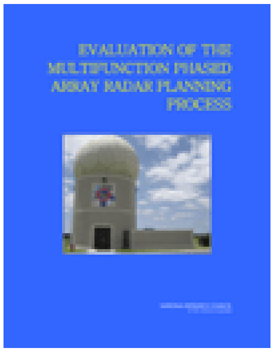

Evaluation of the Multifunction Phased Array Radar Planning Process

Committee on the Evaluation of the Multifunction Phased Array Radar Planning Process; National Research Council

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Evaluation of the Multifunction Phased Array Radar Planning Process

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Planning Process

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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COMMITTEE ON THE EVALUATION OF THE MULTIFUNCTION PHASED ARRAY RADAR PLANNING PROCESS

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Preface

In June 2006, the Office of the Federal Coordinator for Meteorology (OFCM) issued a report titled *Federal Research and Development Needs and Priorities for Phased Array Radar*, prepared by the Joint Action Group for Phased Array Radar Project (JAG/PARP). Recommendation 3 in the report called for the establishment of an interagency MPAR (multifunction phased array radar) Working Group and the identification of "opportunities for review of program plans and progress by appropriate boards or study committees of the National Academies' National Research Council." In the intervening two years, the Working Group has, among other activities, pursued investigations at the National Weather Radar Testbed in Norman, Oklahoma and conducted an MPAR Symposium in Norman in September 2007. Other planning activities have proceeded, and a pair of articles outlining the MPAR concept was published in the November 2007 Bulletin of the American Meteorological Society.

In mid-2007 the OFCM, pursuant to the part of Recommendation 3 quoted above, tasked the NRC to carry out an evaluation of the MPAR planning process. The Committee on Evaluation of the Multifunction Phased Array Radar Planning Process was formed to carry out this task. The committee held three meetings in January-April 2008 to gather updated information about the MPAR planning and prepare this report. At the first meeting at the National Academies' Keck Center in Washington, DC, the committee received overview briefings on the MPAR program and the JAG/PARP report. The committee also heard technical briefings on the potential benefits and challenges of a national MPAR system from federal and industrial scientists and engineers. At the second meeting at the National Oceanic and Atmospheric Administration (NOAA) David Skaggs Center in Boulder, Colorado the committee heard additional briefings from prospective agency users of an MPAR system and technical briefings on some of the key hardware issues; they also began intensive work on this report. The third meeting, at the National Weather Center in Norman, Oklahoma was devoted entirely to work on the report.

The committee considered all of the input received at these meetings, as well as a variety of supplementary information about phased array radars and the MPAR program. The committee's review highlighted significant technical and cost issues that need to be resolved to establish the viability of a national MPAR system that can satisfy requirements for aircraft and weather surveillance (and possibly other requirements not yet clearly defined). Prominent among the technical issues is whether phased array radar can provide the quantitative weather measurements (especially of polarimetric variables) needed to support current meteorological applications. Prominent among the cost issues is whether the cost of individual transmit-receive elements can be reduced enough to make array antennas involving many thousands of such elements affordable.

I express the thanks of the entire committee to the people who provided the briefings and who responded to our requests for additional information. The committee especially appreciates the briefings from developers of Radio Frequency technology, who helped to show us (especially the chairman, who hails from Missouri) that an affordable MPAR may be achievable. I hope that, in the short time available to carry out this evaluation, the committee has correctly understood the current status and plans for future activities and attained a reasonable perspective on what may become possible in the next few years.

I thank the members of the committee who contributed generously of their time and effort to carry out this evaluation of the broad MPAR program in a very short time period. Thanks also to our NRC support staff: Curtis Marshall, Study Director, and Katie Weller, Senior Program Assistant, who also worked long and hard on the committee's activities. I look forward to the evolution of the MPAR concept and hope some day to see the end result of the program in service to the nation.

Paul L. Smith, *Chair*
Committee on the Evaluation of the Multifunction Phased Array Radar Planning Process

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dr. David Atlas, NASA Goddard Space Flight Center, Greenbelt, Maryland
LT Richard Davidson, US Navy, Stennis Space Center, Mississippi
Dr. Elbert W. Friday, Jr., National Weather Service (retired), Norman, Oklahoma
Dr. R. Jeffrey Keeler, National Center for Atmospheric Research, Boulder, Colorado
Dr. John McCarthy, Aviation Weather Associates, Palm Desert, California
Dr. Richard Passarelli, Vaisala/Sigmet Corporation, Westford, Massachusetts
Dr. Matthias Steiner, National Center for Atmospheric Research, Boulder, Colorado

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Kuo-Nan Liou, University of California, Los Angeles. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

Summary

The year 2008 marks the 20th anniversary of the finalization of the design of the approximately 150 ground-based, mechanically rotating radars that comprise the Next Generation Radar (NEXRAD) network, known formally as the Weather Surveillance Radar 1988-Doppler (WSR-88D) network. This is the primary radar network in use by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) for operational surveillance of meteorological phenomena. The design of the newest systems of the nation's civilian network of radars for aircraft surveillance and tracking, operated by the Federal Aviation Administration (FAA), was established at about the same time; some radars in the aircraft network were installed more than 40 years ago. This has prompted agencies including NOAA, the FAA, the Department of Defense (DOD) and the Department of Homeland Security (DHS) to undertake planning for possible upgrades to or replacing of these existing "legacy" systems.

The surveillance requirements and the possible applications of modern radar technology are many and varied across the key agencies. Different candidate replacement systems could be selected by individual agencies to fulfill their mission requirements. However, a potentially cost-effective approach would be to replace several legacy systems with a multifunction system designed to simultaneously meet the surveillance needs and mission requirements of several agencies. One such option, the Multifunction Phased Array Radar (MPAR), is the subject of this report.

In 2002, the Federal Committee for Meteorological Services and Supporting Research (FCMSSR) directed the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) to explore federal needs and potential benefits of a phased array radar capability that would meet the mission requirements of several key agencies. In June 2004, OFCM established the Joint Action Group for Phased Array Radar Project (JAG/PARP), which subsequently issued the report *Federal Research and Development Needs and Priorities for Phased Array Radar* (OFCM, 2006). In 2007, OFCM requested that the National Research Council (NRC) review federal planning for an MPAR system, including a review of the JAG/PARP report and all relevant subsequent planning activities. Appendix A provides a detailed Statement of Task for the NRC committee that carried out this review.

PRINCIPAL FINDINGS

Phased array technology offers significant technical advantages for a next generation of weather and aircraft surveillance radars. A national implementation of approximately 350 MPAR radars could replace existing NWS and FAA radars and offer many performance advantages. Some technical, operational, and cost issues remain to be resolved. Also, there are some agency mission requirements that cannot be met by replacing existing radars. These agency mission requirements relate primarily to low-level weather coverage and the ability to detect and track low-level, non-cooperative aircraft.

The committee agrees generally with the five major findings in the Executive Summary of the JAG/PARP report (see Box S.1), with some exceptions. Regarding finding 2, the committee notes that some emerging requirements cannot be met with a network of 334 MPAR radars because there will be significant gaps in low-level and regional coverage. Regarding finding 4, the committee believes that the "preliminary cost evaluation" is promising, but embryonic. In addition, the basis for determining cost effectiveness of MPAR does not consider the cost effectiveness of other alternatives to the legacy systems, in addition to the legacy systems themselves. Similarly, regarding finding 5, the MPAR risk reduction program will also provide a basis for cost-benefit comparison to the other alternatives to legacy systems.

BOX S.1
Findings from the Joint Action Group for Phased Array Radar Project (JAG/PARP) Report

Finding 1: 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.

Finding 2: 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.

Finding 3: 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.

Finding 4: 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.

Finding 5: The JAG/PARP proposes a risk-reduction 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 committee also agrees generally with Recommendations 1-4 in the Executive Summary of the JAG/PARP report (see Box S.2), but notes that even though Recommendation 4 calls for the FCMSSR to direct a cost-benefit analysis of the MPAR option and competing domestic strategies in conjunction with the MPAR risk-reduction program, this analysis is not explicitly found in Appendix D of the JAG/PARP report (the program plan). However, the Terms of Reference of the Working Group –MPAR (WG/MPAR Item 3b; OFCM, 2007) direct the working group to "[Perform] a cost benefit analysis to establish MPAR's cost-effectiveness against alternative domestic radar options, considering both acquisition and total life-cycle costs." For the JAG/PARP research plan to be effective, defined requirements and a national system architecture are required that will allow cost-benefit tradeoffs to drive the establishment of focused research objectives. The committee also believes that *independent* identification of alternative domestic radar strategies is needed. A thorough and independent cost-benefit analysis of MPAR and those alternatives would be in the nation's best interest.

BOX S.2
Recommendations from the Joint Action Group for Phased Array Radar Project JAG/PARP Report

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 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 substantial progress.
- Identify opportunities for review of program plans and progress by appropriate boards or study committees of the National Academies' National Research Council.
- 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.

The committee's recommendations are grouped below by general topic area.

COMMITTEE RECOMMENDATIONS

Overarching Recommendation

The committee recommends that the MPAR Research and Development (R&D) program be continued with the objective of evaluating the degree to which a deployable MPAR system can satisfy the national weather and air surveillance needs cost-effectively. This program should incorporate the following features:

- Full evaluation of the unresolved technical issues
- An evaluation of the full operational requirements of all participating agencies and the ability of MPAR to meet these requirements
- Development of the basis for reliable and realistic estimates of acquisition and lifecycle costs of a nationally deployed MPAR System
- Independent assessment of the cost effectiveness of the R&D program itself, especially prior to commitment of major funding for the full-scale prototype.

Specific Recommendations for the R&D Plan

Recommendation: The R&D Plan outlined in Appendix D in the JAG/PARP Report should be expanded to provide detailed descriptions of the tasks to be undertaken, their priorities, the associated costs, and key decision points.

Recommendation: The FCMSSR should seek a reasonable and continuous funding stream to support the R&D Program.

Recommendation: The WG-MPAR planning process for the MPAR R&D program should implement frequent updating and improvement of the MPAR program plan to ensure planning robustness and relevance in the face of changing external conditions. As part of this WG-MPAR planning process, the program plan should be periodically evaluated against program goals and objectives, to ensure that these are both fully satisfied and remain relevant, and also the accomplishments of the R&D work. This evaluation should include annual *external* reviews, as suggested by Recommendation 3.5-6 of the JAG/PARP report (see Box S.2).

Recommendation: Probability estimates of the likelihood of success/failure of achieving objectives at critical decision points in the R&D program should be developed.

Recommendation: The committee endorses Recommendation 2 of the JAG/PARP report and would like to see it implemented early in the program. The committee further recommends that the MPAR R&D program be as open as possible, in particular to ensure that interested parties from industry and universities are involved at early stages, and that the engineering development and scientific applications of the MPAR prototype benefit from involvement of the broadest communities possible.

Recommendation: The MPAR R&D program should include the staged development of a prototype MPAR, proceeding through a Line Replaceable Unit (LRU), followed by a single antenna face, two faces, or a full four-faced prototype. Cost effectiveness studies should be carried out to determine how many faces would be required to assess the MPAR concept.

Recommendation: The MPAR R&D Program, instead of developing new X- and C-band radars, should develop linkages with appropriate organizations within the radar community as a way to avoid duplication of effort and take full advantage of ongoing work related to short-wavelength radar technologies.

Specific Recommendations on the Definition of Requirements

Recommendation: The MPAR R&D program should produce a fully vetted set of technical performance requirements for an operational MPAR and radar network. To ensure robustness of the R&D Program in the face of potential re-balancing of stakeholder needs and participation over time, the MPAR planning process for non-weather surveillance should further emphasize the need to fully establish requirements of all participating agencies.

Recommendation: MPAR system design studies and analysis of alternatives should consider the MPAR system as a candidate member of a family of systems, carefully considering design and mission tradeoffs with existing and new surveillance capabilities under development. Agencies must define clearly the role that MPAR will play toward meeting their needs and identify the supplemental sensing networks required to fully meet their needs.

Recommendation: The Airport Terminal Area or T-MPAR concept needs to be developed in sufficient detail to demonstrate that mission requirements for terminal weather and aircraft surveillance can be met. In addition, the ability of a full MPAR to meet Terminal Doppler Weather Radar (TDWR) requirements must also be assessed due to the fact that the beamwidth would be approximately 1 deg (instead of ½ deg) and the frequency choice is S-band (instead of C-band).

Specific Recommendations on Technical Issues

Recommendation**: **The MPAR R&D program should produce a procedure for calibrating the reflectivity and polarimetric measurements at all scan angles. A key decision point for the feasibility of MPAR for weather surveillance, and continuance for the R&D program, will be determination of its capability for dual polarization measurements. Thorough evaluation of the capability of phased array radar to accurately measure polarization variables independent of scan angle must be carried out early in the R&D program.

Recommendation: Given the high demand for bandwidth at the proposed S-band frequency, the MPAR R&D program must determine the total required bandwidth as early as possible in the research program to ensure the feasibility of the design.

Specific Recommendations on the Costs and Cost-Benefit Considerations

Recommendation: A thorough and complete cost analysis of the total MPAR program should be performed and compared with historical life-cycle costs for the more recently and currently deployed systems such as ARSR-4 and ASR-11 that are roughly equal in performance to MPAR for air-traffic surveillance, and for NEXRAD and TDWR radars that provide a performance baseline versus MPAR for weather surveillance. A detailed baseline operations and maintenance (O&M) cost estimate should be determined for all legacy radar types to identify and quantify those highest cost radar types that are the prime candidates for life extension, upgrade or replacement. Independent cost risk analyses for the acquisition of MPAR and T-MPAR by recognized methods should be performed and frequently re-visited and updated.

Recommendation: An alternative weather-only phased array weather radar design trade study and detailed cost analysis should be performed and compared with historical life cycle costs and performance for NEXRAD and TDWR radars. This trade study and cost analysis should be compared with a more detailed MPAR cost analysis and trade study to determine if the marginal cost of adding the required aircraft surveillance capability is worth the perceived benefit of having an all-in-one system.

1

Introduction

In the mid 1990s, the Department of Defense (DoD), Federal Aviation Administration (FAA) and National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) completed the installation of a network of approximately 150 ground-based, mechanically rotating Doppler weather radars, known commonly as the Next Generation Radar (NEXRAD) network and formally as the Weather Surveillance Radar 1988-Doppler (WSR-88D) network. The installation of this network marked a paradigm shift in NWS's capability to observe the atmosphere and provide accurate warnings to the public for severe thunderstorms, tornadoes, and flash floods.

NOAA/NWS and its partners in industry, government, and academia have continually improved the performance and capability of these radars through a variety of research and development efforts. Significant software advances have improved the real-time processing and display of the data. Perhaps most significantly, the network will be retrofitted with dual-polarization capability in the near future. This technology will provide a significant advance in the operational observation of the types and concentrations of hydrometeors in clouds and precipitation-producing systems, as well as an improvement in overall data quality. This will allow significant improvements in such things as rainfall estimation and detection of cloud icing conditions, with the benefits to water managers and the aviation industry such observations afford.

The Federal Aviation Administration (FAA) makes use of the weather observations from this network, and also operates a number of Terminal Doppler Weather Radars (TDWR) at major airports. The TDWRs were designed specifically for detection of wind shear hazards in airport approach and departure zones, but they also provide some more general surveillance of weather in the terminal area. In addition, the FAA operates Airport Surveillance Radars (ASR) at many terminals as well as a network of longer-range Air Route Surveillance Radars (ARSR) across the country. The ASR and ARSR systems are of varying vintage, some being more than forty years old and others just installed in the 21st century. Some of the newer systems provide supplementary weather surveillance capability in addition to their aircraft observations, and others are being retrofitted with such a capability.

Even the newest of these radar systems are based mainly on technology a decade or more old. Research and development efforts continue to advance radar technology and its many applications, including weather surveillance, civil aviation, military, and homeland security. As the existing radar networks age and the nation considers the next steps for its entire civilian radar infrastructure, a variety of advanced technologies have emerged as the basis for possible upgrades or replacement. An overarching issue in these considerations is whether the various existing ("legacy") systems designed for separate applications can be replaced with one or more consolidated systems that could serve multiple functions and multiple agencies. One such candidate under consideration by the federal government is a Multifunction Phased Array Radar (MPAR) network, which is envisioned as a network of radar installations with electronically (as opposed to mechanically) steered antennas. This candidate is but one of many discussed in *Weather Radar Technology Beyond NEXRAD* (NRC, 2002)[1], which specifically recommended the exploration of radar systems with agile-beam scanning capabilities.

In 2000, the United States Navy supplied NOAA's National Severe Storms Laboratory (NSSL) in Norman, Oklahoma, with a phased array antenna. Several agencies contributed funds to construct the National Weather Radar Testbed (NWRT) using this antenna; the NWRT has been collecting data since 2004. It serves as the facility where phased array technology is being tested as part of the federal government's research and development (R&D) for a possible future MPAR network. However, the MPAR R&D effort includes multiple activities within many additional agencies, including the FAA, the Department of Homeland Security (DHS) and the Department of Defense (DOD). In June 2006, these and other agencies, under the auspices of the Joint Action Group for Phased Array Radar Project (JAG/PARP), Office of the Federal Coordinator for Meteorology (OFCM) and the Federal Committee for Meteorological Services and Supporting Research (FCMSSR), issued a report titled *Federal Research and Development Needs and Priorities for Phased Array Radar* (OFCM, 2006; hereafter "JAG/PARP report"). The JAG/PARP report summarized federal planning for the MPAR R&D effort, including estimates of costs and benefits of a future MPAR network.

The purpose of the present report is to evaluate the MPAR R&D plans. The JAG/PARP report provides a starting point for this evaluation, but it also incorporates information from a variety of additional sources (see Preface for more details on the evaluation process). In Chapter 2, the evaluation begins with an overview of the existing U.S. civilian radar infrastructure. Chapter 3 outlines the needs for a next generation system of civilian radars. Chapters 4 and 5 describe the capabilities of phased array radar and discuss why and how those capabilities render MPAR a possible candidate for a next generation system. Chapters 6 and 7 summarize and assess the MPAR planning process, as described in more detail in the JAG/PARP report and additional sources of information. Chapter 8 places a potential MPAR network in the context of a broader family of sensing systems. Chapter 9 concludes the report by providing a principal finding and overarching recommendation.

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[1] This report provides a concise summary of various technical options for a future ground-based system of radars for weather surveillance. These options include phased array technology, polarization diversity, mobile radars, short-range radars, and space-based radars. The reader is referred to various technical documents cited through the present report that provide more detailed technical specifications for each of these options.

2

Overview of the Current National Radar System

The US government civil radar infrastructure comprises four separate radar networks: the Weather Surveillance Radar 1988-Doppler (WSR-88D) and the Air Route Surveillance Radar (ARSR) networks that support national-scale weather and aircraft surveillance, and the Terminal Doppler Weather Radar (TDWR) and the Airport Surveillance Radar (ASR) networks that support regional-scale weather and aircraft surveillance in the vicinity of medium and large commercial air terminals. Table 2.1 summarizes key features of these networks, and Figure 2.1 shows the locations of the 510 radars that comprise the WSR-88D, TDWR, ASR, and ARSR networks.

TABLE 2.1. US Civil Radar Infrastructure. Source: John Cho, Massachusetts Institute of Technology.

Network	No. Radars	Deployment	Freq. (band)	Range	Antenna Size	Tx Power	Update Rate
WSR-88D	156	National grid	S	460 km (Z); 230 km (V,W)	8.5 m dia	750 kW	4-6 min
TDWR	45	45 largest airports	C	460 km (Z); 90 km (V,W)	7.6 m dia	250 kW	1-5 min
ARSR	101	Nationwide	L	370 km (ARSR-1,2,3); 460 km (ARSR-4)	9 m x 7 m	4 MW (ARSR-1,2); 5 MW (ARSR-3); 60 kW* (ARSR-4)	12 s
ASR	233	Commercial airports	S	110 km	5 m x 3 m	1.1 MW (ASR-9) 20 kW* (ASR-11)	5 s

*Uses pulse compression.

