MULTIFUNCTION PHASED ARRAY RADAR

PROGRAM STATUS
AND
POTENTIAL
SERVICE IMPROVEMENTS

Prepared by:
Working Group for
Multifunction Phased Array Radar
(WG/MPAR)

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Foreword

Weather radar has proven its value to the Nation since the installation of the current weather surveillance network began in 1990. In 2020, the WSR-88D radars forming this NEXRAD network will be 23 to 30 years old. In about the same time frame, most of the Nation's aircraft surveillance radars will be nearing the end of their design life. Decisions on replacing or repairing and upgrading these National radar assets must be made over the next 10 to 15 years.

We are now on the threshold of a revolution in civilian radar capability, enabled by the adaptation of established military radar technology to existing civilian applications, plus new capabilities beyond what current systems can provide. The Working Group for Multifunction Phased Array Radar (WG/MPAR) is coordinating an interagency initiative to investigate the feasibility of applying the capabilities of phased array technology to perform weather and aircraft surveillance simultaneously. This paper presents a snapshot of the status of that initiative and projects potential service improvements that would be derived from the operational application of phased array radar to aircraft and weather surveillance.

I wish to thank the members of WG/MPAR—especially Dr. James (Jeff) Kimpel, Director of the National Severe Storms Laboratory (NOAA) and Mr. William Benner, Weather Processors Group Manager (FAA)—as well as the OFCM staff, especially Mr. Judson Stailey (WG/MPAR Executive Secretary) for assisting in the development of this paper.

/S/

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Federal Coordinator for Meteorological Services
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Overview

Twenty years ago the tri-agency Next Generation Radar (NEXRAD) Joint Systems Program Office completed design of the Weather Surveillance Radar 1988-Doppler (WSR-88D). By the mid-1990s approximately 150 of these mechanically rotating radars had been deployed to form the primary radar network used by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) for operational surveillance of radar-detectable weather. At about the same time, the newest systems in the civilian network of aircraft surveillance and tracking radars were designed (although some aircraft surveillance radars still in use were installed over 40 years ago). The age of both of these types of systems, the opportunity to significantly improve service by upgrading the technology, and the lead time involved in research, development, acquisition, and deployment of new systems has prompted several agencies, including NOAA, the Federal Aviation Administration (FAA), the Department of Homeland Security (DHS), and the Department of Defense (DOD), to begin considering a program to replace these systems.

The DOD has employed phased array radar (PAR) technology—characterized by fixed antennas with agile, electronically-steerable beams—for decades to track aircraft and other airborne targets. Efforts began in the mid-1990s to study the potential for applying this technology to weather surveillance. In 2002, the Federal Committee for Meteorological Services and Supporting Research directed the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) to explore the potential benefits of meeting the mission requirements of several agencies by employing phased array radar capability. This initiative took the name "MPAR" for *Multifunction Phased Array Radar* (Figure 1), and prompted a series of further initiatives/events:

- In June 2004, OFCM established the Joint Action Group for Phased Array Radar Project (JAG/PARP)
- In June 2006, JAG/PARP issued the report, *Federal Research and Development Needs and Priorities for Phased Array Radar*
- In October 2007, OFCM convened a symposium around the theme *Leveraging Technology to Build a Next Generation National Radar System* attended by more than 180 representatives from the Federal Government, academia, and industry
- In August 2008, in response to a WG/MPAR request, the National Academy of Sciences Board on Atmospheric Sciences and Climate (BASC) published the report, *Evaluation of the Multifunction Phased Array Radar Planning Process*, which reviewed the JAG/PARP report and other related planning activities associated with MPAR

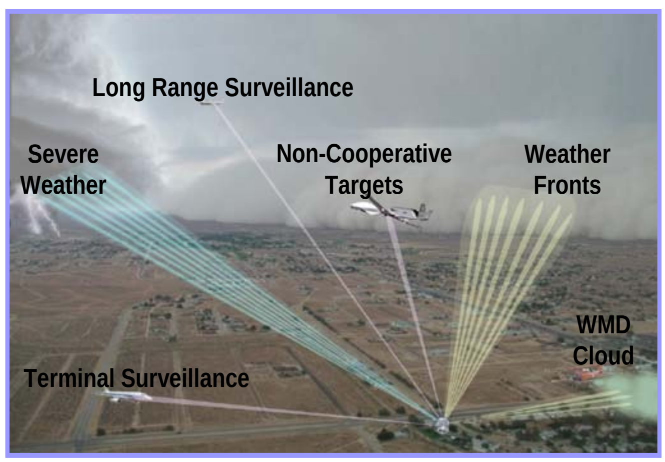


Figure 1: Multifunction Phased Array Radar (MPAR) Operational Concept

Meanwhile, a Navy AN/SPY-1 phased array radar, originally built to support fire control systems on Aegis guided missile cruisers, was installed at NOAA's National Severe Storms Laboratory (NSSL) in Norman, Oklahoma, and became part of the National Weather Radar Testbed (NWRT). It has been operating since 2004, collecting data to study the capability of an operational PAR to support weather surveillance.

This paper describes the progress of the MPAR effort, detailing the part each significant event/initiative mentioned above has played in moving MPAR to the threshold of implementing a rigorous risk reduction program. In doing so, it shows how potential service improvements result from PAR capabilities, what we have observed to date in the NWRT research, and what remains to be done, in terms of quantifying service improvements, as part of risk reduction.

