F-22 RADAR DEVELOPMENT

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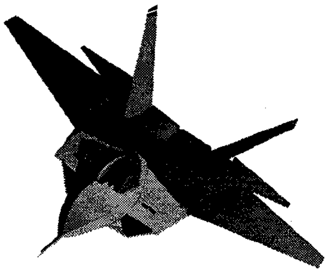


(Figure 1) F-22 Advanced Tactical Fighter

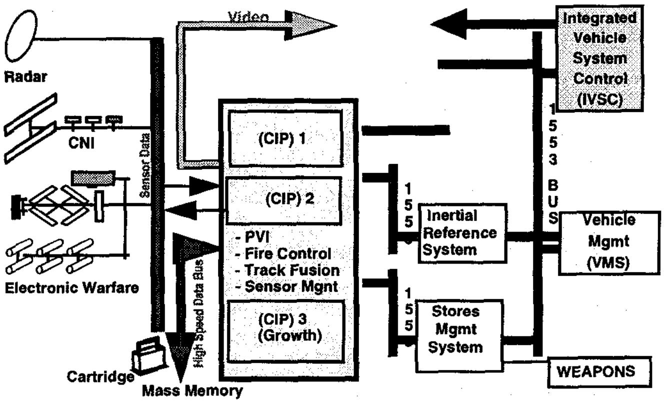
Abstract

The USAF F-22 Engineering, Manufacturing and Development (EMD) program has pushed the state of airborne fire control radar technology well beyond that found in today's fielded systems. Advancements in performance, reliability, and low observability have been realized in the design of the F-22's new APG-77 Radar through the implementation of active array technology, low noise receiver components, high density packaging, and advanced mode development. This paper will explore these advanced features from a systems engineering perspective by first introducing the F-22 Avionics System concept and then summarizing the hardware and software architecture which comprises the F-22 radar system. Unique F-22 advancements in survivability, lethality, reliability, and supportability are outlined briefly. Aircraft trade considerations that are unique to the implementation of an active array into a low radar cross section fighter application are discussed. Lessons learned in design trade areas such as power, cooling, packaging, weight, low radar cross section considerations, receiver design, antenna design, reliability, supportability, maintainability, and waveform design are reviewed. Implementation of this new capability would not be possible without the incorporation of new development processes and the transition of critical technology made available through the benefit of several long term joint government-industry technology base initiatives. Related details regarding solid state transmit/receive modules, electronically scanning arrays, and advanced radomes extending back to the Advanced Tactical Fighter Demonstration / Validation phase of the F-22 program are reviewed.

Introduction

The F-22 Radar EMD program is managed by a joint government/contractor team founded in the concepts of integrated product development emphasizing concurrent engineering, communication, and cross company team work. The Air Force component is located within the F-22 System Program Office, Aeronautical Systems Center, Wright Patterson AFB, Ohio. The contractor team consists of Lockheed-Martin Aeronautical Systems Corporation (LMASC), Boeing Military Aircraft (BMA), Northrop Grumman Electronic Sensors and Systems (ESSD) and Texas Instruments (TI). LMASC is positioned as the prime contractor with BMA having "on aircraft" radar integration responsibility including design and development of the radar power supplies. The radar system is being built under a ESSD/TI Joint Venture with a 40/60% spilt on the construction of the transmit/receive (T/R) modules and a 50/50% share of the antenna subarray construction. TI is building the array power supply and providing the associated supporting software. ESSD is responsible for all remaining hardware and software as well as complete subsystem integration and testing.

The F-22 radar development program has progressed significantly since its initial Demonstration /Validation phase which ended in March 1990 where proof of concept was demonstrated by competing teams (Lockheed/BMA/General Dynamics/WEC/TI & Northrop/McDonnell Douglas/WEC/TI)[1]. Following formal source selection and contract award (Aug 1991), the Radar EMD process moved out toward it's first milestone; System Requirements Design Review Update (RDRU) which was completed in March 1992. Radar System Preliminary Design Review (PDR) occurred in February 1993, and subsequently the System Critical Design Review (CDR) in September of 1994. The first complete APG-77 radar is scheduled to be tested in the avionics lab beginning first quarter of 1998, fly on the F-22 757 Avionics Flying Test Bed in early 1998, and is scheduled to fly on the F-22 aircraft in the second quarter of 1999. To date, hardware for the first unit is complete and is being tested in the Northrop Grumman radar integration lab. Software coding is well underway with Radar S/W CDR for the first and second incremental delivery completed in June 1995 and December 1996 respectively.



(Figure 2) F-22 Avionics System

System Design Summary

The APG-77 Radar system is part of an integrated multisensor avionics design implementation. Unlike the previous federated systems, the F-22 avionics system reflects a highly integrated approach where in many cases the avionics system manages sensor operation automatically while reducing pilot manual work load. The integrated system combines various sensor data to identify

