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MPAR PROGRAM OVERVIEW AND STATUS

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1. INTRODUCTION

The Multifunction Phased Array Radar (MPAR) Program is a congressionally mandated research task to continue the research and testing of phased array radar technology to improve airport/aircraft tracking and weather information for civilian use. Originally a tri-agency program involving the Department of Transportation's (DOT) Federal Aviation Administration (FAA), the Department of Commerce's (DOC) National Oceanic and Atmospheric Administration (NOAA), and the Department of Defense's (DOD), Office of Naval Research (ONR), the program has since expanded to include academia and industry.

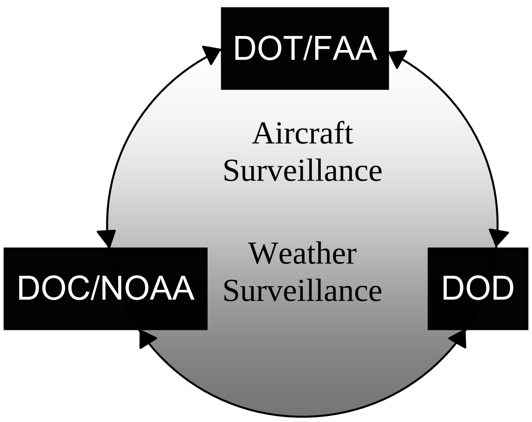

Figure 1: *Tri-Agency Research Partnership*

This unique research partnership was initiated in 2000 with a mission of evaluating new technology for phased array radar and developing the next generation multi-function surveillance radar network as well as to support the Joint Program Development Office (JPDO) 2025 vision for the Next Generation Air Traffic Management System (NGATS). The primary objective of the MPAR Program is to develop an affordable multifunction radar solution that will improve:

- Weather assessment for aviation safety
- Severe weather forecasting with higher fidelity
- Aircraft detection and tracking (non-cooperative and cooperative)
- Airport efficiency and capacity
- Natural disaster planning
- Homeland security assessment

Radar technology design, manufacture and application for the aviation industry continues to mature at a rapid pace and the FAA's William J. Hughes Technical Center (WJHTC), in partnership with the aforementioned Government agencies, is taking on an increasing role in the research and pursuit of the high technology advances available to meet the anticipated increase in air traffic and weather in the decades to come.

2. RADAR FUNDAMENTALS

Radar (RAdio Direction And Ranging) is the enabling sensor for determining the existence of an object in a defined volume of space. That space could be as confined as the entrance to a super market (facilitating automatic door operation), as vast as outer space (detecting ballistic missiles), or any volume in between; such as the National Airspace (aircraft surveillance). Radar has a vast number of varying and complex applications within, aviation, weather, defense, medical and other industries.

In simplistic terms, a radar functions by transmitting a pulse of RF (radio frequency) energy focused into a beam to illuminate objects in space. A very small portion of this energy is echoed back to the radar where it is detected by an integrated receiver. Because of the low-power level of the echoed signal, it is very sensitive to interference and must be amplified before processing. The reduction of the signal power between transmission and receipt is defined in terms of a ratio between the two and is expressed logarithmically in decibels (db), a key measurement of radar performance. The generic architecture of fundamental radar includes an antenna; transmitter, receiver and signal processor (see Figure 2). A workstation is then used to display the processed

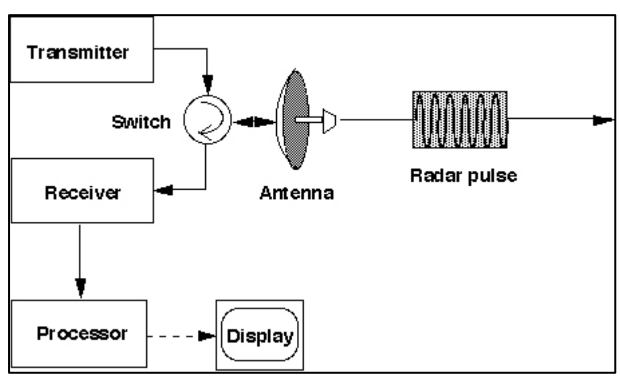

Figure 2: *Basic Fundamental Radar Architecture*

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returns for the operator and to control the operation of the radar. Additionally, real-time computer control of the radar has become an integral part of modern radar systems.

The "radar equation" is the key to making radar design decisions and trade-offs. Radar engineers model performance using the equation's parameters to determine a satisfactory solution in meeting defined user requirements. The basic radar equation, solving for maximum detection range (R), is as follows:

$$R_{\max.}^4 = \frac{P_t \, G \, A_e \, \sigma}{(4\pi)^2 S_{\min.}}$$

Where P_t = transmit power, G = antenna gain, A_e = effective aperture area, σ = target cross section, and S_{min} = receiver minimum detectable signal.

Radar performance and trade-offs with regard to the equation are discussed in the Radar Handbook, (Skolnik, M.I., 1990).

3. WEATHER RADAR HISTORY

The history of radar began with the British, who over 60 years ago during WW II first used radar to detect German aircraft on bombing missions over England. Radar technology progressed at a rapid pace in the years subsequent to WW II giving rise to new applications such as weather and air traffic control. Shortly after the war, enterprising engineers found a use for the war-surplus radar in weather detection. Anomalous "clutter" returns typically seen on radar displays were in fact weather phenomena in the atmosphere. Hence, TV station weather forecasting became the first commercial application of radar.

NEXRAD evolved from a very rich history of the National Severe Storms Laboratory (NSSL) where weather research has been carried on for over 40 years. Established in 1964, the NOAA NSSL leads the way in investigating all aspects of severe and hazardous weather. NSSL is part of NOAA Research and is the only federally supported laboratory focused on severe weather. "Part of NSSL's initial role was to maximize the use of the original WSR-57 surveillance radars for the U.S. Weather Bureau (now the NOAA National Weather Service)" (Cobb, S., NSSL). WSR-74C and WSR-74 S C band and S band radars respectively were added as gap-filler radars during the late 1970s.

In the late 1980's, a joint program office consisting of three federal agencies – National Weather Service (NWS), U.S. Air Force (USAF) and the FAA was formed and named the Joint System Program Office (JSPO). The purpose of this joint effort was to develop a Doppler weather radar, the Weather Service Radar-Model 88 Doppler (WSR-88D), commonly known as NEXRAD. This S-band radar was fielded at approximately 170 sites as the primary weather radar across the nation including, Alaska, Hawaii, the Caribbean, and select Department of Defense (DOD) sites overseas.

For a more thorough history of the evolution of weather radar and Doppler weather radar see History of Operational Use of Weather Radar by U.S. Weather Services. Part II: Development of Operational Doppler Weather Radars (Whiton and Smith, 1998).

In the early 1990's, the FAA recognized the urgency of managing air traffic flow in hazardous weather conditions and the Terminal Doppler Weather Radar (TDWR) was conceived and ultimately deployed at forty-five (45) major airports. Given that the Airport Surveillance Radars (ASR-7, 8, and 9) operate at S-band, it was decided to build the TDWR at C-band to avoid interference. Success of the TDWR prompted a solution for smaller airports that was less costly. This led to the development of the Weather System Processor (WSP). The WSP was built by modifying the ASR-9 receiving chain with stand-alone data acquisition and signal processing capability to process weather information. The WSP is currently installed at 35 medium sized airports.

The Integrated Terminal Weather System (ITWS) integrates products from TDWR, NEXRAD, ASR-9 and other sensors to provide a planning tool for the terminal and en-route environment in the National Airspace System. ITWS displays replace the TDWR displays.

Presently the latest generation of weather systems is the Corridor Integrated Weather System (CIWS). CIWS builds on all the preceding technologies and provides air traffic management personnel an extremely valuable tool to enhance the flow of air traffic.

