar. The shorter the wavelength and the greater the height, the lower the lowest lobe will be.

An early approach to the problem was the wartime CHL (Chain Home Low, fig. L3), where the ratio of height to wavelength was about 40:1. Figure L2 shows a modern solution, the Marconi S711, where the ratio is nearly 200:1.

Probably the ultimate defence solution will be reached by further advanced development of the OTH (over-the-horizon) radars, which our company has pioneered. In such systems the transmitted radio waves are launched in quite a different way, and although ground reflection still occurs it no longer limits the extent of radiation along the earth's surface (fig. L1, and page 38.)

Figure L2. S-band low cover radar type S711 on a 60 foot telescopic tower.

LIN and LOG

At the display and control consoles of many radars the operator is able to select 'linear' or 'logarithmic' radar signals. Each has merits depending on the extent and type of radar clutter – see letters C and D in this series. Where this facility exists the choice is made between the output of a linear receiver channel where the amplified output is always so many times the input signal, or from one where the amplified output is approximately proportional to so many times the logarithm of the input signal. In the latter case much greater variations in input signal strength can be accommodated, and this can be a useful characteristic in dealing with heavy clutter or jamming.

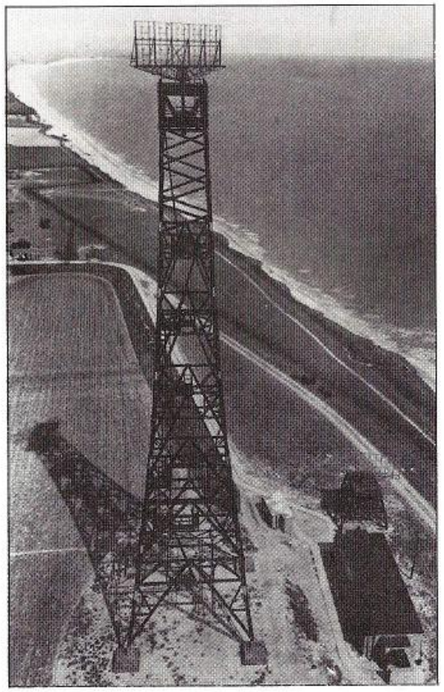


Figure L3. The early low level solution — put the radar on a tall tower.

L-BAND

This is a term often heard in Marconi Radar. It refers to the band of radio frequencies from (usually) 1215 to 1365 MHz having a mid-band wavelength of approximately 23cm.

For defence it is one of the most popular bands for long range surveillance radars, sharing the honours with the shorter wavelength S-band (10cm). Although, for a given beamwidth, L-band antennas must be larger than those for S-band, one compensating advantage of the longer wavelength is the relative freedom from weather clutter. This factor has led to a general world-wide acceptance of L-band for long range air traffic control radars. (Even better, from the weather point of view, is the 50cm band adopted by earlier generations of Marconi long range ATC radars, such as the S264, fig B4, page 11. These are still in use after many years, both in the UK and abroad, but in countries where that wavelength is used for other services – e.g. television – L-band becomes the next best choice.)

I should add that, just to confuse matters, L-band is known in NATO and defence circles as D-band.

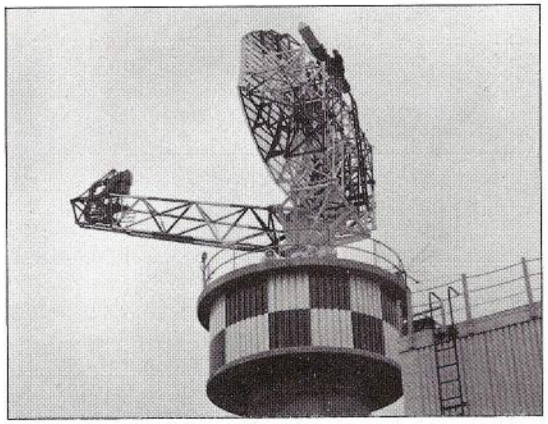


Figure L4. L-band (23cm) air traffic control radar S654 of the RCAF.

M is for magnetron, microwaves & modulators

IT HAS often been said, with much truth, that the British pre-eminence in radar was a major factor in securing victory for the Allies in 1945.

At the outbreak of war it was the early warning provided by the east coast CH stations that dominated the scene and, as the chain was extended around our entire coastline, the CHs were supplemented by CHL stations.

All these, plus ground-based radars for GCI (ground controlled interception) as well as the GEE navigational system, worked on metric wavelengths, using transmitters based largely on established pre-war valve technology.

But that is only part of the story. Important as those systems were, there was another element – then known as 'centimetre' techniques – which made possible, among other things, effective airborne radar. There were many versions for the purposes of air interception (AI) and the location of shipping by aircraft (ASV); plus the magic H2S, which enabled bombers to 'see' targets below them at night and through cloud.

The novel technology of 'microwaves' also brought into being a new generation of ground-based precision surveillance radars with improved low-looking capability to supplement the existing chain, and permitted the refined OBOE precision bombing system (described admirably by Bruce Neale in **News and Views** nos. 5, 6 and 7 in 1983). There were applications, too, for height-finding, and many variants of 10 centimetre radars were built for naval purposes.

Yet none of the wartime microwave radars would have been possible but for the timely conception of the cavity magnetron, in late 1939, by John Randall and Harry Boot of Birmingham University. Of the several groups of scientists throughout the world who had been working on experimental magnetrons it was they who achieved outstanding success.

The magnetron is a diode (a valve with only two electrodes, cathode and anode) in which the electrons are constrained into circular paths by the presence of a magnetic field.

It was well known that it was possible to sustain high frequency oscillations by dividing the anode into separate parts, linked together by external tuned circuits; but power levels were low and reliability was not proven. Randall and Boot made a valve with a heavy copper block anode into which the tuned circuits, in the form of resonant cavities, were formed integrally.

At one bound they demonstrated the consistent generation of unprecedented levels of radio frequency energy at wavelengths around 10 centimetres. High power microwave transmitters became possible for the first time. Their work was taken up by GEC laboratories at Wembley, and in a remarkably short time production magnetrons were available and microwave radar was born.

A prototype magnetron was taken to the USA in 1940, under conditions of great secrecy, as the most important element of the Tizard Mission set up between Winston Churchill and President Roosevelt. Thereafter the vast production capability of that country contributed greatly to the enormous demands for wartime magnetrons needed on land, in the air and at sea.

Figure M1 (above). Randall and Boot who devised the first experimental magnetron. Figure M2 (right). The first magnetron produced peak power in excess of a kilowatt at a wavelength of 9.9cm. Note the penny used as a seal at the end of the top flange.

Although the magnetron may appear, at first sight, to be of simple construction, its operation is complex, and its continuous development right up to the present time has set many mysterious problems requiring highly ingenious engineering solutions.

One American expert of long experience remarked, with masterly understatement, that 'some of the stimuli to which the magnetron responds are quite subtle'. And a British manufacturer, who had successfully moved the rest of his production plant to another part of the country, steadfastly refused to shift the magnetron line, 'in case there's something in the air or the water that will muck it up'.

In fact, I have often thought that the magnetron has a parallel in the mechnical engineering world with the two-stroke petrol engine. Both are basically of simple construction but can be sensitive to operating conditions. Both have been blessed and cursed in the same breath, yet are still with us and likely so to be for a long time to come.

The magnetron is a self-oscillator, and the key component in many radar transmitters: it has by now been produced in many forms at wavelengths both longer and very much shorter than the first 10 cm models. The majority use permanent magnets but water-cooled electromagnets are not uncommon. Some magnetrons are fixed in frequency while others have tuning mechanisms, either manually or automatically controlled.

Modern radars using magnetrons (such as the Marconi S511 airfield series) exhibit a high degree of stability and reliability which is only in part due to improvements in the magnetron itself. Much of the credit must go to transmitter circuits which isolate the magnetron from the effects of unavoidable mismatches in the antenna system, and to improvements in the design of the 'pulse modulators' which supply high level packets of energy to the magnetron. Pulse modulators must provide about twice the power demanded

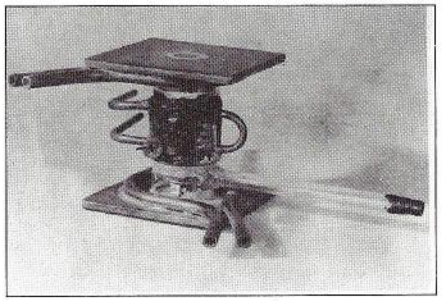


Figure M2.

Figure M3. Modern high efficiency, tunable magnetrons made by English Electric Valve Co. for the Marconi airfield surveillance radar Type S511. It generates a peak pulse power of 600 kilowatts at a wavelength of 10 cms (two versions shown).

Continued

by a magnetron (whose efficiency usually lies in a range around 40–50%), so frequently have outputs of several tens of kilovolts and hundreds of amperes.

In early electrical engineering textbooks it was fashionable to describe electric currents and resistances by analogies drawn from the world of plumbing. If we were to do this for a pulse modulator, which takes in power from the supply mains at a fairly constant rate, only to release it in short, high-power bursts, we have an excellent model in the humble loo!

The cistern, filling up slowly via a small-bore pipe, represents the 'pulse forming network' of capacitors in a modulator, fed from a controlled charging circuit during the radar inter-pulse interval. The handle, or chain, is the 'trigger', and the resulting short flush of water at high rate is the 'output pulse'. I will not pursue this line...it's just something to sit(!) and think about.

The Birmingham cavity magnetron has come a long way since 1939, but is still going strong. First-rate development and manufacturing capabilities are right here in Chelmsford, at EEV. Like the cathode ray tube, it is another thermionic vacuum tube likely to see service in the next century: and when you next use the microwave oven, please spare a thought for Sir John Randall, Dr Harry Boot and the wartime engineers, without whose inspired and often frantic work your supper would be cold...(and the war perhaps lost anyway).

M is also for Marconi

M stands also for another rather important word: Marconi ! — the prophet of radar whose far-sighted remarks in 1922 are quoted on page 42 under the letter R. But by his death fifteen years later, at only 63, he just failed to witness his company's great contribution to the war effort, not only in the well-established field of radio communication but also in the new realm of radar. To take a few examples, the accumulated expertise in short-wave beam transmitting aerials was put to outstanding effect during WW2 by the provision of the massive curtain arrays for the CH stations; the Chelmsford factories coped with high volume manufacture of naval radar equipment and the Research Laboratories at Baddow helped with the work on magnetrons.

After the war, Marconi's Services Equipment Division continued to attract Government contracts which included refurbishment of the RAF's wartime radar chain; but by far the most significant project was that code-named 'Vast & Rotor'. It was indeed a vast job, entailing complete re-engineering of much of the RAF's ground-based radar equipment, mobile and static.

Throughout the 'fifties and 'sixties Marconi's made significant technical progress in all areas of radar technology: transmitters with peak powers to be reckoned in megawatts became the norm rather than the occasional grand exception: radar displays became brighter and clearer and in the constant battle against clutter and potential jamming notable successes were achieved. Defence contracts for Army, Naval and RAF equipments continued to be won at home and for numerous foreign military services abroad; and all the while the company's expertise was widening to embrace not merely equipment design but total systems responsibility as well.

In the post war period the use of ground-based radars for civil air traffic control expanded rapidly. In this new field the company took a leading role, deriving much benefit from the experience gained on defence equipment; in both, the attributes of good design and reliability are paramount.

Figure M4. 'Baddow landmark' — the CH tower moved from Canewden in the mid-fifties.

Reverting again to wartime it was not, of course, just Marconi's who produced radar equipment; much of the British radio and electrical engineering industry was engaged upon it in one way or another. In particular, AEI (Associated Electrical Industries), at its Manchester Metropolitan-Vickers works, produced vast numbers of superb transmitters (for CH, CHL, GCI, GEE, etc) while at the Rugby works of BTH (British Thomson-Houston) great strides were made with new centimetric radar.

After the war, when AEI and Marconi were in strong competition, AEI built a new R & D establishment at New Parks, Leicester, transferring key staff from Manchester and Rugby. Surely no one could then have foreseen that within a few years New Parks, with all its staff and contracts, would become a responsibility of Marconi's! Yet, that is precisely what happened, following the well-known mergers and take-overs of the late 'sixties. As a result, the 'seventies saw New Parks as part of Marconi Radar Systems, Chelmsford, with interchanges of staff taking place in both directions.

Throughout the company's radar history invaluable support has been provided by another great Marconi institution, the Research Laboratories at Great Baddow, where many specialist departments concentrate on particular areas of radar technology and advanced concepts. In the 'fifties, when the coastal CH stations had ceased to operate and were being dismantled, a steel transmitting tower was taken down from Canewdon and re-erected at Baddow so that it might serve for various experimental purposes. Over thirty years later this prominent but now rare landmark, 360 ft high (fig. M4), serves as fitting reminder of Marconi's contribution to radar.

N is for Noise

WHEN, at school, we recited for amusement 'What sort of a noise annoys an oyster?' I hardly expected that the subject of noise could be a serious matter for study by electronics engineers. Yet for those engaged in such branches of technology as communications and radar the presence of noise, which masks legitimate signals, is a permanent annoyance.

Although most people may use the word 'noise' to describe sounds that are unpleasant, obtrusive or unmusical, engineers are concerned equally with the visual and audible effects of noise in a system. To experience both, just detach the aerial lead from a working TV set. As the sensitivity of the set rises automatically in the absence of a signal, the screen will become a random snow-storm, and a rushing sound of no particular pitch will be heard.

