Review of United Kingdom Radar

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A review of primary radar systems in the United Kingdom that have recently entered service or are at an advanced stage of development is presented. Naval, airborne, and land-based types are all discussed covering both civil and military interests, although particular emphasis is given to airborne equipments. Some general supporting radar technology including University programs is also covered.

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INTRODUCTION

The radar industry in Britain is very much alive, as RADAR 82 confirmed, but radar evolution has not precisely paralleled that in the United States. This is partly because of different operational needs and different market conditions, and partly because of local fashion and the accidents of innovation.

Most of the major electronics companies have divisions devoted to one or more aspects of radar. As the radar community marked the advance of technology into this decade with the International Radar Conference in Washington, D.C., it was suggested that a review of radar technology in the United Kingdom should be published in these *Transactions*. Accordingly this portmanteau review has been prepared, and we hope that it excites your interest as well as providing a source of reference.

At the start of this project it was realized that the fields of endeavor that might, perhaps loosely, be described as radar were so wide that a number of constraints would have to be applied. Radars above 300 GHz have been omitted such that laser radar and laser rangefinders are excluded. Secondary radars, instrumentation radars, and a number of radio navigational aids (altimeters, Doppler navigators) have also been omitted in the interests of the page budget available, as have radar data processors. Little has been included on HF radar. Finally, component technology is considered to be generally outside the scope of this review.

The review has been partitioned very simply into the fields of ground radar, naval/marine radar, airborne radar, seekers, and University programs and is presented in that order. For a number of reasons, it has not been possible to give a comprehensive treatment throughout the paper though a serious attempt has been made in this respect in the airborne radar section. The preparation of this review has been hampered by security restrictions, and this is reflected in technical details being unavailable in many areas.

II. GROUND RADAR

Starting with the most powerful systems, two major long-range three-dimensional air defense radars have appeared in the last few years. European weather and target environments make multiple beam search desirable, and both radars have this capability or its equivalent.

The Marconi MARTELLO *L*-band transportable radar was first announced in 1978. It has a wideband coherent frequency-agile transmitter of over 10 kW mean power and a low sidelobe planar antenna made up of a stack of wideband linear arrays (Fig. 1). Nine simultaneous receiving beams are formed at intermediate frequency by a resistive matrix beam forming network which enables the beams to be individually tailored without any orthogonality constraints. The stack of receiving beams

Fig. 1. MARTELLO.

provides three-dimensional data, accurate elevation interpolation being possible since all beams share the same transmission frequency. The antenna is demountable, and the whole radar can be set up on an unprepared site in under 6 hours. A digital signal processor is used with adaptive clutter cancellation, the thresholds being set from a continually updated clutter map. The radar has complete plot extraction, data handling, and display facilities and can operate as a self-contained station or as part of an air defense network.

The second new radar, the *S*-band Plessey/ITT Gilfillan AR320, is based on the earlier Plessey AR3D and ITT Gilfillan S320 designs. The AR320 uses the elevation within-pulse frequency-scanning principle of the AR3D (Fig. 2), the frequency sweep also being used to provide pulse compression. The low sidelobe planar array antenna is developed from that of the S320 and includes phase shifters to permit independent variation of frequency and elevation beam position. This also gives the AR320 a limited look-back potential. The AR320 transmitter uses a crossed field amplifier output stage to provide a mean power of over 24 kW. It can operate over a range of pulse durations and repetition frequencies and has an adaptive Doppler processor. A fully automatic three-dimensional plot extractor is incorporated. The AR320 can be configured to meet fixed site, transportable, or mobile air defense requirements.

The Marconi ASRS511 is an example of an airfield surveillance radar and gives detection of 10 m^2 targets out to 100 nm. The frequency band is 2.7 to 2.9 GHz and a pulsewidth of 0.85 μs is used at 650 kW peak. A 6-period staggered PRF is employed together with a 4-pulse canceler having time varied weighting. Temporal threshold integration is used in both the MTI channel and

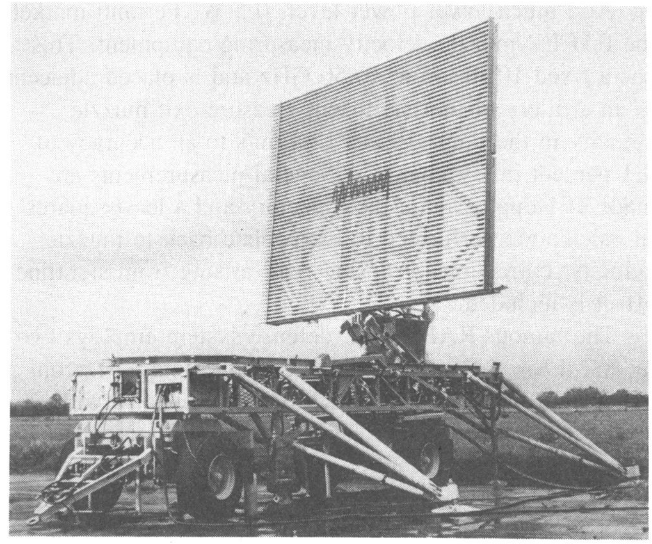

Fig. 2. Plessey AR3D.

a noncoherent processing channel for clutter adaptive thresholding. Two beams, overlapped in elevation, are available from the 33.5 dB gain antenna; the main beam having continuously variable (between circular and linear vertical) polarization and the auxiliary upper beam having fixed circular polarization.

For civilian applications Racal-Decca manufacture and employ *S*- and *X*-band radars in vessel traffic management systems (VTMS): these are pulse radars similar to their large marine radars. Antennas are up to 25 ft aperture (see Fig. 3) with transmitters up to 75 kW, though more typically 20 kW. More than 300 of these radars have been installed for harbor and waterway surveillance; for example, in the United Kingdom there is the English Channel system, the Thames Barrier system, Teesport, and Portsmouth. The radars are often supplied under Racal-Decca turnkey contracts covering operations center, data processor, communications, recorders, etc.

Ferranti continue to develop their high power CW radar technology. The Radar type 86 which is used with the Bloodhound II SAM system has been updated by the incorporation of many improvements including a new advanced digital signal processing system. Extensive modifications to increase reliability and to reduce the costs of maintaining the equipment have also been incorporated. A new experimental CW radar which operates at Ku-band has been produced. This equipment has a very high power transmitter and a sensitive receiver which incorporates clutter cancellation and full target tracking capabilities.

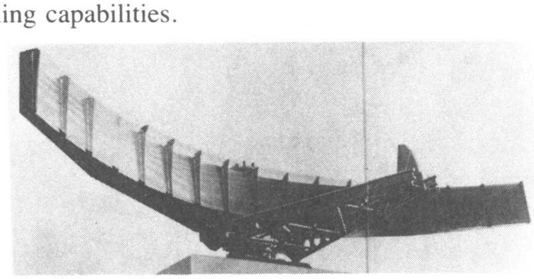

Fig. 3. Decca VTMS.

At a much lower power level, 0.5 W, Ferranti market the PACER muzzle velocity measuring equipment. This has a fixed 10° beam at 10.50 GHz and is placed adjacent to an artillery or mortar. It will measure exit muzzle velocity in the range 100 to 1400 m/s to an accuracy of 0.1 percent in less than 1 s. Several measurements are made of Doppler along the trajectory and a least squares fit calculation performed to extrapolate back to muzzle velocity: correction for cosine error arising from sightline offset is included.

The famous RAPIER air-defense system employs two radars, a Racal-Decca surveillance radar, and a Marconi guidance radar, although optical guidance is also widely used. The weapon system has a range of 12 km and covers from ground level to 3000 m. The system is lightweight and mobile, and there are two basic versions, either towed by a small Land Rover (jeep) or fitted on a tracked vehicle (RCM 748). The surveillance radar is an *S*-band pulse-Doppler type to combat severe ground clutter. The scanner rotates at 360°/s, and this is a key contributor to the average short reaction time of 6 s. The radar features automatic detection, and a PPI display is not provided; the operator does have a sector display by way of a ring of 32 lamps, though this is not essential to engagement. Once a moving target is detected, it is interrogated by way of an integral IFF and, if considered hostile, a system alarm is generated. The four missiles on their turntable slew to the bearing of the target together with the optical tracker and the guidance radar. The operator is alerted by a tone in his earphones. The guidance radar, known as DN181 BLINDFIRE, operates in the millimetric band and hence has a narrow beamwidth, provided by an aperture of 1.5 m approximately. BLINDFIRE, Fig. 4, is a monopulse radar and acquires the target by way of a small vertical scan. The antenna is an offset Cassegrain type. The weapon system can be inhibited in designated sectors by way of a ring of switches next to the sector display lamps. It is of interest to note that the surveillance radar transmitted pulse shape and high receiver selectivity have been specially designed to permit dense deployments.

