of using the very flat sites which had characterised them. Again there was little test equipment and few components available for this frequency band and much of the early period was devoted to developing both. The research was successful in that it demonstrated the feasibility of developing a long range radar with excellent anti-clutter characteristics in this waveband but the objective of carrying out bearing measurement and height finding from one antenna system was not achieved. The idea which was attributed to C.D. Colchester who also led the team was to use three waveguide arrays, each with a radiating flare, mounted above one another. Signals from the upper and lower were combined and compared with that from the centre. Since the combined beam was only half the width of the centre one the ratio of signals varied with angle of elevation but, as they originated from antennas at the same mean height, it was hoped that the effect of earth reflection would be the same for both and that the derived elevation angle would not appear to vary due to site effects as the antenna rotated. The experimental work showed that the variation was in fact sufficient to make the derived angle of elevation, and therefore target height, much less accurate than could be obtained from a dedicated narrow beam heightfinder and the idea was not pursued. Surveillance radars for this band were however developed and marketed by the Company for both military surveillance and civil air traffic control.

4.6 Moving Target Indication

An interesting aspect of this work was that of clutter suppression. The Type 11 referred to earlier had employed a technique of moving target indication (MTI) which involved comparison of the phase of signals received from successive radar pulses, with phase in each case being referred to that of the transmitted pulse by use of either coho-stalo or a coherent drive system. The comparison was made by delaying the earlier received pulse in a water delay line - a temperature-controlled vertically mounted column of water with input and output transducers at the upper end to convert the radio frequency signal to acoustic and vice versa. The pulse recurrence frequency demanded by the system was such that the path through the water, from surface to base and back again had to be about 3 metres (i.e., the tube about 1½ metres high) which made the system cumbersome and impractical for anything other than a static installation. The MTI team led by W.S. Mortley devised an alternative system whereby the delay medium was mercury, in a shallow flat cell, with the acoustic wave transversing it horizontally by a tortuous multi-reflection path. The cell while still very heavy required considerably less space but became obsolete very rapidly when it was appreciated that the same effect could be achieved by passing the acoustic wave through an irregularly shaped multi-facetted slab of quartz, designed so that the signal crossed the slab many times from its launch by the input transducer to its emergence at the output. Quartz being a material with low expansion coefficient the delay cell was not only much lighter and smaller than the mercury equivalent but it also needed no temperature control and was not subject to spillage. In addition to their work on cell materials Mortley and his team developed the amplifiers necessary to drive the input transducers and to amplify the output signals, and this work led subsequently to the use of quartz and other materials in pulse compression for radar.

4.7 Air Surveillance at Jersey Airport

Although much of the work in the radar field was stimulated by the requirements of UK and Overseas Defence Authorities attention was also being given to potential civil uses of radar. In 1948 the Marconi Air Radio Division was awarded a contract for an air surveillance radar to be used for aircraft control at Jersey airport. It was intended that this should be based on the marine Radiolocator II but the requirements for appropriate cover in the vertical plane demanded a new antenna design with switchable beams, one having a Cosec^2 shape for longer range targets, and the other having a fan shaped high cover pattern for use when targets were close in. Removeable circular polarisers were fitted to the antenna to reduce the effect of rain attenuation, which could be relatively severe because of the high operating frequency (10 GHz). In order to achieve the necessary increase in range required for this application a higher power transmitter was also required. It used the English Electric Valve 4J50, delivering a peak power of 200 kW (0.5 μsec, 1000 pulses/second), which was high for that time. Further enhancements in performance were achieved by using both logarithmic and linear receivers, with swept gain and short time constant facilities. The final design has therefore little in common with Radiolocator other than the operating frequency band.

This prototype, designed entirely in and installed by the Research Laboratories and employing a number of new techniques was in operational use in Jersey until 1959 when it was replaced by a new design operating at approximately 600 MHz.

By the mid 1950's a total capability for pulsed radar research was established in the laboratories, G.N. Coop who had worked on television transmitters and on the 1.3 GHz transmitter within the Chelmsford works, having transferred to the laboratories to lead a high power team; O.E. Keall and others working on receivers and R.P. Shipway and colleagues on display and data handling systems, all in conjunction with the antenna and signal processing work already mentioned. The CW and FM work on the other hand had tended to decline, with insufficient market drive to push it forward. However one of the most significant advances of the century, the widescale application of semi-conductor technology was still to come.