JAG/PARP Report—First steps in Interagency Activity

The 2006 JAG/PARP report, *Federal Research and Development Needs and Priorities for Phased Array Radar* was the first comprehensive look at employing PAR technology in a multifunction system. It explored the possibility of replacing FAA's airport surveillance radars (ASRs), air route surveillance radars (ARSRs), and Terminal Doppler Weather Radars (TDWRs), as well as the NWS/DOD WSR-88D with scalable PARs designed to meet the requirements of these systems. In this scenario, a total of 513 of at least seven types of radar systems would be replaced by about 335 MPARs (Figure 2). The report suggested service improvements that would be expected from using PAR for weather surveillance, addressed anticipated technical issues associated with the technology, and presented a preliminary cost comparison. The preliminary cost analysis showed that aggressive MPAR implementation might save $3 billion over twenty-years compared to a "sustain and replace" strategy for legacy radar systems.

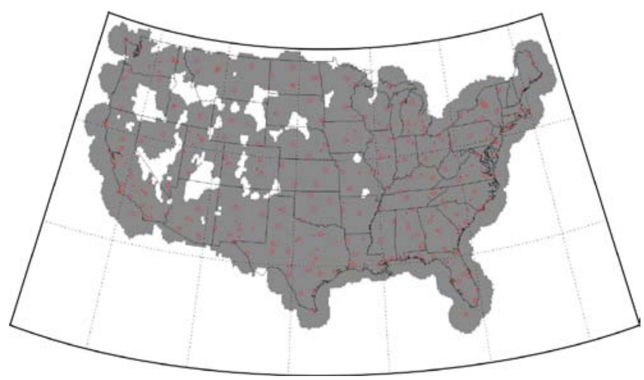


Figure 2: Deployment plan for MPAR systems showing coverage at 5000 ft AGL

MPAR Symposium—Foundation for the Implementation Strategy

The JAG/PARP report served as the stepping off point for further initiatives, including the MPAR Symposium held in October 2007. The program included panels of experts addressing a series of MPAR issues, including views from potential users, status of military applications of PAR, the industry perspective, component technology and cost, and alternative configurations. Finally, the participants proposed two key initiatives to focus and energize the MPAR effort—developing an interagency management approach for MPAR and developing a risk-reduction implementation strategy.

OFCM is now taking the first steps in establishing an interagency management approach for MPAR, considering alternative approaches to providing guidance to the Working Group on MPAR (WG/MPAR) until such time as it becomes appropriate to charter a Program Council or similar body to oversee a more formal program. At the same time, the membership of WG/MPAR is under review to ensure that the right people are in place to represent the agencies and to foster efficient decisions. Meanwhile, joint action groups are being established to address specific technical issues using the appropriate subject matter experts.

Immediately following the Symposium, WG/MPAR moved out to address the action item calling for development of a risk-reduction implementation strategy. The principal basis for the implementation strategy is the agency roadmaps and other planning documents that contain decision points on how to continue the essential functions performed by current radar systems and how to satisfy future missions.

The implementation strategy identifies the need to work closely with the agencies on a long-term management approach that lays out a time-phased plan for RDT&E, mission/service needs analysis and requirements development, development of operations and employment concepts, two-phased concept definition and system development, and long lead time efforts like site and RF spectrum analysis and acquisition/approval (Attachment 1). This original strategy is being reviewed by the agencies and will likely be revised to accommodate schedule changes driven by anticipated funding and updated agency radar roadmaps. The strategy includes a concept definition phase involving multiple contractors demonstrating their phased array architectures followed by an acquisition program, starting with two or more vendors developing systems for a fly-off leading to down-select, limited production, and finally full production. The implementation strategy recognizes several key needs:

- Requirements definition and concept of operations completed in the near term
- Enhancement of NWRT (including eventual development of a pre-prototype system) to improve algorithms, explore service improvements, investigate affordability issues, and demonstrate simultaneous weather and aircraft surveillance capability
- Explore systems design concepts and monitor cost/capability trade-offs of transmit/receive modules
- Complete definitive cost-benefit analyses of alternatives, including non-MPAR solutions
- Address siting and frequency management considerations

BASC Study—Validation and Encouragement

On August 11, 2008, the BASC Committee on the Evaluation of the MPAR Planning Process released its report on the review of MPAR planning activities requested by WG/MPAR. The committee grouped the recommendations into four major areas and presented an additional overarching recommendation. Several recommendations addressed the MPAR R&D Plan, which was published as Appendix D to the JAG/PARP report. Some of those recommendations dealt with the plan itself (e.g., calling for expanding and frequently updating it), while others dealt with detailed suggestions for actions to take during the R&D process. Because PAR technology is mature for aircraft surveillance applications, most of the technical challenges driving the JAG/PARP R&D plan and the BASC comments on that plan addressed weather surveillance applications. Recommendations related to requirements called for developing a set of detailed requirements (including for the proposed airport terminal area MPAR derivative) and considering MPAR as member of a family of systems. Technical recommendations addressed calibration and frequency allocation issues. Finally, the panel cautioned that the preliminary cost evaluation in the JAG/PARP report was “promising, but embryonic,” and recommended a thorough cost-benefit analysis for the multifunction system and for a PAR replacement for weather radars (WSR-88D and TDWR) only.