4. MILITARY WEATHER RADAR

In the early 1960's, the Department of Defense with larger research budgets, made significant advancements in radar technology and focused on phased array radar technology for surveillance and tracking. Multi-functional capability was a driving force. In 1983, the first phased array radar, AN/SPY-1 operating at S-band, became operational on the Ticonderoga Class of U.S. Navy Aegis cruisers, and quickly became a standard for air surveillance performance in the defense community throughout the world.

A phased array antenna uses a flat planar arrangement of rows and columns of equally spaced radiating elements. Each radiator offers a similar output to its adjoining radiators and is designed to avoid any two radiators coupling their outputs. The width of the main beam produced by such a system depends on both the spacing of the individual radiators within the array and an inverse relationship between beamwidth and the number of radiators used. This means that the greater the number of radiators used, the narrower the beamwidth produced. In a passive array, agile beam steering is handled through the use of an item called a phase shifter. By altering the phase shifter settings in a particular pattern across a sub-array or array, it allows the beam to be “steered” in the desired direction without mechanical movement of the antenna. This is the primary discriminator between the mechanical scanned reflector of rotating radar and a planar phased array radar. This capability can provide three dimensional (3-D) coverage with the ability to deduce target range, bearing, and elevation; thereby doing away with the need for a height finding radar with traditional two dimensional (2-D) radar. Another feature of this radar’s electronic beam-steering capability is to perform surveillance and multiple target tracking functions in time sequence, searching/tracking diverse volumes of space anywhere in the hemisphere of coverage. This multi-functional capability is performed in a fraction of the time required by a mechanical scanning radar.

In 1996, the Navy began looking at the clutter returns affecting the AN/SPY-1 performance. A major contributor to clutter was the weather, which needed to be filtered out to perform accurate target tracking. Knowing that the SPY-1A could gather high fidelity weather data then prompted interest for its use for weather processing. Consequently a comparison between the AN/SPY-1 and NEXRAD weather detection performance followed. Initial results were very encouraging and as a follow-up the Navy placed the Tactical Environmental Processor (TEP) (an adjunct weather processor) on the USS O’Kane and commenced at-sea demonstration of the AN/SPY-1 weather capabilities. (See Figure 3 for the comparison of AN/SPY-1 vs. NEXRAD where SPY-1 produced higher fidelity measurements at a higher update rate.) The Department of the Navy’s Office of Naval Research (ONR) also funded a research and development program called Dual Use and Science Technology (DUST) around the year 2000 to investigate the affordability of new module technology for fabricating lower cost phased array systems.

5. MPAR BENEFITS

The advantages and benefits of a multifunction phased array radar are significant. A multifunction radar can support weather, air traffic control, homeland defense and DOD surveillance needs simultaneously. The Multi-functionality is of interest to the FAA as a compliment to Automatic Dependant Surveillance – Broadcast (ADS-B) as well as a possible cost reduction solution for its aging fleet of ground based radars. Figure 4 depicts this operational concept of simultaneous beams performing multiple missions.

Initial studies have suggested that the consolidation of multiple single-mission radars (ASR-9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, TDWR, and ASR-9/11 Weather Channel) can reduce the national radar fleet by 35-40% saving billions of dollars in both production and maintenance costs over the life cycle of the system. Additionally, a scalable approach to the architecture/design can be used to support future agency missions. The higher data rates possible for weather and target data as well as full volume 3D coverage will support FAA Flight Plan goals of reduced separation, reduced delays and increased safety. Currently, NEXRAD weather data update rates while in precipitation mode are on the order of 4-5 minutes. With an MPAR, full volume scans for weather could be completed in 1-2 minutes and through the implementation of resourceful scan strategies and adaptive beam steering, areas of interest can be continuously scanned on demand in well under a minute. With faster and higher fidelity weather data, aircraft can be more efficiently routed around weather systems. In the surveillance and homeland security domains 20 to 30 second scan times in the en-route arena and sub-second scans in the terminal arena could be accomplished.

In the weather area, MPAR will facilitate the use of improved scan strategies allowing increased dwell times that will enable advanced radar processing techniques needed for enhanced weather surveillance. This will bring about increased lead times for tornados, floods and severe weather and improve long range forecasting (e.g., turbulence, icing). Also, split aperture correlation could be used to estimate crossbeam wind components necessary for stormscale forecast model initiation.

From a maintenance perspective, electronically scanned antennas reduce maintenance cost over mechanically steered antennas by the absence of moving parts which is a major operational expense in the current rotating radars. Multiple transmit/receive components eliminate the single point of failure inherent in single transmitter radar systems and provide for graceful degradation and increased mean-time-between-failure (MTBF). An MPAR would be capable of functioning with little impact even if as many as 20% of the T/R modules were to fail. Coupled with the advances being made with semiconductor materials used in integrated circuits the system will provide better power efficiency and thermal management allowing the system to be air cooled verses water cooled reducing weight and cost.

The MPAR program is focused on the use of active array modules due to the rapidly decreasing cost predictions for T/R module technology. A significant amount of investigation pertaining to the cost reduction of T/R modules has already been accomplished by the program and shows a downward trend (see Figure 5).

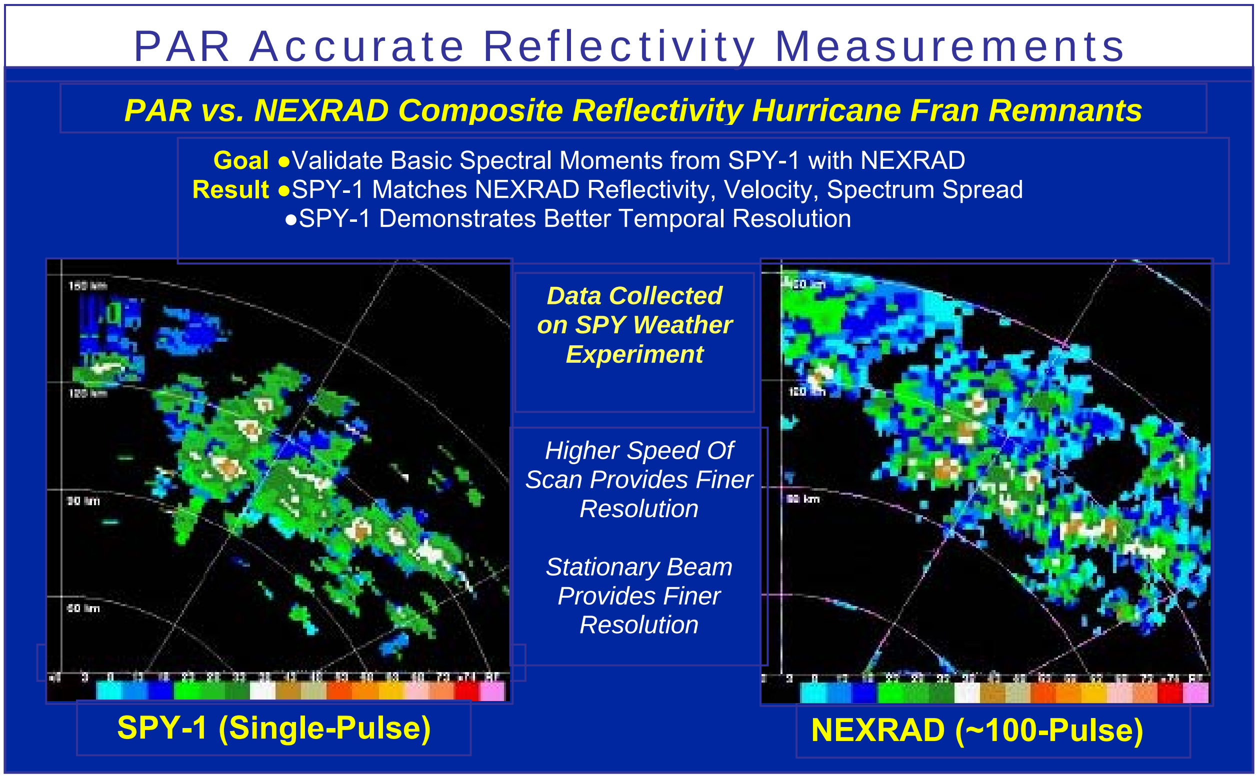

Figure 3: *Comparison of AN/SPY-1 and NEXRAD Displays* (*Graphic Courtesy: Lockheed Martin)*