4.8 Antennas - A New Measurement Facility

One of Franklin's outstanding contributions to the short-wave beam system in 1924 was the flat broadside array of linear radiators supported in front of a wire reflector on tall T-towers. The narrow beams produced by these structures were probably the most effective land-based long-range communication antennae until the Multi Unit Steerable Array some fifteen years later, and they were only replaced in the 1950's by the cheaper rhombic design because of its wider frequency coverage and lower maintenance cost.

In 1953 the Research Laboratories started a program to investigate the performance of wire communication antennae, and for this purpose a wire-mesh covered platform was constructed in the field to serve as an earth plane on which scale models of wire antennae could be mounted. The models worked at 300 to 600 MHz and were rotated to plot the horizontal polar patterns, whilst a 40 foot insulated boom carried a battery fed test oscillator over the earth plane for vertical polar diagrams. Over thirty years this equipment has been used to measure ship, land vehicle, aircraft, television and other antennae, and similar installations were set up at Service establishments. A full size range for testing antennae on vehicles up to 100 tons in weight was installed at SRDE Christchurch using a railway type turntable produced by the Mechancial Engineering Laboratory.

Among the continuing h.f. communication projects was an investigation into the effectiveness of polarisation diversity for receiving long-distance transmissions. It was conclusively shown that antennae at the same site with orthogonal polarisations gave equal performance for diversity reception as pairs spaced several hundred yards apart, and several h.f. receiving stations have been equipped with long-periodic arrays of this type; these are mainly defence installations, the civil h.f. links having been displaced by high capacity satellite and cable methods.

5. PHYSICS-BASED RESEARCH

5.1 Semi-Conductors

In 1948 the advent of the transistor had been announced from the Bell Laboratories in the USA and the whole of the electronics world began to look in that direction. By 1951 Eastwood had set up a semi-conductor research laboratory under the direction of I.G. Cressell and he with a number of colleagues began to grow germanium crystals and study doping techniques. Although the laboratories had some background in crystal growth from Parkin's work on quartz during and after the war, the techniques involved for semi-conductors were very different and like other UK workers the team had to build their experience virtually from scratch. New techniques for refinement and analysis were developed and small quantities of prototype devices made for evaluation by other units within the laboratories and by product divisions of the Marconi Company. All the early work was, as in the rest of the world, devoted to germanium but by the late 1950's the semi-conductor laboratory had extended its skills to the uses of silicon and, to a lesser degree, gallium arsenide. A manufacturing facility had also been set up within the English Electric Valve Company and was producing, inter alia, large area high current rectifiers to designs evolved by the Baddow Laboratories.

By the end of the 1950's much of the work of the semi-conductor laboratory was devoted to the support of a new factory set up as a collaborative venture between English Electric, Mullard and Ericsson. However this proved to be a relatively short term arrangement as by 1962 the collaboration was terminated following the acquisition of the Ericsson interest by the Plessey Company.

5.2 Vacuum Physics

In 1954 R.J. Kemp moved from the laboratories to Chelmsford to become Deputy Engineer in Chief of the Marconi Company and Eastwood took over as Chief of Research. In that year he set up another new activity, the Vacuum Physics Section, under the direction of G.D. Speake. Work on valves had ceased in Baddow at the end of the war, with most of the personnel having moved to Waterhouse Lane, Chelmsford to a manufacturing unit which, following the purchase of the Marconi Company by English Electric, became English Electric Valve Company (EEV). Eastwood believed that there was a need for continued research work in vacuum physics, particularly to fulfil the need for small quantity specialised devices in radar. The team with support from the Royal Radar Establishment worked on devices for radar receiver protection (TR cells) and on noise tubes to be used as standards in receiver noise measurement. The first application of their devices was in radars for the 1,300 MHz band, developed by the Radar Division of Marconi and sold to a number of customers in the military surveillance and civil air traffic control fields. Devices for the 3,000 MHz band followed and, although discussions took place from time to time regarding possible transfer of manufacture to EEV the quantity demand remained small and customers' needs are still being met in 1985 from the pilot facility. Design and manufacture for new requirements was however passed to EEV and from the end of the 1950's only such research work on vacuum and low pressure gas discharge devices as was necessary to support systems research work by other units in Baddow was carried out in the laboratories.

