3 COMPARISON OF ALTERNATIVES FOR FUTURE CIVILIAN RADAR FUNCTIONS

3.1 Why Should MPAR Be Considered Now?

Based on advances in radar technology since the 1980s, the improved meteorological forecasts and warnings that multifunction phased array radar (MPAR) observations will enable, the projected obsolescence of major existing radar components and facilities infrastructure, and the increasing affordability of MPAR, the Nation needs to consider the wholesale replacement of its existing weather and surveillance radar networks with this new technology. Given the complexity of the mission and the technology involved, as well as the long lead times required of national interagency acquisition programs, now is the time to conduct the risk-reduction R&D necessary to determine whether MPAR technology is ready to provide a multifunction capability for the Nation's weather and aircraft surveillance needs.

There are four fundamental reasons why the timing is right to begin a thorough evaluation of MPAR as an alternative to mechanically rotating conventional radar (MRCR) for the applications presented in Chapter 2.

1. The existing radar networks for aircraft surveillance and weather surveillance are aging, and decisions on how to continue the essential functions they perform are on the horizon.
2. More timely warning of hazardous weather events, with greater accuracy, spatial specificity, and reliability (e.g., fewer false positives), is needed than the current MRCR weather surveillance network can provide.
3. Increased aircraft-related risks to homeland security require assured detection and tracking of non-cooperative aircraft anywhere in the National Airspace System (NAS).
4. Advances in materials and manufacturing, coupled with the economics of production for state-of-practice electronic technologies, will substantially reduce the cost of MPAR for civilian surveillance applications.

Each of these reasons is explained further below.

First, as table 3-1 shows, the national radar infrastructure is aging. Many of our existing surveillance radar systems were installed in the late 1980s and early 1990s. Either they will need to be replaced by the middle of the next decade or expensive service-life extension programs will be needed simply to maintain their current level of performance. The NEXRAD Product Improvement Program is expected to extend the useful life of the existing WSR-88D units to 2020. The DOD and FAA aircraft surveillance radars—both ASR and ARSR units—are expected to be either replaced or decommissioned by 2020. The FAA is considering a surveillance strategy for the NGATS that emphasizes automatic dependent surveillance, a cooperative surveillance approach, as the principal surveillance system. Nevertheless, for reasons given in section 2.2, there will continue to be a critical requirement to detect and track non-cooperative aircraft, as well as to validate cooperative aircraft reports with non-cooperative observations.

Table 3-1. Radar System Life Expectancies

Radar System	Design Date	Installation Date	Estimated End-of-Life
WSR-88D	1988	1990-1997	2020
TDWR	1986-1990	1992-1995	2020
ARSR-1, ARSR-2	1960-1970	1965-1975	2015
ARSR-3	1960-1970	1965-1975	2015
ARSR-4	1985-1990	1990-1995	2020
ASR-9	1983-1986	1987-1993	2020
ASR-11	1998-2002	2003-2010	2030

Second, increases in population density and changes in its distribution have increased the societal value of earlier, more precise, and more reliable warnings of hazardous weather events. As U.S. population density increases in urban/suburban areas and along the coasts, the need for more accurate and more timely weather data is becoming acute, even as substantial progress has been made in many forecast skill measures. The needs of the various agencies for surveillance and environmental observational data are becoming more demanding in terms of accuracy, coverage, refresh rate, and resolution. MPAR could significantly improve weather observations and enable substantial improvements in weather forecasting by providing data at much higher resolution (both spatially and temporally) to initialize and correct NWP models. These improvements have the potential to reduce weather-related deaths and injuries, lessen property damage, and increase the efficacy of preparatory and response actions, thereby saving millions to billions of dollars annually.

Third, the risks to homeland security associated with the war on terrorism have forced the Nation to reevaluate the need to track non-cooperative aircraft and other airborne threats to safety. Because of its inherent functional agility, an MPAR network can support the evolving needs of DOD and DHS in protecting the U.S. homeland from terrorist attacks. For example, an MPAR network could simultaneously track non-cooperative aircraft and measure winds at a fine enough scale to substantially improve inputs to ATD models.