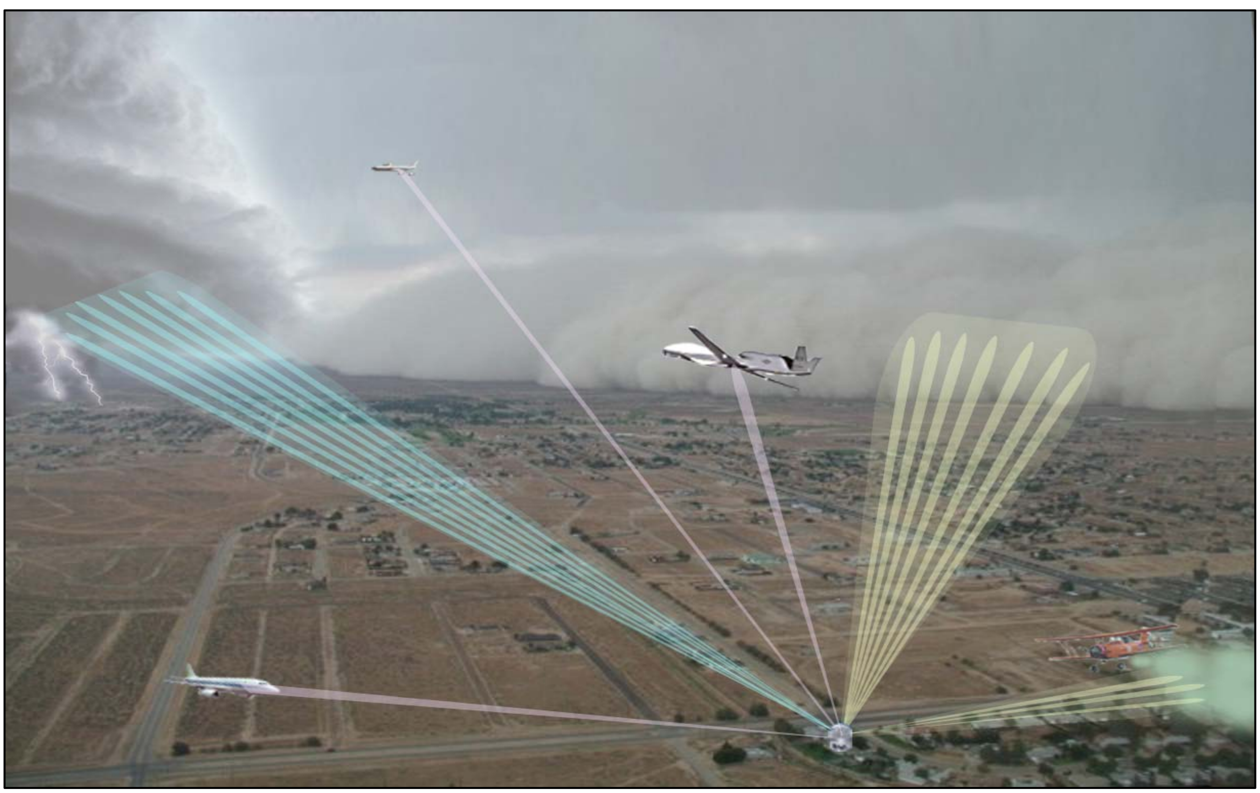

Figure 4*:* *MPAR Operational Concept*

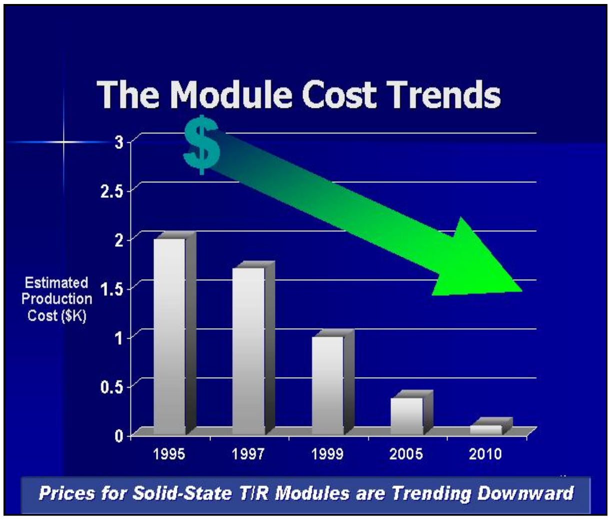

Figure 5: *T/R Module Cost Trends*

The highly directive pencil beams and scanning agility available with this concept should support the demanding operational requirements of the future. Affordability of these designs depends upon the aforementioned T/R module cost and prudent design of the array aperture along with sophisticated algorithms to optimize the use of the radar resources in real time. There are currently several research gains in this area where T/R module cost can be significantly reduced while still supporting the power requirements. It is this advancement in materials and manufacturing coupled with the economics of production for state of the art electronic technologies that will substantially reduce the cost of MPAR. Leveraging breakthroughs from the wireless and cell phone industry will continue to propel this trend. Continued research of low-cost module approaches, sub array beam formers and multi-channel receivers will validate the ability of the MPAR program to meet the performance goals as a multifunction radar solution for both weather and surveillance functions.

6. MPAR PROGRAM STATUS

As previously stated, the impetus for this research effort was the Navy's recognition that SPY technology could detect weather. This recognition, along with the tornado that decimated parts of Oklahoma on May 3rd, 1999 caused Congress to support ONR to contract to build the National Weather Radar Test Bed (NWRT) in 2000. This radar system is housed in a new facility located at NSSL in Norman, OK (Figure 6, NWRT Site). The Navy loaned the project an AN/SPY-1 radar antenna that was coupled with a NEXRAD radar transmitter supplied by the NSSL to build the NWRT. The FAA provided funds to the NSSL to enhance capabilities in support of surveillance functions and research studies in weather phenomena that pertain to aviation. The NRWT is also investigating the ability of the system to significantly increase tornado warning times and other weather phenomena.

Research scientists are currently using the NWRT for advanced weather research. Radar data that characterizes the atmospheric environment is processed much the same as the NEXRAD National Weather Radar System, but at higher update rates and can be focused on a specific area of interest until all the required data is collected for research purposes. Reflectivity, velocity, and spectral width of matter in space is analyzed and updated at a one-minute update rate (see Figure 7 for a comparison between NWRT PAR and NEXRAD reflectivity and velocity). (Forsyth 2005)

As one of the tasks under MPAR, the FAA/WJHTC was tasked to develop the Track Processor (TP) to complement the weather processing capability of the NWRT at NSSL. This Track Processor system is designed as an independent corollary to NWRT though the data can be overlaid with weather data for display. It is designed to receive the same raw radar data that is processed by the weather detection processing algorithms and to locate targets within that data. Air surveillance target detection and track processing algorithms are resident in a separate/parallel signal processor computer suite for operator display at NSSL or remotely at the WJHTC. The initial testing of this system was performed in September 2005 at the NWRT in Norman, OK and illustrated that the digital signal processor used for the Track Processor was successful using a track-while-scan approach. Tracks were correlated against the tracks reported by a local ASR-9 radar from Oklahoma City, Will Rogers Airport. The

