THE FOXHUNTER AIRBORNE INTERCEPTOR RADAR

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In military systems, there has been a continual close link between defence strategies and tactics and the available technology. This paper is concerned with the Foxhunter radar, which is the prime sensor of the Royal Air Force new interceptor, Tornado F Mk2. The paper briefly reviews interceptor radars over the past two decades and demonstrates the important interrelationship between equipment capability and tactical use. In particular, the operational requirements for Foxhunter are explained. The second half of the paper describes the principles of operation of the prime mode of the radar and highlights how new techniques and technology have permitted the implementation of this first British airborne multi-mode pulse doppler radar.

1. INTRODUCTION

Foxhunter is an advanced, coherent radar system designed as the prime sensor for the new Tornado F Mk2 interceptor aircraft, currently entering service with the Royal Air Force. The radar was designed and developed to Air Staff Requirement ASR 395 by GEC Avionics at Borehamwood and Milton Keynes and is now in full production. It is the most recent RAF airborne interceptor (AI) radar in a history stretching back to 1940 when AI Mk 1 first flew in a modified Blenheim bomber. It is perhaps fitting that Foxhunter (designated AI Mk24 by the RAF) formally enters service this year, exactly fifty years after the inception of radar.

The realization of a British fully coherent AI radar is the outcome of many years of research and development work in industry and Government research establishments. Previous British AI radars have all been non-coherent with only modest detection ranges; the development of a long range, coherent radar, fitting into the confined space of a fighter aircraft has only been possible because of significant advances in engineering technology in the 1970's and early 1980's. The area of technology producing the greatest impact on the design has been digital signal processing, but other areas, including steady advances in microwave receiver and transmitter component design and the emergence of lightweight investment castings, have also played an important part. These advances in engineering technology have enabled new radar system design concepts which permit features such as track-while-scan to be implemented in an airborne platform and these, in turn, have permitted radical changes to the operational tactics of recent aircraft like the Tornado F Mk2 compared with earlier interceptors.

Therefore, in addition to a description of the Foxhunter design, this article also attempts to provide an illustration of the link between advances in radar technology and improvements in operational techniques of combat aircraft.

It is beyond the scope of this paper to provide details of all design and equipment advances incorporated in the new radar and, in consequence, the authors have elected to present a sample of the most significant aspects. The paper is structured in three main parts; the first, Section 2, examines the radar from an operational viewpoint and highlights the tactical advances made possible with this new equipment compared with previous radars.

Section 3 selects and describes some of the important system design principles which are used in Foxhunter, concentrating on the special features of a coherent, pulse Doppler radar operating from an airborne platform.

The paper concludes by describing some of the physical aspects of the equipment design with particular emphasis on the requirements for operation in a severe environment and rapid repair in the field.

2. OPERATIONAL REQUIREMENT

Over the years of evolution of military aircraft, their associated avionics and the developments in military ground-based defence systems, there has always been an intimate link between equipment capability and the tactical deployment within either envisaged or real hostilities. Changing requirements on tactics caused by a changing threat normally drives requirements of military equipment but, equally, breakthrough in research and technology can often steer the military authorities to changes in defence strategy. Despite significant advances in infra-red, laser and electronic warfare techniques, radar is still the key sensor in an air defence system.

In order to explain the operational requirement for the Foxhunter radar and the technological advances which needed to be introduced, it is necessary to briefly review recent history of interceptor aircraft, their weapon systems and deployment as these are the factors which crucially affect airborne radar design.

During the 1950's-60's, airborne radar systems in RAF defence aircraft were restricted to non-coherent pulse mode operation with only modest transmitter powers in the centimetric wavelength region. The principal weapon of this era was the infra-red (IR) heat-seeking missile which had very limited performance capability in head-on attack against aircraft targets. The combination of modest transmitter power, the inability to use the Doppler effect to separate airborne targets from ground clutter for look down operation and a missile that requires to

