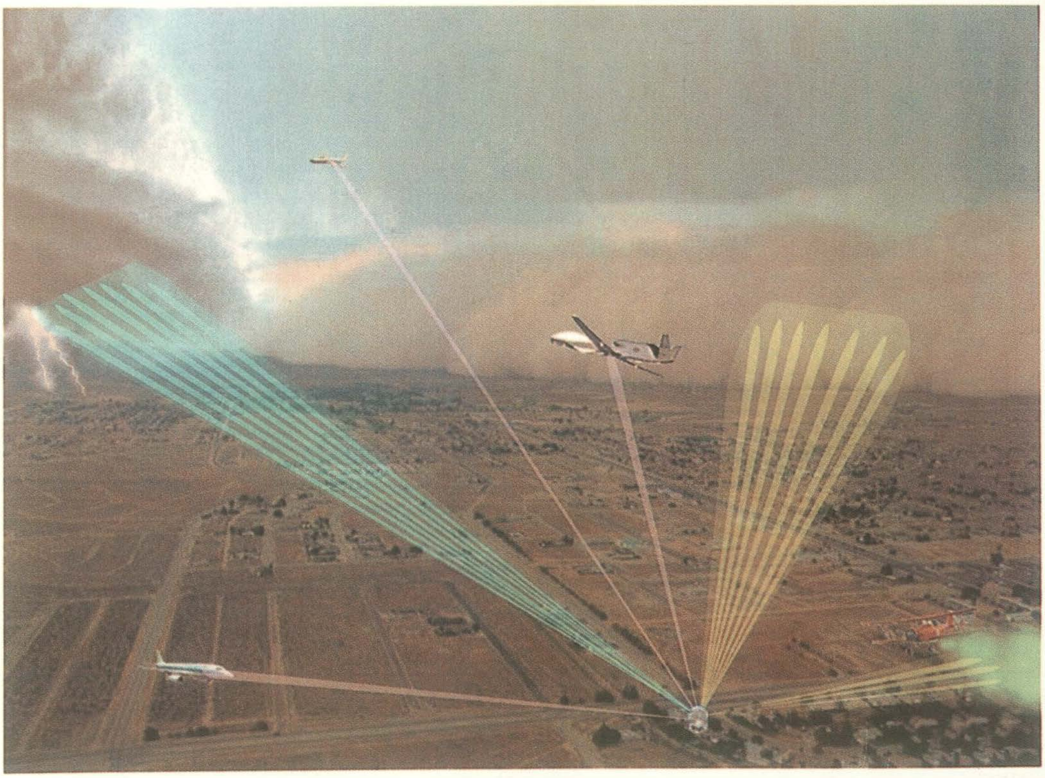
INTERDEPARTMENTAL COMMITTEE FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

COMMITTEE FOR COOPERATIVE RESEARCH (CCR)

JOINT ACTION GROUP FOR PHASED ARRAY RADAR PROJECT
(JAG/PARP)

Federal Research and Development Needs and Priorities for Phased Array Radar

FCM-R25-2006



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Office of the Federal Coordinator
for Meteorological Services and
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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. Historically, civilian radars with large rotating antennas like the NEXRAD weather surveillance network and the aircraft surveillance radars used by the Federal Aviation Administration (FAA) evolved from military radar applications. During the past several decades, a new generation of military radars has matured. These electronically scanning phased array radars with no moving parts (rotating antennas) were originally developed to track multiple airborne objects such as aircraft and missiles simultaneously. The unique beam agility, increased resolution, and faster full-volume scan rate of phased array radar can enable a single radar unit to perform multiple weather and atmospheric surveillance tasks and, at the same time, track multiple airborne craft.

Thus, a single network of multifunction phased array radar (MPAR) units could provide next-generation expansion of our current weather surveillance network, replace the Nation's aging air traffic surveillance radars, meet homeland security and defense requirements for identifying and tracking non-cooperative craft operating over the U.S. homeland, and become an integral part of achieving National and International goals set for the Global Earth Observation System of Systems (GEOSS).

- MPAR will enable continued improvement of the Nation's severe weather warning system. It can provide adaptive sensing for warnings and nowcasts related to severe convective storms and the locally destructive effects of hurricanes (tropical cyclones) after they make landfall. Among the storm phenomena that could be tracked are tornadoes, strong wind gusts, hail, and locally heavy rains responsible for flash floods and mudslides. The result: more timely and accurate high-impact warnings for our nation's populace.

- The enhanced weather surveillance provided by an MPAR network will provide economic benefits to domestic aviation and surface transportation systems. The agility and specificity of its multitasking beams will provide more detailed weather and atmospheric observations for urban meteorology, air quality nowcasts and forecasts, climate variability monitoring and forecasting, wildland fire monitoring and prediction, and atmospheric transport and diffusion modeling. While research has established the proof-of-principle for new applications of weather radar in these and other areas, the adaptive flexibility of MPAR will be essential in transferring these promising radar techniques to operations.

- The non-cooperative aircraft surveillance capability of an MPAR network would complement the cooperative surveillance strategy planned for the Next Generation Air Traffic System (NGATS), while also addressing new craft tracking requirements of the Departments of Defense and Homeland Security.

Because an MPAR network would replace multiple existing networks, it offers an affordable option to the alternative strategy of continuing with the existing civilian radar capability by repairing and eventually replacing aging units. Due to technology breakthroughs in radio frequency components, fueled by the wireless telephony and digital communications industries, the cost of a key MPAR component—the transmit-receive elements in an MPAR antenna—has dropped by orders of magnitude over the past 5 years, and this trend should continue. For a number of reasons, the operations and maintenance costs for MPAR units appear to be a third area of substantial savings relative to continuing to repair and replace current radar units as they age.

Thus, with respect to both capabilities and cost, MPAR is a promising option for meeting the Nation's future domestic radar surveillance needs. The proposal put forward in this report, however, is not to decide now between MPAR or an alternative approach to meeting those needs. Before we can make this important decision with reasonable confidence, a near-term program of targeted research and development (R&D) is necessary to establish definitive answers to specific technical issues, as well as to validate preliminary cost analyses and network concepts. This report, produced by the Joint Action Group for Phased Array Radar Project, documents the current and future Federal agency needs that can be met with domestic surveillance radar systems, details potential benefits that may be realized from this technology, and proposes an R&D plan to evaluate an MPAR option to meet these needs and realize the benefits.

Working with our partners and stakeholders, we must capitalize on emerging science and technology to enhance public and aviation safety. We must seek to reduce hazardous risks through science and service, with the ultimate goal of saving lives, reducing injuries, and, where possible, protecting property and resources. Therefore, I urge Federal agencies with a stake in any of the applications enabled by surveillance radar to study the report and consider integrating its recommendations into their R&D programs.

Samuel P. Williamson
Federal Coordinator for Meteorological Services
and Supporting Research

MEMORANDUM FOR:	Mr. Samuel P. Williamson Federal Coordinator for Meteorology
FROM:	Cochairpersons. Joint Action Group for Phased Array Radar Project (JAG/PARP)
SUBJECT:	Report on Federal Research and Development Needs and Priorities for Phased Array Radar

The JAG/PARP has completed its assigned tasks to: (a) determine the specific needs of Federal agencies that could be met by surveillance radar, (b) show the benefits of phased array radar capability in meeting these needs, and (c) explore opportunities for expanded participation in the Phased Array Weather Radar Project (FCMSSR Action Item 2002-4.1). We are pleased to provide the subject report, titled: *Federal Research and Development Needs and Priorities for Phased Array Radar*.

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CONCURRENCES:

The undersigned concur that the report, *Federal Research and Development Needs and Priorities for Phased Array Radar,* meets the tasks assigned to the JAG/PARP under FCMSSR Action Item 2002-4.1.

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EXECUTIVE SUMMARY

All current civilian radar systems for weather surveillance and aircraft surveillance use a rotating antenna. The transmitted beam is shaped and directed by the antenna's reflective surface. The continuous physical rotation of the antenna around a vertical axis causes this beam to sweep a volume of space surrounding the radar unit. In a phased array radar, by contrast, the beam emanates from a stationary surface and is shaped and steered electronically; there is no rotating antenna. This capability to form and steer a radar beam permits multiple radar functions to be performed with the same radar unit: a *multifunction* phased array radar, or MPAR. Phased array radar technology has been used operationally by the U.S. military since the 1970s. For civilian aircraft and weather surveillance, MPAR can greatly improve capability while reducing life-cycle costs because multiple radar applications can be performed with the same radar unit. The electronically scanning array panels of an MPAR can accomplish diverse surveillance tasks much more quickly, flexibly, and at higher resolution than can the mission-specific, rotating antenna systems in use today.

In 2002, the Federal Committee for Meteorological Services and Supporting Research (FCMSSR) directed the Federal Coordinator for Meteorological Services and Supporting Research to (a) determine the specific needs of Federal agencies that could be met by surveillance radar, (b) show the benefits of phased array radar capability in meeting these needs, and (c) explore opportunities for expanded participation in the Phased Array Weather Radar Project (FCMSSR Action Item 2002-4.1). Initial work on these tasks led to the formation in late 2004 of the Joint Action Group for Phased Array Weather Radar Project. When this group established the feasibility of a single phased array radar unit performing both aircraft surveillance and weather surveillance functions, it was renamed the Joint Action Group for Phased Array Radar Project (JAG/PARP). This report presents the detailed response from the JAG/PARP to the original FCMSSR Action Item.

> **Multiple Federal agencies currently rely on radar networks to provide essential services to the Nation. The principal current uses are for weather surveillance and other atmospheric observations and for aircraft surveillance.**

Agencies whose mission areas already are or could be impacted by improved radar capabilities for weather surveillance include the National Oceanic and Atmospheric Administration (NOAA) and NOAA's National Weather Service (NOAA/NWS), the Federal Aviation Administration (FAA), Federal Highway Administration, National Aeronautics and Space Administration, the Department of Agriculture (including the U.S. Forest Service), the Department of the Interior (National Park Service, Bureau of Land Management, and the U.S. Geological Survey), the Department of Homeland Security (Federal Emergency Management Agency, U.S. Fire Administration, and U.S. Coast Guard), Department of Defense (Air Force, Navy, and Army for domestic and homeland defense operations), and the U.S. Environmental Protection Agency.

With respect to aircraft surveillance, the FAA plans to transition from ground-based radar for civilian aircraft surveillance to the Automated Dependent Surveillance–Broadcast (ADS-B) system, in which cooperating aircraft will transmit identification and position data to air traffic controllers. Even with ADS-B, radar surveillance of the National Airspace System (NAS) will continue to be essential for detecting, identifying, tracking, and—if necessary—interdicting non-cooperative aircraft. MPAR also provides confirmation of ADS-B positions, as well as a backup system for identifying and tracking cooperative aircraft. Radar surveillance thus complements the planned cooperative surveillance strategy.

A single MPAR network with the capabilities described in this report could perform all of the existing civilian radar functions. In addition, other existing and emerging needs not being adequately met by existing systems could be met with this same MPAR network.

The beneficial uses for radar observations of atmospheric phenomena are expanding to new applications with substantial value for increased safety and National economic growth. Radar can be used to detect precipitation type and quantify precipitation rate on the spatial and temporal scales necessary for advanced applications in quantitative precipitation forecasting and flash-flood nowcasting. Wind and turbulence phenomena observable by new radar techniques can improve warning times for tornadoes and severe thunderstorms; for wind shear, wind gusts and shifts, and microbursts; and for the local spin-off effects of cyclonic storms interacting with terrain.

These advanced radar observing capabilities, coupled with the improvements in numerical weather prediction (NWP) modeling that advanced radar data make possible, have application to downstream needs as diverse as fire weather and wildland fire management, debris flow prediction, spaceflight launch and recovery, and "ground truth" for calibrating and validating new generations of satellite-borne remote-observing instruments. Radar can also aid in detecting natural hazards to aviation not caused by atmospheric conditions alone, such as bird flocks and volcanic ash plumes.

A comprehensive list of Federal departments and agencies that would benefit from expanded radar surveillance capability—particularly if the multifunction, agile-beam capabilities of an MPAR network were available—includes all of those listed above plus the Department of Energy, the National Interagency Fire Center and the Fish and Wildlife Service of the Department of the Interior, and the Centers for Disease Control and Prevention. Even longer is the list of State and local partners who work with these Federal entities in providing the Nation with emergency preparedness and response, air quality monitoring and enforcement, and safe and efficient transportation systems and infrastructure.

The timing is right to conduct a thorough evaluation now of MPAR as an alternative to conventional radar for the full range of current and emerging applications described in this report. The aging of our existing domestic

> **radar networks for weather and aircraft surveillance will require substantial commitments of Federal resources to either maintain or replace them.**

Seven of these aging, single-function conventional radar networks could in principle be replaced by a single network of MPAR units, with each unit capable of performing multiple functions. A shift in National strategy from multiple networks of mechanically rotating conventional radars to one MPAR network could provide all the capability of the existing systems while also enabling many new observing capabilities for the growing number of downstream applications summarized above and discussed in chapter 2.

When MPAR capabilities are compared with those of conventional radar technology, as chapter 3 of this report does in detail, the technical advantages of MPAR are overwhelming. However, before a decision is made between continuing with conventional single-function radars or an MPAR network, some specific technical issues, discussed in chapter 4, need further testing and demonstration to ensure that the necessary MPAR technology is mature enough to proceed with this major shift in strategy.

> **A preliminary cost evaluation shows that one MPAR network designed to meet multiple national needs can be developed, implemented, and maintained at a lower cost, on a life-cycle basis, than would be required to sustain the existing conventional radar networks through required maintenance and incremental upgrades.**

An MPAR network using today's technology is likely to be a cost-effective option, and technology trends provide opportunities for further cost reductions. Rapid advances in technology and manufacturing economies of scale, driven by the commercial wireless telecommunications industry, have decreased costs substantially and will continue to do so. In a preliminary study of required radar coverage, analysts from MIT Lincoln Laboratory concluded that a network of about 334 MPAR units could replace the roughly 510 units in the seven aging, disparate networks—a 35 percent reduction in radar units. Replacing current networks with 176 fewer radars with an average cost of $10 million each could yield a $1.8 billion savings just in initial acquisition costs. The preliminary cost analysis estimates a further $3 billion savings in operations and maintenance (O&M) costs over the 30-year lifespan of an MPAR network, if aggressively implemented, compared with the total O&M cost to continue with the legacy systems. These preliminary studies need to be refined and validated before a decision on National domestic radar strategy is made.

MPAR enables a 35% reduction in radar surveillance units to provide weather and aircraft surveillance coverage of current domestic surveillance radar assets.

PLUS

MPAR can save $1.8 billion in replacement acquisition costs.

PLUS

MPAR can save an additional $3 billion in life-cycle costs over 30 years.

The JAG/PARP proposes a risk-reduction research and development (R&D) plan that, for a modest investment, will provide a sound technical and cost basis for a National decision between MPAR implementation versus continued maintenance and upgrade of the aging, existing radar systems. The estimated total cost for this risk reduction plan is $215 million.

The technical, cost, and programmatic risks associated with an MPAR network strategy can be reduced substantially by a targeted R&D program, to be completed prior to the time that substantial resource commitments must be made to sustain current radar coverage and capability. This R&D program comprises three components.

1. A technology development and test program will lead to construction of a prototype MPAR unit.
2. Proof of MPAR operational concepts will be conducted initially using the phased array radar of the National Weather Radar Testbed (NWRT), then using the MPAR prototype.
3. The provisional MPAR network concept will be refined using the NWRT, several research radars with appropriate transmission bands, and analysis of data from the legacy radar systems.

On the basis of these findings, the JAG/PARP makes four recommendations to the FCMSSR for actions that will take the next steps toward a coordinated, rational decision on a National strategy to provide domestic radar capability for the next 30 years.

Recommendation 1. The FCMSSR should endorse the concept of an MPAR risk-reduction R&D program that substantially incorporates the objectives and the three components of the plan outlined in chapter 6 of this report.

Recommendation 2. The FCMSSR should consider organizational options to foster collaborative and joint R&D on the MPAR risk reduction activities by establishing a joint entity, such as a Joint National Center for Advanced Radar Research and Development, to manage agencies' contributions to the risk reduction program outlined in this report.

Recommendation 3. For the period prior to operational standup of a joint management entity, the FCMSSR should direct OFCM to form an interagency MPAR Working Group (WG/MPAR) within the OFCM infrastructure to coordinate and report on the R&D activities of participating agencies in implementing an MPAR risk-reduction program. Activities of the WG/MPAR should include, but not be limited to:

- Identification of agency contributions to the first phase of risk-reduction activities in each component prong of the program.
- Establish a cost basis for near-term agency contributions, sufficient to allow incorporation into agency budget submissions.

- Explore options to foster interagency cooperation and collaboration on MPAR risk-reduction activities.
- Develop a set of specific program progress metrics against which annual progress toward risk-reduction goals and objectives can be assessed.
- Prepare and publish an annual statement of the next-year objectives and activities for the risk-reduction program. This annual statement should include a review of progress in the current year and connections to out-year activities and objectives, to show how each year's activities contribute toward achieving the overall risk-reduction goals. As guidance to the participating agencies, the report should include an estimate of budget resources needed for the next-year activities and a summary of prior-year funding by agency. Progress toward goals and objectives, using the program metrics, should be reported each year, with an analysis of areas of shortfall and of substantial progress.
- Identify opportunities for review of program plans and progress by appropriate boards or study committees of the National Academies' National Research Council (NRC).
- Prepare and publish an MPAR Education and Outreach Plan to build understanding of and garner support for a National surveillance radar strategy decision within all the potentially affected Federal agencies, Congress, State and local governmental entities, the private sector, and the public. This plan should involve the academic community and the media and include dissemination of results from the NRC studies suggested above. A series of workshops, coordinated through the National Center for Atmospheric Research (NCAR), should be considered for engaging the academic research community.

Recommendation 4. The FCMSSR should direct that, in conjunction with the MPAR risk-reduction program, a cost-benefit analysis be undertaken to establish the cost-effectiveness of the MPAR option and competing domestic radar strategies. The basis for MPAR acquisition and life-cycle costs should include results from the technology development and test activities and the MPAR network refinement, as appropriate.

1 INTRODUCTION

1.1 Historical Evolution of Radar Applications

During World War II, radar (radio detection and ranging) was initially conceived as a system to help ships avoid obstacles. It matured into an operational technology to counter enemy military activity, particularly airborne forces. The broader utility of radar was quickly recognized, and the technology was soon applied to meet civilian aviation's growing requirements. As radar technology matured, its utility for observing weather phenomena was recognized and exploited. In effect, the "clutter background" that atmospheric phenomena represent for a primary aircraft surveillance radar application becomes the "signal" interpreted in meteorological applications of radar:

> The major distinction between meteorological radar and other kinds of radars lies in the nature of the targets. Meteorological targets are distributed in space and occupy a large fraction of the spatial resolution cells observed by the radar. Moreover, it is necessary to make quantitative measurements of the received signal's characteristics in order to estimate such parameters as precipitation rate, precipitation type, air motion, turbulence, and wind shear. In addition, because so many radar resolution cells contain useful information, meteorological radars require high-data-rate recording systems and effective means for real-time display [of all this information]. Thus, while many radar applications call for discrimination of a relatively few targets from a clutter background, meteorological radars focus on making accurate estimates of the nature of the *weather clutter* itself. This poses some challenging problems for the radar system designer to address.
>
> (Serafin 1990, pg. 23.2)

Weather surveillance radar has enhanced immeasurably the quality of information on current conditions and the value of warnings and predictions of imminent or future conditions available to the public, to transportation safety communities, and to other segments of the economy affected by the weather.

There have been many significant improvements for both aircraft surveillance and weather surveillance since radar systems were first fielded for these applications. As valuable, and even essential, as these radar applications have become, they are now poised for order-of-magnitude improvement in both performance and reliability. The enabling technology is multifunction phased array radar (MPAR).

Figure 1-1 illustrates the basic difference between a phased array radar and radars that use a rotating parabolic antenna, as do all current civilian aircraft and weather surveillance radar systems. In a mechanically rotating conventional radar (MRCR), the transmitted beam is shaped and directed by the antenna's reflective surface. The

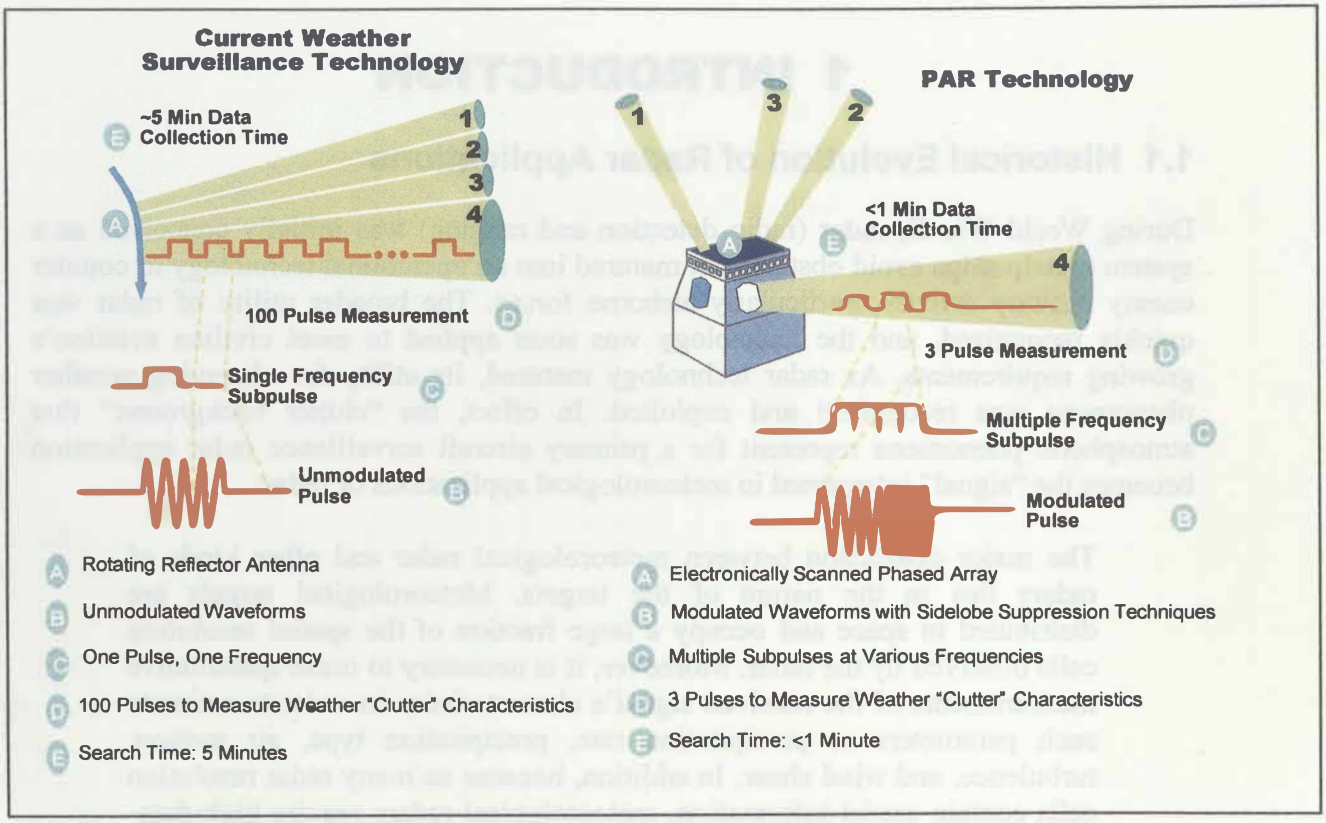

Figure 1-1. Basic differences between a mechanically rotating conventional radar (left) and MPAR (right).

continuous physical rotation of the reflector around a vertical axis causes the beam to sweep a volume of space surrounding the radar unit. The reflector is tilted to change the angle of the beam's center from the horizontal. A phased array radar has no rotating reflector to shape and steer the transmitted beam. Instead, the output from an array of radiators is shaped and steered by controlling the phase and the off-on timing (pulsing) of the electromagnetic field generated by each radiator relative to the phases and pulses of the other radiators in the array. The interference pattern resulting from the interactions of all the radiated fields forms the radio-frequency beam transmitted by this array antenna. Each radiating face of a phased array radar is built up of thousands of solid state modules called transmit-receive (T/R) elements. Each of these elements plays a small part, transmitting a small portion of the total beam energy and receiving a portion of the reflected radar echoes.

Electronically controlled attenuators, phase shifters, switches, channelizing filters, high-speed analog-to-digital converters (ADCs), and high-speed digital processors are the fundamental technologies underlying advances in phased array radar design and applications. New generations of these basic electronic components have enabled rapid and accurate formation and steering of the radar beams. This beam-steering capability in turn permits multiple radar functions to be performed with the same radar unit: a *multifunction* phased array radar, or MPAR. The function-specific beams of an MPAR may be interlaced in time or even generated simultaneously.

Phased array radar technology has been used operationally by the U.S. military since the 1970s. Although extensive technical capability has resulted, applications of phased array radar have thus far been limited to specific types of military surveillance, such as sector air defense against aircraft and missile threats. The technical issues are well understood and surmountable. Representative military applications include the following.