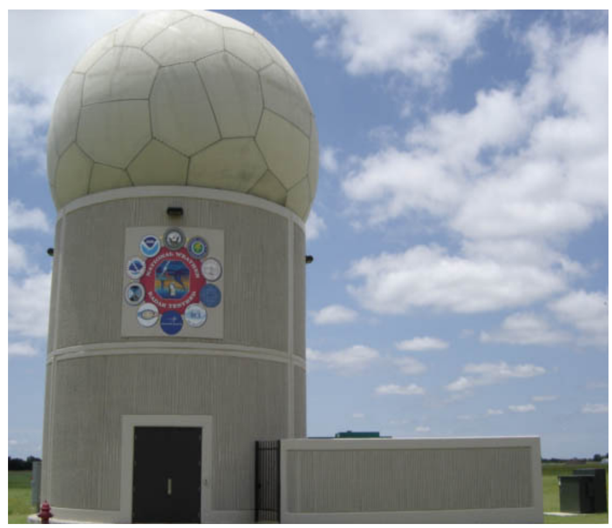

Figure 6: *NWRT Site (Graphic Courtesy: NSSL)*

results showed that data from the Track Processor data could be accurately overlaid on the ASR-9 display demonstrating that the same tracks had been detected in range and azimuth. Additionally, altitude information not available from the ASR-9 primary radar was captured. When completed, the Track Processor will be capable of providing a rapid and accurate air traffic

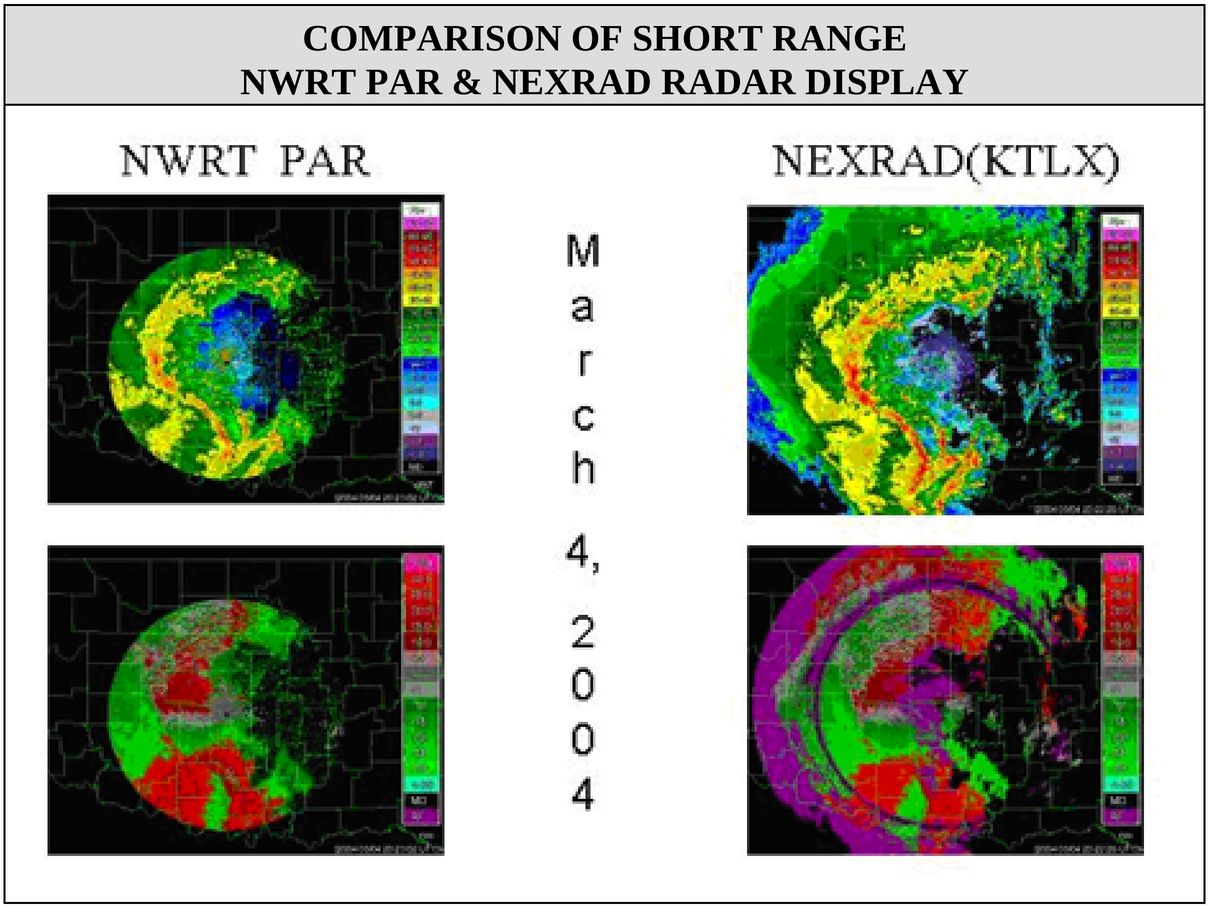

Figure 7*: NWRT PAR vs. NEXRAD Reflectivity and Velocity*

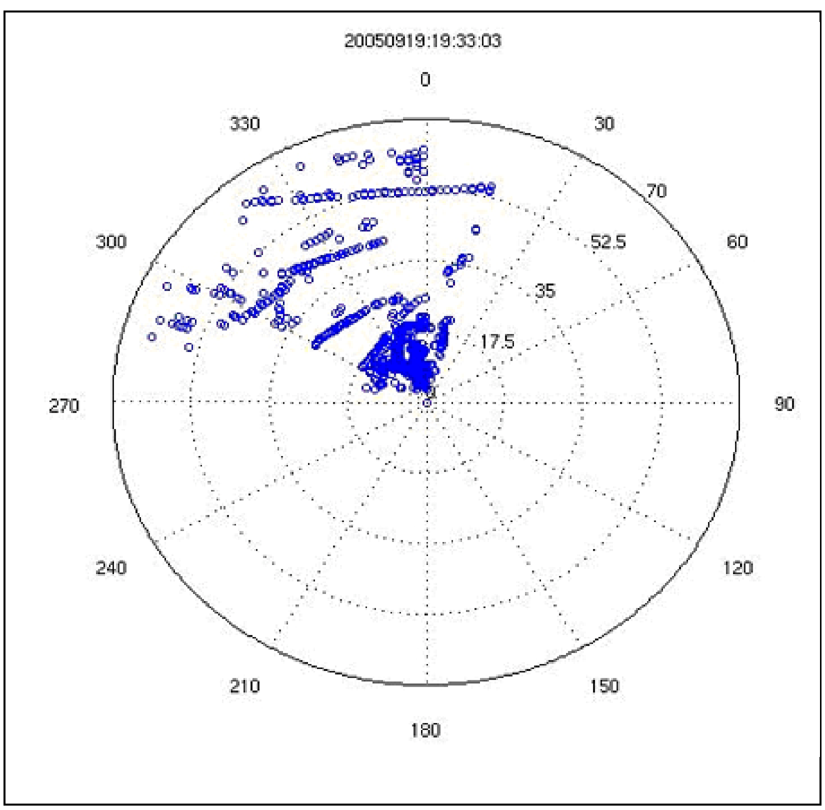

Figure 8: *NWRT Track Processor Detected Tracks During Track while Scan*

picture of targets including non-cooperative aircraft. Figure 8 illustrates the tracks detected in a track-while-scan process during the Track Processor Test. Track history is shown and can be seen as straight-line connectivity on the display. It should also be noted that various clutter sources are clearly apparent since no clutter filtering was applied for this prototype version.