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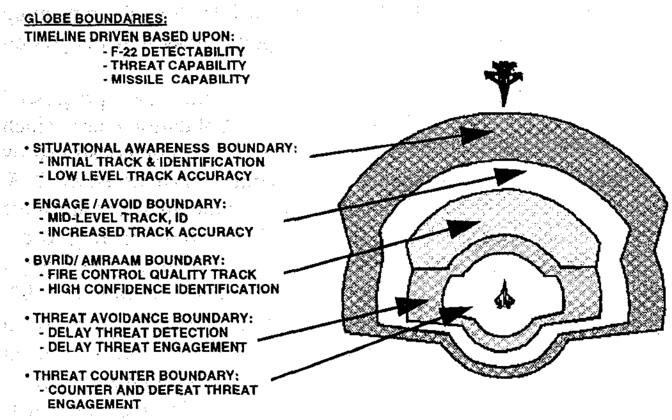
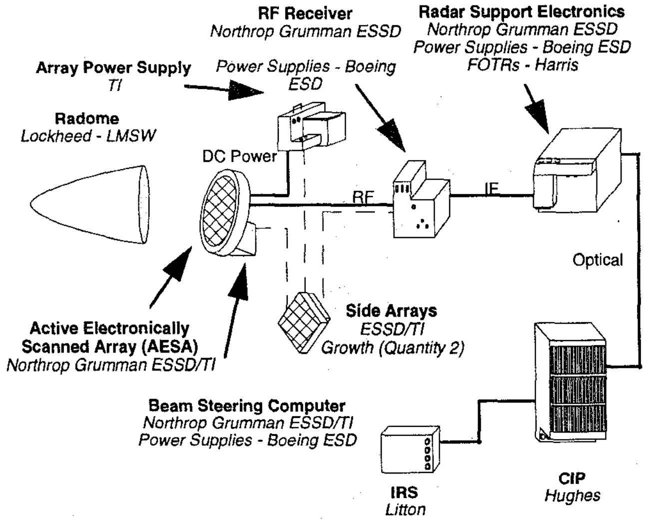
aircraft and presents a completed air combat picture on a single display. As shown in figure 2, areas in which radars have operated autonomously in the past (fire control, tracking, and sensor management) are now controlled at the avionics level. Radar target measurements are passed to the integrated avionics system where inputs are combined with other sensor inputs to form a single track file. Radar activity is controlled by an avionics level sensor manager which provides commands via a high speed data bus. System parameters such as search waveform selection, scan volume size, desired track accuracy, and timeline prioritization are examples of sensor management commands. The Avionics Mission Software component provides mission management, navigation, pilot vehicle interface, fire control, flight path management, track fusion, and sensor management serving all avionics sensors. These unique automation and integration characteristics result in a high degree of interaction between the radar and the avionics mission software functions.



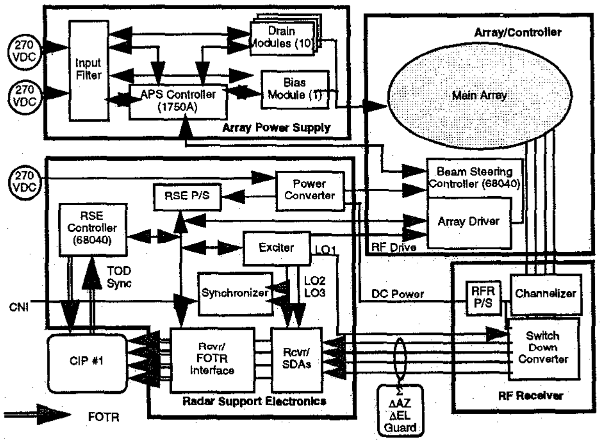
(Figure 3) Requirements Globe Diagram

The radar functional performance requirements have been formulated within the context of this integrated avionics concept. Search, track, identification, and cluster breakout requirements are allocated to the radar based on a target engagement timeline scenario. Figure 3 summarizes a top level view of this engagement scenario in what is referred to as the "F-22 Tactical Globe". Specific radar functional capability is required at respective range increments in order to support the avionics portion of the entire weapon system mission of "First Look- First Kill". The engagement is divided into five zones ranging from situational awareness where the radar is required to provide long range detection; out to ranges where the radar supports high accuracy target track for AIM-120 launch support. Zone boundaries are set based on pilot information needs, weapons capability, threat capabilities, and F-22 signature. These baseline requirements are reflected in the radar design through the implementation of an advanced multi-mode, multi-target interleaved search/track, all weather, fire control radar. The incorporation of agile beam search/track, low observable (LO), electronic counter-countermeasure (ECCM), and low probability of intercept (LPI) design features give the F-22 radar the required quantum leap in combat capability.

The radar hardware consists of five major components; the Array / Beam Steering Controller (Array/BSC), the Radar Support Electronics (RSE), the RF Receiver (RFR), the Array Power Supply (APS), and the Installation Equipment. Figure 4 provides a summary of the APG-77 hardware subsystems. These units receive liquid flow through cooling through the Coolant Distribution Manifold, and electrical power from the aircraft. Control, status, and receiver data interfaces are implemented by a fiber-optic interface between the Common Integrated Processor (CIP) and the RSE. The Main Array is mounted in the nose radome and is composed of transmit/receive (T/R) modules plus several receive modules which comprise the guard channel. The Radar block diagram is shown in figure 5. The steering commands for the array are computed in the BSC which is controlled by the Motorola 68040 microprocessor. The DC power for the array is supplied by the APS which filters and conditions 270 Volts dc from the aircraft generators. The array RF outputs go to the RF receiver unit which contains a switching assembly to route signals between the main and growth side arrays. The RF receiver unit also provides the bandpass filter, RF amplification, and first frequency down-conversion. The RSE comprises 6 major functions for the radar subsystem; the receiver, exciter, final frequency down conversion, controller, synchronizer, analog to digital (A/D) conversion functions, and low voltage power supplies.



(Figure 4) Hardware & Interface Diagram



(Figure 5) Radar Block Diagram

The RSE exciter generates the radar's RF signals, provides RF drive to the array driver, and acts as the radar system clock. The RSE controller transfers four channel I/Q digital data via optical interfaces to the CIP and as such serves as the primary data, status, and control interface with the CIP.