- The AN/SPY-1 is a naval 3D, long-range surveillance-and-track S-Band MPAR. Units are installed in 81 U.S. Navy ships. AN/SPY-1 is currently in development for Navy sea-based (ballistic) missile defense and is the only surface MPAR to demonstrate simultaneous weather and aircraft surveillance. The manufacturer is Lockheed Martin.
- AN/APG-81 is an airborne X-band multifunction active phased array radar for the F-35 fighter (Joint Strike Fighter). The radar has multiple air-to-air and air-ground modes for search, track, and target identification. The manufacturer is Northrop Grumman.
- MP-RTIP (Multi-Platform Radar Technology Improvement Program) is an airborne X-band multifunction active phased array radar for use on the Multimission Command and Control Aircraft B-767 aircraft. The radar has multiple air-air and air-ground modes for search, track, and target identification. It is manufactured by a Northrop Grumman/Raytheon team.
- The AN/SPY-3 surface X-band multifunction active phased array provides horizon search and fire control for the future Navy CVN-77 aircraft carrier and DD(X) warship. The manufacturer is Raytheon.
- The DDX (next generation) destroyer radar suite is composed of an AN/SPY-3 X-Band multifunction radar and an S-Band Volume Search Radar (VSR). Both are the first active, solid state phased arrays to be introduced to the Navy's surface fleet. The beam width of the multifunction radar is too narrow for volume search, which requires the VSR. Lockheed Martin is the developer and manufacturer of the VSR.
- The Multi-Mission Radar (MMR) system is a highly mobile multimission solid state S-band phased array radar that provides the warfighter with capabilities to detect, track, identify, report, and communicate the position and velocity vector of airborne targets. It also detects, classifies, reports, and communicates the firing point and impact point of mortars, artillery, and rockets. To support early entry forces in contingent theaters or maneuvering forces, the MMR system will be configured for installation on a High Mobility Multipurpose Wheeled Vehicle (HMMWV) and transportable on a single C-130 sortie. Syracuse Research Corporation manufactures the MMR using AN/SPY-1 S-Band T/R module technology from Lockheed Martin.
- The LCMR (Low Cost Counter Mortar Radar) is a soldier-portable L-band phased array that will detect and track almost any moving object in its coverage (360° azimuth by 30° elevation). It will automatically detect, track, and locate mortars between 1 km and 7 km and locate weapons within 100 m (50 percent Circular

Error Probable). To minimize false alarms, the LCMR software was designed *not* to provide a weapon location for any track that does not have the characteristics (speed, trajectory, drag, size, etc.) of a mortar round. The system can be set up by two soldiers. Syracuse Research Corporation is the manufacturer for the LCMR.

1.2 Federal Civilian Agency Interest in Phased Array Radar

Although previously limited to Department of Defense (DOD) systems, phased array radar offers the potential for significant improvements in capability and reduced life-cycle costs for civilian aircraft and weather surveillance by performing these distinct functions with a single radar unit. The electronically scanning array panels of an MPAR can accomplish surveillance tasks much more quickly, flexibly, and at higher resolution than can the mission-specific MRCR systems in use today for these applications. In addition, MPAR shows significant potential to diagnose wind fields at the scale needed to track airborne chemical, biological, radiological, and nuclear plumes.

Because of these potential advantages, multiple Federal civilian agencies have expressed interest in MPAR technology.

- As early as 1995, the Federal Aviation Administration (FAA) commissioned a study by Raytheon on the feasibility of using phased array radar for terminal area surveillance. Although this study, *Terminal Area Surveillance System (TASS),* determined PAR could meet most requirements for aircraft and weather surveillance near the terminal, it also concluded that the high cost of phased array systems would be a limiting factor (Raytheon 1995).
- In 2002, the National Research Council (NRC) report *Weather Radar Technology beyond NEXRAD* recommended establishing the technical characteristics, design, and costs of a phased array radar system applicable to weather surveillance. The report specifically recommended exploring agile-beam scanning strategies, which require an electronically scanning phased array radar system, to optimize overall weather surveillance.
- In 2004, the Joint Planning and Development Office released the *Next Generation Air Transportation System Integrated Plan,* which emphasizes the use of new technology and scientific advances to improve airspace capacity and efficiency while enhancing safety for an anticipated threefold increase in air traffic. MPAR can provide the greatly reduced scan times, high resolution, and multifunction capability required for the enhanced severe weather prediction and aircraft surveillance capabilities envisioned in this plan.
- *The Strategic Plan for the U.S. Integrated Earth Observing System* identifies "expanded deployment of …arrays of phased-array radars to significantly increase the quantity, quality, and timeliness of weather information during extreme weather events."
- The *20-Year Research Vision* of the National Oceanic and Atmospheric Administration (NOAA) predicts tornado warning lead times in 2025 will be on

the order of one hour, rather than minutes. Phased array radar technology could be an integral part of this accomplishment.

The growing attention to the intersection of Federal responsibilities in the areas of homeland security and homeland defense has spurred interest in joint civilian/defense air surveillance systems, for which MPAR is particularly well suited. For example, the DOD document "Strategy for Homeland Defense and Civil Support" states:

> "DOD will also continue to work with interagency partners to develop a common air surveillance picture that will improve our ability to identify and ultimately defeat enemy targets. An improved capability is required to detect and track potential air threats within the United States. The current radars maintained by the Federal Aviation Administration to track air traffic within the United States are aging, with high maintenance costs, poor reliability, and reduced capability to track emerging threats…"

This strategy document further states that "the nation will need to develop an advanced capability to replace the current generation of radars to improve tracking and identification of low-altitude threats."

MPAR technology applied to weather surveillance has the potential to save lives and protect property by identifying severe weather activity earlier, improving rainfall predictions and flash flood warnings, and providing better data to initialize runs of numerical weather prediction (NWP) models. The national aviation system would benefit from improved warnings and forecasts of hazardous weather conditions that affect flight safety and airspace capacity. An MPAR network could be critical to the Department of Homeland Security (DHS) and DOD in providing non-cooperative aircraft detection and tracking in U.S. airspace. It could also provide data to support modeling of atmospheric transport and diffusion (ATD) in the event of an accidental or deliberate release of an airborne chemical, biological, or radioactive hazard.

For the National Airspace System Architecture, the FAA has plans to transition from ground-based primary and secondary radar for civilian aircraft surveillance to the Automated Dependent Surveillance–Broadcast (ADS-B) system, in which cooperating aircraft will transmit identification and position data to air traffic controllers. Nevertheless, surveillance of non–ADS-B aircraft will still be needed to resolve airspace conflicts between them and ADS-B–enabled aircraft. The aircraft surveillance ability of MPAR could also be used as a way to verify an aircraft's position, as well as providing a primary backup system if any part of the FAA ADS-B system were to fail.

1.3 The Joint Action Group for the Phased Array Radar Project

The Joint Action Group for the Phased Array Radar Project (JAG/PARP) is part of an effort underway within the Office of the Federal Coordinator for Meteorology (OFCM) to respond to direction provided by the Federal Committee for Meteorological Services and Supporting Research (FCMSSR). This direction supports the National Science and

Technology Council, Committee on Environment and Natural Resources, Interagency Working Group on Earth Observations 2005 *Strategic Plan for the U.S. Integrated Earth Observation System,* which identified the development and deployment of phased array radars as a program to address current gaps in weather forecasting and observing capabilities.

Acting as the principal agent within the OFCM coordinating infrastructure, the JAG/PARP sought to (1) identify and document the potential needs and benefits of the agencies that phased array radar and an adaptive radar sensing strategy would address, and (2) integrate those identified needs into a multi-agency coordinated research and development (R&D) plan that would help focus exploratory research on adapting phased array radar technology to weather and aircraft surveillance.

The JAG/PARP envisions a national MPAR network that, *through affordable phased array radar technology:*

- Provides unprecedented weather observing and forecasting,
- Supports critical surveillance support for homeland defense,
- Saves lives and protects property, and
- Provides economic benefit to the Nation.

In response to this vision, this report presents the following argument for a focused R&D plan to establish the technical feasibility and cost parameters for a national MPAR network as a replacement for the Nation's aging civilian aircraft surveillance and weather surveillance networks.

(a) Multiple Federal agencies—principally but not exclusively the FAA, NOAA's National Weather Service (NOAA/NWS), DOD, and DHS—currently rely on radar networks to provide essential services to the Nation. The principal current uses are for weather surveillance and other atmospheric observations, cooperative aircraft surveillance, and non-cooperative aircraft surveillance.

(b) A single MPAR network with the capabilities described in this report could perform all of these existing civilian radar functions. In addition, other existing and emerging needs not being adequately met by existing systems could be met with this same MPAR network.

(c) A preliminary cost evaluation shows that one MPAR network designed to meet these multiple national needs can be developed, implemented, and maintained at a lower cost, on a life-cycle basis, than would be required to sustain the existing conventional radar networks through required maintenance and incremental upgrades.

(d) MPAR can provide significant improved capabilities to meet existing needs for domestic surveillance radar. It can provide additional benefits beyond the existing systems.

(e) The JAG/PARP proposes an R&D plan that, for a modest investment, will provide a sound technical and cost basis for a National decision between MPAR implementation versus continued maintenance and upgrade of the aging, existing radar systems.

1.4 Report Purpose and Structure

The report consists of seven chapters and seven appendices. Chapter 1 sets the context for the detailed presentations supporting the report's main argument, outlined above. Chapter 2 describes the current and projected future needs of Federal agencies that are being met or could be met with surveillance radar.

Chapter 3 makes the case for a new MPAR network as a better technical solution to meet those needs than MRCR networks. It begins with the technical basis for making a decision about National surveillance radar networks by 2015. It then compares MPAR and MRCR with respect to the full range of current and potential observing functions from chapter 2.

Chapter 4 describes the technical issues that should be addressed through technical risk reduction activities prior to National decisions on major capital investments in domestic radar networks for the future. It describes the R&D that needs to be accomplished before an informed decision can be made regarding MPAR's suitability and effectiveness as an alternative to continuing with MRCR networks for weather and aircraft surveillance.

Chapter 5 lays out a viable time line and strategy to accomplish this risk-reduction R&D within the time frame of planned investment decisions. Chapter 6 presents the preliminary cost assessment by the JAG/PARP to explore the affordability of an MPAR network and the cost requirements for the risk reduction R&D strategy. Chapter 7 highlights the principal conclusions from chapters 2 through 6 and provides recommendations from the JAG/PARP to the FCMSSR and the cognizant agencies for pursuing an MPAR risk reduction program.

References cited in the body of the report, as well as other source documents, are listed in appendix A. Appendix B is a technical analysis by MIT Lincoln Laboratory of an MPAR network capable of performing the civilian agency and DOD/DHS homeland security functions discussed in chapter 2. This analysis provides technical support for chapters 3 through 6. Appendix C contains the results of the cost model used for the preliminary MPAR network acquisition and operations and maintenance (O&M) cost estimates cited in chapter 5. Appendix D serves as an addendum to chapters 5 and 6 by providing detailed time line and cost estimates for the proposed risk reduction R&D plan. Appendix E lists the acronyms used throughout the report and the appendices. Appendix F lists the principal members, alternate members, subject matter experts, and observers who participated in the JAG/PARP. Appendix G is the basic questionnaire used by the JAG/PARP to gather information from Federal agency radar users. Chapter 2 of the report is based on the information received in response to these questionnaires and from additional communications with Federal agency staff.

2 FEDERAL AGENCY NEEDS THAT RADAR CAN MEET

Land-based radars are one of the primary sources of information about the state of the atmosphere and about objects in the atmosphere. The core missions of various Federal agencies drive a variety of requirements for information that radar data can support. The major current, direct applications of land-based radar are weather surveillance and aircraft surveillance. These existing applications generate a range of specifications for radar coverage, accuracy, latency, scan rate, reliability, and resolution that any replacement capability must meet or exceed.

Beyond these current direct applications are a much broader range of indirect applications of information that radar can provide about atmospheric conditions. Some of this information is already used by Federal agencies or provided to their constituencies, in support of agency missions. Many more potential applications are known and being perfected. In general, these indirect applications do not create new or different demands on basic radar unit performance parameters beyond those needed for future aircraft tracking and weather surveillance. However, the need to serve multiple information customers concurrently increases the importance of flexibility and multifunction capability for both individual radar units and the future national radar network or networks.

To establish a baseline of information requirements for which radar data could be applicable across the Federal government, the JAG/PARP developed a questionnaire (appendix G), which was sent to current Federal users of radar data. The following agencies responded:

- DOD, including U.S. Air Force, Navy, and Army users of radar data;
- NOAA/NWS;
- FAA;
- Federal Highway Administration (FHWA);
- DHS, including the U.S. Coast Guard and the Federal Emergency Management Agency (FEMA);
- U.S. Environmental Protection Agency (EPA);
- Department of Energy (DOE).

The questionnaire asked agencies to define their current radar requirements and capabilities and their anticipated future needs, including citation of any published documentation of the future needs. Specifically, the questionnaire asked:

- What phenomena must be sensed?
- What is the required temporal and spatial resolution of the data?

- What is the required volume sampling rate?
- What is the required level of system reliability?
- What coverage (horizontal and vertical) is required?
- Does the system have any size or weight constraints?
- Do the data need to be networked?

The principal radar requirements cited by respondents fell into three major application categories: weather surveillance, air traffic control (i.e., cooperative aircraft surveillance), and non-cooperative aircraft surveillance. Additional specialized needs exist that could be met by established or emerging radar applications. These more specialized applications include tracking of airborne hazards to aviation (e.g., flocking birds, smoke, or volcanic ash) and airborne hazards to populations (e.g., ATD of chemical hazardous materials or of chemical, biological, or nuclear warfare agents). Needs of individual agencies in each of the three major application areas will be described first. Section 2.3 covers all of the more specialized or "emerging" radar applications.

The questionnaire responses were used as the starting point for this chapter. To supplement the responses, JAG(PARP) members and OFCM staff gathered additional information on emerging and potential applications of radar that could serve established Federal agency roles and responsibilities. These applications are also discussed in Section 2.3.

2.1 Weather Surveillance

Weather radar data and the weather products produced with that data are currently used by numerous Federal, State, local, commercial, and private entities for the following purposes:

- Real-time nowcasting of severe weather events (tornados, hail, hurricanes, high winds);
- Nowcasting of wind shear/microbursts/wake vortices at airports;
- Locating convective cells for aviation support and general public information;
- Identification of en route icing hazards and turbulence for aviation safety;
- Locating and deriving instantaneous rates of precipitation for hydrological forecasts, general aviation, and public forecasts and safety (i.e. flood warnings, snow warnings);
- Identification of precipitation type for surface transport and weather forecasting; and
- Initialization of NWP models of winds at and near the planetary boundary layer.

Survey respondents from Federal agencies including NOAA/NWS, DOD, and FAA would like future radar systems to sense additional atmospheric parameters, such as extremely fine drizzle, non-precipitating clouds (bases and tops), aerosols, and lightning. Some of these parameters are largely transparent to the current weather radar system: the Weather Surveillance Radar 1988 Doppler (WSR-88D). Data on these phenomena would help operational aviation support and military planning, in addition to meteorological research.

2.1.1 Current Weather Radar Capabilities

The network of WSR-88D radars is the Nation's principal source of radar-derived weather data. The Next-Generation Weather Radar (NEXRAD) Program, a joint Department of Commerce, DOD, and Department of Transportation effort, acquired and deployed the WSR-88Ds to "detect wind velocity and improve detection of precipitation, severe thunderstorms, and tropical cyclones; increase weather warning lead times; enhance the safety and efficiency of the National Airspace System (NAS); and provide automated exchange of digital weather radar data" (NEXRAD MOA 2004, pg. 2). Of the 164 WSR-88D units in the national network, 120 are operated for NOAA/NWS, 26 are for DOD, 12 are for FAA, and 6 are support systems.

The FAA uses the Terminal Doppler Weather Radar (TDWR) system to detect and predict microbursts, gust fronts, wind shifts, and precipitation near airports. The FAA has 47 TDWR units: 45 operational and 2 support. Like the WSR-88D, the TDWR radar is an MRCR design.

The FAA also derives some near-airport weather data from separate weather channels on its airport surveillance radar (ASR) systems.

2.1.2 NOAA/NWS Current and Emerging Weather Radar Needs

NOAA/NWS relies on the WSR-88D network for accurate, timely, high-resolution radar data to fulfill its mission to "*provide weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy.*" NWS data and products are available through a national information database and infrastructure to other governmental agencies, the private sector, the public, and the global community. To meet its current observing and forecast responsibilities, the NWS needs radars capable of sensing hydrometeors (rain, snow, hail, etc.) and weather features permitting the detection or identification of tornadoes, tropical cyclones, precipitation rates and amounts, thunderstorms, fronts, mesoscale convective systems, and data on various wind structures and boundary conditions.

NWS objectives for improving future radar observations beyond the current capability of weather surveillance radars include increasing refresh rates, decreasing data latency, and increasing spatial resolution. Most severe weather warnings based on radar data (e.g., tornadoes, microbursts, thunderstorms) have short lead times and are usually based on near-real-time data. Phenomena such as tornado vortices are easily missed unless the spatial and temporal resolution of the radar scan can be increased to match the scale of the vortex. Minute-by-minute radar updates are needed to identify incipient tornado vortices before they touch down. The *NOAA Long-Term Research Plan for Revolutionizing Tornado Warnings* (March 2003) established an objective for future radar systems of producing a full volume scan in less than 1 minute, compared with the current capability of a full scan in 4 to 6 minutes. Achieving this objective would contribute to increasing the warning lead time for tornadoes.

NOAA/NWS hydrometeorological forecasts and warnings depend on accurate, rapidly updated radar data. Improvements beyond current weather radar capability are necessary to get better measurements of hydrometeor size and type, including distribution in both the vertical and horizontal dimensions of the scan volume. Dual-polarization Doppler radar could contribute to these objectives. Hydrometeorological data are not only the basis of nowcasts and flash flood warnings; they also feed NWP models capable of quantitative precipitation forecasting (QPF). Such forecasts are becoming an increasingly critical NWP product for applications ranging from stream flow management and agriculture to surface transportation management and urban meteorology.

Improved NWP models—those operating at storm scale and able to resolve squall lines, hurricane structure, and tornadoes—will require extremely high resolution radar data to feed their initial fields. Monostatic Doppler radars like the WSR-88D only provide radial winds. However, initialization of improved NWP models at the appropriate scale demands accurate three-dimensional vectors of wind, highly resolved and rapidly updated, from the boundary layer to an elevation of 60,000 feet.

To get the most information on rapidly developing severe weather conditions, weather radar operators must have the flexibility to interrogate weather features as situations dictate. Current weather radars are constrained to a preset menu of volume scanning options and elevation angles, limiting their operators' ability to quickly scan or adapt to changing conditions. An adaptive scanning capability would enable data to be collected intensively in certain regions of a storm (for instance, where tornadoes are likely to form) while decreasing scans of less-critical regions to periodic surveillance. Adaptive scanning thereby increases the information gathered on critical conditions in a given time interval without diminishing the capability for full surveillance coverage.

As a tropical storm or hurricane approaches a coastline, radar becomes the primary tool for estimating winds, precipitation amounts, and the likelihood of tornadoes. Hazardous weather threats, especially in the form of potential floods and tornadoes, continue for several days after a hurricane makes landfall and travels inland as a tropical storm or depression. Once the storm is over land, flash floods and wind damage, including tornadoes spawned by the interaction of the storm with terrain, typically become the principal threats to safety, essential infrastructure, and property. NOAA/NWS, the media, and private companies rely on weather surveillance radar to issue official watches and warnings and otherwise alert emergency managers, businesses, and the general public to these hazards.

2.1.3 Weather Surveillance Needs of the Department of Defense

The DOD relies on radar weather surveillance data in support of its mission to train, equip, organize, and employ military forces in the defense of the United States. The ability to access remotely, integrate, and analyze weather radar data from multiple areas of interest is a primary military need. These data are needed to support the national defense mission for two primary purposes:

- Resource protection of military assets from weather hazards; and
- Effective operational employment of military forces in all weather conditions.

Resource Protection. Multimillion dollar weapon systems, especially aircraft, are extremely susceptible to severe weather events such as hail and tornados. Weather surveillance radar provides the capability to detect these weather phenomena in time to protect systems at risk. Advance warning to guide protective actions (tying down, hangaring, or evacuation) is essential in maintaining the combat readiness of military assets. Even in clear air, weather radar can provide wind information essential for accurate atmospheric diffusion forecasts if chemical weapons are launched against U.S. forces.

Operational Employment. Many military operations are inherently weather-sensitive. Besides the inherent weather sensitivity of basic aviation, other specialized military operations (e.g., precision airdrops, aerial refueling, precision-guided munitions employment, aerial training, artillery firing, airborne gathering of intelligence) are susceptible to wind, precipitation, and reduced visibility. Timely, high-resolution radar data greatly improve the weather information needed to guide effective decisions on these and many other operations. For example, both precision airdrop and wind correction for Army artillery are greatly assisted by accurate wind profiles—data that can be provided by weather surveillance radar in clear air mode. Timely location and tracking of convective cells with radar can improve decisions on whether an air refueling track must be relocated. Concentrated precipitation reduces trafficability—the ability of terrain to support the movement of Army land forces—and accurate localized precipitation rates from weather radar can guide estimates of trafficability changes. The Army Corps of Engineers relies on accurate flood forecasts obtained from radar-derived precipitation estimates.

2.1.4 FAA Weather Surveillance Needs

Weather affects the safety of flight, the efficiency of aircraft in the NAS, and the efficiency of Air Traffic Control. Accurate, timely information regarding small-scale phenomena such as wind shear, downbursts, wake vortices, turbulence, and icing, especially in the terminal area, is essential to flight safety. En route and terminal thunderstorms must be accurately characterized to vector aircraft safely around them. By interagency agreement, NOAA/NWS provides critical en route weather data and products to the FAA. The data provided by FAA terminal-area systems, such as the TDWR, together with the en route data and products from NOAA/NWS, are critical for advising pilots of conditions and for making decisions related to traffic movement and separation.

Improved weather data, including tailored forecasts and observations, are prerequisites for the planned threefold increase in aviation capacity over the next two decades, as discussed in the *Next Generation Air Transportation System (NGATS)* integrated plan prepared by the Joint Program Development Office. The NGATS plan requires finer-resolution radar data to identify aviation weather hazards, both at terminals and en route, as capacity increases and weather impacts are magnified. Current FAA-owned weather surveillance systems are aging and are unlikely to be able to handle the NAS weather surveillance needs of 2025.

2.1.5 FHWA Weather Surveillance Needs

FHWA promotes the use of radar weather data by State, local, and commercial entities to track weather hazards to the safety and efficiency of transportation on the Nation's roads and highways. Other forms of surface transport (rail, port, inland waterway, and public transport) are also subject to weather hazards and come under the purview of other Federal entities. Although FHWA does not own or operate roadways, it provides funding to further the understanding of weather impacts on roads and to advance the effective use of weather information (both observed and forecasted) for the roadway environment. The main FHWA customers are State and local highway agencies.

A 2004 NRC study, *Where the Weather Meets the Road*, identified the following deficiencies in the current WSR-88D radar network with respect to the needs of users and managers of surface transportation systems: substantial gaps in boundary layer coverage, lack of precipitation phase discrimination, and excessive ground clutter. In response to the OFCM survey on radar needs, FHWA identified a future need for low-level radar coverage. Priority locations for such coverage include urban areas and other high-traffic zones where weather effects on surface transport are magnified. The planetary boundary layer is inadequately sampled by the current weather surveillance radar network. Current weather radars sample less than 30 percent of the lowest one kilometer of the troposphere. Intensive low-level coverage of the atmosphere is mainly confined to major airports where a TDWR has been fielded. Complex meteorological processes within the lowest few kilometers remain an observational and modeling challenge. Yet these interactions must be better known to improve forecasts of weather affecting surface transportation.

During the requirements phase of the Maintenance Decision Support System project, which is supported by FHWA's Road Weather Program, participating State departments of transportation indicated that the onset and duration of precipitation are the single most important parameters for winter road maintenance. Other parameters high on their list include type and amount of precipitation and wind character (gustiness). The State departments of transportation require finer range and azimuth resolutions than are now available, with better coverage in the lowest portion of the atmosphere. They need faster data refresh rates to capture the onset and cessation of precipitation and changes in the wind field, which are used to detect downbursts/microbursts and wind shifts in the boundary layer. They require precise information about precipitation type to determine maintenance and traffic management strategies.

2.1.6 Reliability—A Shared Requirement

Reliability is a critical requirement for all of these weather surveillance radar applications. Having a WSR-88D unit out of commission in the midst of severe weather is a dangerous situation. Any new system will be required to meet or exceed the reliability of current WSR-88D units, summarized in section 2.4. As the in-place units age, maintenance and engineering retrofits to maintain this level of reliability will become an increasing operating cost. Future reliability requirements should balance this need for continuous operation against design cost, maintenance staff cost, and the cost of maintaining sufficient spare parts on site to keep units operating.

2.2 Aircraft Surveillance Radar

The current civilian aircraft surveillance infrastructure operated by the FAA includes radar as the "primary" surveillance system and a transponder-based system as the "secondary" surveillance system.

- The "primary" surveillance uses radar to detect the radio-wave "echo" from reflection or backscatter from the surface of an aircraft. This surveillance mode is also called "skin painting" radar. Because the radar detects aircraft without any signal originating from the aircraft, it is also called "independent" or "non-cooperative" surveillance.
- The current "secondary" aircraft surveillance method is called "cooperative surveillance" because it relies on the aircraft having a transponder on board. The transponder automatically transmits information (e.g., an identification code and aircraft altitude) in response to the signal transmitted from a beacon antenna. On current FAA units, the antenna for this cooperative surveillance beacon is typically mounted on top of the rotating radar antenna used for primary surveillance.

Although the FAA has historically used a combined primary (skin-painting) radar and secondary (transponder-based) surveillance network for air traffic control, it is planning to shift to an entirely cooperative surveillance system for the NAS (see Section 2.2.4). Nevertheless, for homeland security needs and for aircraft lacking a cooperative transponder, a requirement for non-cooperative surveillance throughout the NAS will continue. Note that "non-cooperative" does not necessarily mean "hostile"; it simply means the aircraft is not announcing its position to air traffic controllers and other aircraft in the NAS by means of a transponder.