Recently, further work has been undertaken in the field of Airport Surface Surveillance Radar by Racal-Decca: their ASMI-18X uses a low cost, modular approach while still providing good performance by comparison with 35 GHz types. The scanner has an 18 ft slotted waveguide radiator horizontally polarized, producing 36 dB gain and 0.4° azimuth beamwidth; the rotation rate is 60 rev/min. The radar operates at 9410 GHz and transmits 40 ns pulses from a 20 kW magnetron at a PRF of 4 kHz. The receiver noise figure is better than 10 dB and a logarithmic successive detection IF amplifier is employed. The sensitivity is sufficient to detect a crawling person at 2 km on the runways, and resolution is sufficient to clearly show the shape of large aircraft. The display is fed via a high resolution scan converter. The use of *X*-band allows maintenance of this performance in all weathers, including blowing sand.

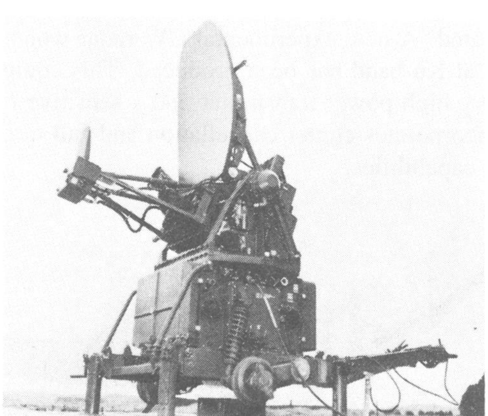

Fig. 4. RAPIER BLINDFIRE.

The ZB298 radar, manufactured by Marconi Avionics, is a radar in use by the British Army for the ground surveillance role. It is an *X*-band clutter-locked pulse-Doppler type with a range of 5000 m against personnel and 10 000 m against vehicles. It can be either vehicle mounted or used from the ground. In the latter case the radar can be carried by only two men and can be put into operation within 3 min.

When operated from the ground the equipment comprises three major units:

(1) radar head (0.5 m × 0.5 m × 0.2 m), which contains all the microwave circuitry including the 2 kW peak power magnetron transmitter
(2) tripod and angulation head
(3) control box and visual display unit, which allows remote operation of the radar head at distances greater than 20 m.

In its surveillance role ZB298 can acquire targets to an accuracy of ± 20 m in range and ± 10 mil in bearing. It can also be used for the adjustment of artillery fire and surveillance of frontiers, rivers, and coasts. The system is in use by the infantry, artillery observation units, and armored units of the British Army. The radar has been exported to several countries, including Holland and Denmark.

A series of a hand-held and manpack radars has been produced over the last decade for use by the Army. One of the latest is the surveillance radar SCAMPI, conceived by RSRE and partly designed and built by the Marconi Research Laboratories. The equipment employs a tripod mount for mechanical scanning of the radar head which may be used independently or combined with a remote visual display and control unit. The Ku-band radar head employs a planar array antenna, a fully coherent solid-state transmitter, and a microwave integrated circuit duplexer/receiver. The display and control unit controls the scanning mechanism, gives a full sector visual display (using a dc electroluminescent panel), automatic detection, and programmed setting up instructions. Extensive trials of SCAMPI have shown the system to perform very well. The system is being extended to allow target tracking and artillery fire control modes. A larger antenna and more powerful transmitter are being used together with FFT signal processing and microprocessor controlled data and display processing.

The Hostile Fire Indicator GS20 was put into production in 1978 by MESL for the British Army [1, 2]. This is an *X*-band radar for the detection of all calibers of projectile, including bullets. It provides continuous coverage of 360° azimuth by the use of 4 static heads (Fig. 5). Each head contains a CW transmitter and a bonded triplate microwave circuit providing 4 balanced mixers. The mixers are used as homodyne receivers by utilizing a −13 dB bleed from the transmitter. The Doppler band of interest is 10 to 110 kHz and sensitivity of −100 dBm with an overall noise figure of 10 dB achieved. Signal processing and target declaration are mainly digital using custom LSI. The false alarm interval is of the order of months. The display is one of the smallest units and indicates the direction from which a ballistic projectile was fired.

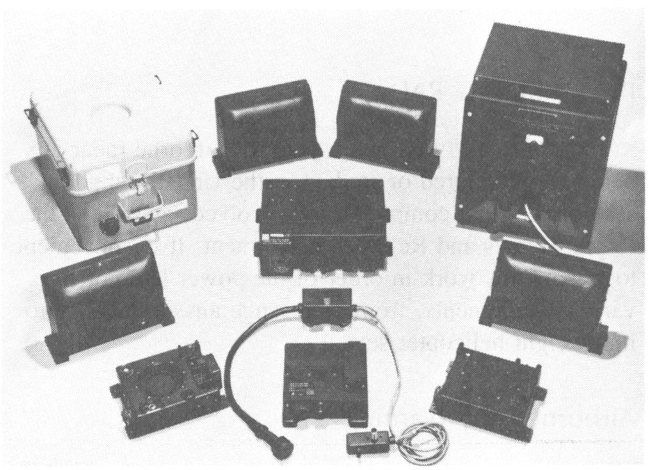

Fig. 5. Hostile fire indicator.

III. NAVAL/MARINE RADAR

Britain continues to develop advanced two-dimensional radars, a recent example being the Marconi type 1830 *S*-band naval surveillance and target indication radar. This has back-to-back parabolic cylinder reflector antennas with low sidelobe linear array feeds. The 16 ft equal path "squintless" feeds are machined from solid aluminum by a numerically controlled mill. The antenna operates over the band 2.7 to 3.2 GHz. It has a first sidelobe level better than −35 dB and a wide angle sidelobe level better than −60 dB. The high power frequency agile transmitter has nonlinear chirp pulse compression. The receiver is of advanced design with multiple-mode processing and automatic velocity compensation for the clutter cancellation system. The prototype has successfully completed its sea trials.

The newest production radar is the Type 1022 *L*-band system, which uses a single rotating antenna of the same wideband low sidelobe configuration. This radar is based on the Dutch LW-08 radar (HSA) and is fitted with a Marconi manufactured antenna.

The combination of a high power coherent transmitter and a rotating linear array antenna is again used in the Marconi Type 967 naval search radar. This is an *L*-band pulse Doppler radar designed specifically for the detection of small fast approaching targets in severe clutter, for interception by the Seawolf missile system. A medium PRF gives a wide blind blind velocity spacing enabling sea, land, and weather clutter to be filtered out. The radar is range ambiguous, and an unusually high stability has to be maintained to ensure that distant targets are not masked by near-in clutter break-through.

The DOLPHIN radar is an important new addition to the Plessey product line; it was designed specifically to meet target indication requirements of close-in weapon systems and is included within the Contraves Seaguard defence system. It is a lightweight system suited for craft as small as fast patrol boats. The radar is a dual-beam *C*-band type [3] with high angle coverage, up to 70°, provided by a linear array of dipoles housed in a corner reflector (Fig. 6); this array is Taylor weighted by the strip-line feed network to produce −29 dB first azimuthal sidelobe. The cosec^2 low coverage beam is produced by a reflector fed by an array similar to the high beam. The azimuthal beamwidth is 1.5° and providing this beamwidth from a modest 2.5 m masthead aperture was one of the main driving forces for the choice of the RF band. The beam is 2 axis stabilized and rotates at 60 rev/min. The total masthead weight is 500 kg. The 1 kW mean transmitter uses a single TWT fed from a solid state driver and this feeds the two antenna feeds by a frequency multiplexing diplexer. The agile transmitter operates over a 500 MHz bandwidth. The use of a TWT transmitter allows phase weighted pulse compression