The hardware is managed as one configuration item and is partitioned into the Array/BSC, RSE (24 modules), RFR (5

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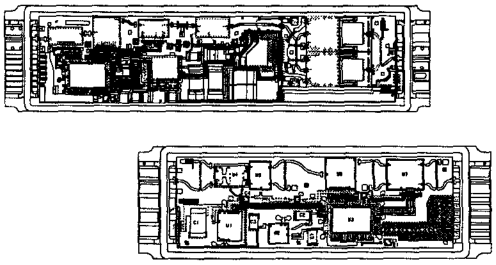
modules), Array Power Supply (3 modules), and Rack/Installation hardware. A SEM-E module configuration has been chosen as the standard for the majority of the hardware components (APS and channelizer LRMs are not SEM-E). These SEM-E modules are installed into their respective LRU backplane assembly. The physical installation into the forward fuselage equipment bay is accomplished within limited space in the converging volume of the aircraft nose. The array is installed in a backward detent with the beam steering controller mounted directly to the back of the array. The RFR and RSE are secured on a stable platform in the upper cavity within the forward equipment bay. The array power supply is located just behind the antenna.

At the heart of the system is the array subsystem. The array is designed to provide electronically scanned beam coverage within a conical volume normal to the antenna face. The array incorporates 4 forward looking guard antennas with any two connected and in operation at any one time. The basic building block for the antenna is the "subarray". This is an assembly of mechanical and electrical parts formed in a long slat which extends the total diameter of the antenna. Several subarray lengths will be used to form the circular shape of the antenna. The subarray consists of a single vacuum brazed cold-plate on which RF manifolds, logic/power manifolds, transmit and receive modules, and a radiator strip are mounted. All subarrays contain the same functional components. The only difference is in length, hence they will vary in the number of T/R modules and radiators they accommodate. The subarrays, when assembled with T/R modules, signal manifolds, and radiators, are mounted to an enclosure to form the bulk of the completed antenna. The beam steering controller computes phase and amplitude for the individual active array T/R modules based on beam shape and scan commands from the radar operational flight program (OFP).



Transmit module (Top): Actual Size (.3 oz)
Receive Module (Bottom): Actual Size (.225 oz)

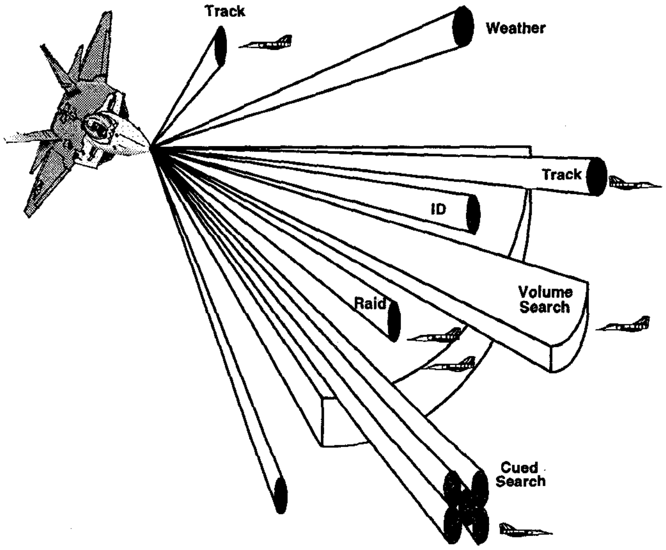
(Figure 6) T/R Module Pair

The transmit and receive modules form the core of the T/R function of the antenna. As shown in figure 6, the transmit and receive modules are packaged as separate items in the antenna. Combining of the individual modules to form the T/R function is performed in the circulator assembly which feeds the radiating element. The transmit module is a microwave power amplifier component which provides RF power amplification, phase control, DC transmit timing, data transfer, and voltage regulation. The receive module provides low noise amplification, phase shifting, and post amplification functions as well as receiver protection. The T/R module design utilizes multiple GaAs processes (MESFET, HFET, VPIN) to produce the six MMIC chips and five ASICs implemented on the combined T/Rmodule pair.

The receive chain is broken into four major blocks: the antenna which is comprised of the receive elements and manifolds, the channelizer which provides RF bandpass filtering, the Switch Downconverter which selects between arrays and performs the first frequency downconversion, and the IF Receiver which completes the down conversions to the baseband and does the analog-to-digital conversion of the data.

The computer software configuration is composed of four computer software configuration items. The software components are broken down into the Radar Processing and Management (160K SLOC; provides top level radar control of mode activity managers), Radar Support Electronics Control Program (6K SLOC; configures receiver and provides calibration), the Array Power Supply Control program (6K SLOC; monitors power and local control of APS), and the Beam Steering Controller Control Program (4K SLOC; performs beam pointing computations). The Radar Processing Manager (RPM) comprises the major controlling software component with three major functional components; Radar Manager, Activity Managers, and Measurement Functions. The Radar Manager provides an overall executive function performing state control, radar timeline management, and navigation utilities. The activity managers act as the link to the avionics mission software interface and control the overall execution of broad functional tasks like Air Volume Search, Air Track, Cued Operation, Missile Update, System Health, and air to ground actions. The measurement function component of RPM represents the lowest order functionality performing single radar measurements like HPRF search, all aspect search, and track. This software architecture has been designed to minimize the need for extensive regression testing through the design of an underlying software architecture which decouples the dependencies between new functionality added to the existing code. Specifically, the Radar Manager services contain no knowledge of which activity managers or measurement functions are present. Measurement functions perform a single measurement with no knowledge of which activity manager requested the measurement or for what purpose .

The software code within the RPM is written in Ada using the Ada Based Design Approach for Real Time Systems (ADARTS) which provides a detailed process to bridge functionally defined S/W requirements to an Ada based design and implementation. The radar operational flight program (OFP) is delivered to the Avionics Integration Lab in three scheduled blocks beginning with block one (initial track, search, BIT, CAL, LPI), block two (final search, track, gun track, & ECCM), and block three (ID, Raid Assessment, Missile update, Air Combat Maneuvering, & Weather Map).