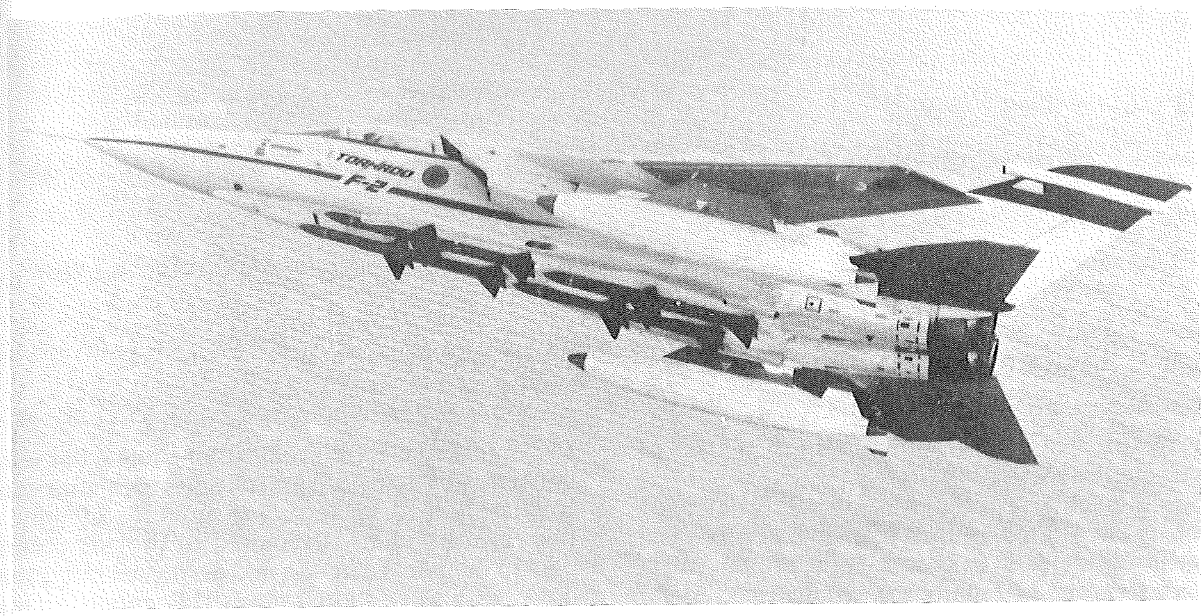

Fig. 1. Tornado F Mk2 aircraft with four Sky Flash missiles mounted beneath the fuselage. (Photograph by courtesy of British Aerospace)

attack targets from the rear led to the use of a particular operational technique called "Close Control".

This entailed the initial detection of targets by a long range, ground based surveillance radar followed by radio telephone transmissions to the pilot to provide vectoring information needed for the initial phases of the approach. This usually brought the interceptor into the rear hemisphere of the target at a range and aspect where the pulse radar would have a strong target signal and would not be troubled by ground clutter. The final phase of the approach and launching of the IR missile was made using data from the radar. In recent years, the main threat is seen as fighter-bomber raids and cruise missiles flying at very low levels. The use of ground based surveillance radar and "Close Control" of fighters is not a very effective method of defence in such scenarios and clearly illustrates the operational limitations imposed by airborne pulse radar.

Advances in the air-to-air missile field in parallel with advances in airborne radar has resulted in radar guided missiles with longer ranges than IR missiles and, more importantly, the capability of attacking aircraft in a head-on aspect. Examples of this type of missile are the US AIM-7 Sparrow and the British Aerospace Sky Flash. The missiles operate at X-band in a bistatic mode with the launch aircraft providing the transmission signals and, as they employ the principles of coherent Doppler radars, they have good discrimination of targets against a background of ground clutter. The missiles require the target to be continuously illuminated so the radar operates in an angle lock mode. In order to exploit the full potential of these radar guided missiles, AI radars require longer ranges and a good look-down capability.

The first use of this type of missile by the RAF was

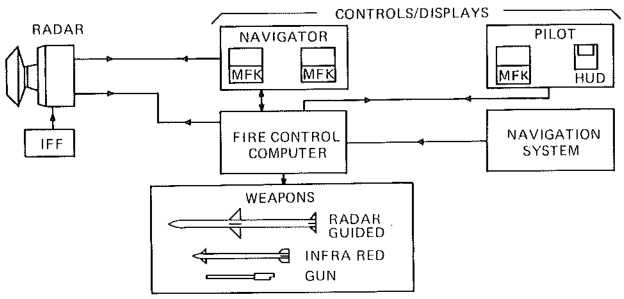

Fig. 2. Weapon system.

Sparrow on the F4-M Phantom aircraft which were acquired in 1969. The Phantom radar (AWG 11/12) is the first fully coherent airborne radar in use in the RAF. It has a powerful transmitter giving good long range detections in a look down mode. The system is very effective in head-on engagements against single low level intruders but has not been specifically designed to combat multiple-target raids.

The current threat is now seen as the deployment of mass offensive raids planned to saturate the defence forces of the UK/NATO Regions. The interceptor is required to carry as many air-to-air missiles as possible and its fire control system must be capable of engaging multiple targets in rapid succession. The major enhancement to previous systems is thus, undoubtedly, the inclusion of 'track-while-scan' (TWS). This, then, led to the requirements of Tornado F Mk2 (fig. 1) and its associated radar.

The Foxhunter radar is an integral part of a complete weapon system in which the prime medium range radar-guided missiles supported by short range IR missiles and a gun, provide the basic fire power (fig. 2). Other important elements are the fire control computer and the navigation and target identification sub-systems. The radar requirements are derived by

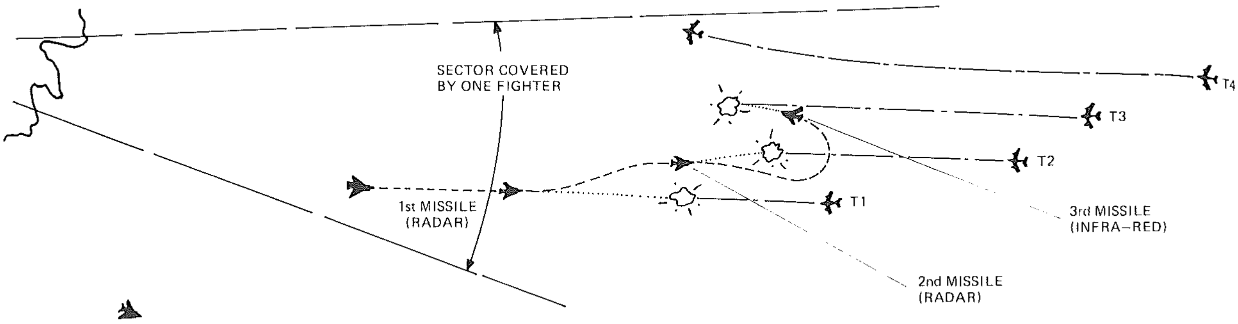

Fig. 3. Intercept profile.

applying this complete weapon system to the task of countering the threat.