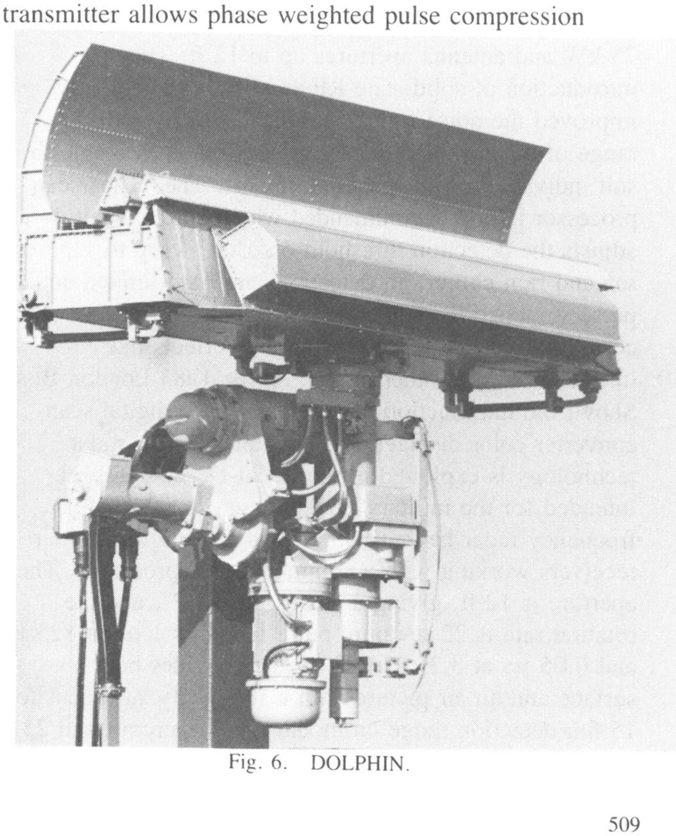

Fig. 6. DOLPHIN.

operation as well as fully coherent processing. The equipment frequency reference is 70 MHz and the IF chirp is coherent with this. Direct frequency synthesis is used for the RF channels, based upon the use of 4 crystal oscillators: change of frequency can be accomplished within 5 μs and the spectral noise of the source is less than -77 dBC/Hz at 1 kHz from carrier. In the receiver, echoes are compressed to a pulse length of 125 ns with time sidelobes below -36 dB (equivalent range cell 19 m). The main signal processing is digital and includes [3] multiple MTI loops, adaptive notch, and CFAR detectors. A parallel non-MTI channel is also provided which includes an adaptive clutter map. The Dolphin design addresses a difficult detection range requirement of 0.1 m^2 RCS at 8 km at a data rate of 1 Hz with accuracies of 50 m in range and 0.5° in azimuth.

The Plessey AWS5 is a high power *S*-band radar for surface and air target warning which has recently entered service with a NATO navy. A dual beam stabilized antenna combined with a high mean power TWT transmitter provides the long range detection capability required by ships of frigate class. The use of adaptive high speed MTI processing and small radar resolution cell provides good detection performance in heavy clutter as demonstrated by comprehensive trials. The system includes a number of advanced features to combat ECM.

It is of interest to note that the use of millimeter-wave radars to overcome multipath errors in low level tracking has been investigated and a 2-plane monopulse system at 80 GHz developed. A maritime version of the DN181 BLINDFIRE RAPIER tracking radar is being purchased by the Royal Navy for incorporation into the Sea Wolf weapon system.

Racal-Decca have a large range of marine radars in both *S*- and *X*-bands. Power levels range from 6 kW to 75 kW and antenna apertures up to 12 ft. The introduction of solid-state RF amplifiers has recently improved the noise figure of *X*-band sets by 4 dB. A range of displays and display processors is available to suit individual customer requirements. The "Clearscan" processor is now recommended which automatically adjusts the detection threshold on each sweep to suppress sea and rain clutter; all detections are hard-limited and pulse stretched to ensure visibility; pulse-to-pulse correlation is also applied to remove effects like interference from other radars. At the 1983 London Boat Show, the introduction of a new range of digital scan-converter color displays was announced. This radar technology is exploited in the Racal-Decca 2459 F/I intended for the military market (Fig. 7): it is a dual frequency radar having both *S*- and *X*-band transmitter/receivers working with a common signal processor. The aperture is 12 ft, giving a beamwidth of 2°, and the rotation rate is 22 rev/min; pulse length is 1 μs at 825 Hz and 0.05 μs at 3.3 kHz. The radar provides both a surface and an air picture with a sensitivity sufficient for 15 nm detection range on medium-sized aircraft and 25 nm on large aircraft.

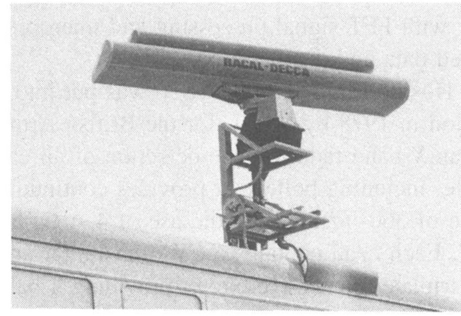

Fig. 7. Racal-Decca 2459 F/I.

Recent innovations at Racal-Decca have been directed toward signal and data processing improvements to meet automatic radar plotting aids (ARPA) standards set by IMCO and the U.S. Coast Guard. Automatic tracking of 20 targets is now achieved in severe clutter by the provision of automatic threshold control in each tracking window. The tracker uses an α–β algorithm with twin coefficient sets dependent upon the track life.

IV. AIRBORNE RADAR

Virtually all types and aspects of airborne radar are being manufactured or studied in the United Kingdom; several different companies are involved, as well as the Royal Signals and Radar Establishment. It is convenient to review this work in order of the power level of the various equipments, from long range air-surveillance to lightweight helicopter sets.

Airborne Early Warning

Airborne Early Warning (AEW) is considered to be a very important capability and for 30 years the *S*-band AN/APS-20 has been in service continuously, although several different fixed-wing propeller aircraft have been used as platforms. The radars are currently fitted in a squadron of Shackletons. Some years ago the radars were uprated to APS-20 FI standard by the addition of a digital AMTI signal processor specially developed by the Post Design Service contractor Marconi Avionics. The new processor is contained within a single 1-ATR case and its output is fed to the standard display. The digital clutter canceler has proved to be effective in enabling air target detection in heavy sea clutter.

As a successor to that AEW, a medium-PRF pulse-Doppler radar [4] has been developed by Marconi Avionics and will enter service this year in the NIMROD Mk 3 airframe. Good, though undisclosed, performance has been demonstrated in the system development program. The radar design is unique in that two scanners are used, each having an angular coverage of 180°. This approach has the particular advantage of providing the radar with a field of view clear of any airframe obstructions by locating the antennas at the longitudinal extremities of the vehicle. Conventional electrically driven scanners providing a 10 s data rate are located in large radomes. The twist reflector Cassegrain antennas operate at both the *S*-band radar frequency and at the SSR/IFF frequency; their elliptical apertures are 8 ft × 6 ft as shown in Fig. 8. The two antennas are alternately fed from a single transmitter. Received signals are similarly fed from the fore-and-aft antennas to a common receiver and processing system. The transmitter includes the basic microwave sources, a medium power amplifying stage, and the high power output stage.

The radar receiver design complies with stringent requirements for linearity. Pulse compression and phase-locked local oscillators (compensating for aircraft velocity and radar beam pointing angles, hence the removal of self-movement) are applied prior to analog-to-digital conversion. Initial digital signal processing is undertaken in hard-wired fast processors which include the frequency analysis stage. Target detection is automatic using CFAR techniques, and resolution of the range and velocity ambiguities is achieved using the staggered PRF transmission. Azimuth and elevation beam sharpening are applied to give the radar plot report.

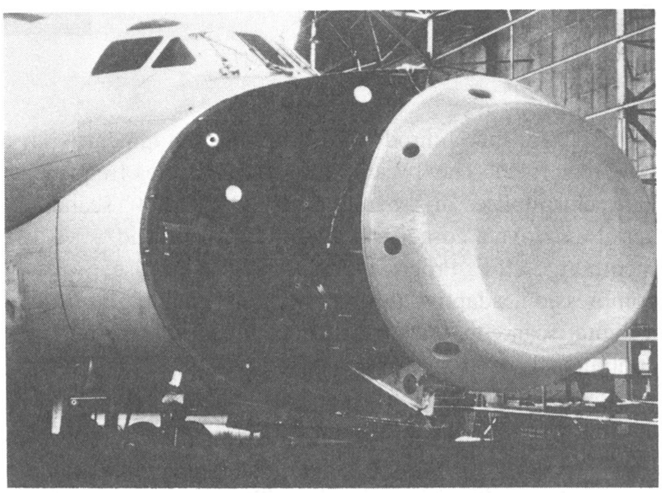

Fig. 8. Nimrod AEW Mk 3.

Airborne Interception

The United Kingdom has a long history of airborne interceptor (AI) radars for fighters, dating from operational service in World War II. Still in use is the Ferranti AIRPASS 1 (air interception radar pilot attack sighting system) which was designed and developed for the RAF Lightning aircraft. This was the first high power monopulse airborne radar to enter squadron service anywhere in the world and it is still in service with the RAF and Saudi Arabian Forces.