The NWRT successfully demonstrates the concept of a phased array radar to perform surveillance and weather functions with phased array technology. This capability provides a true multifunction PAR test bed to be used for both the weather researchers and the air surveillance community at a single site. New functions and applications under consideration by NSSL include the addition of a dual polarization capability, and wind and chemical/biological profiling.

7. TECHNOLOGY ADVANCEMENTS

In the past, phased array radar technology was deemed too expensive for non-DOD applications and therefore not a viable solution for civilian purposes such as aviation or general weather. Through the leveraging of 30 years of DOD investment (e.g., the DUST program) along with new technological advances and the tremendous growth within the cellular and WIFI industries, a significant reduction in antenna component and packaging costs is being realized, to the point where application to the various agencies' missions can be achieved.

Phased array architecture has advanced from the *passive* aperture design to the *active* aperture design architecture. In the passive architecture, very high power RF tube transmitters are used with a high power combiner. This system was noted for its high receiver losses and high energy losses, but served as the forerunner of technology advances to bridge the way to active array components. The active aperture has low receiver and transmit losses and has transmit/receive (T/R) electronics at each element of the array. The major phased array architectural components are illustrated in Figure 9.

For the active array design, the passive array common transmitter chain is being replaced with several thousand individual duplexed T/R modules. Each of these independent modules or radiators takes the form of a solid-state Microwave Monolithic Integrated Circuit (MMIC), which utilizes semiconductor material such as Silicon Carbide (SiC) or Gallium Arsenide (GaAs) and generate a typical output of about 5 Watts (see Figure 10).

A more promising class of wideband gap semiconductor (WBGS) materials, such as Gallium Nitride (GaN) and Silicon Germanium (SiGe), which are capable of increased power and better thermal efficiency are now being researched though manufacturing cost remains a challenge. Use of these materials in T/R modules virtually eliminates loss of RF energy and simplifies the thermal management for the phased array radar. These advances facilitate more efficient packaging of the modules. (See Figure 11)

Beginning in March, 2005, the Defense Advanced Research Projects Agency (DARPA) began funding awards totaling $144.5M over the next five years to investigate the wide bandgap GaN effort to fabricate and manufacture wideband gap semiconductors for radar applications (RFDesign, 2005). The Department of Defense is also investigating SiGe technology. "The DOD is attempting to leverage silicon-germanium integrated chips to create a low-cost, high performance technology". (EETimes, 1/6/2006).

Further advantage can be gained from applying digital adaptive beam-forming techniques with overlapped sub-array technology. Electronic adaptive beam-forming allows pulses of energy to be directed on demand to any point in azimuth and elevation in the scan region. Unlike a conventional rotating radar, the phased array radar system does not have to wait for the radar dish to rotate in azimuth. Also known areas of clutter (e.g., obstructions from buildings, mountains) can be avoided. Additionally, radar algorithms will modify the volume scan strategy in real-time to concentrate on areas of high interest, such as tracking uncooperative targets and scanning tornados and developing storm formations (see Figure 12).

The overlapped sub-array enables multiple receive beams to be formed simultaneously from a single broad (i.e., spoiled) transmit beam enabling much faster scanning times. For example, eight 1^{o}x1^{o} receive beams could be formed from a single 1^{o}x8^{o} transmit beam covering more surveillance area in a single dwell.

8. FUTURE EFFORTS

Passive phased array technology has been employed operationally by DOD for the last several decades. However, there still remain significant challenges requiring critical research and development (R&D) in the area of active phased array technology. New scan strategies and advanced techniques for weather data surveillance and processing need to be validated, the multifunction capability required to fulfill the various agency's mission's needs to be demonstrated, and the affordability of the technology, including manufacturing cost, must be proven.