5.3 Magneto-Physics

A third physics-based activity, also started in the early 1950's and led by Dr R.J. Benzie, was concerned with the study of magnetic materials for use at microwave frequencies. Benzie, a wartime RAF colleague of Eastwood, had carried out research on magnetic phenomena for his D. Phil at Oxford and had taken up a teaching post at Exeter University. There he was sponsored by the Marconi Laboratories to study nuclear magnetic resonance which it was thought might, because of the narrow line width involved, offer a means of separating moving targets from the often much larger signals returned from fixed objects such as hills or buildings in radar systems. In 1952 Benzie left the University to join the laboratories on similar work. His experiments on nuclear magnetic resonance did not result in a practical system for a number of reasons, not the least of which was the necessity for the resonance material to be at liquid helium temperature, a considerable disadvantage in an operational radar. He turned his attention therefore to a range of new materials, commonly known as ferrites, which were being studied because of their potential use in microwave devices with non-reciprocal properties - i.e., devices in which phase change and/or attenuation of electromagnetic waves passing through them was dependent on the direction of propagation. Demand for isolators and circulators based on the use of ferrite materials grew rapidly with the development of microwave communication links and of new generations of radar, the latter requiring components capable of handling high peak and mean powers. A range of materials in a variety of sizes was necessary in order to cover the different frequency bands, operating power levels and attention/phase characteristics required and this was achieved by study of the precise constituents of the ferrite mixture, and of processing parameters such as pressure and sintering temperature. Early requirements for isolators and circulators within the Marconi operating divisions were met from the research facility but by the early 1960's the demand had grown to the extent that it was decided to set up a development and manufacturing facility within the Specialised Components Division and the bulk of the staff from the research group on ferrites was transferred to new premises in Billericay to undertake this task. (Benzie had by this time transferred to English Electric, Stafford as Director of the Nelson Research Laboratories.)

All these physics-orientated activities were aimed at fulfilment of system needs of the Marconi Companies and much of the research in other parts of the laboratories was devoted to the study of system parameters, including the assembly and testing of prototypes, usually in association with one of the operating divisions.

6. THE LATER 1950's

6.1 Fur Hat and Linesman

In 1957 the Marconi Radar Division was approached by the Royal Swedish Air Force with a requirement for a study of the Swedish Defence and Air Traffic Control System. A contract was awarded to the Company and Eastwood and other colleagues who had been involved in the studies for the RAF were instrumental in carrying it out. On completion of the study, proposals were invited for design and installation of a Control and Reporting Centre and a fixed price contract was won by Marconi, with a large proportion of the design and commissioning work being allocated to the Research Laboratories. It drew substantially on the expertise acquired by Shipway's team on earlier projects, amongst which were a number of specialised displays.

For example, a large diameter (21") PPI display mounted horizontally so that four users could group around it had been developed under the ROTOR contract. In the same project, techniques had been developed for automatic positioning of a nodding height finder by overlaying a strobe marker on a selected target on a PPI. Circuits for displaying alpha numeric data on displays in positions controlled from a joystick or rolling ball had been designed during technique studies carried out on behalf of RSRE in the middle 1950's. Also for RSRE raid analysis techniques, whereby areas of interest in an operational scene could be examined in detail on a 'B' scope (bearing/time display) or a Magic Carpet, were studied on specially designed equipment. (The Magic Carpet was a display on which horizontal deflection was a combination of range and bearing, and vertical deflection of time and signal strength, the overall effect being a picture in which the signal pulses appeared in three dimensions from the background).

All these techniques were used in fulfilling the requirements for the Royal Swedish Air Force Board in a project known as Fur Hat.

By the time that the contract was received, developments in transistor technology were beginning to make the use of digital techniques in circuitry practical particularly in the processing of raw data received from the radar heads. The Fur Hat system incorporated a purpose built programmable digital computer light-heartedly christened TAC (an acronym for transistorised automatic computer which also happened to mean "Thank You" in Swedish), for fighter interception computing. Its main data processor was a hard-wired logic device in which data storage was carried out in a parallel array of acoustic delay lines. The first station was completed successfully by 1963 with the result that a further contract for a second station was placed and was fulfilled approximately 2 years later.

While the Swedish Air Force was modernizing its control and reporting system the Royal Air Force was carrying out a similar, albeit more extensive, exercise to culminate in an up-to-date control centre at West Drayton. In this also the expertise of the laboratories was utilised in the design of fully transistorised marked raw radar displays with much higher transition and character writing speeds than had been achieved previously. Interface units were also designed to couple the displays to the digital data processing system for which

Plessey was the contractor. Regrettably the periods involved in the specification, design, manufacture and commissioning of the UK system (known as Linesman) were so prolonged that it came into operation several years later than the Swedish counterpart, and was less advanced in terms of the technologies employed.