(Z = radar reflectivity factor; V = Doppler velocity; W = spectrum width)

WEATHER RADAR NETWORKS

National Weather Surveillance Radar Network

The WSR-88D, or the Next Generation Radar (NEXRAD), weather radar network comprises 156 long-range Doppler radars sited on a grid covering the contiguous United States (CONUS) as well as portions of Alaska, Hawaii, Puerto Rico, and Guam. The radars operate unattended according to selected scanning patterns, and radar data (reflectivity, mean radial velocity, and Doppler spectral width) and products derived from these data are disseminated to offices of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD), as well as to the private sector and the public. Crum and Alberty (1993) summarize the timeline for the creation of this system, beginning with the establishment of the Joint Doppler Operational Project at the National Severe Storms Laboratory (NSSL) in 1977, proceeding through the award of competitive pre-production contracts to Raytheon and Unisys in the period from 1983 to 1989, followed by the award of a full-scale production contract to Unisys in 1990. The system was deployed as a joint program between the Departments of Commerce, Transportation, and Defense (DOD) during the early to mid-1990's as a replacement for the 1957 (WSR-57) and 1974 (WSR-74) predecessor radar networks. The National Research Council (NRC, 1995) evaluated coverage of the NEXRAD system in comparison to that of the predecessor systems.

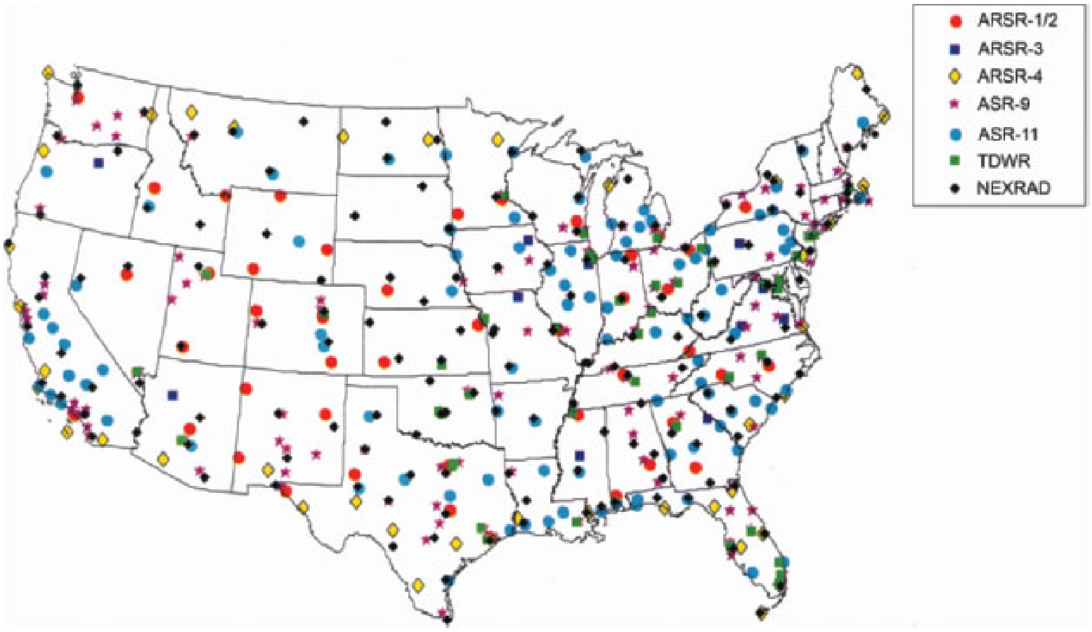

FIGURE 2.1. Locations of U.S. operational weather and air traffic control radars. Source: Office of the Federal Coordinator for Meteorology. Source: OFCM, 2006.

Terminal Doppler Weather Radar Network

The Terminal Doppler Weather Radar (TDWR) network comprises 45 Doppler weather radars deployed at major commercial airports near medium-to-large-sized US cities with greatest wind-shear risk. This system addresses the FAA's requirement for surveillance of weather close to airports with higher sensitivity and faster updates than can be provided by the WSR-88D system (Whiton et al., 1998). The TDWR system was developed in the late 1980s after low-altitude wind shear events caused a series of commercial aircraft accidents. It operates at C-band to avoid interference with the ASR radars, the WSR-88D, and other systems operating in the 2.7 - 2.9 GHz band. The system was manufactured by Raytheon on the basis of specifications developed by the FAA, Lincoln Laboratory, and the National Center for Atmospheric Research (NCAR).

The network is owned and operated by the FAA, but the NWS is developing a means for its forecast offices to access data from TDWR radars having coverage in specific metropolitan areas.

AIRCRAFT SURVEILLANCE RADAR NETWORKS

National Air Route Surveillance Radar Network

The ARSR network is the nation's primary radar means of detecting and tracking aircraft throughout the national airspace. There are four ARSR generations and a total of 101 L-band radars in this network. The ARSR-1, ARSR-2, and ARSR-3 systems were developed in the 1960s and deployed in the nation's mid-section and inland areas. The more recent ARSR-4 system is deployed around the perimeter of the CONUS; this system was built by Westinghouse. These newer radars also have a capability for providing limited weather surveillance data. The DOD and DHS recently assumed responsibility for support of the operation, maintenance, and upgrades of this system.

Airport Surveillance Radar Network

The ASR network comprises 233 radars deployed at commercial airports near medium-to-large US cities. These radars are used principally for tracking commercial and private aircraft in the vicinity of the air terminal locations; they also provide some indications of precipitation, and a subset of the radars can detect low-altitude wind shear.

SITING, MAINTENANCE AND LIFECYCLE ISSUES

Leone et al. (1989) describe the site selection procedure for WSR-88D radar installations. The system is jointly owned by the NWS, DOD, and FAA, and each of these agencies established criteria for siting the radars based on factors including population distribution, climatology, approach and travel directions of severe weather, locations of airports and airways, and the location of NWS forecast offices and high-priority military and civilian facilities. The radars in the WSR-88D network, like those in the TDWR and ARSR networks, are long-range (> 400 km) high-power systems. In order to penetrate through heavy precipitation, long-range operation requires the use of wavelengths not subject to substantial attenuation. This in turn necessitates the use of large antennas to achieve km-scale spatial resolution throughout the coverage region. The radars use high-power transmitters[1] and mechanically-rotated antennas that require

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[1] The latest-generation ASR and ARSR systems are being fielded using lower-power solid-state transmitters and pulse compression techniques to achieve the needed sensitivity. Service-life extension programs are in place to convert the early-generation transmitters in these networks to

dedicated land, towers, and other support infrastructure. The large physical size of these systems, combined with potential environmental impacts and possible interference by and to other radars, limits the availability of potential sites. Scanning of the WSR-88D antenna below 0.5° elevation is prohibited owing to public concerns about radiation safety.

The acquisition cost of each radar unit (including radar equipment as well as land and other installation costs) in current dollars would be approximately $10 million. The annual per-radar operating and maintenance cost has been estimated by Lincoln Laboratory to be $500,000 per radar (JAG/PARP report, Appendix C).

WEATHER RADAR COVERAGE

The coverage of the WSR-88D network has been reviewed in several NRC reports (NRC, 1995; 2002; 2005). The protection of lives and property requires weather radar coverage from the height of cloud tops (~ 18 km or 60,000 ft.) down to near-ground level, where damaging storm features such as tornadoes, hail, and downbursts impact both the public and low-flying aircraft. The Weather Service Modernization Act of 1992 established a criterion that the network should provide complete coverage over the CONUS at a height of 3.05 km (10,000 ft.) above ground level (AGL) without degradation in service, compared with the WSR-57 and WSR-74 predecessor networks. Coverage of the WSR-88D network is nearly complete at 10,000 ft AGL over the eastern United States, while gaps exist in the mountainous regions of the Midwest and Pacific Northwest (Serafin and Wilson, 2000).

A 1995 National Research Council study (NRC, 1995) investigated the adequacy of WSR-88D coverage relative to the detection and warning of a variety of weather phenomena (e.g., landfalling hurricanes, supercells, mini-supercells, mesocyclones, tornado vortices, microbursts, macrobursts, and various types of precipitation and snowfall). This study found that WSR-88D coverage over the nation was generally excellent in terms of providing superior forecasting and warning capability compared with the predecessor radar systems. The improved coverage and performance of the WSR-88D network has led to a significant improvement in the short-range forecasts and warnings of severe thunderstorms, tornadoes, and flash floods (Serafin and Wilson, 2000). Nevertheless, the report found a significant lack of low-level coverage that limits the detection of the full range of hazardous weather conditions over large expanses of the CONUS. This issue is discussed further in Chapter 8.

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solid-state as well. The WSR-88D and TDWR radars use high-power microwave tube transmitters.

3

Needs for the Next Generation System

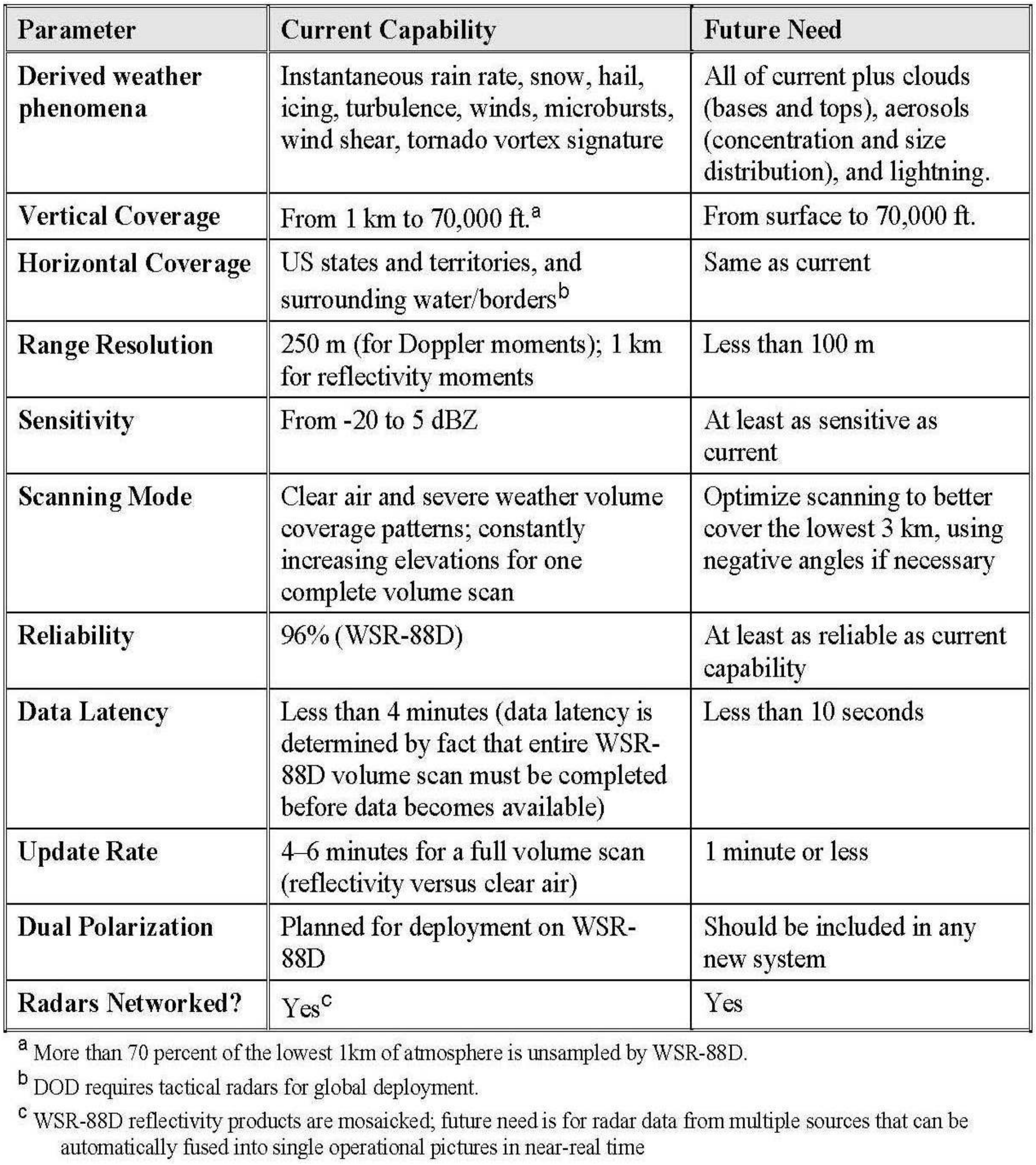
Chapter 2 of the Joint Action Group/ Phased Array Radar Project (JAG/PARP) report covers federal agency surveillance needs that can be met with radar. The chapter is based on a survey of the federal agencies using a capabilities questionnaire reproduced in Appendix G of the report. Seven federal agencies responded, including the Department of Defense (DOD) (Air Force, Army and Navy), National Oceanographic and Atmospheric Administration/National Weather Service (NOAA/NWS), the Federal Aviation Administration (FAA) and the Department of Homeland Security (DHS), as well as the Federal Highway Administration (FHWA), the Environmental Protection Agency and the Department of Energy (DOE). The questionnaire responses (not reproduced in the JAG/PARP report) were provided to this committee for review. Tables 3.1 and 3.2 summarize current and future weather and aircraft surveillance needs, as well as other surveillance needs, without identifying the specific agency or agencies stating the need.

The JAG/PARP report highlights three main areas (weather surveillance, aircraft surveillance, and other functions) where radar could potentially address the needs of the federal agencies. To a large degree, the stated needs are based on existing missions and capabilities and the report only briefly notes current limitations and potential new missions. However, current system limitations and new or evolving missions are likely to be important in driving future system requirements.

MULTI-AGENCY MISSION: OWNERS, USERS, AND BENEFICIARIES

The JAG/PARP report speaks to the needs of several agencies and the potential benefits for other agencies; however, it does not clearly speak to the degree of ownership each agency has or would have for a future radar system. This is particularly important in assigning responsibility and defining the requirements for a future radar network. The current owners of US government weather radars are the NOAA/NWS, FAA and DOD. In addition, there are many commercial and research weather radar installations that support a local entity such as a university or a news station. The remaining federal agencies, whether directly using radar information or only relying on derived products from NOAA/NWS or commercial providers, can only be counted as users or downstream beneficiaries. The general public also falls within this category; hence, there are few true owners but numerous beneficiaries.

TABLE 3.1. Needs Summary Table – Weather Surveillance. Source: OFCM, 2006.



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

TABLE 3.2. Needs Summary Table – Aircraft Surveillance. Source: OFCM, 2006.

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.

The radar aircraft surveillance picture is even murkier. The current systems of US civilian aircraft surveillance radars were acquired, and are operated and maintained, by FAA. These radars are used to detect and track aircraft within FAA airspace; they also provide information to the Air Force (DOD/AF) and DHS to facilitate their mission of protecting the U.S. from hostile aircraft. DOD/AF also owns airfield terminal radars and additional surveillance assets for US perimeter protection. Recently, FAA's mission has been redirected such that FAA is now only responsible for cooperative aircraft; FAA is therefore pursuing the fielding of an independent non-radar system such as the Automatic Dependent Surveillance-Broadcast (ADS-B) (JPDO, 2005) for tracking cooperative aircraft. The current (or any future) radar aircraft surveillance system will then become only a secondary or emergency backup system for FAA. Detection and tracking of non-cooperative aircraft would become a DHS and DOD/AF mission. FAA recently turned over responsibility for the cost of operation and maintenance of the long-range aircraft surveillance radars to DOD/AF and DHS.

The JAG/PARP report notes a number of potential additional uses of Multifunction Phased Array Radar (MPAR): detection and tracking of airborne toxic releases and volcanic ash; measurement of fine-scale winds in support of fire suppression and evacuation, air quality assessment, or tracking of low-level toxic releases; detection and tracking of birds; and accurate typing and tracking of precipitation for hydrology, mudslide prediction, and agriculture. All of these potential uses are deemed possible for MPAR technology; however, in most cases they would represent the most stressing requirements for a radar system, either in higher sensitivity or in greatly increased coverage (such as low-level coverage in mountainous areas for fire suppression support). Furthermore, these capabilities do not yet fully exist. Consequently, the owners, users and beneficiaries of such capabilities are not yet fully identified. These groups must be adequately identified before they can define requirements.

LIMITATIONS OF THE CURRENT RADAR NETWORK

One of the primary drivers of any future weather and aircraft surveillance system should be the limitations in the ability of the current system to meet existing surveillance requirements. Some of the limitations of the current system, such as the lack of dual polarization, high radar maintenance costs and inadequate radar system networking, have been acknowledged and are being addressed. However, a number of studies have demonstrated significant limitations that are not being addressed with current radar acquisition or upgrade programs.

Looking specifically at weather surveillance requirements, a variety of limitations of the current WSR-88D radar network have been identified. The WSR-88D has proven to be particularly important for hydrological applications. With the current single-polarization design, estimates of radar reflectivity factor Z are used with empirical Z-R relationships (where R designates rainfall rate) to perform Quantitative Precipitation Estimation (QPE). Unfortunately, these relationships are notoriously inaccurate and highly dependent on storm type, season, and location. As a result, hydrologists almost always use rain gauges as ground-truth sensors to adjust the radar estimates of rainfall rate. This process is cumbersome and costly, and severely limits the coverage over which rainfall can be estimated accurately and economically. Dual-polarization radar techniques have emerged as the most promising remote sensing technology for obtaining more accurate QPE. In addition, hydrometeor classification can be accomplished with these types of radars (e.g., Ryzhkov et al. 2005). Because of the potential value of dual polarization, the NWS has embarked on an extensive upgrade to the entire network of WSR-88D radars to polarimetric capabilities. Maintaining this capability would be required for any future national weather radar network.

A primary limitation is the inability of any radar network comprising widely spaced long-range radars to provide comprehensive low-altitude coverage (eg, at altitudes below 1-2 km). In the mountainous Western United States, flood prediction, hydro-electric power management, agriculture and fire detection and suppression efforts depend critically on accurate assessment of precipitation amounts. Westrick et al. (1999) examined the ability of the current radar network to provide QPE in the West and determined that radar now detects as little as one quarter of the precipitation falling in many regions, and greatly misrepresents precipitation type. Addressing this shortfall in the current weather surveillance network could be particularly stressing for the development of a replacement system.

An NRC study carried out for the FHWA (NRC, 2004) identified a serious deficiency in defining low-level precipitation for road traffic management. Better radar observation of the planetary boundary layer could provide fine-scale winds for air quality and tracking toxics or smoke, support to fire suppression efforts, and better detection of clear-air wind events. To observe the fine-scale winds and non-precipitating cloud bases mentioned in the JAG/PARP report and to meet requirements for sensing low-level precipitation, this serious coverage deficiency would need to be addressed.

The current WSR-88D data update interval of over four minutes has been identified as a significant limitation for tornado and severe hail prediction. Examples (such as Vasiloff, 2001) have shown that more frequent updates can greatly improve the detection and proper interpretation of tornadic precursors, leading to enhanced warning lead times.

Better assimilation of radar information into mesoscale numerical weather prediction (NWP) systems can also increase tornado warning lead times. This will require treating radar information as part of an integrated prediction system, instead of a stand-alone sensor. The concept of integrating sensors and NWP into networked systems for rapid response again raises ownership issues. NOAA/NWS has ownership of most continental U.S. NWP. The FAA does execute some processing and warning algorithms using data from their radar systems, but model predictions beyond a few minutes are the responsibility of the NWS. Under a recent agreement with DOD, NOAA/NWS provides all operational continental US mesoscale NWP, with the exception of coastal regions and possible classified operations. NOAA/NWS is proceeding with efforts to acquire and assimilate radar information into NWP systems. However, to date this has not been a driver for radar systems acquisition.

Identification of limitations of the current aircraft surveillance network is clearer, as stated in the *Strategy for Homeland Defense and Civil Support* (DOD, 2005). Limitations are primarily in the areas of update interval (less than four seconds desired) and coverage (contiguous coverage desired of all US states, territories, borders and surrounding waters at 3000 ft and higher above ground level, extending 600 nmi beyond the boundaries.) The *Strategy* report specifically highlights limitations in low-level radar coverage and sensitivity. While the coverage limitation is simple to state, increasing radar coverage to meet such aircraft surveillance requirements would be stressing (see also Chapter 8). The need for very rapid updates also highlights the question of multi-tasking weather and aircraft surveillance, and the issue will have to be examined carefully.

Only by acknowledging the limitations of the current radar networks can a realistic cost-benefit study be performed, or realistic development programs proceed. The JAG/PARP report highlights a study by Weber et al. (2005; also 2007) which identifies substantial budgetary benefit in replacing the current systems with a future MPAR system—*while only meeting current capabilities*. This study may obfuscate the true cost of upgrading the existing network to *only* meet current requirements.