Future aircraft tracking capability must meet or exceed current refresh rates and range resolution capability. As with weather radar applications, aircraft tracking requires a highly reliable system. Future aircraft tracking systems must maintain or improve on current requirements for minimum availability of units in the system. These requirements on existing capability are included in the summary of radar performance requirements in section 2.4.

2.2.1 Current Aircraft Surveillance Radar Capabilities

Radars currently used for aircraft surveillance in the NAS include airport surveillance radar (ASR) systems and air route surveillance radar (ARSR) systems. Non-cooperative surveillance is considered the primary surveillance mode of these existing systems, whereas their cooperative surveillance capability is typically referred to as "secondary surveillance."

The ASR-9, a short-range (60 nmi) aircraft surveillance radar, is the airport surveillance radar used at 129 high-density airports. Within its coverage area, it provides non-cooperative surveillance at 10 cm wavelength and, with Mode Select, cooperative surveillance. ASR-9 has a separate weather channel with associated processing, which can provide six-level weather contours to measure the location and intensity of storms. The ASR-9 is based on 1980s technology and had an initial planned service life to 2005. A Service Life Extension Program for the ASR-9 has been initiated to ensure that essential units remain functional through 2025. Thirty-five ASR-9 units have been modified with a Weather Systems Processor, which provides automated detection and warning of low-altitude wind shear.

The ASR-11 is a digital terminal air traffic control radar that is being procured by the FAA and the Air Force Electronics Systems Center to upgrade existing radar facilities at DOD and civilian airfields. Intended for smaller airports, it is replacing ASR-7, ASR-8 and AN/GPN-12, -20, and -27 radar systems, many of which are more than 20 years old, Like the ASR-9, the ASR-11 has both non-cooperative (primary) and cooperative (secondary) surveillance subsystems. The primary surveillance radar uses a continually rotating, tower-mounted antenna with a range of 60 nmi. The monopulse secondary surveillance radar uses a second antenna attached on top of the primary antenna to transmit and receive aircraft location data (aircraft identification code, barometric altitude, and emergency conditions). Air traffic control can use the ASR-11 cooperative surveillance system to verify the location of aircraft within a 120-nmi radius of the radar site.

ARSRs are used by Air Route Traffic Control Centers to detect and display an aircraft's position while it is en route between terminal areas. ARSR-1, ARSR-2, and ARSR-3 systems were deployed across the United States in the 1960s for FAA and U.S. Air Force use. They provide non-cooperative (primary) en route aircraft surveillance to a range of 200–250 nmi. The radars operate in the L-band (30 cm wavelength), with antennas that continually rotate at 5 rpm. In general, these ARSR models do not provide aircraft altitude information from the non-cooperative signal, although variants of the ARSR-3 have been developed that provide coarse altitude information.

The ARSR-4, which was developed in the 1980s, is deployed at 40 sites around the perimeter of the United States for joint FAA and U.S. Air Force use. Like the earlier ARSR models, the primary surveillance radar transmits a 30 cm wavelength beacon. The rotating antenna uses a phased illuminating array that forms stacked receiving beams, allowing the ARSR-4 to provide aircraft altitude measurements (within the constraints of the 2-degree stacked beams).

2.2.2 DHS and DOD Homeland Security and Defense Needs

DHS coordinates with FAA and DOD in tracking and responding to non-cooperative aircraft flying within and toward U.S. airspace. Non-cooperative aircraft must be quickly located within the vast stream of cooperating aircraft and then further characterized to identify those with possibly hostile or unlawful intent. Currently this information is provided by aircraft surveillance radar systems owned and operated by FAA and covering much of the continental United States (CONUS) and U.S. territorial waters. However, there are many gaps in the coverage, particularly at low altitudes as depicted in figure 2-1.

According to DOD's *Strategy for Homeland Defense and Civil Support* (2005), "the nation will need to develop an advanced capability to replace the current generation of radars to improve tracking and identification of low-altitude airborne threats." DHS must be able to react to non-cooperative, possibly hostile aircraft operating at all altitudes over the CONUS and territorial waters.

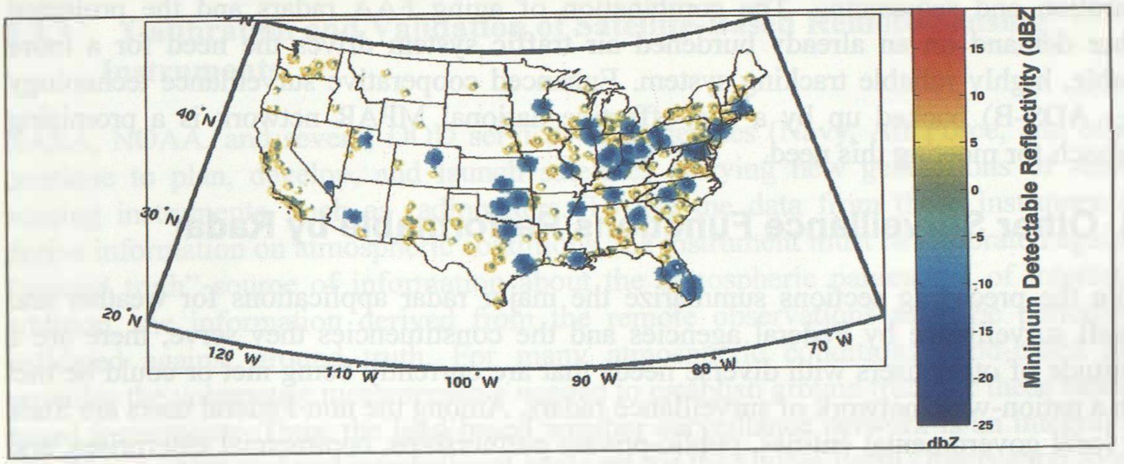

Figure 2-1. Minimal detectable reflectivity of current aircraft surveillance radar at 1000-ft. elevation.

2.2.3 FAA Requirements for Non-Cooperative Aircraft Data

Although FAA does not have primary responsibility for identification and tracking of non-cooperative aircraft, it does require real-time data on the location of non-cooperative aircraft so that air traffic controllers can deconflict cooperative aircraft flying in the same area as the non-cooperative aircraft. The concept of *domain awareness* is emerging as the complement to cooperative aircraft surveillance for the next-generation air traffic control system. The draft *Next Generation Air Surveillance Plan* (2005) requires performance improvements for sensing and tracking non-cooperative aircraft to ensure domain awareness. In general the plan demands greater vertical and horizontal coverage, increased sensitivity, finer resolution in all three dimensions, and improved data update rates.

2.2.4 Cooperative Aircraft Surveillance

Cooperative aircraft surveillance is currently provided by the same units used for non-cooperative surveillance, as a secondary surveillance mode (see section 2.2.1). For purposes of air traffic management (e.g., vectoring and separation), cooperative surveillance data are used for instantaneous location of aircraft aloft, both en route and in terminal airspace.

On a typical day, approximately 60,000 flight plans for Instrument Flight Rules flights are filed with the air traffic system, with 145,000 En Route Center Operations handled throughout the NAS. According to the *Next Generation Air Transportation System (NGATS) Integrated Plan*, the number of passengers supported may range from 2 million per day to 4 to 5 million per day by the year 2025. It is clear from the NGATS plan that the current system cannot handle future aviation system needs. To fulfill the NGATS goal, the FAA must accurately track all aircraft (cooperative or otherwise) in an environment of increasingly high traffic density and reduced standard intervals for separation and sequencing. The combination of aging FAA radars and the projected higher demand on an already burdened air traffic system drives the need for a more capable, highly reliable tracking system. Enhanced cooperative surveillance technology (e.g., ADS-B) backed up by a cost-effective national MPAR network is a promising approach for meeting this need.

2.3 Other Surveillance Functions Performable by Radar

While the preceding sections summarize the major radar applications for weather and aircraft surveillance by Federal agencies and the constituencies they serve, there are a multitude of other users with diverse needs that are currently being met or could be met with a nation-wide network of surveillance radars. Among the non-Federal users are State and local governmental entities, public-private partnerships, commercial enterprises, and the academic research community. Other Federal agencies known to use information derived from the NEXRAD weather surveillance network include DOE (weather data to support predictions of consumer energy use), the Department of Agriculture (rainfall data), and the National Park Service and National Interagency Fire Center of the Department of the Interior. A sample of the diverse current and potential applications for radar is presented below.

2.3.1 Airborne Releases of Toxic Materials

DHS and State and local emergency preparedness agencies must be able to quickly identify airborne releases of toxic chemical, biological, or radioactive agents, and then track the plume of the hazardous material as it travels by atmospheric transport and diffusion. In sufficient volume density, airborne release of hazardous materials can be detected directly by radar. In all cases, accurate and real-time data on local winds, particularly within the planetary boundary layer, are crucial for tracking the plume and predicting, with the aid of ATD models, where it will travel and what the risk level is for any location downwind. Current temporal and spatial resolution of wind data is inadequate for this purpose, as is the skill in forecasting plume movement and concentration. The recent OFCM report, *Federal Research and Development Needs and Priorities for Atmospheric Transport and Diffusion Modeling* has identified the need for sufficiently high resolution data to allow modeling at the microscale/urban scale (OFCM 2004). Radar can provide the needed measurements. Federal agencies with responsibility for monitoring or responding to airborne releases of toxic agents include DHS, DOD, DOE, Nuclear Regulatory Commission, EPA, and NOAA/NWS.

2.3.2 Weather Surveillance in Support of Spaceflight Operations

Flight operations where details of localized downrange atmospheric conditions can be critical, as in NASA space launches and vehicle reentry and landing, can be made safer by a capability to dwell on a spatial volume of high interest, such as a front or cell that could produce sudden turbulence. Radars currently used for atmospheric research do this; the application is established. However, for a single-beam radar unit, dwelling on high-interest features must be balanced against the primary continuous-scan function of weather surveillance.

2.3.3 Calibration and Validation of Satellite-Based Remote-Sensing Instruments

NASA, NOAA, and several DOD services and agencies (Navy, Air Force, and others) continue to plan, develop, and launch satellites carrying new generations of remote-sensing instruments, such as radiometers. To use the data from these instruments to derive information on atmospheric conditions, the instrument must be calibrated against a "ground truth" source of information about the atmospheric parameters of interest. In addition, the information derived from the remote observations must be periodically validated against ground truth. For many atmospheric conditions, land-based radar provides the volumetric measurements needed to establish ground truth for these satellite-based instruments. Thus, the land-based weather surveillance network is an integral part of achieving National and international goals set for the Global Earth Observation System of Systems (GEOSS).

2.3.4 Fire Weather and Wildland Fires

Radar has much to offer to the fire weather community. In addition to detecting and tracking airborne aerosols such as smoke, radar can track in real time the fine-scale changes in wind field due to terrain-atmosphere interactions and the influence of the fire itself on local wind and weather conditions. Radar can be used to track the smoke plume and estimate air quality in the vicinity and downwind of wildland fires. Rainfall can assist in controlling and possibly extinguishing a fire, and radar is invaluable in locating precipitation that may affect burning or endangered areas and determining its intensity. Convective cells can also produce wind shifts that cause the fire line to change direction. These direction changes can pose threats to firefighters, people who were formerly in safe zones, and property. Radar indications of thunderstorms and associated lightning over areas with high-risk levels of dry fuels can give indication of where new fires may ignite.

Federal agencies that need improved fire weather information include the Department of the Interior (U.S. Park Service, Bureau of Land Management, Fish and Wildlife Service, U.S. Geological Survey), Department of Agriculture (U.S. Forest Service), DHS (FEMA and the U.S. Fire Administration), EPA, the Department of Health and Human Services (Centers for Disease Control and Prevention), and NASA. Beyond these Federal users, State and local fire hazard management and fire control agencies down to the level of volunteer fire departments need the timely fire weather information that radar can provide.

2.3.5 Debris Flows (Mudslides)

Many emerging, specialized applications for radar use information from a known radar phenomenon but apply it for an innovative purpose. The emergence of weather surveillance radar from early aircraft surveillance applications is an historical example. New applications of radar are emerging now that use weather surveillance radar data. For example, radar information on precipitation intensity and duration at a specific location is now being used to estimate the total precipitation falling on hillsides prone to debris flows (e.g., mudslides).

Accurate rainfall amount is a key piece of information for the debris-flow warning system because even small amounts of precipitation beyond ground saturation can trigger strong flash floods and debris flows. Rain gauges are relatively sparsely located on such slopes, and convective cells often produce intense rainfall amounts over very small areas, which may not contain a rain gauge. The debris-flow models being developed and applied by the U.S. Geological Survey require high-resolution precipitation data, such as QPF and near-real time precipitation rates from observations. Radar provides the only available tool to continuously monitor the spatial distribution of precipitation at horizontal scales small enough to link convective downpours to specific terrain at risk. Radar-derived precipitation amounts are compared to thresholds for debris flow derived from hydrologic models based on historical data. The thresholds for debris flow for a given canyon, for example, are based on a combination of rain intensity and duration—data that can be provided continuously by radar. Localized rainfall estimates for this and other applications, such flash floods in hilly terrain and field-specific agricultural management, will improve as dual-polarization weather surveillance radar systems are implemented.

2.3.6 Air Quality and Health

More accurate routine monitoring and prediction of air quality at regional and intra-urban scales depends on the same degree of knowledge of local wind fields required for the emergency response to a point release of an airborne hazardous material. Air quality warnings and assessments use diagnostic and predictive models of atmospheric constituents of concern, but the models depend on accurate observations, at the required spatial and temporal scales, of the wind field within the planetary boundary layer, precipitation, and other atmospheric parameters that can be measured with advanced radar techniques. Monitoring air quality is a responsibility of EPA, the Centers for Disease Control and Prediction, and NOAA/NWS.

2.3.7 Volcanic Ash

Airborne volcanic ash is a hazard to aviation and, in sufficient density, to surface transportation. It can cause public safety and health problems. Since the ash can be carried aloft as high as the tropopause, volcanic ash plumes need to be detected quickly and then tracked from surface elevations to a height of 50,000 ft. Radar sensing of volcanic ash plumes can augment satellite observations.

2.3.8 Birds as an Aviation Hazard

Bird strikes pose a severe hazard to aviation, particularly when birds are flying in large flocks. The ability to identify and track bird flocks in flight will be a continuing need for aviation safety. Dense flocks of birds produce radar signatures, even with the current weather surveillance and aircraft surveillance radars. Dual-polarized radars are capable of distinguishing bird radar signatures unambiguously from those of aircraft or meteorological phenomena.

2.3.9 Agricultural Applications of Radar Data

The agriculture industry and family farms use radar-based products and services to time the application of insecticide and fungicides to crops. Radar-derived precipitation estimates and short-range forecasts are used to set irrigation strategies and crop spraying schedules. The Department of Agriculture is also very interested in, and uses, hail data (swath coverage), high-resolution reliable storm rainfall estimates (especially over data-sparse areas), and surface-adjusted wind vectors and peak surface winds.

The WSR-88D radar has been used to track insect swarms that travel with the winds for hundreds of miles. The low-level jet in the Great Plains is remarkably efficient in transporting insects from south to north in the early morning hours. These pests are harmful by themselves, but they also carry molds and fungi (Wolf et al. 1995).[1]

2.4 Summary of Radar Performance Needs

The questionnaire sent to Federal users of radar data asked respondents about the performance needs for their existing applications or envisioned for future radar applications essential to Agency missions and responsibilities. Common themes among the responses are summarized below and in tables 2-1 and 2-2.

- **Resolution**. Spatial resolution (beam width, horizontal and vertical) and temporal resolution (scan rate) of radar must increase to match the scale of the phenomena of interest. This applies to both weather and aircraft surveillance.

[1] In addition to the report by Wolf et al. (1995), summaries of the use of NEXRAD to track insect crop pests can be found in research reports at the website of the North Central Regional Committee on Migration and Dispersal of Biota. See, for example, research summary on "Mid-season Insect Migration" by John Westbrook, Texas A&M Univ., and "Ground-truth of NEXRAD Doppler Radar Measurements" by Wayne Wolf, Texas A&M University, at http://www.inhs.uiuc.edu/cee/movement/more_res.html.

Table 2-1. Needs Summary Table—Weather Surveillance

Parameter	Current Capability	Future Need
Derived weather phenomena	Instantaneous rain rate, snow, hail, icing, turbulence, winds, microbursts, wind shear, tornado vortex signature	All of current plus clouds (bases and tops), aerosols (concentration and size distribution), and lightning.
Vertical Coverage	From 1 km to 70,000 ft.[a]	From surface to 70,000 ft.
Horizontal Coverage	US states and territories, and surrounding water/borders[b]	Same as current
Range Resolution	250 m (for Doppler moments); 1 km for reflectivity moments	Less than 100 m
Sensitivity	From -20 to 5 dBZ	At least as sensitive as current
Scanning Mode	Clear air and severe weather volume coverage patterns; constantly increasing elevations for one complete volume scan	Optimize scanning to better cover the lowest 3 km, using negative angles if necessary
Reliability	96% (WSR-88D)	At least as reliable as current capability
Data Latency	Less than 4 minutes (data latency is determined by fact that entire WSR-88D volume scan must be completed before data becomes available)	Less than 10 seconds
Update Rate	4–6 minutes for a full volume scan (reflectivity versus clear air)	1 minute or less
Dual Polarization	Planned for deployment on WSR-88D	Should be included in any new system
Radars Networked?	Yes[c]	Yes

[a] More than 70 percent of the lowest 1km of atmosphere is unsampled by WSR-88D.

[b] DOD requires tactical radars for global deployment.

[c] WSR-88D reflectivity products are mosaicked; future need is for radar data from multiple sources that can be automatically fused into single operational pictures in near-real time

- **Coverage.** Near-surface coverage with minimized clutter is needed. Blind spots widen with increasing distance between radars; mountains exacerbate blockage. Technology must be developed to fill these gaps in coverage.
- **Integration.** Individual radar units must be connected in an integrated network. Information from multiple units in a radar network must be fused automatically into a single coherent four-dimensional view that is easily displayed to and understood by users and decision-makers.

Table 2-2. Needs Summary Table—Aircraft Surveillance

Parameter	Current Capability	Future Need
Derived aircraft parameters	Aircraft position	Aircraft position, speed, direction, elevation, and type
Vertical Coverage	From 1 km to 60,000 ft.[a]	From surface to 100,000 ft.
Horizontal Coverage	All U.S. states and territories, including surrounding waters and borders.[b]	Same. Perimeter extends 600 nmi beyond border/coast
Range Resolution	1/8 nmi (1/16 nmi at airports)	Less than 1/8 nmi.
Sensitivity	2.2 m^2 cross-section (probability of detection >80%)	0.1 m^2 cross-section; targets separated by <0.125 nmi reported as separate targets
Scanning Strategy	Repeated base scans every minute; fixed surveillance mode does not allow interrogation of individual objects	Optimize scanning to better cover the lowest 3 km, using negative angles if necessary; agile scanning to interrogate individual objects
Data Latency	120 seconds	<2 seconds
Update Rate	10–12 seconds en route; 4–5 seconds near terminal	<5 seconds
Reliability	99%	At least as reliable as present units
Dual Polarization	Not available	Should be included in any new system
Radars Networked?	Yes[c]	Yes. Data available in common, interoperable formats.

[a] Lowest 1 km of atmosphere is unsampled by aircraft surveillance radars over 70% of CONUS.

[b] DOD requires air traffic control radars for global deployment.

[c] The minimal need is for aircraft surveillance radar data readily shared among FAA, DOD, and DHS.

- **Scanning Agility.** Capability is needed for intensive interrogation of a phenomenon of priority interest, while maintaining surveillance of the remainder of the sky. With respect to requirements for intensive focus and sustained breadth of surveillance, the need is typically for both capabilities at once, not a choice between one or the other.

- **Data Assimilation.** Weather radar data must be readily assimilated into NWP models, including mesoscale models. As an NRC committee has stated, "Currently radar is the only observing system with the potential of providing initial conditions for very high-resolution numerical weather prediction models" (NRC 2002).

- **Reliability.** High levels of reliability, including rapid repair/replace maintenance capabilities, are essential for weather surveillance and aircraft surveillance applications. Future radar units and networks must be at least as reliable as current operational radars for these critical applications.

The user needs listed in tables 2-1 and 2-2 are effectively performance requirements on future observing systems. They derive from the responses received to the OFCM questionnaire. Future weather and aircraft surveillance radar units and networks should be able to meet these needs.

In summary, future radar technology must improve upon inherent limitations of present radars for both aircraft surveillance and weather surveillance tasks. The parameters where improvement is needed include low-level coverage, multifunction capability, agile scanning, higher refresh rates, increased spatial resolution, and improved reliability.

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.

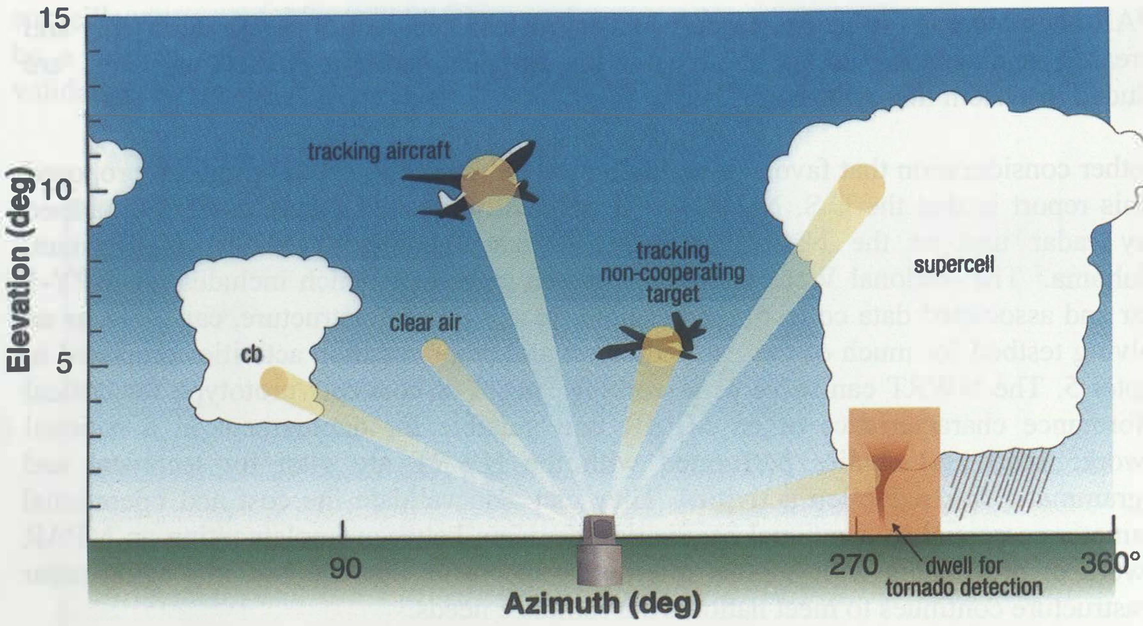

Figure 3-1. Capabilities of agile beam phased array radar.

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.

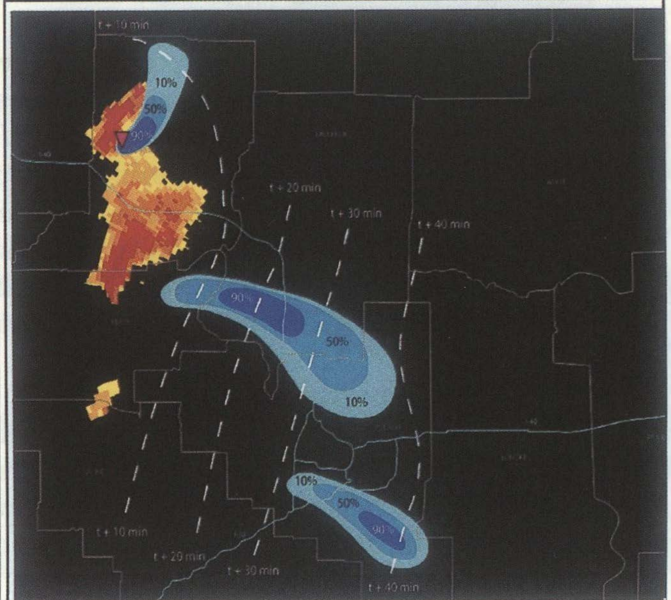

Figure 3-2. Tornado lead times.

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.

4 TECHNICAL ASPECTS OF MEETING SURVEILLANCE RADAR NEEDS

Despite the inherent multifunction capability of agile-beam MPAR, meeting the varied user needs described in Chapter 2 with a single radar poses technical challenges. For example, weather radars use high-power, narrow "pencil beams," which scan relatively slowly in azimuth and elevation to provide accurate measurements of precipitation and winds. By contrast, aircraft surveillance radars typically use much broader, fan-shaped radar beams that scan rapidly to provide the frequent target echoes necessary for reliable tracking. Figure 4-1 illustrates these contrasting surveillance strategies. Supporting these two surveillance applications concurrently with one MRCR unit would be extremely challenging technically. This chapter will show how MPAR technology already in use for military radar systems can provide the capability to conduct both strategies (and others) concurrently.