In carrying out its major tasks on behalf of the defence and air traffic control authorities the digital data processing team was looking for opportunities for exploiting its expertise in civil applications. One was the control system of a nuclear power station (WYLFA) in North Wales, for which two TAC processors were required.

Another was a status monitoring system for an electricity generating station, which made use of the X2000, an ultra-high resolution CRT display with strobe-written characters. Both of these products were sold via the English Electric Industrial Products Unit at Kidsgrove. (It is interesting to note that although the X2000 was never manufactured in quantity it gave very satisfactory service as part of a system for flight trials analysis and software proving at Baddow for nearly two decades from the early 1960's onwards.)

Bright Radar Displays

The display systems designed for Fur Hat and Linesman were to be used in control rooms where subdued lighting was the norm. There was, however, a requirement for a display which could be used in aircraft control towers and other daylight applications. For such purposes English Electric Valve Company developed the E702 five inch diameter direct-view storage tube which was capable of giving a display many hundred times brighter than the standard cathode ray tube. A unit based on this tube was developed by D.W.G. Byatt and colleagues and was installed in 1962 at Gatwick Airport where it displayed signals received by the S232 radar. After evaluation at Gatwick and subsequently at Heathrow Airport, the system was put into development by the Marconi Radar Division and many were sold for use in airfield control towers, where they gave the controller the facility to determine the exact range of an approaching aircraft and the ability to follow its movements until it could be seen through the tower window.

An alternative method of obtaining a bright display was to use a scan conversion tube, made by CSF in France, in which the radar PPI data, produced by a rotating time base synchronised with the antenna rotation in the normal way, was written on a target and subsequently read off by a raster scan process in a manner very similar to that used in a television camera. Displays on this principle were in operation in the laboratories in the early 1960's.

6.2 AJ Studies

Although the Linesman programme was unduly prolonged and to some extent out-dated there was one facet of the newly emerging UK ground defence system in which it was well up with the latest technology and in which the concept had not been previously employed. This involved the detection of individual aircraft carrying jammers in the presence of many others. The effect of such a raid on a normal radar would be to block out at least the whole of the sector in which the aircraft were concentrated, and probably much of the remainder of the display also.

The laboratories in association with the Royal Aircraft Establishment undertook during the period 1955-1958 a study of a system (WINKLE) whereby signals from the jammers were collected by two antennas - the normal radar antenna and a second 'high speed' antenna, perhaps 100 kms distant, which produced a narrow beam scanning the whole sector of interest in the period during which any single target would be in the main radar beam. Signals from the high speed antenna were passed over a radio link to the main radar site where they went through a series of delay lines before being combined in correlators. Correlation was only achieved when the delay in the line corresponded to the difference in paths traversed by the noise signals in reaching the correlation point. Thus from the known delay a target could be placed on a particular hyperbola and its precise position determined as the intersection point between the radar beam direction at the moment of correlation and the relevant hyperbola. This system also used a programmable digital processor (a re-engineered version of TAC). The delay lines were quartz into which an acoustic wave was launched via a quartz crystal transducer, with a similar transducer being used to collect the output. The necessary high speed of scan which enabled a sector of about 70 degrees to be covered in the interval during which the normal radar scanned over a single target was achieved by using a torus reflector with a series of feeds in the half-radius plane, individual feeds being connected to the output receiver sequentially through a rotating pick-up which scanned a circle of secondary collectors, each of which was coupled to one of the main feeds. Thus for each rotation of the pick-up the antenna beam scanned a sector of space determined by the total angle subtended by the torus at its centre.

Initial trials of the system in the North Sea were satisfactory and the equipment was then put into development and manufacture for use by the RAF.

6.3 Doppler Radars

While not commanding the attention given to pulse radar during the 1950's work on various forms of CW radar continued, one of the earlier activities being a study of FM CW radar for use at sea. This was followed in 1950 by a further study, led by Mervyn Morgan, of a pulsed doppler navigation radar for the Royal Air Force. The equipment, then code named Green Satin, determined the direction and speed of an aircraft relative to the ground, using the ground reflection of slanted microwave beams radiated from the aircraft. From observations of the Doppler frequencies in the returned signals, and alignment of the antenna array relative to a compass bearing, the position of the aircraft relative to its starting point could be determined without any reference to ground based equipment. The system was ready for aircraft trials by September 1951 and became standard for RAF planes until the 1970's. Later versions were sold by Marconi Aeronautical Division for use in civil aircraft across the world.