NEEDS VERSUS RESEARCH

The JAG/PARP report highlights the requirements for weather and aircraft surveillance as well as the potential for additional capabilities that could possibly be provided by MPAR technology. It lays out a Research and Development (R&D) plan to explore an MPAR architecture and additional capabilities that an MPAR system could provide. However, this can only be considered exploratory research of a promising technology. In order to achieve a focused R&D effort leading to a proposal for a replacement weather and aircraft surveillance system, specific program management criteria must be met. These are (broadly):

1. An agency or multi-agency agreement of ownership of the future system.
2. A multi-agency agreement of interest (acknowledgement as a user or clear beneficiary) and willingness to work with the owner(s) to establish requirements and budgetary support.
3. The development of nominal system architecture to meet expected US and US territory weather and aircraft surveillance requirements, which will allow meaningful cost-benefit tradeoffs and drive a focused radar, networking and communications R&D effort.

4

Capabilities of Phased Array Radar

In contrast to the usual scanning “dish” antenna illuminated from a single feed point, a phased array antenna uses electronic control of the signal phase at individual array elements to produce constructive interference in the desired beam-pointing direction. Consequently, no mechanical motion, with the associated inertial effects, is necessary; this allows arbitrary steering of the radar beam on a pulse-to-pulse basis, which is typically at intervals of order 0.001 s. The beam can be steered at this rate to any direction in a typical angular range of +/- 45 degrees. This flexible beam steering is in stark contrast to mechanically scanned radars, which must scan in a systematic and angularly continuous pattern to minimize stress on pedestals, motors, gears, and other associated mechanical components.

Phased array radars have been used by the military for aircraft surveillance and tracking for some three decades. Figure 4.1a shows a prototype phased array radar for weather observations - the National Weather Radar Testbed (NWRT) located in Norman, Oklahoma (Zrnic et al., 2007; Forsyth et al., 2008). This S-band radar uses a passive phased array antenna (one in which the signals sent to individual elements originate from a single transmitter) from the AN/SPY1-A radar of the Navy’s Aegis system. Other parts of Figure 4.1 illustrate several important capabilities of phased array radars which are briefly discussed below.

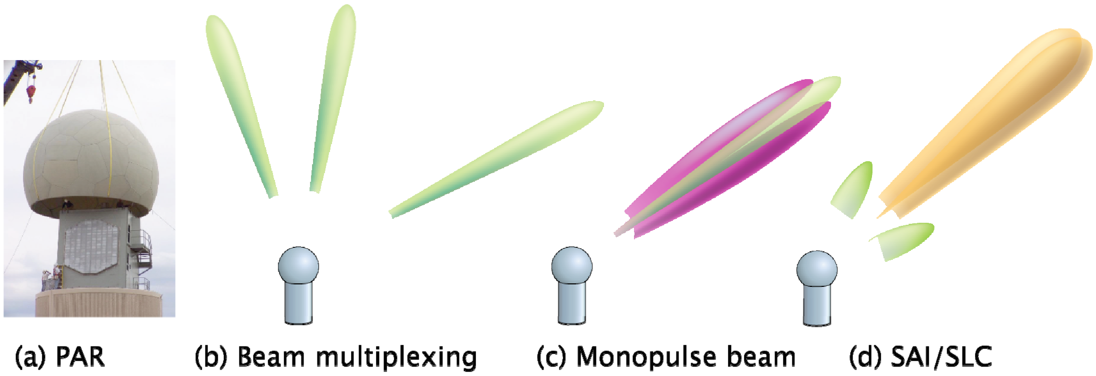


FIGURE 4.1. Illustration of capabilities of phased array technology for radar observations of distributed targets (weather) and point targets (aircraft). (a) Photograph of National Weather Radar Testbed in Norman, Oklahoma, (b) Rapid beam steering (beam multiplexing), (c) Monopulse tracking, (d) Spaced antenna interferometry (SAI) and sidelobe clutter cancellation (SLC).

CAPABILITY FOR RAPID UPDATE (BEAM MULTIPLEXING)

Conventional scanning radars must rotate at a rate slow enough to allow a number of pulses (typically 20-50 for weather observations) to be transmitted to approximately the same pointing angle. However, since the antenna is *continuously* rotating, each pulse is actually transmitted to a slightly different direction. Nevertheless, significant overlap in the illuminated volumes (occurring due to finite beamwidth effects) allows the use of these numerous pulses to estimate the reflectivity, radial velocity, and Doppler spectrum width signal moments with estimation errors below the desired thresholds. For WSR-88D radars, these thresholds are typically set to 1 dB[1] and 1 m/s for reflectivity and radial velocity, respectively.

Due to the overlap of the resolution volumes and the time required for decorrelation of echoes from atmospheric targets to occur, the echoes from successive pulses are not independent. (In fact, signals with some correlation are required to make Doppler measurements.) To achieve the desired estimation error for reflectivity, the number of pulses required for conventional radar processing is therefore larger than what would be needed if the successive echoes were independent. Time essentially wasted while waiting to acquire the needed independent data could be employed to acquire data from other beam directions by taking advantage of the fast beam steering capability of phased array radars.

Beam Multiplexing (BMX) was recently developed for this purpose (Yu et al., 2007). As illustrated in Figure 4.1b, the general idea is to transmit a small number of pulses (typically two) needed for Doppler measurements in one direction, and then steer the beam to a set of *spatially diverse* pointing angles. After the atmosphere effects (turbulence, shear) have led to decorrelation of the signal, the beam is directed back to the original pointing angle. Thus, numerous pairs of pulses are gathered from each pointing direction and the moment estimation is then performed. Given the independence of these pulse pairs, the estimation scheme will have significantly lower errors for the same total number of pulses, especially for cases with high signal-to-noise ratio (SNR) and small spectrum widths. As a result, it is possible to either produce moment estimates with lower errors or have a more rapid update with consistent errors.

Figure 4.2 provides examples from the work of Yu et al. (2007). The upper two panels show the reflectivity and radial velocity fields from BMX while the corresponding conventional scanning results are provided in the lower panels. The scan times here are essentially the same for the two different techniques, and the qualitative improvement in the fields is remarkable. A quantitative analysis has shown a 2-4 times possible improvement in scan time (Yu et al., 2007), with a dependence on SNR and other signal characteristics.

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[1] Increments and uncertainties should be measured in units of dB, not dBZ. The latter represents an absolute value, specifically 1.26mm^6/(m^3).

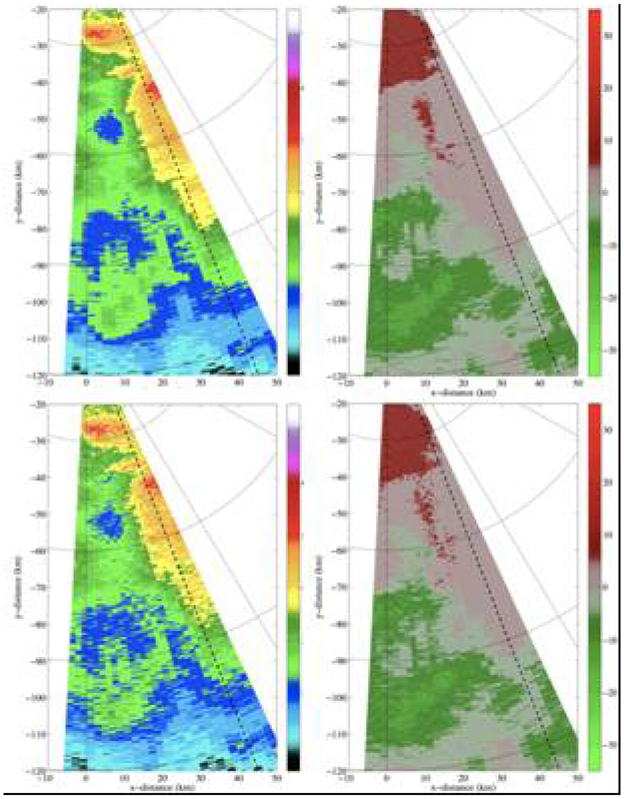

FIGURE 4.2. Reflectivity (left) and radial velocity (right) fields from BMX (top panels) and conventional (lower panels) scanning. These data were taken over the same time period with the same overall scan time. Note the improved quality in the BMX results, which could be exploited to produce faster updates. Source: Yu et al., 2007. Reprinted with permission from the American Meteorological Society (AMS), copyright 2007.

Phased array radars are also useful for the surveillance and tracking of aircraft. Here operation in the surveillance mode differs from the weather surveillance process mainly in the smaller number of pulses (which need not be independent) usually required for aircraft detection. That allows faster coverage of a given volume of the atmosphere for aircraft surveillance. For aircraft tracking functions, the rapid beam steering capability allows the radar time to be allocated to provide frequent updates on tracks of designated targets, according to criteria that might include such things as priority, location or speed of movement. For acquiring and tracking multiple targets simultaneously, phased array radars are highly advantageous (Skolnik, 2001). The tracking function could be interleaved with a more general aircraft surveillance function (probably requiring a slower update rate) to locate new targets that come within the purview of the radar system.

In addition, monopulse radar techniques can provide higher track accuracy using either power- or phase-comparison methods. By properly segmenting a phased array antenna, a monopulse configuration can be readily implemented. Non-phased array systems require multiple antennas, or possibly a multiple-lobe feed, in order to implement monopulse tracking; multiple-target tracking would be difficult with such a system.

ADAPTIVE CLUTTER SUPPRESSION

With the temporal sampling advantage of phased array radars also comes a major challenge. For example, the BMX technique achieves the desired accuracy of reflectivity estimation by using very short dwell times (with the two-pulse minimum) with spatially diverse pointing angles to provide the capability of averaging with independent samples. As a result of the short dwell times, however, ground clutter filtering can be problematic since conventional filters depend on differences in *temporal* correlation between weather and clutter signals. Such differences are difficult to determine with short dwell times. A phased array radar can exploit the *spatial* correlation of "auxiliary channel" signals (ones designed for sidelobe cancellation [SLC]; see Fig. 4.1d) to reduce the effect of clutter contamination through adaptive beamforming techniques. These techniques can place antenna pattern nulls in the directions of the undesired clutter signals (Palmer et al., 1998; Cheong et al., 2006). Larger regions of clutter will be more difficult to suppress using SLC; however, for the weather radar application, clutter is often manifested in very narrow angular regions, especially given the fact that the cancellation is done on each azimuth and range gate independently. The effect of this type of clutter mitigation has been studied for the NWRT configuration using detailed numerical simulations of a tornadic environment (Le et al., in press).

Figure 4.3 shows examples of simulated NWRT reflectivity and radial velocity fields for weather only (without clutter), severe clutter contamination (with clutter), and with the use of the adaptive SLC techniques. The SLC algorithm does reduce the clutter contamination for this case, and this benefit has been quantified in the work of Le et al. (2008).

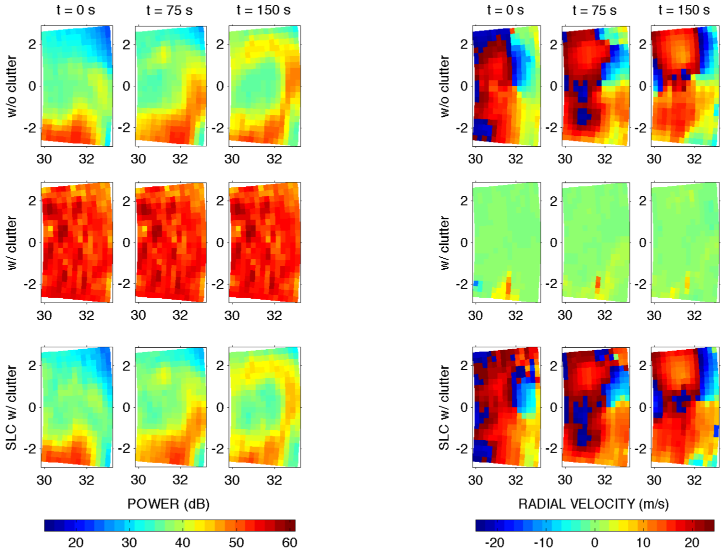

FIGURE 4.3. Preliminary results from the SLC algorithm of Le et al. (2008) using a NWRT simulation. The top panels provide a three-frame time sequence of imaged backscattered power (left) and radial velocity (right) uncorrupted by ground clutter. The middle panels show the results when severe ground clutter is present in every imaged pixel. Note the complete loss of the true fields. The bottom panel provides results using the proposed SLC technique with the same severe clutter field. Source: Le et al., 2008; copyright 2008 IEEE.

CROSSBEAM WIND ESTIMATION

Conventional Doppler weather radar measures the *radial* velocity component along the beam pointing direction. Phased array radar offers the possibility of measuring wind components *perpendicular* to the pointing direction (Zhang and Doviak, 2007; 2008). The monopulse capability could facilitate estimates of the transverse components of the wind, though even without this feature the MPAR rapid-scan data would lead to better estimates of the 3D wind field using existing algorithms. The related so-called *spaced antenna interferometry (SAI)* technique (see Figure 4.1d) has been used for years in the wind profiling radar community (Mitra, 1949; Briggs et al., 1950), but has only recently been applied to weather radar. The technique requires multiple, independent, spatially separated receivers, which is not the norm for weather radar. But a phased array radar is ideally suited for such a technique, since the array can easily be segmented into independent receivers. The fundamental theory behind SAI for weather radar has been developed (Zhang and Doviak, 2007), and the capability has been implemented on the NWRT.

ELIMINATION OF BEAM SMEARING

Scanning weather radars inherently have so-called *beam smearing* due to the fact that samples comprising numerous pulses must be collected while the antenna is rotating (Doviak and Zrnic, 2006). As a result, the effective beamwidth of the radar is increased since the resolution volumes corresponding to the individual pulses are not coincident. Furthermore, clutter filtering becomes more difficult due to the widening of the Doppler spectrum associated with the antenna rotation. Finally, the inherent accuracy of the radar products (reflectivity, radial velocity, spectrum width, and future dual-polarization products) is limited by such beam smearing. Since beam steering with phased array radar is not accomplished by mechanical rotation, such beam smearing can be eliminated.

Analyzing overlapping samples from a scanning radar does permit so-called "super-resolution" data, in which the data are output at angular intervals smaller than the antenna beamwidth. While such outputs are not truly independent, they do appear to reveal features in the weather echoes that are of finer scales than the beamwidth resolution would provide. This capability is being implemented on the Next Generation Radar (NEXRAD), and the value of the "super-res" data should be considered in assessing the benefits of the phased array technology.

ADAPTIVE SENSING

Given the varying nature of aircraft operations and the inhomogeneous nature of weather (spatially and temporally), adaptive sensing (also known as *Knowledge-Based Resource Management*) holds promise for the optimization of limited radar resources (Miranda et al., 2006). For example, the WSR-88D weather radar system provides essentially similar data about all weather within its surveillance domain with a fixed update rate dependent upon the antenna scan program. A phased array radar would provide an adaptive scanning capability that could be directed to devote more time (and hence provide more accurate data) to more threatening weather locations, or vary the update rate according to the degree of perceived threat. Vertical ("RHI") scans could readily be included in the mix.

Similarly, today's aircraft surveillance radars typically provide rapid updates by scanning rapidly in azimuth with a beam broad in the vertical. This provides no height information; any needed height data is provided by transponders or voice communications. A phased array radar could provide the same rapid updates with a narrower beam that would provide height data directly. It could also adjust the update rate for aircraft being tracked according to the observed characteristics of the targets and the quality of the track data obtained.

Currently, only limited research has been conducted on the advantages of adaptive waveforms and scanning strategies for overcoming this challenge for weather targets (Zrnic et al., 2007). One example of where adaptive sensing is already being applied to weather observations is research related to the National Science Foundation (NSF) Engineering Research Center—*Collaborative Adaptive Sensing of the Atmosphere* (CASA) (e.g., Brotzge et al., 2006). Adaptive sensing for weather observations and hard-target applications is clearly an important area for making effective use of phased array radars and will be integral to any success in this area.

OTHER CAPABILITIES

A phased array radar would permit a variety of other enhancements over the capabilities of mechanically scanned radar. For example, digital control of the elements in an active electronically scanned array (AESA) would allow formation of different transmit and receive beam patterns, by appropriate manipulation of the amplitude and phase characteristics of each element in the array. This permits such things as use of a broad transmit beam at high elevation angles, where the targets are necessarily nearby and great sensitivity is not needed. Processing the received signals to yield simultaneous narrower receive beams would retain the inherent spatial resolution capability of the system but reduce the time required to scan that sector of the atmosphere. This capability could also be used at all elevation angles for aircraft observations in the terminal area, where again the targets of interest are nearby. At radar sites with irregular horizons due to topography or nearby obstructions, the beam elevation angles could be programmed to follow the true horizon (including even negative angles where appropriate). This could eliminate gaps in the low-angle coverage, reduce the illumination of ground clutter, and minimize scan time wasted because of beam blockage.

GRACEFUL DEGRADATION

Individual transmit/receiver (T/R) modules which have dimensions of order half the radar wavelength and separate, solid-state amplifiers for each element are used in *active* phased array radar systems. Such a phased array antenna would have the advantage of what is called *graceful degradation*. Since each element of the array has its own T/R module and the entire array is made up of thousands of such modules, limited failures in these components would not significantly affect the performance of the radar. A theoretical example of the expected degradation in the antenna pattern for randomly located T/R failures is shown in Figure 4.4. The top panels provide three examples of failure scenarios (no failures, 20% failure, and 40% failure). The bottom panel shows the one-way antenna patterns for the three cases, with uniform weighting assumed. As the number of failed T/R modules increases, the main lobe decreases, the nulls in the pattern are filled, and the sidelobe envelope is retained. T/R module failures could also have a serious effect on polarization capabilities and should be addressed in the MPAR R&D process. Nevertheless, the general shape of the pattern is retained. Non-random locations of the failed modules, or complete failures in larger groupings or subarrays, could have a more significant effect on the pattern; the overall aperture performance of the array is retained under this simplified scenario.

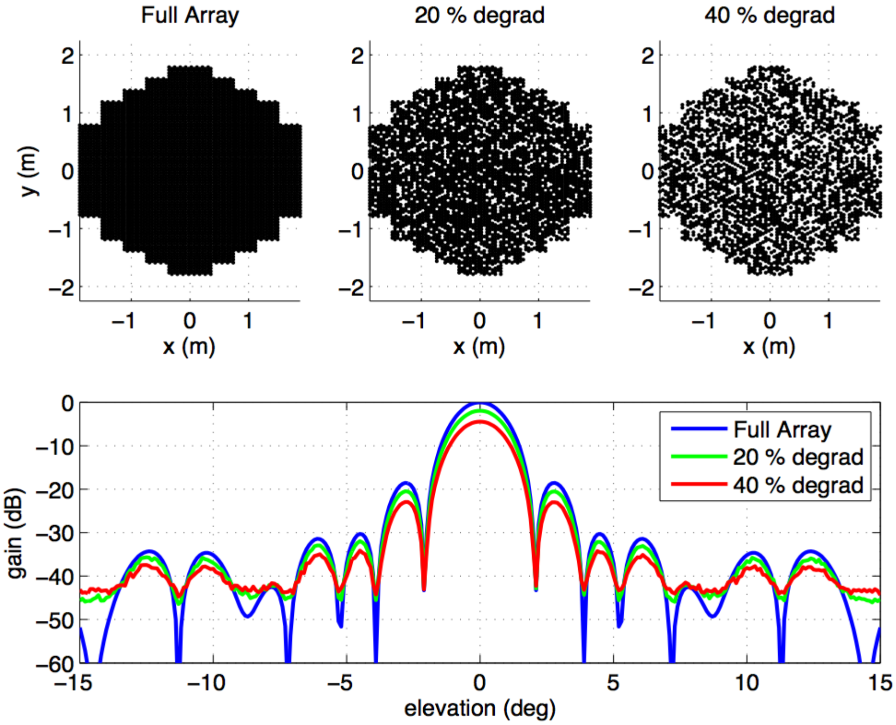

FIGURE 4.4. One-way phased array antenna pattern for varying number of T/R module failures. The top panels provide the locations of the operational T/R modules, with failures randomly dispersed across the array. The bottom panel gives the antenna pattern for the three different failure ratios (no failure, 20% failure, 40% failure).