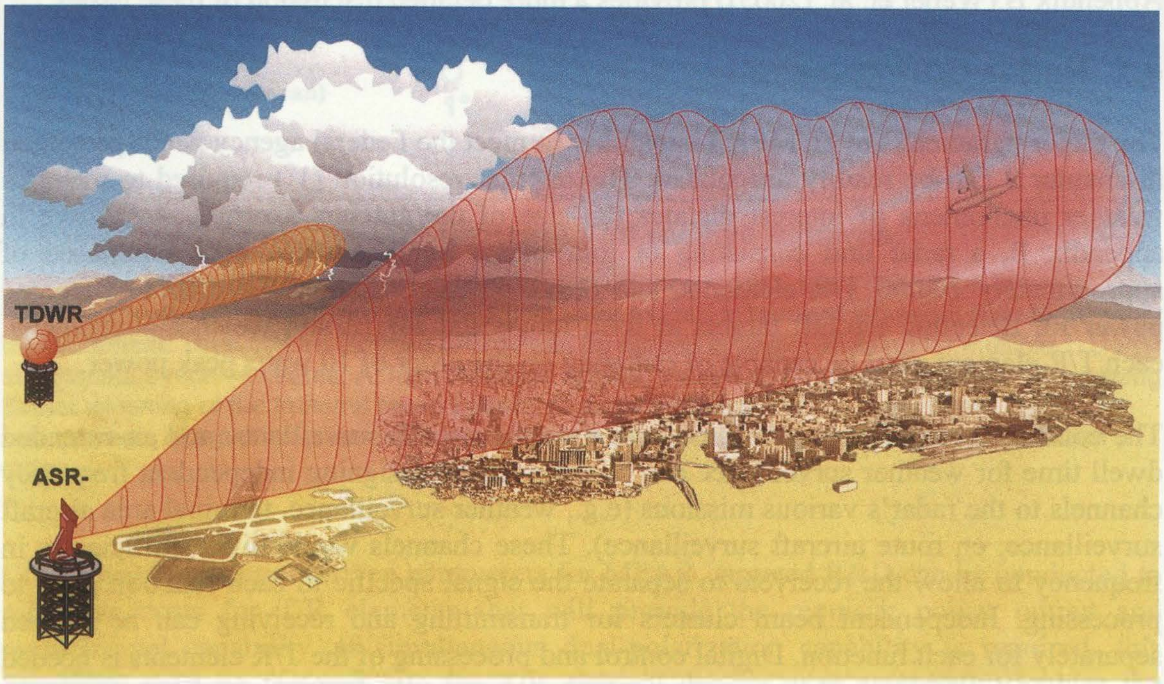

Figure 4-1. Contrasting surveillance strategies.

Different beam patterns are required for aircraft and weather surveillance. To define the three-dimensional structure of storms, weather radars employ narrow pencil beams that are scanned in azimuth and elevation. Aircraft surveillance radars use broad beams that are fan shaped in elevation. The beam is scanned in azimuth only at a high rate to provide the rapid sequence of target echoes needed to track fast-moving aircraft. This artist concept shows a Terminal Doppler Weather Radar (TDWR) and an airport surveillance radar (ASR), both located in the immediate vicinity of an airport outside an urban area.

A second technical consideration is the significant interest within the user community for more continuous surveillance of boundary layer weather phenomena (for both severe and non-severe weather events) and for better tracking of aircraft at low altitudes. The significant enhancements in weather diagnosis and forecast capability that would accrue from improved boundary layer measurements have motivated the NSF-funded Collaborative Adaptive Sensing of the Atmosphere (CASA) project. CASA is developing short-wavelength, electronically scanned radar technology as an enabler for a proposed dense network of atmospheric boundary layer sensors. While CASA continues to move toward its objectives as a separate research activity, the risk reduction R&D proposed here for MPAR as a national surveillance radar option would complement the CASA project. Development of a scalable active array architecture will provide a common technology base for both an MPAR network for long-range surveillance and a dense network of boundary layer–observing phased array radars.

This section outlines the high-level technical implications for MPAR to serve multiple surveillance applications. It lists engineering and implementation issues associated with these implications, which the R&D program described in chapter 6 is intended to address. Appendix B (Weber et. al. [2005]) provides a more detailed discussion of these issues.

4.1 Radar Configuration

The major parameters of an MPAR capability to meet the Federal agency needs presented in chapter 2 can be readily articulated. The angular resolution (1°) required to measure weather phenomena of interest dictates the size of the antenna aperture. As shown in appendix B, a radar unit consisting of four planar antenna faces, each composed of approximately 20,000 T/R elements, can provide this resolution. To provide adequate power for detecting aircraft targets at long range and for certain weather phenomena, each T/R element must be capable of radiating on the order of 10 watts peak power.

The conflict between a short volume-scan time for aircraft surveillance and an extended dwell time for weather surveillance can be resolved by assigning independent frequency channels to the radar's various missions (e.g., weather surveillance, terminal area aircraft surveillance, en route aircraft surveillance). These channels would differ sufficiently in frequency to allow the receivers to separate the signal specific to each function prior to processing. Independent beam clusters for transmitting and receiving can be formed separately for each function. Digital control and processing of the T/R elements is needed to generate these independent beams.

High angular resolution can be maintained for all surveillance functions by using the full aperture for receive-beam formation. Where needed, rapid volume scanning can be achieved by dynamically widening the transmit beam pattern so that the beam illuminates multiple resolution volumes concurrently. Figure 4-2 depicts notional transmit-beam and receive-beam patterns appropriate for three surveillance modes. Appendix B includes a detailed discussion of how a single active, electronically scanned radar can meet all of the required surveillance functions.

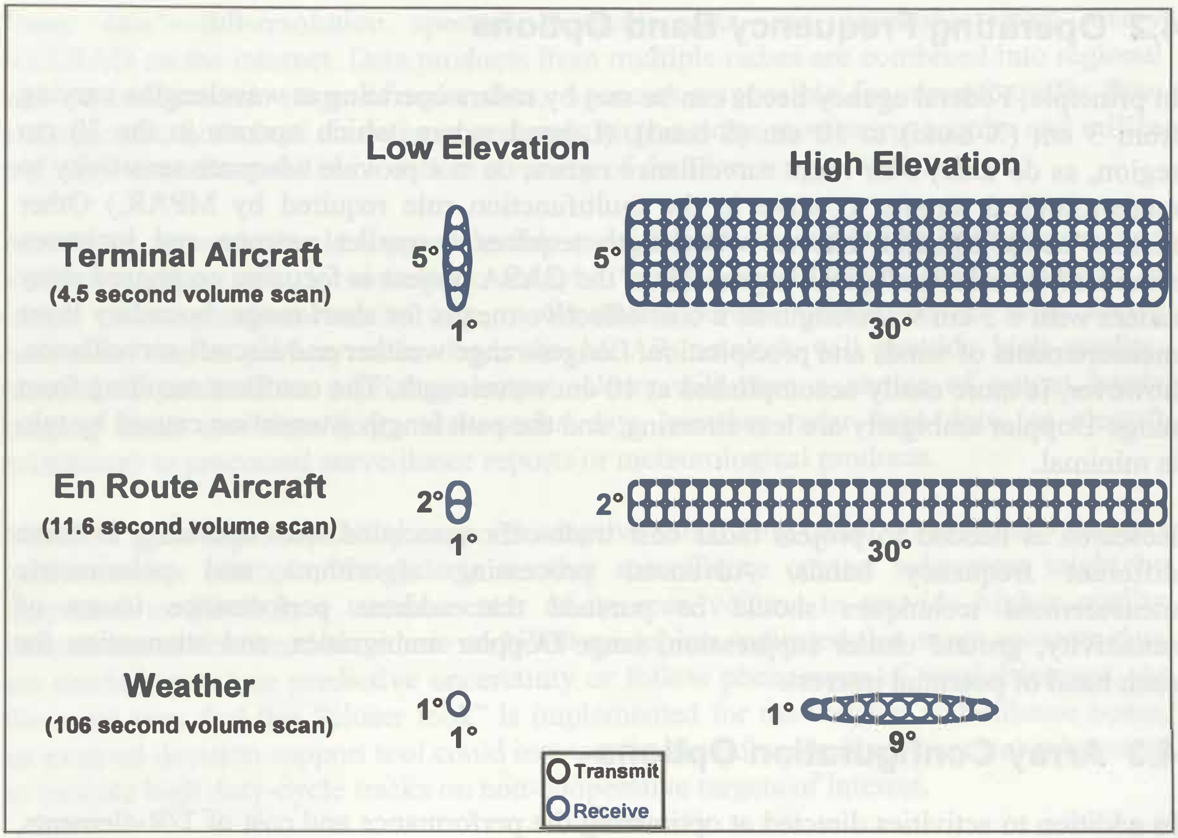

Figure 4-2. Transmit and receive patterns.

Notional beam patterns for multifunction radar surveillance modes. Less energy on target is required for aircraft surveillance (particularly at short ranges in terminal airspace) than for weather measurement. Thus, the transmitted energy can be spread in angle, allowing for multiple, simultaneous receive beams. At high elevation angles, maximum range to target falls off, allowing further widening of the transmit beam pattern. Optimal adaptation of the radar beam pattern to requirements of a particular surveillance mission is a core capability essential to multifunction radar.

Given these application-driven parameters for MPAR, targeted R&D can be conducted to minimize costs for T/R elements that will provide the requisite power output and multichannel capability. If simultaneous dual-polarization capability is required, this capability must be factored into the T/R element design, as it essentially doubles the number of components (e.g., phase shifters, amplifiers) required per T/R element. A second research focus is needed on array digitization issues, including cost minimization for "overlapped sub-array" beamforming technology, which is likely to be the most effective approach to implementing the necessary beamforming capability. A third focus should be to develop efficient, cost-effective processing architectures to form the large number of concurrent beams required to meet user needs.

4.2 Operating Frequency Band Options

In principle, Federal agency needs can be met by radars operating at wavelengths varying from 3 cm (X-band) to 10 cm (S-band). (L-band radars, which operate in the 30 cm region, as do today's air route surveillance radars, do not provide adequate sensitivity to meteorological targets to serve in the multifunction role required by MPAR.) Other factors being equal, a shorter wavelength requires a smaller antenna and increases sensitivity to meteorological targets. Thus, the CASA project is focusing on phased array radars with a 3 cm wavelength as a cost-effective means for short-range, boundary layer measurements of winds and precipitation. Longer-range weather and aircraft surveillance, however, is more easily accomplished at 10 cm wavelength. The conflicts resulting from range-Doppler ambiguity are less stressing, and the path length attenuation caused by rain is minimal.

Research is needed to project radar cost trade-offs associated with operating in these different frequency bands. Advanced processing algorithms and polarimetric measurement techniques should be pursued that address performance issues of sensitivity, ground clutter suppression, range-Doppler ambiguities, and attenuation for each band of potential interest.

4.3 Array Configuration Options

In addition to activities directed at optimizing the performance and cost of T/R-elements, alternative array geometries and "element-thinning" options should be evaluated. Since the major radar applications in chapter 2 require 360^{o} azimuthal coverage and significant above-horizon coverage in elevation, cylindrical, conical, or hemispherical array configurations may provide more efficient coverage than a multifaced planar array would.

Element-thinning is a technique for reducing the required number of T/R-elements in an array by spacing the elements in a non-uniform pattern such that inter-element spacing sometimes exceeds the optimal half-wavelength distance. This results in "grating lobes": undesirable secondary beams pointing in directions away from the main beam. However, through careful design of the overall array, these grating lobes can be managed so that the radar's measurement capabilities are not degraded. Element thinning is more easily accomplished using planar arrays. Options for element thinning also depend on the power output achievable from the individual T/R elements and the potential impact on beam patterns from failure of a small number of elements. Finally, options for the geometry of the T/R element grid (e.g., a triangular versus rectangular grid) should be assessed, as grid geometry can also affect the number of T/R elements necessary to achieve a required performance capability.

4.4 User Connectivity

Both the meteorological and aircraft surveillance communities are investing significant resources in combining the output from surveillance radars to facilitate incorporation of radar data products into decision support tools. For instance, real-time weather radar "base data"—full-resolution spectral moments data—are accessible from every NEXRAD on the internet. Data products from multiple radars are combined into regional and national *mosaic* maps of radar data. Agencies responsible for aircraft traffic flow management, homeland air defense, and even airport noise monitoring acquire and utilize real-time aircraft surveillance data in a variety of decision support tools.

An MPAR network should support flexible and efficient data access for both primary and ancillary applications. In contrast to today's "single-sensor" surveillance paradigm, in which each operational entity (e.g., a Weather Forecast Office, an en route sector controller) has a primary radar feed, the MPAR network will provide high quality, mosaicked products as a primary output. Users will have a choice of output levels ranging from raw data (e.g., time series data, weather radar base data, or aircraft primitives) to processed surveillance reports or meteorological products.

MPAR's agile-beam capability supports adaptive scheduling based on externally derived guidance. For example, the radar's weather surveillance control subsystem might be instructed to dwell in a certain sector of its scan volume to provide higher quality measurements for locations where an NWP model has indicated that more accurate data are needed to reduce predictive uncertainty or follow phenomena of special interest. At the same time that this "closer look" is implemented for the weather surveillance beam, an external decision support tool could instruct the aircraft surveillance control subsystem to execute high duty-cycle tracks on non-cooperative targets of interest.

The research activity for MPAR can explore these and other performance enhancements that can be realized through collaborative surveillance strategies that exploit MPAR's unique capabilities for flexible scanning agility. Associated communications, control, and conflict resolution architectures should be developed and tested.

4.5 Aircraft Surveillance Post-Processing

Relative to current aircraft surveillance radars, an MPAR network would support more-selective antenna patterns and flexible scan strategies, thereby improving the quality of non-cooperative aircraft surveillance. However, as depicted in figure 4-3, the radar front end will be significantly transformed with respect to the flow and content of the data provided to the post-processing algorithms. New post-processing techniques must be developed to meet or exceed the performance of existing air traffic control search radars. The following examples represent some of the supporting developmental work needed.

- The use of multiple beam clusters significantly expands the amount of data to be processed. How can commercial off-the-shelf solutions, within an efficient and affordable open architecture, be used to reduce acquisition costs? This architecture must also enable technology refresh and the future insertion of new technology and algorithms.
- Target detections will occur in multiple beams within each beam cluster. These detections will require a new algorithm for correlation and interpolation to the single centroided target report that is input to air traffic control display systems.

- Because selective elevation patterns will allow the altitude of detected targets to be estimated, new and highly simplified clutter elimination algorithms will be of value.
- ADS-B will replace beacon radars in some regions. Efficient scan strategies should be developed to allow MPAR units to confirm and augment ADS-B reports.

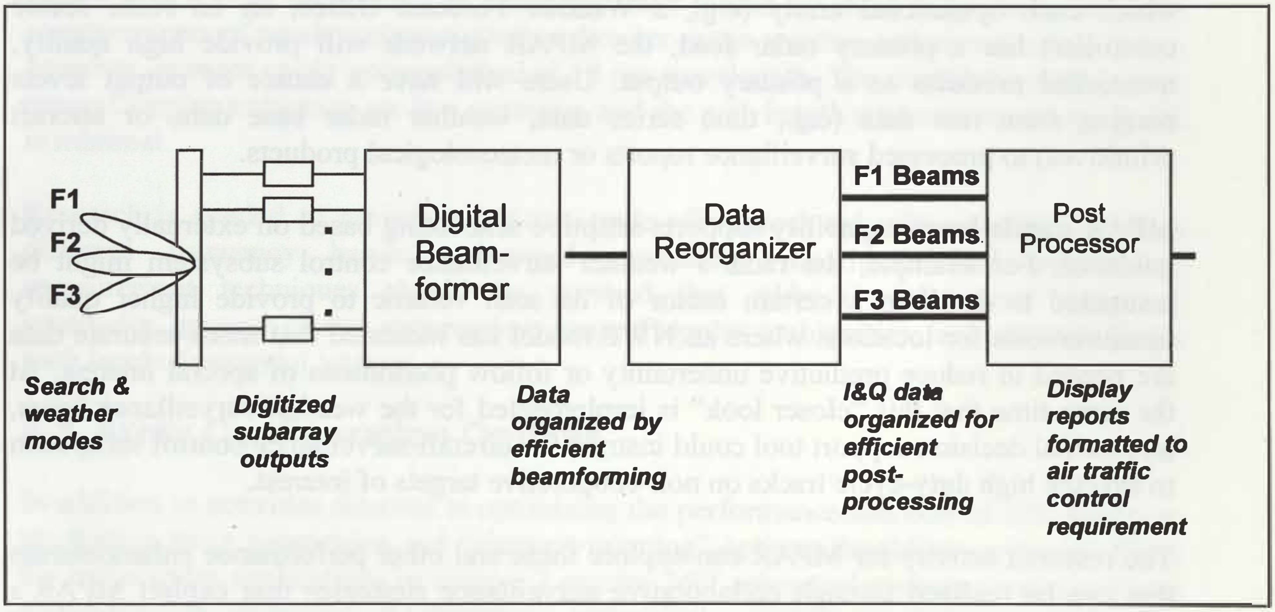

Figure 4-3. Post-processing block diagram for MPAR.

4.6 Weather Surveillance Post-Processing

To realize the performance advantages discussed in chapter 3, weather scan strategies and data processing algorithms should be developed that exploit the unique capabilities of MPAR. Data-adaptive beam steering, pulse scheduling, and processing techniques will revolutionize the quality of the meteorological data provided by MPAR, but these advances will also increase the complexity of the weather post-processing software. Multiyear algorithm development and validation efforts will be required to fully realize MPAR capabilities in this area. These efforts will require development and utilization of a full-up MPAR prototype as discussed in chapter 5.

Developing such techniques can significantly decrease the volume scan-time and/or improve data quality by allowing for longer dwell time along "high-value radials" such as low-elevation tilts for boundary layer wind mapping, tracking non-cooperative airborne targets, or investigating regions of suspected tornadic formation.

Spaced aperture techniques can be applied by separately processing received signals from halves or quadrants of the full aperture. Such techniques can potentially be used to estimate the cross-range wind component and three-dimensional turbulence fields and to provide information on hydrometeor size and shape (independent of the use of dual-polarization). These techniques should be investigated with respect to both capability enhancements and increased complexity of beamforming and post-processing.

Meteorological surveillance requirements for high-power aperture, angular resolution, and long dwell times are likely to have a significant influence on MPAR unit architecture and cost. Therefore, significant effort should go into evaluating and demonstrating efficient MPAR design options and processing approaches for meteorological surveillance applications.

5 COST CONSIDERATIONS

5.1 Rapidly Evolving Technology Will Contribute to MPAR Affordability

As chapter 1 noted, phased array radar technology has been used in DOD radar systems for 30 years, but a common perception has been that the technology was too expensive for civilian applications, even those as essential to the Nation as aircraft tracking and weather surveillance. However, the technology that has enabled an era of affordable, consumer-oriented wireless communications—cellular telephones, Wi-Fi computer networking (IEEE 802.11b wireless networking), and Internet access—has also brought opportunities to lower the cost of MPAR units substantially. MPAR for civilian applications has become a cost-effective alternative to a repair-and-replace strategy for meeting the Nation's radar needs as documented in chapter 2.

The continuing cost drops anticipated for solid-state T/R elements are fueled by a revolution in monolithic microwave integrated circuits (MMICs). MMICs are to radio frequency (RF) technology what digital integrated circuits (microchips) are to computing technology. The DOD spurred MMIC development through large investments in the 1990s. Investment in MMICs by the commercial wireless industry continues to drive improvements in their affordability.

High performance MMICs are generally made from semiconductors that are compounds of two elements, one with valence III and the other with valence V, called III-V semiconductors. With the exception of the power amplifier, highly functional MMICs for radar application can now be produced using lower-cost silicon technology. The tradeoff depends on the level of performance required. Low-cost silicon devices are used in modern cell phones for operation up to 2 GHz, with only the power amplifier made from III-V material. Silicon-germanium (SiGe) materials have demonstrated performance for the lower-power parts that approaches that of devices made of III-V semiconductor material.

Recent advances in solid state microwave circuitry using gallium nitride (GaN), one of the III-V semiconductors, has enabled design and production of MMICs for RF applications that are more powerful and efficient, yet less costly to build and cooler in operation, than competing technologies. The GaN-based MMICs currently being developed for use in military and commercial applications may further reduce the cost of phased array antennas like those needed for the proposed MPAR network. Relative to other high-power T/R element technologies, GaN-based devices will have the added benefit of not requiring a water-cooled heat dissipation and removal subsystem in the MPAR antenna, substantially reducing the design and manufacturing cost of the antenna structure. The GaN devices will also yield the same power as today's gallium arsenide chips in one-fourth of the chip area. These gains in device efficiency will reduce the cost per unit of performance.

The Defense Advanced Research Projects Agency (DARPA) has invested substantial R&D funds—currently $120 million—in its Wide Bandgap Semiconductor Technology program, which is pursuing the use of GaN devices for military applications. This investment will also accelerate the use of GaN-based MMICs in the commercial marketplace, likely resulting in further per-unit cost savings in production.

By leveraging technology trends in electronics and particularly in solid state devices, stable and highly reliable MPAR units can be fielded. By adopting commercial technology, system designers can keep the cost of spare parts and components low. Risk reduction R&D studies should be directed toward architectures that support this flexibility, such as open architectures. By contrast, there are no technological breakthroughs on the horizon that will lower the cost of conventional radars significantly from current levels.

5.2 Rough Order-of-Magnitude Acquisition and Operations and Maintenance Cost Summary

Appendix C contains a preliminary cost analysis comparing a national MPAR network with the cost for replacing existing networks with single-function MRCRs. Essential summary information about this analysis is presented below.

5.2.1 Acquisition Costs

A radar coverage analysis recently performed by Lincoln Laboratory at the request of the FAA indicates that the 510 radars in use today for weather and aircraft surveillance could be replaced with 334 MPAR units (Appendix C). This represents a 35 percent reduction in the number of surveillance radar units needed to perform current functions for current airspace coverage.

Per-unit average costs for the 334 MPAR units needed to replicate today's airspace coverage are estimated to be approximately $10 million, based on initial design work for an MPAR pre-prototype. This compares favorably with costs of today's MRCR systems and is likely to decrease substantially in the future as critical MPAR technologies evolve due to military and wireless industry development. Replacing current networks with 176 fewer radars with an average cost of $10 million each yields a $1.8 billion savings in initial acquisition costs.

5.2.2 Operations and Maintenance (O&M) Costs

In addition to the technical advantages of MPAR relative to MRCR, which are discussed in chapters 3 and 4, a second key consideration is the cost of operating national networks to meet existing and planned radar surveillance objectives. Maintenance and repair for the current MRCR units are significant contributors to life-cycle costs of their respective networks.

The current national weather and aircraft radar surveillance networks consist of 510 radars of seven different types. As shown in Table 3-1, the age of most of these radars ranges from 10 to 40 years. All seven have rotating antennas and high-power vacuum tube RF transmitters. Failure of either a moving part or a transmitter generally results in shutdown of the radar unit, which can have unavoidable economic and public safety consequences. Furthermore, the life-cycle cost of these units has been escalating due to:

- The age and cost of replacement parts;
- Training required on outdated technologies with different types of unique capability equipment; and
- More frequent upgrades to keep up with greater demands and capability.

An MPAR network with its graceful degradation characteristics will also reduce recurring maintenance costs by eliminating single-point-of-failure subsystems such as MRCR transmitters and antenna drive units, which require 24 hours-per-day, 7 days-per-week, maintenance contracts for guaranteed quick response to radar unit outages. To reduce the risk of a unit being down, preventive maintenance must be performed in advance of anticipated failure rates and adequate spares for any part or subsystem subject to single-point failure must be kept on hand. In comparison, MPAR maintenance and operations support is reduced because the radar unit has no moving parts and sufficient redundancy of operating elements to eliminate the need for maintenance personnel to be on call at all times, with spares available, for emergency repairs. Advanced techniques and architectures developed on military MPAR programs like Aegis allow trouble-shooting approaches that automatically isolate faults to the lowest replaceable unit. These approaches eliminate costly fault isolation procedures and reduce the use of scarce technical resources. The preliminary cost analysis by Lincoln Laboratory estimates a $3 billion savings in O&M costs over the 30-year lifespan of an MPAR network, if aggressively implemented, compared with the total O&M cost of continuing with the legacy systems. (See appendix C, figure 3, and accompanying text for the basis of this estimate.)

5.3 Summary

This preliminary comparison of cost factors suggests that an MPAR network could save $1.8 billion in acquisition costs and $3 billion in O&M costs. The cost per MPAR unit will be roughly comparable to the replacement cost for the legacy units based on MRCR technology. However, before a decision can be made, careful value engineering analysis is needed to establish a firm basis for the procurement, implementation, and O&M costs of an MPAR network. The risk-reduction R&D program proposed in chapter 6 includes this requisite cost-analysis effort.

6 R&D PLAN TO SUPPORT DOMESTIC RADAR NETWORK DECISIONS

This chapter outlines an R&D plan of risk reduction activities to support a decision on how best to meet the Nation's future needs for surveillance radar. After the overview of goals and objectives in section 6.1, sections 6.2 through 6.4 present the three major components of the proposed R&D work:

- Technology development and testing;
- Proof of MPAR operational concepts; and
- Refinement of the MPAR network concept.

Section 6.5 summarizes the JAG's estimates of resources and schedule time required to conduct all the proposed activities in these three R&D components. Further details of the resource and schedule estimates are provided in appendix D.

6.1 R&D Strategy

6.1.1 Goal and Objectives

The goal of the proposed R&D strategy is to demonstrate that an affordable, high power, multipurpose phased array radar can be developed to provide the revolutionary capabilities described in chapters 3 and 4 of this report. The major objectives to be achieved by the proposed activities are:

4. Technical risk reduction for the issues discussed in chapter 4;
5. Establishment of a documented basis for cost comparisons between the MPAR and MRCR alternatives for meeting national domestic radar surveillance needs (building on the preliminary cost factor comparisons presented in chapter 5); and
6. Formulation of the path forward for required research, development, test, and implementation, if an MPAR option for future surveillance is selected.