In the latter half of the decade Morgan and his team undertook a study of a pulse doppler radar (Green Sparkler) using a 1 KW 10 GHz klystron manufactured in the USA by Varian. The initial work was devoted to a study of noise performance and other relevant parameters but it led to four practical applications for a radar based on a low power CW klystron. They were:

1) Measurement of the velocity of approach of aircraft landing on a naval carrier.

2) Determination of the precise velocity of a shell after emergence from the muzzle of a gun,

3) Measurement of velocity of vehicles on the public roads, and

4) A speed meter for a hovercraft, requiring no contact with the water and therefore no drag.

Equipment with the acronym EVA (Electronic Velocity Analyser) for shell velocity measurement was delivered to the British Army and worked satisfactory under the arduous conditions experienced in the field, and PETA (Police Electronic Traffic Analyser) was used by the Police Force in many countries for detection and proving of speeding offences on the public highway.

6.4 Microwave Communication

The advances in radar techniques during this decade were accompanied by similar developments in communication. In 1947 Rudy Kompfner, who worked for the Admiralty during the war and moved to the Bell Laboratories in the USA thereafter, had conceived the idea of a travelling wave tube for use as an amplifier or oscillator. Rapid advances in the development of different structures for use at both ends of the power spectrum, i.e., for high power transmitting tubes and low noise microwave amplifiers, took place, led from the USA but with considerable effort also in the UK and France. The English Electric Valve Company undertook development and manufacture and the Baddow Laboratories studied potential applications. As microwave amplifiers and power generators the tubes were particularly useful in broad band radio link systems, such as those required from transmission of television or radar signals, but the commercial importance of such links for carrying many telephone channels over inaccessible paths was also very quickly realised. The early work was carried out in a group led by Rupert Collins. (His team also designed the first i.f. amplifiers, using "lighthouse tubes", for the 1.3 GHz radar mentioned in 4.5, although they were replaced very early in the programme by wired-in miniature valves.) Collins left the company in 1954 and thereafter the work was shared between two teams. One, led by W.L. Wright, concentrated on transmission of radar and television signals. Experimental links were installed between the Company's own radar sites (at Bushy Hill and Rivenhall) and the Baddow Laboratories, and between Baddow and RRE, Malvern. The team was also responsible for design and installation work on the links for the WINKLE system described in 6.2 and for operational links used for transmitting information from RAF stations to control centres. The second team, led by S. Fedida, carried out the initial research work on telephony application and, when the decision was taken to embark on manufacture and marketing, Fedida transferred to the Communications Division of the Company and led the development team based at Writtle. (Some years later Fedida left the Company to join the Research Laboratories of the British Post Office at Martlesham, Suffolk and led the research team which conceived the Prestel system).

The work in Wright's team on radar links continued throughout the 1950's and 1960's, although Wright himself transferred to a newly formed Space Division in 1965. Amongst these achievements were demonstration links in the UK (between RAF Bawdsey and RAE Farnborough) in 1956 and in North Norway in 1958/59. Following this work they undertook, on behalf of Marconi Radar Division, development of a private venture link (SX 120) and assisted in its installation in Norway and Cyprus in 1963/64, and in the UK Air Traffic Control system in 1967. Parallel work on link channelling for the Linesman System began with a Ministry sponsored study in 1962, followed by development and installation over the period 1963-68. Consultancy work in this field continued until 1973.

6.5 VHF, UHF and Tropospheric Scatter Propagation

The regular ionospheric predictions which had been made by the propagation experts for the users of h.f. services in time of war continued throughout the peacetime years from 1945 onwards. The Propagation Group also gave support to communication and radar engineers in wave propagation matters at all frequencies from 10 kHz to 50 GHz, including the performance of site surveys and experimental measurements. It had become the recognised UK source of information on propagation effects in all the radio communication bands, including the effects of obstacles such as building and hills on the reliability of transmission of a signal - much of the theoretical work on the subject, being carried out by Millington. It was not therefore surprising that when the independent television was launched in the UK in 1955, advice on site selection and on the coverage likely to be obtained from individual stations was sought from this group. A contract was placed on the laboratories by the Independent Television Authority to cover both prediction of performance, using detailed information regarding the topography of the area concerned and density of population, and measurement of field strength achieved in practice. The correlation between the predicted and measured performances was so close that for the later stations measurement was not usually regarded as necessary.