The fourth reason for considering the MPAR alternative for a nationally deployed network now is that new materials and manufacturing processes, combined with the economics of volume production, could permit significant reductions in the cost of phased array technology. With these advances, the JAG/PARP projects that the cost of a truly adaptive, multifunction phased array radar has decreased to a level that could make MPAR the system of choice for a much wider customer base. The cost advantage of the

MPAR alternative is further increased when estimates of increased system reliability and decreased maintenance costs, relative to life-extended current MRCR systems, are included in system life-cycle cost.

Another consideration that favors undertaking the risk-reduction R&D program proposed in this report is that the U.S. Navy has “permanently” loaned a surplus SPY-1 phased array radar unit to the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma.[2] The National Weather Radar Testbed (NWRT), which includes this SPY-1 radar and associated data collection and scientific analysis infrastructure, can serve as an evolving testbed for much of the risk-reduction and demonstration activities proposed in chapter 5. The NWRT can serve as a working “proof of concept” prototype for critical performance characteristics of an MPAR unit suitable for deployment in a national network. Tests and studies performed with the NWRT are vital for technical and programmatic risk-reduction activities. They can also validate the cost and operational parameters essential to a rational acquisition decision between implementing an MPAR network or proceeding with another alternative to ensure that the Nation’s aging radar infrastructure continues to meet national surveillance needs.

3.2 Technical Comparison of MPAR and MRCR for a Civilian Radar Surveillance Network

This section compares *technical* capabilities, constraints, and opportunities (e.g., growth potential) of a network of MPAR units—incorporating electronic scanning, agile beam-forming, and wide-bandwidth capabilities—with the corresponding characteristics of a network of MRCR units like those currently deployed in the Nation’s civilian weather surveillance and aircraft surveillance networks. Although this section develops the technical foundations for cost comparisons between MPAR and MRCR alternatives, a full treatment of cost and affordability is reserved for chapter 6. Performance features covered here apply to both atmospheric and aircraft surveillance applications.

3.2.1 Multifunction Capability

With MPAR, aircraft tracking and environmental surveillance (including weather surveillance) could be performed simultaneously with the same radar unit. The agility of phased array radars to form and steer beams in any direction at millisecond intervals will allow a single affordable system to perform these multiple functions, as illustrated in figure 3-1.

By contrast, mechanically scanned reflector radars cannot simultaneously meet weather surveillance requirements for high angular resolution and non-cooperative aircraft surveillance requirements for rapid volume scan update rates. Today's weather and aircraft surveillance radars, for example, employ fundamentally different, non-compatible beam shapes and scanning patterns to accomplish their respective missions. (Section 4.1 gives details on these differences and how an MPAR design can perform both missions.)

---

[2] As noted in section 1.1, the SPY-1 S-band phased array radar was developed by RCA for the Navy Aegis weapon system.