The air defence task comprises the early detection of enemy aircraft intent upon offensive missions and the neutralization of this force before it can inflict damage to ground or sea-borne installations. As far as the United Kingdom and Western Europe are concerned, the critical air space ranges from Iceland to the Mediterranean Sea and the airborne threat comprises numerous, all altitude, well armed and agile aircraft. The normal tactic of the offensive aircraft will be to fly at very low level so that the earth's curvature provides screening from ground based radars and to fly fast in the hope that any airborne defensive cordon is penetrated before it has had time to react. In this situation the principle tasks of an airborne interceptor radar are:

- the detection of low flying aircraft at the longest possible range – ranges in the region of 50–100 nm are required
- the identification of the detections as friend or foe
- the simultaneous tracking of many targets and the measurement of their flight paths in order to build-up a picture of the tactical situation and to provide attack steering data, that is, the new process of track-while-scan (TWS)
- the provision of priming, aiming and guidance signals (CW illuminator) for the medium range, radar guided missile (i.e., Sky Flash).

In many situations, all four of the above phases will have taken place, the missile fired and the target destroyed before it has reached the airborne defensive screen (fig. 3). In certain other situations, however, the target will have reached and passed through the defending screen before it had been possible to launch a missile. In this situation, an attack on the rear hemisphere of the target or even aerial combat will ensue. This operational role places very different requirements on the radar compared with the long range interception role. The radar range to the target will generally be short, (the target may even be within visual range), but its angular co-ordinates will be changing rapidly. Therefore, a rapid angular search followed by rapid acquisition of the target in an angle lock mode is required.

The identification of the target should be accomplished electronically at long range but in certain circumstances it is necessary to obtain visual confirmation of an intruding aircraft's identity. In this case the radar is required to provide accurate data to the pilot so he can make a precision approach down to a very short range. This entails accurate range measurements and, in the closing phases, operation at ranges of a few hundred feet. This operation is called Visident.

A multi-mode radar is clearly necessary to carry out the variety of tasks defined above and the modes of the Foxhunter radar that accomplish these tasks are shown in Table 1.

The first five modes in the list are mutually exclusive whereas the CW illumination mode is an optional additional facility in either of the angle lock modes. Similarly, IFF Interrogation is an optional additional facility in Modes 1 to 4, but will usually be used during the tactical evaluation phase of Mode 1. As the prime role of the aircraft is with the radar in a look-down air defence mode, pulse modulation and pulse compression modulation are used far less frequently than pulse Doppler. The special circumstances in which they are used are indicated in the Table.

Advances in medium-range missile design are currently taking place in the United Kingdom and the United States. The AIM-120A advanced medium range air-to-air missile (AMRAAM) is well into development at the Hughes Aircraft Corporation and the feasibility of integrating the new missile with Tornado F Mk2 is being studied. Unlike Sky Flash, AMRAAM will not require dedicated CW illumination during flight; it requires instead updates of target location transmitted by a guidance command link. This will increase the effectiveness of the overall weapon system in that several missiles may be in flight simultaneously and the radar can remain in track-while-scan mode throughout the engagements, maintaining uninterrupted coverage of the total threat.

3. RADAR DESIGN

3.1. Design Principles

The provision of the suite of operational modes shown in Table 1 requires radar sub-systems, such as the aerial and transmitter, to have different func-

TABLE 1

Modes of Operation

Mode	Normal Operational Usage
1. Search and TWS with Pulse Doppler Modulation	Long Range Detection, Tactical Evaluation, Fire Control of Sky Flash and IR Missiles
2. Angle Lock with Pulse Doppler Modulation	Maintenance of Antenna on Target during Sky Flash Flight
3. Combat (Pulse Modulation)	Rapid Acquisition of Angle Lock from Visually Sighted Target
4. Angle Lock with Pulse Modulation	Fire Control of Gun (occasionally missiles), Visident
5. Search with Pulse Compression Modulation	Ground Mapping
6. CW Illumination	Sky Flash Guidance
7. IFF Interrogation	Identification Friend or Foe

tional characteristics in different modes. It is not always possible to obtain optimum performance from each sub-system for each mode and hence it has been necessary to accept some compromises in the performance in certain modes in order to obtain optimum performance in others. By carefully matching the radar system design, however, to the operational needs it is possible to avoid any significant reduction in overall effectiveness. It has been shown above that the operational effectiveness of Tornado is mainly determined by the performance of the Pulse Doppler, Search and Track-While-Scan mode and consequently priority in design has been given to this mode. The functional characteristics required from the individual sub-systems of a pulse Doppler radar are very different from those required for a non-coherent pulse radar because performance is influenced more by ground clutter than thermal noise in the receiver. To establish the sub-system requirements, it is firstly necessary to explain the basic principles of operation of a pulse Doppler radar operating from an airborne platform.

In an air-to-air search mode where a look down situation occurs, a conventional pulse radar has the disadvantage that targets can only be detected if they scatter more power back to the radar than the earth's surface at the same range and within the same range gate. Using a continuous wave (CW) system with frequency analysis to achieve detection, the target signal needs only to be large compared with clutter in the same frequency cell.