In the same period interest grew in communication beyond the horizon at frequencies above 30 MHz by various forms of scatter mode propagation, a phenomenon for which Marconi and the early radar users had found evidence. G.A. Isted made measurements of signals caused by scattering in the E-layer of the ionosphere 85 to 100 km above the earth, the ionisation for the background signal being due to solar radiation, and strong bursts of signal being scattered from meteor trails. A test circuit was set up between Gibraltar and East Hanningfield, and as a result of this work an operational two-way link using a high power 40 MHz transmitter with curtain broadside antenna arrays was installed for MOD between Ventnor and Malta by the Communications Division of the Company.

A more prolific source of business was the investigation of scattering from the troposphere, up to about 5 km height, at higher frequencies. This began as propagation experiments in the mid 1950's on a test link between Bromley, Essex and Grantham. A further experiment in 1955 utilised the high power 1300 MHz radar transmitter at Chelmsford to measure signals at every 160 km range from Grantham to Aberdeen. The results of the propagation measurements led in 1957 to setting up a demonstration link between Start Point in Devon and the old racecourse at Galleywood, using a 10 kW CW transmitter produced by the Communication Division and 10 m parabolic antenna made at Newcastle. The link on 858 MHz was run daily by D.A. Paynter for more than a year, carrying 24 high quality telephone channels, as well as telegraphy, and finally some rather sub-standard television pictures. As a result of these demonstrations tropospheric scatter systems became an established product line, providing commercial telephone links of several hundred kilometres over sea and desert, for island chains, oil rigs and defence networks.

6.6 Radio Guidance for Blue Streak

In 1956 Eastwood was approached by the Ministry of Defence about a radio guidance system for the Blue Streak inter-continental missile, which was at that time one of the elements in the U.K.'s defence strategy. He assembled a team of senior engineers and was awarded a contract for design and development. Trials of the system were to be carried out in Essex and a 360 ft. mast from the wartime CH Station at Canewdon was transferred to Baddow to form a platform for missile control experiments. The team of about 100 engineers was well advanced in the system design, including microwave components to be mounted in the missile for reception of guidance signals, when the Ministry decided to abandon radio guidance in favour of inertial guidance, the technology of which had advanced rapidly in the period concerned. The Canewdon mast was not therefore put into use for its intended purpose but has been applied for many other projects since. It was for some time the receiving end of a microwave link bringing live radar signals from the Bushy Hill Site to the Laboratories and has on a number of occasions served as one end of an antenna polar diagram measurement site.

6.7 Integration of Broomfield Radar Team into Baddow

The major expansion in activities which had taken place in the 1950's caused considerable pressure for space within the 1939 building and the various hutments around it. In 1958 a new 2-storey building, approximately doubling the floor space of the original one was completed and the opportunity was taken to transfer a group of engineers from Broomfield (Chelmsford) to Baddow. This team had been involved in development of a range of radar equipments, a number of which had been sold to NATO countries, and its members were integrated with those at Baddow who were engaged on similar tasks for the Ministry of Defence and the Swedish Air Board and on private venture research and development work. This meant that Eastwood had at his disposal a considerable technical force, probably unrivalled in the UK in terms of its breadth of experience and capability. This, added to his own personal reputation, ensured that the laboratories were often approached when new national projects, demanding outstanding technical capabilities, were being considered. However, the sudden loss of the Blue Streak commitment left a substantial number of engineers available for other work, most of which had in the short term to be company-sponsored.

6.8 A New Generation of 600 MHz Radar

The opportunity was taken to reexamine the requirements of the air traffic market for radar. The Company's S232 radar, developed in the early 1950's and operating in the 600 MHz frequency band, had proved to be very successful for civil air traffic control, primarily because of its freedom from weather clutter and its good MTI performance (resolution of moving from fixed targets). Developments in high power travelling wave tube amplifiers gave promise of even better MTI performance and in association with English Electric Valve Company, who designed a t.w.t. for the purpose, studies of a new system at 600 MHz were undertaken. A new antenna with a linear slotted waveguide feed and single curvature rodded reflector was also designed and feasibility of the total system rapidly demonstrated. Further development was undertaken within the same teams and the equipment was sold successfully as the S264 radar to many civil traffic authorities across the world. By the advent of this particular equipment research on delay lines for MTI purposes had moved from the liquid to the solid state as previously described. The research carried out into the launching of ultrasonic energy into such lines was also destined to be used subsequently in other applications of quartz, such as surface wave filters and frequency dispersive delay lines for pulse compression radar systems.