(Figure 7) APG-77 Functional Modes

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Radar processing resources reside in the Common Integrated Processor (CIP) and consist of 10 signal processing elements (SPEs) and 4 data processing elements (DPEs). The F-22 contractor team has set a goal of 70% on CIP throughput and memory usage for EMD thus providing 30% spare for growth and design/development margin.

The APG-77 functional capability is illustrated in figure 7. The design implements multiple modes of operation including long range search (Range Search), long range cued search (Cued Search), all aspect medium range search (Velocity Range Search), track (Multiple Target Track), AMRAAM data link capability (Missile Update), target identification (ID), target cluster breakout (Raid Assessment), and weather detection (Weather).

Radar growth features include the incorporation of air-to-ground synthetic aperture mapping, air-to-ground ranging, enhanced identification capability, and expanded field of regard. The increased field of regard growth feature involves the incorporation of side "cheek" arrays. Growth provisions for space, power, and cooling have been included in the design allowing for minimal impact upon incorporation into the system.

Advancements

# Targets Limited	Large # of Targets
Long Range Detection	Improved Detection Range
Functional Timeline Limited	Improved Reliability
No RCS Design	Low RCS Design
	Increased Survivability
	Increased Functionality
	Functional Timeline Expanded

(Figure 8) F-15 vs. F-22 Performance

F-22 radar technology has targeted several key areas for increased survivability, lethality, reliability, and supportability. The active array design approach has brought enhancements over conventional fighter radar designs in the area of functional performance. Increased power aperture product provides longer range target detection, ID, and track performance supporting longer range missile engagement envelopes. Agile beam steering allows for significant improvements in multifunction interleaving and enhanced waveform design. Conventional track-while-scan implementations restrict the number of targets tracked, limit the amount of search space, and in general bound functional capability to a very tight timeline driven by the rigidity of mechanical antenna scanning. Agile beam steering has opened up a whole new set of options for the radar designer. Multidimensional waveform designs provide adaptability in search and track. This adaptability supports improved timeline efficiency which transfers directly into available search and track time. A fundamental design feature involves the decoupling of the search and track measurement functions. Radar search tasking is accomplished in conjunction with scheduled track and tactical measurement updates yet maintains it's own optimized waveform characteristics. Long range search waveforms utilize alert-confirm detection strategies minimizing dwell times while reducing the likelihood of false alarms. Improved beam agility also permits search through multiple volumes providing the pilot with situational awareness in several spatial sectors while maintaining tracks on priority targets throughout the radar field of regard. These advancements in functional performance are central to the F-22's increased lethality as shown by the F-15 comparison in figure 8.

In the area of survivability, the APG-77's antenna design supports the F-22's stealthy RCS thus reducing the enemy's ability to detect and track the F-22. Low probability of intercept (LPI) techniques have been incorporated into all aspects of the radar functional waveform design limiting the ability of the threat systems to identify and exploit F-22 emissions. Low RCS and LPI implementations give the pilot increased survivability supporting the "First Look" advantage.

The APG-77 is designed to provide lower support costs through high reliability in conjunction with two level maintenance (operational/depot). Predicted low failure rate estimates are based on design initiatives described in the system trades section and are highly leveraged on the inherent reliability of the active ESA design. The system is supported with an estimated design service life of 11,350 hours and an MTBM of 246 hours. This contrasts with existing Air Force fighter radar systems which provide an MTBM in the range of 20 to 50 hours.

Enhanced supportability features are consistent with Air Force Air Combat Command's (ACC) policy for new systems characterized by reduced manpower, scaled down mobility assets and reduced support equipment in the field. This field simplification supports short repair times which are required due to the overall increased flight line response tempo. Specific design features include; modular replacement packaging, easy access/ no alignment, Built In Test fault isolation to the LRM level with 98% confidence, quick disconnects for cooling lines, minimized calibration for torquing fasteners, electrostatic discharge compatible connectors, and graceful array degradation.[3]

System Trades

The design, development, and integration of a fire control radar into the nose of a high performance, low observable fighter airplane has been achieved through a disciplined systems engineering process. Traditional design boundaries in areas such as power, cooling, space and weight have been complicated by new challenges. As a result, the F-22 radar development program has generated an extremely large set of "top down" design trades extending in focus from the lowest component level trade to the highest system level trade.[4]

Power: The radar system incorporates localized power supplies resident within the RSE, RFR, BSC, and array. A particularly important power trade involved limiting the system effects of pulsating noise on the A/C power bus. The active array expends considerable power when radiating and can produce undesirable surge effects which are realized as periodic noise on the common avionics power bus. Trades involving multiple avionics power conditioning configurations were analyzed in terms of effectiveness, space, and weight effects. Radar utilization scenarios were used in conjunction with aircraft power system models to measure the effects of high duty radar operation. A distributed design was chosen which provided power conditioning at the radar surge source and at the point of regulation.

A high density power supply approach was considered for implementation at the array power supply level. Early technology demonstrations during EMD yielded very favorable results but the technology was not considered mature enough to make it into the baseline design. The design considered would replace the existing single array power supply with a smaller and lighter unit capable of providing identical power performance. Recent advances in

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switching speed performance and efficiency have made this a viable candidate for design weight/cost improvement initiatives prior to production.

Cooling: Cooling design trades focused on heat transfer efficiency, performance, and equipment life. Inlet coolant temperatures and heat transfer approaches were traded against weight, reliability, noise figure, and other performance features in order to arrive at the optimal cooling design for each radar assembly. The RSE and BSC's relatively low operating temperatures and heat dissipation characteristics allowed for liquid conduction cooling. System performance trades tied directly to the RFR's sensitivity to temperature required liquid flow through cooling which would support lower junction temperatures. Temperature gradient effects dictate effective thermal management at the array requiring liquid flow through cooling within the subarray assemblies. A single entrance and exit port is provided at the back side of the antenna with coolant distributed via an internal plenum to the subarrays.