The overarching recommendation of the BASC study was to continue the MPAR R&D program. WG/MPAR reviewed the other recommendations carefully in the context of the Risk-Reduction Implementation Strategy. Many of the BASC recommendations were on a different level from the Strategy and could not be logically mapped into it. However, the appropriate recommendations were mapped into the Strategy to facilitate a comparison between it and the BASC report. Although a few minor adjustments are planned to synchronize the Strategy with the BASC report, it is fair to say that the appropriate BASC recommendations are, for the most part, consistent with and validate the MPAR Risk-Reduction Implementation Strategy.

The BASC MPAR study is available at http://www.nap.edu/catalog.php?record_id=12438.

Risk-Reduction Implementation Strategy—Translating Capabilities into Service Improvements

The capabilities of PAR systems are fairly well understood. Several publications—including the JAG/PARP and BASC reports, *inter alia*—detail these capabilities and suggest how they contribute to new and/or better observational products, which in turn should foster service improvements. However, projecting service improvements from advanced PAR capabilities is a complex process. Figure 3 illustrates the relationships as we now understand them between basic PAR capabilities and potential service improvements for the weather surveillance function. Figure 4 presents illustrates the relationships for the aircraft surveillance function. The following brief explanation of PAR capabilities aids in interpreting the figure:

- Adaptive Beam Width—Beam width is fixed on conventional radar based on antenna size. A PAR beam can be adjusted electronically for better spatial resolution at longer range and better temporal resolution (i.e., faster scans) at closer ranges.
- Adaptive Scanning—Conventional radars have limited flexibility in scan strategies constrained by the necessity to mechanically steer and point a large antenna. Antennas normally scan continuously in the horizontal; some incrementally adjust the vertical angle after each horizontal scan to obtain volumetric data. PARs can change scan strategies quickly and automatically based on the returns being received at any time.
- Agile Beam—Changing the pointing angle of a conventional radar beam requires physically repositioning a large antenna. The position of a PAR beam can be changed in a fraction of a second. In addition to allowing for rapid scanning, this capability allows for specialized data gathering processes (beam multiplexing) that produce higher quality data.

- Electronically Steerable Beam—Allows for very precise pointing of the beam (e.g., to avoid terrain or focus attention on areas of interest)
- Sidelobe Cancellation—A standard characteristic of radars is that all the energy emitted is not confined within the primary beam. Some energy spills outside the beam to form additional beams called sidelobes that can contaminate the data received from intended targets. PARs can manipulate the beam to mitigate the effects of sidelobes.
- Dual Polarization—Allows two different views of the returned radar signal from the same object to be compared to aid in identifying and/or discriminating between types of targets (e.g., raindrops, snow, birds).
- Adaptable Antenna Face—Allows the antenna to be divided into parts and operated as if it were two separate antennas located in close proximity. Processing returns from the two separate "antennas" together allows application of interferometry techniques to learn more about the targets, including direct measurement of crossbeam winds. This allows for the assimilation of radar-measured true winds into storm-scale numerical weather prediction models.
- Physical Design—Conventional radar has one device to transmit and receive signals. When it fails, the radar no longer works. In addition, mechanically rotating antenna radars are subject to failure of the drive motors and servo mechanisms. PARs have no moving parts to fail, and the tens of thousands of transmit/receive (T/R) modules operate in such a way as to mitigate the impact of individual outages (graceful degradation). In studies and operational experience PARs show remarkable tolerance to random T/R outages. That is, the quality of data remains quite good with as many as 10 to 20 percent of T/R modules inoperable.

As seen in the figures, specific capabilities do not necessarily directly result in service improvements. In most cases, basic capabilities foster derived (intermediate) capabilities, which contribute to service improvements. Some individual capabilities support more than one service improvement, and some service improvements derive from several basic capabilities.

Some progress has been made in investigating service improvements in the weather surveillance function. Scientists from the NSSL, augmented by operational forecasters from NWS forecast offices, have used the NWRT to compare data from the PAR to data from a WSR-88D radar for the same storms. In actual storm cells, the basic MPAR capabilities that lead to faster scans have resulted in earlier and more reliable detection of severe weather indicators (Attachment 2). Statistics alone would suggest, given the difference between scan rates, that lead times for severe weather forecasts based on radar data would increase by two to three minutes. However, the ability of forecasters to observe the evolution of a storm rather than view just 5-minute snapshots may well provide additional insights that further increase the potential lead time. More importantly, severe weather warnings in the future are expected to be based on storm-scale numerical weather prediction models—a concept called "warn on forecast." These models will be viable only if accurate observations of storms and their surroundings are available to initialize and adjust the models as they run. MPAR will be able to provide much of the key initialization data. Finally, it is possible that entirely new paradigms in applying radar data to severe weather forecasting, unimagined at this time, will become manifest with broader MPAR weather sensing experience. Such advances are beyond the scope of the information in Figure 3.

The FAA, meanwhile, is exploring MPAR's impact on safety- and efficiency-enhancing weather support to aviation operations. Data will be collected from NWRT in support of this effort. The analysis will focus on the potential to improve tactical and strategic thunderstorm forecasts using MPAR's higher temporal resolution and improved data quality relative to today's radars. In addition, the potential contribution of new measurement capabilities, such as crossbeam winds, to forecast capability will be assessed. While the tasks focus on the convective forecasting challenge, the results should expose MPAR benefits for other aviation weather services such as improved wind shear and turbulence detection, improved forecasts of the growth and decay of storms, near-airport wind forecasting, and probabilistic forecasting required for the Next Generation Air Transportation System (NextGen).