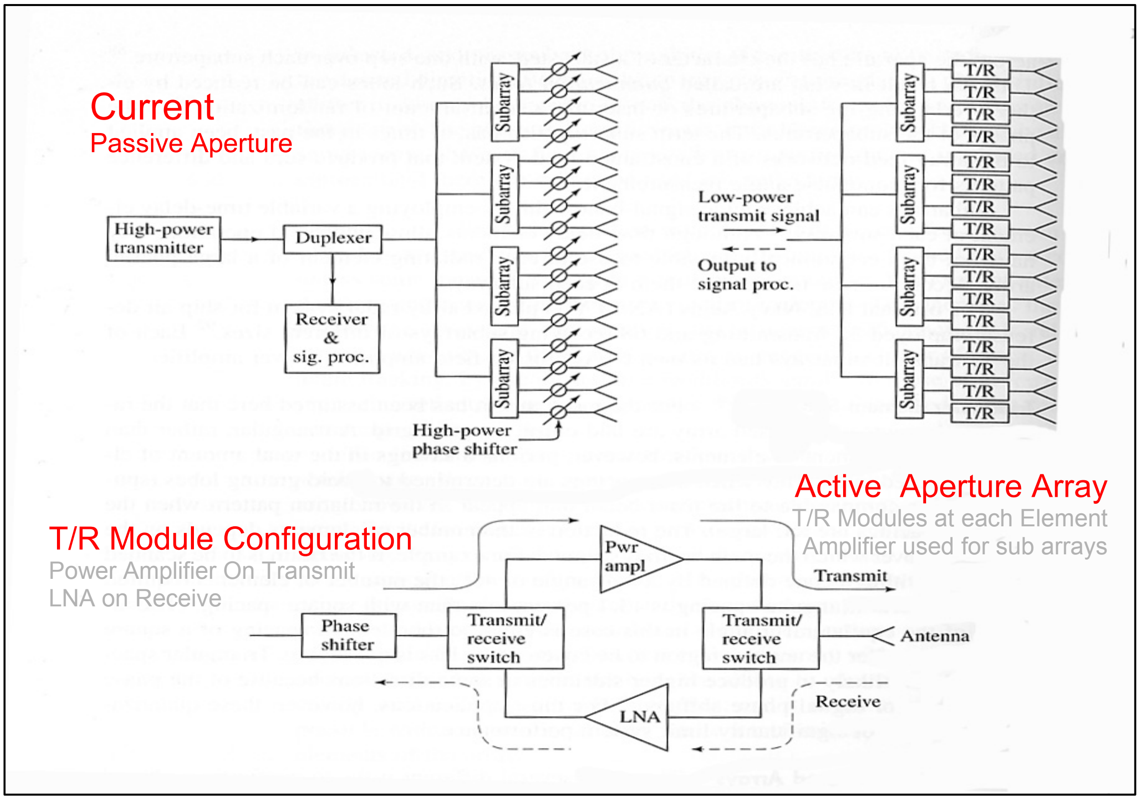

Figure 9*:* *PAR Architectural Components*

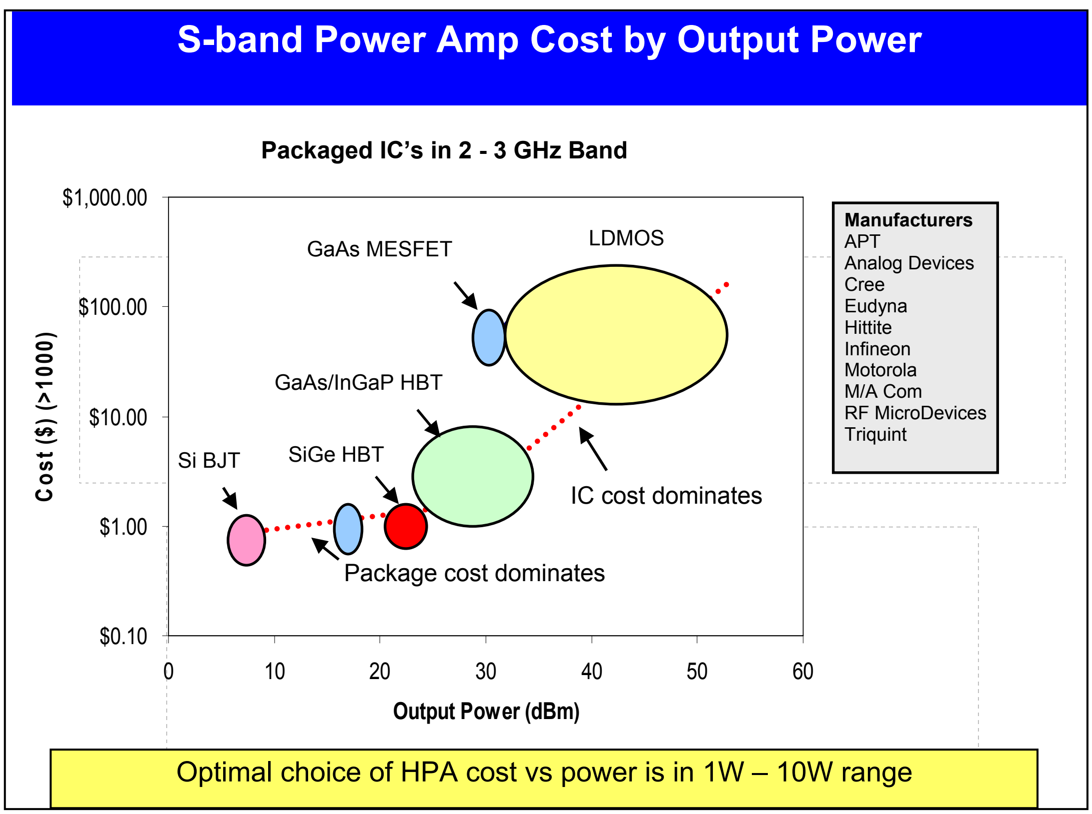

Figure 10*:* *Semiconductor Power/Cost Trend*

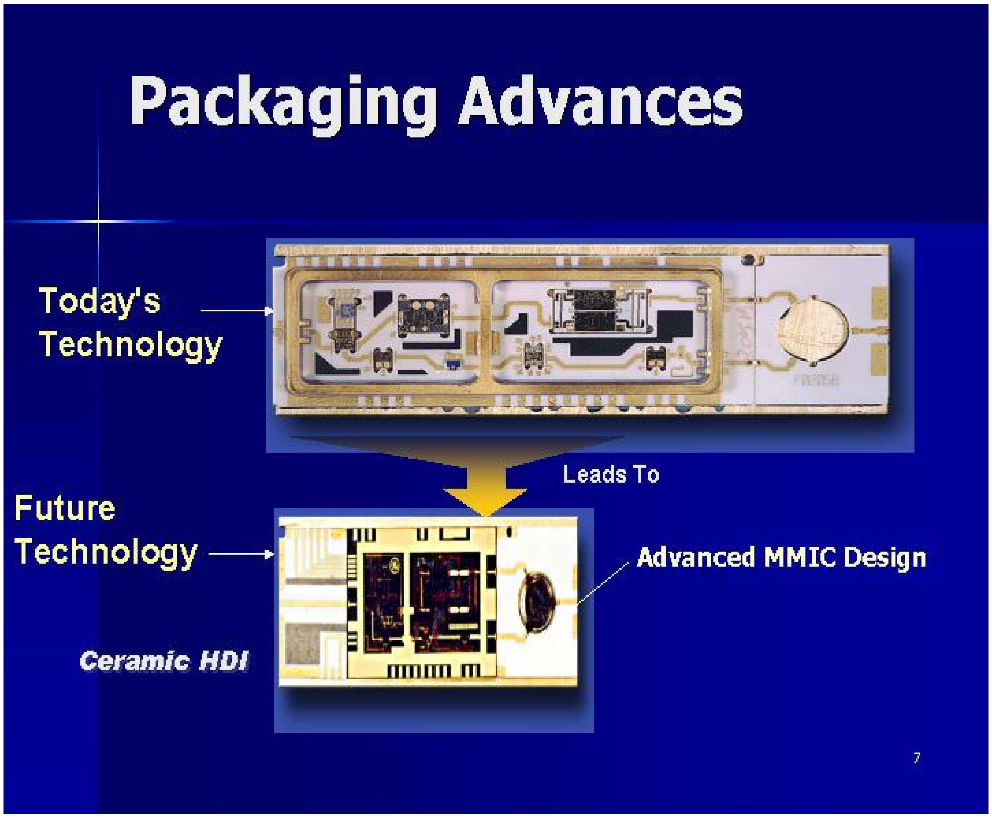

Figure 11: *Active Array Technology* (*Graphic Courtesy: Lockheed Martin)*

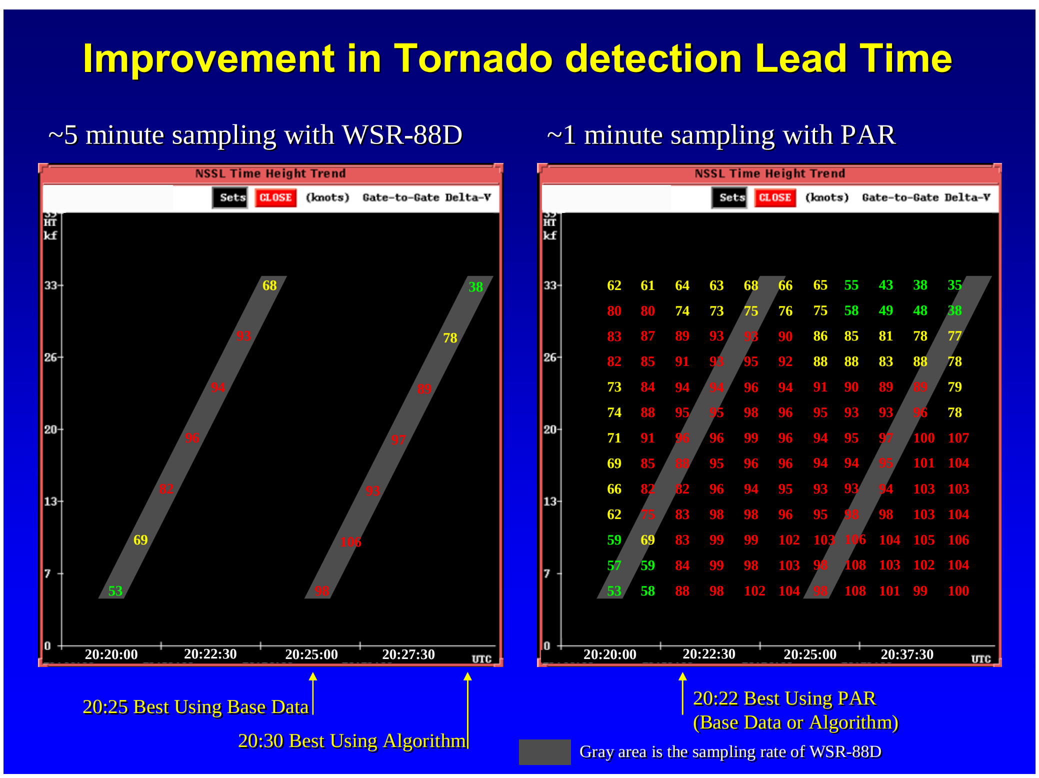

Figure 12: *Tornado Detection Lead Time* (*Graphic Courtesy: NSSL)*

The MPAR program continues to pursue these goals through trade studies, extended research and the development of a pre-prototype MPAR system to support the above R&D tasks. Studies are being conducted to investigate techniques such as range averaging and pulse compression to reduce scan times, and reducing the number of pulses required for bias corrections in clutter filter algorithms. The flexibility of adaptive weather surveillance dwell scheduling opens a broad window of opportunity to explore new surveillance and processing methods.