The space available in an airborne platform limits the designer to the use of a single aerial for both transmission and reception. Without suitable protection the leakage of transmitter power into the receiver would become unacceptably high. A solution to this is to transmit an interrupted continuous wave (ICW) waveform. Although other arrangements are possible, the ICW is considered here to be a high pulse repetition frequency (prf) mode with a relatively high mark to space ratio. During transmission, the receiver is then isolated by suitable switching, but during reception, the signal is allowed to pass without attenuation. The choice of the prf in an airborne pulse Doppler radar is a crucial decision and depends on the operational role of the aircraft, the detection range required, the spread of target velocities, the radar operating waveband and many other factors.

For a fighter aircraft operating at frequencies in X-band or above, it is usually not possible to select a prf that enables both target range and target range rate to be measured unambiguously over the total operational regime, nor one that provides an operating regime unobscured by ground clutter returns for the full spread of target velocities (both positive and negative with respect to own aircraft) and the spread of target ranges. More details on the characteristics of pulse Doppler radars with low, medium and high prf's are given in Hovanessian[1].

A high prf has been chosen for Foxhunter because it provides a region in Doppler space completely clear of ground clutter at all target ranges for the main threat of closing targets. The prf selected is very high (i.e. above one hundred kilohertz) so the measurement of target range is highly ambiguous. Several techniques are available to provide an unambiguous measurement of target range, such as the multiple prf scheme described in Hovanessian[1], but the method chosen for Foxhunter involves superimposing a low frequency, frequency modulated (FM) signal on the high prf transmission. Comparison of the phase shift between the FM signal on target returns with transmitted FM signal provides a measure of target range. The accuracy of the measurement is determined by the precision of the frequency modulated signal and the resolving power of the signal processing system.

An effective track-while-scan system requires frequent and regular measurements of target range, and ideally target range rate. In a radar system with a mechanically scanned aerial, it is not practical to have either adaptive beam control (which provides a variable dwell time) or a variable transmitted waveform and signal processing system adjusted to provide the optimum detection and measurement process on every target. The modulation waveform and signal processing system must be compatible with a continuously scanning beam. In other words, the waveform and processing must enable the detection and measurement of target parameters to be accomplished during the brief period during which the beam passes through the targets. This entails the completion of a high resolution frequency analysis process and the extraction of target range from the FM signal in a few milliseconds. Track-while-scan is an automatic process which relies on a signal processing system that automatically decides on the presence or absence of a target return rather than depending on an operator to make this decision. This requires the signal processor to have a fast acting, automatic detection process that operates within the few milliseconds of the beam dwell time.

Two further aspects of the search and track-while-scan mode that require to be discussed are dynamic range and the spectral purity of the transmitted signal. The amplitude of the ground clutter returns are very large because the high prf, high duty ratio, transmission integrates the clutter from many range cells into a single gate. The magnitude of the clutter is typically 80 to 90dB greater than thermal noise, requiring the whole receiver and signal processing chain to have a dynamic range of this order to prevent intermodulation products of clutter spreading into the Doppler band of target returns. The very large amplitude of clutter also necessitates a very pure transmitted signal such that the close-to-carrier noise superimposed on any clutter return does not blanket the much smaller target signals in adjacent Doppler cells.

In addition to the features described above which enable the radar to discriminate a Doppler-shifted target signal from ground clutter, the requirement to achieve the maximum possible target detection range requires the radar to achieve the usual features of the maximum possible transmitter power, receiver sensitivity and aerial gain within the allocated space and weight budget of the aircraft nose.

The key features required in the Search and Track-While-Scan mode are summarized in Table 2.

A similar assessment of the principles of operation enables requirement tables to be established for all the radar operating modes and examples for the Pulse Doppler, Angle Lock mode and Pulse Compression Search Mode are shown in Tables 3 and 4 respectively.

Examples of the way the above requirements have been provided in the radar, either by the use of multiple function sub-systems (e.g. the aerial) or by two or more separate sub-systems (e.g i.f. Receivers), are described below.

TABLE 2

Key Requirements in the Pulse Doppler, Search and TWS Mode

1. High prf ICW operation, frequency analysis in beam dwell time, automatic detection.
2. Application of precision frequency modulation to ICW signal, range extraction in beam dwell time.
3. Wide dynamic range receiver and signal processing chain, high spectral purity transmission.
4. Plot extraction and track-while-scan on multiple targets.
5. Maximum transmitter power, receiver sensitivity and aerial gain.

TABLE 3

Key Requirements in Pulse Doppler, Angle Lock Mode

1. High prf FMICW operation.
2. Narrow band Doppler tracking filter with robust acquisition and re-acquisition system.
3. Monopulse operation.
4. Integration of CW illuminator transmission with radar transmission for Sky Flash guidance.

TABLE 4

Key Requirements in Pulse Compression, Search Mode

1. Application of pulse compression waveform to transmitted signal.
2. Receiver unit with pulse compression and sensitivity time control (STC) modules.
3. Scan converter unit to match slow scanning aerial beam to TV raster format.

3.2. Key equipment features

An outline block diagram of the radar is shown in fig. 4. The angle lock receiver channels have been omitted in order to simplify the presentation.

Frequency generator and transmitter

Three crystal controlled source modules are used to provide the radar transmitter drive, the radar local oscillator and the CW illuminator drive.