5

The MPAR Concept

The ability of a phased array radar to form and steer the radar beam electronically, and to reconfigure the beam between any two transmitted pulses or even between transmit and receive modes, permits multiple functions to be carried out with the same radar. For example, the radar could direct narrow beams successively over a sector of the atmosphere to detect weather activity, a process that might take a minute or more depending upon the size of the sector and the dwell time required to measure the necessary weather variables in each beam direction. Interspersed with those observations, the radar could also search the approach path to an airport every few seconds to locate incoming aircraft. Thus the basic concept underlying the Multifunction Phased Array Radar (MPAR) initiative is to use a single radar type to carry out the multiple functions of weather and aircraft surveillance. The same radar might also carry out aircraft tracking missions, as well as possibly others to be determined (Figure 5.1).

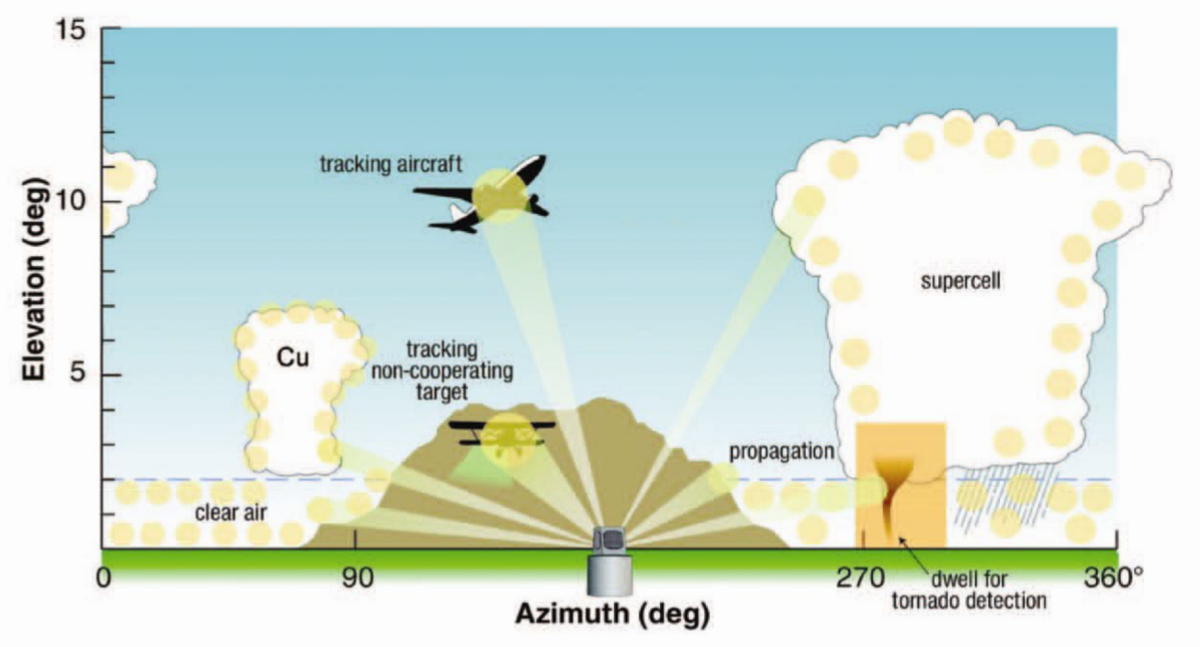

FIGURE 5.1. Capabilities of agile-beam phased array radar are shown in a panoramic view. Illustrated are (a) surveillance scan through the planetary boundary layer (extending to 2 km) for mapping winds, (b) surveillance scan through a cumulus "Cu" cloud, (c) surveillance scan through a supercell storm, (d) high-resolution scan with a longer dwell time through the region in the supercell where the potential for tornado development exists, (e) scan that grazes the mountain contour for "surgical precision" avoidance of ground clutter, (f) determination of propagation condition, i.e., cumulative humidity along the beam between radar and the edge of the mountain, and (g) detection and tracking aircraft including noncooperating aircraft. Source: Zrnic, 2007, Reprinted with permission from AMS.

Some military phased-array radars have been designed to perform multiple functions. For example, the AN/APG-81 and MP-RTIP airborne radars and the AN/SPY-1 and SPY-3 shipboard radars routinely perform multiple functions, typically including a mix of surveillance and tracking activities and in some cases other functions as well. These functions are usually carried out sequentially using a prioritized control scheme, but the SPY-1 has even demonstrated concurrent weather and aircraft surveillance capabilities. One face of a SPY-1 system is used in the National Weather Radar Testbed (NWRT) facility in Oklahoma.

There has been previous interest in the MPAR concept for aircraft and weather surveillance. A Federal Aviation Administration (FAA)-sponsored study (ITT 1997) determined that phased-array radar could meet most of the requirements for both aircraft and weather surveillance in an airport terminal area. However, the anticipated cost of such a system (in the mid-1990s time frame) was too high to warrant implementation of the concept at that time. Cost remains a major consideration in the feasibility of implementing the MPAR approach.

The potential introduction of MPAR presents an opportunity to combine the diverse radar missions of weather surveillance, civil aircraft tracking and possibly homeland defense against airborne threats on a single[1] standardized advanced technology platform. Implementation of an MPAR system to provide multiple functions could obviate, or at least diminish, the need for separate radar systems to support the individual functions. This could permit reduction in the total number of different radar types and radar units required to meet the nation’s coverage goals for weather and aircraft surveillance. Weber et al. (2007) provide a hypothetical example of this, wherein some 334 MPAR radars of one basic type (two distinct configurations) might replace 510 existing radars of seven unique types, while providing essentially the same coverage of weather and aircraft targets at 5,000 ft or more above ground level. If one assumed that the ongoing support costs per unit remained the same as the average for the systems the MPARs replaced, this would substantially reduce the annual system support costs. With the absence, in a full Active Electronically Steered Arrays (AESA) system, of a single high-power transmitter and a rotating antenna (both sources of major maintenance costs with many present-day radar systems), there is expectation that the ongoing support costs per MPAR unit should even be smaller. Furthermore, the support functions would be required to deal only with the one (or two) MPAR system types, in contrast to the seven or eight different systems providing those coverages today. That suggests important potential savings in engineering, logistics, and training areas.

Developing time budgets for sequential allocation of scan capabilities to achieve the needed combinations of aircraft and weather data outputs could prove a difficult challenge. Consequently, two or more essentially separate radar systems, perhaps operating at different but nearby frequencies and using the same antenna, may be required to accomplish the desired concurrent missions (Weber et al., 2007).

Operation in the S-band frequency range (2.7-2.9 GHz) of the current NEXRAD and FAA terminal area aircraft surveillance radars would provide desired characteristics

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[1] The JAG/PARP report (Chapter 6) and more recent supporting literature advocates the development of two separate but related radar designs, the MPAR and the Terminal-MPAR or T-MPAR. This distinction is discussed further below.

of sensitivity to both aircraft and precipitation targets, minimal effects of atmospheric attenuation along the beam path, and manageable range-Doppler ambiguity problems. In general, adequate sensitivity to precipitation echoes of interest would also provide adequate sensitivity to aircraft targets. Thus data on both target types could be extracted from each look in any beam direction; using polarimetric techniques would improve discrimination of aircraft from weather targets. To be sure, differing requirements on update rates might produce some redundant weather data in directions where frequent aircraft surveillance data are required.

The work accomplished with the phased array radar (PAR) at the NWRT to help evaluate these possibilities has been excellent from both engineering and applications perspectives. The committee heard presentations from government and private sector representatives who stated strongly that the technology exists today to accomplish this vision. The cost arguments given are persuasive, namely that solid-state S-band transmitter/receiver modules are already being mass produced for commercial purposes and that further integration will lead to dramatic cost reductions for future radar applications.

TECHNICAL CHALLENGES

While the concept of a single, agile-beam multifunction radar design is appealing, many technical issues and questions remain to be resolved. True multifunctionality of PAR, with capabilities equivalent to those now available or soon to be available on the existing radar systems, has yet to be demonstrated. PARs have been used effectively for military purposes, and research at the NWRT has demonstrated that PAR technology can be used effectively for weather surveillance. However, not all of the needed weather capabilities have been demonstrated, nor has simultaneous aircraft tracking been demonstrated. Mark Weber's presentation to the committee, illustrating how systematic electronic scanning with multiple radar frequencies might be used for both aircraft and weather surveillance purposes, did demonstrate that considerable thought has already gone into the issue of multifunction electronic scanning. Adaptive scanning, on the other hand, is an issue that remains to be addressed.

The need for polarization diversity with the capabilities required for weather observations may present technical obstacles for phased array implementations. The NEXRAD polarization diversity upgrade will feature simultaneous transmission of orthogonal linear polarizations. It is not evident that this will be feasible with phased arrays, and sequentially alternating transmission of the two polarizations (with the attendant doubling of the dwell time requirement) may be needed. This issue is currently under study by Lincoln Laboratory (Weber et al., 2007). Another fundamental issue is the extent to which polarization diversity measurements will be degraded in beam directions other than in the principal horizontal and vertical planes, and whether these effects can be compensated through appropriate data processing (Zhang et al., 2008).

Accurate and reproducible calibration of weather radars is essential for reliable interpretation of radar echoes. With phased array antennas the beam patterns and gain, as well as the polarization characteristics, change as functions of beam pointing angles. Moreover, the transmit and receive beam patterns may differ. These effects may be calculable for ideal conditions, but for actual systems the results must be experimentally verified and the associated errors quantified. With conventional single-transmitter radars the transmitted power and the receiver response characteristics can be readily measured. With an active phased array system this seems not to be possible, so calibration procedures will probably need to rely primarily on observing targets with known radar cross section. Such measurements would be required for all pointing angles, for both polarizations, and under various T/R module failure scenarios—not a simple task. Solar calibrations, possible only for a limited range of pointing angles, can provide some measurements of receiving antenna gain and beamwidth.

The volume of weather data from an MPAR will be considerably greater than that from the current NEXRADs. More rapid volume scans and possible over-sampling in range and azimuth, in order to achieve higher resolution, will lead to data rates an order of magnitude higher than those experienced today. Undoubtedly the state of the art of signal processing hardware will allow sufficient speed to meet the need. However, communications, data storage, and data access may present substantial challenges. Secure historical archiving of radar track files may become a requirement. In designing the MPAR system, the data rates and volumes must be accommodated for all users. It was many years after the introduction of the NEXRAD system before the real-time data access problem had been satisfactorily addressed through CRAFT (Collaborative Radar Acquisition Field Test). In addition, easy access to archived data will be essential for system evaluation and product improvement research.

A lesson learned with NEXRAD was that its initial proprietary architecture created obstacles to system upgrades. Open architectures have subsequently been adopted to facilitate the introduction of new capabilities and forecasting products. In an MPAR era, open architectures should be adopted to the greatest extent possible.

COST ISSUES

Chapters 5 and 6 and Appendices C and D of the Joint Action Group/Phased Array Radar Project (JAG/PARP) report provide information related to the anticipated cost of MPAR. Significant questions pertaining to developing realistic cost estimates for MPAR seem evident. Antenna element cost, overall system cost including requisite software, costs to site the MPARs nationwide, and costs of data dissemination and archiving are among the main uncertainties. Costs related to implementing the requisite capability for polarimetric observations and radar calibration need to be determined. Also, costs to conduct the adaptive scanning activities of an MPAR system are likely to be significant. In addition, costs for maintaining and adapting extensive software libraries after the prototype is deployed should be detailed. A complete MPAR cost analysis, including supporting data, an analysis of cost risk, and also a process for periodically revisiting and refining cost estimates, will be necessary to support any eventual implementation decision.

As with any system designed to serve the needs of multiple federal agencies with multiple missions, MPAR cost increases are likely once the uses of MPAR by these various agencies are fully explored and understood. It is also quite possible that additional uses of MPAR will be identified prior to its operational phase, again with the potential for increasing overall costs. These issues alone dictate the need for a flexible cost structure and a detailed cost uncertainty analysis. Furthermore, a mechanism is needed for revisiting the projected cost as the risk reduction project grows nearer to completion.

Several significant cost elements in addition to the cost of the T/R modules, such as software development, system integration, training, development of data exploitation tools, and data dissemination and archiving, must be considered in the overall MPAR system cost estimates. The advent of multifunction phased array radar will add to the complexity of all of these elements. Many of these costs are likely to be non-recurring development costs that would be amortized over the total production run of MPAR systems. However, these costs will likely be front-loaded at the early stages of the MPAR program, including initial deployment, and will have a significant effect on required program funding profiles. Some cost elements, such as software development and training, will continue to some degree over the life of the program. All will need to be estimated with care by alternative and independent methods.

Even well-managed software development projects are seldom completed on schedule, and their cost will inevitably multiply significantly as their completion date is delayed. The complexity of the software development effort needed for a complex multi-function phased array radar, especially if it includes adaptive scanning capability, should not be understated.

Siting costs of MPAR will hopefully be minimized by employing existing legacy radar sites. It may be impossible to avoid the cost of both physical and Radio Frequency environmental impact studies, particularly if new radar frequencies and scanning plans differ significantly from the systems already in place. Sites near densely populated areas will require careful attention and may be subject to rollout delays through local opposition (due to possible concerns about appearance or (RF safety), adding to cost. Since each site is unique, it is unlikely that siting cost will drop as the deployment of new MPAR systems approaches completion. Organized opposition and public litigation, whether warranted or unwarranted, to a large scale radar deployment, as has been experienced in the cellular industry during tower buildout, is a possibility. Any necessary addition of site-specific software lockouts at low elevation angles would also add to deployment cost.

Cost Models and Cost Risk Analysis

Cost models and cost analysis packages are applied in both the government and private sectors, and MPAR costs will need to be modeled using accepted tools and practices. The Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) routinely use sophisticated cost estimation techniques employing statistical analysis to determine a range of likely costs for individual systems and entire programs. The profession of cost estimation, encompassing the disciplines of mathematics, statistics, application software and accounting, is active within industry and academia. The cost estimating methods used in the JAG/PARP report are highly preliminary and should be revisited in greater detail using professionally recognized methods.

The DOD and other government agencies have recognized for years that both government and contractor cost estimates on major acquisitions are generally inaccurate and, despite best efforts, they are frequently too low (Anderson 2008). Examples of programs that have been put at risk because of (among other factors) poorly executed or overly optimistic cost estimates include:

The NOAA GOES-R system, which, originally estimated to cost $6.2 Billion, was re-estimated to cost $11.4 Billion in May 2006 for a satellite scheduled for launch in 2012 (GAO, 2006a). This follows on the heels of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) that is estimated to be approximately $3 Billion over budget and three years behind schedule.

Software acquisition for Air Traffic Control (ATC) modernization at the FAA, which resulted in a 1997 Government Accountability Office (GAO) report that noted "many FAA failures in meeting ATC projects' cost, schedule and performance goals, largely because of software related problems…" A decade later, the GAO found the FAA in an improved position on software acquisition, while ATC modernization is still listed as high risk. Cost estimates for the Next Generation Air Transportation System (NextGen) are currently at $15 Billion per year in 2005 dollars (GAO, 2006b). How accurate this estimate is and whether appropriate cost risk analysis has been applied in its estimation will be revealed over time.

Point design cost estimates are highly unreliable, since component and activity costs (often referred to as Work Breakdown Structure or WBS elements) are probabilistic in nature (Anderson and Cherwonik, 1997). A total "best guess" cost based on an arithmetic sum of "best guesses" is almost guaranteed to be wrong. The cost estimation community has developed statistical techniques that account for both parametric relationships in costs and the uncertainty and risk in estimating them. The resulting cost estimates arrived at by Monte Carlo simulation can show a much higher cost risk than might be otherwise assumed, and total cost probability curves are often (and unfortunately) skewed asymmetrically to the right of average or "most likely cost" in the form of a lognormal distribution (Book, 2001). Figure 5.2 shows an example of a lognormal cost distribution.

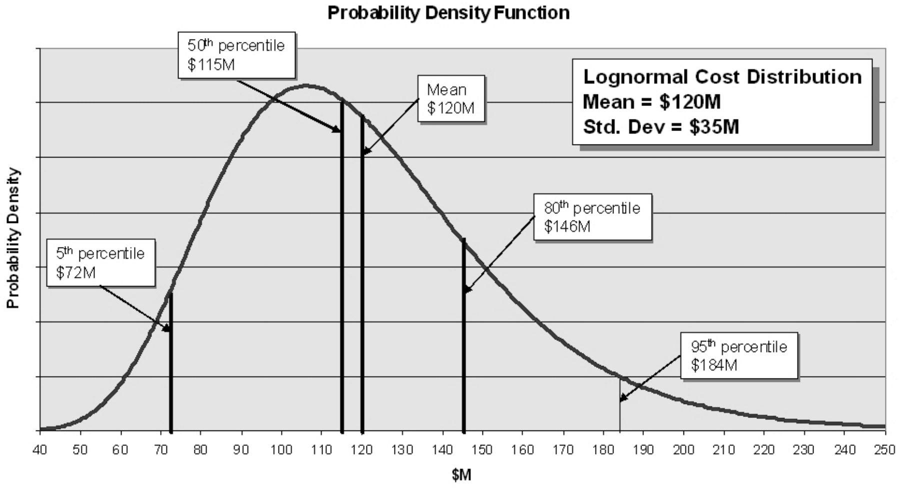

FIGURE 5.2. A lognormal probability density function. Source: Timothy P. Anderson, MCR Federal, LLC, Copyright 2004.

The cost estimates will also change over time due to unforeseen setbacks, changes in scope, and other problems that inevitably occur in the life of a project. An additional and frequent reason for cost growth is program underfunding or "stretch out". This almost always leads to cost growth due to the continuation of fixed costs, additional inflation, and increased risk of programmatic disruption.

CAPITAL ASSET PLANNING

Successful completion of preliminary MPAR risk reduction R&D activity would enable the planning and budgeting phase for eventual deployment to begin. A large public acquisition such as an operational MPAR system would require preparation of detailed capital asset and business plans. A useful planning reference framework is described in the Office of Management and Budget (OMB) document "Capital Planning Guide: Planning, Budgeting and Acquisition of Capital Assets" (2006).

In advance of any budget submission to OMB, written justification in the form of a "Capital Asset Plan and Business Case Summary" or "Exhibit 300" document is required by federal statute from all agencies of the Executive Branch. The Office of the Federal Coordinator for Meteorology (OCFM) with the Joint Agency Working Group (JAWG) in consultation with OMB and Congress would agree whether or not to fund the MPAR program to a level necessary to accomplish full-scale development and acquisition.

ACQUISITION PLANNING AND CONTRACTING

After completion of the planning and budgeting phase, the JAWG (or a newly created MPAR Joint Program Office) would proceed with development of the MPAR acquisition plan. When funding has been approved, the acquisition phase would begin. When requests for proposals for MPAR are drafted, a performance/capabilities based requirements strategy that leaves specific implementation decisions up to the contractor will offer more opportunities for creative and cost-effective solutions, as opposed to driving a hard requirement leading to a single architectural solution.

Actions to upgrade or replace the nation's surveillance radar systems would likely be phased in over time,[2] and careful consideration of the acquisition methods and tempo will be needed. The Capital Programming Guide encourages "Modular Contracting," which divides large acquisitions into smaller, more manageable segments or modules. Project phases could be executed and contracts could be written to optimally match achievable economies of scale for mass-produced components such as T/R modules, but also to provide budgetary and programmatic continuity to nurture and maintain a healthy contractor-industrial base for the life of the program.

The Guide encourages robust competition at all stages of the acquisition, such as "competitive prototyping" before proceeding to full-scale development. In competitive

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[2] Some cost implications of different rates of phase-in are considered in the cumulative cost graphs presented in Appendix C of the JAG/PARP report.

prototyping, both contractors and the government agencies can exchange information so that a common set of standards can be written into the requirements for a full-scale development. Awarding more than one development contract provides an incentive to competing contractor teams to strive for an optimum balance between performance and cost.

An essential attribute of successful cost control in large acquisitions such as an operational MPAR network is the provision of sufficient and predictable project funding by sponsors at the correct time that is fully consistent with project plans. Interruptions, delays or reductions in the planned funding profile will cause significant and unrecoverable cost growth in a full-scale acquisition as well as in the R&D program.