The most recent AI radar is the Marconi Avionics FOXHUNTER radar for the Tornado ADV aircraft. Target acquisition range is over 100 nm, and TWS allows multiple target tracking. Digital processing, including microprocessors, is used to reduce size and weight while increasing reliability. The Cassegrain antenna has a very clean radiation pattern, which confers good performance, ground-clutter rejection, and ECM resistance. The *X*-band antenna has a front hyperbolic subreflector and a larger rear parabolic reflector; the dual reflectors are separated by a glassfiber-honeycomb skirt at the periphery. The four common horns for transmit and receive are in the center of the rear reflector at the focal point of the front reflector. A transmitted wave (horizontally polarized at the horn) reflects from the front reflector back on to the main reflector, which collimates and vertically polarizes the signal. The polarized signal can pass through the subreflector because it is composed of parallel, horizontal conductors. Ferranti is responsible for the development and production of the transmitter and scanner mechanism (Fig. 9) for the FOXHUNTER radar. The transmitter uses TWTs and also provides a CW illumination for missile guidance.

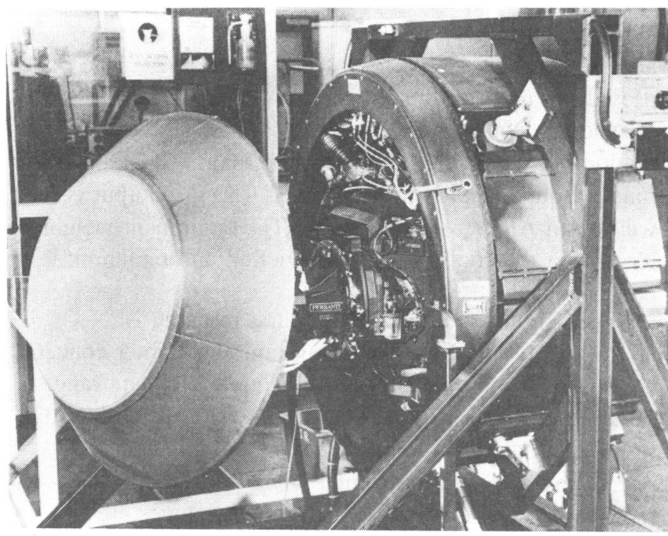

Fig. 9. Foxhunter for Tornado ADV.

The Sea Harrier is fitted with the BLUE FOX radar (Fig. 10) for both interception and surface attack. This Ferranti radar was developed from their SEASPRAY experience (see below). The radar operates in *X*-band with frequency agility and a two-plane monopulse split, using planar antenna for increased detection range and low sidelobes. A digital scan converter provides a bright TV raster display with picture freeze facility. It is in production and being delivered to both the Royal Navy and Indian Navy. The total radar system weight is 187 lb. Ferranti are continuing to develop this class of radar with BLUE FALCON, a coherent pulse-Doppler radar. Accent is on flexibility in operation and novel concepts are being employed in the application of medium and high PRF transmissions and in the associated signal processing. A major design goal is to achieve compatibility with the stringent size and weight constraints of the emerging lightweight and VSTOL fighter aircraft.

Marconi Avionics also manufacture a lightweight *X*-band airborne ranging radar consisting of only 3 line replaceable units (LRUs); it is suited to small airframes

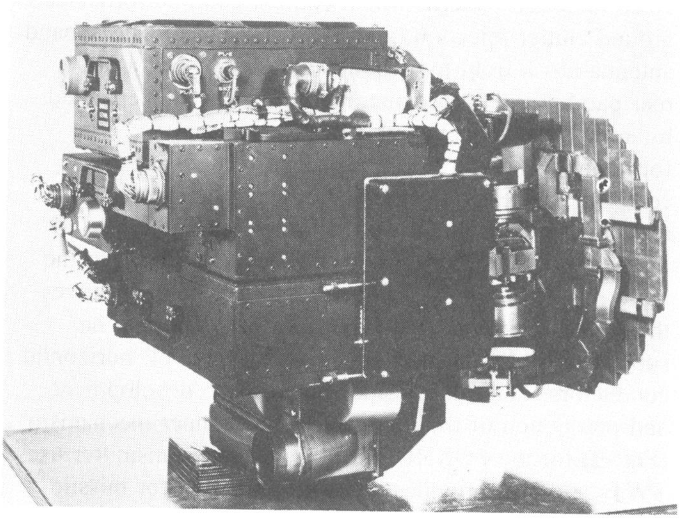

Fig. 10. Blue Fox for Sea Harrier.

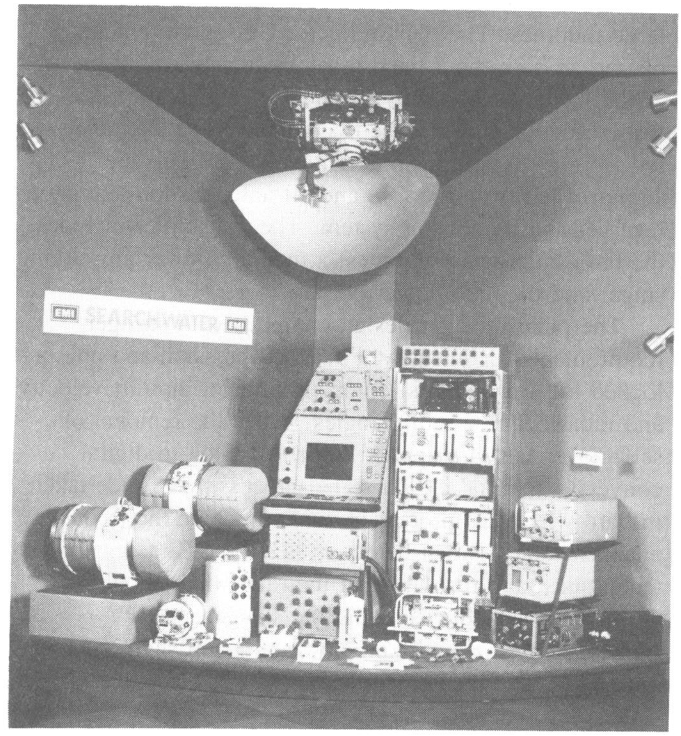

Fig. 11. SEARCHWATER.

and is especially suited for retrofit into MIG21. The radar provides range and range-rate measurements for gun and missile fire control. The radar exhibits pulse-to-pulse random frequency agility over more than a 5 percent RF range. Range resolution achieved is 150 m. Output is by way of an ARINC 429 highway. The equipment weight is 37 kg and the cooling is by conduction and radiation; power consumed is about 400 W.

Looking toward future AI radars, research is dominated by the needs of a multimission fighter concept employing a multimode radar offering a complete range of air-to-air and air-to-surface modes. This is feasible due to the continual developments in the digital signal processing area and the availability of programmable radar signal processors in which mode changes are accomplished by loading, from bulk store, a variety of program segments. This study is currently being supported by RSRE, Marconi Avionics, and Ferranti where efforts are directed toward identifying the algorithms which will be required and the signal processing architectures which are suitable. Airborne trials are being staged using a low duty ratio pulse-Doppler radar, including clutter data gathering.

Maritime Reconnaissance

Another important area in which the United Kingdom has always been active is maritime reconnaissance, for antisubmarine and antiship roles as well as other duties. A long established equipment is ASV21 which is in service use in several countries including the United Kingdom (Nimrod MR1) and Canada (Argus). Transmission is in *X*-band using a magnetron to generate pulses which vary in width according to displayed range selected. The stabilized 360° scanning aerial employs a cosec^2 elevation beamshape. The PPI display uses a long persistence phosphor. Additional facilities include variable width sector scan about any desired heading. Thorn-EMI have developed the SEARCHWATER radar (Fig. 11) for the Nimrod MR 2, and this equipment is now in service. The TWT transmitter generates frequency agile chirp pulses in *X*-band. The stabilized 360° scanning aerial employs a cosec^2 elevation beamshape and incorporates IFF. Processing includes SAW pulse compression, adaptive thresholding, and integration using a digital scan converter. The detection threshold is continuously adjusted using a control signal derived from the instantaneous clutter level so that a constant false alarm rate is presented to the operator. In addition the radar has a multitarget automatic tracking capability. *A*-scan, *B*-scan, PPI, and file data outputs are presented on a raster display with a bright phosphor. The radar has built-in test equipment which provides automatic detection and diagnosis of faults during flight.