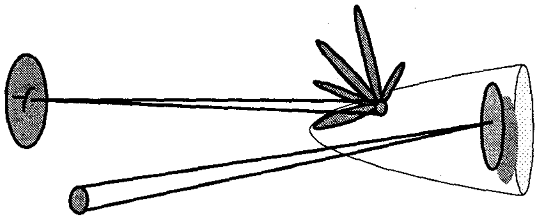
Volume Packaging: Volume and packaging trades were critical to conforming the radar hardware to the allocated space in the forward fuselage. Partitioning of vibration sensitive receiver components allowed for minimizing the use of space consuming isolation materials while meeting environmental requirements. Aircraft vibration requirements were refined in terms of realistic flight maneuver envelops and correlated to specific radar modes of operation; thus reducing the likelihood of over specification of induced vibration. Tight space allocations made for challenging access design trades. Predicted maintenance rates, supportability needs, and access conditions were used to define hardware orientation, connector design (quick disconnects), and handling clearance for each assembly. Examples include; integration of the highly reliable BSC into the array, relatively limited physical access conditions in the RFR, RSE, APS, and the array supported quick disconnect cooling connectors on all four LRUs, and predicted very low removal rates for the antenna allowed for a simplified, static radome installation without hinge attachments.

Array/Beam Steering Controller	**252**
Intallation Equipment	**35**
Array Power Supply	**89**
RF Receiver	**37**
Radar Support Electronics	**111**
TOTAL	**524 lbs**

(Fig. 9) Radar System Weight

Weight: Weight reduction efforts extended through system CDR and yielded favorable results. Early hardware prototyping (30% of EMD hardware) provided accurate weight estimates prior to system CDR and allowed for early design adjustments in challenging areas. Results of these efforts yielded nearly 50 lbs of reduced weight from early EMD estimates. Light weight materials for assembly level enclosures were rejected in favor of more ridged materials (aluminum) providing lower risk to vibration and load effects. High density power supply technology options for the APS were rejected in EMD due to the relatively low maturity level of this technology. This high density power supply technology is being studied through EMD and will be considered for the production configuration. Potential weight savings are estimated in the 50 lb. range. Current weight performance is given in Figure 9 with the total system weight reporting under the allocated 530 lb. requirement.

Radar Cross Section: Low radar cross section design trades were central to the final configuration of the antenna and radome installation.



(Figure 10) Integrated Forebody Concept

The highly integrated nature of this combined assembly is termed the "Integrated Forebody". Multiple design options were explored during the Dem/Val phase of the program with the YF-22 band pass concept (Lockheed, Boeing, General Dynamics) being the chosen design strategy at program source selection. Figure 10 illustrates the frequency filtering characteristics of the IFB which allow for transmissions but limit exposure of the radar antenna and forward cavity to outside radiators. Low RCS factors have had strong implications throughout the radar design having influenced many areas including radome complexity, array installation, and antenna design.

Waveform Design: Increased processing resources and active array technology have added waveform adaptability design options that are not available to conventional systems. Avionics level control of radar measurement tasking provides a software interface which lends itself to radar "submodes of operation" offering the pilot more flexibility in the cockpit. Trades were conducted in the area of search and track mode design to explore the implications of timeline management, target measurement maintenance, and low probability of intercept in building these submodes.

The new concepts of integrated avionics tracking have complicated the options for radar tasking rates and priorities. Classical federated radar designs have utilized an autonomous radar tracker for examining historical conditions and managing target measurement update rates. While the radar still maintains it's own internal tracker function, the F-22 avionics architecture provides for extensive interface between the radar and the avionics sensor management function (ASM) with clear radar control to ASM. This high degree of interface control has resulted in an increase in complexity between the display and the sensor requiring much cooperation and coordination across avionics team members.[6]

Antenna: A large number of important hardware trades were conducted including several which have shaped the APG-77 antenna. Among the most significant were the multiple active/passive ESA configurations which were studied during the Dem/Val phase of the F-22 program. These trades looked at weight, power, cooling, volume, and cost performance. The active configuration was chosen on several figures of merit including weight and volume. The mechanically scanned antenna configuration was rejected because of it's inherently limited radar cross section characteristics. The relatively low beam steering agility of the mechanically scanned approach was also determined to be inadequate to support multi-target search and track requirements. The electronically scanning antenna configuration options were grouped into the active and passive categories. Both types of concepts were evaluated and aircraft constraints such as volume, weight, & prime power were defined for each within the context of the fixed long range detection requirements. At the higher detection ranges required in the F-22, the active electronically scanning array (ESA) configuration required

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significantly less volume, weight and prime power. The passive ESA configuration exceeded air vehicle volume and prime power allocations and nearly doubled the weight achievable in the active ESA design. Cost estimates for both were comparable but the active ESA involved higher risk in producibility while in general achieved the target detection range performance within the F-22 platform constraints. Additional benefits in the active ESA were identified in the area of wider transmit bandwidth and in the "graceful" degradation to performance offered with failed individual modules versus the traveling wave tube single failure possibility in the passive design.

The 6 bit phase shift T/R module design represents a complex trade in itself. Performance parameters such as transmit power, efficiency, and gain were traded against each other in order to arrive at an affordable yield and ultimate module cost which supports the system performance requirements. Several iterations to the monolithic microwave integrated circuits (MMIC) GaAs chips were required in order to reach this balance. Packaging trades evolved the design into a T/R pair mounted in separate transmit and receive aluminum housings.