Decades of experience applying PAR technology within the DOD provides confidence that MPAR could support basic surveillance for air traffic management and national and homeland defense. However, MPAR shows promise to significantly improve upon the baseline capabilities of current surveillance radar systems (See Figure 4). It is possible that some of the relationships in this figure could be validated by leveraging existing DOD radar systems. This might involve detailed technical studies of documented

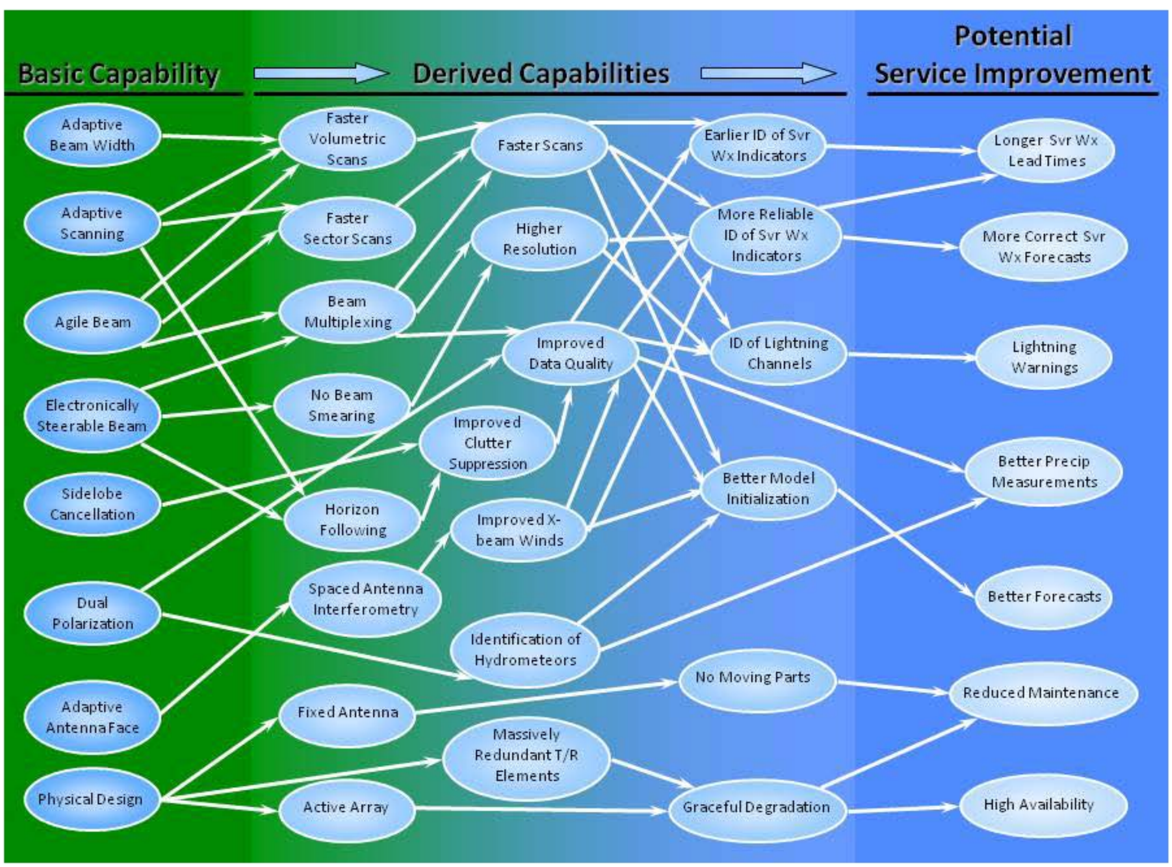


Figure 3: Illustration of potential for PAR capabilities to translate into weather service improvements

capabilities, field experiments with current systems to gather new data, or the modification of operational or prototype systems to target specific capabilities or technologies (e.g., dual polarization or new T/R module architectures).