A very compact design has been achieved by utilising a single crystal oscillator and a frequency synthesizer technique to obtain multiple selectable operating channels rather than the more conventional approach of a bank of separate crystal oscillators. The frequency modulation required for target range

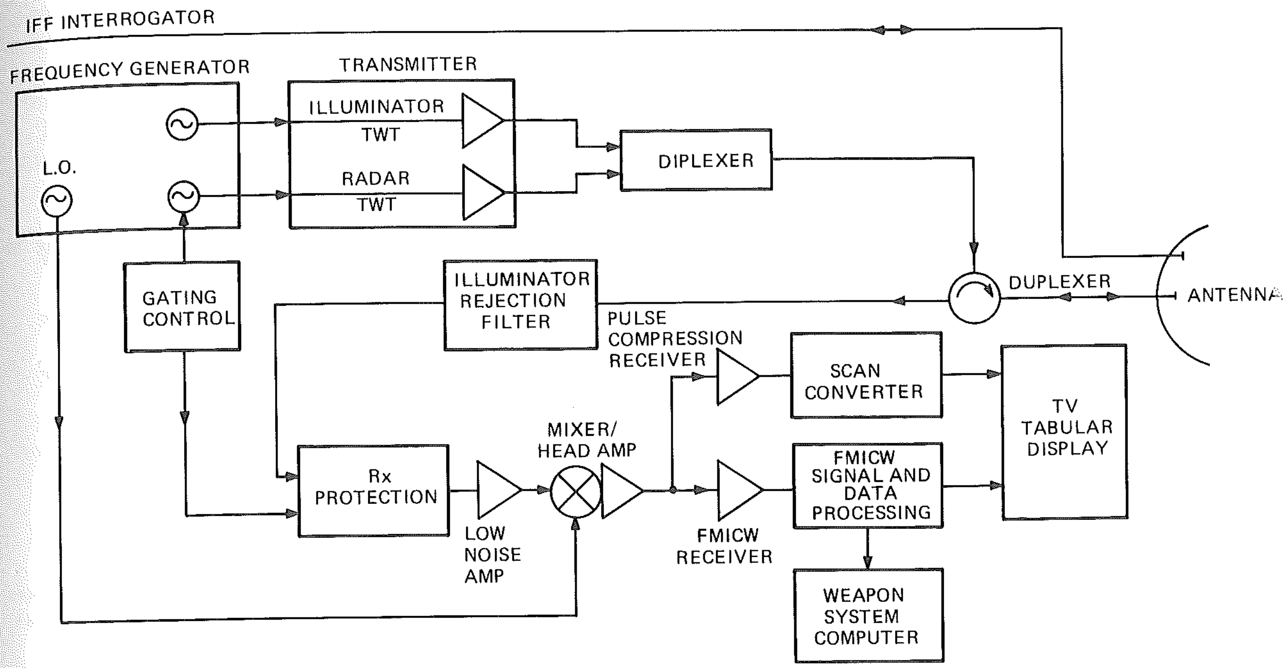

Fig. 4. Outline radar block diagram.

measurement is obtained by "pulling" the single crystal oscillator which has the advantage that precisely the same ranging modulation is obtained on every channel. An important feature of the design is the achievement of low incidental AM and FM noise levels and very low levels of spurious signals in a frequency synthesizer system. The source for the transmitter drive also produces the pulse and pulse compression waveforms for the other modes of operation.

High mean power travelling wave tubes, (TWTs) developed specifically for the radar are used in the transmitter unit to amplify the radar and CW Illuminator drive signals. The two output signals, which are at different RF frequencies, are combined in a low loss diplexer before passing to the ferrite duplexer module. The TWTs are achieving efficiencies in the region of 25% which has enabled the weight of the EHT supplies to be kept within the tight budget limits. Special attention has been paid to minimizing the ripple voltage and noise on the TWT supplies and to reducing mechanical vibration in order to achieve the required low levels of AM and FM noise on the output. Pulse compression is used in order to utilize the high mean power available in the TWT and simultaneously to obtain a pulse with good range resolution.

Aerial and scanner

The aerial uses the twist polarization, Cassegrain principle of the type described by Jasik [(2)], with wide r.f. bandwidth to accommodate the radar and CW illuminator operating bands. This type of aerial enables the high gain required for long detection ranges to be achieved simultaneously with the low far sidelobe levels required for operation of an FMICW radar at low altitudes. A two-plane monopulse feed is provided for the angle lock modes and separate dipoles are provided at a lower frequency for the transmission and reception of IFF interrogation signals.

Nomex honeycomb and glass fibre materials are used in the construction to produce a rigid, low inertia assembly. Agile slewing and precise tracking over wide angles are achieved by a hydraulically driven scanner fed directly from the aircraft supply. Digital electronics are used in the scanner servo system to give high reliability and to enable the dynamic performance to be matched to the operational situation.

Receiver

The microwave receiver employs a multiple section, waveguide band pass filter with low loss in the radar band and very high attenuation in the CW illuminator band. The filter, together with the isolation provided by the ferrite duplexer, reduces any leakage from the CW illuminator into the radar receiver to tolerable levels. The receiver protection device uses PIN diodes and provides switching times faster than 100 ns in order to minimize the transmit/receive gating losses in the high prf FMICW mode. The low noise pre-amplifier is followed by double balanced mixers with good image rejection. Separate i.f. receivers are used for the FMICW and pulse compression modes because their requirement specifications are quite different. The main feature of the FMICW receiver are the techniques used to amplify and discriminate between the small target signals and massive ground clutter signals without causing intermodulation. The pulse compression receiver is more conventional and features a modest dynamic range, sensitivity time control (STC) and a surface acoustic wave (SAW) delay line for recovering the short, high resolution, pulse from the expanded transmitted signal.