Receiver: The receiver trades extend across the entire system architecture. In the hardware area, an important trade study was conducted to explore the use of Low Temperature Co-fired Ceramic (LTCC) as the IF receiver substrate. Although the use of LTCC offered a significant thermal advantage and a small weight advantage, the material was costly and experience in fabricating substrates as large as the IF receiver was very limited. The selection of LTCC at the end of this trade study initiated an aggressive material and process development effort. After several "learning failures" on prototype substrates, the appropriate processes and manufacturing/handling techniques were developed to consistently fabricate these substrates. In general, LTCC has been implemented in the exciter, sample data converter, channelizer, and array circulator substrates/feedthrough areas where the benefits to packaging and performance offset the cost factors.

The receiver interference effects associated with active array radars required trades to the channelizer (RF preselector) design necessitating a great deal of external environmental emission analysis. Derived third order intercept (TOI) values were determined at the system level. Trades were conducted to determine the sensitivity of the radar system TOI to variations in T/R module gain, T/R module noise figure, and array prime power in order to establish a point of balance in the system design which supported the derived TOI requirement. This effort concentrated primarily on the receive module (R-module) in the array because of it's overwhelming contribution to both system noise figure and TOI.

Receiver stability characteristics were driven to challenging levels by requirements to detect small targets in high background clutter. Associated spectral purity levels were allocated down to the lowest level and isolation trades performed to minimize environmental effects and conform to installation constraints. Extensive vibration isolation was implemented at the exciter and close attention given to controlling discretes in the frequency synthesizer. A ridged antenna and associated mounting hardware were designed to prevent phase errors caused by vibration in the subarray structure. Measures were taken to minimize effects of vibration on the 18 inch cable extending from the array to the RFR. The A/D dynamic range as well as the spectral purity allocations throughout the radar were based on performance trades associated with detecting a small target at characterized conditions. The selection of these conditions involved extensive trades in clutter characterization in various tactical engagement profiles. These specified characteristics have had pervasive effects throughout the entire radar system. It is this specification which has driven the spurious free operation point and associated target visibility performance.

Reliability: Radar reliability and life cycle cost considerations have been influenced through the Avionics Integrity Program (AVIP/MIL-A-87244).[5] The AVIP process is an organized and disciplined approach to the design, development, qualification, production, and life management of the final product. The AVIP process emphasized safety, performance capability, reliability, maintainability, supportability, producibility and reduced cost of ownership. The integrity process can be divided into three general areas. The first area, the defining of initial requirements, conducted performance/integrity trades establishing relationships between functional performance (detection range, probability of ID, search time, etc...) and integrity parameters (environments, manufacturing variability, etc.,). The development of the Environmental Criteria Document (ECD) was instrumental in formalizing the results of these trades and defining the natural and induced environments for the radar within the air vehicle. Second, the integrity process addressed failure control and elimination for the F-22 environments. Tasks such as material characterization testing, development testing, design analyses, variability reduction, and statistical process control are utilized to meet the hardware performance requirements set forth in the first phase. Vibration and thermal analyses were performed to support the strength and fatigue analyses. Development tests were used to validate analyses and provide information on new analytical techniques for several areas such as leadless chip carriers, T/R modules, and module crossover interconnections. Fatigue analyses and durability life tests are planned in EMD to support the verification of life requirements for the radar. Finally, production and support are addressed with respect to cost effective life management. The products of all three phases of the AVIP process will be used to minimize inspection, rework and maintenance on the radar. The integrity process provides a methodical application of sound engineering principles designed to incorporate the essential balance of performance, cost and support requirements.

Maintainability: The radar system design was focused at eliminating periodic inspection, ease of access and servicing, and minimizing the need for test equipment and personnel in the field. In addition to compatibility with fielded support equipment, the system was designed for use with the fewest possible hand tools selected from the Standard Tools for Aircraft Maintenance (STAM) list. Self calibration was strongly emphasized with a desire to eliminate all calibrated torquing and associated hand tools. Radar module installation has evolved to ultimately require calibrated torquing due to the incompatibility between the module injector/ejector design and the substantial mounting force requirements of the radar LRMs. Antenna removal can be an involved procedure in adverse weather conditions due to the delicate RCS interface between the radome and the aircraft. Low maintenance access requirements and strict procedures (guide pins, removal friendly antenna/radome interface components, cold weather contact gloves, and positive locking fasteners) have mitigated the support community's concerns regarding radome removal and antenna extraction/installation.

In general, access to all radar LRMs require the removal of a maximum of two aircraft panels. Following fault isolation using BIT, modules are readily inspected or removed through the release of wedge-lock clamping devices.

Antenna T/R module failure modes were analyzed and traded against multiple failure detection design options. Failure mode categories were refined and a life cycle cost study performed to

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determine the optimal fault detection design. Performance trades were conducted to determine the antenna removal threshold for each failure mode. These thresholds were used as the determining failure point within the BIT design in which the pilot receives a failure flag thus requiring the antenna to be removed and repaired. These trades were critical to realizing the potential lower life cycle costs associated with the advertised benefits of ESA graceful degradation.

Backplane removal and repair alternatives were explored and life cycle cost assessments performed resulting in a final design configuration which supports limited organizational level and primary depot level maintenance for the RSE, RFR, and APS backplane/wired chassis assemblies. This trade received a great deal of attention early in the EMD program due to the radar's deviation from the F-22 Avionics standard rack/backplane configuration and associated maintenance concept (due to space limitations). Here, the radar LRUs must be removed from the aircraft to perform any backplane maintenance. Removal of these backplanes is considered to occur very infrequently as evidenced by the predicted Mean-Time Between-Critical Failure (MTBCF) of the respective backplane units (RSE: 44,843 hrs, RFR: 476,190 hrs, APS: 42,194 hrs).