To facilitate R&D activity, the MPAR Program plans to develop a pre-prototype active array system to provide researchers the means to validate concepts and designs as well as to facilitate further research. The pre-prototype system would be a scaled version of the envisioned operational prototype system using the same or similar architecture and would be installed in a field environment (e.g., co-located with the NWRT) after development.

To understand the functionality required for a pre-prototype MPAR, it is first necessary to discover and understand what the end-user, e.g., research scientist, requires the system to be capable of in order to support the above R&D tasks. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OCFM) commissioned a committee for Cooperative Research (CCR) Joint Action Group for Phased Array Radar Project (JAG/PARP) to look at the research needs and priorities of the Federal Agencies for PAR that resulted in the publishing of the Federal Research and Development Needs and Priorities For Phased Array Radar Report (FCM-R25-2006, June 2006). Subsequent to that report, a Concept of Operations (CONOPS), focused on the pre-prototype system, is being developed for this purpose and will act as the foundation for the development of the pre-prototype system requirements. The system must provide the functionality and performance (e.g., maximum detection range, detection sensitivity, waveform options) necessary for the users to accomplish their objectives. The CONOPS identifies several payoffs, which will drive the goals of the MPAR pre-prototype. The payoffs are:

- Reduction of MPAR hardware costs through the optimization of MPAR adaptability in performing multiple surveillance functions,
- demonstration of the applicability of consumer commercial technologies to the building of MPAR, with the impact of significantly reducing overall MPAR production costs,
- performance validation of the overall MPAR architecture, and
- validation of MPAR production costs.

Using the payoffs and goals identified in the CONOPS, preliminary system requirements are being developed, again with the focus on the intended user, which will subsequently drive the pre-prototype's final architecture and design.

The Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL) was tasked with developing a scalable architecture for an active phased array antenna and a preliminary design for a pre-prototype system. The architecture proposed by LL operates in the S-Band and employs a digital beamformer (DBF) network with overlapped sub-arrays allowing for the formation of the receive beam clusters (i.e., multiple pencil beams) from a single broad (e.g., fan beam) transmit beam effectively reducing scans times (see Figure 13). The single face pre-prototype will be a scaled version of the operational prototype system with a reduced number of T/R modules capable of surveilling in azimuth 45^{o} either side of broadside and in elevation 0^{o} to zenith with an approximate detection range of 60nm (see Figure 14). The overlapped sub-array structure will support formation of eight $2^{o} \times 2^{o}$ receive beams from a single $2^{o} \times 16^{o}$ transmit beam on two separate frequency channels simultaneously.

The long-term goal for the program is to develop, demonstrate and then transfer a low-cost, full-size DBF technology to a selected development contractor for manufacturing and deployment. The pre-prototype development and test is expected to be a four-year effort from initiation, once funded, and will employ a building block approach starting with the T/R module design, the modular packaging of multiple T/R modules into "bricks" and the interconnection of multiple bricks forming sub-arrays and the digital beamforming network (see Figure 15) The successful development, testing and validation of the pre-prototype system will be succeeded by the development of a full-scale four-sided prototype MPAR system that will validate the full aperture performance and the integration of the four antenna faces. The full scale MPAR will have the same architecture as the pre-prototype but with approximately 20,000 T/R modules per antenna face and will operate with three frequency channels verses the pre-prototype's two. The development project is planned to be put out for solicitation and follow the timeline projected in Figure 16.

10. SUMMARY

The development of the MPAR Pre-prototype and the continuing research it will facilitate will go a long way in the retirement of risks and confirmation of technology insertion as the MPAR program strives to be recognized as an equitable solution to agency weather and aircraft surveillance needs. The MPAR with all of its inherent capability cannot be ignored when considering radar systems of the future and as a replacement for presently aging single purpose ground based radar systems. The anticipated cost savings coupled with the