Signal processing

A block diagram of the signal processing system of the FMICW search mode is shown in fig. 5. For convenience, the track-while-scan module described in the next section is also shown.

A high speed, wide dynamic range analogue-to-digital converter is used to sample the output of the i.f. receiver at the radar pulse repetition frequency. A fast stream of digital samples is produced and is passed to the frequency analyser which performs a fast Fourier transform (FFT) algorithm on the data. Several FFT algorithms are performed during the beam dwell time corresponding to different periods of the FM ranging modulation. A weighting process is then carried out to reduce the spectral spreading caused by the short sampling time and this is followed by an automatic detection process. This is effectively a constant false alarm (CFAR) process with a threshold being automatically adjusted as a function of the combined clutter and receiver thermal noise levels.

Signals exceeding this variable threshold are passed to the range correlator which, by comparing the outputs from different phases of the FM waveform, determines target ranges. The final module in the system is a plot extractor which produces a well defined and unique output of the range and range rate of every detected target.

The fastest and highest precision digital processing occurs in the frequency analyser and a compact and robust design has only been possible since the emergence of new digital technology in the middle 1970's. In particular, multiple gate Schottky TTL logic and the availability of special purpose LSI devices provide the necessary speed and precision for the FFT algorithms.

The automatic detection module calculates a threshold using an adaptive process implemented in a high speed, microprogram controlled processor with bit slice arithmetic and logic units (ALU). Use of a wide microprogram word enables many functions to be carried out in parallel, effectively increasing the processing speed still further.

Full advantage has been taken of the power and flexibility of the microprocessor with programmable read-only memory, in the plot extraction module. Microprocessors are also used extensively in the built-in-test facilities of the radar.

Track-while-scan

Track-while-scan (TWS) is a technique for accurately observing the progress of one or more targets whilst operating the radar in search mode. A complete scan pattern may take several seconds and consequently fresh information concerning a target is only available to the tracking logic at this rate. The TWS logic accepts the new information of range, range rate and antenna position for each target during

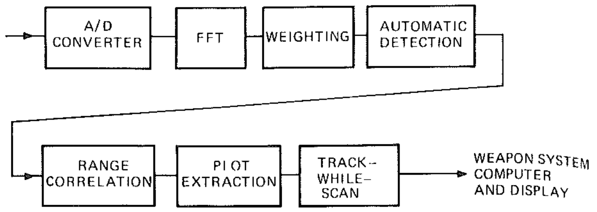

Fig. 5. Block diagram of signal and data processing in FMICW search mode.

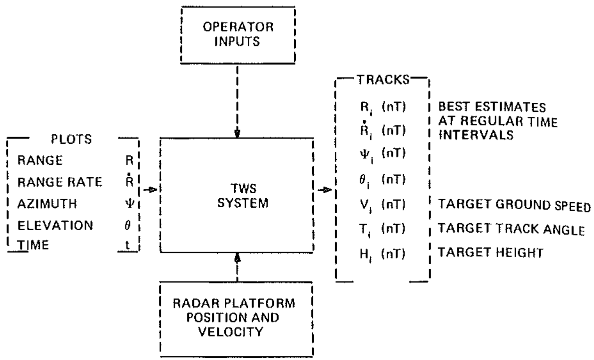

Fig. 6. Track-while-scan data interfaces. The suffix i indicates the track number.

the scan and, by remembering and combining this sampled data from several scans, the process produces a smoothed trajectory of the target. The individual inputs from each scan are known as 'plots' and the processed output is termed a 'track'. The track provides estimates of target course and speed which cannot be provided directly from the radar and also provides measurement of target position to an accuracy which because of the implicit averaging, is normally better than the raw radar measurements. The tracking algorithm cannot successfully operate unless due corrections are made for own platform motion and manoeuvre. In consequence, the process features the input of aircraft parameters from the navigation system.

The radar system includes a radar data processor which is basically a compact, general purpose computer with specialised interfaces to all radar units and the rest of the weapon system. The track-while-scan function is one of the main tasks of the radar data processor. The software has been produced in Coral 66, the high level, real time language currently adopted as standard by the UK Ministry of Defence.

Fig. 6 shows the basic inputs and outputs of the TWS process. Plots are formed by combining the signal processor outputs with synchronized samples of antenna position and they are then entered into a plot store. Each plot in turn is compared with predictions of track parameters and, if the plot is deemed to belong to the track, the data is used to update the track parameters. The prediction process includes own platform motion data provided by the aircraft inertial navigation (IN) system. The track(s) are held in a track store from which independent, regular outputs may be made to the weapon system comprising best current estimate of track state.

The heart of the process is a continual loop involving:

★ prediction of track status forward to the time when the next plot is expected
★ construction of suitable multi-dimensional capture gates at this position
★ accepting any plot which lies within the capture gates
★ filtering the plot into the track.