	Special Support Equipment	*MTBM Operational Flight Hours*	*Line Replaceable Backplane*	*Line Replaceable Modules*	*# A/C Panels Required to Be Removed*	*Mean Time To Repair*
ARRAY/ BSC	Sling/ Guide Pins	1432	N	Y	5	5.08
APS	None	1354	Y	Y	2	3.35
RSE	None	583	Y	Y	2	3.32
RFR	None	4139	Y	Y	2	3.60

(Figure 11) Maintenance Summary

The potential for maintenance induced failures was reduced through the examination of all end-to-end maintenance procedures. Using this approach on the array, several improvements were made. Test points on circuit cards were switched from male pins to female sockets, due to the fact that pins are far more likely to be damaged than sockets (and have greater potential for introducing ESD damage). Since test harnesses are much cheaper and easier to repair than circuit cards, this design change made sense. Access covers (which also provide electromagnetic interference (EMI) protection) were redesigned so that they can be installed in any direction. Connectors were repositioned to allow a better hand approach angle for installing harnesses (thus preventing pin damage). Changes were also made in the design to reduce the number of steps required to remove and install components, resulting in a twofold benefit; fewer steps usually means fewer opportunities to induce a failure, and a overall reduction in maintenance action time.

Failure Modes and Effects Criticality Analysis (FMECA) provided a methodical process to address many of these concerns and to provide source data for Logistical Support Analysis.

Early EMD maintenance assessments were accomplished using a scaled mock up model and the extensive use of the human factors three dimensional drawings available on the computer aided design system. Close attention was given to the effectiveness of the maintainer when fitted with Chem-Bio protection gear. A summary of maintenance characteristics is provided in figure11.

Radome: The integration of the radar into the F-22 radome represents one of the dominant design trades of the F-22 Radar EMD program. Enhanced aerodynamic performance and low observability requirements levied by the future user (ACC) resulted in several challenges in the radar design. The improvements in aerodynamic stability and drag dictated a sharp A/C nose design reflecting a chined radome characterized by high fineness. These ridged constraints resulted in a small nose cavity restricting antenna aperture area, volume and complicating radar operation through the radome. Radar aperture area and volume allocations were analyzed in conjunction with power aperture product trades in the antenna. From these trades came the critical T/R module performance requirements which have been flowed down. The complex shape of the radome introduced high reflection characteristics into the electrical performance of the radome which had to be considered in the radar all aspect search performance in clutter. This drove considerable radome characterization efforts in early EMD. Testing of a prototype radome using an EMD test array validated extensive sidelobe modeling data central to the EMD design. The success of these tests were critical in supporting the radar search performance in clutter (false alarms and detection performance).

Development Processes

Several of the unique development processes are being implemented in the F-22 EMD program. The concept of integrated product development became a center piece of the teaming arrangement early in the program. The radar requirements and design were constructed and managed from all aspects including performance, cost, maintainability, supportability, and producibility. A joint government/contractor team assembled engineering, manufacturing, and cost experts together with Air Force representatives from ACC to ensure that needs of ACC's pilot and support community. Design details were traded within this balanced integrated perspective.

Radar hardware and software prototype builds were conducted prior to the system CDR. Eighty percent of the total radar hardware functionality was built and tested prior to launching into the EMD build thus providing valuable early insight into validated performance estimates, manufacturing processes, durability testing, multilevel integration, weight verification, environmental testing, and RCS refinement. Software bench marking reduced timing and sizing risk by assessing software execution in real processors as early as possible. This was achieved by developing OFP timing models and allocating execution times to processing algorithms, the development of code prototype radar algorithms in Ada, and the compiling of Ada source code using early versions of the Ada compiler. These efforts provided a great deal of confidence early on that the radar software would fit within the allocated memory and processing resources.

Specific driving threat details were identified in the DEM/VAL phase of the program and a firm threat baseline established at contract award. Evolving threat data is managed through a formal team review process where new requirements are considered on a case by case basis. All disconnects between the baseline design and new threat requirements are presented periodically to program management and ACC. This process has been key to keeping the radar design current and relevant to the projected threat at ACC's initial operational capability date.

Communication and coordination networks were critical to supporting the highly integrated radar design process. A computer design network (Software Engineering Environment) was implemented across all team sites facilitating real time access by all members to aircraft level drawings, specifications, and technical publications. All design work performed including all hardware and software interfaces are performed on this common system. An interface design tool (IDT) was implemented early to consolidate and control all interface requirements across all of avionics. Various notes conferences were established on the SEE where

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members of the team at all levels could exchange critical design data within their respective IPT.

The F-22 contract provided several unique program management attributes which proved to be effective. In order to ensure an event driven program and to avoid schedule driven program progression, a development milestone event map was constructed at program initialization and an integrated master plan developed to track critical milestones to each major phase of the program (RDRU, PDR, CDR, First Delivery, First Flight, etc...). This management tool proved to be very useful in pointing the team to many relevant issues when the pace and flurry of activity reached it's peak during major design reviews. Team incentives were implemented and directed toward successful completion of both software and hardware milestones. Target incentives which addressed weight performance were quickly achieved in early EMD and replaced with very aggressive challenges allocated from other areas on the aircraft which were not meeting weight. The cost plus award fee contract has also proven to be an effective tool in highlighting significant positive or negative trends.