Digital Techniques

Some of the engineers released from the Blue Streak programme were also made available to work on the Fur Hat programme where they developed display and data handling processes extensively based on digital techniques. (It was the proposal to use digital techniques which had contributed to the award of the Fur Hat contract to the Marconi Company rather than to Decca, who had offered equipment based on more conventional analogue techniques.)

6.9 Radar Ornithology

While this practical systems work was in progress Eastwood and a number of dedicated colleagues were making a systematic study of the causes underlying the clutter effects which had characterised radar from its earliest usage. Some of these such as the reflections from large stationary objects e.g., hills or building were easily identified, but the origin of the phenomenon known as "angels", whereby a display could be substantially covered by very large numbers of apparently stationary or slow moving targets, was less clear. In one formation known as "ring angels" the targets would emanate from a particular point on the display and move radially outwards from it to form a ring, with further rings being generated from the same centre at intervals of about 15 minutes. It was not uncommon to observe several of these rings arranged concentrically, with each expanding outwards at the same velocity, but the effect was usually confined to a few fixed sites in the area covered by the radar and a period of an hour or so after dawn. The origin of the expanding rings could be determined precisely from the radar display and by visiting the relevant spot at the appropriate time the research team was able to correlate the formation of the rings precisely with the departure of flocks of starlings from their roosting site at dawn. The relatively slow movement of dense echoes on the display were also correlated with the known migration routes of birds and a line of echoes generated from objects a mile or two off the coast line at night was attributed to swifts feeding on airborne insects. It became clear that the majority of "angels" seen on radar displays were indeed birds flying singly or in small groups, and the results of the very effective programme of research were collated by Eastwood in his book "Radar Ornithology".

One other prominent effect observed during this research activity was the appearance of a band of noise on the radar display in the direction of the sun, as the latter crossed the horizon at dawn and dusk. This was by no means the first time that noise emanating from the sun had been seen on a radar display but it did lead to a realisation that radio noise from stellar sources could be used to determine, or at least to verify, the polar diagram attributable to the radar antenna. The technique is not likely to be used for checking horizontal polar diagrams because it is relatively easy to measure the signal received from a ground based source by the antenna as it rotates, but it was used in a number of instances for checking vertical polar diagrams where the only other way of making on-site checks would have been to install a radiating source in an aircraft or balloon.

6.10 Antenna Research - Early Work on Electrical Beam Scanning

Such on-site checks were often the culmination of a research and development exercise on an entirely new form of antenna. The laboratories had been gradually building up expertise in antenna design from the late 1940's when J.F. Ramsay published the series of articles on Fourier Transforms mentioned earlier. Apart from the general objective of producing cheaper and more effective designs for communication and radar systems there were two central themes for the antenna work over the period. The first was to produce systems with as wide a bandwidth as possible in order to provide users with the facility of changing channels as required in order to get better performance or, less constructively, to enable jammers to interfere with a wider range of users!. The second was to provide means whereby a radiating beam could be moved in space without the necessity for moving the whole antenna structure i.e. scanned electronically. Much of the work in these areas was carried out in association with Ministry of Defence research establishments; RAE for airborne and ASWE for shipborne applications.

Amongst the most important of the broadband antenna studies was that originally led by M.F. Radford on log-periodic arrays i.e. a planar structure of dipoles, or similar radiators, of length and separation increasing logarithmically from one end to the other. Many versions of the antenna, at frequencies ranging from the h.f. band into the microwave region of the spectrum were designed and used by Marconi Companies and by other companies under licences granted in connection with one of Radford's patents.

Two techniques for electronically scanning a radar beam were investigated, the antenna in each case consisting of a number of discrete elements. The combined beam from the elements radiated in a direction determined by the phase separation between them. Thus if the phase separation was a multiple of 2π the separate elements would add constructively in a direction perpendicular to the array, giving a beam in that direction. For any other phase separation, the beam would emerge at a different angle. In one technique the phase between the elements was changed by inserting ferrite elements to which a controlled magnetic field could be applied. In the other, a relatively long waveguide path was introduced between the elements either as a zigzag in normal rectangular waveguides, or as a helically wound guide with radiating elements tapped off at each turn. The effect of changing the radio frequency in such a system is to cause the phase at the successive elements to change (by an amount depending on the length of path between them). Thus the output beam moves in space as the frequency of the system changes. (It is interesting to note that in the 1940's C.D. Colchester and C.S. Cockerell had filed a patent describing a system in which the frequency of a radar signal was varied during the pulse duration, achieving thereby a within-pulse beam scan.)