In generalised mathematical terms the basic equations[3, 4] in vector form are:

(Prediction)	$\tilde{\mathbf{X}}_n = \phi_n(t)\,\hat{\mathbf{X}}_{n-1}$
(Filtering)	$\hat{\mathbf{X}}_n = \tilde{\mathbf{X}}_n + K_n(\mathbf{Z}_n - H\tilde{\mathbf{X}}_n)$
(Composition of Measurement)	$(\mathbf{Z}_n = H\mathbf{X}_n + V_n)$

where ϕ_n is the state transition matrix, H the observation matrix, $\mathbf{X}_n$ the state vector, K_n the filter gain matrix, $\mathbf{Z}_n$ the measurement vector, and V_n is the noise in the measurement vector. The symbols $\tilde{}$ and $\hat{}$ stand for a prediction and an optimum estimate respectively, while n represents the count of plots on a selected target.

The crucial parameter in this equation set is the filter gain matrix. This determines the credence given to the track prediction compared to the new measurement. The optimum filter for such applications is a Kalman filter, which utilizes knowledge of the respective accuracies of the track state and plot in order to give appropriate weighting to their combination. In reality, the full Kalman filter algorithm is normally simplified for real time operation.

The above briefly describes the equation loop when tracking has settled on a non-manoeuvring target. In the design of a robust, operational TWS system several other features must be built into the logic to cater for specific occurrences associated with target or radar behaviour; the following lists the main necessary additions:

(a) Memory
The logic must be capable of accepting periods during which no plots are received because of target fades or eclipsing or because the target has temporarily moved out of the radar field of view. Also the radar ceases to refresh the TWS logic during periods of lock-on for firing and guiding the Sky Flash missile. In such situations, a record must be kept of the time interval from the last successful plot capture and the track predictions and associated gate sizes are made a function of elapsed time, increasing as a function of track state uncertainty.

(b) Track Confusion
In conditions where two or more targets are in close proximity a confused situation can arise where one track may lay claim to more than one plot or, conversely, two or more tracks may fight for a particular plot. This problem is further compounded when it is borne in mind that not all targets are necessarily being tracked and that some targets may fail to provide a plot on a particular scan. In these conditions, a self-consistent set of rules must be adopted in order to allocate the plots to tracks.

(c) Target Manoeuvre
The input of ones own navigation data to TWS permits the effects of ones own manoeuvre to be almost totally removed. The targets may, however, perform various manoeuvres and the logic must cater for such events. The standard process is to introduce alternative multi-dimensional capture gates during prediction, which are larger than the normal gate. Their size should ideally cater for the maximum target manoeuvre in any direction from the time of the last plot. Should a subsequent plot fail to fall in the normal gate, but is captured in the larger manoeuvre gates, then the target is deemed to have commenced manoeuvring. In this circumstance, alternative prediction logic and filter gains should be introduced until the target settles back to small gate captures.

(d) Initiation and Track Deletion
Facilities must be provided within the system to commence tracking on a particular plot and also to cease tracking when the target is no longer of interest. Systems can be designed where these are performed automatically or, more usually, with operator participation. With automatic initiation, the plots rejected by the main TWS logic are passed to a separate initiation routine which attempts to form an 'infant' track over a few scans on each of the rejected plots.

This may be performed in a similar manner, that is 'prediction – gates – filter' as used in the main logic, but it must be remembered that gate positioning will not be as precise since full trajectory data is not available. Criteria must be chosen to define when an 'infant' track is sufficiently mature to enter the main TWS logic. The normal criterion is based on "n plots associated during m successive scans". Care must be taken to ensure that the initiation routine is given lower priority access to incoming plots otherwise it may steal data from mature tracks resulting in two or more tracks sharing one target.

Deletion is a simpler process and is normally based on the unexpected absence of plot capture of a particular track on several successive scans. Finally, attention must be paid to track overload in automatic systems. The system is normally designed for a maximum number of tracks and when this figure is reached, system decision must be built in to decide whether to reject any new tracks or to auto-delete existing low priority tracks. This task, provided the occurrence is not frequent, is best performed in conjunction with the operator.

4. EQUIPMENT PHYSICAL CHARACTERISTICS

The mechanical design of the radar posed a challenging task because of the high packaging density required, the odd shape of the space allocated and the need to protect the electronic components from the harsh environment in the forward fuselage of the aircraft. In addition, the essential requirement for rapid diagnosis and repair of faults on front-line squadrons led to a modular design in which the radar was divided into a series of first-line replaceable units (LRU's) which could be changed in the field with the minimum of support equipment and no adjustment or re-alignment.

The selected mechanical design for the transmitter is a cylindrical container pressurised to prevent electrical breakdown at high altitudes. This shape obtains the maximum strength to weight ratio. Optimum space utilization and the provision of a uniform LRU shape for the remaining electronics is then realised by placing the transmitter in the centre of the circular airframe and dividing the ring outside it into several wedge-shaped segments. This layout culminates in twelve LRU: the main frame, the transmitter, eight electronic units, the scanner and aerial. The configuration is illustrated in figs. 7 and 8, where it can be seen that the radar is installed in a short cylindrical section of fuselage connected on one side by hinges to the main fuselage and on the other by hinges to the radome. This arrangement provides excellent access for servicing. The eight electronic units are designed to slide into the main frame on rails until they locate on dowels and simultaneously make electrical and cooling connections.

The high packing density and cooling load of several kilowatts means that air cooling is impractical and the aircraft manufacturer has installed a liquid cooling system using a silicate ester fluid. The electronic units are cooled by using a liquid filled 'cold wall' system. The cold walls form two opposite sides of the box and the circuit boards slot into grooves on the inside faces. Heat is transferred from the electronic components to the cold wall by mounting them across the rungs of a 'heat ladder', the stiles of which are in contact with the cold wall grooves. A typical LRU showing these features and a circuit board removed for display purpose is shown in fig. 9. This arrangement enables a very high packaging density of electronic components to be obtained in an environment where the ambient temperatures can vary by as much as −50°C to +80°C.