All electrical circuits, even when switched off, exhibit a random movement of electrons to an extent depending upon temperature, and it is this very low level of 'thermal noise' which the TV set amplifies in the absence of a strong signal. TV and radar engineers refer to a 'noisy picture' when the signal-to-noise ratio is poor.

Noise can also be picked up from external sources but on the wavelengths used for the majority of microwave radars it is the inherent noise in the early stages of the receiver that is a limiting factor in detecting weak signals. Thus the effective range of a given radar depends very much on the noise factor of its receiver.

External noise, where it does affect a radar, can sometimes be alleviated by special features of antenna and receiver design. But thermal noise, because of its random nature, is not amenable to tricks of cancellation which would require noise of equal waveshape but opposite polarity to be subtracted from it without cancelling wanted signals. The only viable approach is to use the lowest-noise receiver circuits that are available. This applies especially to the early stages, or front-end, of a receiver because of the subsequent amplification.

There are many examples in the natural world that help us to appreciate the difficulty of finding an exact match to cancel a random input. Think, for example, of a typical pebbly beach which, from a distance, presents an appearance of uniform texture and colour. Close examination will reveal that every square foot is unique. Photograph in detail a small area and try to find another that matches it exactly: it is a pretty safe bet that the whole world cannot provide one. The infinite variety of randomness can be mind-bloggling; try to repeat the patterns on a child's kaleidoscope! Try to find two areas of grass lawn where the blades are identical and in the same position! So it is with thermal noise.

Because noise as seen on an oscilloscope (and on the range displays of early radars) looks rather like fine blades, and possibly because green is a favourite display colour, radar noise is sometimes called 'grass'. The height of the grass may be adjusted by the receiver gain control or by applying an amplitude limiter, but what is important is the ability of the operator (or automatic signal extractor) to see a weak signal within the noise.

A radar designer selects the most suitable receiver front-end for his purpose. In early microwave radars of wartime vintage the best available crystal diodes were used in the first stage (the superheterodyne frequency mixer). In later times we have seen the evolution of low-noise microwave amplifiers. Travelling-wave tubes become available in the '50s and parametric amplifiers appeared in the '60s. In the '70s, new generations of microwave transistors came to the fore, and now gallium-arsenide semiconductors offer exciting prospects.

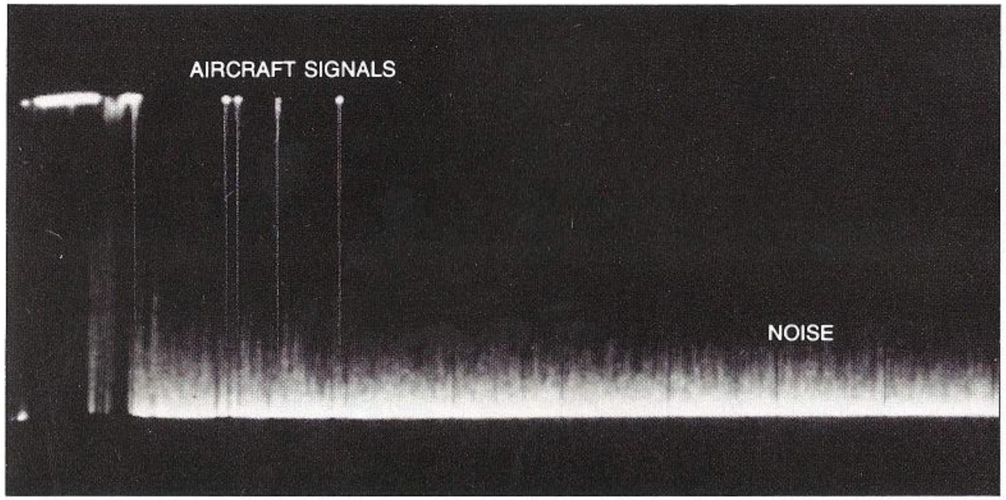


Figure N1. 'A' Scope presentation of typical radar video showing noise and aircraft signals.

For a radar with a given antenna, the maximum range on a defined target depends largely on the transmitter power and the receiver noise figure. We may, therefore, imagine two different radars with the same range performance, one having a comparatively noisy receiver and very high power transmitter, and the other a very low-noise receiver and low power transmitter. The latter has advantages but is not necessarily better under all conditions. For example, if both were subjected to noise-jamming the one with the 'noisier' receiver and more powerful transmitter would be less affected. That is one reason why some radars are available in different forms to suit individual customer's needs (e.g. Martello S713 with high power transmitter, and S723 with low-noise receivers).

For radio astronomy, where the very maximum receiver sensitivity is essential in order to detect a distant radiating source, use has sometimes been made of cryogenic amplifiers; that is, receiver front-ends cooled down as nearly as possible to absolute-zero temperature to minimise thermal noise. This method is not used in normal radars, not only because such receivers are prey to external noise but also because the power expended on the cooling plant could be better employed in driving a larger transmitter.

And now, having made such a noise about noise, I'll be quiet until the next issue!

O is for OTH (Over the Horizon)

TWO facts of nature — that the surface of the earth is curved and that radio waves travel through space in straight lines — together limit the range of conventional radar to the line-of-sight to its target. Thus, targets such as high-flying aircraft can be seen by normal ground-based radars for several hundreds of miles but those at very low altitudes are invisible beyond the horizon (fig O1).

A partial solution to the problem is to extend the effective horizon by elevating the radar as much as possible: likely methods include selection of high natural sites (e.g. cliff-tops, mountains), and the use of towers. More expensive and complicated means may be provided by aircraft and balloons but these have obvious disadvantages for continuous operation. In all the cases mentioned it is, of course, necessary to ensure that the radar is 'low-looking' (letter 'L' in this series) by appropriate choice of wavelength in relation to height above ground.

Now, although radio waves travelling in free space follow straight lines, it has been found possible, under controlled conditions, to launch them close to a conducting surface in such a way that they follow the contours of that surface. Salt water is a fair conductor and it has been found that a suitably polarized transmitting antenna, erected close to a beach, can send out radio waves which in effect cling to the surface of the sea and continue well beyond the horizon. Such waves, on meeting a ship or low-flying aircraft, are reflected back again and can be detected by a similar antenna.

Extensive trials with special radars using this principle have been conducted by our company in the last few years, and there is now no doubt that such a system is viable as part of a total defence network. Excellent detections of low-level targets have been achieved far beyond the range of microwave radars.

I refer to microwaves deliberately, for comparison, because the essential phenomenon of 'sticking to the surface' demands a radio wavelength of some tens of metres, or frequencies well below 30 megahertz. Thus our OTH radar has to operate in what are normally the HF (high frequency) communication wavebands, with resultant problems of frequency allocation and interference.

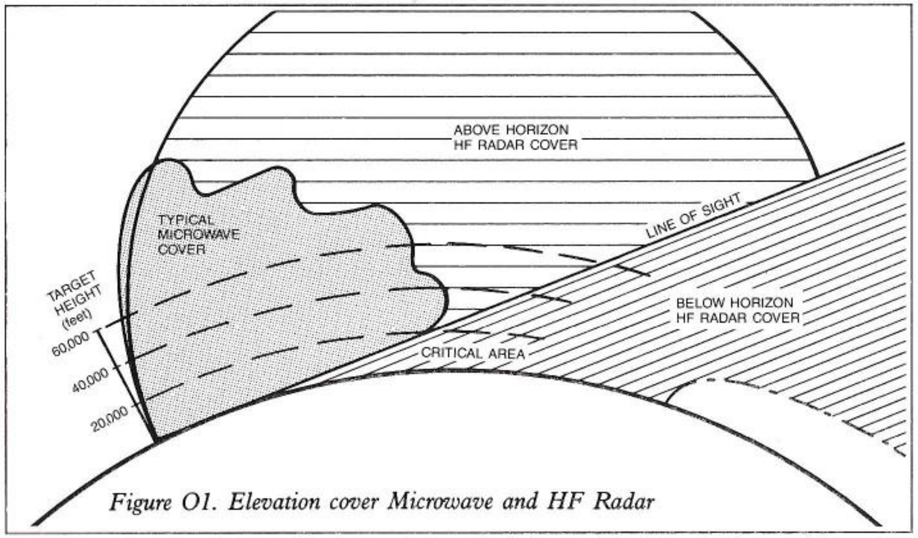


Figure O1. Elevation cover Microwave and HF Radar

Noise, too, can be a problem, and here I am not referring to the inherent receiver noise that I mentioned under letter 'N but to all sorts of external noise that can be picked up on these metric wavebands. The problems of interference and noise are made even more severe by the willingness of such radio waves to travel very long distances around the earth by successive reflections between ground and ionosphere (in other words, normal long-range, short-wave transmission). This means that an OTH radar with a working range of, say, 100 miles, may have to contend with interference and noise from sources many thousands of miles away!

However, the picture is not entirely black, because recent advances in signal processing techniques make it much easier to sort out wanted and useful signals from masses of useless scrabble. For this solution to be applied successfully to OTH, computers are required with speeds and powers that were unthinkable only a few years ago. Such is the rate of advance in these fields that we can look with confidence to the increasing effectiveness and use of OTH in the future.

Many techniques are involved, including specially adapted communications transmitters and receivers, special communication-like antennas, fast signal processing and automatic channel selection. For all of this our company is particularly suited. We have not only our own OTH department at Marconi Radar but also the backing of the Marconi Research Centre at Great Baddow and Marconi Communication Systems in Chelmsford.

This article describes what is known as a 'surface wave' radar because the transmitted wavefront 'clings' to the sea surface. Another form of OTH radar uses reflections from the ionosphere and is known as 'sky-wave' (fig. O2). This technique permits very long-range detection but suffers from huge range gaps due to the 'skip' distance, i.e. the distance from the transmitter to the area where the energy is returned to earth via the ionosphere. While this technique has other applications, it is of no value in filling the low-level range gap just over the horizon.

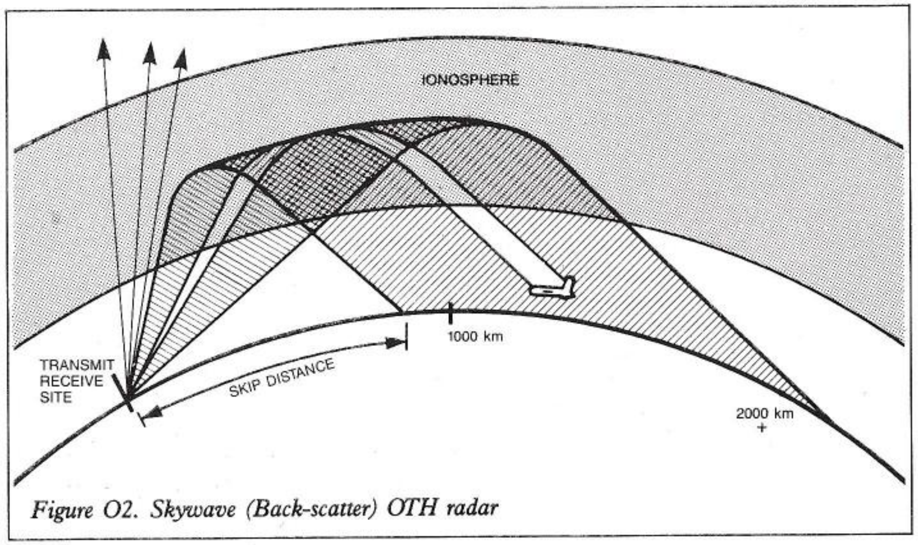


Figure O2. Skywave (Back-scatter) OTH radar

P Q for …

ON REACHING this stage of the alphabet I am reminded of pre-war school teachers who liked to say, 'Mind your Ps and Qs'. It was only years later that I discovered a plausible explanation for that saying – apparently it originated in the printing trade.

And now it seems I must heed it once again. Since P has plenty of implications for radar and Q very few, I propose this time to deal with both of them at one go.

P must stand primarily for PULSE, the essential feature of almost all types of radar, the following being just a few of the ways in which it crops up:

PULSE WIDTH (or pulse length, or pulse duration). Can be anything from a fraction of a microsecond (a millionth part of a second) to perhaps hundreds of microseconds. For most of the ground-based and naval radars in which we are involved the range is usually from a few microseconds to perhaps a hundred or so. Martello S713 transmits a pulse of 10 microseconds duration , and Martello S723, 150; airfield control radars, such as the S511, about a microsecond.

PULSE RECURRENCE FREQUENCY (PRF). The number of pulses per second radiated by a radar transmitter. Probably one of the lowest ever was the wartime CH system at 25 pps (pulses per second), but PRFs up to several thousands are sometimes used for special radars. But again, the most commonly used PRFs range from several hundred per second (e.g. Martello 250 pps) to about a thousand (typical of medium-range airfield radars).

PULSE FORMING NETWORK (PFN). Can take many forms, but the name usually implies one of the major components in a radar transmitter. It is an electrical energy storage device, comprising capacitors and inductors, whose discharge provides the pulse power for the transmitter. It is charged relatively slowly during the interval between radar pulses; and, in sophisticated radars such as Martello, by clever circuits to very precise levels.

PULSE TRANSFORMER. Like transformers used in other branches of electrical engineering (but quite unlike the ingenious toys of the same name currently in vogue with young children!) they are used to step voltages up or down. Pulse transformers need special design techniques to deal faithfully with carefully shaped pulses, and come in all sizes. However, the pulse transformer of a radar transmitter is another of its major components and is used to step up the pulse from the PFN in order to supply a magnetron or klystron ('M' and 'K' in this series of articles).