COMPARISON OF ALTERNATIVES

Part of the Exhibit 300 submission is a section entitled "Alternatives Analysis." In this section the desired capital expenditure is examined along with the status quo or current baseline, as well as alternate implementations including the one involving MPAR and T-MPAR. Other possibilities would include a next generation weather radar (that might or might not use phased-array technology) or a Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) radar network, with later generational developments of legacy systems such as the ARSR-4, ASR-11, and the Terminal Doppler Weather Radar (TDWR), and various potential blends of candidate architectures. Such an alternatives analysis would of necessity consider solutions other than MPAR.

Characteristics of Success and Failure in Large Government-Funded Engineering Projects

The MPAR planning process should take note of best practices employed in the planning and execution of other successful megaprojects and adopt them as part of any MPAR planning and acquisition activity. In 1999, a National Research Council (NRC) study on Project Management at the Department of Energy DOE was convened to determine the root causes in long delays and budget overruns by as much as 50 percent for certain classes of projects over comparable projects at other government agencies or in the private sector (NRC, 1999). The Executive Summary of that report notes that DOE projects were abandoned before completion, cut back or delayed such that upon completion they served no useful purpose. The NRC report identified severe deficiencies in project planning and management at DOE in 16 areas. In Appendix C of the report, entitled "Characteristics of Successful Megaprojects or Systems Acquisitions," a checklist was developed of conditions essential to, important to, and beneficial to success in a megaproject from the standpoint of general conditions, special conditions, and technical conditions of scope, costs and schedule for major stakeholders and participants in the project. MPAR planners, stakeholders and participants would benefit from applying the lessons learned from prior project successes and failures to avoid repeating the mistakes of the past.

6

The MPAR Planning Process

The report *Weather Radar Technology Beyond NEXRAD* (NRC, 2002) specifically recommended the exploration of radar systems with agile-beam scanning capabilities. A 2004 report (Aerospace Corporation, 2004) provided a preliminary look at possible PAR implementation for weather surveillance. In 2005, the National Science and Technology Council (NSTC) identified phased array radar as a technology that could potentially be developed and deployed to "increase the quantity, quality, and timeliness of weather information during extreme weather events." They also noted that "the greatest set of unmet observational requirements is for systematic, widespread coverage." This assessment was provided by the NSTC Committee on Environmental and Natural Resources' US Group on Earth Observations in their "Strategic Plan for the U.S. Integrated Earth Observation System" (NSTC, 2005).

Based on this direction, the Federal Committee for Meteorological Services and Supporting Research (FCMSSR) charged the Office of the Federal Coordinator for Meteorology (OFCM) with exploring phased array radar technology for addressing gaps in weather observing and forecasting capabilities. OFCM formed the Joint Action Group/Phased Array Radar Project (JAG/PARP) in response and assigned the following specific tasks: (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). The project chairpersons were experts from the U.S. Air Force (Col. Mark O. Weadon, USAF Weather Deputy for Federal Programs) and NOAA (Dr. James J. Kimpel, Director, National Severe Storms Laboratory). The other project members came from the National Weather Service (NWS), Federal Aviation Administration (FAA), Federal Highway Administration (FHWA), U.S. Navy, National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), Department of Homeland Security (DHS), Department of Energy (DOE), National Park Service and U.S. Department of Agriculture.

THE JAG/PARP REPORT

Although many groups were represented in this inclusive project, NOAA and FAA participants provided the leadership and initiative that ultimately culminated in the JAG/PARP report. This may have been anticipated, as the expertise gathered by these agencies in prior years was particularly relevant, and their own future needs may be met by MPAR. In the case of NOAA, the National Severe Storms Laboratory (NSSL) was experimenting with a Navy SPY-1 phased array radar antenna at the National Weather Radar Testbed (NWRT), intended to serve as a working Phased Array Radar (PAR) system for proving various future surveillance concepts. In the case of FAA, research during the 1990s on the Terminal Area Surveillance System (TASS) showed that both terminal weather and aircraft surveillance functions could be met by a single multifunction phased array radar system, though cost was then prohibitive. Taking a fresh look at this technology makes sense for them, as industry advancements over the last decade have enabled new radar designs and greatly reduced PAR costs. Finally, with existing radar assets 10 to 40 years old, both agencies will have to initiate large scale radar replacement activities in the next decade, with some early key decisions required in the next few years.

Although NOAA, FAA, and some DOD current and future requirements for radar surveillance are fairly detailed (Chapter 3), the gathering of requirements from the other agencies appears to be more problematic. Briefly, FAA near-term requirements include sustaining current surveillance capabilities while reducing overall FAA cost of ownership (e.g., via consolidation of assets, reduced O&M costs, or agency cost sharing). Future FAA requirements include a decrease in weather volume coverage update intervals from ~5 minutes to 1 minute and detection of icing, turbulence, and volcanic ash. NWS near-term requirements also insist on sustaining current or soon-to-be implemented surveillance capabilities (including hydrometeor identification). Emerging requirements include increased volume refresh rates and spatial resolution, decreased data latency, and mobile radar operations for improved hazardous weather detection and warning lead time. However, it is not clear that any agency is seriously addressing any requirement for systematic widespread coverage of non-cooperative aircraft targets or of low-altitude storm intensity that correlates well with quantitative precipitation measurements. Also, the JAG/PARP report notes other surveillance functions performable by radar but not currently articulated as federal requirements, such as fire weather, airborne toxic releases, or spaceflight weather support.

The central core of the JAG/PARP report (Chapters 3-5) solidly reflects the planning of NOAA and FAA primary stakeholders. These chapters include comparison of alternatives for future civilian radar functions, technical aspects of meeting surveillance radar needs, and cost considerations. These chapters were presented in the spirit of providing some specificity, while neither expecting nor intending them to be taken as more than preliminary point examples of the types of analyses that a properly conducted MPAR research and development (R&D) program would tackle. Chapter 6 outlines an R&D plan to support technical risk reduction studies for the various surveillance capabilities, to document the basis for cost/benefit tradeoffs of various surveillance systems, and to lay out the required R&D program if an MPAR does appear feasible (Appendix D provides time lines and cost estimates for this plan). Chapter 7 then rolls up the key findings and recommendations of the JAG/PARP. More thorough discussion of these chapters can be found elsewhere in our report.

The JAG/PARP report was issued in June 2006 and MPAR planning and R&D activities have continued since that time. As recommended by the JAG/PARP report, the Interdepartmental Committee for Meteorological Services and Supporting Research established a Working Group for the Multifunction Phased Array Radar (WG/MPAR) under the OFCM standing Committee on Integrated Observing Systems to develop an implementation plan for MPAR research and development. Current membership is defined as “stakeholders”, the loosely-defined membership of this committee is charged with oversight of the MPAR research program until a joint program office is established.

MPAR SYMPOSIUM

The OFCM held a Multifunction Phased Array Radar Symposium in Norman, Oklahoma, October 10-12, 2007. The theme was "Leveraging Technology to Build a Next Generation National Radar System," and the purpose was to build consensus for an MPAR risk-reduction program. Over 180 people attended the conference, and the organizers have made the proceedings available to all via the World Wide Web (*http://www.ofcm.gov/mpar-symposium/index.htm*).

The various special presentations and senior leader perspectives offered at the Symposium advanced the OFCM goals of supporting a comprehensive and inclusive planning process. There was excellent participation with agency programmatic leadership present to address the attendees. The six symposium panels discussed many of the common themes that were echoed within our committee. Below we list each of the six symposium topics and highlight several important themes, as excerpted from the MPAR Symposium Summary Report[1] (see Appendix D).

MPAR User Communities of Interest

- For both weather and aircraft surveillance, a national primary radar network is going to be needed into the foreseeable future.
- New systems such as MPAR must show both improvements in capability and reduction in overall life cycle costs to be viable candidates for acquisition.
- MPAR R&D efforts must be anchored to solid requirements from the user community.

Current State of Military Investment in Phased Array Radar

- Military PAR systems are increasingly based on open architectures, drawing upon commercial off-the-shelf versus very high-priced military specification parts.
- The goal is to have a scalable system with reusable parts and modules; technical improvements should require little to no retro-engineering.
- A great deal of military PAR research has direct relevance to MPAR R&D efforts.

Latest Innovations in PAR: An Industry Perspective

- A major issue to be determined is *cost*. While ultimate cost of a national MPAR system is yet to be determined, building an architecture around open systems and building in scalability will both serve to drive down future costs.

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[1] Available at *www.ofcm.gov*.

- Many user "requirements" are not requirements at all, but simply the upper performance level of legacy systems; users must not confuse what they really need with what they have had to settle with in the past.

Component Technology: What the Future Holds in Cost and Performance

- Sheer volume of a national MPAR acquisition of any configuration would tend to drive down cost of T/R modules through economies of scale.
- Integration of more functions onto the same chip lowers cost and increases reliability because fewer high-cost Radio Frequency (RF) interconnects are needed on surface-mounted chips.
- New semiconductor materials provide much higher efficiency, allowing low-cost air cooling for heat dissipation, rather than complex, high-cost liquid cooling.
- Component manufacturers look to exploit dual use (same components for military and civil applications) as key to affordability.

MPAR Alternative Configurations

- Weather will be the principal radar resource driver in any multifunction phased array system of the future. If MPAR can meet weather requirements (in particular, for clear air reflectivity), it can almost certainly meet any aircraft surveillance requirements that will be levied against it.
- Gaps in low-level (boundary layer) coverage inherited from legacy radars need to be addressed by any follow-on radar system. Earth curvature and topographic blockage create blind spots in current radar coverage that are important from both meteorological and air defense perspectives. Blanket coverage may not be feasible; rather, coverage may be "grown" on the network over high-priority areas.

The Way Ahead to Address MPAR Risk Reduction

- The overall conclusion was that the symposium demonstrated solid consensus on both the desirability and feasibility of MPAR to meet national surveillance requirements for both weather and aircraft, but that developing an effective interagency management structure for MPAR risk reduction will prove challenging.
- MPAR must engage the four principal agencies involved: NOAA, FAA, DOD, and DHS.
- The NEXRAD interagency management model may prove an effective precedent for MPAR.
- Engaging agency support for risk reduction will depend on building a compelling business case; the need for more robust DOD involvement was highlighted.
- The most urgent requirement is to develop a risk-reduction implementation strategy, which includes the building and field-testing of a prototype with modern active

phased array radar technology that will actually demonstrate simultaneous multifunction capability.

Attendees of the Symposium agreed that evaluation of MPAR needs to begin, and a series of near-term actions to ensure this were identified.

When the OFCM MPAR planning exhibits consisting of the JAG/PARP report and the MPAR Symposium are examined together, the process may appear more inclusive than it actually was. The apparent agency consensus for funding significant advancements in our nation's surveillance may actually be more muted. The NOAA and FAA stakeholders have been clear leaders in the MPAR planning effort. Industry is clearly energized and moving out on innovative MPAR radar designs.

DEVELOPMENTS TO DATE: ACTIVITIES IN THE NWRT

Significant time and effort were originally necessary to retrofit the SPY-1A antenna for weather observations using a WSR-88D transmitter. Since then, the maintenance and operation of the system have required a large investment in personnel and funding, with the bulk of this effort being led by the NSSL. In addition, NSSL is working closely with engineers from both Lockheed Martin Corporation and Basic Commerce & Industries, Inc. Several research projects are also ongoing in collaboration with scientists and engineers from the University of Oklahoma (OU).

The NWRT has been collecting data since 2004. With the impetus of experimentally testing the MPAR concept, data from the NWRT have been used for numerous R&D activities. The following list provides a brief summary of this work; more complete discussion can be found in a series of American Meteorological Society (AMS) conference presentations by Forsyth et al. (latest in 2008).

Severe Weather Observations/Validation

Data from numerous high-impact weather events have been collected with the NWRT. Ongoing scientific studies emphasize validating the advantages of high-temporal-resolution observations against more conventional measurements from the WSR-88D network (Heinselman et al., 2008). (The spatial resolution of the NWRT is poorer than that of the WSR-88D; however, the manually controlled adaptive scanning can produce higher temporal resolution.)

Hardware Upgrades

To implement true adaptive scanning, upgrade to the Real-Time Controller of the NWRT is necessary. This modification is currently being pursued, along with the required software enhancements. At present, emphasis has been placed on adaptive beam pointing rather than waveform agility. An OU grant from the NSF Major Research Instrumentation Program has allowed the development of an eight-channel receiver for the NWRT, which will allow implementation of numerous techniques not possible before.

Data Quality

Several methods of enhancing data quality in various stages of study (research, development, operational) for the WSR-88D radar are also being investigated for the NWRT. Examples include staggered pulse repetition intervals, phase coding, range oversampling/whitening, and conventional clutter filtering. With the new eight-channel receiver, spatial clutter filtering will also be possible.

New Products and Techniques

Research has been conducted on new techniques made possible with phased array radar, with the goal of operational implementation on the NWRT. The Beam Multiplexing (BMX) technique is now a standard scanning mode, with a detailed analysis of its limitations currently underway. Real-time refractivity (moisture) fields are now available on the NWRT with the advantages of eliminated beam smearing and rapid update of this new product (Cheong et al., 2008). The Spaced Antenna Interferometer (SAI) method is now being implemented on the NWRT with the recent availability of the monopulse channels and the new eight-channel receiver.

Aircraft Detection/Tracking

Although the NWRT system has been used for aircraft detection, tracking has not been pursued due to the lack of the monopulse channels. With the successful completion of the new eight-channel digital receiver, advanced tracking will soon be possible using either power- or phase-comparison methods.

DEVELOPMENTS TO DATE: 2007 ANNUAL MPAR STATEMENT AND 2008 PLANS

Agencies including NOAA, the FAA and DOD have initiated or continued several activities that were in their nascent stages when the JAG/PARP report was released. Several of these activities were completed in 2007 or are scheduled for completion during 2008. Box 6.1 provides a brief summary of those activities, which are discussed in more detail in the *Annual Statement of MPAR Research Priorities and Previous Year Accomplishments 2007-2008*,[2] (This summary includes only those activities that were identified as scheduled for completion in 2007 or 2008.). The Statement also covers

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[2] Available at *www.ofcm.gov*.

activities and accomplishments related to the NWRT, which are outlined above. The reader is referred to the Statement for further details.

BOX 6.1
Summary of CY2007 Research Accomplishments

MPAR Concept of Operations (CONOPS): Description of a multifunction system supporting multiple agencies and agency missions.

Legacy Radar Life Cycle Cost Study: Collection and analysis of legacy radar (ground-based rotating radar systems) operations and maintenance (O&M) life cycle costs, in preparation for an MPAR business case.

ADS-B Backup Requirements: Description of a network of radars to provide surveillance in the event of a regional loss of GPS signal.

MPAR Impact on Safety- and Efficiency-Enhancing Weather Services: A study to explore MPAR's impact on aviation weather algorithms.

Risk Reduction Program: Completed initial risk-reduction effort begun during FY06, including proposed phased array architecture, and design and component cost for a transmit/receive module.

7

Evaluation of the Planning Process

INTRODUCTION

Planning stages of a potential the Multifunction Phased Array Radar (MPAR) program for its entire life cycle from inception through decommissioning would include risk reduction studies, needs assessment, requirements definition, business case development, cost estimation, cost risk analysis, cost-benefit-analysis, appropriations, budgeting, research and development, full-scale acquisition, production, test, system integration, phased deployment, and operation. Initial planning for MPAR is in progress; the MPAR planning process is not static, but continuously evolves. Consequently, any evaluation of the process, however comprehensive, is at best a snapshot in time.

Chapter 6 and Appendix D of the Joint Action Group/Phased Array Radar Project (JAG/PARP) report summarize the proposed Research and Development plan developed by the Joint Action Group formed by the Office of the Federal Coordinator for Meteorology (OCFM). Emerging elements of the planning process to date, which will culminate in an MPAR Program Plan, are described earlier in the present report as presented to the committee.

Included within the MPAR Program Plan will be the MPAR Research and Development (R&D) Plan. This chapter evaluates the planning process to date and provides recommendations for its improvement. The committee recognizes that some planning elements that are identified as either deficient or missing may be implemented before the publication date of this report.

PURPOSE OF THE MPAR PLANNING PROCESS

The MPAR planning process, if successfully executed, will provide stakeholders and policy makers with reliable and sufficient evidence to support or reject a decision to proceed with the project at key decision points. Among these key decision points are whether to proceed with a risk reduction research and development program, whether to proceed with development of MPAR and T-MPAR prototypes, and whether to proceed with full-scale acquisition, development and phased production and deployment of MPAR.

The JAG/PARP report and additional materials and accounts of activities presented to the committee provide an opening round of MPAR planning that touches on some of the areas listed above. However, significant further work and strengthening of the planning process itself is needed.

Recommendation: The WG-MPAR Planning Process for the MPAR R&D program should implement frequent updating and improvement of the MPAR program plan to ensure planning robustness and relevance in the face of changing external conditions. As part of this process, the Program Plan should be periodically evaluated against program goals and objectives to ensure that they are both fully satisfied and remain relevant, as well as against the accomplishments of the R&D work. This evaluation should include annual external reviews, as suggested by Recommendation 3.5-6 of the JAG/PARP report.

THE MPAR STAKEHOLDERS

The OFCM is the primary executive for the MPAR program as now constituted. Prime stakeholders are the Federal Aviation Administration (FAA), National Oceanographic and Atmospheric Administration (NOAA) (including the National Severe Storms Laboratory [NSSL] and the National Weather Service [NWS]), the Department of Homeland Security (DHS), and the Department of Defense (DOD) (including the US Air Force, US Navy and US Army). Secondary MPAR stakeholders include the Federal Emergency Management Agency and the US Coast Guard, the Federal Highway Administration (FHWA), National Aeronautics and Space Administration (NASA), the Departments of Agriculture, Energy and Interior, and the Office of the Director of National Intelligence, as well as the NextGen Joint Planning and Development Office (NextGen JPDO).

Primary stakeholders that have a stated commitment to fund MPAR research and development activity are:

- FAA—for a cost-effective backup to the next-generation cooperative surveillance system and a possible replacement for legacy radars; FAA is currently funding phased array radar R&D.
- NOAA—for continued funding of the National Weather Radar Testbed and additional funding for a MPAR risk reduction program beginning in FY 2010.

As yet, neither DOD nor DHS have promised to fund MPAR activities, although discussions are underway.

Both the OCFM and FAA agree that the large cost of R&D for MPAR and the need for interagency harmonization of requirements will require extensive interagency collaboration and the eventual creation of an MPAR Joint Inter-Agency Program Office.

EXTERNAL PRESSURES ON EXISTING AND EMERGING MPAR STAKEHOLDERS

As noted in the JAG/PARP report, planning for MPAR is driven by many factors including the rising Operations and Maintenance (O&M) costs of legacy radar platforms and societal expectations for improved performance in weather surveillance. It is also affected by the emergence of the NextGen and its reliance upon cooperative transponder technology, known as ADS-B, as the primary means of civil aircraft surveillance. As the traditional role of air traffic surveillance radar correspondingly changes to that of a backup system for ADS-B,[1] the existing FAA surveillance infrastructure will likely incur additional pressure to justify or reduce its rising O&M costs. As noted earlier (see also Box 7.1), this is already happening in the case of the Air Route Surveillance Radar (ARSR) system. En route aircraft surveillance by radar is expected to decrease in FAA priority while terminal area aircraft surveillance by radar is expected to remain the same. Support and funding for en route surveillance by MPAR by the FAA could weaken over the long term in a competitive budgetary environment with competing national priorities. On the other hand, if ADS-B fails to meet requirements for surveillance of cooperative aircraft, the potential posture of FAA vis-à-vis requirements for a future MPAR system may change.

Weather surveillance requirements of NOAA, NWS and FAA for a future NEXRAD and Terminal Doppler Weather Radar (TDWR) upgrade or replacement are among the principal drivers behind their support of MPAR. Shortcomings of the NEXRAD system, as well as capabilities and opportunities afforded by new candidate architectures including phased arrays, are discussed in an earlier the National Research Council (NRC) committee report (NRC, 2002). The TDWR suffers high maintenance costs and for this reason is a candidate for upgrade or replacement.