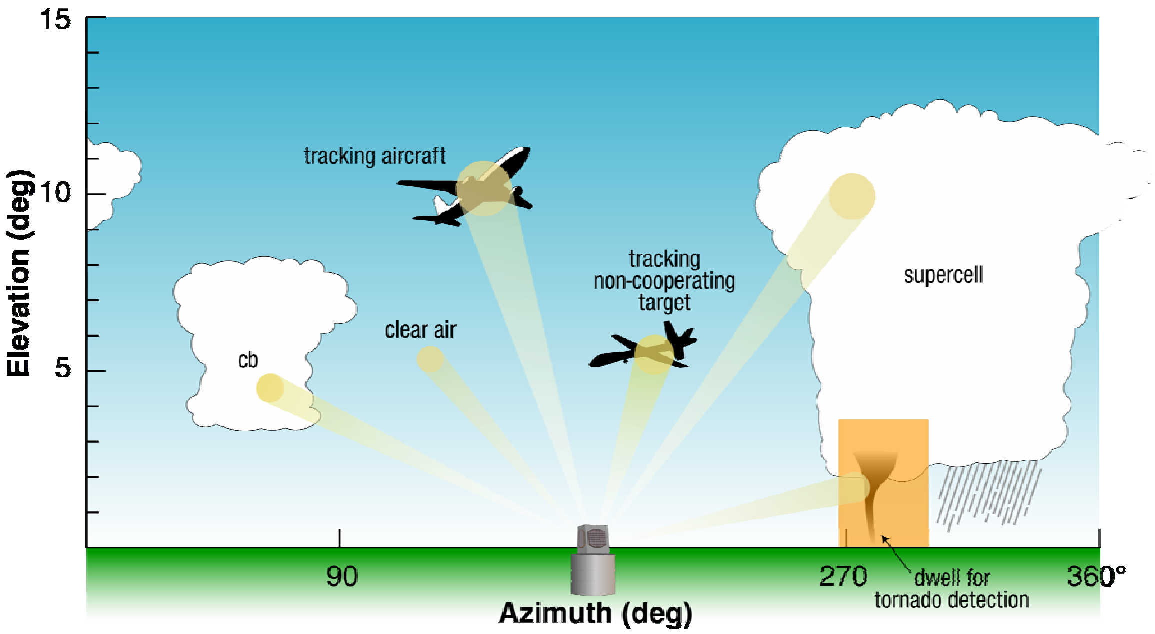

Figure 3-1. Capabilities of agile beam phased array radar.

Panorama of the coverage is shown over a full 360° in azimuth and 15° in elevation, but the radar adaptively covers and observes the whole hemisphere; i.e., up to 90° in elevation. Illustrated functions clockwise from left: full-volume continuous scan through a developing cumulonimbus cloud, full-volume continuous scan through the planetary boundary layer (clear air) for mapping winds, detection and tracking of aircraft including non-cooperative targets, full-volume continuous scan through a supercell storm, and long-dwell scan through a region of a potential tornado.

3.2.2 Rapid Scan Capabilities

A properly designed and configured MPAR will be able to complete full 360° volumetric scans for both its weather and aircraft surveillance modes at faster rates than today's radars (see, for example, figure 4-2). For the weather function, scan periods of 20 to 60 seconds—significantly shorter than the 4 to 6 minutes provided by the WSR-88D—are achievable.

3.2.3 Flexible Tracking

The flexibility of MPAR allows tracking of designated targets (such as a non-cooperative aircraft) at the rate necessary to prevent loss of track. Tracking rates are not restricted to the rotation rate of the antenna, as they are with MRCR. MPAR capability for intensive interrogation of particular phenomena enables detailed documentation, never before available, of the life cycle of short-lived features such as aircraft performing unusual maneuvers, atmospheric vortices (including tornadoes), and updrafts and downdrafts (including microbursts). With MRCR, observation of such phenomena cannot be achieved because of the time lag required to rotate the antenna to the target location.

3.2.4 Resolution

Phased arrays provide better angular resolution of the beam than does MRCR with the same beam width and wavelength because there is no smearing due to antenna angular motion. With all other operating parameters the same, an MPAR unit will provide environmental data clarity that far surpasses current MRCR systems for weather or aircraft surveillance.

3.2.5 Radar Unit Maintenance and Operational Availability

The MPAR units proposed for evaluation as a national radar network will be active solid state phased radars. As described in section 1.1, each unit will be built as an array of solid state devices with no moving parts. The Navy's experience with the SPY-1 phased array radar demonstrates that up to 10 percent of the transmit-receive (T/R) elements on a face can fail before there is significant degradation in performance of the radar. There is no single point of failure in the system, such as in the vacuum tube transmitters still employed in many current MRCR units or in the antenna pedestal common to all MRCR designs. The robustness of this built-in redundancy of MPAR systems has been demonstrated with deployed DOD phased array radars, which have been successfully maintained for extended periods of operation by high school graduates with system-specific training but no advanced engineering expertise. The capacity for graceful degradation, rather than catastrophic loss of function, means that an MPAR network will not require continuous-on-site technical and maintenance support staff contracted for quick response, thereby lowering O&M costs, as discussed in chapter 5.