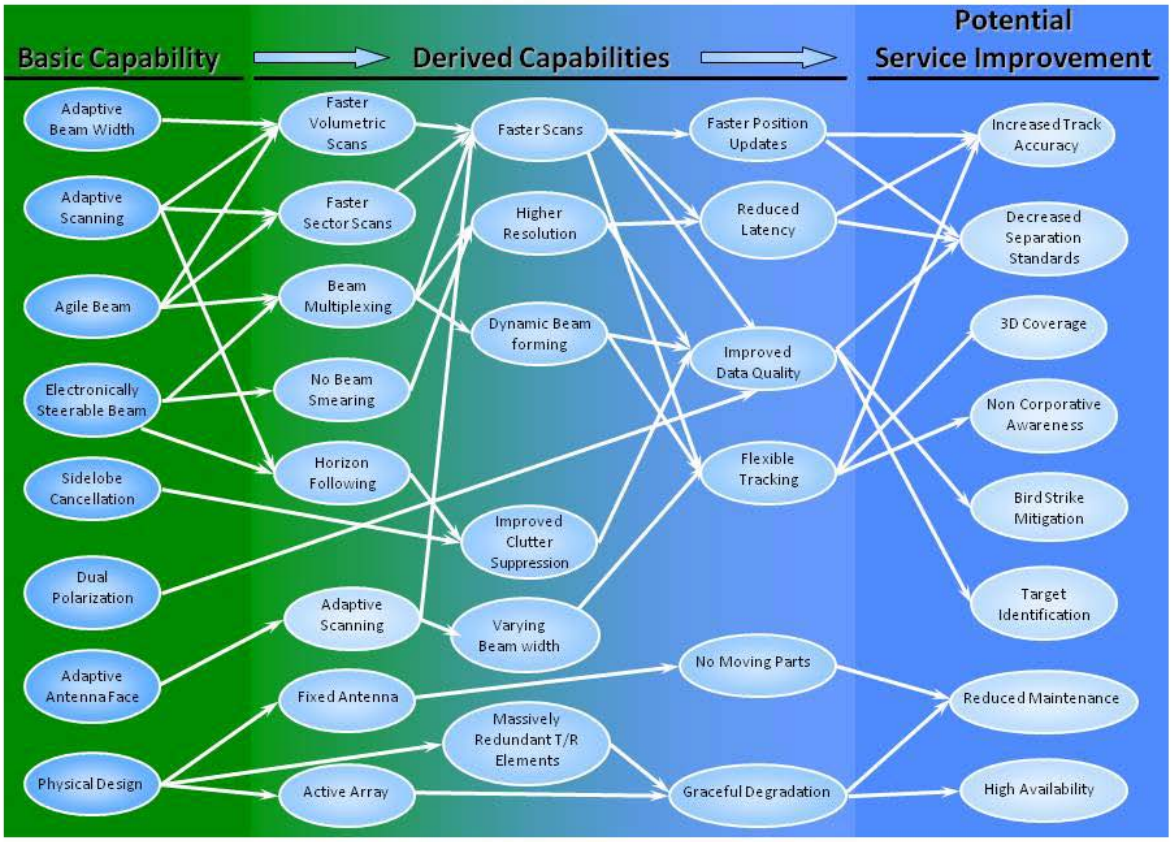


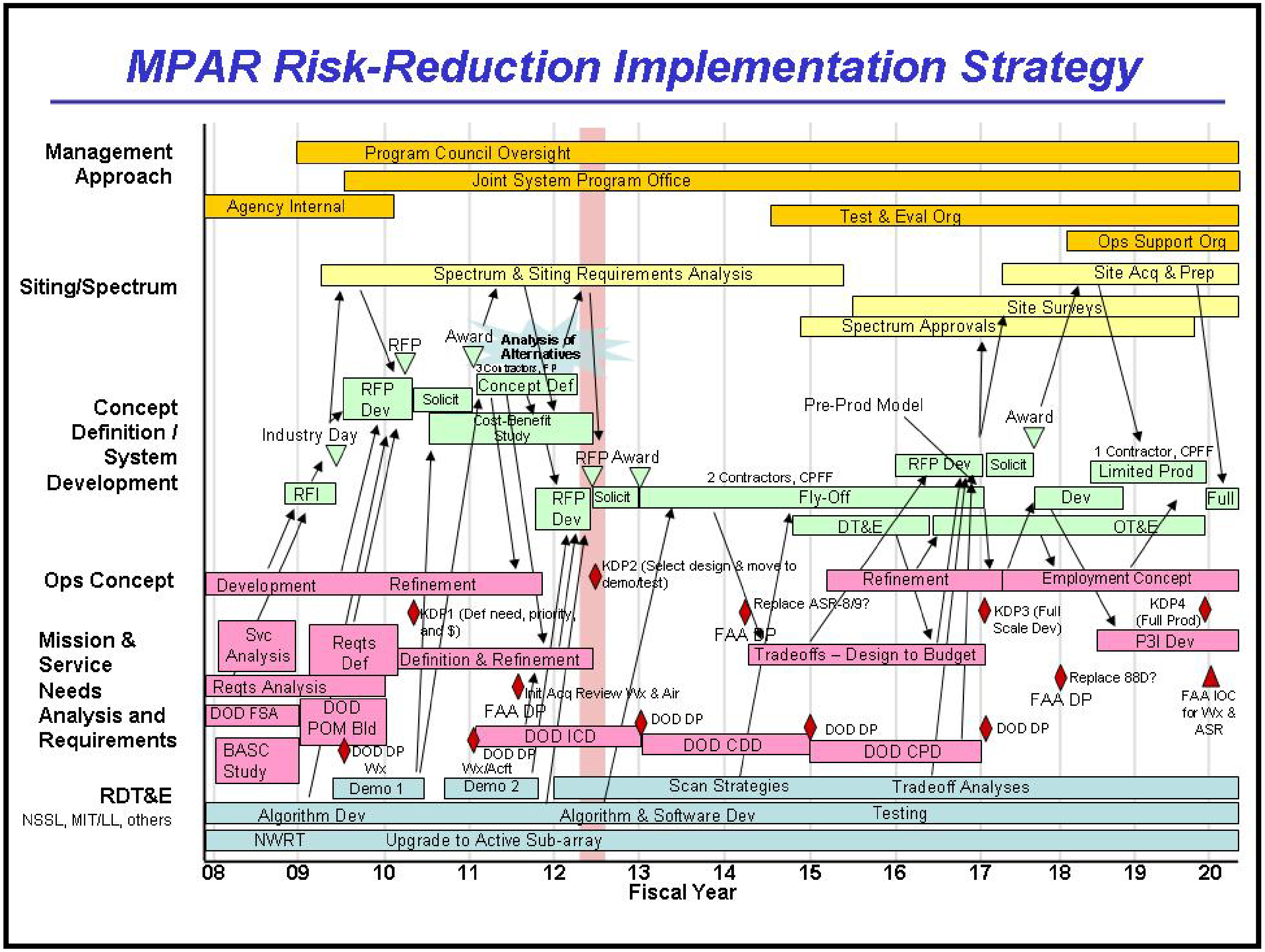
Figure 4: Illustration of the potential for PAR capabilities to translate into aircraft surveillance service improvements