NEED FOR QUANTITATIVE REQUIREMENTS AND SPECIFICATIONS FOR MPAR

A clearly stated set of requirements is needed to develop various candidate architectures for MPAR. At present, the only clearly defined requirements in existence are those for the four classes of existing weather and aircraft surveillance services; by default, these define the baseline capability required. This is shown in the "Current Capability" column of Tables 2.1 and 2.2 of the JAG/PARP report (reproduced as Tables 3.1 and 3.2 herein). One candidate MPAR architecture to meet this existing requirement is described in Appendix B of Weber et al. (2005), with an updated version in Weber et al. (2007).

The multiple stakeholder needs survey response described above and summarized in the "Future Need" column of Tables 3.1 and 3.2 is the first step in defining a set of fully vetted requirements for MPAR.

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[1] The FAA's Surveillance/Positioning Backup Strategies Alternatives Analysis Report "recommends that the FAA retain approximately one-half of the Secondary Radar Network as a backup strategy ADS-B". It also recommends that "terminal area primary radar coverage will not be reduced from current levels".

BOX 7.1
The ARSR-4 Legacy System for En Route Surveillance

The current ARSR-4 unattended radar platform, or a derivative of it or similar system, might be adequate to fulfill future requirements for backup and non-cooperative en route surveillance of civilian aircraft. This is a well understood low-risk option for possible deployment and replacement of much older ARSR models, beyond the 40 sites[2]—mostly around the perimeter of the continental US—where it is presently employed. The network of ARSR-4s was delivered and installed between 1993 and 1999. The radar is estimated to cost $6.5 million per system. The total program cost is $800 million to date, half of which has been funded by DOD. The ARSR-4s are now operated jointly by the FAA and U.S. Air Force for air defense and drug interdiction operations, in addition to en route surveillance. The North American Air Defense (NORAD) fuses its data with that from other sensors for a common air defense picture of the continental United States (Forecast International Inc., 2003).

The O&M responsibility for the ARSR network, as well as upgrades to it, have already been assumed by the DOD and DHS (Weber et al., 2007). As would be expected, the performance, reliability and maintainability of the ARSR-4 represent a significant advance over its predecessor systems. It employs a phased primary feed (a form of phased array technology) that provides a stack of 2-degree-elevation receive beams for simultaneous tracking of multiple targets in three dimensions. The JAG/PARP report (Table 3-1) estimates the ASR-4's end of life in 2020, but this may assume that the government (DOD and DHS) will no longer fund FAA to upgrade the systems or replace service parts (Forecast International Inc., 2003). On the weather surveillance side, the ARSR-4 has been identified as having future development potential as a "gap-filler" for the NEXRAD network (Istok, 2005).

FIGURE 7.1. Photo of an ARSR-4. Source: Northrop-Grumman Corporation.

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[2] A total of 61 earlier generation ARSR-1/2/3 radars are sited around the country and will eventually need to be replaced.

Where these needs exceed present capabilities, a careful exercise of architectural trades should be performed including Cost as an Independent Variable (CAIV).[3] From this exercise, a realistic set of requirements could be generated. From these requirements, various candidate architectures could be proposed and one or more could be selected for further evaluation. For the winning architectures, conceptual designs could be developed and further refinement leading to the selection of an optimum design could be accomplished. A prototype would then be built to the optimum design for further testing and refinement.

Two stated “Future Needs” (listed in Table 3.2), for the sensitivity of non-cooperative airborne surveillance at 0.1m^2 radar cross section and vertical coverage from the surface to 100,000 ft, are examples of where a possible CAIV design trade could balance cost against achievable performance. Candidate architecture to satisfy these two needs for homeland defense would be particularly costly if 100 percent coverage of the Nation’s borders is to be achieved. The architecture proposed in Appendix B of the JAG/PARP report would not satisfy either of these two stated needs, even in areas where full scale MPAR coverage is provided.

Other Potential Requirements

The task of defining the evolving spectrum of “air-breathing” threats for homeland defense is the responsibility of the Joint Air and Missile Defense Organization (Evans, 2004; Mathis, 2004). This is the organization within the DOD chartered to plan, coordinate, and oversee Joint Air and Missile Defense (AMD) requirements, joint operational concepts, and operational architectures. An expanding but as yet only preliminarily defined role for future radars to provide surveillance against a variety of non-cooperative airborne threats for Homeland Defense could become a significant factor in determining MPAR requirements. The current baseline air surveillance capability against such threats is inadequate, particularly at low altitudes.

The present MPAR plan for some 334 systems appears only to address the current FAA baseline surveillance requirement for commercial aviation. If, as seems likely, significantly more than 334 MPARs should be deemed necessary to provide comprehensive low altitude coverage for homeland defense, then even if the aggregate cost projections were accurate, they would only apply to an established FAA requirement rather than a new DHS/DOD requirement. An alternative approach similar in concept to the dense, low cost, low power CASA radar architecture (see Chapter 8) could possibly be investigated for seamless low altitude coverage of airborne threats crossing the nation’s borders. Section 6.4.3 of the JAG/PARP report indicates that “coordination and collaboration with the CASA program will be essential to this part of the risk reduction program.” The relationships between the proposed MPAR system and potential future

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[3] For a discussion of CAIV and its relationship to Total Ownership Cost (TOC) or Life Cycle cost, See Boudreau, M. W. 2005. “Total Ownership Cost Considerations in Key Performance Parameters and Beyond.” *Defense Acquisition Review Journal*, Feb – March. Available at *http://www.dau.mil/pubs/arq/2005arq/2005arq-38/boudreau.pdf* accessed July 24, 2008.

needs, and a potential future system based on the CASA concept, are unclear. Indeed, the relationship between the MPAR and CASA projects is unclear and needs to be clarified to understand how requirements, benefits, and costs are being assessed.

Looming upon the horizon are two national directives that have the potential to significantly influence the technical direction and scale of the MPAR program: National Security Presidential Directive 47 and Homeland Security Presidential Directive 16. These two Presidential directives direct the production of the National Strategy of Aviation Security and several supporting plans including the Air Domain Surveillance and Intelligence Integration Plan[4] that address surveillance radars (which would include MPAR) as a collection source for National Intelligence to promote the goal of Air Domain Awareness.

Recommendation: The MPAR R&D program should produce a fully vetted set of technical performance requirements for an operational MPAR and radar network. To ensure robustness of the R&D Program in the face of potential re-balancing of stakeholder needs and participation over time, the MPAR planning process for non-weather surveillance should further emphasize the need to fully establish requirements of all participating agencies.

EVALUATION OF THE MPAR R&D PLANNING PROCESS

A Research and Development plan is an essential component of the MPAR planning process. Such a plan is needed to reduce identified key technical risks or potential "show stoppers" (such as whether a phased array radar can effectively perform dual polarization measurements) and other issues identified in Chapter 5 above and Chapter 4 of the JAG/PARP report that, if not mitigated, would effectively halt a decision to proceed with further MPAR development. A second goal of the R&D plan as identified in the JAG/PARP report is the "establishment of a documented basis for cost comparisons between the MPAR and mechanically rotating conventional radar (MRCR) alternatives for meeting national domestic radar surveillance needs…" This goal is not fully supported by the stated R&D activities, but the committee views it as essential to providing the basic business case for whether or not to proceed with an MPAR acquisition.

TECHNICAL ISSUES

The proposed R&D program addresses many of the technical risks listed in Chapter 5 above, but not other essential capabilities, such as "demonstrating the operational capability enhancements that can be realized through collaborative

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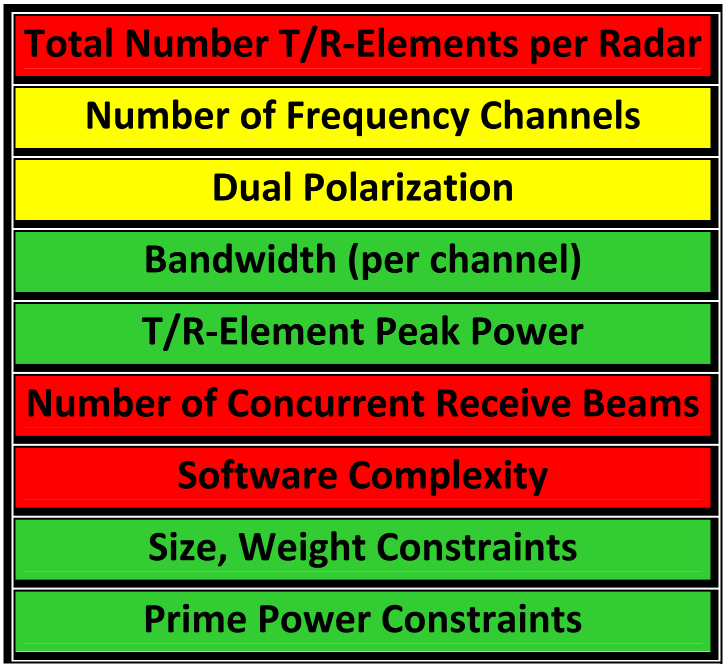
[4] See *http://www.dhs.gov/xlibrary/assets/hspd16_domsurvintelplan.pdf.*

surveillance strategies that exploit the unique capabilities of a highly interconnected phased array network." Table 6.1 in the JAG/PARP report (reproduced below; see Table 7.1) summarizes the key MPAR "technical parameters" posing the most significant challenges that should be addressed by the R&D program. Twelve critical tasks are listed in the Technology Development and Test Program. Successful execution of the first five tasks constitutes the first go/no-go decision point.

TABLE 7.1. MPAR Key Technical Parameters. Source: OFCM, 2006.



🟥 **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**

NOTE: 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.

The capability of phased array radars for aircraft surveillance and tracking has been well established through several decades of military experience. However, the same cannot be said for the capability for weather surveillance—especially for the quantitative measurements required for most effective use of the observations. Suitability of an MPAR system for weather surveillance will be predicated on achieving measurement capabilities comparable to those that will exist in the NEXRAD and TDWR systems at the time any decision to proceed with implementation of an MPAR network must be made. This includes not only the present capability for reflectivity and Doppler velocity measurement, but also the soon-to-be-deployed NEXRAD polarimetric capability. Moreover, the narrower beamwidth and higher frequency of TDWR provide capabilities differing from those of NEXRAD. The narrower beamwidth of the TDWR provides sufficient vertical resolution to observe shallow air motions above airport runways, reduces ground clutter, and provides high resolution weather measurement in the terminal area. A requirement to retain these capabilities would have substantial impact on an MPAR or T-MPAR design.

Reflectivity

Quantitative reflectivity measurements to accuracy of 1 dB (the NEXRAD Technical Requirement goal) require careful system calibration, a topic notably absent from the table. In an MPAR system the characteristics of the antenna beam, including the beamwidth and antenna gain, vary with squint angle and may also differ between transmit and receive modes. Although in principle these variations can be determined and accounted for, a means of verifying these corrections in field-deployed systems will be needed. Measurement of transmitted power and receiver response characteristics is also challenging with a distributed array. The R&D planning for MPAR must include development of a practical approach for dealing with this problem in an operational environment. Preliminary testing of the approach could be carried out at the NWRT, but the committee received no information about any such effort.

Polarimetric Variables

An MPAR system could offer some advantages over the NEXRAD polarimetric capability—for example, the possibility of obtaining LDR measurements. However, the polarization characteristics of the antenna beam vary with squint angle. Part of the variation results from simple geometric considerations, and here again the variations can in principle be determined and accounted for. However, other factors such as mutual coupling between array elements at large squint angles complicate the situation and are not so readily analyzed. This represents a major challenge to the suitability of MPAR for weather surveillance, and the challenge in verifying any specified procedure with field-deployed systems is even greater than the reflectivity problem. The MPAR R&D planning process should include a well-developed concept for evaluating the polarization capabilities of real MPAR systems.

Recommendation: The MPAR R&D program should produce a procedure for calibrating the reflectivity and polarimetric measurements at all scan angles. A key decision point for the feasibility of MPAR for weather surveillance, and continuance for the R&D program, will be determination of its capability for dual polarization measurements. Therefore, thorough evaluation of the capability of phased array radar to accurately measure polarization variables independent of scan angle must be carried out early in the R&D program.

Frequency Requirements

The MPAR R&D program should address the frequency allocation/interference issue. Given the current design concept proposed to accomplish the multi-function capabilities (Weber et al., 2007), independent transmitter frequencies will be needed for each function in order to provide the necessary time-on-target. In addition, use of pulse compression methods may require additional "fill pulses" to provide short-range coverage, necessitating yet another frequency allocation (as well as increasing the needed dwell times). The MPAR would have four faces, essentially four separate radars, and it is possible that each face would require an independent set of frequencies in order to eliminate face-to-face interference. In a worst-case scenario, the full four-face MPAR could require as many as 16 frequencies, with associated bandwidths and guard-bands. Access to the required frequency spectrum in S-band, where the commercial demand for spectrum allocations is ever increasing, could become a challenge to MPAR implementation. This factor must be considered in the planning process.

Recommendation: Given the high demand for bandwidth at the proposed S-band frequency, the MPAR R&D program must determine the total required bandwidth as early as possible in the research program to ensure the feasibility of the design.

T-MPAR Planning Process

The conceptual system design described by Weber et al. (2007) suggests that a national MPAR network may consist of two radar types. Approximately one-half would be full-scale MPARs with maximum sensitivity, resolution, and operating range; the other half would be less-costly "Terminal-MPARs" (T-MPARs) with smaller apertures. The full-scale MPARs would be used as the Next Generation Radar (NEXRAD) replacements and at airports currently served by the TDWRs. The T-MPARs would be used, as a lower cost option, at smaller airports and as gap fillers. As noted in the JAG/PARP report and in Weber et al. (2007), this is a preliminary and "not fully worked out" design concept. The adequacy of this concept, ranging from the ability to track aircraft to the required weather sensing capabilities, should be fully scoped out.

The T-MPAR transmit/receive (T/R) modules could be designed to operate at S-band (as for the full MPAR), or possibly at C- or X-band. A T-MPAR design operating at S-band[5] would achieve commonality of T/R modules across the full national system and maximize the economies of scale achieved through mass production. If shorter-wavelength options appear desirable, economies of scale may be compromised in both the production phase and later in the operations and maintenance phase after deployment.

The FAA's surveillance roadmap identifies a "New Primary Radar" to replace the ASR-8/9/11 terminal platforms around the year 2020. The T-MPAR could be a candidate for this new "Primary Radar." As noted in Weber et al. (2007): "T-MPAR would be deployed primarily at smaller airports where today, either wind shear protection services are not provided, or are provided by the less capable ASR-9 Weather Systems Processor." This suggests a lower level of terminal weather surveillance performance for certain regions of the country.

For example, if modules having the same transmit power are used for both MPAR and T-MPAR, the total transmitted power for the T-MPAR would be reduced by the ratio of the antenna aperture areas. Consequently, the power-aperture product of T-MPAR would be reduced (compared to MPAR) by the square of the ratio of the aperture areas.

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[5] Statement by Mark Weber of Massachusetts Institute of Technology/Lincoln Laboratory at the committee's second meeting in Boulder, Colorado on March 6, 2008.

Section 2.3 of Appendix B of the JAG/PARP report notes, for one design of a dual-density active array for the "gap filler" radar, that "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." Therefore, the suitability of the T-MPAR design for meeting functional requirements must be fully evaluated. Without a clearly defined set of requirements for MPAR, or a completed design concept for T-MPAR, one cannot state whether one or two radar types is the preferred (or indeed, lowest-cost or optimal) approach.

Recommendation: The Airport Terminal Area or T-MPAR concept needs to be developed in sufficient detail to demonstrate that mission requirements for terminal weather and aircraft surveillance can be met. In addition, the ability of a full MPAR to meet Terminal Doppler Weather Radar (TDWR) requirements must also be assessed due to the fact that the MPAR beamwidth would be approximately 1 deg (instead of ½ deg) and the frequency choice is S-band (instead of C-band).

COST ISSUES

A number of assumptions underlie the preliminary MPAR cost estimate provided in the JAG/PARP report (Chapter 5 and Appendix C). The pre-prototype component cost estimates presented in Table 2 of Appendix C are extrapolated to full-scale MPAR component costs based on "economies of scale or new technologies expected to mature over the next three years." These advances are no doubt likely to happen to some degree (as noted in the section below on element cost), and the effects may be describable via parametric relationships such as the "learning effect." However, it is difficult to quantify the size or sensitivity of the parameters or to predict the level of cost reduction that will be achieved by these and other advances in the future (as is implied in the cost column titled "Full Scale MPAR"). A key question seems to be: "what is the probability of deploying MPAR at or below the projected cost of $3.34 billion?" Only after a prototype is developed and evaluated does it seem possible to be more specific about the overall cost of MPAR.

Approximately one half of the MPAR radars are projected to be the smaller and lower-cost T-MPARs providing limited coverage underneath the radar horizon of the national-scale network. The mix of short-range and long-range MPARs in the final network configuration appears to be a major driver of costs and therefore cost estimate uncertainties. A more thorough and systematic approach to cost estimation is needed; various DOD-related publications present an introduction to modern cost estimation methodology (Book, 2001).

Cost of Array Elements

Table 2 in Appendix C of the JAG/PARP report shows a target price for T/R modules of $20 each in a production MPAR system. The cost of T/R modules has long been seen as prohibitive to the use of phased array radars in applications other than high-performance military missions. A compelling argument presented to the committee by commercial representatives is that through careful electronic design and judicious choices of electronic materials, foundry, physical packaging and production line, a T/R module cost in quantity of below $50 is achievable. This argument is based on cumulative production experience in developing Radio Frequency (RF) componentry on commercial lines for mass-produced portable wireless handsets, radio frequency identification readers and automotive radars. It is argued that commercial packaging and production techniques used for these high-volume commercial products would permit similar economies of scale to be achieved for MPAR.

The most likely cost that will be achieved for MPAR T/R elements is difficult to predict with precision, but this one item will receive considerable attention from the system designers and cost modelers. A key consideration is the question of whether a common T/R module design will suffice for both the MPAR and T-MPAR systems. Another major consideration is the cost and added complexity associated with T/R module design involving dual polarization and multiple frequencies.

From the standpoint of total system cost, the difference between $20 and $50 for a T/R module is highly significant. An extra $30 per T/R module equates to an extra $2.4 million per MPAR. Further uncertainties in other hardware costs will only add to the possible range of total cost per system.

The MPAR cost analysis as presented in the JAG/PARP report only addresses an MPAR architecture that meets the baseline requirements. Where an entirely new and unproven architecture is presented that meets but does not substantially exceed the performance baseline, a compelling and robust cost-reduction argument would need to be presented; this has not yet occurred. The basic cost-saving argument centers upon providing coverage, from a reduced number of fielded MPARs and T-MPARs, that is essentially the same or marginally better than that presently provided by the existing network of legacy radars. From Table 2 of Appendix C, the target total cost of all the electronics normalized per T/R element (including $20 for the T/R module itself) is $133.50. From this basic building block, the total cost for a full 80,000 element MPAR is projected to be $10.7 million and the T-MPAR with about 8,000 elements to cost $2.8 million. These cost estimates are at best rough order of magnitude estimates and, as they stand, are inadequate to form the basis of an informed procurement decision. These could be optimistic figures and will need to be revisited throughout the R&D risk reduction program and beyond to ensure that a viable economic argument for fielding MPAR can be made.

With the prospect of a production run of hundreds of nearly identical radar systems and millions of T/R modules, it would be useful to engage multiple sources to manufacture and deploy MPAR and T-MPAR systems, sub-systems and components. Competition can be used advantageously both to minimize cost and to enforce the development of and strict adherence to an open-standards-based architectural framework. As noted earlier, an open-standards-based approach is preferable to an architecture that is based on closed, proprietary standards from a single contractor. Future expansion and enhancement of MPAR would be greatly facilitated by open standards. The JAG/PARP report correctly notes the value of open architecture in the use of commercial off-the-shelf software (section 4.5) and hardware (section 5.1). However, this needs to be an enforced requirement that is written into the acquisition contract.

Federal authorities could require redundant MPARs to be installed in overlapping coverage areas or locations deemed of critical importance. The consequences of losing both weather surveillance and backup air-traffic surveillance from the failure of a single radar could be deemed risky. Fielding additional MPARs to reduce this "all eggs in one basket" risk could significantly increase the number of fielded systems above the 334 proposed and therefore reduce the economic advantage cited.