3.3 Comparison of MPAR and MRCR for Atmospheric Measurements

Performance features covered in this section are specific to atmospheric sensing for environmental surveillance applications, including the weather surveillance functions currently performed by the NEXRAD network of WSR-88D radar units.

3.3.1 Beam Blockage Mitigation

The elevation angle of an MPAR beam can be programmed to follow the true horizon, taking into account the blockage pattern of ground objects within the scan range of the unit (buildings, trees, mountains, etc.). This feature allows compensation for the spectral moments and polarimetric variables for the beam blockage effects, enabling the beam to be positioned to provide data for the best rainfall estimates near the ground, where precipitation rates and amounts are most important for most meteorological and hydrologic applications, including flash flood forecasting, surface trafficability, and wildfire management. Because MRCR in continuous full-scan mode lacks this flexibility to follow the true horizon, these compensation techniques are not applicable.

3.3.2 Mitigation of Ground Clutter Effects and Improved Spectrum Width

The motion of the rotating antenna in MRCR increases radar data uncertainties at or near the surface. The Doppler effect from the relative motion of the beam over surface features introduces variability from scan to scan that limits ground clutter cancellation techniques. However, the beam of a phased array radar does not have azimuthal motion relative to ground clutter, so clutter cancellation techniques are more effective. Phased array radar is thus better at compensating for biases caused by clutter filtering in the polarimetric variables and spectrum widths.

3.3.3 Enhanced Observation of Weather Phenomena Enabled by MPAR

MPAR offers the prospect of routinely sampling the atmosphere with volume scan rates up to an order of magnitude faster than some of the operational scan modes of the WSR-88D radar. Real-time access to data with this higher level of temporal resolution would offer immediate and tangible societal benefits through improved hazard warning (e.g., microburst and tornado/mesocyclone detection), nowcasting, and guidance for aviation operations. By enabling quantitative analysis of convective phenomena on time scales of less than 1 minute, rapid-scan MPAR would also have profound and wide-ranging benefits for storm-scale and mesoscale meteorological research.

Data processing algorithms can use the radial wind speed measured by a single radar unit to estimate the complete wind vector field. The accuracy of these algorithms in estimating the vertical velocity depends critically on the availability of rapidly scanned data. Research suggests that a dramatic reduction in velocity error can be achieved as volume scan time decreases from 5 minutes to 1 minute. Although MPAR is capable of full-volume continuous scans near the low end of this range, MRCR scan times are constrained by the speed at which the mechanically rotating antenna can turn.

Turbulent Storm Characteristics and Consequent Phenomena. Smaller scale, more transient features of convective storm structure are well suited for observations with an MPAR unit. Vortex flows abound in nature. The smallest of these vortices are generally short-lived. Repetitive, rapid observations made possible by MPAR at close range can detect and provide warning of some of the more hazardous of these vortices. MPAR measurements can aid in formulating and testing theories of one of the major unanswered questions of meteorology: how tornadoes form.

Better NWP Parameterization. The improved wind field estimates from MPAR will provide better parameterizations of the atmospheric boundary layer in mesoscale, regional, and climate NWP models. Convective models of actual weather situations require accurate knowledge of wind vectors refreshed at intervals of less than one minute. Indeed, it has been found that convective structures have large amounts of kinetic energy on spatial scales of 1–2 kilometers and temporal scales of 1–3 minutes. Capturing these energy-containing structures properly requires knowing the wind speed at intervals of less than 1 minute.