One key goal of the risk-reduction implementation strategy is to validate the assumptions associated with Figures 3 and 4 and to verify the service improvements. The risk reduction process also includes validation of the multifunction concept by demonstrating the ability to perform robust weather surveillance (including full volumetric scans in conjunction with multiple sector scans on individual cells) while fulfilling FAA terminal control requirements, NextGen backup, and DHS/DOD surveillance (Figure 1). In addition, risk reduction involves confirming the assumption that the cost of the T/R modules will drop significantly as new manufacturing methods are developed in conjunction with the requirement for production of large numbers of the units (each standard MPAR could include upwards of 80,000 T/R modules).

Ultimately, validating and quantifying the potential service improvements, proving the multifunctionality of MPAR, and developing the industrial base necessary to produce PAR components efficiently are contingent upon carrying out the risk-reduction strategy rigorously and effectively. This will require the technical, political, and financial commitment of the MPAR partners over the course of the entire R&D program.

Attachments:

1. MPAR Risk-Reduction Implementation Strategy
2. Assessment of Potential Service Improvements for MPAR as Compared to the WSR-88D


MPAR Risk-Reduction Implementation Strategy
Management Approach
Siting/Spectrum
Concept Definition / System Development
Ops Concept
Mission & Service Needs Analysis and Requirements
RDT&E
NSSL, MIT/LL, others
Program Council Oversight
Joint System Program Office
Agency Internal
Test & Eval Org
Ops Support Org
Spectrum & Siting Requirements Analysis
Site Acq & Prep
Site Surveys
Spectrum Approvals
RFP
Award
Analysis of Alternatives
3 Contractors, FP
RFP Dev
Solicit
Concept Def
Cost-Benefit Study
Industry Day
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RFP Dev
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2 Contractors, CPFF
Fly-Off
Pre-Prod Model
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1 Contractor, CPFF
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KDP2 (Select design & move to demo/test)
Refinement
Employment Concept
KDP1 (Def need, priority, and $)
Replace ASR-8/9?
FAA DP
KDP3 (Full Scale Dev)
KDP4 (Full Prod)
Svc Analysis
Reqts Def
Definition & Refinement
Tradeoffs – Design to Budget
P3I Dev
Reqts Analysis
Init Acq Review Wx & Air
FAA DP
Replace 88D?
FAA DP
FAA IOC for Wx & ASR
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BASC Study
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Demo 1
Demo 2
Scan Strategies
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Algorithm Dev
Algorithm & Software Dev
Testing
NWRT
Upgrade to Active Sub-array
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ATTACHMENT 2

Assessment of Potential Service Improvements for MPAR as Compared to the WSR-88D

Prepared by Pamela Heinselman, PhD

The development and evolution of the NEXRAD system has resulted in significant improvements in detecting, measuring and tracking hazardous weather, such as hurricanes, supercell thunderstorms, and tornadoes, to name a few. The deployment of the NEXRAD system has also resulted in increased mean warning lead time for tornadoes from 6 to 13 minutes and reduced tornado-related injuries (40%) and fatalities (45%; Simmons and Sutter 2005). Nevertheless, there are at least two desirable features of radar technology that can only be achieved by replacement technology like Multifunction Phased Array Radar (MPAR): 1) fast scanning with volume scan updates at intervals of one minute or less, and 2) multifunction use to provide nearly simultaneous surveillance of weather and aircraft (Weber et al. 2007; Zrnić et al. 2007). The achievement of fast volumetric scanning is a crucial component for the success of the NOAA Weather and Water performance objective to increase lead time and accuracy for weather and water warnings and forecasts (F72008–FY2012 NOAA Strategic Plan: http://www.nrc.noaa.gov/plans_docs/5yrp_2008_2012_final.pdf).

Since May 2004, the National Severe Storms Laboratory has used phased array radar technology from the late 1970s, called the National Weather Radar Testbed Phased Array Radar (NWRT PAR), to demonstrate the fast volumetric scanning capability of MPAR and to examine the impact of fast scanning on the capability to manually detect and monitor hazardous weather, compared to the NEXRAD Weather Surveillance Radar-1988 Doppler (WSR-88D). A comparative analysis of three severe convective storms that occurred during the spring and summer of 2006 shows that volumetrically sampling these storms at intervals of 58 s or less provides superior depictions of the evolution of rapidly evolving reflectivity and velocity features key to determining storm severity (Heinselman et al., in press).

One of the three storms analyzed by Heinselman et al. (in press) was a microburst that produced radial wind speeds meeting National Weather Service severe criteria (58 mph). A microburst is a small-scale (< 4 km diameter) outflow induced by strong downdrafts in thunderstorms that frequently cause damage to property and are a hazard to aviation (Proctor 1988). Since these storm cells typically have a life cycle of 20–40 minutes, and because the WSR-88D and Terminal Doppler Weather Radar (TDWR) typically only sample the upper portions of a storm once every four to six minutes (depending on scanning strategy), they may or may not sample key precursor features aloft. In this case, the PAR scanned an elevated reflectivity core that rapidly descended a few minutes prior to the onset of strong outflow near the surface (Fig. 1). The first indication that this storm might produce a microburst was seen 13 min prior to the onset of strong outflow near the surface. The KTLX WSR-88D scanned this storm with an update rate of 5 minutes between volume scans, thus missing much of the evolution that was captured by the PAR (Fig. 1). This case clearly illustrates the potential for fast volumetric scanning to increase the lead time and accuracy of high wind warnings due to microbursts.