The O&M costs for the entire population of legacy radars are estimated, based upon Lincoln Laboratory's involvement with the life-cycle support and enhancement programs for TDWR, NEXRAD and ASR-9 programs, at $0.5 Million per unit per year. It was stated to the committee that the TDWR and NEXRAD radars have the highest maintenance costs[6] because of high rates of wear on the azimuth and elevation antenna drive axes. If these three radars form the basis of an O&M cost estimate for legacy radars that is then extrapolated to include the newer ASR-11 and ARSR-4 systems, which require less maintenance, these costs could be incorrectly averaged over the wider legacy radar population. It is possible that the same O&M savings could be realized with less investment and lower risk by replacing just the two weather surveillance radars with a new design, and simply replacing the least reliable legacy aircraft surveillance radars with newer models.

The O&M cost estimates for MPAR are assumed to reduce to $0.3 Million per radar per year, based in part on the synergy effects caused by a reduction in the required number of program offices, personnel, and non-recurring engineering (NRE) expenditures. This optimistically assumes a steady-state condition after transition costs associated with a complex changeover to a new system. However, a period of overlap would likely occur between the deployment and operation of each new MPAR and the decommissioning of the legacy radar at each operational site. Integration of the new radar into a new or modified legacy network would likely consume additional time and effort at additional cost, particularly if unforeseen problems arise in the later stages.

The current assessment of the potential cost paths with MPAR versus MRCR, as illustrated in Figures 3 and 4 of Appendix C of the JAG/PARP report, does not account for the fact that the likely start date of any MPAR system implementation would lie a decade or more into the future. This assessment does not indicate a net present value based on common methods for discounting and accounting for risk. A more complete and acceptable net present value should be presented, in conjunction with a sensitivity analysis for key unknowns—such as uncertainty with respect to the likely cost of T/R components.

Recommendation: A thorough and complete cost analysis of the total MPAR program should be performed and compared with historical life-cycle costs for the more recently and currently deployed systems such as ARSR-4 and ASR-11 that are roughly equal in performance to MPAR for air-traffic surveillance, and for NEXRAD and TDWR radars that provide a performance baseline vs. MPAR for weather surveillance. A detailed baseline operations and maintenance (O&M) cost estimate should be

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[6] By William Benner, FAA, at a presentation to the committee on January 14, 2008.

determined for all legacy radar types to identify and quantify those highest cost radar types that are the prime candidates for life extension, upgrade or replacement. Independent cost risk analyses for the acquisition of MPAR and T-MPAR by recognized methods should be performed and continuously re-visited and updated.

Recommendation: An alternative weather-only phased array weather radar design trade study and detailed cost analysis should be performed and compared with historical life cycle costs and performance for NEXRAD and TDWR radars. This trade study and cost analysis should be compared with a more detailed MPAR cost analysis and trade study to determine if the marginal cost of adding the required aircraft surveillance capability is worth the perceived benefit of having an all-in-one system.

NEED FOR COMPLETE INCLUSION OF ALL ASSOCIATED SYSTEM COSTS

The cost estimates for MPAR in Appendix C of the JAG/PARP report are based solely on component hardware costs, normalized to cost per T/R module. Software development costs (internal, application and system), integration cost, site preparation, deployment, testing, management and other NRE design costs are not considered. For a large production run of a mature product, assuming that design changes are not implemented during the production run, early-stage NRE would be averaged into the cost of individual components. Thus, total component and production costs would eventually dominate the cost per radar. However, at the early stages of the project, research and development expenses (including software development activity) would dominate the cost picture.

Other cost issues raised in Chapter 5 would affect the life-cycle costs of MPAR. Accounting for these issues should include evaluation of not only technical issues, but also logistical (e.g., frequency allocation and siting) and implementation (e.g., education and training) issues. For example, if parallel operation of the legacy system with the new MPAR system is required for some limited time to transition smoothly from one to the other, then the site occupied by the legacy system cannot be used by the MPAR system. Also, it would be overly optimistic to assume that extensive software development activity will not extend well into the operational life of an MPAR program. The experience with NEXRAD suggests that it will more likely extend for years beyond the initial deployment period. MPAR cost estimates should include all likely software development, integration, testing and upgrade costs beyond initial operational capability that extend from the initial first fielded system through final deployments up to a defined baseline level of individual radar and fully integrated system-wide performance

COST-BENEFIT ANALYSIS

Recommendation 4 of the JAG/PARP report states: “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." We note that the purpose of the cost-benefit analysis is not to establish the cost-effectiveness of a program but rather to quantify the net benefits of that program and potentially compare those to the net benefits of a baseline or alternative programs.

Chapter 2 of the JAG/PARP report discusses a wide range of potential needs that radar could meet, including weather surveillance, aircraft surveillance, and a variety of other uses. None of these uses—i.e., benefit areas—are quantified or monetized as part of a benefits assessment. Support for the MPAR R&D project in the JAG/PARP report is based entirely on a comparison of projected costs between MPAR and MRCR, rather than on anticipated benefits compared to costs of the various alternatives.

As there is little available information on the economic benefits of the current radar systems, the R&D project should include a research component to identify the current and potential communication, perception, use, and values for radar-based information for a broad range of users. This would include both weather and aircraft surveillance functions and a broad spectrum of users including different economic sectors and subsectors (such as transportation, energy, agriculture, or insurance), public sector users (such as emergency management, water resources, environmental management, aviation, or homeland security), and the public at large. Economists have developed methods to address the challenging task of monetizing seemingly intangible benefits, such as public safety and saving lives. For example, the value of a statistical life (VSL) is used to estimate the monetary benefit of reducing premature mortality risks using available willingness to pay (WTP) estimates for changes in mortality risks on a per-life-saved basis. VSL is a theoretically valid and widely used measure for evaluating the benefits of programs that affect mortality rates, including environmental protection issues (Dockins et al., 2004).

As the project develops, an ongoing effort is needed to track, assess, quantify, and monetize the benefits and costs as these develop over the course of the effort. This will provide ongoing feedback assessing the net benefits of the project and identifying areas of highest potential benefits to focus potential research and applications efforts. Ongoing benefit-cost assessment will also account for unanticipated changes in technology, societal needs, and newly developed or identified application areas that could generate previously unaccounted benefits.

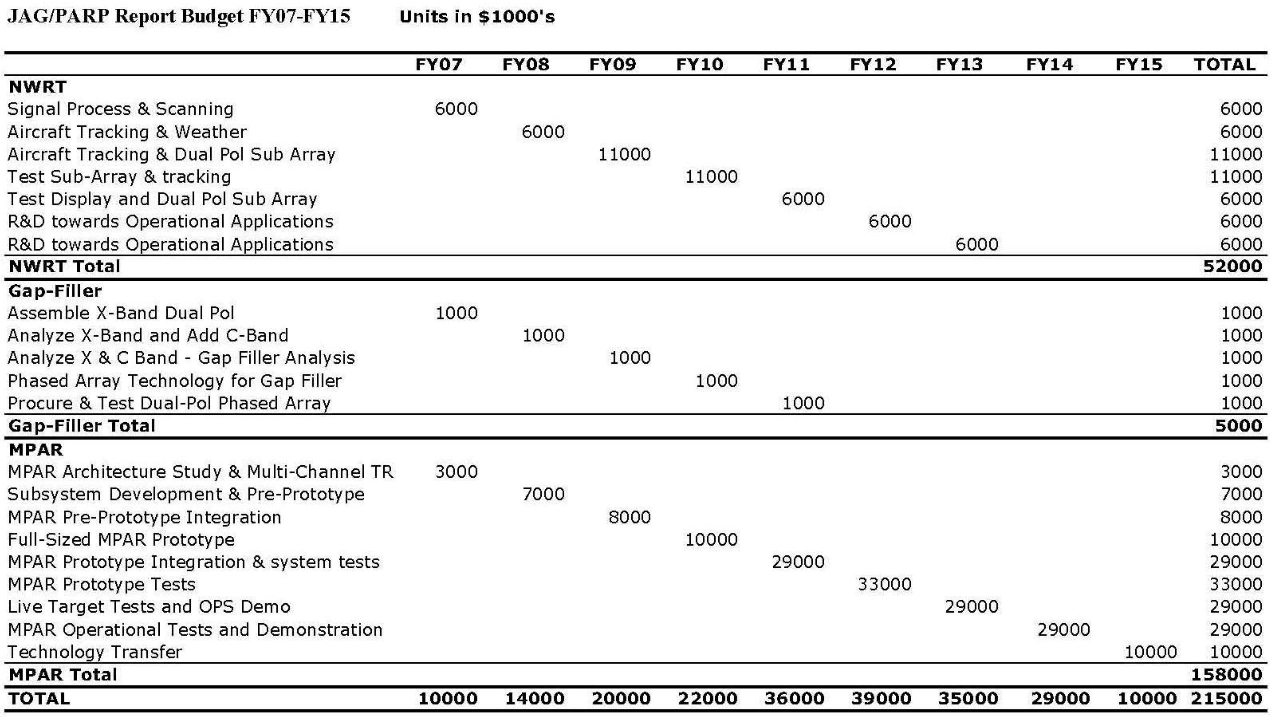
The design of the MPAR system as described to the committee appears to be based entirely on functions provided by the current system. Unless there are binding constraints requiring maintaining the current coverage, an assessment of the future of the U.S. radar system should be based on an optimal design for future needs. Whether this means more or less coverage (or the same) compared to the current system should be determined in an empirical assessment of system needs. This requires a thorough assessment of the benefits and costs of the current system and likely future requirements based on spatially optimal needs in a benefit-cost analysis framework.

Cost of the R&D Program

The $215 million R&D plan, as originally envisioned and described in Appendix D of the JAG/PARP report, is divided into three major areas that were to be executed in parallel beginning in FY07 and ending in FY15:

- A total of $52 million is to be spent on "Proof of MPAR Operational Concepts" at the NWRT in Norman OK.
- A total of $5 million is to be spent on "Refinement of MPAR Network Concept" for X-band and C-band dual-polarization phased array "Gap Filler" radar development that "would compliment the CASA research"[7] (MPAR, and probably T-MPAR, would operate at S-Band).
- A total of $158 million is to be spent on "MPAR Technology Development and Test," including the MPAR architecture study; development of T/R modules and subsystems; and an MPAR pre-prototype and full-scale prototype.

TABLE 7.2. JAG/PARP Report Budget FY07-FY15



JAG/PARP Report Budget FY07-FY15 **Units in $1000's**

	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	TOTAL
NWRT										
Signal Process & Scanning	6000									6000
Aircraft Tracking & Weather		6000								6000
Aircraft Tracking & Dual Pol Sub Array			11000							11000
Test Sub-Array & tracking				11000						11000
Test Display and Dual Pol Sub Array					6000					6000
R&D towards Operational Applications						6000				6000
R&D towards Operational Applications							6000			6000
NWRT Total										**52000**
Gap-Filler										
Assemble X-Band Dual Pol	1000									1000
Analyze X-Band and Add C-Band		1000								1000
Analyze X & C Band - Gap Filler Analysis			1000							1000
Phased Array Technology for Gap Filler				1000						1000
Procure & Test Dual-Pol Phased Array					1000					1000
Gap-Filler Total										**5000**
MPAR										
MPAR Architecture Study & Multi-Channel TR	3000									3000
Subsystem Development & Pre-Prototype		7000								7000
MPAR Pre-Prototype Integration			8000							8000
Full-Sized MPAR Prototype				10000						10000
MPAR Prototype Integration & system tests					29000					29000
MPAR Prototype Tests						33000				33000
Live Target Tests and OPS Demo							29000			29000
MPAR Operational Tests and Demonstration								29000		29000
Technology Transfer									10000	10000
MPAR Total										**158000**
TOTAL	**10000**	**14000**	**20000**	**22000**	**36000**	**39000**	**35000**	**29000**	**10000**	**215000**

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[7] R&D funding clarification memo. March 19, 2008, Jeff Kimpel, Director, National Severe Storms Laboratory, Norman, OK.

NOAA provided supplementary budget details for the MPAR R&D program, reproduced in Table 7.2 below. We note that the FY07 and FY08 funding provided has been insufficient to fully execute the R&D plan as outlined in the report.

Recommendation: The FCMSSR should seek a reasonable and continuous funding stream to support the R&D Program.

Finding

The planned expenditures in the second major area are aimed at developing new dual-polarized mechanically- and electronically-steered radars at C and X band, and analyzing data obtained with those radars to support possible alternative configurations to multifunction S-band arrays. In contrast to the S-band MPAR work, the specified funding levels and range of activities represent only a fraction of the research needed for risk reduction at shorter radar wavelengths. Risk reduction activities in support of X-band phased array radar, signal processing, and data communication technologies are currently being carried out by the CASA Engineering Research Center with support from the National Science Foundation. The committee appreciates the intent of the MPAR activity to link with the CASA center but notes that no specifics are given on how that linkage would be made. The committee has some concern that many of the short-wavelength activities described appear to duplicate some of the efforts of CASA and other projects. The latter include a number of well-calibrated dual-polarized mechanically-steered radars that currently exist within the remote sensing community and that can support new phenomenological investigations. Better utilization of these capabilities can be a more effective approach to achieving some of the MPAR R&D goals than developing an entirely new set of C-and X-band radar systems.

Recommendation: The MPAR R&D Program, instead of developing new X- and C-band radars, should develop linkages with appropriate organizations within the radar community as a way to avoid duplication of effort and take full advantage of ongoing work related to short-wavelength radar technologies.

The Full Scale Prototype Stage

Of the $158 million to be spent in the third major area, the cost of the MPAR pre-prototype stage is $18 million, whereas the full-sized MPAR prototype and subsequent testing stage totals $140 million. Chapter 6 of the JAG/PARP report states that tasks 1 through 5 of the list in Section 6.2 pertain to a pre-prototype MPAR, where the most critical technical issues are to be addressed earliest at the lowest cost. A decision to proceed with full-scale prototype development will be required before the bulk of planned MPAR R&D funding needs to be spent. The full-scale prototype is only needed for tasks 9 through 12, and only after major decision hurdles have been met.

The committee senses that the majority of R&D issues associated with MPAR surveillance of aircraft and weather could be addressed with a prototype single full-scale antenna face, or possibly two faces (to examine handoff issues and continuity of calibrations across faces). A capability to position this face to all azimuths would be useful. A capability to transport the prototype platform could also be useful to allow investigating MPAR capabilities in a variety of weather and air traffic regimes.

Recommendation: The MPAR R&D program should include the staged development of a prototype MPAR, proceeding through a Line Replaceable Unit (LRU), followed by a single antenna face, two faces, or a full four-faced prototype. Cost effectiveness studies should be carried out to determine how many faces would be required to assess the MPAR concept.

Recommendation: The committee endorses Recommendation 2 of the JAG/PARP report and would like to see it implemented early in the program. The committee further recommends that the MPAR R&D program be as open as possible, in particular to ensure that interested parties from industry and universities are involved at early stages, and that the engineering development and scientific applications of the MPAR prototype benefit from involvement of the broadest communities possible.

Cost-Benefit Analysis of the R&D Program

No direct link is made in the JAG/PARP report between the discussion of benefits and costs of a fully implemented MPAR system and the R&D program, in terms of the assessment of the full system providing information on the potential benefits of the R&D program. Realizing the potential benefits of the full MPAR system is dependent on success in the R&D program, and one purpose for assessing the potential costs and benefits of an MPAR system is to provide information for a cost-benefit analysis of the R&D program itself.

A valid cost-benefit assessment of the R&D program requires sufficiently detailed and supported information on the likely cost of the R&D effort and probabilistic assessment of cost uncertainties. Appendix D of the JAG/PARP report outlines the MPAR R&D Plan with costs indicated in parentheses by each task-year. The total of $215 million is based on a series of estimates for sub-components of this project, but there is not adequate documentation of the source of these estimates. In response to an information request from the committee ("How were the estimates arrived at in Chapter 6 and Appendix D of the JAG report?"), James Kimpel provided the following response:

> "c. Based on the team members . . . experience (20 years plus for most members), an educated estimate of what it would take to accomplish each of the tasks was prepared. Some of the tasks use in-house expertise and some require contracting out. Some of the tasks required the purchase of state-of-the-art hardware, building a dual-polarized sub-array or a full sized Multi-function Phased Array Radar.
>
> d. Based on staffing and hardware requirements, the estimates were drafted and then refined several times. Expertise from NOAA, FAA, and Lincoln Labs all participated in refining the estimates."

The information developed to date on costs appears inadequate as justification for the MPAR R&D effort. Given the magnitude of the proposed effort, more complete information is needed on the estimation of the costs of the MPAR risk-reduction program.

Recommendation: The R&D Plan outlined in Appendix D in the JAG/PARP Report should be expanded to provide detailed descriptions of the tasks to be undertaken, their priorities, the associated costs, and key decision points.

The major potential benefits from the MPAR R&D effort are the likely benefits from an MPAR system in whatever form that system is deployed. A cost-benefit analysis of the deployed MPAR system is needed, as described earlier, in order to determine the potential benefits from the R&D effort. These potential benefits would be weighted by the (subjective) probability that the R&D program would establish the viability of the MPAR alternative to MRCR. There is no discussion in the JAG/PARP report of probability estimates for success or failure at any critical decision points in the R&D program.

Recommendation: Probability estimates of the likelihood of success/failure of achieving objectives at critical decision points in the R&D program should be developed.

The discussion of cost savings of an MPAR program in the JAG/PARP report focuses on a future system implemented to replace the legacy systems. In addition to the need for a cost-benefit analysis (CBA) of the full implementation of an MPAR system based on results of the risk reduction R&D program, there needs to be a complete CBA of the risk reduction program *itself* prior to funding of the program. This CBA would assess the expected net benefits of the MPAR R&D program in relation to the proposed $215 million R&D cost. In order to accomplish this it is necessary to have baseline information on the expected long-term benefits from a future MPAR system. A CBA of the R&D program should consider a range of alternatives, including such things as partial replacement of the legacy radar system with T-MPAR and the potential benefits of investing in R&D to improve MRCR systems. The probability estimates of success could be derived from an expert assessment (Delphi method or other methods). These probabilities should then be updated if and as the R&D program proceeds and more information becomes available.

8

Family of Systems

The Joint Action Group/Phased Array Radar Project (JAG/PARP) report outlines a comprehensive research plan to investigate the capability of a Multifunction Phased Array Radar (MPAR) system to replace the current radar network comprising the WSR-88D, Terminal Doppler Weather Radar (TDWR) and Airport Surveillance Radar/Air Route Surveillance Radar Version (ASR/ARSR) aircraft and weather surveillance radars. However, the entire set of surveillance needs described by the various Federal agencies as part of the JAG/PARP investigation and summarized in the JAG/PARP report, which are not all being satisfied by the current network, likely cannot be met economically with any one network of widely-spaced surveillance radars. An MPAR network may be able to economically replace the current radars and enhance some capabilities while lowering life-cycle costs. However, to fully meet the Nation's surveillance needs, any future MPAR surveillance network must be viewed as a member of a family of sensing systems.

The MPAR system as conceived in the JAG/PARP report would provide nearly complete coverage of the National Air Space (NAS) at and above 5000 ft above ground level, and low-level coverage of the atmosphere in the vicinity of the 334 radar sites. However, neither that MPAR system nor any architecture based on widely spaced radars (including the current system) can provide comprehensive vertical coverage of the NAS down to the surface. As discussed in Chapter 2 of that report, the MPAR concept does not address a key aspect of the DOD's strategy for Homeland Defense & Civil Support (2005), namely, "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." Also, it does not address current deficiencies related to gaps in boundary layer coverage or meet the future needs for low-level radar coverage identified in numerous places in the report, such as the Federal Highway Administration (FHWA) needs articulated in *Where the Weather Meets the Road* (NRC, 2004).

A 1995 National Research Council (NRC) study, *Toward a New National Weather Service—Assessment of NEXRAD Coverage and Associated Weather Services* (NRC, 1995) investigated the adequacy of WSR-88D coverage relative to the detection and warning of a variety of weather phenomena, including landfalling hurricanes, supercells, minisupercells, mesocyclones, tornado vortices, microbursts, macrobursts, and various types of precipitation and snowfall. This study found that WSR-88D coverage over the nation was generally excellent in terms of providing superior forecasting and warning capability compared with the WSR-57 and WSR-74 systems that preceded the WSR-88D. It is generally agreed that the improved coverage and performance of the WSR-88D network has led to a significant improvement in the short-range forecasts and warnings of severe thunderstorms, tornadoes, and flash floods (Serafin and Wilson, 2000). Nevertheless, the incomplete low-level coverage limits the detection of the full range of hazardous weather over large expanses of the Continental United States (CONUS).