Initialization and Data Assimilation for Convective Cloud Modeling. Weather instabilities can be predicted by incorporating rapidly updated wind vector data in models at convective cloud scales. Perhaps the most important application for such predictions is for initialization and data assimilation of fine-scale and mesoscale NWP models. In addition, when convective weather is present, assimilation of radar data and derived fields into these models has the potential to reduce the time for representations of physical processes in the models to generate convective elements with non-convective background fields.

3.3.4 Improving Tornado Lead Times

Tornado lead times are a performance metric applied to the U.S. Department of Commerce under the Government Performance Results Act of 1993. The improvements in weather observations from MPAR could increase tornado lead times from the current 12–13 minutes to perhaps 45 minutes. Tornado warnings are based on *detecting* precursors to tornado formation and extrapolating these features forward in space and time. The current limit on detecting tornado precursors is approximately 20 minutes. This 20-minute threshold could be crossed by using very high resolution NWP models that are programmed to *forecast* thunderstorm rotation and tornado circulation in advance of their occurrence. Figure 3-2 shows what a tornado forecast of this kind might look like. Because of constraints on the refresh rate and resolution issues, MRCR technology is highly unlikely to break the 20-minute threshold for tornado warning lead times.

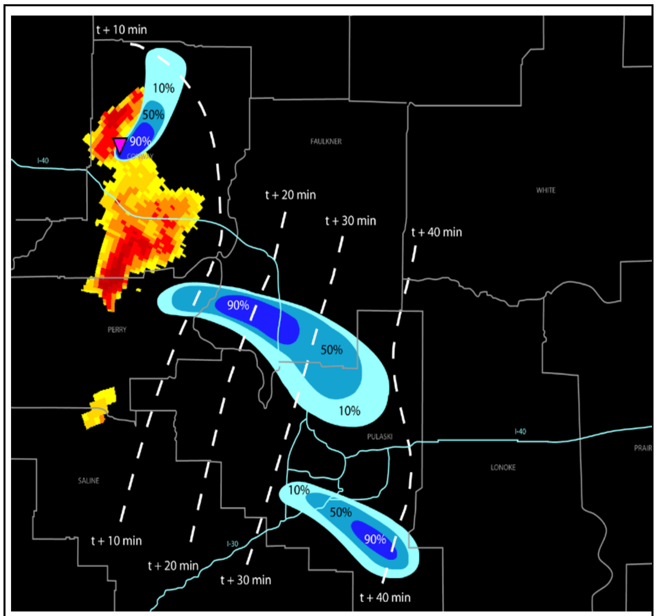

Figure 3-2. Tornado lead times.

MPAR may enable average tornado lead times to be extended to 45 minutes by issuing warnings based on forecasts from earlier precursor conditions.

3.4 Comparison of MPAR and MRCR for Aviation Applications

The United States operates an aircraft surveillance infrastructure comprising almost 350 aging MRCR units of more than five different design types (see table 3-1). A single network of MPAR units could replace all of these aging radars, providing the following capabilities to the NGATS.

3.4.1 Confirming Reports from Cooperative Aircraft

As explained in chapters 1 and 2, the FAA plans to expand the role of cooperative surveillance in the air traffic control system by implementing Automated Dependent Surveillance–Broadcast (ADS-B). The accuracy and reliability of the position information transmitted by a cooperating aircraft will depend on radio navigation systems such as the Global Positioning System (GPS) satellite navigation system and on proper operation of the ADS-B equipment installed in the aircraft.

By providing an independent source of non-cooperative surveillance information, a network of MPAR units can verify the position transmitted by the cooperating aircraft. A network of MPAR units can provide an accurate three-dimensional track, including the altitude of all targets. This MPAR network will track the targets at a rate that will ensure a track is not lost. The track rate will not be limited to the rotation rate of the antenna, as it would be with MRCR alternatives. Instead, the track rate can be adjusted, based on the quality of the existing track.