The MEL Company of Philips also manufacture maritime reconnaissance radars in the United Kingdom such as the MAREC II which fits a range of aircraft from the 748 Coast Guarder to the Dornier 128-6. This radar is again in *X*-band with a fixed frequency 100 kW magnetron transmitter using a solid-state modulator. A choice of 0.4 and 2 μs pulses is available to the operator and coupled with the use of horizontal polarization, a logarithmic receiver, and STC; this allows optimization of the signal clutter ratio on the display. The reflector is 42 × 16 in and scans 360° in azimuth or in a steerable and variable-width sector scan. The radar beam is pitch and roll stabilized. A 17 in diameter flat screen tactical display (Fig. 12) is provided, and it is both ground and north stabilized by digital processing. By use of a roller-ball marker a high accuracy digital LED readout of target range and bearing is obtained, corrected for aircraft

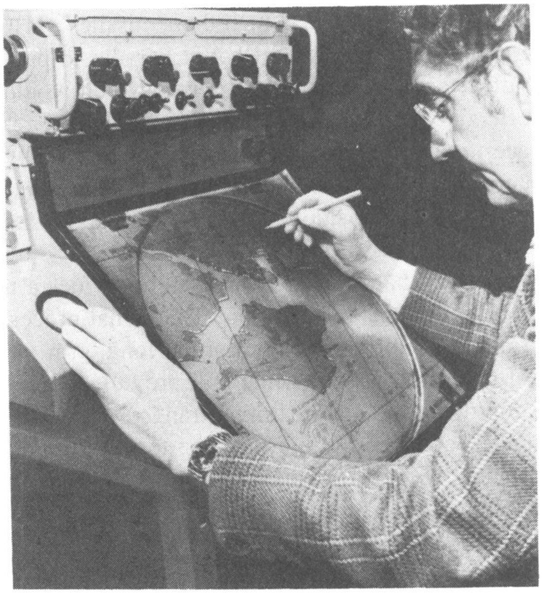

Fig. 12. Marec display.

height. A smaller color TV-raster display is an option. The sensitivity is such that 1000 ton ships are detected at 100 mi and a submarine snort has been detected at over 15 mi. The total power demand is 1 kVA.

Racal-Decca has reconfigured one of their marine radars into an airborne surveillance radar; it has been designated ASR-360. This *X*-band radar has a 30 in horizontal aperture and is in use on a Norwegian Navy Cessna 337 and a Piper Navajo. The antenna gain is 25 dB, beamwidth 3°, the polarization horizontal and the data refresh rate 3 s. The magnetron is nominally 25 kW peak and the pulse lengths 0.05 μs, 0.25 μs, and 1 μs at a minimum PRF of 825 Hz. The signal processing includes a CFAR detector. The 12 in PPI has a choice of eight scales out to 95 nmi range with options for off-centering and for true or relative motion.

Sideways looking airborne radar (SLAR) is another aspect of reconnaissance and EMI manufactured the P391 system as one of the sensors in the reconnaissance pod fitted to the Phantom RF4M. The radar is still in service with the French Mirage 3RD. It operates at 35 GHz and employs a magnetron transmitter to generate 0.1 μs pulses at 50 kW peak. A multielement slotted array antenna produces a horizontal beamwidth of 3.5 mrad. The photographic record gives ground mapping information up to 10 mi on both sides of the aircraft. Moving target indication (MTI) may be optionally selected. The use of synthetic aperture (SAR) techniques for reconnaissance is also being pursued. RSRE has developed a real-time digitally processed, short range synthetic aperture radar. The radar was first flown and demonstrated in 1976 and has subsequently completed a successful series of flight trials. It has a range of 5 mi and a range and azimuth resolution of 3 m. The meanpower of the transmitter is 4 W. The range resolution is achieved using pulse compression with a transmitted bandwidth of 100 MHz and a chirp compression ratio of 500. The success with the short range SAR has prompted a program to build and fly a long range synthetic aperture radar. It utilizes ground based processing in conjunction with airborne recording and, at a later stage, will use an air-to-ground data link. This radar is essentially an upgrading of the short-range SAR by the addition of a higher power T/R and a new antenna. Research has also started on the investigation of short range high resolution millimeter-wave SAR for use in unmanned aircraft.

Helicopter Radars

A variety of helicopter radars have been developed in the United Kingdom. MEL developed the first of these, the ARI 5955, in the early 1960s and over 350 went into service in 12 countries on Westland and Agusta helicopters. The radar currently being fitted to the Sea King Mk 5 is the MEL SEA SEARCHER. The transmitter is in *X*-band and the specific frequency can be varied in flight. The stabilized antenna has a gain of 34 dB and scans at 30 rev/min; a manual tilt range of ± 10° is available to the operator. The logarithmic receiver is matched to the transmitted pulse length (two options) and has a noise figure of 8.5 dB. STC is provided. The 17 in flat-screen projection display is employed as in MAREC; five range scales are provided from 0.5 to 16 nm/in. The display unit incorporates two tracking markers and interfaces with on-board navigation systems.

The new generation system is SUPER SEARCHER. It has a three pulse length, multiple PRF, frequency-agile transmitter-receiver with 4.5 dB noise figure. The short pulse mode is compatible with Sea Skua missile guidance. The system has a digital signal processing and scan-conversion unit driving a bright color display. The display has the capability of overlaying ESM, IR, and navigational data on the radar picture: 10 tracking and 40 fixed markers are provided with video map overlay. The digital signal processing is realized on 8 Eurocards and integrated with the display tube into a single unit. The combination of improved transmitter–receiver and signal processing has resulted in a markedly improved detection range, and in addition, SUPER SEARCHER has a vastly improved display capability. Nevertheless, the weight of SUPER SEARCHER (60 kg) is lower than SEA SEARCHER (90 kg) and the volume and power consumption are less also.

Ferranti manufacture the lightweight helicopter radar SEASPRAY. It was designed specifically to detect and track small surface targets at sea in high states and bad weather. Also it is designed to provide target illumination for Sea Skua missiles. Frequency agility, using a spin-tuned magnetron, and monopulse techniques are employed in this *X*-band radar. Total weight is 140 lbs. The display and control unit is shown in Fig. 13. The inclusion of track-while-scan in the Mk 2 was announced at Farnborough 82. Over 160 SEASPRAY radars have been delivered to 7 navies; the SEASPRAY has also been fitted to the Lynx helicopter.

Fig. 13. SEASPRAY display.

The BLUE KESTREL radar is in development for the Royal Navy by Ferranti and is suitable for the WG34/EH 101 helicopter which is the Sea King replacement aircraft. Operating in *X*-band and using pulse compression, the wideband aerial (Fig. 14) can scan continuously through 360° or in a chosen sector. This is a

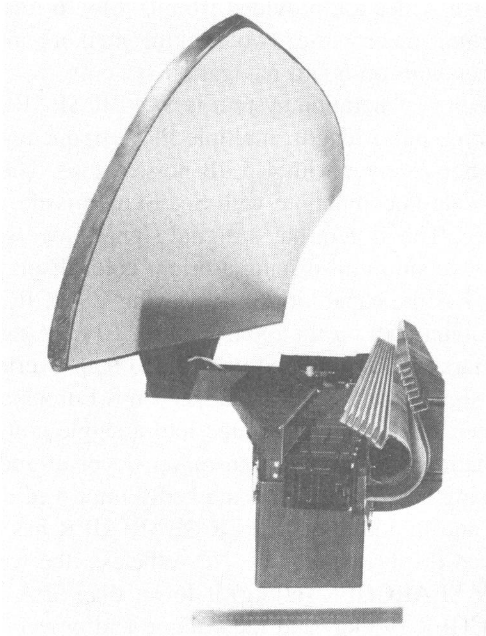

Fig. 14. Blue Kestrel antenna.

high performance multimode radar with long range detection performance, flexibility in operating altitude, and multiple target track while scan. It can be fully integrated into an avionics suite through a MIL SPEC 1553B bus control interface.

During the Falklands conflict it was clear that the British Naval task force without an airborne early warning radar capability was vulnerable to attack by low flying aircraft armed with air-to-surface missiles. By making use of the screening from the islands, hostile aircraft could approach beneath the ship's radar cover to a range where they could launch their missiles. THORN EMI modified the SEARCHWATER radar to provide an aircraft detection capability at ranges which would allow the effective deployment of combat air patrol aircraft or surface-to-air missiles. In order to provide a 360° uninterrupted view, the antenna is mounted on an arm projecting from the side of the Sea King and protected from the elements of an inflatable radome. The reflector is larger than that of Searchwater and provides a pencil beam with circular polarization. The signal processor has been modified to remove the normal long term integration used for ship detection, while still providing false alarm rate control in the clutter limited range.

RSRE and Ferranti are working together on a rotor blade radar (Fig. 15). This unusual *X*-band radar consists of a long antenna radiating from the trailing edge of a helicopter rotor blade. The narrow azimuth beamwidth coupled with a very short pulse at high PRF produces a clear, high definition radar picture. The system has been flying in a trials aircraft since 1980.