In conventional designs, a PFN might produce a pulse of 10,000 volts at, say, 400 amps, the pulse transformer with a ratio of 1:4 converting it to around 40,000 volts at 100 amps, a suitable input for a medium power magnetron. Some modern pulse modulators use pulse transformers with ratios in the region of 1:100, enabling magnetrons and klystrons to be fed from transistor circuits.

P also stands for **POWER,** and in radar transmitters we are concerned not only with the power radiated during the pulse, known as the peak power, but also with the average (or mean) power over a period embracing many pulses. The relationship between peak and average powers follows directly from the pulse width and the PRF. For example, consider a transmitter producing 250 pulses per second, each of four microseconds duration. Clearly, in one complete second it will have transmitted for a total of 1000 microseconds, which add up to one thousandth part of a second.

Thus, in this particular case, which is fairly typical of many surveillance radars, the 'on' to 'off' ratio is one to a thousand. So every thousand watts of peak power during the pulse represents one watt averaged over a full second. Or, in other words, a transmitter running under these particular conditions and producing so many megawatts of peak power will also produce the same number of kilowatts of average power.

Another pre-eminent P is the **PLAN POSITION INDICATOR (PPI)**. This is the form of radar display almost universally used on which, as the name implies, echoes are represented to the radar operator as though on a map. When first introduced, early in the war, it represented a major breakthrough in display technology and enabled effective ground controlled interception (GCI) to be carried out by Fighter Command against enemy intruders. I will not enlarge on the PPI here as it has cropped up in other articles (e.g. D for Display, page 14).

Turning now to the letter Q, for radio and electrical engineers it may stand for the ratio of energy-stored-to-energy-lost in a resonant circuit; it also stands for **QUALITY;** two very different but important things. But neither of these terms, being applicable to other branches of engineering, is peculiar to radar.
However, when I think of Q in relation to radar one particular memory (and it's a quotation – another Q!) stands out above all others.

It was when a party of American visitors, all employees of a major US radar company, had been shown around the Writtle Road Works. Clearly and genuinely impressed by the quality of the Marconi technical, commercial and project teams, they obviously found it difficult to come to terms with the site itself.

It was so utterly different from anything they had seen in their own country — mainly purpose-built modern plants — that they were quite nonplussed. Yet they felt bound to offer some comment as they were taken to lunch. 'QUAINT', they said diplomatically, 'very QUAINT'.

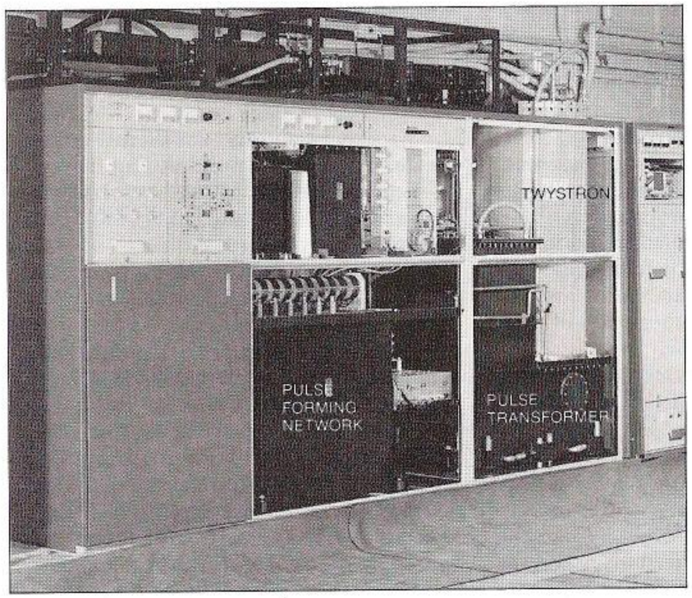


Figure P1. The Martello S713 transmitter showing pulse forming network and pulse transformer which delivers a peak pulse power of 12 megawatts at 140 kV to the Twystron output tube.

R for...

IN ARRIVING at the letter 'R' I would like to look at the key word itself and to discuss some misconceptions about Britain's part in its development.

In Britain, where the main thrust of the original work took place – and I will come to that later – the technique of locating objects by the reflection of radio waves was first known as RDF, for '**R**adio **D**irection **F**inding' and later, from an official public announcement on 17th June 1941, as 'radiolocation'. This was a very satisfactory name and many people then engaged upon it felt a sense of disappointment when, in 1943, it was superseded in this country by the American term RADAR.

It appeared at first to be an ugly word, although one had to admit the sensible derivation from '**RA**dio **D**irection **A**nd **R**anging' as well as its palindromic construction which gives a clue to the essential two-way nature of the reflected radio signal. Anyway, like it or not, 'radar' has become the universally adopted term and is now used, I believe, in most languages of the world.

I regret to see that recently there has been a tendency in some columns of the national press to publish articles and letters which diminish Britain's leadership in radar during the last war. It is as if a new generation has just learned, with great surprise, that Germany also was well-advanced in radar techniques in the war, and that the basic principles had been expounded long before that in many other parts of the world.

From these 'revelations' it now appears to be fashionable to allocate the primary credit anywhere but where it truly belongs; namely, to the engineers, scientists and Service personnel of this country. It was they who did the most important thing: they made it really work and, with American help, laid the foundations for the present world-wide industry.

By the mid-thirties radio communication was well established on a global scale. Large industries had been built up in many countries to meet the demands for equipment for domestic entertainment and for the radio services required commercially and for defence. The phenomenon of reflection of radio signals was commonly observed: indeed it would have been strange if no one had commented upon it nor speculated on how it might be used to locate distant objects. Marconi himself was one of several who drew attention to the effect, commenting as follows in a lecture to the American Institute of Electrical Engineers in 1922:

'In some of my tests I have noticed the effects of reflection of these waves by metallic objects miles away. It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a...beam of these rays in any desired direction, which rays if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver...on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.'

Experimental work was carried out in many parts of the world during the 'twenties and 'thirties with varying degrees of success and, as is often pointed out, the French liner Normandie was equipped with iceberg detecting equipment which relied upon reflected radio signals.

These were all steps in the direction of radar but nothing like positive three-dimensional identification of objects, or established techniques, existed in early 1935 when Arnold Wilkins made his famous experiment at Daventry, described in News & Views, No. 9, February 1985. From that experiment this country embarked, in secret, upon the most forceful development of equipment for detection-at-a-distance by radio, then known as RDF, that had ever been attempted. By stupendous efforts the parameters of wavelength, polarisation, pulse length and repetition frequency, power output and receiver sensitivity were all established.

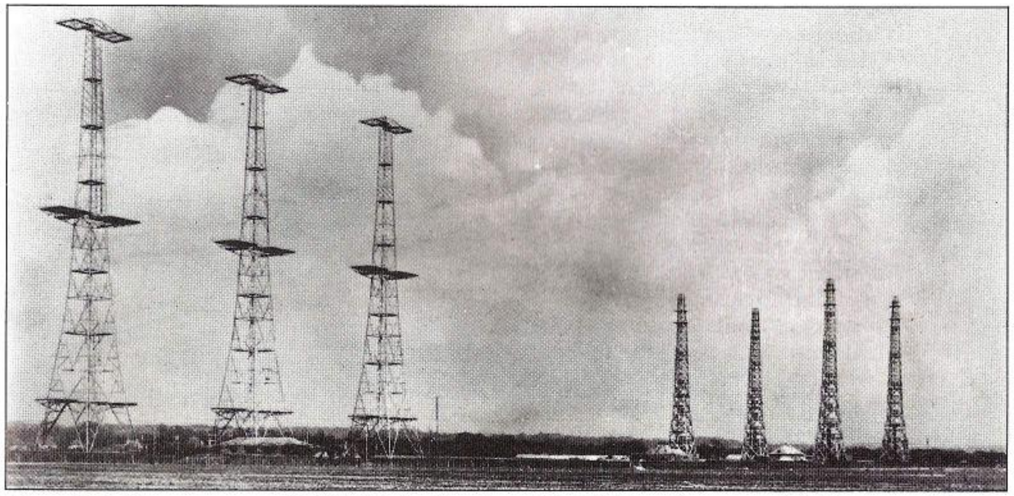


Figure R1. East coast type of CH (Chain Home) aerials. 360ft steel towers at left for transmitting. 240 ft wooden receiver towers at right.

Practical equipment designs were realised in a remarkably short time. Indeed, by September 1938 when Prime Minister Chamberlain flew to Munich to meet Adolf Hitler, his plane was tracked by five RDF stations: Bawdsey, Great Bromley, Canewdon, Dunkirk (Kent) and Dover. A year later, when war broke out, the east coast chain of twenty stations was not only operational day and night but passing range, bearing and height plots via central filter rooms to the integrated air defence system of the RAF!

At the 1985 IEE Seminar in London to mark 50 years of radar it was a scientist from abroad who rose to say that, whilst several countries had made minor early contributions to the development of radar, it was the British who, outstandingly, had built a large-scale, fully-operational radar-based defence system years ahead of anyone else.

In the real terms of an effective, long range 3-D early warning system we were undoubtedly ahead: as George Millar puts it in his superb book **'The Bruneval Raid'**: '...if the British had

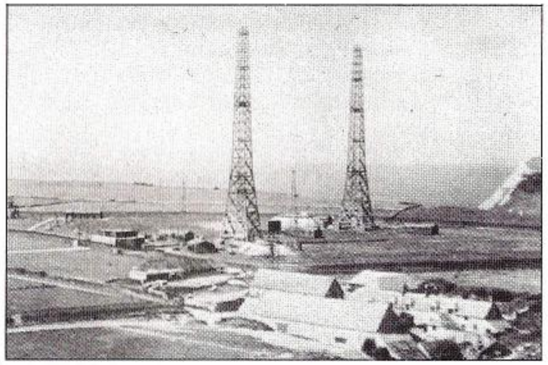


Figure R2. After the move from Bawdsey, radar research went to Worth Matravers, near Swanage.

Continued

failed in many respects to ready themselves for the fight against Nazi Germany…they had done wonders with their early warning system; they had been as thorough and as painstaking as they had been inventive. Invisible walls had been built round the United Kingdom, walls twelve miles high and one hundred and twenty miles thick. H.G.Wells himself could never have imagined such defences…'.

Yes, the Germans had 'Seetakt' and 'Freya' and 'Würzburgs' and 'Lichtenstein' and the 'Hummelbett Line' and other things too, and there is no question about the good quality of their equipment.

An impressive list of developments? In isolation, perhaps so. But by comparison with the realisation of the full east coast chain by the outbreak of war and the speed with which it was extended, geographically and in wide frequency diversity until literally hundreds of stations existed, working around the clock, it pales into insignificance. We must remember also IFF (Identification Friend or Foe) and the many pulsed beacons, the Army gun-laying and searchlight control sets, the GEE, G-H and OBOE precision bombing/navigational systems, the many airborne, naval and gound-based centimetric sets based on the British cavity magnetron and, perhaps most novel of all, the airborne H2S which enabled aircrew to 'see' otherwise invisible ground below them.

With all this in mind we may begin to understand how it was that Reichsmarschall Göring felt bound to comment: 'We must admit that in this sphere the British and Americans are far ahead of us. I expected them to be advanced, but I never thought they would get so far ahead. I did hope that even if we were behind we could at least be in the same race'.

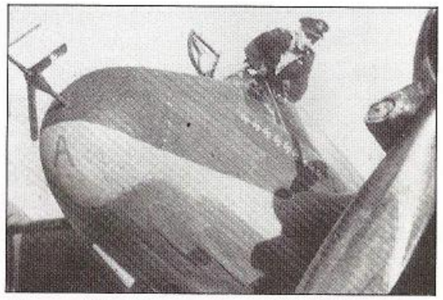


Figure R3. First version of AI (Air Interception) fitted to the nose of a night fighter.

Personally, I am saddened when I read published letters implying that, since Germany had some radar equipment early in the war, or even before, the British claim to leadership can be dismissed as a myth! Such a conclusion is grossly unfair to those who worked so hard and so brilliantly. I believe that the matter is confused by the consideration of who may be said to have 'invented' radar. To that question, 'Who invented radar?' many could claim the honours, not least Hülsmeyer, a German engineer who obtained a patent in 1904, long before the enabling technology had materialised. As I mentioned earlier, many could claim that the idea occurred to them because the phenomenon of reflection was observed repeatedly in the course of radio work.

But to the question, 'Who first successfully developed radar into an operational defence system?' the answer is unquestionably the British from 1935 onwards. This, I believe, is readily accepted by the Americans too, although they had done promising experimental work before the war. Later, after the transfer of the secrets of the British magnetron (letter M in this series), they were to assist us enormously in equipping our services with radar sets for use in the fight against Germany.

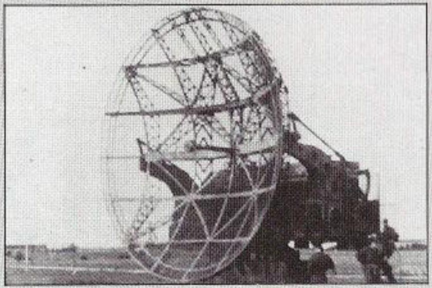
Figure R4. Strange bedfellows! Left to right: Generalfeldmarshall Albert Kesselring, Commander of German's Air Fleet 2 (Battle of Britain); Sir Robert Watson Watt; General Wolfgang Martini, Director General of Air Signals responsible for German radar. The meeting was held after the war to discuss mutual radar problems encountered in World War 2.