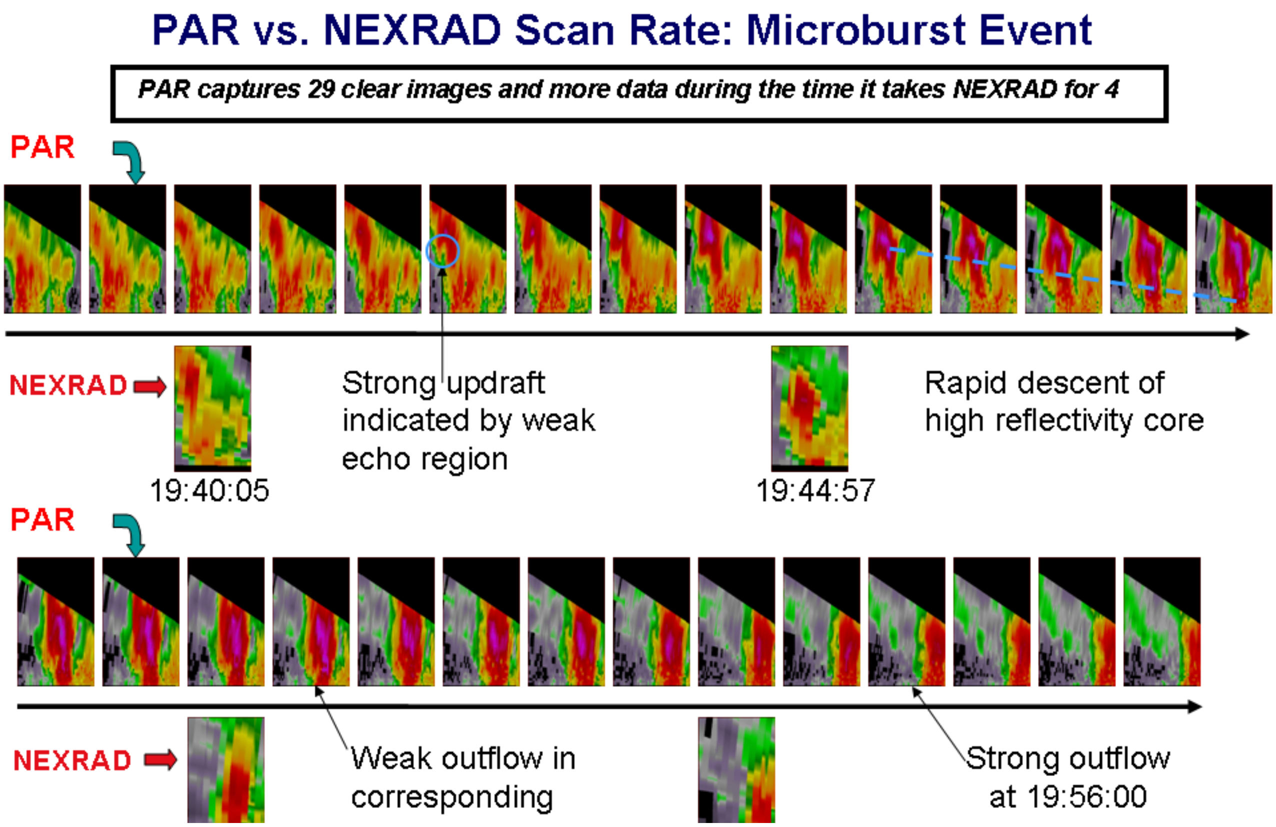

Figure 1. A time series (UTC) of vertical cross sections of radar reflectivity comparing the life cycle of a microburst sampled by the PAR and the Oklahoma City NEXRAD (KTLX) on 10 July 2006. The 34 s updates of the PAR clearly depict precursors beginning ~13 min prior to the occurrence of strong outflow (winds) at the ground. The NEXRAD radar is located 20 km northeast of the PAR.

Another case illustrating the importance of fast scanning to increased lead time and accuracy for weather warnings is 19 August 2007. In this case, with 43 s volumetric updates, PAR sampled the initial development of a tornadic vortex signature (TVS) at the 0.5° elevation 3.33 min prior to the WSR-88D (Fig. 2). Within that 3.33 min period, the PAR velocity data showed rapid intensification of the TVS indicative of a tornado. A damage survey later revealed that the rapid intensification of the TVS was associated with a tornado that produced EF0–EF1 damage near Norge, Oklahoma. The WSR-88D sampled the tornado approximately 1 min prior to its dissipation. Since short-lived tornadoes like the one illustrated here are common, fast scanning is likely required not only to increase lead time and accuracy, but in some cases to even be able to issue a warning.