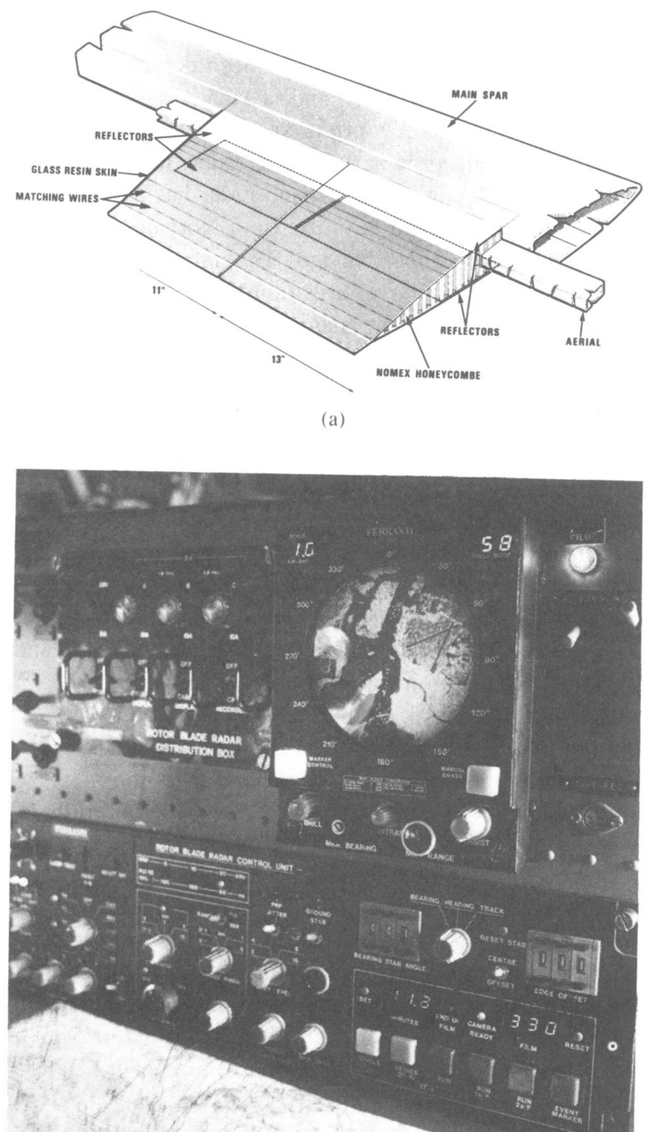

Fig. 15. RSRE/Ferranti rotor blade radar.

Weather Radar

A wide range of weather radars have been made in the United Kingdom, including the EKCO range now handled by MEL. Here the technology used in these radars will be indicated rather than details of the many individual types. All operate at a wavelength of 3.2 cm (*X*-band) which has been found to produce adequate returns from the larger droplets in turbulent clouds while not suffering from excessive attenuation. Both two-axis and three-axis scanners are in use with vertical plane beam tilt available to the operator. A pencil-beam radiation pattern is provided for the normal weather mode and in some types beam spoiling is available as an in-flight option so that a ground mapping capability is available. Horizontal polarization has been preferred. Transmitter powers are in the range 10 to 70 kW. The RF pulse is obtained from a magnetron, both tube and solid-state (thyristor) modulators are in use. A PRF of 400 Hz or 200 Hz is employed locked to the aircraft ac power lines, and the pulse length is usually in the range 2 to 6 μs.

Millimeter-Wave Efforts

In the millimetric field a significant amount of work is being undertaken in order to identify the potential performance of future weapons systems. For example, at British Aerospace a millimetric program started several years ago with radar concept studies. This rapidly led to a measurement program in order to identify real-world effects. Measurements on tactical targets, clutter of all types, and potential countermeasures are continuing. Three equipments in use are a monostatic noncoherent solid state radar which has been flown in the United Kingdom and Germany; a twin antenna ground based, noncoherent, radar which gives outputs of the orthogonal amplitudes of the received complex polarized wave, as well as the phase difference between them; and a solid state, pulsed radar which can operate in several modes—viz. coherent fixed frequency, frequency agile on a pulse-to-pulse basis, chirp pulse compression to give narrow range gate widths, a range of fixed pulsewidths and pulse-to-pulse polarization agility for all linear and circular polarizations. Investigations are in hand to produce a radar which can be flown on a high speed aircraft in order to demonstrate the potential of such a sensor.

Antennas

To conclude this section particular mention must be made of U.K. efforts, largely MOD funded, in airborne antennas. Design of airborne radar antennas is dominated by the needs for light weight, large angular scan range, and low sidelobes and also in some cases by requirements for broadband or multiple-band operation. Over the years, research has evolved techniques for providing these properties, though not necessarily all simultaneously. As antenna performance has improved, however, the degradations introduced by the radome have come to dominate installed performance by introducing transmission loss and angular boresight error and increasing the sidelobe level. Moreover, radomes have limited frequency passbands, not necessarily well matched to requirements, and often also carry additional hardware such as lightning diverters or pitotstatic tubes, which exacerbate the degradations. Study of electromagnetic scattering by radomes is thus an important aspect of airborne radar antenna research in the United Kingdom. Prediction of scattering by detailed numerical modeling is being pursued by several groups. The problems are the establishment of techniques which are adequately accurate yet do not require excessive computing power, and the provision of experimental verification. Some success is being achieved with techniques such as the method of moments; an example is the recent work of Waterman [5]. Investigations are also in progress on methods of designing microwave radomes with more control of frequency passbands than is offered by conventional structures. The use of dielectrics loaded by thin wires or other metallic structures appears to be a very promising approach for modifying passbands, providing stopbands, and for making RF structures which are "invisible" outside the frequencies of their primary function [6].

V. SEEKERS AND FUZES

Radar missile guidance has been undertaken for more than 30 years by Marconi Space and Defence Systems Ltd. (MSDS). Their first monopulse semiactive radar seeker (40 cm diameter) was for Sea Dart, a long range surface-to-air missile providing area defence for ships. Sea Dart is in service with the Royal Navy and Argentinian Navy. An improvement program is currently underway. The design of Sky Flash, a medium range air-to-air missile, was based on the existing Sparrow 7E wing, motor and warhead, but with a new British forebody, including an MSDS semiactive monopulse seeker (Fig. 16). The effects of target glint have been made small and very low miss distances have been achieved; about 50 percent of the firings have been direct hits. Multiple target discrimination, using Doppler techniques, has significantly improved the kill probability

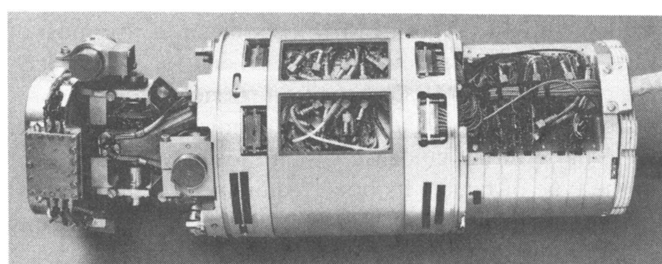

Fig. 16. Sky Flash Seeker.

against operational target groups. Sky Flash is in service with the RAF and Royal Swedish Air Force.

A semiactive radar seeker has been developed for Sea Skua, a sea-skimming antiship missile which can be carried by the Lynx helicopter. The development firing trials were outstandingly successful. Sea Skua entered service with the Royal Navy in 1981.

Much work has been completed on active air-to-air seekers using both solid-state and tube devices. The development of digital detection, acquisition, and response to ECM threats all under the microprocessor control is at an advanced stage. A beneficial feature is the flexibility available for dealing with new forms of countermeasures. This program has included the construction of a prototype 150 mm antiair seeker which has a wide angle of look to meet the requirements of short range engagements. This 6 in diameter seeker is very much smaller than any active seeker in service and is suited to the NATO ASRAAM program. Considerable research has been undertaken on millimeter wave systems and from this has stemmed an active seeker suitable for use in a terminally guided submunition (TGSM) in an antiarmour application such as the multiple launch rocket system.

The development is well advanced of the active radar seeker for Sea Eagle (Fig. 17), a long range sea-skimming missile capable of being launched from the Buccaneer, Tornado, and Sea Harrier. The design of this 15 in diameter seeker uses an advanced concept of software control by means of an on-board computer to provide autonomous operation in fire-and-forget engagements.