Work on both types of antenna (phase scanning and frequency scanning) was supported by the Admiralty Surface Weapons Establishment, with the Marconi Laboratories concentrating on frequency scanning, but having a peripheral interest in phase scanning because of its work on ferrite materials. However, neither system was developed for operational use at that stage; phase scanning proved to be too expensive because of the need for many ferrite elements, each of which had to be reproducible in magnetic performance and was therefore costly to manufacture; frequency scanning arrays were also expensive to make and had the disadvantage that, since frequency change was the means of moving the beam, it could not also be used as a way of avoiding jamming. Thus although the work at that time demonstrated successfully the principles of beam scanning by electrical means, it was some years before the technology of component manufacture had advanced sufficiently to make it possible to design systems which could be manufactured at an acceptable cost.

Also in the late 1950's interest grew in the possibility of designing a single antenna which could receive beams from different directions simultaneously. One application could be a height finding antenna by which the angle of elevation of a target could be determined from the particular beam in which it was detected, or more precisely, by comparing the amplitudes of signals received from the same target in two overlapping beams. Another which was receiving much attention from designers on both sides of the Atlantic was the isolation and possible tracking of individual targets in a multiple attack, such as might come from inter-continental missiles with fragmenting warheads. To achieve the required resolution of targets, large antennas were necessary and studies were carried out on techniques for producing spherically symmetrical structures of diameter up to 80 ft. from materials in which the dielectric constant could be adjusted in order to give lens like properties. Multiple feeds distributed on one side of such structures (Luneberg lenses) would produce the desired multiple beams on the other. The required lens characteristic had been achieved in the USA on relatively small structures by making a sphere as a series of concentric shells, each being of a material of a different dielectric constant from the others. In an ingenious variant studied by E.F. Goodenough the variation of dielectric constant was achieved by disposing table tennis balls at an appropriate density in a dielectric foam. Had this system been put into operational use it would have had a major affect on the turnover of the "ping-pong" ball industry!

As part of the same investigation the Ministry of Defence entrusted the Laboratories with the task of developing a modulator for a very high power radar transmitter which might be used in such a system.

6.11 High Power Radar Transmitters

The transmitter was intended to produce an output pulse with a peak power of 100 megawatts, nearly 2 orders of magnitude greater than that generated by most high power radar transmitters of the period. In order to achieve the equivalent of an even higher peak power it was planned that pulse compression techniques would be used to reduce the effective pulse length in the ratio 1 to 20. Thus the system would have an effective peak power of 2000 megawatts! The output valve, a klystron operating in the 400 MHz frequency band, was being specially developed by the Services Electronics Research Laboratory, Baldock. Extremely high voltages (about 500 kilovolts) had to be applied to the valve during the pulse period and there was consequently a high X-ray flux in the system. The modulator was therefore enclosed in a lead-lined pit with all the controls outside the danger area. The very formidable problems involved in this unique activity were well on the way to being overcome, i.e. the modulator was operational and the klystron oscillating at about two thirds of the peak power of 100 kilowatts, when the decision not to proceed further with the system was taken by the customer. While it had not resulted in an operational requirement, the work had demonstrated that the Laboratories had an unrivalled team in high power modulator and antenna work. The decision not to exploit it fully was one of defence strategy, not a consequence of technical shortcomings.

6.12 Satellites

One of the most important advances of the 1950's not previously mentioned was the launch of artificial satellites, beginning in 1958 with the first Sputnik. Because of its potential importance for long range communication, interest in this work in the Marconi Laboratories was considerable and very early measurements were made on Doppler shifts associated with satellite movement, using techniques developed by Lea and his colleagues for frequency control and measurement. By 1959 studies on potential uses of satellites were in progress in several parts of the laboratories, one of the earliest being carried out in association with the Royal Aircraft Establishment and the Royal Society on a scientific satellite, to be equipped with a large telescope and aligned by television. Other system studies followed, covering communications equipment and antennae for defence links, navigation, satellite to ship and satellite to aircraft communication. In order to make best use of the limited power available from the satellite, both analogue and digital methods were studied, much of the work being carried out under study contracts placed by the European Space Agency.