A more recent case currently under investigation is the 24 May 2008 cyclic tornadic supercell thunderstorm located approximately 110 km from the PAR that produced at least 8 confirmed tornadoes during its lifetime. Preliminary analysis of one-min PAR data illustrates the evolution of each supercell cycle in more detail than the 4.2 min WSR-88D data, including important features like strong updrafts, rear-flank downdrafts, and regions of strong shear. These three features often play an

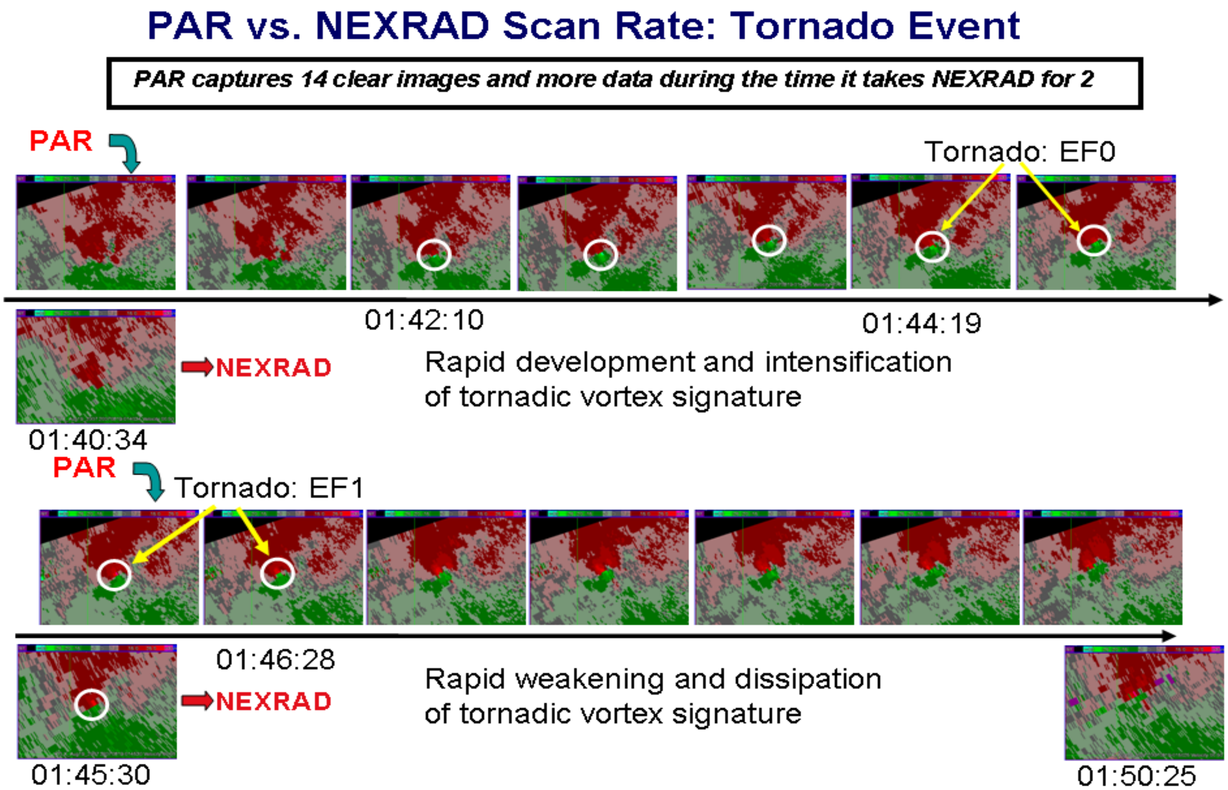

Figure 2. A 10-min time series (UTC) of 0.5° velocity data sampled by the PAR and the Oklahoma City NEXRAD (KTLX) on 19 August 2007. These images show the rapid development and intensification of a tornadic vortex signature indicative of a tornado that is sampled by PAR several minutes prior to NEXRAD. The green pixels indicate radial velocities toward the radars, whereas red pixels indicate radial velocities away from the radars. The NEXRAD radar is located 20 km northeast of the PAR.

important role in operational decisions of whether or not to issue a tornado warning at a particular point in time.

This spring 19 National Weather Service (NWS) forecasters from 17 Weather Forecast Offices assessed the potential service improvements for MPAR, as compared to the WSR-88D, while participating in the PAR Real-time Experiment. An important part of the experiment was forecaster evaluation of the microburst and Norge, Oklahoma tornado cases presented. During simulated real-time playback of these data, forecasters were asked to evaluate the operational use of weather information provided by the PAR compared to the WSR-88D. For the microburst case, forecasters unanimously reported that the 34 s-volumetric updates from the PAR allowed them to track and monitor the evolution of the microburst better than the 5-min-volumetric updates from KTLX. Forecasters also indicated that the faster updates gave them high confidence in issuing high wind warnings and helped them issue the warnings quicker than the WSR-88D data. For the tornado case, forecasters unanimously reported that the 43 s-volumetric updates from the PAR allowed them to see velocity signatures critical to decision making quicker, and gave them more confidence in the persistence of the signatures. Several forecasters also said that the PAR data allowed their tornado warning to be issued before the TVS appeared in the WSR-88D. In both the microburst and tornado cases, forecasters stated that using PAR data would likely improve their ability to communicate detailed, timely severe weather information to their stakeholders (e.g., the public, Emergency Managers, Spotters, and the Media).

To date, the comparative analysis of weather information provided by the PAR and the WSR-88D by both researchers and NWS forecasters strongly suggests that fast volumetric scanning is a crucial component for the success of NOAA Weather and Water performance objective to increase lead time and accuracy for weather and water warnings and forecasts.

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