6.1.2 Leveraging Available Facilities and Ongoing Radar R&D Programs

To the extent possible, the R&D activities should leverage existing capabilities at Federal and university research laboratories and in industry. Ongoing weather radar R&D, specifically using the National Weather Radar Testbed (NWRT) and existing short-wavelength polarimetric radars, can be leveraged to substantial advantage. In the near-term, the NWRT will play a major role in activities such as testing scanning strategies, time management use for tracking aircraft and weather, and specialized signal processing and advances afforded by the agile beam. An X-band polarimetric radar that is already under development will be used to study short-wavelength radar units as potential low-level, short-range radars in a nationwide MPAR network. However, the most important aspects of multiple use coupled with digital beam forming will require developmental work using a prototype active phased array radar unit. This MPAR prototype will be developed as part of the Technology Development and Test component of the risk-reduction R&D plan.

Maximum use will be made of available and emerging military technology, as well as components used by the cellular telephone industry, by researching announcements of the latest developments and acquisitions in these fields. An up-to-date inventory of devices and developments will be maintained.

6.1.3 Provisional Concept for an MPAR Network

As a provisional concept for a nationwide, domestic radar network of MPAR units, the JAG/PARP envisions a scalable unit architecture used for both larger, long-range MPAR units and smaller units to provide low-level coverage, particularly near airports (Terminal MPARs). To improve coverage beyond that of existing systems and meet desired future capability, the network of these two MPAR sizes could be augmented with a dense network of boundary layer radars, as discussed in section 6.4.3.

Appendix B describes the provisional concept for long-range and Terminal MPAR units in detail. The risk-reduction R&D program will solidify requirements for units in this network—such as the component radar power-aperture configurations, waveforms, numbers of independent channels, numbers of concurrent beams per channel, and multifunctional tasking—in sufficient detail to define subsequent tasks and subsystem-level specifications, if a decision is made to pursue MPAR implementation.

- Scanning strategy options will be tested and assessed.
- Concepts will be tested with simulations in the laboratory and on the MPAR prototype.
- Comparative evaluations will be made of polarimetric operational performance at different wavelengths.

6.2 Technology Development and Test

Key engineering activities will include development and test of low-cost, critical component technologies such as T/R elements, analog and digital beamforming architectures, and efficient processing algorithms. A prototype MPAR unit will be developed and tested in an operational environment.

Chapter 5 describes the technology advances and capability requirements driving military and commercial sector progress in MPAR components and subsystems. Recent U.S. Navy programs have demonstrated the application of commercial packaging techniques to RF modules for high-performance phased array radars. The T/R Line Replaceable Unit (LRU) drives the performance, cost, and reliability of a solid-state antenna. Recent research has shown that reduction in T/R element and LRU costs can be achieved without sacrificing radar performance.

The proposed Technology Development and Test program combines these recent advances in solid-state technology with application know-how obtained from operating weather and air traffic control radars. Some aspects of the technology have been proven in other applications; other aspects require further development and testing. Whereas the core technology components of MPAR have been demonstrated in military applications, the scale and complexity necessary to support the multifunction capabilities described in chapter 4 will require concept verification and engineering test and evaluation. Another aspect that needs concept testing and refinement is the use of dual-polarization phased array antennas on a multiple-use radar unit.

Table 6-1 summarizes key parameters of the envisioned MPAR approach and indicates which parameters pose significant cost and technical development challenges. The most challenging are in red; the least challenging are in green.

TABLE 6-1. MPAR Key Technical Parameters*

Total Number T/R-Elements per Radar
Number of Frequency Channels
Dual Polarization
Bandwidth (per channel)
T/R-Element Peak Power
Number of Concurrent Receive Beams
Software Complexity
Size, Weight Constraints
Prime Power Constraints

** The background colors denote the level of technical and/or cost challenge imposed by each parameter. Red denotes substantial challenge, yellow denotes moderate challenge, and green denotes minimal challenge.*

To meet these challenges, the Technology Development and Test program includes the following tasks:

1. Reduce the cost of the T/R elements that provide the requisite power output and multichannel capability to well below $100 per element. To accomplish this reduction, leverage both DOD-sponsored development and commercial sector technology (e.g. the wireless telephone industry).

2. Assess the requirements for simultaneous (versus sequential-pulse) dual-polarization measurement capability. If the former is required, the impact on T/R-element cost and complexity must be quantified since this would essentially double the number of components (e.g. phase shifters, amplifiers) required per element.

3. Verify and validate the requirements for pulse bandwidth (for example, to support non-cooperative target length measurements or weather-radar "rapid scan" modes). Bandwidth requirements are an important factor in the cost of T/R elements, in downstream processing complexity, and in central processing unit requirements.

4. Demonstrate that highly digital array technology is affordable. For example, "overlapped sub-array" beamforming technology is an effective approach for generating the multiple concurrent receive beam clusters required to meet the time lines of the multiple surveillance functions. Significant opportunities exist to reduce the cost and complexity of sub-array beamformers.

5. Develop and demonstrate affordable transceivers that perform channel separation, down-conversion, and digitization for the T/R elements or sub-arrays in a modern phased array radar system.

6. Develop and demonstrate efficient, cost-effective processing architectures for the real-time beamformer. Multiple array outputs must be processed in parallel to form the large number of concurrent beams required to meet user needs. The associated processing load may be very large and will require careful design of both the processing algorithm and the processor configuration.

7. Conduct analyses to project radar cost trade-offs associated with operation in X-, C-, or S-band. Evaluate the capability of advanced processing algorithms and polarimetric measurement techniques that address performance issues at the different bands associated with sensitivity, ground-clutter suppression, range-Doppler ambiguities, and attenuation.

8. Evaluate alternative array geometries (e.g. planar, cylindrical, hemispherical), element grid geometries (e.g. rectangular, triangular), and "element-thinning" options.

9. Develop an MPAR prototype to provide an end-to-end demonstration that affordable, component technologies are realizable and that required multifunction surveillance capabilities can be realized at the projected level of performance. Field tests of this prototype will solidify key technical requirements such as number of independent channels and number of concurrent beams per channel.

10. Use the MPAR prototype to demonstrate the operational capability enhancements that can be realized through collaborative surveillance strategies that exploit the unique capabilities of a highly interconnected phased array radar network. Develop and test associated communications, control, and conflict resolution architectures. (This task dovetails with tasks to define the MPAR network concept. See section 6.4.2.)

11. Develop and test new aircraft surveillance post-processing techniques that exploit the unique capabilities of phased array radar to meet or exceed the performance of legacy air traffic control search radars. Consider at least the following capabilities: dedicated track modes, height resolution, non-cooperative target identification and integration with future cooperative target surveillance technologies such as ADS-B. (This task dovetails with late-stage tasks for proof of MPAR operational concepts. See section 6.3.4.)

12. Develop and demonstrate the unique capabilities and associated algorithm/system requirements for MPAR meteorological surveillance using the MPAR prototype.
    - Develop and demonstrate the use of MPAR in "warn on forecast" severe weather mitigation concepts and in improved aviation weather diagnosis and forecast services.
    - Develop common, scalable radar technologies that support long-range severe weather surveillance, hydrometeorological applications, and a dense network of boundary-layer radars.
    - This task dovetails with late-stage tasks for proof of MPAR operational concepts. See sections 6.3.1 and 6.3.3.

6.2.1 MPAR Component Technologies and Pre-Prototype Array

Tasks 1 through 5 in the preceding list, which demonstrate the cost reduction required in T/R elements having the requisite performance characteristics, are critical to the risk-reduction effort prior to a decision on the Nation's next-generation radar surveillance systems. The T/R elements used for military system applications may not be appropriate, as military applications often require very high performance under difficult conditions (e.g., high output power under environmental extremes). Such systems must operate on military platforms that impose constraints on size, cooling, or prime power. Technologies developed for the commercial wireless industry may be exploited to provide the performance necessary for domestic MPAR units at much lower cost per T/R element. This task will thus require close collaboration with industry to develop and test affordable, prototype T/R elements with multichannel and dual-polarization capability. Bench tests on the power, efficiency, and polarimetric characteristics of candidate T/R elements and associated sub-array components will provide an early test of many of the assertions made in this report.

Demonstrations of low-cost module approaches, sub-array beamformers, and multi–channel transceivers are needed to validate their ability to support the performance goals of MPAR. To conduct these demonstrations, a fractional array consisting of a few hundred T/R elements and comprising an aperture several square meters in area will be developed. The array will support two to three concurrent frequency channels, with 5 to 10 simultaneous receive beams per channel. Development and test of this small-scale, "pre-prototype" PAR antenna will enable exploration and resolution of key technical issues, while demonstrating whether the core technologies underlying the envisioned MPAR approach are viable and sufficiently robust. Figure 6-1 illustrates a possible physical implementation of this pre-prototype antenna, which could share most of its components (pedestal, processor, and display) with the existing NWRT.

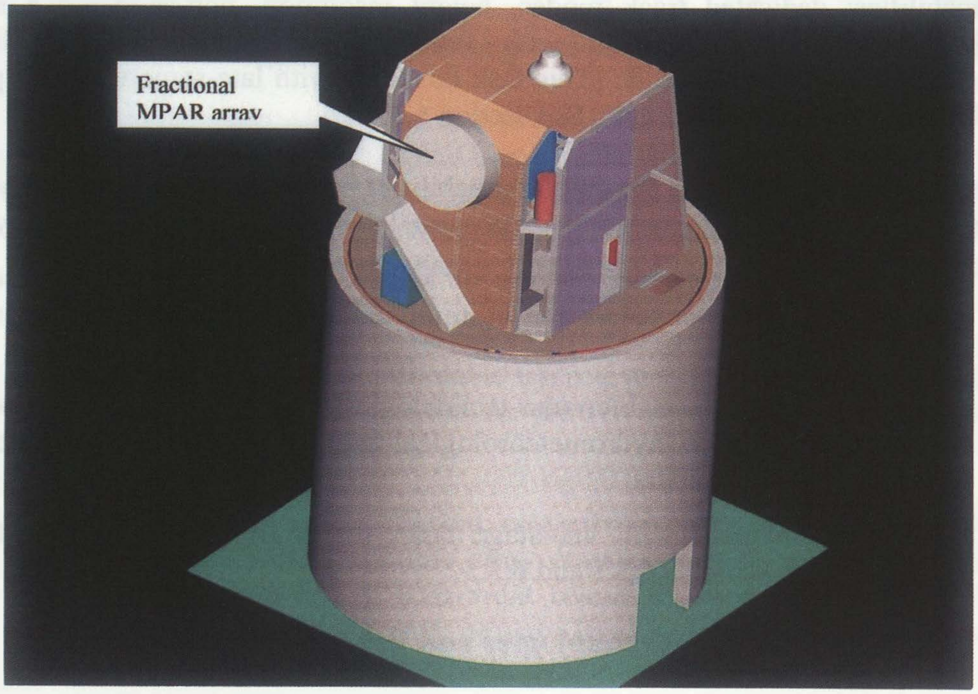

Figure 6-1. Artist's concept of a fractional MPAR array mounted on the backside of the current NWRT frame.

6.2.2 Full MPAR Prototype

Tasks 9 through 12 in the list of Technology Development and Test activities pertain to a "full-up" MPAR prototype unit. Subsystem-level technology development and small array testing in the 2006–2009 time frame (tasks 1 through 8) will set the stage for development of this prototype MPAR unit. The prototype, which will be developed in collaboration with industry, should be capable of providing the full range of operational services described in this report. A multiyear technical and operational test program will be conducted to establish that all key user needs are satisfied and that MPAR is economically and logistically viable.

6.3 Proof of MPAR Operational Concepts

The second component of the MPAR risk-reduction R&D plan encompasses a set of proof-of-concept experiments. Early-stage, proof-of-concept experiments can be conducted on the NWRT. Late-stage experiments will require use of the MPAR prototype described above. Others will be stand-alone evaluations, and some will be software procedures.

Early-stage experiments, conducted in parallel with tasks 1 though 8 in the Technology Demonstration and Test component, will use the existing NWRT in Norman, Oklahoma, and existing shorter-wavelength radars. These assets will be used to collect appropriate data to test, validate, and refine key operational concepts for a nationwide MPAR network, including severe weather "warn on forecast" capabilities, simultaneous surveillance of weather and aircraft, and evaluation of short wavelength (C-band and X-band) technology and phenomenology as applied to the preliminary Terminal MPAR concept for low-level, smaller units in the MPAR network. An early goal of the risk-reduction program will be to demonstrate that MPAR units can meet or exceed the capabilities of the systems they would replace. The specification for each system to be replaced will be the basis for these comparisons, which will form a crucial and integral part of the test plan and objectives.

6.3.1 Signal Design for Weather Monitoring

Two major complementary technological developments make rapid acquisition of weather radar data possible. These are transmission and processing of wide bandwidth signals and beam agility of an active phased array radar. Both will be tested on the NWRT and the prototype MPAR unit. With beam agility and adaptive scans, the existing NWRT phased array radar should achieve a twofold to fourfold decrease in the time required for a full-volume scan. A five- to ten-fold decrease in full-volume scan time will require simultaneous scanning from multiple antenna faces, combined with advanced signal designs and processing. These capabilities can be demonstrated on the MPAR prototype.

Oversampling and decorrelation of signals in range is a candidate signal processing technique that will be tested. This technique is effective at large signal-to-noise ratios and has been accepted as an improvement for the existing WSR-88D units. Testing can start in the near future, as this capability is built into the NWRT and the provision exists to record time-series data. The MPAR prototype, when developed, will provide further capabilities that support rapid data access, specifically the capability to process in parallel multiple radials of received data from a target that has been illuminated simultaneously by a broader transmit beam.

6.3.2 Beamforming and Processing

Concept definition studies and subsequent prototype testing will define the number of concurrent beam modes needed for MPAR units in the envisioned network and the functionality of each beam mode. For example, a fan beam similar to that produced by the current ASRs could be transmitted. The digital beamformer on receive could be programmed to focus simultaneously in a pencil-beam fashion at all the elevations illuminated by the transmit beam. Other possibilities for wideband illumination and pencil-beam reception will be explored. A common feature of these options is that multiple array outputs must be processed in parallel to form the required number of concurrent beams. Substantial theoretical study will be followed by careful design of both processing algorithms and processor configuration.

6.3.3 Weather Processing Algorithms

A key feature of an electronically steerable phased array radar beam is that it can be used to obtain volumetric data with variable spatial and temporal resolutions. Because positioning of the beam has no associated mechanical inertia, the beam can be moved nearly instantaneously in arbitrary directions. Thus, a target volume of interest can be covered by a constellation of data samples of differing data density, similar to the differences in density that occur in a three-dimensional wedge of fruitcake. Certain regions in the target volume can be represented by high-resolution data, while regions of lesser interest are represented by a relative paucity of reflection data.

These adaptive volume coverage patterns can be developed and tested initially on the NWRT. Adjustments of the standard weather processing algorithms can be made to adapt them to the phased array radar environment. The best way to make these adjustments to exploit the unique features of phased array radar will be determined. Moreover, the variable resolution of phased array meteorological radar data presents new and exciting challenges for display and visualization in both research and operational applications. Important early work in this area can be accomplished on the NWRT or using NWRT data sets.

6.3.4 Aircraft Processing Algorithms

Early demonstrations of multifunction capability will use the single, electronically scanned agile beam of the NWRT. Although full-capability non-cooperative aircraft surveillance will require dedicated frequency channels and multiple, concurrent receive beams, as described in chapter 4, early proof-of-concept demonstrations with the NWRT will be useful. Significant effort is needed to develop and demonstrate efficient multipurpose use, but these studies can be accomplished with the existing NWRT in Norman.

As explained in section 2.2, the FAA's NGATS plan emphasizes cooperative surveillance technologies such as ADS-B for air traffic control services. Nevertheless, a complementary non-cooperative target tracking capability is required in the event of equipment failure, GPS signal jamming, or intentional spoofing. MPAR is one option for providing this complementary capability, but a detailed understanding of the role of complementary tracking capability in the future air traffic control system should be developed.

Once the MPAR prototype is developed, it can be used to refine and demonstrate non-cooperative aircraft surveillance capabilities. MPAR's capability for height resolution and dedicated track modes is expected to provide significant reductions in false-track occurrence and should provide more accurate estimates of target location and track velocity. This part of the risk-reduction plan is intended to assess the impact of these enhanced capabilities on air traffic control procedures and non-cooperative target threat assessment.

6.4 Refinement of the MPAR Network Concept

The network concept presented in appendix B will require further validation and refinement. Many of its assumptions can be tested through the first two components of the proposed MPAR risk-reduction R&D program. Prior to a commitment to network acquisition, however, there are two network-level confirmatory studies that the JAG/PARP considers essential to validating and refining its preliminary network concept. One study will test the option of using shorter-wavelength radars for the Terminal MPAR units in an MPAR network. The second will explore and test strategies for collaborative surveillance of the same target by several units in the network.

6.4.1 Short-Wavelength Terminal MPAR

The provisional concept for a national network of MPAR units includes smaller, lower-cost radars, to provide a denser network that extends radar coverage closer to the ground at strategically important locations such as airports (appendix B). These Terminal MPAR units would be less expensive versions of the main MPAR unit design, hence the risk-reduction R&D in the Technology Development and Test tasks will be directly applicable to them as well.

For reasons explained in appendix B, it may prove advantageous to operate the Terminal MPAR units at shorter wavelengths than are used for the main MPAR units. Therefore, a network-related study is proposed that would evaluate the utility of C-band (5 cm) and X-band (3 cm) polarimetric radars in the Terminal MPAR role. The initial part of this study can use existing MRCR units operating at these wavelengths. Tests of polarimetric capability at C band wavelengths will be made after adding polarization diversity to existing mobile MRCR units. Similarly, testing of polarimetric capability at X-band wavelengths will be made using a research radar that is currently being developed. The study will capitalize on data from other sources, including private firms and foreign weather services.

6.4.2 Collaborative Surveillance Strategies

Throughout the MPAR risk-reduction R&D program, consideration should be given to operational enhancements that can be achieved with surveillance strategies that make use of collaboration among radar units in the MPAR network. Collaborative surveillance strategies are already being investigated for some of the legacy radar systems, such as collaborations involving WSR-88D units, TDWR units, and the weather data component of ASR units. For this element of the MPAR risk-reduction program, data collected with the NWRT can be combined with the collaborative data from these legacy radar types. Additional conceptual studies for the design and simulation of surveillance strategies will be used to seek collaborative strategies that best exploit the advanced capabilities of a highly interconnected phased array radar network. For example, a proof-of-concept Terminal MPAR prototype will be used in experiments on complementary (and somewhat overlapping) scanning and data collection employing both sizes of the MPAR unit.

6.4.3 Network Coverage for Aircraft Surveillance at Low Elevations

The provisional concept for a nationwide MPAR network described in appendices B and C includes larger, long-range MPAR units and smaller Terminal MPAR units. Such a network would give 90 to 95 percent coverage of the National airspace at 5,000 ft. elevation and above, and probably about 55 percent coverage from 5,000 ft. down to 1,000 ft. This coverage is at least equivalent to that of existing air surveillance networks. The long-range MPARs and Terminal MPARs would use a scalable unit architecture for efficiencies in acquisition and savings in both acquisition costs and total life-cycle costs.

As table 2-2 shows, the desired future capability for aircraft surveillance is total coverage of the National airspace from the surface to an elevation of 100,000 ft. One option to explore for increasing coverage at lower elevations is the addition of a dense network of low-level, atmospheric boundary-layer radars to augment the long-range and Terminal MPAR units. Such radars could be similar in design to the CASA (Collaborative Adaptive Sensing of the Atmosphere) radars, which are being developed for comprehensive sampling of the boundary layer. As noted in section 4.1, development of a scalable active array architecture could provide a common technology base for all three phased array radars: long-range MPARs, Terminal MPARs, and low-level boundary-layer radars. Technical and cost trades to achieve various levels of coverage approaching the ideal of "surface to 100,000 ft. everywhere" coverage will be explored. Coordination and collaboration with the CASA program will be essential to this part of the risk reduction program. However, neither the current CASA program objectives nor the CASA cost structure is reflected in the technical and cost estimates in this report.

6.5 Time Line and Resource Estimate

This section presents high-level milestones and costs for the three components of the MPAR risk-reduction R&D program. The plan for the 2006–2007 time frame includes parallel paths for tasks 1 and 2 in the Technology Development and Test program: addressing the key cost drivers for an MPAR unit, the multichannel T/R elements, and the overlapped sub-array beamformer. Industry contracts will be awarded to implement previously demonstrated, low-risk designs for these subsystems. Innovative designs of "ultra low cost" subsystems will be developed, implemented, and tested. The JAG/PARP expects that these designs can reduce the costs of key MPAR subsystems by a factor of 10. A comparative performance and cost evaluation will be conducted to determine which subsystem design should carry forward into follow-on development and test activities for the full-up MPAR prototype.

Figure 6-2 shows a time line and cost for the three major program components discussed above: MPAR technology development and test, proof of MPAR operational concepts, and refinement of the MPAR network concept. Appendix D contains a detailed breakout of tasks, including task definitions, for each program component.

	Year	2007	2008	2009	2010	2011	2012	2013	2014	2015
MPAR ops concepts ($52M)	Signal Processing Scan/Weather Obs.	6								
	A/C track/weather observations-Des/Bld DP Subarray		6							
	A/C track/Dual Pol Subarray test			11	11	6				
	Operational App						6	6		
Tech dev. and test ($158M)	Concept Study/pre-proto array	3	7	8	10					
	PAR Des/Fab/test/OT&E					29	33	29	29	
	Operation Test and Demo, Technology Transfer									10
Refine MPAR network concept ($5M)	X/C band tests	1								
	Architecture/subsystem Des.&Dev.		1							
	Proof of Concept			1	1	1				
Annual totals ($215M)		10	14	20	22	36	39	35	29	10

Figure 6-2. MPAR risk-reduction R&D program schedule.
Numbers in the schedule blocks are the planned FY costs per year in millions of dollars.

7 KEY FINDINGS AND RECOMMENDATIONS

Decisions must be made by the 2010–2015 time frame on the best way to sustain and improve the Nation's domestic radar capabilities for weather surveillance and aircraft surveillance. The JAG/PARP has formulated a set of recommended next steps by which the FCMSSR, OFCM, and individual Federal agencies can prepare for an informed decision on whether a single network of multifunction phased array radar (MPAR) units should become the Nation's next-generation technology for these surveillance applications. The recommendations are presented in section 7.2. Section 7.1 rehearses the key findings from chapters 2 through 6 on which the JAG bases its recommendations

7.1 Summary of Key Findings Supporting the Next Steps

The numbered paragraphs below summarize and draw conclusions from much more detailed discussions in chapters 2 through 6. The source section(s) are indicated in brackets at the end of the paragraph.

1. Building on the proven weather surveillance capabilities of the NEXRAD network, radar research is expanding the capability of phased array radar to sense more and more weather phenomena of substantial value for safety and National economic growth. Research has shown how radar can be used to detect precipitation type (hydrometeors) and quantify precipitation rate on the spatial and temporal scales necessary for advanced applications in quantitative precipitation forecasting and flash flood nowcasting. Wind and turbulence phenomena observable by new radar techniques can improve warning times for tornadoes and severe thunderstorms; for wind shear, wind gusts and shifts, and microbursts; and for the local spin-off effects of cyclonic storms interacting with terrain. These advanced radar observing capabilities, coupled with the improvements in NWP modeling that advanced radar data make possible, have application to downstream applications as diverse as fire weather and wildland fire management, debris flow prediction, spaceflight launch and recovery, and "ground truth" for calibrating and validating new generations of satellite-borne remote-observing instruments. Federal agencies whose mission areas already are or could be impacted by improved radar capabilities include NOAA/NWS, FAA, FHWA, NASA, Department of Agriculture (including the U.S. Forest Service), Department of the Interior (National Park Service, Bureau of Land Management, U.S.G.S.) Department of Homeland Security (FEMA, U.S. Fire Administration, U.S. Coast Guard), Department of Defense (Air Force, Navy, and Army for domestic and homeland defense operations), EPA, and others. **[sections 2.1 and 2.3]**

2. Radar surveillance of the National Airspace System will continue to be essential to detection, identification, tracking, and—if necessary—interdiction of non-coopera-tive aircraft. Radar surveillance can complement the planned cooperative

surveillance strategy, which depends on reception of signals from aircraft-borne transponders, by providing assured backup and transponder signal validation. Radar can also aid in detecting natural hazards to aviation not caused by atmospheric conditions alone, such as bird flocks and volcanic ash plumes. Federal agencies whose mission areas depend on these capabilities include the FAA, Department of Homeland Security, and Department of Defense. **[sections 2.2 and 2.3]**.

3. Aging of the existing domestic radar networks for weather surveillance or aircraft surveillance will require substantial commitments of Federal resources to either maintain or replace the networks **[section 3.1]**.