German Radar in World War II

Germany was well advanced with radar at the beginning of WW2, especially at the (then) short wavelength of 50cm used in the Wurzburgs. But, curiously, radar data was not so effectively integrated in to the total defence system as in Britain (Thanks to Tizard – see Z). Nor did Germany advance technically to centimetric wavelengths, the key to numerous improvements and essential for high-performance airborne radar.

Figure R5. Würzburg

Figure R6. Giant Würzburg



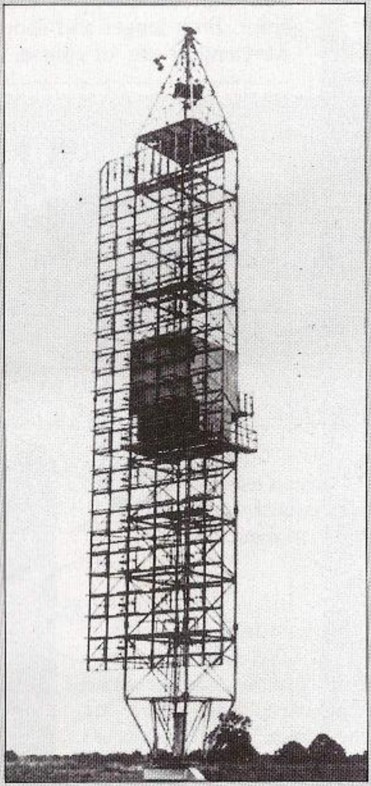


Figure R7. Wasserman.

S is for S-band, systems and signal processing

PROBABLY the most commonly heard S in everyday radar conversation is 'S-Band'. This arises because, many years ago when the various radar wavebands were designated by letters, S was allocated to the ever-popular 10 cm band. (Although, in the newer NATO system of waveband designation this band has officially become 'E/F band', you will hear many people still using the time-honoured title 'S-Band' and I expect they will continue to do so for a long time to come.)

It is the band in which the first cavity magnetron and thus the earliest centrimetric radars worked, and it has been much favoured by designers ever since. Both longer and shorter wavelengths are, of course, also used, each having its own particular advantages for various applications; nevertheless the good old well-tried S-band (in practice usually 2700 – 3100 MHz) is still extensively employed for many ground-based radars such as the Marconi S511 and S711 series for medium range air traffic control and defence purposes respectively.

* * *

'Systems' is a word frequently heard, but its significance in Marconi Radar is not always clear to newcomers to the company. This is a pity since it is included in our title, so I will attempt briefly to explain it. My dictionary has several definitions, of which I will quote two:

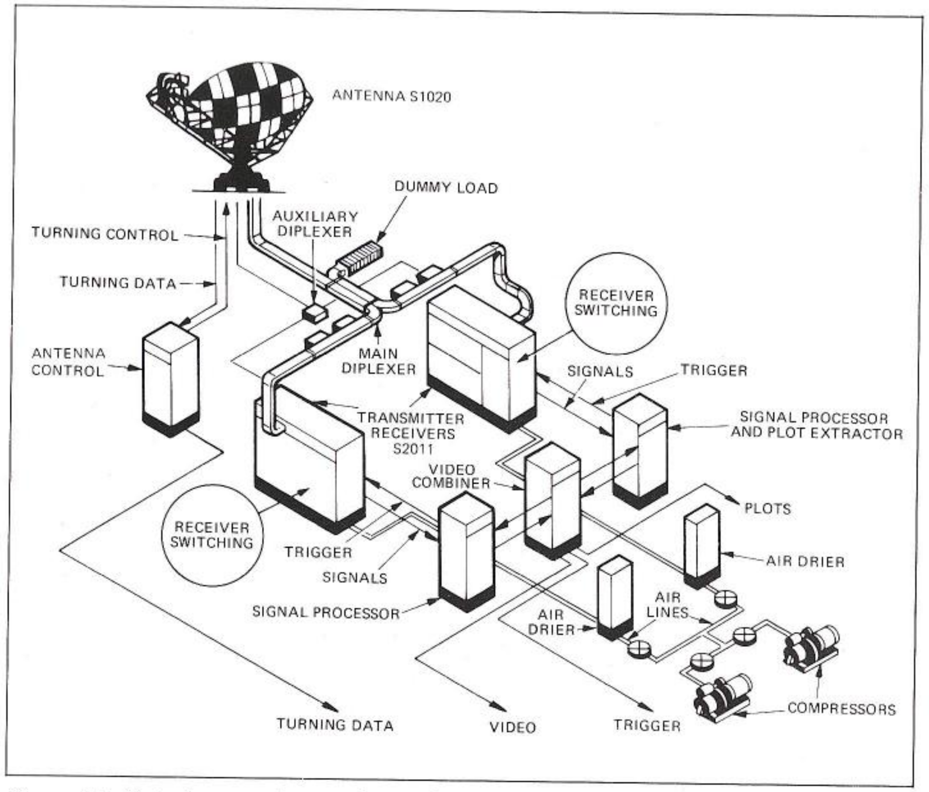


Figure S1. Typical system diagram for an S654 long range ATC radar (circa 1972).

1. **'Any assembly of electronic, electrical or mechanical components with independent functions usually forming a self-contained unit.'** On this basis many of the complex elements of a radar, such as the transmitter, the receiver or the display would certainly qualify as a system. In fact, even a single fully-assembled printed circuit board would meet those criteria. But that is not the general meaning in Marconi Radar, although it may well be so in some other companies.

2. **'A group or combination of interrelated, independent, or interacting elements forming a collective entity.'** This definition is much nearer to home if by 'elements' we understand transmitters/receivers, antennas, displays, computers and other major electronic/electrical/ mechanical units. (Where some of these radar elements are complex we do permit them to be called 'sub-systems'.)

Consequently, in systems engineering we are concerned with the overall design of a complete radar installation, usually to meet a customer's requirement, and this may involve the consideration and specification of a very wide range of equipments. Not only must the choice of all the elements be suitable for the task but they must work in harmony together. Problems of mutual incompatibility – electrical, mechanical and logistic – must be anticipated and allowed for. This is especially so in Naval installatons: a large ship may have several radars, necessarily close together, (see fig. E1 page 17). Often the responsibility of the systems designer extends beyond the normal radar elements into other associated fields such as communications (e.g. radio and telephone links), standby diesel power supplies, or equipment for security and fire protection, to name just a few. This is an aspect of our work which is not always appreciated by applicants for employment since the term 'system' can have such different

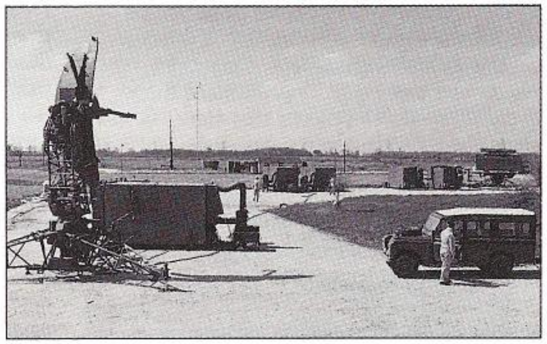


Figure S3. S600 Series system with two antennas and several containers.

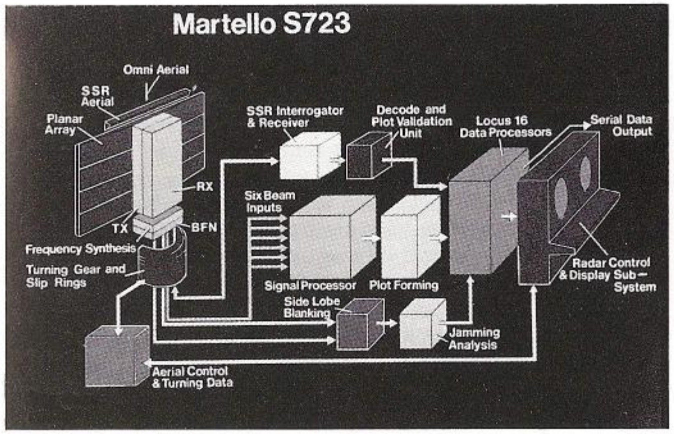


Figure S4 — System or sub system? Martello S723 is pretty complex: yet it is merely the "radar head" providing the input to a full display and data handling installation.

meanings in different companies.

It follows that a broad outlook and operational experience are desirable qualitites for systems engineers, with the result that it is a subject not easily taught in universities or colleges. It is no accident that some systems engineers have spent their earlier years, after basic technical education, in field services or in one of the Armed Forces where they will have gained practical experience.

Now for SIGNAL PROCESSING:

In the history of radar it appears that, incredibly, most of the basic techniques were established by the end of the war. Since then we have seen a continual process of refinement in all aspects of design but most notably in the way in which radar echoes, once obtained, are handled electronically before presentation to a human operator by means of a radar display. It has been an unending and continuous process of improvement but of the many developments that have taken place two distinct phases stand out.

Firstly, there was the introduction of moving target indication (MTI) which resulted largely from the initial work at Great Baddow in the early '50s. MTI circuits permitted the reduction or elimination of fixed targets on a radar display and largely overcame the long-standing problem of ground clutter. Unfortunately, by the nature of their operation, which involves examining the precise radio frequency contained within a returning pulse, MTI circuits also cancel out signals from aircraft that just happen to be flying towards or away from the radar at certain critical speeds. This defect, in turn, was overcome by various tricks but for some years the main problem was to keep all the critical MTI circuits at the peak of fine adjustment. They tended to drift in service and rarely were customers' technicians able to restore performance to the ex-factory level.

The second important phase, in parallel with the advances in computer technology of more recent years, has been the advent of digital techniques for handling radar signals. This has allowed much more freedom in the operating parameters of a radar (for example the PRF may be varied more easily to avoid problems such as blind speeds) and the signal circuits have become far more stable and reliable. Consequently the standard of MTI performance achieved on operational sites has improved enormously.

As I mentioned under letter 'L' of this series we may use linear or logarithmic radar receivers; we may also employ, in the receiver chain, pulse length discrimination circuits (PLD) that favour returns from our own transmitter rather than interfering pulses. So, amongst other goodies, a radar may possess the facilities of 'Lin', 'Log', PLD and MTI. All that lot, plus a few other tricks in some cases, such as automatic plot extraction, are swept up in the general term 'Signal Processing'. Hurrah, I've got there at last!

To permit such refinements in signal processing to be achieved by the circuits handling the received signals it has been necessary to improve vastly the performance of radar transmitters in many respects: frequency stability, pulse shape, pulse-to-pulse jitter and noise content have all been targets for development over the years, and that brings me nicely to the aspects I will be talking about next time under 'T for Transmitters'.

('S' stands also for secondary radar, that broad classification of radar-like equipments relying upon retransmitted signals rather than natural echoes. I referred to these under letter 'I', for Identification and IFF, so will not repeat myself here.)

T is for transmitters

NOT very long after the war, when I was teaching radar in India, a young Air Force officer student came up to me. Putting his hands together in greeting and giving me a big smile he said 'Please, sir, I am having one question'. I probably mumbled something about being glad it wasn't two so he continued:

'You see, sir, you have been telling us about radar and how transmitter of your CH is working for just about ten microseconds twenty-five times in every second. That is coming to be on-off ratio of 4000:1. What I am meaning is that in one whole year jolly transmitter is working about two hours only. That is not being very much.'

He paused to let this sink in, then continued, 'Also, sir, you are telling us that, because of two-way inverse square law of radiation, since radar signals are going and also coming, to double range of radar we must increase power of transmitter sixteen times. This surely also means that if we reduce power to one-sixteenth, range is only halved. I am thinking that because of these things transmitter cannot matter greatly, and I am wondering if we could do away with him altogether.'

This took me aback. Was he just pulling my leg or was he a genuine but misguided thinker? I'd met one or two, like the chap who wanted to build, in his spare time, an airborne radar system for a demonstration over Delhi, and was convinced that the least problem would be the making of a magnetron out of a few odds and ends in the laboratory junk box.

Anyway, I gave him the benefit of the doubt, we settled down to a long chat and I reiterated the basic principles of radar, adding something to the effect that, in practice, reducing transmitter power too far might make the range fall off disproportionately if the receiver were subject to noise or jamming.

At the end of about an hour he smiled even more broadly, thanked me profusely, wished me good night and disappeared.

Some months later, while glancing through the students' note books to make sure I had covered the syllabus, I came across a one-line statement in his book, dated at the time of our chat. Obviously he had got the message at last. It was underlined and said simply, 'NO JOLLY TRANSMITTER, NO JOLLY RADAR'.

The situation is no different today. The transmitter, whether of high or low power, be it dead simple or highly complex, is a vital element of every radar. Designs vary widely but the one essential feature that all transmitters must have is utmost reliability, for the very good reason that my Indian friend had stated so clearly. That is why the advance of transmitter design, especially where powers are high and components are severely stressed, often entails extensive life-testing which can account for much of the cost of development.

The purpose of a radar transmitter is to generate pulses of radio frequency energy to feed the antenna, but it must emit absolutely no radiation or noise

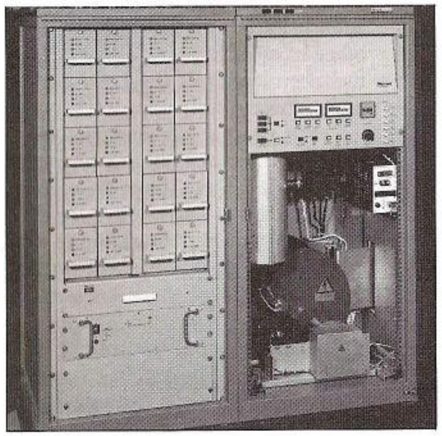


Figure T1. Modern transmitter with TWT and modular modulator.