Initially the electronic units were made by dip-brazing aluminium components together but distortion inherent in the process prevented it from becoming a viable method for the quantity production of precision boxes. Significant advances in the design of lightweight aluminium investment castings have been made in this country and North America in the last ten years and castings of the required size, complexity and accuracy are now available. This process has been selected as the basis for the Foxhunter electronic units which, together with the

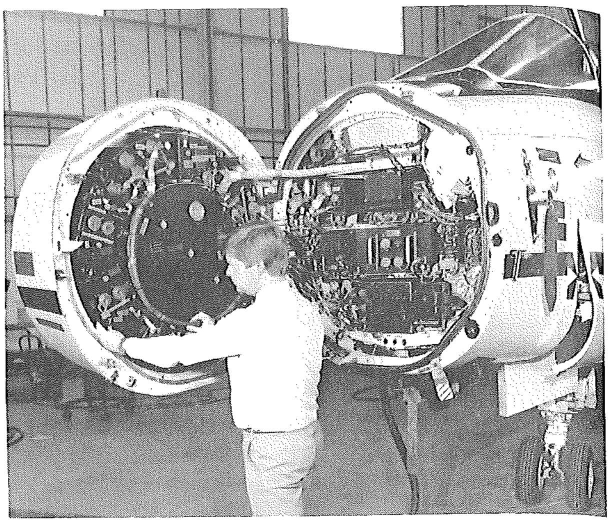

Fig. 7. Installed radar, rear view.

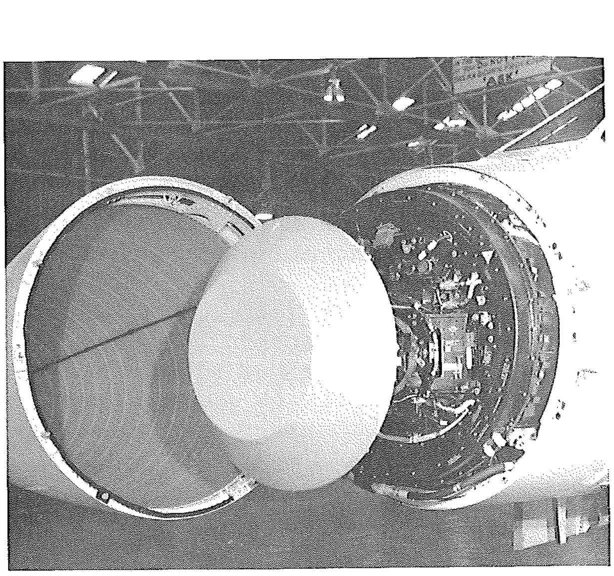

Fig. 8. Installed radar, front view.

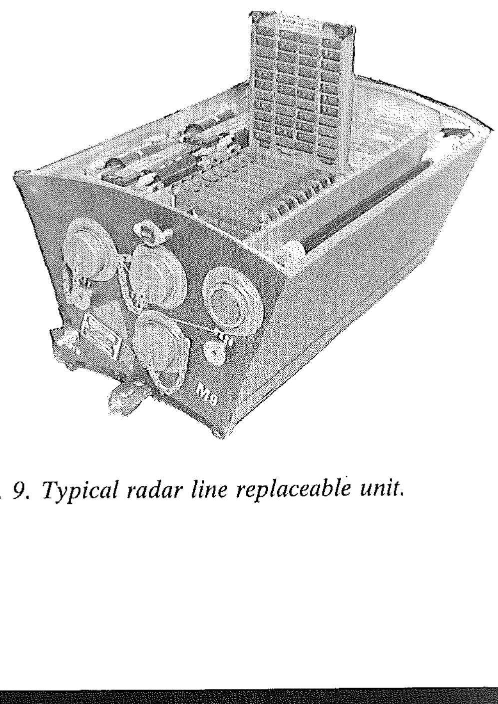

Fig. 9. Typical radar line replaceable unit.

specially developed machining and bonding techniques, is producing an economical and reliable supply of boxes.

The reliability of many electronic components would be greatly reduced if they were subjected to the high levels of mechanical vibration present in the forward fuselage of Tornado. To enable the reliability targets to be met, the complete radar is anti-vibration mounted at the aircraft fixing points, the centre of gravity of the radar lying in the plane of the mounts. A critical feature of the design has been the selection of the natural frequency and deflection characteristics of the mounts so that the required attenuation is obtained at the high frequencies of vibration (which cause most damage to electronic components) and, at the same time, maintaining the radar assembly stable for precise angular measurement with the scanner. Two of the four anti-vibration mount modules can be seen in fig. 8 in the small gap between the radar assembly and the aircraft fuselage.

Throughout the design and development of the Foxhunter radar, as much importance has been placed on the reliability and maintainability of the service equipment as has been placed on the challenging performance requirements described earlier. The key element in modern day military equipment is cost-effectiveness; 'cost' represented by total cost of ownership, that is prime equipment, spares holdings, test equipment, maintenance and repair labour charges etc and the 'effectiveness'—defined as equipment with adequate performance which is available and operates whenever required. Foxhunter is proving itself to be a rugged cost-effective radar.

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