4. As many as seven of these aging, single-function conventional radar networks could in principle be replaced by a single network of MPAR units, with each unit capable of performing multiple functions. A shift in National strategy from multiple networks of mechanically rotating conventional radars to one MPAR network could not only provide all the capability of the existing systems, but also enable many of the new observing capabilities to support the full range of advances and downstream applications listed in points 1 and 2 above. **[chapters 3 and 4]**

5. However, before a decision is made between continuing with conventional single-function radars or an MPAR network, some specific technical issues need further testing and demonstration to ensure that the necessary MPAR technology is mature enough to proceed with this major shift in strategy. **[chapter 4]**

6. The JAG/PARP estimates that an MPAR network using today's technology is likely to be a cost-effective option. Technology trends provide opportunities for further cost reductions. In a preliminary study of required radar coverage, analysts from MIT's Lincoln Laboratory concluded that a network of about 334 MPAR units could replace the roughly 510 units in the seven aging, disparate networks—a 35 percent reduction in radar units. Preliminary analyses indicate that both the acquisition cost and the life-cycle cost of this MPAR network concept compare favorably with either continuing to repair, maintain, and replace the existing networks or replacing them with networks of newer, single-function conventional radars. However, these preliminary studies need to be refined and validated before a decision on National domestic radar strategy is made. **[chapter 5]**

7. The technical, cost, and programmatic risks associated with an MPAR network strategy can be reduced substantially by a modest R&D program, to be completed prior to the time that substantial resource commitments must be made to sustain current radar coverage and capability. This R&D program comprises three components, which merge toward the end of the program. (1) A technology development and test program will lead to construction of a prototype MPAR unit. (2) Proof of MPAR operational concepts will be conducted initially using the phased array radar of the National Weather Radar Testbed (NWRT), then with the MPAR prototype. (3) The provisional MPAR network concept will be refined using the NWRT, several research radars with appropriate transmission bands, and analysis of data from the legacy radar systems. **[chapter 6]**

7.2 Recommended Next Steps

On the basis of the preceding findings, the JAG/PARP recommends the following actions as next steps toward a coordinated, rational approach to deciding on the Nation's strategy for domestic radar capability for the next 30 years.

Recommendation 1. The FCMSSR should endorse the concept of an MPAR risk-reduction R&D program that substantially incorporates the objectives and the three components of the plan outlined in chapter 6.

Recommendation 2. The FCMSSR should consider organizational options to foster collaborative and joint R&D on the MPAR risk-reduction activities by establishing a joint entity, such as a Joint National Center for Advanced Radar Research and Development, to manage agencies' contributions to the risk-reduction program outlined in this report.

Recommendation 3. For the period prior to operational standup of a joint management entity, the FCMSSR should direct OFCM to form an interagency MPAR Working Group (WG/MPAR) within the OFCM infrastructure to coordinate and report on the R&D activities of participating agencies in implementing an MPAR risk-reduction program. Activities of the WG/MPAR should include, but not be limited to:

- Identification of agency contributions to the first phase of risk-reduction activities in each component prong of the program.
- Establish a cost basis for near-term agency contributions, sufficient to allow incorporation into Agency budget submissions.
- Explore options to foster interagency cooperation and collaboration on MPAR risk-reduction activities.
- Develop a set of specific program progress metrics against which annual progress toward risk-reduction goals and objectives can be assessed.
- Prepare and publish an annual statement of the next-year objectives and activities for the risk-reduction program. This annual statement should include a review of progress in the current year and connections to out-year activities and objectives, to show how each year's activities contribute toward achieving the overall risk-reduction goals. As guidance to the participating agencies, the report should include an estimate of budget resources needed for the next-year activities and a summary of prior-year funding by agency. Progress toward goals and objectives, using the program metrics, should be reported each year, with an analysis of areas of shortfall and of substantial progress.
- Identify opportunities for review of program plans and progress by appropriate boards or study committees of the National Academies' National Research Council (NRC).
- Prepare and publish an MPAR Education and Outreach Plan to build understanding of and garner support for a National surveillance radar strategy decision within all the potentially affected Federal agencies, Congress, State and

local governmental entities, the private sector, and the public. This plan should involve the academic community and the media and include dissemination of results from the NRC studies suggested above. A series of workshops, coordinated through NCAR, should be considered for engaging the academic research community.

Recommendation 4. The FCMSSR should direct that, in conjunction with the MPAR risk-reduction program, a cost-benefit analysis be undertaken to establish the cost-effectiveness of the MPAR option and competing domestic radar strategies. The basis for MPAR acquisition and life-cycle costs should include results from the technology development and test activities and the MPAR network refinement, as appropriate.

APPENDICES

APPENDIX A

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APPENDIX B

Multi-Function Phased Array Radar for U.S. Civil-Sector Surveillance Needs

12R.2

MULTI-FUNCTION PHASED ARRAY RADAR FOR U.S. CIVIL-SECTOR SURVEILLANCE NEEDS

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1. INTRODUCTION

This paper is a concept study for possible future utilization of active electronically scanned radars to provide weather and aircraft surveillance functions in U.S. airspace. If critical technology costs decrease sufficiently, multi-function phased array radars might prove to be a cost effective alternative to current surveillance radars, since the number of required radars would be reduced, and maintenance and logistics infrastructure would be consolidated. A radar configuration that provides terminal-area and long-range aircraft surveillance and weather measurement capability is described and a radar network design that replicates or exceeds current airspace coverage is presented. Key technology issues are examined, including transmit-receive elements, overlapped sub-arrays, the digital beamformer, and weather and aircraft post-processing algorithms. We conclude by discussing implications relative to future national weather and non-cooperative aircraft target surveillance needs.

The U.S. Government currently operates four separate ground based surveillance radar networks supporting public and aviation-specific weather warnings and advisories, and primary or "skin paint" aircraft surveillance. The separate networks are:

(i) The 10-cm wavelength NEXRAD or WSR88-D (Serafin and Wilson, 2000) national-scale weather radar network. This is managed jointly by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DoD).
(ii) The 5-cm wavelength Terminal Doppler Weather Radars (TDWR) (Evans and Turnbull, 1989) deployed at large airports to detect low-altitude wind-shear phenomena.
(iii) The 10-cm wavelength Airport Surveillance Radars (ASR-9 and ASR-11) (Taylor and Brunins, 1985) providing terminal area primary aircraft surveillance and vertically averaged precipitation reflectivity measurements[1].
(iv) The 30-cm wavelength Air Route Surveillance Radars (ARSR-1, 2, 3 and 4) (Lay et al., 1990) that provide national-scale primary aircraft surveillance.

The latter three networks are managed primarily by the FAA, although the DoD operates a limited number of ASRs and has partial responsibility for maintenance of the ARSR network. In total there are 513 of these radars in the contiguous United States (CONUS), Alaska, and Hawaii.

The agencies that maintain these radars conduct various "life extension" activities that are projected to extend their operational life to approximately 2020. At this time, there are no defined programs to acquire replacement radars.

The NWS and FAA have recently begun exploratory research on the capabilities and technology issues related to the use of multi-function phased array radar (MPAR) as a possible replacement approach. A key concept is that the MPAR network could provide both weather and primary aircraft surveillance, thereby reducing the total number of ground-based radars. In addition, MPAR surveillance capabilities would likely exceed those of current operational radars, for example, by providing more frequent weather volume scans and by providing vertical resolution and height estimates for primary aircraft targets.

Table 1 summarizes the capabilities of current U.S. surveillance radars. These are approximations and do not fully capture variations in capability as a function, for example, of range or operating mode. A key observation is that significant variation in update rates between the aircraft and weather surveillance functions are currently achieved by using fundamentally different antenna patterns—low-gain vertical "fan beams" for aircraft surveillance that are scanned in azimuth only, versus high-gain weather radar "pencil beams" that are scanned volumetrically at much lower update rates. Note also that, if expressed in consistent units, the power-aperture products of the weather radars significantly exceed those of the ASRs and ARSRs.

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[1] A limited number of ASR-9 are equipped with the Weather Systems Processor (Weber, 2005), which additionally provides a capability for low-altitude wind-shear detection.

	Sensitivity	Coverage Range	Coverage Altitude	Angular Resolution Az	Angular Resolution El	Waveform	Update Rate
Terminal Aircraft Surveillance	1 m^2	60 nm	20,000'	1.4°e	5.0°e	>18 pulsese PRI ~ 1 mse	5 s
En Route Aircraft Surveillance	2.2 m^2	250 nm	60,000'	1.4°e	2.0°e	>10 pulsese PRI ~ 3 mse	12 s
Terminal Area Weather	-20 to -5 dBze	60 nmi	15,000'	1°	1°	>50 pulsese PRI ~ 1 mse	60 s
National Scale Weather	-20 to -5 dBze	250 nmi	60,000'	1°	1°	~50 pulses PRI ~ 1 ms	300 s

Table 1. Summary of current U.S. surveillance radar capabilities.

In the next section, we present a concept design for MPAR and demonstrate that it can simultaneously provide the measurement capabilities summarized in Table 1. In Section 3 we present an MPAR network concept that duplicates the airspace coverage provided by the current multiple radar networks. Section 4 discusses technology issues and associated cost considerations. We conclude in Section 5 by discussing implications relative to future national weather and non-cooperative aircraft target surveillance needs.

2. RADAR DESIGN CONCEPTe

2.1 *Antenna Configuration and Scan Patterns*

Four antenna faces are assumed so that azimuth scanning of ±45°e is required. The angular resolution and power-aperture requirements of the weather function drive the size of each face. To compensate for beam squinting, a broadside beam-width of 0.7° is needed. Roughly 20,000 elements per face would be required and, at S-band, an 8-m diameter circular aperture (50 m^2e). Antenna gain would be 46 dB or greater depending on scan angle. We assume each transmit-receive (TR) module can provide 10-W peak power, thus providing 200 kW total for the array.

Three different surveillance functions (terminal aircraft, en route aircraft, and weather) are assigned to separate frequency channels. These frequencies are within the same band, but are separated sufficiently that pulse transmission, reception, and processing can be accomplished independently. Pulse transmissions for the three functions will not be synchronized. Thus, isolated "dead gates" will be introduced into the coverage volumes of each function when energy is transmitted for one of the other functions. It is assumed that these blanked gates will shift around on successive volume updates so as to minimize operational impact. Figure 1 illustrates the pulse transmission sequence.

We show below that transmission of 5 μs, 200-kW peak-power pulses provides sufficient energy on target to realize the weather and en route aircraft surveillance functions. Five-to-one pulse compression is assumed to maintain the ~150-m range resolution of current surveillance radars. For the terminal aircraft surveillance function, a 1-μs uncoded pulse provides sufficient energy on target. This pulse can also be used as a "fill pulse" to measure weather at very short ranges.

The separate frequency channels allow for the formation of independent transmit beams and receive beam clusters separately for the different functions. High angular resolution can be maintained for all surveillance functions by using the full aperture for receive beam formation. Where needed, rapid volume scanning can be achieved by dynamically widening the transmit beam pattern so as to illuminate multiple resolution volumes concurrently.

Figure 2 depicts notional transmit and receive beam patterns appropriate for the various surveillance modes. Digital control and processing of the TR-elements is needed to generate these independent beams. Since, at any one time, the receive beams are clustered in relatively small angular intervals, an overlapped sub-array beamforming architecture (Herd et al., 2005) with digitization at the sub-array level can be used. As seen from Figure 2, the maximum number of concurrent beams in our concept is approximately 200, which sets a lower limit on the number of sub-arrays. For specificity, we will assume that 400 sub-array channels will be digitized to support synthesis of low-sidelobe (< 40 dB) receive beam patterns.

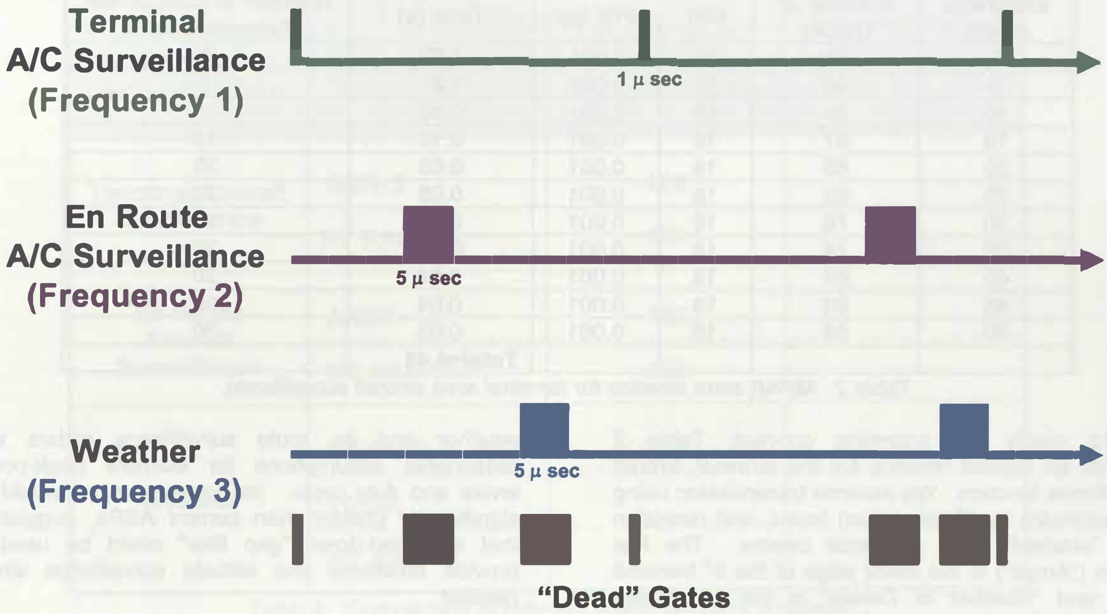

Figure 1. Pulse scheduling for MPAR.

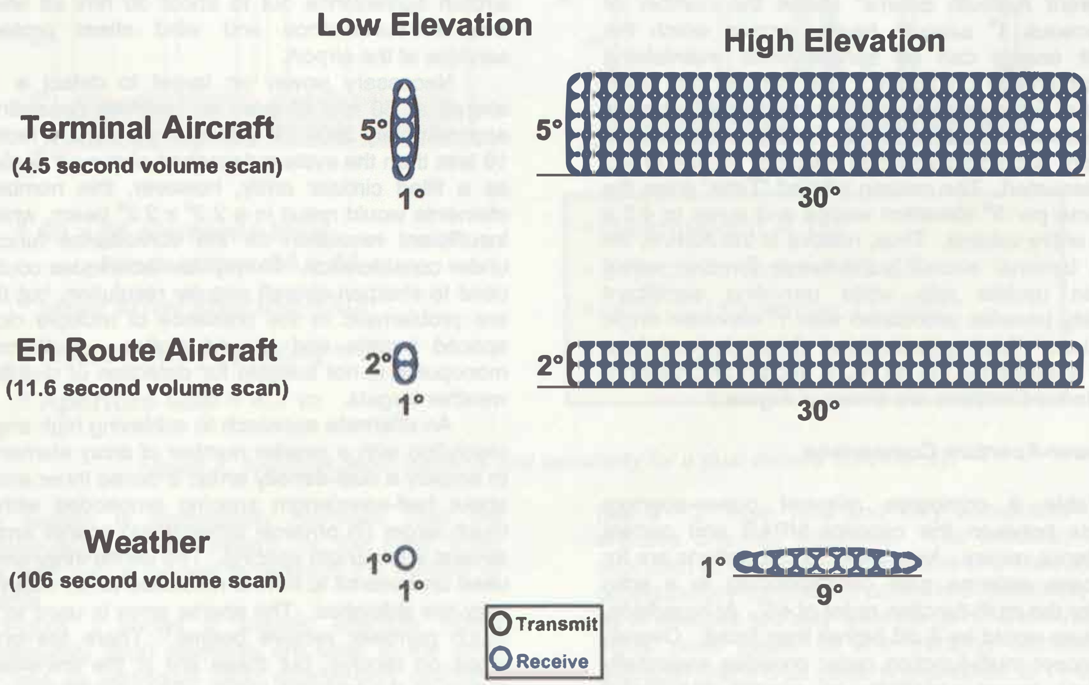

Figure 2. Notional beam patterns for multifunction radar surveillance modes.

Elevation Angle	Number of Dwells	CPI	PRI (s)	Time (s)	Number of Concurrent Azimuth Beams
0	90	18	0.001	1.62	1
5	90	18	0.001	1.61	1
10	89	18	0.001	0.80	2
15	87	18	0.001	0.12	13
20	85	18	0.001	0.05	30
25	82	18	0.001	0.05	30
30	78	18	0.001	0.05	30
35	74	18	0.001	0.04	30
40	69	18	0.001	0.04	30
45	64	18	0.001	0.04	30
50	58	18	0.001	0.03	30
				Total=4.46	

Table 2. MPAR scan timeline for terminal area aircraft surveillance.

To clarify the scanning concept, Table 2 presents an explicit timeline for the terminal aircraft surveillance function. We assume transmission using a 1° (azimuth) by 5° (elevation) beam, and reception using "stacked" 1° x 1° pencil beams. The first column ("Angle") is the lower edge of the 5° transmit beam and "Number of Dwells" is the associated number of 1° azimuth dwells required. For each dwell, the ASR-9 transmitted waveform is assumed so that the coherent processing interval (CPI) utilizes 18 samples at an average pulse repetition interval (PRI) of 1 ms.

At higher elevation angles, it is possible to increase the scan rate by further spoiling the transmit beam pattern, since, for a fixed altitude ceiling, the maximum range requirement falls off as the cosecant of the elevation angle. The column "Number of Concurrent Azimuth Beams" shows the number of simultaneous 1° azimuth beams across which the transmit energy can be spread while maintaining sufficient energy on target. This number has been capped at 30 to limit the number of beams that must be processed simultaneously. For this calculation, a maximum aircraft surveillance height of 15,000 m (49 kft) is assumed. The column labeled "Time" gives the scan time per 5° elevation wedge and sums to 4.5 s for the entire volume. Thus, relative to the ASR-9, the MPAR terminal aircraft surveillance function would maintain update rate while providing significant capability benefits associated with 1° elevation angle resolution. Total volume scan times derived from similar analysis for the en route aircraft and weather surveillance functions are shown in Figure 2.

2.2 *Power-Aperture Comparison*

Table 3 compares relevant power-aperture products between the concept MPAR and current surveillance radars. Note that the calculations are for worst-case antenna gain corresponding to a scan angle for the multi-function radar of 45°. At broadside, the values would be 4 dB higher than listed. Overall, the concept multi-function radar provides essentially the same target sensitivity as current operational weather and en route surveillance radars with reasonable assumptions for element peak-power levels and duty cycle. Its power-aperture would be significantly greater than current ASRs, suggesting that a scaled-down "gap filler" could be used to provide additional low altitude surveillance where needed.

2.3 *Gap-Filler Radars*

The siting analysis described in Section 3 indicates that half of the total number of radars required to replicate current airspace coverage would be devoted to surveillance below 10,000' altitude at relatively short ranges. For this, it would be inefficient to use the large aperture radar described above. A down-scaled MPAR, or "gap-filler", could provide aircraft surveillance out to about 30 nmi as well as weather surveillance and wind shear protection services at the airport.

Necessary power on target to detect a 1-m^2 aircraft at 30 nmi dictates an aperture consisting of approximately 2000 TR elements per face, a factor of 10 less than the system described above. If deployed as a filled circular array, however, this number of elements would result in a 2.2° x 2.2° beam, which is insufficient resolution for the surveillance functions under consideration. Monopulse techniques could be used to sharpen aircraft angular resolution, but these are problematic in the presence of multiple closely spaced targets and ground clutter. Furthermore, monopulse is not suitable for detection of distributed weather targets.

An alternate approach to achieving high angular resolution with a smaller number of array elements is to employ a dual-density array: a dense inner array at about half-wavelength spacing embedded within a much larger (in physical dimensions) sparse array at several wavelength spacing. The dense inner array is used on transmit to form a moderate-width beam with very low sidelobes. The sparse array is used to form much narrower receive beams. There are grating lobes on receive, but these are in the low-sidelobe region of the transmit beam. The resulting two-way

Function	Radar	Point Target $P_T G_T G_R \lambda^2$ (dB)	Weather Target $\frac{P_T G_T G_R \Delta \vartheta \Delta \phi}{\lambda^2}$ (dB)
Terminal Aircraft Surveillance	ASR- 9	108	
	MF RADAR	120	
En Route Aircraft Surveillance	ARSR – 4	132	
	MF RADAR	129	
Weather	NEXRAD		171
	TDWR		173
	MF RADAR		170

Table 3. Comparison of relevant power-aperture products.

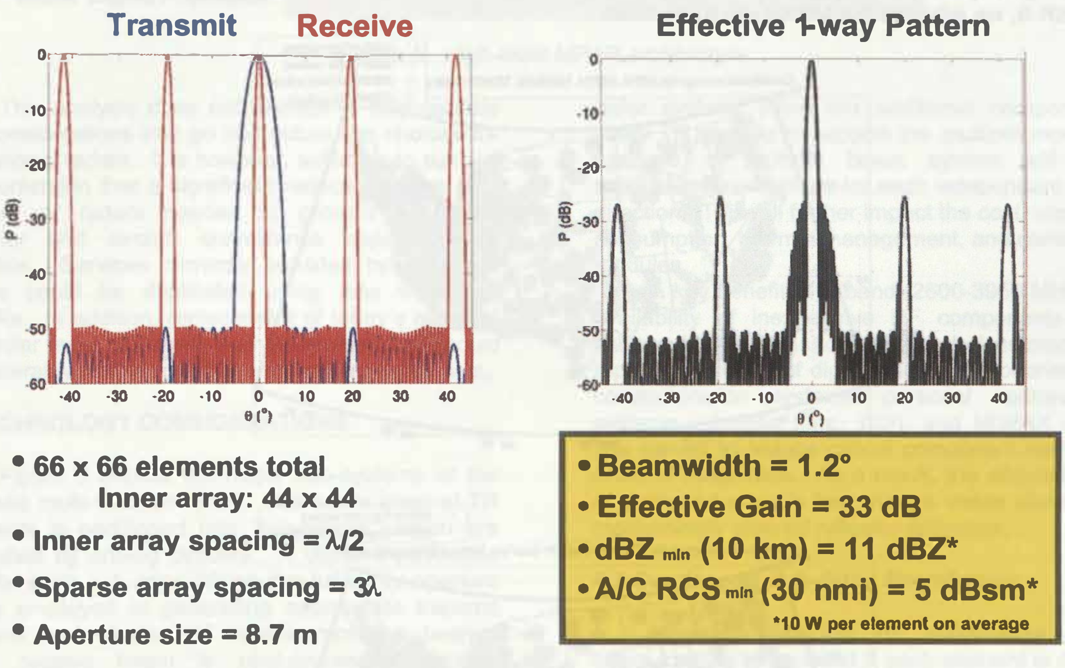

Figure 3: Example beam patterns and sensitivity for a dual-density active array.

beam pattern is dramatically narrower than the corresponding two-way pattern for the inner array alone, with only a modest increase in the number of elements.

Figure 3 shows a specific example where approximately 2000 elements are used in the inner array and an additional 2400 receive-only elements comprise the thinned outer array. The total aperture is 8.7 m in diameter. The resulting antenna pattern has a 1.2° main lobe and very acceptable -25-dB effective one-way sidelobes. The limitation to this approach is, of course, that relative to a filled aperture configuration, transmitted power is substantially lower as is effective two-way antenna gain. Sensitivity with 10-W peak power for the transmit elements (on average) and a 5-µs pulse is equivalent to 11 dBZ for weather targets at a range of 10 km. Although possibly adequate for precipitation mapping and many

Doppler measurement applications, this gap-filler configuration would be substantially less sensitive at short range than are current TDWR or NEXRAD systems.

3. MPAR NETWORK AIRSPACE COVERAGE

A second aspect of our study was to determine how many multi-function radars would be required to replicate airspace coverage provided by the current operational radar networks. To accomplish this, we developed a three-dimensional (3D) CONUS data base that defines current coverage capabilities for each of the surveillance functions we are considering: en route aircraft, terminal aircraft, national-scale weather, and terminal weather. For each grid point we determined whether an appropriate radar provides coverage and, if so, what available sensitivity and spatial resolution are provided. High-resolution digital terrain elevation data (DTED) were used to account for terrain effects in this analysis.

We used current NEXRAD locations as the initial site choice for the full-aperture MPAR described in Section 2. For radars located within approximately 50 km of large airports currently equipped with TDWR and/or ASR-9, we adjusted the MPAR site to be close enough to the airport to meet current siting criteria for the terminal radars. A total of 145 full-aperture MPARs so sited would provide near-seamless airspace coverage above 10,000 ft AGL, replicating the national scale coverage currently provided by the NEXRAD and ARSR networks. In addition, the terminal area weather and aircraft surveillance functions provided by TDWR and ASR would be duplicated at many airports. An additional 144 gap-filler MPARs as described in Section 2 could provide terminal-area weather and aircraft surveillance at remaining U.S. airports.

Figure 4 compares airspace coverage at 1000 ft AGL between current operational radar networks and the concept MPAR network. Differences are minimal and within the coverage areas, MPAR would meet or exceed current radar measurement capabilities—horizontal and vertical resolution, minimum detectable target cross section, and update rate—with one exception. As noted, the gap-filler MPAR would not have the sensitivity for very low cross-section wind-shear phenomena that is currently provided by the TDWR.