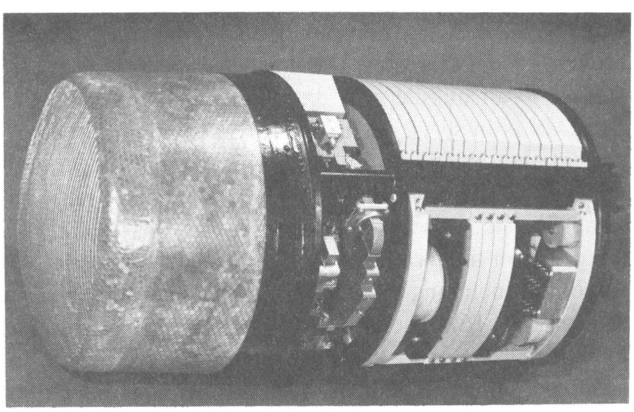

Fig. 17. Sea Eagle Seeker.

Radar proximity fuzes have been developed and manufactured by Thorn-EMI Electronics Ltd. for most of the U.K. antiaircraft missile systems and for antisurface target applications. Each specific fuze needs to be matched to the characteristics of the missile which carries it, to those of the guidance system, to the warhead, and to the type of target. Its basic requirement is the need to generate a precisely timed output trigger pulse in response to the immediate proximity of the target without compromising the mission by premature operation. Detection of a target is achieved by the use of a hollow conical beam from an antenna mounted on the skin of a missile, typically 4 slot arrays equally disposed around the missile body diameter. The manufacture of electronic circuits is based on hybrid thick-film technology, which permits the high component packing density needed in missiles to ensure a low volume and weight. The electronic circuitry, for a representative in-service fuze, occupies a volume of approximately 350 cm^3. Microwave stripline and microstrip both have relevance to fuzing, but stripline circuits offer an overall volume-saving because of the elimination of the air space associated with microstrip circuits. Proximity fuzes currently in service include those in the Bloodhound, Sea Dart, Seawolf, and Sky Flash missiles.

VI. UNIVERSITY PROGRAMS

Radar work in U.K. universities has traditionally been concentrated more on components, signal processing, and antennas. However, a number of current projects involve a range of new ideas for complete systems.

Radar for Detection of Buried Objects

Several workers have discussed a range of techniques for the detection of buried objects. Applications range from the detection of cables or public utility pipes to military requirements for mine detection. One of the basic problems is that of bandwidth and choice of carrier frequency. A large bandwidth is needed to obtain adequate range resolution but low carrier frequencies are preferable for ground penetration. The situation leads to very large percentage bandwidths and corresponding problems of wide bandwidth antenna design. Other constraints are concerned with the strong energy reflection at the ground interface and the need for a good angular resolution in the near field of the antenna.

An interesting approach to these problems is being pursued at Queen Mary College, London [7]. Here a wideband feed horn illuminates an offset parabolic reflector from a position away from its true focus. The resultant waves are then brought to focus at a point below the surface of the ground under investigation. It is thus possible to focus the beam into a small volume to achieve a high angular resolution in the near field. By focusing energy into the ground at an angle to the vertical, it is also possible to significantly decrease the backscatter from the surface of the ground which would otherwise cause receiver overload problems. The experimental equipment has been designed on a small three wheel trolley for portable use.

The QMC design employs FMCW modulation over a frequency band of 2–4 GHz for high range resolution performance. The modulation is sawtooth over a 10 ms period which also corresponds to the equivalent of a substantial coherent integration of the radar returns over this period. An attractive feature of FMCW is that the bandwidth of the beat note spectrum can be far less than that of the frequency deviation of the transmitter. It is thus far easier to process. In the above example the spectrum extends to only 5 kHz and this has made it convenient to employ digital processing for filtering and spectral analysis [8]. The processing may also be modified in order to optimize returns from known target shapes. The combination of FMCW and simple narrow band digital processing appears a particularly attractive scheme which may well have applications in many other types of high resolution radar systems.

A completely different approach to the above problem has been studied by the University of Sheffield. Here a three dimensional image is reconstructed from signals derived from mechanically scanning a pair of receiving antennas across an aperture and storing the amplitude and phase information at suitable intervals. By processing this data it is possible to synthesize an equivalent antenna aperture of several meters square which effectively images the radar returns from below the surface.

The above system works in the near field of the synthesized aperture and is designed to focus the beam at specific ranges. In principle, it is also possible to add modulation for additional range resolution if required. The work has been operated with off-line processing, but for suitable applications this could also be converted to real time operation. Sheffield is studying a whole range of applications of microwave and acoustic imaging systems including the use of microwave holography [9]. They have also studied the use of superdirectivity and multiplicative processing to improve angular resolution in imaging systems.

Radar for Remote Sensing of the Sea Surface

For the last five years the University of Birmingham has been involved in some particularly interesting developments using HF radar in both sky-wave and ground-wave modes for studying the sea surface [10–12]. The project also involves collaboration with the Appleton Laboratories of the U.K. Science and Engineering Research Council. By the use of coherent techniques and with range gating it is possible to note the Doppler shift of the return signal and hence get accurate information on surface current (resolved along the line of the radar). In most situations the presence of waves on the surface will produce a complex Doppler spectrum exhibiting pairs of lines due to Bragg diffraction. Careful examination of the spectra can provide information on wave height and wave direction and hence on wind direction and wind speed. Fig. 18 shows a typical experimental spectrum from the Birmingham results together with an indication of the features that can be derived from such radars; these are specifically:

(A) ratio of advance to recede first-order Bragg line amplitude: this gives mean direction of wind-sea and hence of surface-wind;

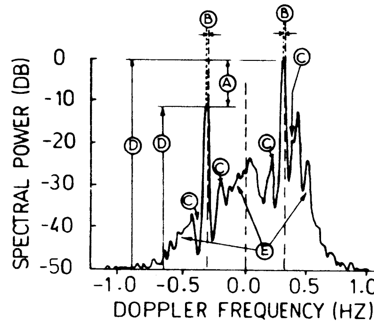

Fig. 18. HF Doppler Sea-Echo Spectrum.

(B) Doppler shift of first-order Bragg lines from expected values; this gives radial component of surface current;

(C) separation of inner edge of second-order structure from first-order Bragg lines: this gives low-frequency cutoff of ocean waveheight spectrum (the pattern of peaks in this region gives the direction and frequency of long-wavelength swell components);

(D) magnitude of first-order Bragg lines: this gives Ocean wave-height spectral values for one wave frequency and two reciprocal directions;

(E) magnitude and shape of second-order structure: this gives Ocean wave-height spectrum for all wave frequencies and directions.

This particular result is ground-wave radar data at 9.25 MHz and 37 km range. The early Birmingham experiments on ground-wave radar utilized a 1.95 MHz Loran A transmitter on the Welsh coast and were aimed at demonstrating the technique for sea state and surface current surveillance. Spectra are obtained with a single range gate processor employing an on-line 8 bit Fourier transforming with digital processing. To achieve some directional performance on the receiving antenna some results were also taken with a receiving antenna in a vehicle slowly moving along a straight road and processing the signals to form a synthetic aperture. This produces an equivalent 1 km synthesized aperture giving an azimuthal resolution of 8°.

Complementary work has been undertaken on a sky-wave radar where it is necessary to change the operating frequency with time of day in order to control the sky-wave propagation. This radar uses coherent transmissions of FMCW with Doppler processing. It employs a 300 m wide antenna array giving a beamwidth of about 4°. The radar has provided wind and wave data of good accuracy but there are limitations due to traveling wrinkles in the ionospheric surface which results in Doppler spreading of the echo. As with many HF radars, there is a need to try to reduce the angular beamwidth, and Birmingham are examining a scheme of switching the transmit antenna between the end elements of the array in order to halve the beamwidth of the overall two-way pattern. Since such radars could work at ranges out to 3000 km it is very important to reduce the angular resolution cell by keeping the beamwidth down to a minimum.

Bistatic Radar

Work at University College London [13] has resulted in the production of a very simple form of bistatic radar system. It is based upon the transmitter of a 600 MHz air traffic control radar located at Heathrow Airport where it is situated approximately 15 mi from the University College receiver site. The receiver can detect the pattern of transmitted pulses of the radar through the main beam and most of the sidelobe region. These received signals are used to synchronize local oscillators to both the rotation of the transmitting antenna and to the PRF of the radar (making allowance for its staggered pattern). These signals are then used to drive a ppi display at the receiving site.

The receiving antenna consists of a simple dipole which is used to pick up the synchronizing signals. The same dipole also picks up reflections due to the direct illumination of targets by the rotating radar transmitter and these target signals are fed to a receiver and displayed on the ppi. The resulting picture looks like a fairly normal ppi display though the range and angle information is distorted due to the separation between transmitter and receiver. The angular resolution is set by the 3° beamwidth of the transmitting antenna and the sidelobe performance is determined by the transmitting directional pattern alone.