Continued

between successive pulses, since to do so would prevent the receiver from detecting the comparatively weak echoes and cause interference on the radar displays.

In assessing the power of a transmitter we speak both of the power during the pulse, i.e. the 'peak power', and the 'average power' over many pulses, which takes into account the duration of the pulse ('pulse width' – usually of so many microseconds) and the pulse repetition frequency (PRF).

For typical ground-based and naval surveillance radars the peak transmitter output power is usually between about a half and several megawatts and the average power a similar number of kilowatts.

For other applications there are wide variations; for example a small marine navigation radar might manage with a few kilowatts peak and merely a few watts average power. On the other hand a transmitter for a defence radar capable of detecting small targets at long range might have to generate tens of megawatts and kilowatts. (I am here ignoring the relatively rare cases of continuous-wave radars.)

Many types of transmitter circuit have been used but all fall into one or the other of two different classes. They may, like pretty well all the early designs and many currently in production, generate for each pulse a packet of radio frequency waves that, starting up in a casual sort of way, have no consistent phase relationship to previous or succeeding pulses. Such is the character of transmitters that use self-oscillators be they conventional thermionic valves or magnetrons.

Alternatively the transmitter may emit, for each pulse, an amplified sample taken from a continuously running radio-frequency source, in which case both the start-up and the detailed content of all pulses is the same: such a transmitter is said to be 'coherent' and is sometimes referred to as a 'driven system'.

For the early radars of wartime, which had little in the way of signal-processing and consequently experienced difficulty in separating wanted targets from clutter, non-coherent transmitters were entirely satisfactory. Soon after the war, when serious work started on MTI (moving target indication) systems, there was a strong body of opinion that effective clutter suppression could only be achieved with coherent transmitters since the radio frequency within each echo had to be compared with a reference to determine whether or not it was from a moving target: it was essential that transmitter pulses were coherent to the reference source.

However, the relatively simple and much cheaper self-oscillating transmitters were not to be dismissed so easily; promising developments took place with the so-called low power 'COHO' (coherent oscillator) which locked on to the output of a non-coherent transmitter during its pulse and continued to run until just before the next pulse, thereby providing the necessary reference for MTI throughout the receiving period in a much less expensive manner.

Subsequently such systems have been refined and self-oscillating transmitters, including those using magnetrons, have been improved greatly in terms of stability because of developments in the design of the pulse modulators that feed them. The Marconi S511 airfield surveillance radar is a good example.

Nevertheless, it is still true to say that for sophisticated defence radars, where the ultimate in sub-clutter visibility is required, (like seeing a small missile against a dense background of unwanted returns), a fully coherent driven system has advantages. It also permits other clever tricks to be performed.

One such is improvement of the radar's ability to discriminate between targets closely spaced in range by modulating slightly ('chirping') the radio frequency within the pulse to achieve 'pulse compression' in the receiver. Another is the combating of deliberate jamming by making the transmitter move about rapidly in radio frequency, perhaps on a pulse-to-pulse basis, in either a programmed or random fashion. In fact, once a driven system has been decided upon, all sorts of possibilities, which designers have not been slow to exploit, present themselves. For example, a 3-D radar might, for its height-finding process, use a different frequency for each of several elevation beams.

Very small radars apart, (and these are not usually the concern of Marconi Radar), whatever the form of a transmitter – self-oscillating magnetron or driven system using klystons, travelling wave tubes or even solid-state amplifiers as in Martello S723 – large amounts of power are involved. This means that transmitter designers are involved in many non-electronic problems to do with the extraction of waste heat and the pressurisation of waveguide systems.

For all but the solid-state designs there is the handling of high and dangerous voltages and the attendant risk of X-rays. Consequently, safety is an important aspect of design and a fool-proof, fail-safe control system is necessary to bring on the various services in the correct sequence, and to shut the transmitter down in the event of a fault arising.

Such a control system must also indicate clearly and unambiguously the state of the transmitter to assist in rapid fault location. This is an essential feature and not the least important of the designer's tasks because, as the wise man from the East had noted: no transmitter, no radar!

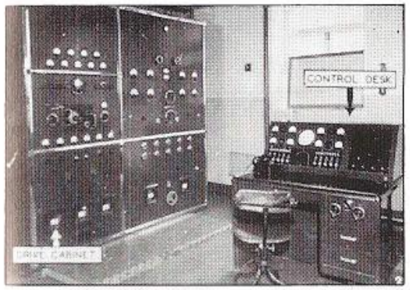


Figure T2.

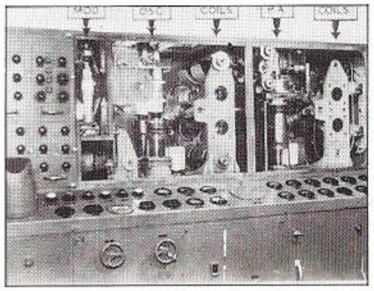


Figure T3.

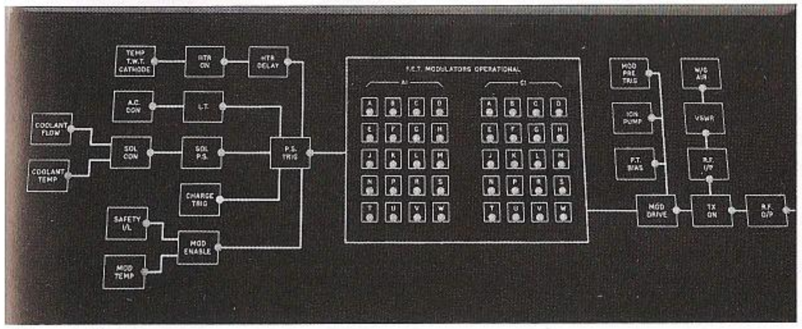


Figure T4.

Control and monitoring systems are essential for radar transmitters, to permit rapid fault diagnosis and repair. Fig. T2 Complex wartime east coast CH transmitter with many indicators and central control desk. Excellent design. Fig. T3, simpler west coast CH transmitter had comprehensive array of meters and lamps to show exact state of all circuits and services. Bold and unambiguous. Fig. T4, typical modern indicator panel for high power transmitter covers all parts of sub-system.

U for umbrella, unusual, unique and unwelcome radars

THROUGHOUT this alphabetical series I have tended to concentrate on matters which I felt might be of most interest to **News and Views** readers; namely, radar topics having a direct connection with the principal products of our company for traditional applications in defence and air traffic control. However, since the letter U appears to have no particularly outstanding radar connotation, this may be an appropriate time to take a wider look at the total radar scene.

It is well known that the original objective of radar – simply, early warning for defence – spread quickly in wartime to many related purposes including pulsed navigational systems, blind bombing, and aircraft landing aids. Furthermore, the period immediately following the war saw much activity in ships' navigational radars and the control of civil airways.

But many more applications have arisen from the principle of detecting reflected radio signals, most of them nowadays being included (not always strictly accurately) under the umbrella term 'radar'.

Starting with unusually small equipments I am reminded of the 'Manpack' sets designed at Leicester and the subsequent 'Prowler' at Chelmsford (see fig. U1). Both of these were light enough to be carried by a soldier and provided warning of battlefield movements.

Received signals are fed not into a normal visual display but into headphones where approaching and receding targets can be identified by their characteristic sounds. Amazingly good interpretation of battle-ground movement in pitch darkness becomes possible given good training and experience. Different moving objects produce quite different sounds so that, with practice, a walking man is easily distinguished from, say a person on a bicycle.

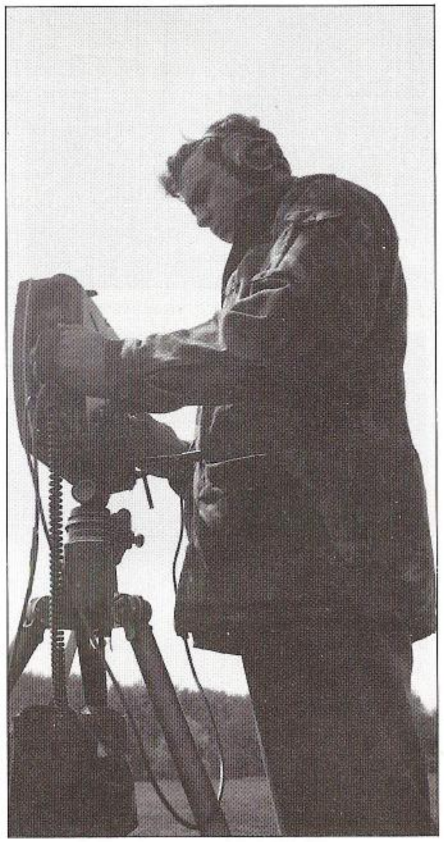


Figure U1. Prowler

Some enthusiastic development engineers used to claim that it was possible to tell a walking man from a walking woman, due to the difference of the moving parts! (But others, in the absence of visual authentication, preferred to rely more upon close-range tactile methods.)

Turning to aviation, 'Taxi' radars, as they have been called in the USA, otherwise known as airfield movement radars or ASDE (airport surface detection equipment), operate at the short centimetric wavelengths with pulse lengths of about a fiftieth of a microsecond and recurrence rates of ten or more thousand pulses per second. With a maximum range of just a few miles, sufficient only to include the boundaries of an airfield, these sets provide a valuable detailed picture of all aircraft and vehicle movements by day or night to the control tower.

Microwave radars help aerial navigation in another way: the detection of storms. Throughout the world ground-based meteorological radars (see fig. U2) provide a continuous flow of data for weather forecasts whilst most airliners carry a similar but smaller weather radar in the nose to warn of unforeseen rainstorms which may develop en route.

In the USA, where exceptionally damaging storms have been experienced, several specially strengthened, radar equipped, Lockheed P3 aircraft are maintained by the Weather Bureau and are capable of flying through the eyes of hurricanes off the coasts of California and Florida. In this way more accurate predictions of the storms' movements have become possible, enabling advance warnings to be given to inhabited areas in the danger path.

Radar can transform the methods of surveying. The more accurate long-range wartime navigational and bombing systems, such as Oboe and GEE-H, revealed discrepancies of registration between the maps of the British Isles and those of the Continent.

Evidently, optical triangulation methods could be improved upon and this discovery has since been put to good use in some under-developed territories where accurate surveying is now required. For example, in remote parts of Australia and Africa, where traditional methods of triangulation are hardly feasible, highly accurate mapping has become possible by aircraft which carry out vertical photography whilst simultaneously checking their position by interrogating distant ground-based beacons.

Another peaceful result of wartime radar work was the tremendous activity in radio astronomy that began almost immediately afterwards.* As scientists and lecturers returned to their universities many in this country took advantage of the readily available ex-Government surplus radar equipment for their initial experiments.

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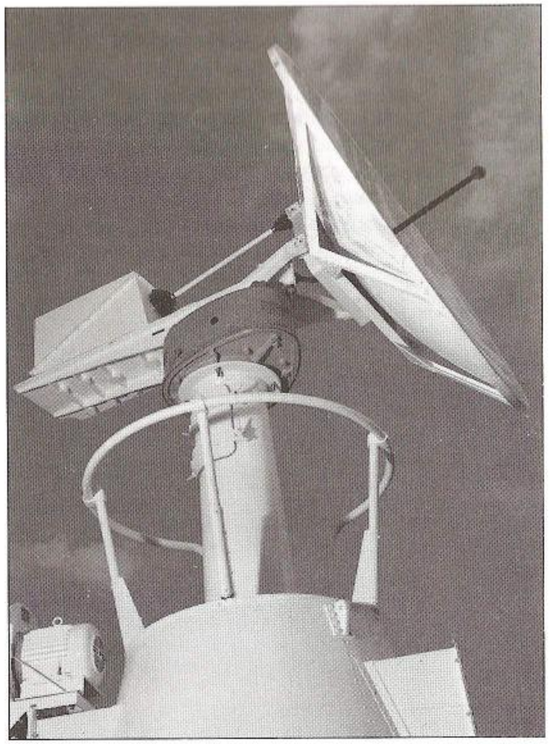


Figure U2. 'Rainbow' meterological radar from Marconi in the mid-60s.

*For anyone interested in the subject I recommend 'The Evolution of Radio Astronomy, by J.S.Hey. Also, the really excellent new book on wartime airborne radar, 'Radar Days', which I have mentioned previously, is very relevant: after the war its author, Dr E.G.Bowen, became the leading figure in the Parkes telescope project in Australia.

Continued

Such gear tided them over while they planned ahead and sought the funding for more ambitious projects. Probably the best known of these is the giant 250 ft diameter reflector at Jodrell Bank, Cheshire; but within a few years radio telescopes appeared also at Cambridge and Malvern and in most of the technically advanced countries overseas. A major project in the southern hemisphere was the construction of the 210 ft diameter radio telescope at Parkes, Australia (see fig U3). This set extremely high standards both in the reflecting surface contour (deviations not exceeding 9 mm) and the accuracy of the servo control system (pointing accuracy within 1 minute of arc).

Incidentally, for this huge fully steerable dish the design (astronomers please note that it was complicated by the use of an altazimuth mount) of the servo system and its gearing was entrusted to the control engineering department at New Parks, Leicester, with excellent results.