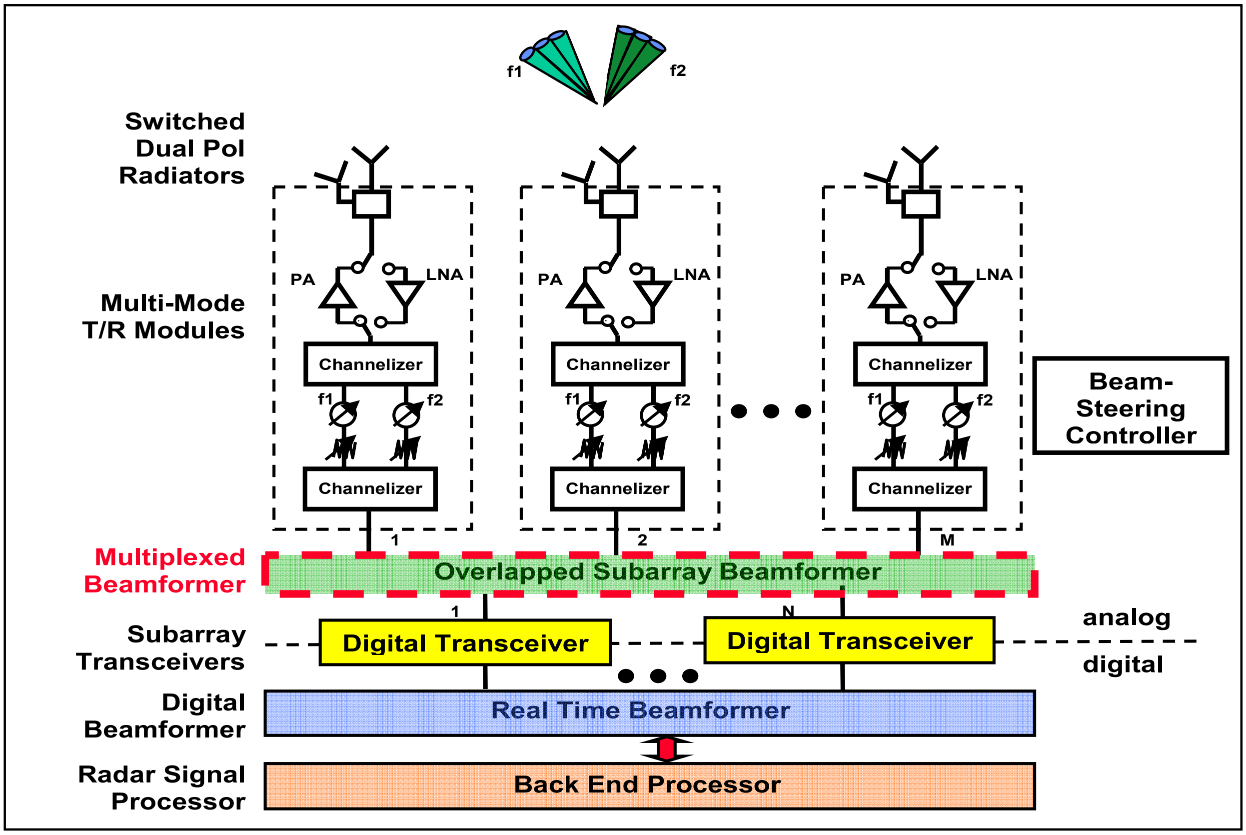

Figure 13: *Pre-prototype MPAR Architecture (Weber, 2006)*

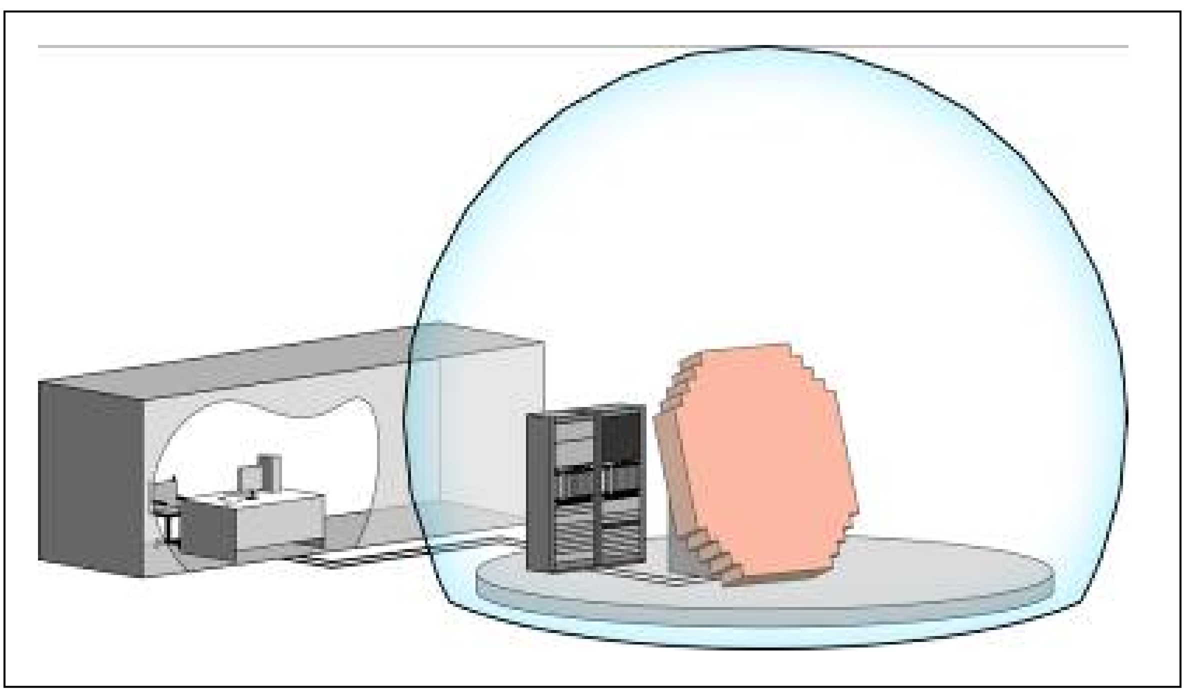

Figure 14: *Pre-prototype MPAR Physical Concept (Weber, 2006)*

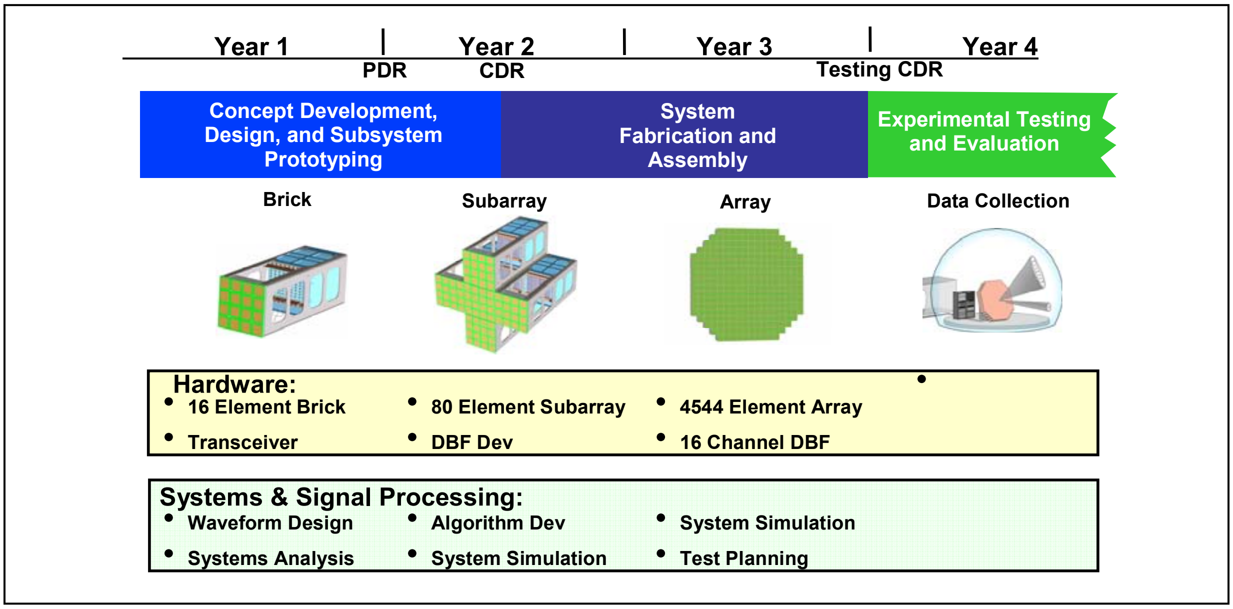

Figure 15: *MPAR Development Timeline*

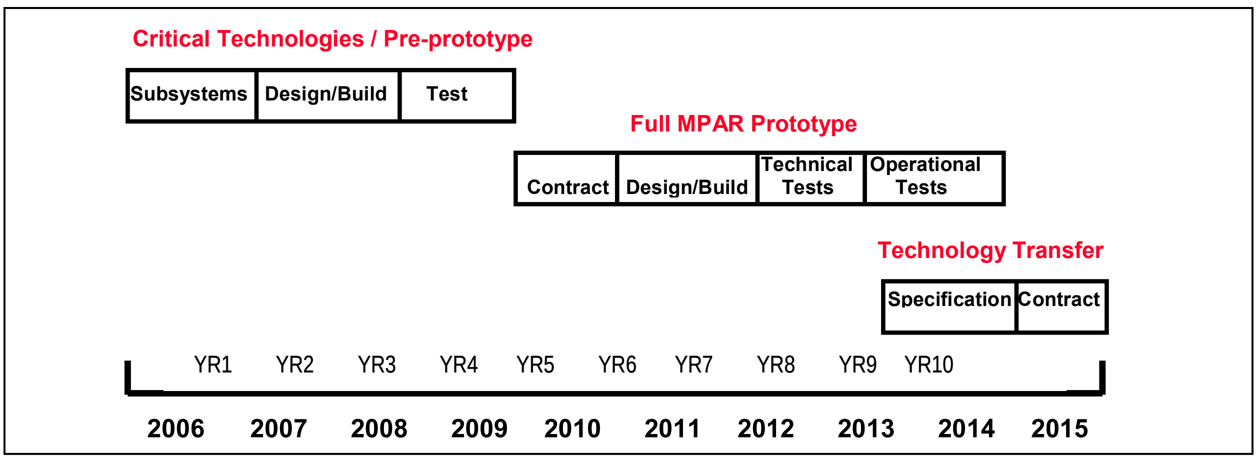

Figure 16: *MPAR Pre-prototype Development Timeline*

multifunction capability confirm this technology as a valid and necessary research program.

The realization of an affordable active solid state MPAR is on the horizon. Using the interagency model employed by the NEXRAD program and continuing to exploit the technologies in the DOD, and commercial industry, and following the recommendations of the Federal Research and Development Needs and Priorities for Phased Array Radar, (FCM-R25-2006) will help assure a viable future to the MPAR program and a safer more secure nation in the areas of public safety, safer air travel and security.

11. ACKNOWLEDGMENTS

We acknowledge the support of our various organizations in funding and helping to implement this national program. We especially acknowledge the dedicated work of the team including the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory, the Tri-Agencies' (Department of Commerce, Defense & Transportation) Radar Operations Center (ROC), the United States Navy's Office of Naval Research, the University of Oklahoma's Electrical Engineering Department and School of Meteorology, the Oklahoma State Regents for Higher Education, the Federal Aviation Administration's William J. Hughes Technical Center and industry.

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