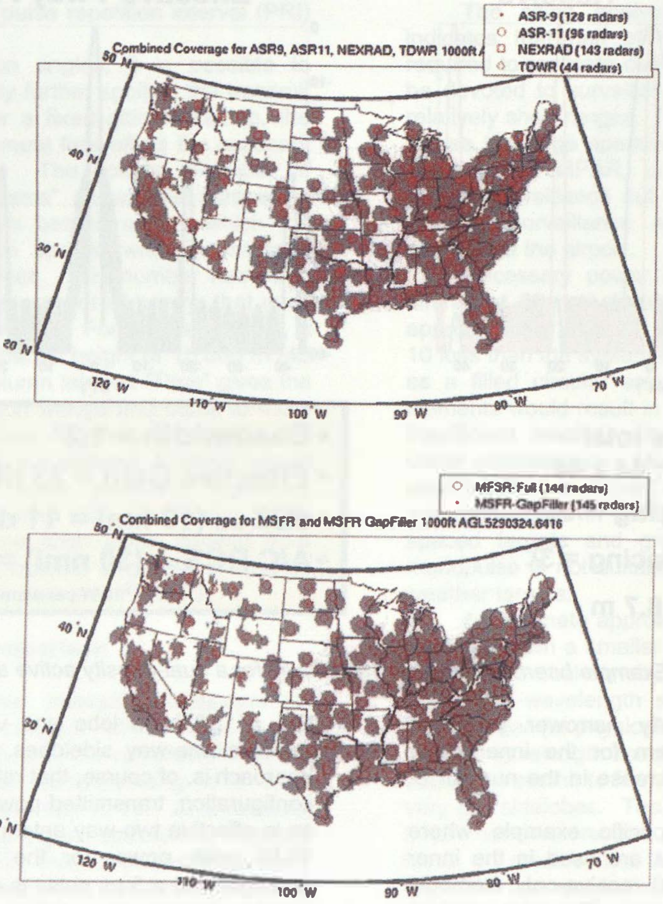

Figure 4. Airspace coverage at 1000 ft AGL provided by current U.S. surveillance radar networks (top) and conceptual MPAR network (bottom).

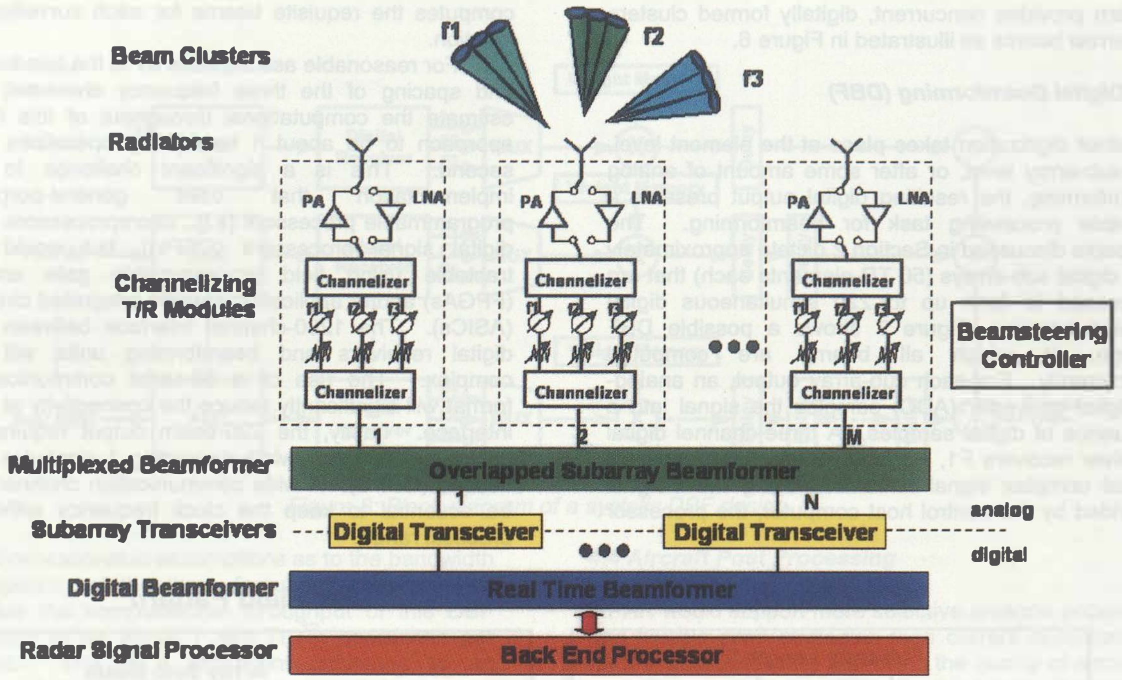

Figure 5. High-level MPAR architecture.

This analysis does not attempt to fully capture the considerations that go into actual site choices for operational radars. It is however, sufficient to support the contention that a significant reduction in the total number of radars needed to provide necessary weather and aircraft surveillance capabilities is possible. Services currently provided by over 500 radars could be duplicated using less than 300 MPARs. In addition, replacement of today's multiple, dissimilar radar types with a single architecture should considerably reduce logistics and maintenance costs.

4. TECHNOLOGY CONSIDERATIONS

Figure 5 depicts the major sub-systems of the requisite multi-function radar. The active array of TR elements is partitioned into "sub-arrays," which are controlled by analog circuitry. A digital input/output port for each sub-array allows the full array aperture to be employed in generating appropriate transmit patterns and clusters of narrow receiving beams. Each receive beam is post-processed through appropriate Doppler filters, parameter estimation algorithms, and target tracking algorithms.

4.1 *Transmit-Receive Elements*

A major cost driver in an active phased array system is the large number of TR modules. Each element of an active array has a TR module with a phase shifter, a low-noise receive amplifier (LNA), and a high-power transmit amplifier (HPA). In addition, the modules have DC power circuits and beam-steering control functions. In a multifunction radar system, there are additional components in every TR module to support the multiple modes. For example, a multiple beam system will require separate phase shifters for each independent pointing direction. This will further impact the cost, size, power consumption, thermal management, and control of the modules.

A key benefit at S band (2600-3950 MHz) is the availability of inexpensive RF components (phase shifters, LNAs, HPAs) due to the wireless market. The rapid proliferation of digital cellular telephones, digital communication systems, personal communication systems, wireless data, WiFI, and WiMAX systems has served to reduce critical component costs by an order of magnitude. As a result, the acquisition cost of a phased array is becoming a viable alternative to mechanically steered reflector antennas.

4.2 *Overlapped Sub-Array Beamformer*

Maximum flexibility for active-array antenna beam-forming is provided if each element is digitized. However, element-level digitization for a large array is unnecessary for most applications. A more effective approach is to partition the aperture into overlapping sub-arrays, whose elements are controlled via analog circuitry, combined and digitized to allow simultaneous beams to be formed digitally at the sub-array combination level. The spacing of the sub-arrays is significantly greater than one-half wavelength, resulting in grating lobes. Analog manifolds control the sub-array elements to produce a flat-topped pattern whose width is less than the spacing of the grating lobes. Thus the composite pattern provides concurrent, digitally formed clusters of narrow beams as illustrated in Figure 6.

4.3 *Digital Beamforming (DBF)*

Whether digitization takes place at the element level, the sub-array level, or after some amount of analog beamforming, the resulting digital output presents a sizeable processing task for beamforming. The concepts discussed in Section 2 dictate approximately 400 digital sub-arrays (50 TR-elements each) that are processed to form up to 220 simultaneous digital receive beams. Figure 7 shows a possible DBF design, in which all beams are computed concurrently. For each sub-array output, an analog-to-digital converter (ADC) samples the signal into a sequence of digital samples. A three-channel digital receiver recovers F1, F2, and F3 into three separate digital complex signal streams. Using the weights provided by the control host computer, the processor computes the requisite beams for each surveillance function.

For reasonable assumptions as to the bandwidth and spacing of the three frequency channels, we estimate the computational throughput of this DBF approach to be about 1 tera (10^{12}) operations per second. This is a significant challenge to an implementation that uses general-purpose programmable processors (e.g., microprocessors and digital signal processors (DSPs)), but would be tractable using field programmable gate arrays (FPGAs) and/or application-specific integrated circuits (ASICs). The 1200-channel interface between the digital receivers and beamforming units will be complex. The use of a bit-serial communication format will significantly reduce the connectivity at this interface. Lastly, the 220-beam output requires a communication bandwidth exceeding 1 gigabytes per second (GBPS). A wide communication channel will be essential to keep the clock frequency within a practical range.

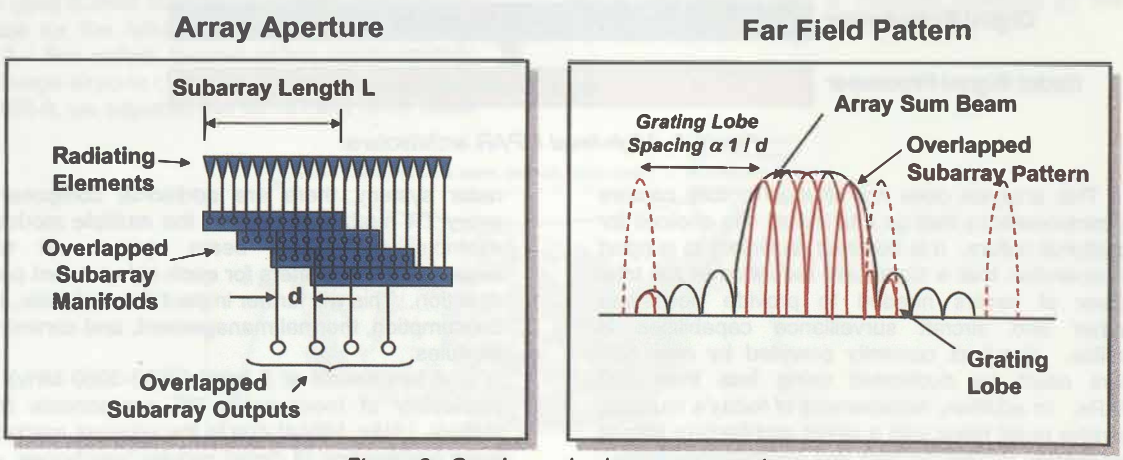

Figure 6. Overlapped sub-array concept.

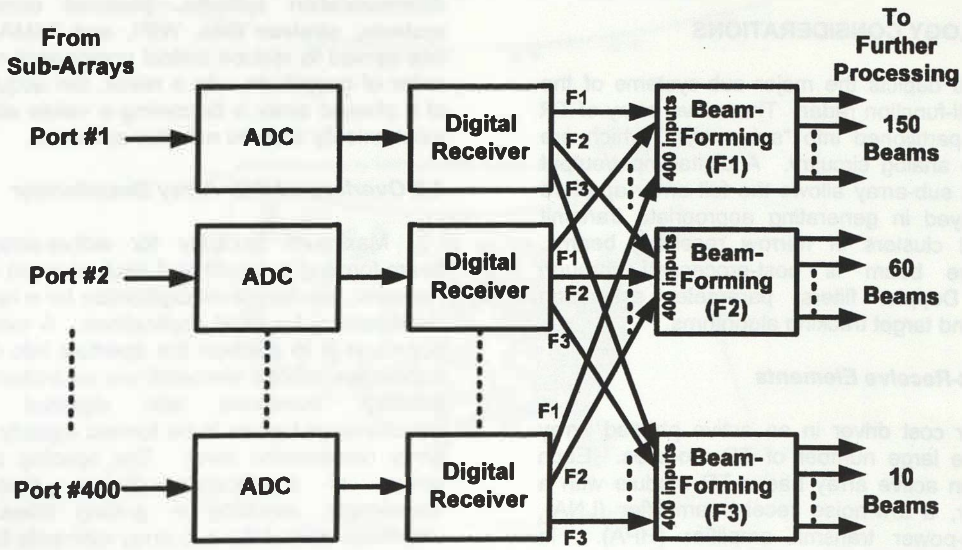

Figure 7: Block diagram of a fully parallel DBF design.

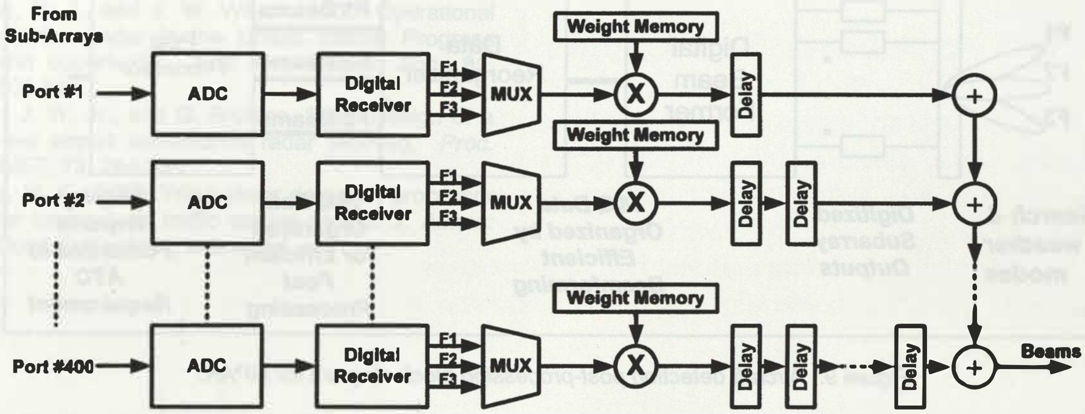

Figure 8: Block diagram of a systolic DBF design.

For reasonable assumptions as to the bandwidth and spacing of the three frequency channels, we estimate the computational throughput of this DBF approach to be about 1 tera (10^{12}) operations per second. This is a significant challenge to an implementation that uses general-purpose programmable processors (e.g., microprocessors and digital signal processors (DSPs)), but would be tractable using field programmable gate arrays (FPGAs) and/or application-specific integrated circuits (ASICs). The 1200-channel interface between the digital receivers and beamforming units will be complex. The use of a bit-serial communication format will significantly reduce the connectivity at this interface. Lastly, the 220-beam output requires a communication bandwidth exceeding 1 gigabytes per second (GBPS). A wide communication channel will be essential to keep the clock frequency within a practical range.

The high computational throughput can be mitigated by reducing the parallelism of operations. Instead of computing each beam in an individual beamforming unit, a group of beams can be sequentially computed in the same unit. Figure 8 illustrates a systolic design that embodies this concept to the extreme, in which all the beams are computed sequentially. In addition to a much simplified interconnection requirement, the beam output bandwidth is also significantly reduced, since only one beam is produced at a time.

In this approach, the three signals (F1, F2, and F3) coming out of each digital receiver are sequentially multiplied with corresponding weights to form partial beams. Each partial beam is delayed with an amount according to its position in the summing chain. A 400 sub-array implementation will require a maximum of 400-cycle delay. The multiplication, delay, and addition can be readily implemented with FPGA technology.

4.4 *Aircraft Post Processing*

MPAR would support more selective antenna patterns and flexible scan strategies than current operational radars, thus potentially improving the quality of aircraft surveillance. However, the radar front end will incur a significant transformation in the flow and content of the data provided to the post-processing algorithms as depicted in Figure 9. New post-processing techniques will need to be developed to meet or exceed the performance of the legacy Moving Target Detection (MTD) (Karp and Anderson, 1981) air traffic control search radars. Examples are:

(i) The use of multiple beam clusters significantly expands the amount of data to be processed. An efficient and affordable open architecture must be defined that reduces acquisition cost by making appropriate use of commercial off-the-shelf solutions. This architecture must also enable technology refresh and the future insertion of new technology and algorithms.

(ii) Target detections will occur in multiple beams within each beam cluster requiring a new algorithm for correlation and interpolation to the single centroided target report needed for input to existing Air Traffic Control display systems. Also, since the merging of primary and beacon radar target reports cannot depend upon the azimuth and range registration advantages of collocated antennas, modified reinforcement algorithms will also need to be developed.

(iii) A selective elevation pattern will allow the altitude of detected targets to be estimated, motivating the development of a new highly simplified clutter elimination algorithm.

(iv) Automatic Dependent Surveillance Broadcast (ADS-B) will replace beacon radars in some regions. Efficient scan strategies should be developed to allow phased arrays radars to confirm and augment ADS-B reports.

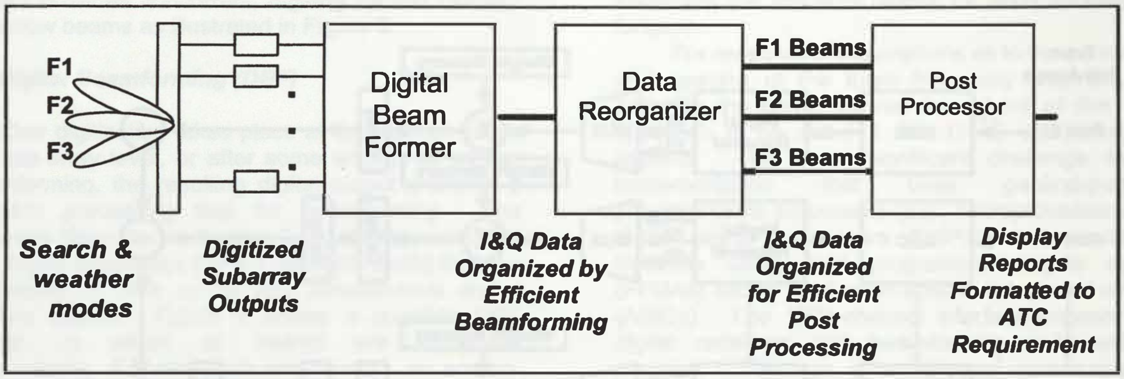

Figure 9: Aircraft detection post-processing block diagram for MPAR.

4.5 *Weather Post Processing*

As with the aircraft surveillance functions, the weather scan strategies and data processing algorithms should be optimized to exploit the capabilities of a phased-array radar. Significant optimization of scan time can be realized by:

(i) Removing the requirement for 360° coverage from a single aperture.
(ii) Exploiting the ability to form concurrent receiving beams along radials where either signal-to-noise ratio is uniformly high or maximum range coverage is limited.
(iii) Utilization of "decorrelated pulse-pairs" for radials where long CPIs are not required for clutter suppression or spectral-domain weather echo processing.

Such techniques can significantly increase the volume scan update rate and/or improve data quality by allowing for longer dwell time along "high value radials" (e.g., low-elevation tilts for boundary layer wind mapping).

Spaced aperture techniques can be applied by separately processing received signals from halves or quadrants of the full aperture. Such techniques can potentially be used to estimate the cross-range wind component and 3D turbulence fields. Meteorological surveillance requirements for high power-aperture, angular resolution, and long dwell times are likely to have a significant influence on system architecture and cost. It is essential that significant effort go into the evaluation and demonstration of efficient phased-array radar designs and processing approaches for this application.

5. SUMMARY AND DISCUSSION

We have described a concept for a next-generation multifunction phased array radar (MPAR) network that could provide high-quality weather and primary aircraft surveillance capabilities. The authors are optimistic that continuing advances in the critical technology areas described in Section 4 will make MPAR a technically and economically effective replacement strategy for current radar networks.

A key operational consideration is the future role of primary radar aircraft surveillance in U.S. airspace. The Air Traffic Control system is increasingly moving towards cooperative surveillance technologies (secondary or "beacon" radars and/or GPS-based dependent surveillance). It is likely, however, that there will always be a need for backup primary surveillance to handle the possibility of non-compliant intruders in controlled airspace. DoD and DHS currently rely on FAA primary radars as a major input to their airspace monitoring activities; it seems highly likely that an equivalent capability will be needed for the foreseeable future.

In any scenario, an operational weather radar network remains a critical observing system for the nation. We noted that the power-aperture and angular resolution requirements for weather surveillance significantly exceed corresponding requirements for aircraft surveillance. Thus MPAR will allow the future weather radar network to additionally provide high quality aircraft surveillance services at modest cost. This fact should be considered in discussions about future national surveillance architectures.

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APPENDIX C

Preliminary Cost Analysis for Multifunction Phased Array Radar

Current U.S. weather and aircraft surveillance radar networks vary in age from 10 to more than 40 years. Ongoing sustainment and upgrade programs can keep these networks operating in the near to mid term, but the responsible agencies (FAA, NWS, DOD, and DHS) recognize that large-scale replacement activities must begin during the next decade. In 2005, the FAA asked Lincoln Laboratory to participate in a multi-agency evaluation of technology issues and cost trades associated with a replacement strategy involving multifunction phased array radars (MPARs).

Cost considerations are a key element of this study. The current operational ground radar network is composed of seven distinct radar systems with separate Government program offices, engineering support organizations, and logistics lines. A single national MPAR network could reduce life-cycle costs by consolidating these support functions. The total number of deployed radars could also be reduced since the airspace coverages from today's radar networks overlap substantially.

Today, a total of 510 Government-owned weather and primary aircraft surveillance radars operate in the contiguous United States (CONUS). To quantify the potential reduction in radar numbers, we developed a three-dimensional database that defines the current airspace coverage of these networks. High-resolution digital terrain elevation data were used to account for terrain effects. An iterative siting procedure was used to delineate MPAR locations that at least duplicate current coverage. Figure 1 shows that 334 MPARs would provide near-seamless airspace coverage above 5,000 ft AGL, replicating the national-scale weather and aircraft coverage currently provided by the NEXRAD and ARSR networks. The figure indicates that these MPARs would, in addition, provide low-altitude, airport-area weather and aircraft surveillance functions that are today provided by TDWR and ASR-9 or ASR-11 terminal radars. Approximately half of the MPARs are smaller terminal-area units providing range-limited (50 nmi.) coverage underneath the radar horizon of the national-scale network. These terminal area MPARs would be smaller-aperture, lower-cost radars employing the same scalable technology as the full-sized MPAR units.

If the reduced numbers of MPARs and their single architecture are to produce significant future cost savings, the acquisition costs for the network of active electronically scanned array (AESA) radars must be at least comparable to the mechanically scanned radars they replace. To define the technical parameters of the required MPAR and estimate its costs, we developed a conceptual radar configuration, described in detail in Weber et al. (2005). Table 1 summarizes the configuration.

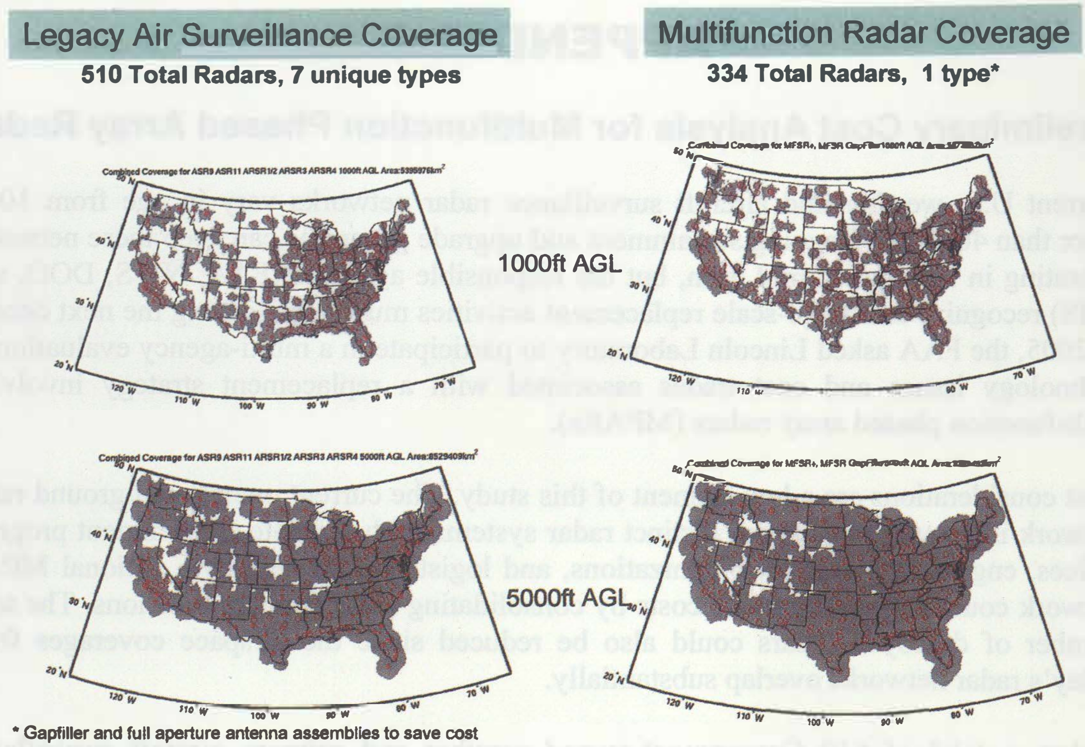

Figure 1. Airspace coverage comparison between current U.S. operational radar networks (ASR-9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, TDWR) and a conceptual MPAR network.

Table 1. Concept MPAR Parameters

Transmit/Receive Elements	Wavelength (frequency)	10 cm (2.7-2.9 GHz)
	T/R element peak power	1 Watt
	Bandwidth (per channel)	1 MHz
	Frequency Channels	3
	Pulse Length	1-50 µsec
Active Array (4-faced, planar)	Diameter	8 m
	T/R elements per face	20,000
	Beam width	
	- broadside	0.7°
	- @ 45°	1.0°
	Gain	46 dB
Architecture	Overlapped sub-array	
	No. of sub-arrays	300-400
	- max. no. concurrent beams	~160

Based on this concept development work, a team led by Jeff Herd in Lincoln Laboratory's RF Array Systems group has commenced detailed design of a scaled "pre-prototype" MPAR array that incorporates the required technologies (Figure 2). This design work is providing technical and cost details that can be used to evaluate the viability of the MPAR concept.