Such antennas may be used both as passive listening devices and as active radars. Fairly ordinary radars were adapted successfully soon after the war to investigate the behaviour and characteristics of meteors but much longer range echoes have been obtained subsequently from many objects in the universe. For this work radars need unusually high power transmitters and ultra-sensitive receivers of exceptionally low noise figure, usually employing cryogenic techniques of super-cooling (e.g. the MASER).

Many radio telescopes exist, especially in the USA. Although each may have its own special attributes, many share common design features and to a causal glance appear very similar.

The installation that I would call unique – for surely it must be so – is the deep space radar of Cornell University at Arecibo, Puerto Rico. A natural valley of coral limestone has been modified by excavation to form a hemispherical depression, which, lined with aluminium mesh, has produced a reflector over 1000 feet in diameter with surface inaccuracies of little more than an inch.

Figure U3. The 210ft Parkes radio telescope in Australia.

This vast dish looks up vertically to the sky, and though some limited adjustment of the beam's direction can be made by altering the position of the feed, major scanning of space occurs only as the earth rotates.

Just imagine working on the feed/transmitter/receiver assembly, suspended by cables some 500ft above the surface of the dish! When first installed the average transmitter power was some 150 kilowatts but I understand that this has now been exceeded substantially by later developments.

In the hands of professional astronomers, and aided by extensive data processing, radars of this kind can reveal much new information about our universe, in particular valuable measurements of distances and velocities.

But accurate measurement of velocity by the reflection of radio signals is not only of value in astronomy. 'Electronic velocity analysers' (EVA) are employed successfully in the field of armaments to determine the muzzle velocity of projectiles. (see fig U4).

And if you would like to see a practical demonstration of yet another kind of velocity-finding radar, you might find that a smart gentleman in a blue suit will be kind enough to oblige if you just drive along the A12 at 90 – 100 m.p.h. Thanks (?) to the research work of our good friends at Great Baddow several years ago, the boys in blue have for some time been very adequately equipped. Even the illustrious Sir Robert Watson Watt, often named as 'the father of radar' was once caught that way after the war! Just imagine his feelings. Watch it!!

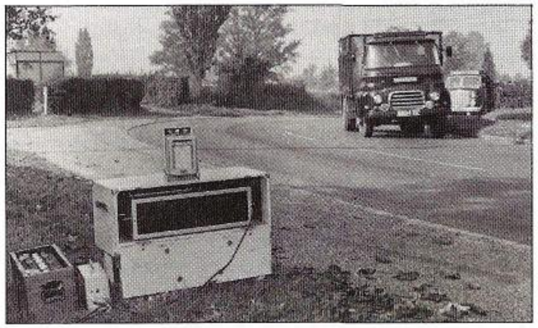


Figure U5. Traffic analyser (PETA) at work.

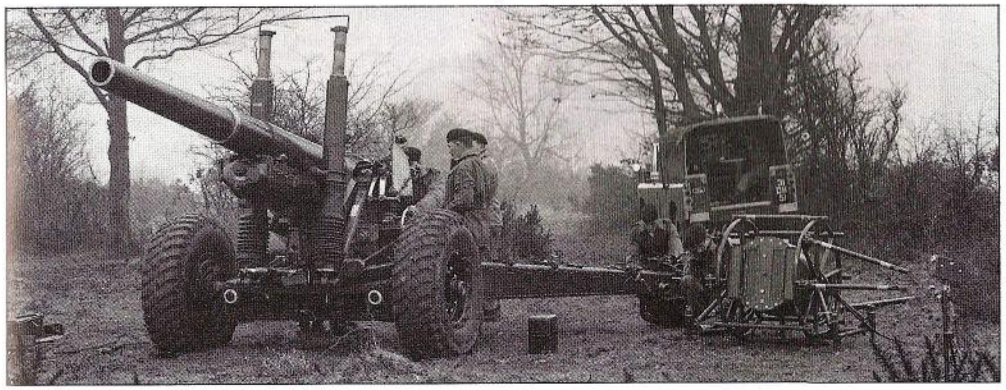


Figure U4. EVA

V for victory, volumetric radar and variously viable ventures

I CAN'T help recalling that for those of us who lived through wartime, the letter V will always shout 'V for Victory' because that's what the posters on every wall said.

I hope readers will forgive some degree of repetition in my dealing with these tail-end letters of the alphabet, because there are some very different words in common usage which mean nearly the same thing. For example, the term 'volumetric radar' is used to describe one that explores a volume of space, or sky, to detect what is there (as distinct from a radar looking only in a limited direction). That, indeed is the role of a normal gound-based surveillance radar which, having located an object within its complete volume of cover, gives the basic information of range and bearing. It might also, in some cases, if it employs suitable circuits for extracting the doppler shift of the received frequency, give an instantaneous reading of targets' approaching or receding velocities.

The volume of the airspace covered by a long-range surveillance radar is considerable. Take for example, a Martello with a range of some 250 miles and a height coverage up to around 100,000 feet. The volume of sky swept out by the rotating antenna beam, as illustrated in fig. VI, is in the region of four million cubic miles! No wonder then, that with the high density of present-day air traffic, there are constant demands to enhance the capacity of the data-handling equipment.

Whether or not our volumetric surveillance radar is designed to give height information will depend upon the application. For civil purposes it is not necessary because that is done by communication with individual aircraft by means of secondary radar, but for defence it is essential. All through the history of radar development accurate height-finding (see letter H, page 22) has been something of a running problem and there had been various attempts along the way before the state of the art reached the form exemplified by radars such as Martello.

Two Vs occurred at an early stage along that path of development where engineers were always seeking better height-finding performance. There was VEB, the large experimental vertical elevated beam system erected in wartime at (appropriately for this article!). Ventnor, and the American V-beam radar. That, as its name implies, had two fan beams displaced at an angle to form a VEE in the vertical plane. With the two beams rotating in azimuth together, targets at low altitude would appear almost simultaneously in both but there would be an increasing time difference for those higher where the separation was greater. Height was derived from measurement of the time delay between the signals from each beam for every target; a workable system when dealing with only a limited number of targets, but a recipe for confusion with high traffic densities.

All ground-based height-finding radars, whether of the 3-D volumetric form (like Martello), or of the separate narrow-beam nodding type, are really instruments for measuring the angle of elevation of a distant target, the height being calculated from that angle and the range.

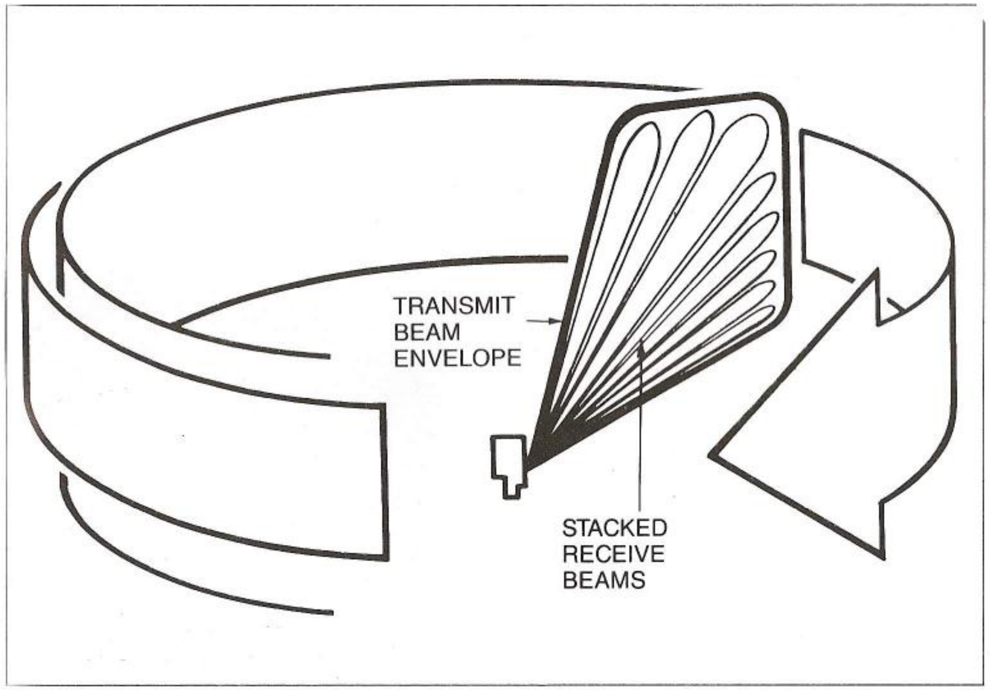
The slightest error in measurement of the angle, especially when targets are at long range, will make a large difference to the estimated height. Consequently, it is essential that the antennas of height-finding radars should rotate about a truly vertical axis: or, if that cannot be guaranteed, the deviation from the vertical should be known and taken into account in the height calculation.

The end result is that all practical height-finding radars incorporate a vital piece of equipment – the vertical reference unit (VRU) – built into the antenna structure. Various types have been used but all are basically transducers giving an electrical output proportional to the verticality (a handy word for our key letter!) of the antenna system.

Such a unit is particularly valuable on mobile radars where it is unlikely that the antenna can be deployed as accurately as on a fixed site: also, if the VRU is quick-acting it may pass data to the height computer sufficiently fast to compensate for temporary disturbances, such as the effects of wind (an unfortunate complaint not confined to radars).

Before leaving V, let us remember that many radars still employ valves, known also to our American friends as vacuum tubes. The main ones are the magnetron (letter M in this series), the klystron and the travelling wave tube. The last two, which are very closely related, employ the important principle of velocity modulation (mentioned under letter K, page 28).

Figure VI. How a volumetric radar sweeps out a gigantic portion of sky, some 500 miles in diameter and 20 miles high.



W for Wizards for worked wonders

UNDER this letter I shall dwell on the two outstanding men who were leaders of radar at its very beginning: a double W and a single W, without whom its development might never have started in time to influence the war in this country's favour.

I am, of course, referring to Watson Watt and Wilkins, respectively the director and his assistant, at the Radio Research Station at Slough, in 1935. However, I shall not repeat in detail the well known story, told fully elsewhere and previously covered in **News and Views** by Bruce Neale, of how Watson Watt was formally approached by a Government committee for his view of the feasibility of a death ray for defence, nor how Wilkins, having calculated that that was not possible, suggested the alternative of detection of aircraft at a distance.

Sir Robert Watson Watt is often credited with the invention of radar. That was not so, because others had thought of it before him: neither did he claim this, freely acknowledging the earlier work of others. But the popular appellation, 'the father of radar', is by no means inappropriate because it was largely his personal drive, energy, enthusiasm and persistence that brought it about.

Like Marconi, who appears in countless encyclopedias as the 'inventor' of wireless communication, he took a set of tentative, partly-formed ideas and forged them into a working reality in a remarkably short period of time. Remarkable is the operative word: from the rudimentary experiment conducted for him by Wilkins at Daventry in 1935 the south east part of the early warning defence chain was developed to a fully operational state even before the war broke out in September 1939.

Afterwards, his book **Three Steps to Victory** presented a fascinating account of what had been achieved. Unfortunately, it seems to me, many who read it comment to the effect that they find perhaps too much emphasis on the achievements of WW himself. If this is a valid criticism it is a pity and he has done himself an injustice: his very forcefulness and ability to present plans and ideas in compelling terms (one might even say high-flown language) were surely some of the very characteristics needed to get such an enormous pioneering job done on time.

To illustrate his delightful style I quote from his address to – of all people – a German audience after the war:

'...because it may well appear that I am claiming special credit – as indeed I am – for those who initiated and guided the work, I want to give one of the most important of these reasons. It is that I believe that our success in radar depended fundamentally on the informed academic freedom which was accorded in peacetime radio research to my colleagues and myself, and to the scientific and technical researcher and developer. If I appear immodest in my summary, it is because I believe the most valuable lesson from radar history is that of the intellectual and organisational environment from, and in which, it grew.'

Figure W1. Sir Robert Watson Watt

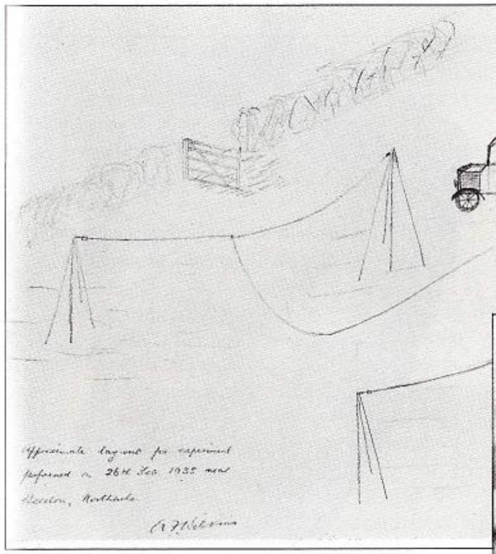


Figure W3.

50 years on — February 1985. Arnold Wilkins OBE (below) at the site of the 1935 Daventry experiment. Left is the sketch of the site he drew as a reference for the artist of the picture, part of which is used as the front cover.

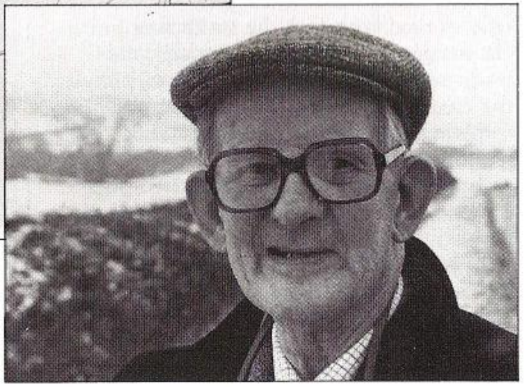


Figure W2. Arnold Wilkins

He goes on to mention the scientists who explored the relevant physics prior to 1920 adding, 'Its application awaited the recognition of a pressing need and the execution of a simple arithmetical determination. Both these initiating conditions were satisfied within, and only within, the few months in which 1934 merged into 1935.'