Test, verification, and integration are highly leveraged on models and simulations. Although planned levels of flight test are consistent with those conducted in the past, the highly integrated nature of the system necessitates the use of several system models. MIST (Mode Interleaved Search & Track) has been developed by the BMA/ESSD team to exercise the radar functionality in a target rich environment. Each mode and function within the radar has been modeled to closely resemble the actual OFP code (the actual OFP code is used quite frequently). Threat target scenario scripts can be generated at the avionics level and specific radar tasking inputted into MIST. This provides an extremely valuable tool with which the radar system design can be exercised to verify functionality and timing. Flight test profiles can be run several times in MIST before they are exercised in flight to study anticipated results and optimize flight plans. This modeling tool is anticipated to provide a great deal of integration risk reduction as well as improve flight test efficiency. MIST provides the system analysis tool which the individual detail mode models developed by ESSD can not.

Technology Development Investments

Technology transfer programs have proven invaluable to the F-22's technology base. The experience and technical equity of these programs are responsible for the relatively low risk and successful incorporation of advanced hardware into the F-22 Radar. The revolutionary step toward active ESA implementation involved many joint government/contractor programs including a series of Wright Laboratory initiatives; Advanced Solid State Radar Module (Hughes; 2 watt hybrid module that demonstrated feasibility of direct power amplification at X-band), Solid State Phased Array (TI; First 2000 element active array with direct X-band amplification), Ultra Reliable Radar (WEC; Program took solid state SSPA phased array and developed radar around it), X-Band Satellite Aperture Development Program (TI; First work on successful X-Band monolithic power amplifier that lead to Monolithic Radar Module), Monolithic Radar Module (TI; First solid state module with MMIC chips instead of hybrid components), Monolithic Phase Shifter Development (TI; Development of GaAs monolithic phase shifters that established foundation for array use of monolithic phase shifters), Evaluation of GaAs Substrate Materials (TI; Comparison of GaAs material for optimizing low noise device performance for X-Band LNAs), High Efficiency Microwave Amplifier Program (Raytheon; Findings made available to industry/TI via conferences and reports), WideBand Multifunction Module Program (WEC; Addressed efficiency issues & radiating element designs for increasing the bandwidth of active phased arrays), and Active Side Array Demonstration (WEC). This technology base provided the avionics industry (including ESSD) with the experience required to implement an affordable and producible ESA. Central to the packaging, cost, and performance of the radar, the T/R module programs managed by the Manufacturing and Technology office (MANTECH) at Wright Patterson AFB contributed to critical producibility risk reduction activities by providing initial factory builds of 650 MANTECH modules and early identification of potential producibility issues. The Microwave Monolithic Integrated Circuits (MMIC) program addressed MMIC yield issues and helped to establish the GaAS material processes used in F-22 MMIC production.[7]

The radome represents a significant portion of the radar system solution. Lockheed Martin Skunk Works (LMSW) Independent Research & Development (IR&D) program efforts in variability reduction and fabrication process refinement have resulted in significantly reduced program risk in achieving an affordable F-22 design which reached very challenging levels in sidelobe control and low RCS. Models and design iteration tools developed by both ESSG and LADC were merged to support radar/radome/aerodynamic trades in early EMD. This iterative analytical ability to examine the electromagnetic impacts to radome outer mold line and wall design changes represents a major advancement in integrated weapon system design. This tool allowed for scientific mitigation and negotiation with the aerodynamic designers early in the program when high fineness characteristics in the radome were being strongly emphasized. Radome production cost risks are currently being addressed through a MANTECH program where alternative manufacturing processes will be considered for EMD and production F-22 radomes. The transition risk to a new radome build process has been significantly reduced by the analysis tools outlined above.[8]

The trend for future avionics systems is toward more capability in less space. Receiver functionality will continue to progress toward the aperture level with the first down convert at the array being the next likely step. Extremely stable crystal technology will be needed to support small target detection requirements anticipated in the future. Low volume, efficient power supplies will be in demand to support high fidelity power requirements in advanced low noise avionics systems. High density distributed power supply approaches are likely applications at the array level with each array subunit powered by it's own power supply. "Tile" architecture based antenna designs will move the ESA technology away from the "brick" approach used in the F-22 design toward innovative ESA approaches which will be needed to support "thinner", more conformal arrays. Smarter array designs will be required to support "self healing" features which extend the maintenance free life of the active array. Aperture and radome integration will require continued attention in order to bring the arrays closer to the inner mold line of the aircraft. Conformal multifaceted aperture technology will continue to advance in order to meet increased field of regard requirements brought on by integrated EW/radar systems. Combined system approaches will bring electronic warfare and radar systems under one system hardware configuration pushing bandwidth limits in microwave components and apertures.

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Conclusions

The F-22 Avionics system design embraces an integrated approach which has strongly influenced the APG-77 Radar design. The program has completed the second unit build and has successfully entered the software/hardware integration phase. Performance enhancements over fielded systems should meet and exceed Air Combat Command's projected war fighting requirements. The F-22 EMD Radar design team conducted a disciplined top-down systems engineering process where many trades were performed to arrive at the total weapon system solution. In order to implement the final design, the F-22 Team has leveraged heavily on advanced technology development with acceptable risk for production. The positive results of strategic technological investment should be noted by all who embark on such advanced development programs. The complex and integrated nature of the APG-77 will continue to challenge the LMASC/BMA/ESSD/TI team as they move to the final build and more advanced integration stages of the program.

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John Malas currently serves as Lead Engineer for the F-22 Radar EMD Program located within the Air Force Aeronautical Systems Center's F-22 System Program Office. From 1983 until the present, Mr. Malas has worked primarily in the radar / fire control area supporting the development of several platforms including the B-52, B-1B, and F-15 aircraft. Mr. Malas is a graduate of Wright State University where he received his Bachelor's Degree and Master's degree in Systems Engineering in 1983 and 1990 respectively. He is also a registered Professional Engineer in the state of Ohio and a reserve officer in the United States Navy.

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