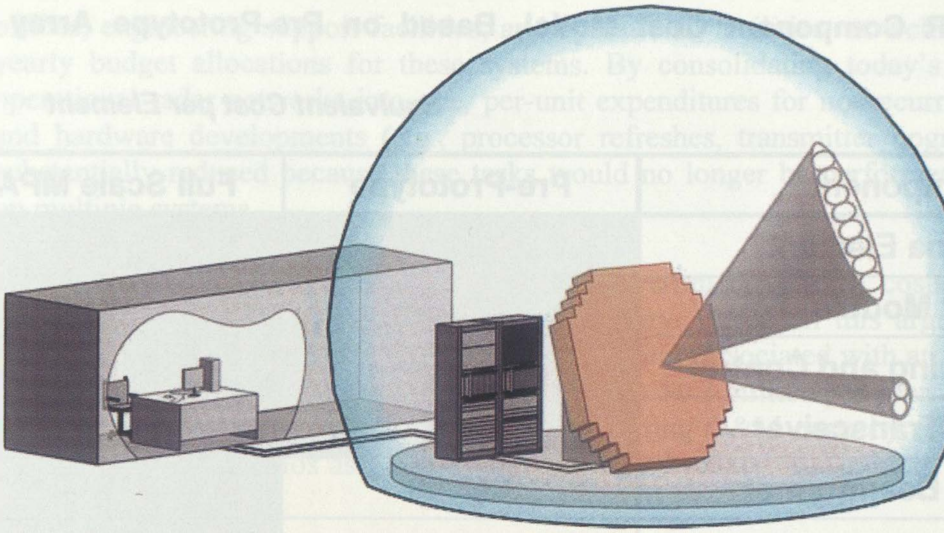

Figure 2. MPAR pre-prototype array.

The pre-prototype array will be 4.2 m in diameter, providing sufficient radiated power, antenna gain, and angular resolution (2.0° pencil beam) to demonstrate key weather and aircraft surveillance functions. The array will radiate and receive in two 1 MHz sub-bands and will utilize a one-dimensional, 16-channel sub-array beamformer to digitally form a vertical cluster of 8 receive beams for each sub-band. A brick module design is utilized with the major RF subsystems in a 6U Eurocard chassis behind the radiating elements. The dual-channel transmit-receive (T/R) element design incorporates low-cost commercial-off-the-shelf (COTS) components and a Lincoln-designed phase shifter to maintain the total parts cost at less than $20 per T/R element. Key to maintaining low T/R element cost is the use of a modest peak power (1 to 10 W) COTS high-power amplifier. The sub-array beamformer will initially be implemented using a multilayer printed circuit board design based on the Laboratory's X-band Space and Airborne Radar Transformational Array (SPARTA) program (Herd et al. 2005). It is anticipated that the current Laboratory efforts to develop an ASIC-based sub-array beamformer will significantly reduce the costs of this MPAR subsystem relative to the circuit board design. The sub-array output receiver design is derived from the Lincoln Digital Array Radar program (Rabideau et al. 2003) and provides high performance at a modest cost. A scalable, high performance digital beamformer preliminary design was developed by Michael Vai in the Embedded Digital Systems Group. Workable COTS implementation technologies include field programmable gate array (FPGA), ASIC, multichip module (MCM), and mixed signal designs.

Table 2 summarizes MPAR component cost estimates based on this pre-prototype array design. The tabulated numbers are normalized to a per–T/R element basis. Cost reductions indicated in the right-hand column result from either economies of scale or new technologies expected to mature over the next three years. Component costs are consistent with an MPAR that is cost-competitive with current operational radar systems.

Table 2. MPAR Component Cost Model, Based on Pre-Prototype Array Design

	Equivalent Cost per Element	
Component	Pre-Prototype	Full Scale MPAR
Antenna Element	$1.25	$1.25
T/R Module	$20.00	$20.00
Power, Timing and Control	$18.00	$18.00
Digital Transceiver	$12.50	$6.25
Analog Beamformer	$63.00	$15.00
Digital Beamformer	$18.00	$8.00
Mechanical/Packaging	$105.00	$25.00
RF Interconnects	$163.00	$40.00

The component costs of the full MPAR system summarized in Table 1 would be approximately $10.7 million. The smaller-aperture system suitable for low-altitude terminal area surveillance would have component costs of approximately $2.8 million. The pre-prototype subsystem designs support automated fabrication and integration so that, in quantity, the average per-unit cost of the terminal MPAR and full-aperture MPAR networks may be expected to be cost-competitive with the $5 million to $10 million procurement costs for today's operational air traffic control and weather radars.

Figures 3 and 4 provide very preliminary estimates of national radar network costs for three scenarios. In scenario one, current radar networks are maintained until their plausible end of life (2012–2025), which depends on the age of the individual network, and then replaced with the same number of single-function radars. In scenario two, an aggressive MPAR development effort allows for replacement of the current radar networks with a reduced number of MPARs in the period 2011–2016. In the third scenario, the current networks are maintained until their end of life and then replaced by MPAR units. Per-unit replacement cost estimates for the legacy radars are based on actual costs in previous procurements. For MPAR, we have set the full aperture unit cost at $15 million and the smaller terminal area MPAR unit cost at $5 million. Recall that approximately equal numbers of these two sizes of MPAR units are needed to efficiently duplicate today's airspace coverage.

Based on the Laboratory's long-term involvement with the TDWR, NEXRAD, and ASR-9 life-cycle support and enhancement programs, we have estimated the yearly, per-unit operations and maintenance (O&M) costs of the legacy radars as $ 0.5 million per year. This figure considers the numbers of personnel in the associated Government program offices, engineering support facilities, and operational facilities, as well as the agency's yearly budget allocations for these systems. By consolidating today's seven separate operational radar networks into one, per-unit expenditures for nonrecurring engineering and hardware developments (e.g., processor refreshes, transmitter upgrades) could be substantially reduced because these tasks would no longer be performed independently on multiple systems.

We estimate that approximately half of the Government's O&M costs for the legacy radar networks fall into this nonrecurring category. Based on this argument, we have estimated that the 7-to-1 system support consolidation associated with an MPAR network could reduce per-unit O&M costs to approximately $0.3 million per year. We view this as conservative since MPAR may also reduce recurring O&M costs by eliminating single point-of-failure scenarios associated with the legacy radars' transmitters and mechanical drive subsystems.

As seen from Figure 3, for the 20-year period considered the aggressive MPAR implementation scenario reduces total costs by approximately $3.0 billion relative to a "sustain and replace" strategy. The majority of this saving accrues from reduced O&M costs associated with the smaller number of radars required and our assumption that a consolidated national radar network can substantially reduce nonrecurring engineering costs. A downside to this scenario is that cumulative costs are actually higher in the first half of the time period because MPAR acquisition expenditures are not fully offset until legacy radar system replacements become mandatory.

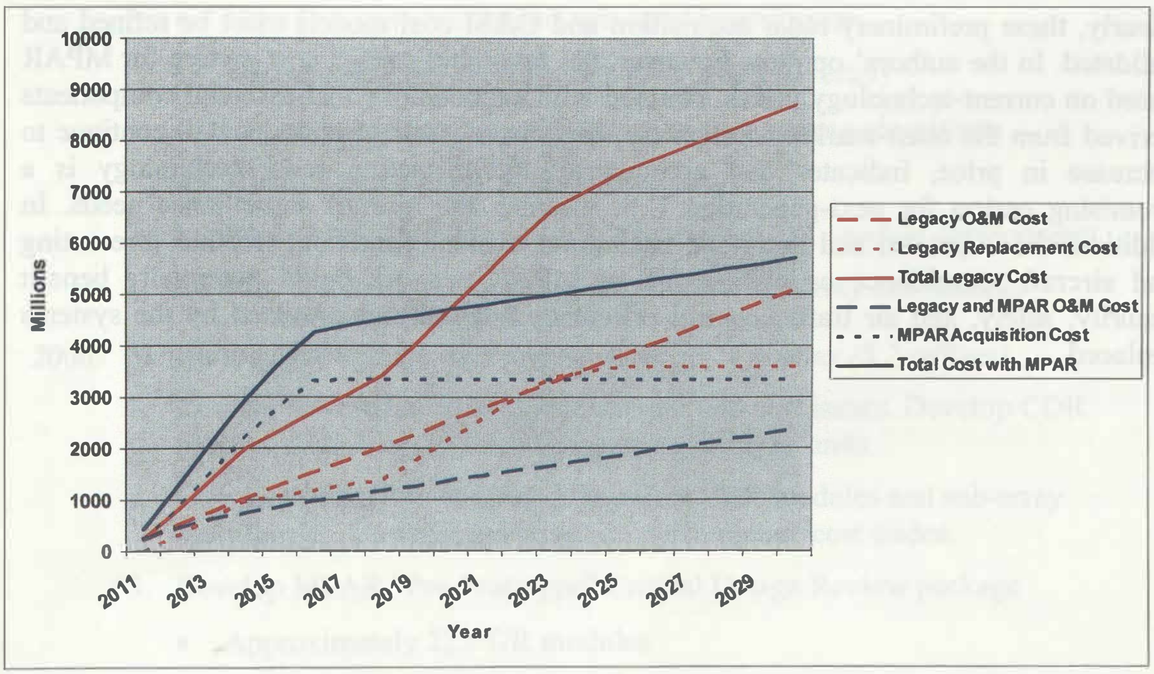

Figure 3. Comparison of cumulative costs for a "sustain and replace legacy radars" strategy (red) versus aggressive implementation of MPAR (blue).

In the third scenario, illustrated in Figure 4, MPAR units are fielded on an as-needed basis. This fielding approach minimizes the early-period cost disadvantage of the second scenario but reduces (to $2.4 billion) the net savings over the total 20-year time period.

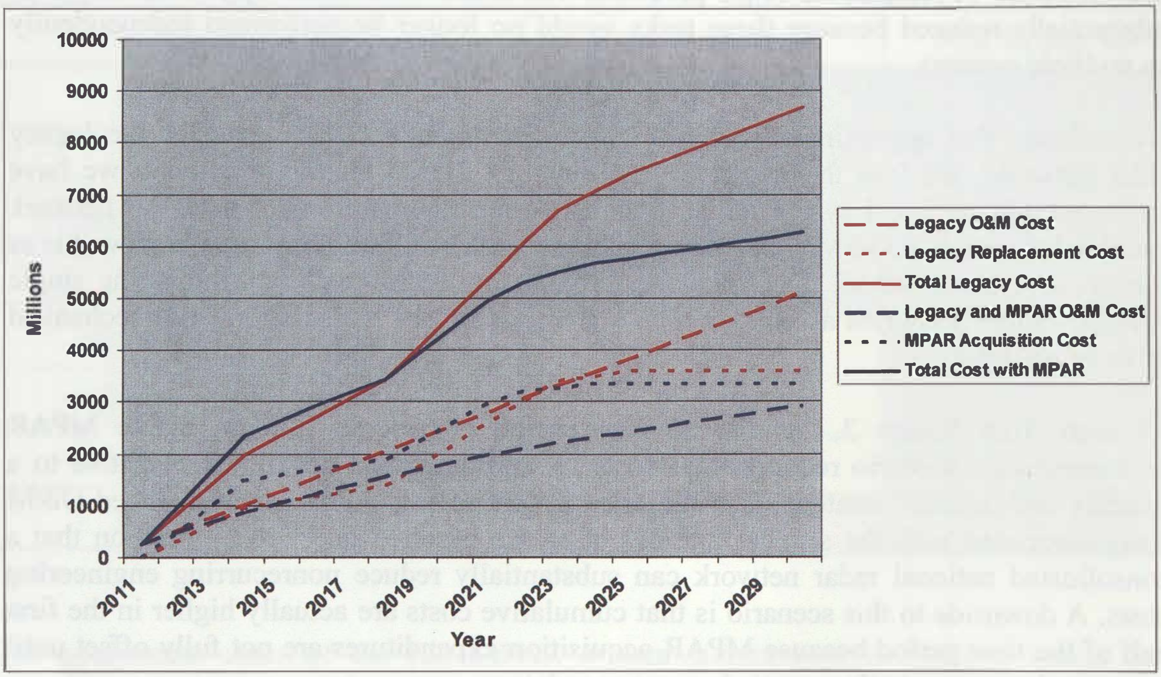

Figure 4. Comparison of cumulative costs for a "sustain and replace legacy radars" strategy (red) versus "replace with MPAR when needed" strategy (blue).

Clearly, these preliminary radar acquisition and O&M cost models must be refined and validated. In the authors' opinion, however, the favorable overall cost picture for MPAR based on current-technology prices, coupled with expectations that essential components derived from the mass-market wireless and digital processing industries will continue to decrease in price, indicates that active-array, multifunction radar technology is a promising option for next-generation U.S. weather and aircraft surveillance needs. In addition, the improved and expanded hazardous weather detection, weather forecasting and aircraft surveillance capabilities of an MPAR network could potentially benefit security, safety, and air traffic control efficiency beyond that provided by the systems replaced.

APPENDIX D

MPAR R&D Plan
Detailed Task Time Line and Cost

The following time line breaks down R&D tasking and cost by year for the three major components of the proposed R&D plan:

- Technology development and test
- Proof of MPAR operational concepts
- Refinement of the MPAR network concept.

MPAR Technology Development and Test

2007 *Architecture and Subsystem Development for an MPAR Prototype ($3 million)*

1. Detailed MPAR Architecture study. Develop MPAR Preliminary Design Review package based on completed concept definition study.
2. Develop design concept for key MPAR subsystems. Assess critical performance and cost issues. Lay out plan for subsystem prototype development and test.
   - Ultra low-cost, multichannel T/R module
   - Ultra low-cost overlapped sub-array beamformer
   - Multichannel transceiver (sub-array A/D converter)
   - Digital beamforming architecture and processing algorithms
   - Weather and aircraft post-processors
3. Industry contract for "low-risk" multichannel T/R-module development
4. Industry contract for "low-risk" overlapped sub-array beamformer

2008 *Subsystem Development and "Pre-prototype" Contract ($ 7 million)*

1. Resolve subsystem critical performance and cost issues. Develop CDR packages. Develop and test subsystem prototype units.
2. Compare "ultra low-cost" and "low-risk" T/R modules and sub-array beamformer. Down-select based on performance/cost trades.
3. Develop MPAR "Pre-Prototype" Critical Design Review package
   - Approximately 225 T/R modules
   - 2 or 3 frequency channels
   - Approximately 6 sub-arrays

- Approximately 5 concurrent beams

2009 MPAR Pre-Prototype Integration ($8 million)

1. Integrate MPAR subsystems into functioning small aperture radar
2. Continue subsystem refinement and cost-reduction assessments
3. Develop final pre-prototype test and demonstration plan
4. Commence pre-prototype test and demonstration program

2010 Full-Sized MPAR Prototype Contract Award ($10 million)

1. Complete MPAR pre-prototype tests. Finalize sub-system designs.
2. Develop Critical Design Review Package for full-sized MPAR Prototype
   - Approximately 20,000 T/R elements per face x 4 faces, or equivalent cylindrical array
   - 2 or 3 frequency channels
   - Approximately 200 overlapped sub-arrays
   - Approximately 100 concurrent beams
3. Contract award for MPAR prototype development

2011 MPAR Prototype Development and Test Plan ($29 million)

1. Develop MPAR prototype
2. Develop Test Plan
   - Subsystem tests
   - "In-plant" tests
   - Live-target tests
   - Operational tests

2012 MPAR Prototype Tests ($33 million)

1. Conduct subsystem and in-plant tests
2. Deploy prototype to Government-designated site for live target tests
3. Develop interfaces to Government-designated operational facilities supporting targeted multiple mission (e.g. NWS WFO, FAA Terminal Approach Radar Control (TRACON) Centers and Air Route Traffic Control Centers (ARTCCs), North American Aerospace Defense Command NORAD)

2013 Live-Target Tests and Operational Demonstrations ($29 million)

1. Maintain and adapt MPAR prototype as necessary
2. Conduct live-target tests

- Demonstrate weather surveillance requirements
- Demonstrate non-cooperative target surveillance requirements

3. Deploy prototype to Government-designated operational test site. Interface to operational facilities.

2014 *MPAR Operational Test and Demonstration ($29 million)*

1. Maintain and adapt MPAR prototype as necessary
2. Conduct MPAR prototype operational tests involving NWS, FAA, DOD/DHS and private sector users. Operate prototype 24/7 in operational environment
3. Collect and analyze data on user acceptability

2015 *Technology Transfer ($10 million)*

1. Continue prototype operational demonstration
2. Prepare technology transfer package
   - Functional requirements
   - Subsystems performance specifications
   - Technology exhibits

Total for MPAR Technology Development and Test $158 million

<u>Proof of MPAR Operational Concepts</u>

2007 *Signal processing and scanning strategies for weather observations ($6 million)*

1. Upgrade NWRT transmitter with pulse compression and dual frequency capability
2. Start development of adaptive scan to fine tune interrogation of storms
3. Implement oversampling and whitening to speed volume update
4. Finish design of aircraft tracking enhancements
5. Continue display and algorithm development to match the MPAR capabilities (i.e., non-sequential, 3-D data stream)

2008 *Aircraft tracking and weather observations ($ 6 M)*

1. Add aircraft tracking capabilities to NWRT
2. Evaluate simultaneous collection of weather data and detection of aircraft

2009 *Aircraft tracking and dual polarization sub-array ($ 11 M)*

1. Use NWRT and/or other existing units to evaluate capability of dual polarization modules

2. Design and build dual-polarized phased sub-array
3. Modify displays and algorithms to handle dual-polarized phase array data
4. Test algorithms for acquisition of aircraft
5. Assimilate MPAR data into numerical models

2010 Aircraft tracking and dual polarization sub-array ($ 11 M)

1. Test dual-polarized phased sub-array
2. Collect data with the dual-polarization sub-array
3. Test algorithms for tracking of aircraft
4. Assimilate MPAR data into numerical models

2011 Dual polarization sub-array ($ 6 M)

1. Evaluate dual-polarization data from the sub-array
2. Test display and dual-polarization algorithms with data from the sub-array
3. Assimilate MPAR data into numerical models

2012 Research and Development towards operational applications ($ 6 M)

1. Research using NWRT data
2. Assimilate MPAR data into numerical models
3. Evaluate results

2013 Research and Development towards operational applications ($ 6 M)

1. Research using NWRT data
2. Assimilate MPAR data into numerical models
3. Evaluate results

Total for Proof of MPAR Operational Concepts : $ 52 M

<u>Refinement of MPAR Network Concept</u>

Testing of Short Wavelengths

2007 Polarimetry at 3- and 5-cm wavelengths ($ 1 M)

1. Assemble 3-cm polarimetric radar (parabolic dish)
2. Study and understand scattering specificities of dual-polarized signals at the 5-cm and 3-cm wavelengths
3. Examine existing polarimetric data at 5-cm wavelength
4. Collect data with the 3-cm polarimetric radar

2008 Polarimetry at 3- and 5-cm wavelengths: study and subsystem development ($1 M)

1. Analyze the 3-cm polarimetric radar data
2. Add polarimetric capability to NOAA's C-band mobile radar
3. Explore phased array antenna technology for 3- and 5-cm radars and identify cost-effective solutions
4. Detailed gap-filler study
5. Develop gap-filler Preliminary Design Review package
6. Procure and test various flatplate 3-cm wavelength antennas

2009 Subsystem development and proof of concept ($ 1 M)

1. Collect data with both the 3- and 5-cm polarimetric radars
2. Establish relative merits of the 3- and 5-cm wavelengths using data
3. Continue search and evaluation of inexpensive phased array technology for the 3- and 5-cm wavelengths

2010 System development and proof or concept ($ 1 M)

1. Work on algorithms for rainfall measurement and precipitation classification with short-wavelength radars
2. Identify a relatively inexpensive phased array technology for the 3- and 5-cm wavelengths
3. Make the choice between the 3- and 5-cm wavelengths

2011 Proof of concept development ($ 1 M)

1. Procure and test an appropriate dual-polarization phased array antenna
2. Devise strategy for correction attenuation and mitigating range and velocity ambiguities
3. Incorporate the critical functional requirements into the MPAR phased array

Total for Refinement of MPAR Network Concept $5 million

Total for Three Components of MPAR Risk Reduction R&D $215 million

APPENDIX E

Acronyms

ADC	analog-to-digital converter
ADS-B	Automatic Dependent Surveillance Broadcast
AESA	active electronically scanned array
ARSR	air route surveillance radar
ASIC	application-specific integrated circuit
ASR	airport surveillance radar
ATD	atmospheric transport and diffusion
CASA	Collaborative Adaptive Sensing of the Atmosphere
CONUS	contiguous United States
COTS	commercial off the shelf
CPI	coherent processing interval
DARPA	Defense Advanced Research Projects Agency
DBF	digital beamforming
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DHS	U.S. Department of Homeland Security
DTED	digital terrain elevation data
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FEMA	Federal Emergency Management Administration
FPGA	field programmable gate array
FHWA	Federal Highway Administration
GaN	gallium nitride
GEOSS	Global Earth Observation System of Systems
GBPS	gigabytes per second
GPS	Global Positioning System
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HPA	high-power transmit amplifier
ICMSSR	Interdepartmental Committee for Meteorological Services and Supporting Research
JAG/PARP	Joint Action Group for Phased Array Radar Project
LCMR	Low-cost Counter Mortar Radar
LNA	low-noise receive amplifier
LRU	Line Replaceable Unit
MCM	multichip module
MIT	Massachusetts Institute of Technology
MMIC	monolithic microwave integrated circuit
MMR	Multi-Mission Radar

MPAR	multifunction phased array radar
MP-RTIP	Multi-Platform Radar Technology Improvement Program
MRCR	mechanically rotating conventional radar
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Radar
NGATS	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NRC	National Research Council
NSSL	National Severe Storms Laboratory
NWP	numeric weather prediction
NWRT	National Weather Radar Testbed
NWS	National Weather Service
O&M	operations and maintenance
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
PRI	pulse repetition interval
QPF	quantitative precipitation forecasting
R&D	research and development
RF	radio frequency
SME	subject matter expert
SPARTA	Space and Airborne Radar Transformational Array
TDWR	Terminal Doppler Weather Radar
T/R	transmit-receive
TRACON	Terminal Approach Radar Control
VSR	Volume Search Radar
WG/MPAR	[proposed] MPAR Working Group
WSR-88D	Weather Surveillance Radar 1988 Doppler

APPENDIX F

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APPENDIX G

PHASED ARRAY RADAR PROJECT JOINT ACTION GROUP

Capabilities Questionnaire

January 23, 2005

The purpose of the Phased Array Radar Project Joint Action Group (PARP/JAG) Capabilities Questionnaire is to gather information about existing radar systems from all relevant agencies. The information gathered will be used to develop a research and development plan that will determine the feasibility and affordability of acquiring a multi-agency, multi-purpose PAR in the 10 – 25 year timeframe.

In answering the questions be as specific and detailed as possible when naming the systems, requirements, and capabilities of the radars used by your agency or organization. Please complete this questionnaire for your agency or organization by February 28, 2005 and forward it to the JAG/PARP Executive Secretary (robert.rizza@noaa.gov).

Present Capability

1. If your agency or organization currently operates ground-based radar systems, or uses data from such systems, please provide current capabilities / requirements for each system. (Some questions below apply only to agencies that own/operate radar systems)

   a. What is (are) the phenomenon (phenomena) you need to sense (e.g., aircraft, hydrometeors, debris, birds, volcanic ash, clear air, etc.)?

   b. What spatial and temporal resolution is required to characterize your phenomena? Consider horizontal and vertical resolution, rate of change, refresh rate, separation distance, etc. (Use current observational resolution in the absence of stated requirements.)

   c. What sampling volume is required for you to detect a particular phenomenon? What scanning mode(s) do you employ?

   d. Are your radars networked? If so, please describe the network. What geographical area do they cover (CONUS?, regional?, local?)

   e. Do you employ mobile radars for specific events? If yes, please describe these events.

   f. Once the phenomenon is detected, do you employ the radar to interrogate it further (e.g., change scanning strategy, stare or dwell, etc.)? If yes, please explain.

Do you require general surveillance and interrogation modes to operate simultaneously? If yes, please explain.

g. Describe the processing your system's raw data undergoes prior to dissemination to users. This might include deriving such things as where the phenomenon came from, where it will be in the future, 2D winds from Doppler winds, etc.

h. Is your current radar system constrained to some physical size/weight? If yes, please provide the rational for the constraints.

2. What are your current requirements for system reliability? Please state the rationale for your requirements.

3. Is there a commercial market for data and/or information from your radar system(s)? If yes, please explain.

4. Are there any estimates of the socio-economic value resulting from your radar system(s) (e.g., costs avoided, lives saved, economic activity enabled, etc.)? If yes, please provide them.

5. Is there any additional information you wish to provide?

Anticipated Additional Future Needs

This section follows the format of the Present Capability section immediately above, although emphasis is now focused on additional future needs. Please provide estimates of your agency's or organization's future ground based radar needs in the 2015 – 2030 timeframe. Recall that the goal here is to provide input that can be factored into a research and development plan.

1. Please provide your best estimate of future needs for data and information from ground based radar system(s).

a. What additional phenomenon (phenomena) might you need to sense? What present phenomena might need improved surveillance?

b. What spatial and temporal resolution might be required to characterize your identified phenomenon (phenomena)? Consider horizontal and vertical resolution, rate of change, refresh rate, separation distance, etc.

c. What sampling volume might be required for you to detect this (these) phenomenon (phenomena)? What scanning mode(s) might you employ?

d. Will your radars be networked? If so, please describe the network. What geographical area will it cover? (CONUS? regional? local?)

e. Will you need to employ mobile radars for specific events? If yes, please describe these events.

f. Once the phenomenon is detected, will you employ the radar to interrogate it further? (e.g., change scanning strategy, stare or dwell) Will you require general surveillance and interrogation modes to operate simultaneously? If yes, please explain.

g. Describe any additional processing requirements of your future system's raw data prior to dissemination to users.

h. Are there any additional system "size" constraints that could/should be considered that would enhance your future system?

2. What will be your new requirements for system reliability?

3. Do you foresee new commercial markets for the additional data and information from your future radar system(s)?

4. Are there any anticipated additional socio-economic value resulting from your future radar system(s)?

5. Please provide any known or anticipated cost constraints on upgrading or replacing you present system(s).

6. Is there any additional information you wish to provide?

Due Date: 28 Feb 05