Those who read his words and study his achievements sometimes conclude that such a purposeful and successful figure must necessarily have been detached and unapproachable. Yet we read of his 'benign influence' and his reputation 'of being a very relaxed and pleasant administrator, who kept closely in touch with the technical work...much loved by the staff...'. That indeed, accords with the impression gained by Bruce Neale who, as an RDF mechanic in the RAF during the early part of the war, met the great man briefly and unexpectedly.

Bruce, in devising some ad hoc modification, was fighting a piece of sheet metal with a pair of shears when a Scottish voice beside him advised, 'Ah would'na do it that way, Laddie!' It was WW himself, passing on his own experience of the dangers of nipping one's tummy between the ends of the handles! Perhaps that incident serves to illustrate how his academic side was complemented by a strong practical outlook, the same that led to his dictum about providing the third best solution because the second best would take too long and the best would never come.

In leading the development of wartime radar, WW was supported by an ever-growing team of scientists, many of whose names are well known today for their later work in related fields such as astronomy and particle physics. But the one who was in it with him at the very start, Arnold Wilkins, and the next to join them, a bright young Welsh PhD from King's College (whose W in his name had unfortunately, for me, slipped from first to third letter), 'Taffy' Bowen, between them carried the responsibility for two main branches of radar – ground and airborne.

It was Wilkins who suggested the now famous Bawdsey as the research site, who did early work on IFF, who devised many of the features of CH radars and carried the responsibility for setting up the early warning chain of stations, a vast job by any standards. Regarded highly by all who worked with him, he was a first class engineer with a quiet manner and warm sense of humour whose ideas, and the credit that went with them, were sometimes taken up readily by others.

While Wilkins took on the ground radar work, Dr Bowen became the leader of the seemingly impossible task of developing airborne radar. Once again I shall mention his excellent new book 'Radar Days' published in 1987, quoted above, and well reviewed by Sir Bernard Lovell (another wartime radar man of note) in the New Scientist of 5 November 1987.

After the war WW, AW and EG Bowen were the principal recipients of the sum awarded for work on radar by the Royal Commission for Awards to Inventors but thereafter their paths diverged.

Several years after Arnold Wilkins had retired it was a joy for our company to welcome him, as our guest of honour, to present prizes at the 1985 Annual Apprentice Award Ceremony. Sadly, that was to be his last public appearance, but his family still affirm that the occasion, with its public recognition of his work to new generations of engineers, was an unexpected highlight much appreciated by him before his death in August of that same year.

For WW I wish I could conclude with a happy sequel to his wartime work. Instead, here are some extracts from Lord Bowden of Chesterfield's Foreword to 'Radar Days': 'The story of the last days of WW is so tragic that I must recount it if only briefly...he was divorced by his wife and left Britain for a new career in Canada...had difficulty in adjusting to civilian life. During the war he had been imaginative and creative and almost ruthless in getting his own way. These qualities made him great and radar possible...they appeared to have deserted him and he never settled to a peacetime career. After several changes of fortune he finally died in an old people's home in Scotland, unknown and apparently forgotten'.

Figure W4. Dr. E.G. 'Taffy' Bowen

Forgotten then and there perhaps, but surely not in fact, and in retrospect? The term, 'father of radar' must apply for all time.

Happily I can report that Dr 'Taffy' Bowen CBE FRS is fit and well in Australia. Both Bruce and I get letters from him and he has been kind enough to encourage me in my own attempts to write about radar. Do read his book and learn the real facts about the early days of radar from one of the three front runners!

...for X-band, X-ray, and Yagis...

GENERALLY, in this series, there has been no great problem in finding radar terms for each letter of the alphabet; in fact, it was sometimes a case of deciding which of several contenders to choose. I have to confess that it isn't quite so easy now that we are near to the tail end. Consequently, I shall consign two letters to the same article.

Let us not, however, underrate X & Y (those close companions, standing for inscrutable quantities, to whom most people are unwillingly introduced at a tender age when first attempting algebra) which crop up to describe circuits producing horizontal and vertical deflection, respectively, on the screens of radar displays. X and Y waveform generators and amplifiers will surely be with us as long as radar continues.

Under the letter S, I mentioned S-band as being the first and probably the most lastingly popular centimetric radar waveband. Historically speaking, the three centimetre waveband, known as X-band, was the next microwave band to appear and continues still to be used for many classes of radar.

Dramatic advances, notably the development of effective S-band airborne radar, followed closely the invention of the 10cm magnetron in 1940. Yet within an incredibly short period X-band radars, even more compact and with improved abilities for target discrimination, also appeared in service during the war. The 3cm H2S, permitting our bombers to 'see' the ground below, through cloud, was a prime example.

Today, X-band is used universally for marine navigational radars and finds application also in some short and medium range ground-based systems. It is particularly suitable for highly accurate height finders and target tracking radars where a narrow beam is required from an antenna array of modest dimensions.

A very short range, and comparatively recent, use for X-band is in very low power doppler radar intruder detectors which are sometimes found in home burglar alarm systems. (Just to complicate matters, X-band is now known in NATO terms as I-band.)

X also stands for X-rays which, although not at all necessary for the

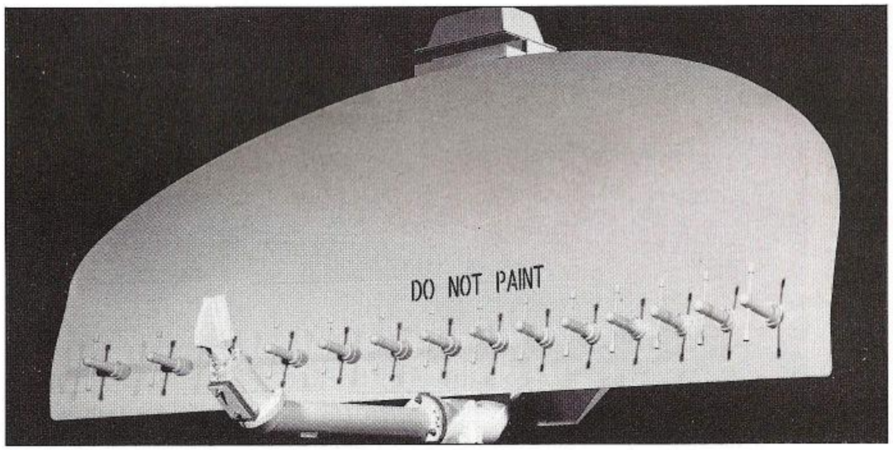


Figure X1. Modern X-band surveillance radar antenna suitable for small ships. The row of dipoles across the base forms an IFF antenna (see page 24). An X-band tracker is illustrated in fig. A1 on page 8.

Continued

operation of radars, are often unfortunately produced as an unwanted by-product of powerful transmitters.

All of the high power radio frequency generators that I have mentioned in previous articles – the magnetron, the klystron and the travelling wave tube – rely upon the controlled movement of high velocity electrons, in vacuum, brought about by the application of many tens of kilovolts. Consequently, the combined effects of such applied voltages, plus the internal radio frequency fields in these valves, can cause X-rays of substantial energies; levels which, if unchecked, could constitute a hazard to persons in close proximity.

The severity of the problem depends upon the valve type and the design of the radar in that where very high peak powers are demanded the operating voltages, and hence the X-rays, are greater.

For a small short range radar the X-ray production may be minimal, but for a powerful long range set producing megawatts of peak power it has to be considered very carefully.

Consequently, this is a problem that must always be faced by transmitter designers; they have to ensure that adequate shielding is incorporated in the design and that reliable safety checks are carried out. (But, as some transmitter engineers may reflect with joy and thanksgiving, the availability nowadays of high power solid state rectifying diodes for power supplies means that we do not now have to suffer the miseries of that other dreaded X – Xenon filled rectifiers! I think they will know what I mean.)

Turning now to the letter Y, I feel that pride of place must be given to the Yagi form of directional antenna. This no longer finds its main application in radar since almost every TV antenna in the land (and abroad too) is a form of Yagi. Nevertheless, it has had many useful and important roles to play in radar, such as on some of the early static low-looking metric radars and on the transportable 'Light Warning' radars made in large numbers for use by our forces overseas (see fig. Y1).

In free space (i.e. when situated away from any reflecting surfaces) a simple horizontal dipole antenna will have an area of sensitivity (if receiving) or a radiation pattern (if transmitting) as shown in fig. Y2a. The effect of adding a simple reflecting dipole is shown in fig. Y2b.

The directivity can be enhanced by adding another element, known as a director, in front of the dipole, fig. Y2c. In a Yagi antenna a reflector and many directors are used, all made to a critical length in proportion to the main dipole and all very precisely positioned. Therein lies the secret of successful Yagi design.

The coverage of a 7-element Yagi is shown in fig. Y2d. In general, the more directors that are added the greater the directivity. As you can see by glancing at the chimneys in the neighbourhood, most TV antennas have perhaps six or eight or ten elements but some have as many as 18 or 21 where maximum pickup of distant stations is required.

In the next issue I shall tackle the letter Z. I little thought that I would get this far when, in a 'brain-storming' session in Bob Scott's office years ago, I lightheartedly suggested this alphabet! I suppose, if you have a YZ, you learn to keep quiet.

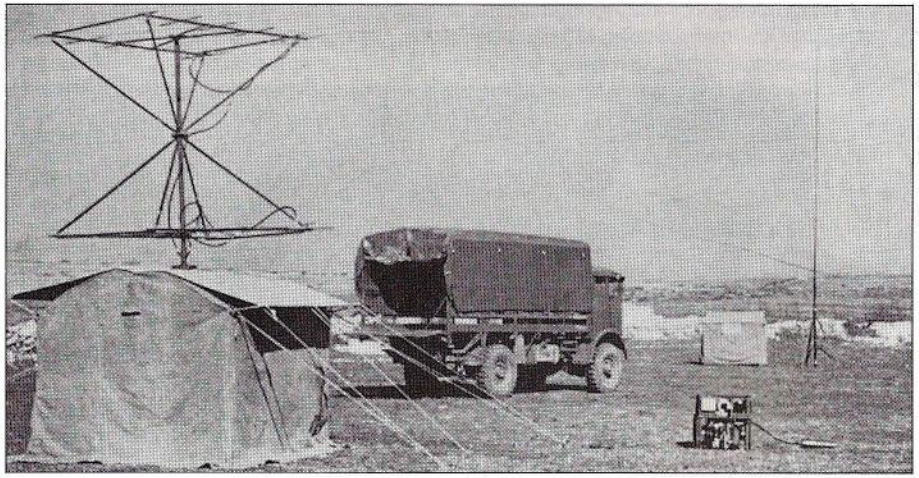


Figure Y1. Light Warning radar (Type 6 Mk III) used in WW2 for early warning and GCI. Aerial system has four 6-element Yagi arrays on a plastic framework. Lower pair can be phase/antiphase switched for simple heightfinding. System includes IFF and HF comms. and is powered by a motorcycle engine (in foreground). Range 50 miles. Nearly 1000 built.

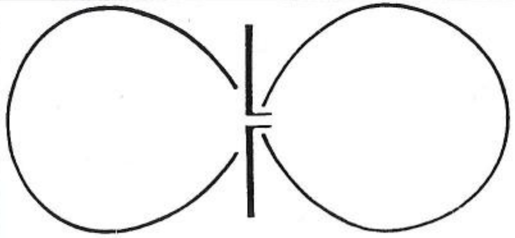


Figure Y2a: Bi-directional radiation pattern of single dipole.

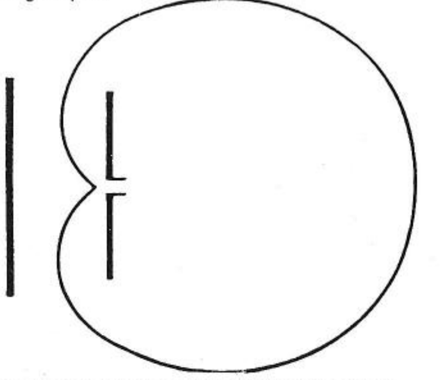


Figure Y2b: A reflector added behind the dipole increases the forward gain

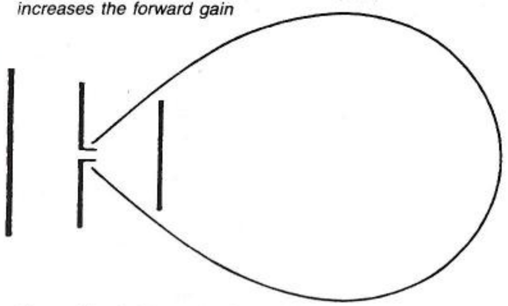


Figure Y2c: A director in front of the dipole further increases the gain and directivity.

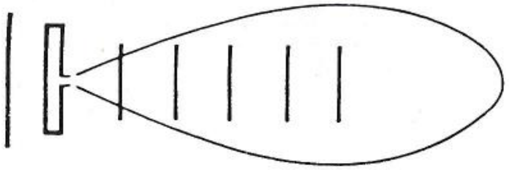


Figure Y2d: Typical TV Yagi aerial with folded dipole, reflector and five directors.

Figure Y2. Plan view of radiation patterns of horizontal dipole showing effects of adding various passive elements (side and back lobes have been omitted).