This display distortion may be corrected either by modifying the drive circuits to the CRT or by means of a computer processing system which stores, recalls and repositions the targets on the display. The latter approach has been adopted for the UCL experimental system. Work on this project is now looking at the application of MTI to this bistatic radar and data is being collected on clutter and target characteristics. Fig. 19 shows a comparison between the corrected and uncorrected PPI displays using an omnidirectional receiving antenna.

Future plans include the possibility of introducing directional arrays on reception and a scheme involving digital beam forming is currently under study. Other variants involve interferometric arrays in order to provide very high resolution data at the receiving site. Although most bistatic systems are seen as being fairly complex and defence related, it is interesting to note that there may also be applications for omnidirectional antenna schemes with no display correction for very simple radar applications where the receiver can easily obtain its synchronization from direct transmission from the primary radar.

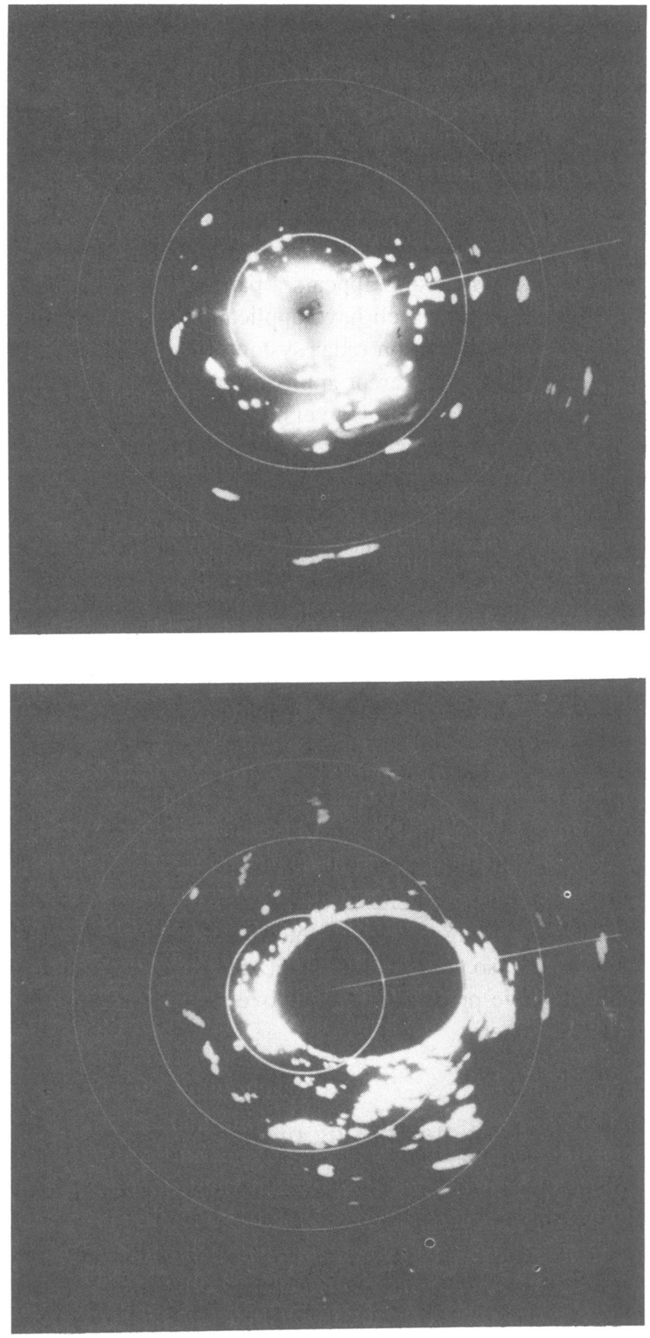

Fig. 19. UCL bistatic radar results (32 nmi display). (a) Uncorrected display. (b) Corrected display.

Noise Radar

The use of a continuous, noise-modulated, microwave signal is an attractive concept for a radar system because of the random character of the signal and the fact that the signal energy is spread over a wide band. University College London started work on this topic with the realization that microwave solid-state sources can be easily noise-modulated, either through low-frequency noise introduced into the bias circuit, upconverted on to the microwave carrier, or by low-frequency noise applied to a varactor in a voltage-controlled oscillator. Such techniques were shown to produce a microwave noise signal with bandwidth up to several hundred megahertz.

A CW noise radar was constructed to operate around 8-GHz in *X*-band, principal attention being directed toward different systems for correlation of received signals from targets with a delayed sample of the transmitted signal. Initial experiments, for short ranges of up to 10 m, made use of microwave coaxial cable as a delay and simple correlation with a microwave mixer and low-pass filter. For extended ranges up to 1 km, both transmitted sample and target return signals were downconverted to intermediate frequency, the correlation process being achieved with a variable surface acoustic wave delay line and an IF mixer. A later version of the same system used a digital correlator (TTL logic), which had the advantage of presenting information simultaneously from all range cells. Both these IF correlators had bandwidth limitations in the region of 25 MHz, so this limited the useful noise bandwidth of the microwave signal [14].

The conclusion of the work was that such noise radar systems are only suitable for short ranges and preferably for a single target situation. Performance is limited to the amount by which the signal processing gain exceeds the leakage between transmitter and receiver: in the experimental radars this was about 35 dB. The most useful applications for the concept probably relate to very short range systems (e.g. 10 m), as in fuzing. The use of a noise signal and a correlator with fixed delay could also provide an excellent guard-ring radar.

VII. SUMMARY

In the space available it has not been possible to mention every item of radar work that is underway in the United Kingdom. Furthermore, new advances and developments were being announced throughout the preparation period of the material, so it is not possible to claim that this review is definitive. However, this paper does give a representative picture of the wide range of radars that are in production or being developed.

For the future, the increasing power of digital signal processing will be exploited in flexible programmable processors, relieving or even eliminating operator workload. The use of planar antennas, broadband antennas, and other features will continue to improve the ECM resistance of military radars. Wide bandwidth and low sidelobes are considered important, and there is a growing interest in multiple beam radars compatible with future multistatic concepts. Increasingly self-test functions will be provided as a major contribution to lowering operating costs.

The capable U.K. radar industry looks forward to the future with confidence in its own abilities.

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John Clarke (SM '81) graduated in Electronic and Electrical Engineering at the University of Birmingham, England, and for a thesis on Synthetic Aperture Radar was awarded the Ph.D. degree in 1968. Since then he has held several appointments on the scientific staff of the Royal Signals and Radar Establishment. His long standing interest in the subject of radio location has been sustained by a variety of responsibilities on various airborne radars together with the advancement of microwave techniques and devices for radar and electronic warfare applications. His main work recently has been in the field of air defense surveillance systems.

He has been prominent in international conferences within his chosen field both as a speaker and as a member of organizing committees. 1980 saw him as Conference Chairman of Military Microwaves 80 and he has served on the TPC of all conferences in this series. In the International Radar Conferences he has served on many of the organizing committees, including London, Washington and Bangalore as well as chairing technical sessions. He is author of many technical papers and has published 3 books.

He edits the radar, avionics, and EW portion of IEE Proceedings and has been Vice-Chairman of the IEE Radar, Sonar, Navigation and Avionics Committee, previously he was Chairman of the IEE Microwave Devices and Techniques Committee. Within the IEEE Aerospace and Electronic Systems Society he is a member of the Radar Panel.

D.E.N. Davies graduated from the University of Birmingham where he completed his Ph.D. on Phased Arrays and subsequently joined the Academic Staff; he also spent part of his time on secondment at the Royal Signals & Radar Establishment, Malvern. In 1967 he became an Assistant Director in the Research Department of British Railways where he was concerned with communications signalling automation. In 1971 Professor Davies was appointed to his current Chair in Electronic and Electrical Engineering at University College London, where his Research Group is concerned with antennas, radar and fibre optics. He has currently published over 100 papers in these fields. Professor Davies has been Chairman of the Electronics Division of the Institution of Electrical Engineers and is currently President of the Institution of Electronic and Radio Engineers. He was elected to the Fellowship of Engineering in 1978 and received one of the IEEE Centennial Medals in 1984.

Matthew Radford was born in 1929. After military service in the Royal Signals he read Mathematics and Engineering at St. Johns College, Cambridge. In 1953 he joined the Marconi Company as a graduate apprentice and subsequently entered the Research Centre at Great Baddow, where he became Chief of Antenna Research in 1960. In 1967 he was transferred to the Radar Research Laboratory, where he now leads a specialist group engaged in future system studies. He is a Master of Arts and a Member of the Institution of Electrical Engineers.