The MPAR technology proposed for evaluation includes an advanced monopulse measurement system. This system ensures the radar unit will have the capability to measure the position of a target to within 1/10th of the beam width. Thus, if the radar has a 1° beam width, the angular position of a point target will be observed to a precision of 0.1°. The system will take advantage of the latest in monopulse technology, like that on the Navy SPY-1 phased array radar units, which have implemented advanced algorithms to enable accurate monopulse measurements at low angles. This technology will enable the proposed MPAR to make very accurate altitude measurements.

An MPAR network could thus serve as a seamless backup for and complement to the FAA's primary cooperative aircraft surveillance system. It will provide the FAA with assured independent confirmation of the accuracy of the ADS-B system. This confirmation capability can eventually eliminate the need for the Mode-S transponder system and the radar that supports it, resulting in significant savings by both the FAA and the air transport industry.

3.4.2 Situation Awareness of Non-Cooperative Aircraft

An MPAR network can track all objects of interest in the NAS. Both the ADS-B system and the MPAR network will provide three-dimensional tracks on objects. Correlation of the tracks between the two systems will establish the identity of most objects and confirm their location and heading. The track rate on objects that correlate (i.e. known objects) can be adjusted to ensure that the MPAR system maintains a track on the object. All objects not identified as known cooperating aircraft (or birds, balloons, and other identifiable non-aircraft objects) will be defined as non-cooperating. Track correlation can thus produce fast and accurate position identification of non-cooperating objects of concern. The MPAR-produced position, including altitude measurements, will have the accuracy required for law enforcement aircraft to locate threats without the need for ancillary sensors.

3.4.3 Bird Strike Mitigation

The FAA has long recognized the threat to aviation safety posed by bird strikes and estimates their cost to civil aviation as $1.2 billion annually.[3] Flocks of birds produce a radar signature recognizable to weather surveillance radar researchers. The unique characteristics of this signature need to be evaluated to develop algorithms for recognizing bird targets, which can then be tracked. Polarimetric data from MPAR could be automatically processed with such algorithms to substantially reduce the risk of bird strikes. Whereas MPAR provides the beamforming and signal processing flexibility to implement a secondary objective like bird strike mitigation, a single-function, single-beam MRCR could not perform this task at the same time as its primary surveillance tasks.

3.4.4 Weather-Related Improvements

All of the weather surveillance improvements with MPAR, described in section 3.3, will enable improvements in aviation operations. Air traffic controllers and dispatchers will be able to route traffic around hazardous weather more efficiently. Carriers and airports will be able to predict delays due to weather more accurately. Improvements in severe weather observations and forecast skill will increase safety while enabling the air traffic system to function more efficiently.

3.4.5 Decreasing Aircraft Separation Safely

With the redundancy and improved tracking and position reporting provided by correlation of the ADS-B aircraft locations with track data from an MPAR network, as well as better aviation weather information, the current aircraft separation standards for near-terminal and en route flight can be reduced without compromising safety. Reducing the separation standards will allow air traffic in the NAS to increase, particularly in the vicinity of airports, thereby helping to meet NGATS objectives.

3.5 Summary

Agile beam phased array radars like the proposed MPAR have unique capabilities and advantages relative to conventional rotating-antenna radars. A single MPAR unit can be used for multiple applications, including non-cooperative aircraft surveillance, rapid full-volume weather surveillance scans, and increased dwell time on weather phenomena or airborne objects of concern. Adaptive scanning of volumes can be directed to where it matters most, be it to observe the weather, detect and track intruding aircraft, or confirm the track of cooperating aircraft. Compared with MRCR alternatives, MPAR provides vastly superior data quality—including minimization of ground clutter—because of its more rapid updates (faster scan rate) and absence of beam smearing. Unlike current MRCR Doppler weather radars, MPAR can measure winds transverse to the radar beam, as well as radial winds. As chapter 6 will explore in detail, MPAR's multifunctional capability also means that the long-term cost of maintenance, training, and operations

---

[3] FAA Advisory Circular No. 150/5200-32A. *Reporting Wildlife Aircraft Strikes.* 22 December 2004.

would be less than required by the multiple networks of different MRCR units operating today.