Z for Brilliance and Tizard

Occasionally, during the last few years as I have worked my way through this radar alphabet, I have been asked how I shall cope with the final letter. The answer is that I am going to cheat!

I hope that, having flogged rigorously through the preceding twenty-five, I may be forgiven or granted a little literary licence, especially when the subject I have in mind is of such importance.

Anyway, I have not cheated entirely: Z-modulation is the process of applying signals to a radar display so that its brilliance varies. It happens all the time on PPI displays (see letter D), but was first used on the range displays of some wartime radars to assist in the recognition of weak signals. (It helped to make them stand out against the noise.)

No, of course, Z is not the initial letter of the name Tizard; but it is certainly the one that gives it its distinctive flavour. ('Tis 'ard to think of Z without Tizard!)

At several points in this series I have alluded to men whose contribution to the early development of radar was outstanding. There are, of course, very many more whose names I have not mentioned. Yet I feel that I cannot let this opportunity go by without a very special reference to Sir Henry Tizard.

A radio engineer? No: although in the Great War he was a pioneer in the use of radio, then still in its infancy, for the purpose of scientifically organised aircraft flight trials.

An electrical engineer? Not at all; instead he was a mathematician who had specialised in chemistry!

Was he one who invented or developed a particular form of radar? No, not really: yet his contribution was magnificent and unique. Without his support radar might never have materialised in this country in time to be a decisive element, as indeed it was, in the second world war.

What then were his remarkable qualities, and the attendant circumstances, that together enabled him to make such a significant contribution to the success of British radar?

By the age of forty, in the mid-1930s, years after student days that had included a stint in Germany, he had, amongst many notable activities, visited Australia, held academic appointments at Oxford, served as a scientific officer in the Great War, become an accomplished pilot of fighter aircraft, visited Canada in an official capacity and become established as Rector of Imperial College, London.

His wartime work in establishing scientific procedures for the comparative evaluation of aero engines and aircraft performance, hitherto a fairly hit-and-miss business, was just one reason for his increasingly widespread influence in official scientific affairs.

In short, Henry Tizard was unique: a blend of accomplished scientist and practical airman, equally at home on academic committees or in the cockpit. Little wonder then, when the Government's committee for the Scientific Study of Britain's Air Defences was set up in 1934, that Tizard should be nominated chairman.

That was a lucky choice for Britain since it was largely through his efforts that Treasury approval was obtained for the work of Watson Watt and his team. Without Tizard's formal backing and personal encouragement it is doubtful if those famous radar pioneers could have made the incredible progress that they did.

Yet there is much more to a total air defence system than a chain of early warning radar stations, however good. A defending air force must be able to make quick and effective use of radar data: this is the point that Tizard, with his combination of flying experience and scientific training foresaw so clearly. It led to his instigation of the RAF air exercises in 1936 that have gone down in history as the 'Biggin Hill Experiment'. Having encouraged the early workers throughout 1935, in the firm belief that their efforts would very soon lead to a chain of viable early warning stations, he realised that no time must be lost in getting the RAF conditioned to the idea of using intercept information transmitted from ground to aircraft. It was necessary to overcome the reluctance of some airmen to accept the idea of relying upon a stream of such radioed instructions; also they must be given practice in using it to achieve aerial interceptions.

Today, when ground control by radio is a perfectly normal procedure for both military and civil purposes, it is easy to forget that it was a revolutionary idea in the 'thirties. Until then it was the pilot who decided the details of how and where to fly and some feared that the new system might lower their effectiveness by curtailing their freedom in the skies. (They appear to have adopted an attitude similar to that of the masters of present-day ships when the idea of radar surveillance and strict radio control of movements in the crowded English Channel is sometimes suggested.)

Tizard obtained the co-operation of the RAF in setting up a two-month exercise in aerial interceptions in the autumn of 1936. Three Hawker Hind aircraft from Biggin Hill aerodrome in Kent would take off on an undisclosed route and act as dummy raiders, while a squadron of Gloster Gauntlets from the same base would presently attempt to intercept them by following instructions given by radio.

At first it was not permissible to disclose that the radioed information came from secret experimental radar stations, so the information to the intercepting fighters was updated only at modest five minute intervals although, in fact, a continuous stream of data was available.

There were, naturally, some teething troubles: a serious radar failure on one important occasion provoked Tizard into sending a blistering note to Watson Watt and difficulties arose for the ground controllers in predicting new courses for

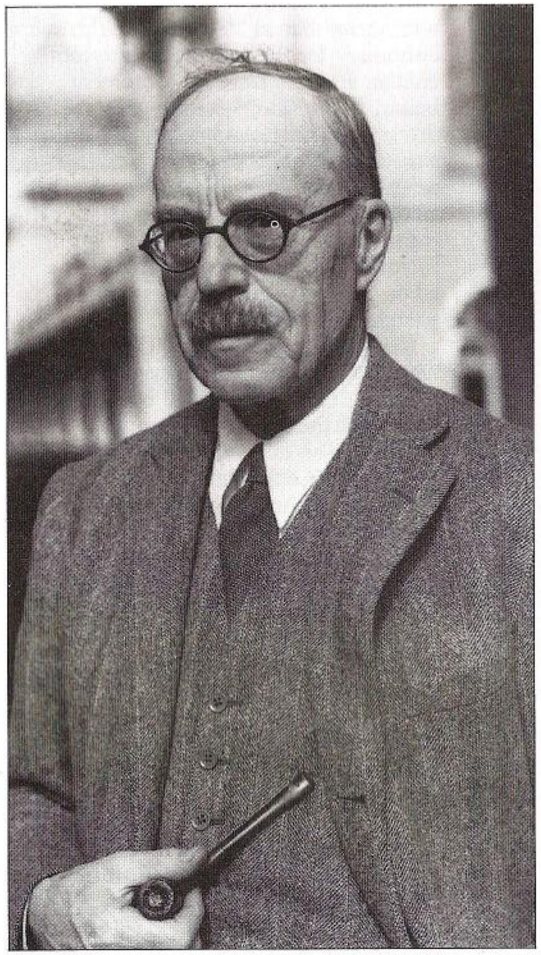


Figure Z1. Sir Henry Tizard

Z *continued*

their fighters if the 'bombers' changed course.

The latter problem was solved by Tizard himself, using his knowledge of flying and of mathematics, in an elegant and simple manner, so that for years afterwards controllers were still referring to the technique of finding the 'Tizzy Angle'.

However, overall results were so encouraging that a further series of trials was carried out in 1937 in which it was customary for the fighters to intercept civilian airliners from the Continent bound for Croydon. Step by step the procedures for ground control of aircraft were evolved and became so well practised that when the war started the whole defence system with its chain of radars, underground filter and plotting rooms, sector operations centres and a whole web of telephone lines swung straight into action.

It appears, in retrospect, that Germany never devoted the same efforts to marrying the scientific and operational aspects of their defence system.

There is no doubt that our superiority was due to the foresight of Henry Tizard; and what is quite amazing is that much of his work was done on an entirely unofficial basis. In fact, for much of the time he was at loggerheads with a former fellow student, Churchill's official scientific adviser, Professor Lindemann (later Lord Cherwell). But his integrity and standing, not only in the academic field, but with senior service chiefs and high ranking government officials, guaranteed his widespread influence.

That influence assisted greatly, in quite another way, the rapid development of the technology of radar itself: during 1938 and 1939 he took positive steps to earmark, at the universities, young and able scientists to augment the existing small band of those dedicated to radar. Thus were the foundations laid for the strong scientific teams at Swanage, and later Malvern, which innovated new sytems so quickly and brilliantly as the electronic war, with all its devious countermeasures, expanded.

So far, then, we have seen Sir Henry as one who strongly backed the original work, prepared the RAF for the use of radar when it became operational, and largely solved the problem of scientific recruitment. Yet he was to perform another significant task that had a profound effect upon the progress of the war.

Through his leadership of the British Technical and Scientific Mission to the United States in September 1940, he solved a potential production problem by ensuring that Britain received enormous help in procuring radar equipment.

A year earlier Tizard had proposed scientific liaison with the USA but not everyone in power agreed that this was sensible: after all, it was argued, America was not yet at war and therefore any secrets disclosed – such as radar – might well find their way to Germany.

However, Tizard's firm contention was that an open and frank exchange of secret scientific progress, devoid of any element of bargaining, should be conducted with the USA. Eventually he received Churchill's approval, the mission was highly successful and paid off well. The outcome was far-reaching: to summarise it in the simplest terms, we gave the Americans the cavity magnetron and centrimetric airborne radar: in return we were soon to receive vast quantities of radar equipment, especially of the airborne varieties, manufactured to very high standards.

The fear of secrets leaking turned out to be ill-founded and of course, America was soon to be in the war with us, anyway, following Pearl Harbor.

In a short article such as this I cannot, of course, hope to do justice to the enormous work of Sir Henry Tizard. If you find the subject of interest I would refer you again to Dr Bowen's 'Radar Days' where the story of the Mission to the USA is told at first hand in fascinating detail and throughout the book you will find comments testifying to Tizard's support of radar development. Phases like 'as always it was Tizard who took the lead', abound. The definitive work on Tizard is Ronald W.Clark's 'Tizard' with a short but telling foreword by Sir Solly Zuckerman. (There, I've got my Z at last!)

In that fat book there is much of interest, apart from radar, about Tizard. One learns, for instance, that it was his objection to the flicker of the 25 Hertz lighting system in Canada, experienced during an official visit in 1924, that probably swayed the UK to choose a national electricity grid at twice that frequency.

Engineers may like to ponder on the effects, on electronic equipment design, of a 25-cycle supply! They may then remember for one more reason, and with gratitude, Sir Henry Tizard, 1885 – 1959.

● Sorry I cheated: but surely this has been better than droning on about Zeros, Zones and Zeners? Anyway, I hope so.

ABBREVIATIONS

AI	Air interception
ASV	Anti-surface vessel
ATC	Air traffic control
BTH	British Thompson Houston - now part of GEC
CB	Citizens band
CH	Chain home (the world's first operational radar)
CHL	Chain home low
ECM	Electronic counter measures (anti-radar)
ECCM	Electronic counter counter measures (by radar)
EW	Electronic warfare or Early warning
GCI	Ground controlled interception
Hz	Hertz (1Hz = 1 cycle / sec)
KHz	Kilo-Hertz — one thousand cycle / sec
MHz	Mega-Hertz — one million cycle / sec
GHz	Giga-Hertz — one thousand million (10^9) cycle / sec
IFF	Identification friend or foe
MTI	Moving target indicator
OTH	Over the horizon (radar)
PPI	Plan position indicator
PPS	Pulses per second
PRF	Pulse repetition frequency
RADAR	**RA**dio **D**irection **A**nd **R**anging
RDF	Radio direction finding (British name for Radar)
RF	Radio frequency
RT	Radio-telephony
SSR	Secondary Surveilance Radar (eg Marconi Messenger)
TWT	Travelling-wave Tube
μS	Micro second (one millionth part of a second)
VHF	Very high frequency
W	Power (watts)
kW	Kilowatt — one thousand watts
MW	Megawatt — one million watts
WAAF	Womens Auxiliary Air Force (forerunner of the WRAF)

Index

Bibliography

Of the many excellent 'readable' books and papers (i.e. as distinct from engineering textbooks) covering the working of radar and the way it came into being, the following selection is suggested for anyone wishing to seek more information

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SECRET WAR
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THE BRUNEVAL RAID
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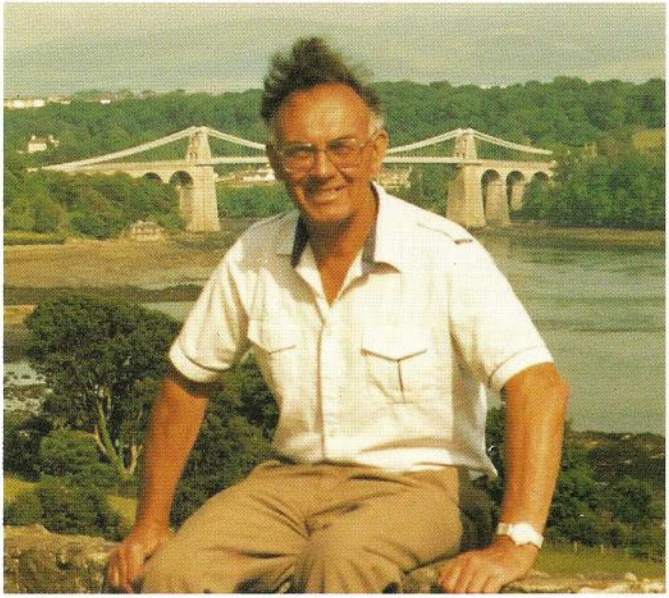

ABOUT THE AUTHOR

When, in 1940, bombs landed on the Royal Aircraft Establishment at Farnborough and some departments evacuated, the most junior member of the technical staff, Colin Latham, opted to join the RAF. After training ("the best technical instruction of my life") he became a radar instructor for the rest of the war and continued teaching afterwards as a civilian, both with the Air Ministry and the Indian Air Force in Bangalore.

On returning to the UK in 1953 he joined Marconi's as a radar development engineer. After contributing to several major technical developments he filled a succession of senior engineering management appointments at Leicester and Chelmsford before retiring as Chief Engineer, Airspace Control Division, at the end of 1985.

Now living happily in Anglesey he enjoys writing and is a Visiting Fellow of the University College of North Wales, Bangor.

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