Table 8.1 shows the percent of vulnerable CONUS land-mass over which the WSR-88D system is incapable of detecting various types of weather events. These percentages, taken from calculations performed for the 1995 National Research Council study, reveal that the WSR-88D is able to observe certain hazards in only 29-69 percent of vulnerable regions. The NWS does make use of TDWR and ASR data to address some of the gaps in populated regions where these radars provide additional coverage.

TABLE 8.1. Fraction of Vulnerable CONUS Land Mass Where WSR-88D Coverage is Inadequate to Detect Specific Weather Events. Source: NRC, 1995.

Event	Insufficient Coverage Fraction
Supercell	29%
Mini-supercell	69%
Macroburst	42%
Lake effect snow	46%
Stratiform snow	31%

Westrick et al. (1999) assessed the impact of limited WSR-88D coverage for detection and quantitative estimation of precipitation amounts over the US west coast regions. This study concluded that, as a result of significant terrain blockage in that region combined with shallow depth of precipitation during cold seasons and low melting levels, 67-75 percent of the land surface in the region has inadequate radar coverage to support quantitative precipitation estimation.

Figure 8.1 shows the coverage provided by the combined WSR-88D, TDWR, ASR, and ARSR systems at 1,000 ft Above Ground Level (AGL). The white spaces reveal that the majority of the airspace at the 1000 ft level is not observed by these radar networks. This fundamental limitation of the ability of any widely-spaced network of ground-based radars to observe close to ground level results from both the curvature of the earth and blockage of the radar beam by mountainous terrain.

An MPAR network like that envisioned in the JAG/PARP report may be able to economically replace the current weather and aircraft surveillance system, and possibly enhance its capabilities while lowering life-cycle costs, but it will not be the entire national weather and aircraft surveillance solution. A number of DOD and DHS systems are currently used to help meet NAS surveillance requirements and likely will continue to be a key part of the NAS surveillance system. Weather surveillance is supplemented by a variety of independent radar and non-radar systems. Other new sensing systems which could address portions of the national surveillance needs are also being developed, including low-power, low-cost boundary layer radars (see Box 8.1) and acoustic and lidar systems.

Consequently, any proposed MPAR system must be designed and developed as part of a larger family of systems. Economic and design tradeoffs must be considered across the entire family of systems in order to meet national surveillance requirements by the most economic means.

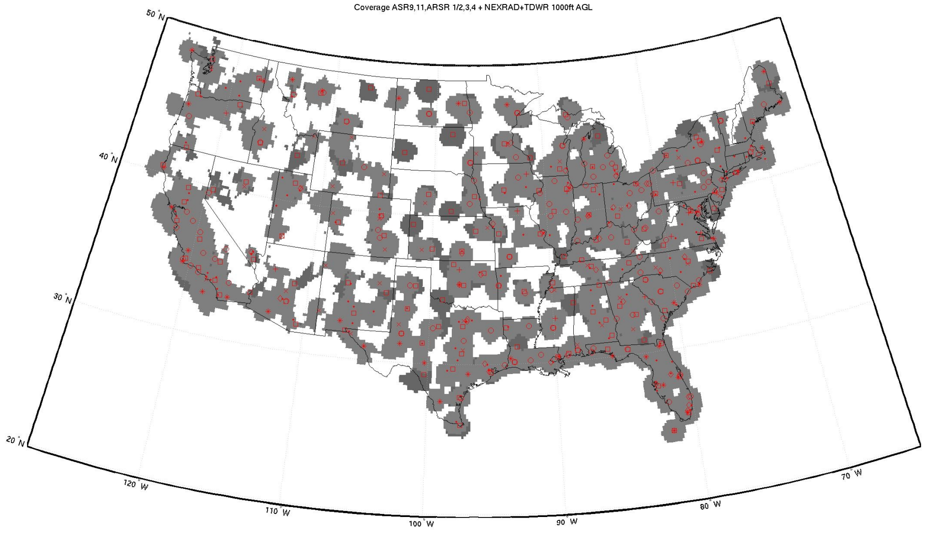

FIGURE 8.1. CONUS coverage at 1000 ft AGL for the combined WSR-88D, TDWR, ASR, and ARSR systems. Source: Weber, 2007; printed with permission from the American Meteorological Society.

Recommendation: MPAR system design studies and analysis of alternatives should consider the MPAR system as a candidate member of a family of systems, carefully considering design and mission tradeoffs with existing and new surveillance capabilities under development. Agencies must define clearly the role that MPAR will play toward meeting their needs and identify the supplemental sensing networks required to fully meet their needs.

BOX 8.1
Low-altitude coverage

A fundamental limitation of any network comprising widely-spaced radars is the inability to comprehensively cover the lowest regions of the troposphere, owing to both the curvature of the earth and terrain blockage. The solid curves in Figure 8.2 show the percentage of the volume in a thin layer at various heights above ground level covered versus radar spacing, assuming a smooth earth. At 230 km separation, which is the approximate spacing of the NEXRAD radars in the eastern half of the United States, coverage is nearly complete at a height of 3000 m but decreases to less than 10 percent at 300 m above ground level.

Denser radar placement can overcome this limitation, but larger numbers of radars would be needed in the network, as shown in the dashed line in the figure. Achieving comprehensive coverage down to 300 m, for example, would require a network of several thousand radars spaced tens of kilometers apart. Realizing such a network cost effectively would require substantial reductions in radar acquisition, siting and recurring costs compared to today's radars. The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), an Engineering Research Center chartered by the National Science Foundation, is investigating the feasibility of small low-cost radars and the associated software architecture and data handling issues that would enable future deployment of such networks (McLaughlin et al., 2007).

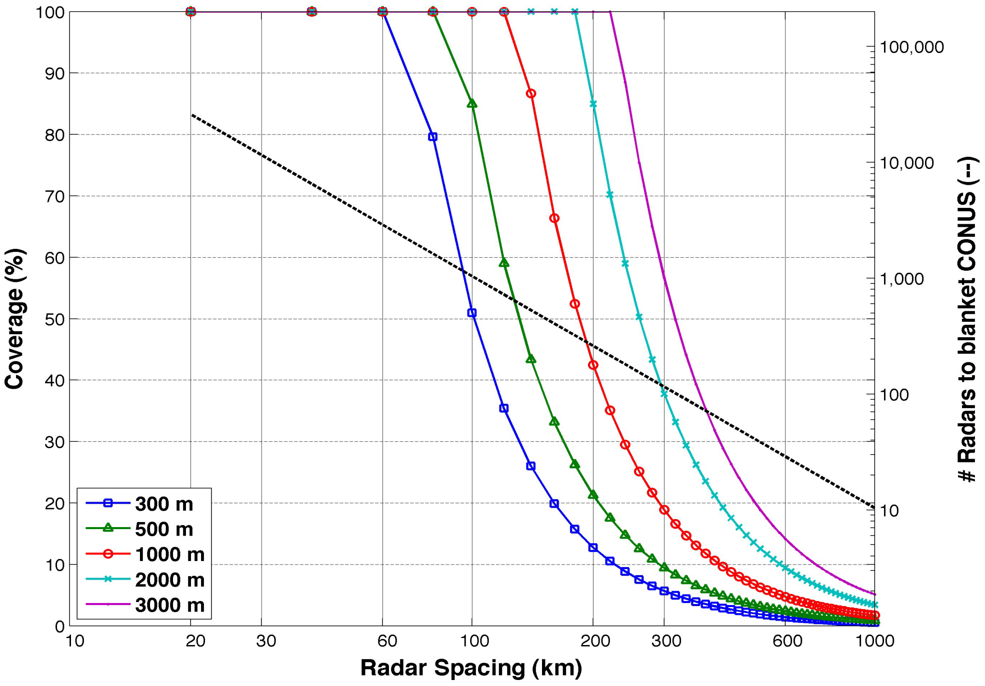

FIGURE 8.2. Volume coverage at different heights (solid lines) and number of radars needed for CONUS coverage versus radar spacing (calculations based on smooth earth).

9

Concluding Thoughts

PRINCIPAL FINDINGS

Phased array technology offers significant technical advantages for a next generation of weather and aircraft surveillance radars. A national implementation of approximately 350 Multifunction Phased Array Radar (MPAR) radars could replace existing National Weather Service (NWS) and Federal Aviation Administration (FAA) radars and offer many performance advantages. Technical, operational, and cost issues remain to be resolved. There are, however, some agency mission requirements that cannot be met by replacement of existing radars. These agency mission requirements relate primarily to low-level weather coverage and the ability to detect and track low-level, non-cooperative aircraft.

The committee agrees generally with the five major findings in the Executive Summary of the Joint Action Group/Phased Array Radar Project (JAG/PARP) report (see Box S.1), with some exceptions. Regarding finding 2, the committee notes that some emerging requirements cannot be met with a network of 334 MPAR radars, because there will be significant gaps in low-level and regional coverage. Regarding finding 4, the committee believes that the "preliminary cost evaluation" is promising, but embryonic. In addition, the basis for determining cost effectiveness of MPAR does not consider the cost effectiveness of other alternatives to the legacy systems, as well as the legacy systems themselves. Similarly, regarding finding 5, the MPAR risk reduction program will also provide a basis for cost-benefit comparison to the other alternatives to legacy systems.

The committee also agrees generally with Recommendations 1-4 in the Executive Summary of the JAG/PARP report (see Box S.2) but notes that even though Recommendation 4 calls for the Federal Committee for Meteorological Services and Supporting Research (FCMSSR) to direct a cost-benefit analysis of the MPAR option and competing domestic strategies in conjunction with the MPAR risk-reduction program, this analysis is not explicitly found in Appendix D (the program plan). However, the Terms of Reference of the Working Group –MPAR[1] (WG/MPAR Item 3b; OFCM, 2007) direct the WG to "[Perform] a cost benefit analysis to establish MPAR's cost-effectiveness against alternative domestic radar options, considering both acquisition and total life-cycle costs." For the JAG/PARP research plan to be effective, defined requirements and a national system architecture are required that will allow cost-benefit tradeoffs to drive the establishment of focused research objectives. The committee also believes that *independent* identification of alternative domestic radar strategies is needed.

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[1] Available at *www.OFCM.gov*

A thorough and independent cost-benefit analysis of MPAR and those alternatives would be in the nation's best interest.

OVERARCHING RECOMMENDATION

The committee recommends that the MPAR R&D program be continued with the objective of evaluating the degree to which a deployable MPAR system can satisfy the national weather and air surveillance needs cost-effectively. This program should incorporate the following features:

- Full evaluation of the unresolved technical issues.
- An evaluation of the full operational requirements of all participating agencies and the ability of MPAR to meet these requirements.
- Development of the basis for reliable and realistic estimates of acquisition and lifecycle costs of a nationally deployed MPAR System.
- Independent assessment of the cost effectiveness of the R&D program itself, especially prior to commitment of major funding for the full-scale prototype.

References

The Aerospace Corporation. 2004. Future Weather Doppler Radar Feasibility Study. Chantilly, VA and El Segundo, CA.

Anderson, T.P and J.S. Cherwonik. 1997. Cost Estimating Risk and Cost Estimating Uncertainty Guidelines. *Acquisition Review Quarterly – The Journal of the Defense Acquisition University* 4(3): 339-348.

Anderson, T.P. 2004. NRO Cost Group Risk Process. The Aerospace Corporation, 72nd Military Operations Research Society Symposium, Monterey, CA.

Anderson, T.P. 2008. Why Initial Cost Estimates are (Almost) Always Too Low. Cost Risk Tutorial. The Aerospace Corporation, Space Systems Engineering Risk Management Symposium.

Book, S.A. 2001. Estimating Probable System Cost. The Aerospace Corporation. *Crosslink Magazine.* Available at *http://www.aero.org/publications/crosslink/winter2001/02.html.* Accessed May 8, 2008.

Briggs, B.H., G.J. Phillips, and D.H. Shinn. 1950. The analysis of observations on spaced receivers of the fading of radio signals. *Proceedings of the Physical Society* 63B: 106-121.

Brotzge, J., K.K. Droegemeier, and D.J. McLaughlin. 2006. Collaborative adaptive sensing of the atmosphere (CASA): New radar system for improving analysis and forecasting of surface weather conditions. *Journal of the Transportation Research Board* 1948: 145-151.

Cheong, B.L., M.W. Hoffman, R.D. Palmer, S.J. Frasier, and F.L. Dekker. 2006. Phased Array Design for Biological Clutter Rejection: Simulation and Experimental Validation. *Journal of Atmospheric and Oceanic Technology* 23: 585-598.

Cheong, B.L., R.D. Palmer, C.D. Curtis, T.-Y. Yu, D.S. Zrnic, and D. Forsyth. 2008. Refractivity retrieval using the Phased Array Radar: First results and potential for multi-mission operation. *IEEE Transactions on Geoscience and Remote Sensing*: in press.

Crum, T.D. and R.L. Alberty. 1993. The WSR-88D and the WSR-88D Operational Support Facility. *Bulletin of the American Meteorological Society* 74(9): 1,669-1,688.

Dockins, C., K. Maguire, N. Simon, and M. Sullivan. 2004. Value of statistical life analysis and environmental policy: A White paper. U.S. Environmental Protection Agency. Natinoal Center for Environmental Economics.

DoD (Department of Defense). 2005. Strategy for Homeland Defense and Civil Support. Washington, D.C. Available at *http://www.defenselink.mil/releases/2005/nr20050630-3843.html*. Accessed May 8, 2008.

Doviak, R.J. and D.S. Zrnic. 2006. Doppler radar and weather observations, 2nd ed., Academic Press, 562 pp.

Evans, R.C. 2004. National Air Defense: Challenges, Solution Profiles, and Technology Needs. The MITRE Corporation. Available at *http://www.mitre.org/work/tech_papers/tech_papers_04/04_1108/04_1108.pdf.* Accessed May 8, 2008.

Forecast International Inc. 2003. Forecast International Electronic Systems Forecast ARSR-4 (FPS-130) - Archived August 2003. Available at *http://www.forecastinternational.com/archive/es/es6100.doc.* Accessed July 29, 2008.

Forecast International Inc. 2003. Forecast International Electronic Systems Forecast ARSR-4 (FPS-130) - Archived August 2003. Available at *http://www.forecastinternational.com/archive/ls/FA0963.htm*. Accessed July 29, 2008.

Forsyth, D.E., J.F. Kimpel, D.S. Zrnic, R. Ferek, J.F. Heimmer, T. McNellis, J.E. Crain, A.M. Shapiro, R.J. Vogt, W. Benner. 2008. Another Update on the National Weather Radar Testbed (Phased-Array), 24th Conference on IIPS, AMS Annual Meeting, New Orleans, LA.

GAO (Government Accountability Office). 2006a. Geostationary Operational Environmental Satellites. Steps Remain in Incorporating Lessons Learned from Other Satellite Programs. GA0-06-993.

GAO. 2006b. Air Traffic Control Modernization. Status of the Current Program and Planning for the Next Generation Air Transportation System. GAO-06-653T.

Heinselman, P.L., D.L. Priegnitz, K.L. Manross, T.M. Smith, R.W. Adams. 2008. Rapid sampling of severe storms by the National Weather Radar Testbed Phased Array Radar. *Weather and Forecasting*: in press.

Istok, M. J., P. Pickard, R. Okulski, R.E. Saffle, and B. Bumgarner. 2005. NWS use of FAA radar data – Progress and plans. Preprints, 21st Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology, San Diego, CA. *American Meteorological Society*. CD-ROM, 5.3.

ITT Industries. 1997. Multifunction radar for terminal area surveillance system TASS. Van Nuys, CA.

JPDO (Joint Planning and Development Office). 2005. Progress report on the Next Generation Air Transportation System Integrated Plan. Washington, D.C.

Le, K., R.D. Palmer, B.L. Cheong, T.-Y. Yu, G. Zhang, S. Torres. 2008. On the Use of Auxiliary Receive Channels for Clutter Mitigation on Phased Array Weather Radar. *IEEE Transactions on Geoscience and Remote Sensing*, in press.

Leone, D.A., R.M. Endlich, J. Petriceks, R.T.H. Collis, and J.R. Porter. 1998. Meteorological Considerations Used in Planning the NEXRAD Network. *Bulletin of the American Meteorological Society* 70(1): 4-13.

Mathis, RADM, M. 2003. "Emerging Threats and Challenges for Homeland Air Security". Joint Missile Defense Organization. Presentation to the National Defense Industrial Association.
http://proceedings.ndia.org/3310/JTAMDO_web_presentation.pdf

McLaughlin, D.J., E.A. Knapp, Y. Wang, and V. Chandrasekar. 2007. Distributed Weather Radar Using X-Band Active Arrays. *Proceedings of the 2007 IEEE Radar Conference*, April 17-20, 2007, pp. 23-27.

Miranda, S., C. Baker, K. Woodbridge, and H. Griffiths. 2006. Knowledge-based resource management for multifunction radar. *IEEE Signal Processing Magazine* 23(1): 66-76.

Mitra, S.N. 1949. A radio method of measuring winds in the ionosphere. *Proceedings of the Institute for Electrical Engineering* 99: 441-446.

NRC (National Research Council). 1995. Toward a New National Weather Service - Assessment of NEXRAD Coverage and Associated Weather Services. Washington, D.C.: National Academies Press.

NRC. 1999. Improving Project Management in the Department of Energy. Washington, D.C.: National Academies Press.

NRC. 2002. Weather Radar Technology Beyond NEXRAD. Washington, D.C.: The National Academies Press.

NRC. 2004. Where the Weather Meets the Road. Washington, D.C.: The National Academies Press.

NRC. 2005. Flash Flood Forecasting over Complex Terrain: With an Assessment of the Sulphur Mountain NEXRAD in Southern California. Washington, D.C.: National Academies Press.

NSTC (National Science and Technology Council). 2005. Strategic Plan for the U.S. Integrated Earth Observation System. NSTC Committee on Environment and Natural Resources, Washington, D.C. Available at *http://www.usgeo.gov/docs/EOCStrategic_Plan.pdf.* Accessed May 27, 2008.

OFCM (Office of the Federal Coordinator for Meteorological Services and Supporting Research). 2006. Federal Research and Development Needs and Priorities for Phased Array Radar. FCM-R25-2006.

OFCM. 2007. Terms of Reference – Working Group for Multifunction Phased Array Radar. Available at *http://www.ofcm.gov/wgmpar/references/WG%20MPAR%20TOR.pdf.* Accessed May 13, 2008.

OMB. (Office of Management and Budget). 2006. Capital Programming Guide V 2.0 Supplement to Office of Management and Budget Circular A-11, Part 7: Planning Budgeting and Acquisition of Capital Assets. Available at *http://www.whitehouse.gov/omb/circulars/a11/current_year/part7.pdf.* Accessed on May 8, 2008.

Palmer, R.D., S. Gopalam, T.-Y. Yu and S. Fukao. 1998. Coherent Radar Imaging Using Capon's Method. *Radio Science* 33(6): 1,585-1,598.

Ryzhkov, A.V., T.J. Schuur, D.W. Burgess, P.L. Heinselman, S.E. Giangrande, and D.S. Zrnić. 2005. The Joint Polarization Experiment. Polarimetric rainfall measurements and hydrometeor classification. *Bulletin of the American Meteorological Society* 86: 809-824.

Serafin, R.J. and J.W. Wilson. 2000. Operational Weather Radar in the United States: Progress and Opportunity. *Bulletin of the American Meteorological Society* 81(3): 501-508.

Skolnik, M.L. 2001. Introduction to Radar Systems. 3rd edition, McGraw Hill.

Vasiloff, S.V. 2001. Improving tornado warnings with the Federal Aviation Administration's Terminal Doppler Weather Radar. *Bulletin of the American Meteorological Society* 82(5): 861-874.

Weber, M., J. Cho, J. Flavin, J. Herd, and M. Vai. 2005. Multi-function phased array radar for U.S. civil-sector surveillance needs. in 32nd Conference on Radar Meteorology, 24-29 October, Albuquerque, NM. *American Meteorology Society*. Available at *http://ams.confex.com/ams/pdfpapers/96905.pdf.* Accessed on May 8, 2008.

Weber, M.E., J.Y.N. Cho, J.S. Herd, J.M. Flavin, W.E. Benner, and G.S. Torok. 2007. The Next-Generation Multimission U.S. Surveillance Radar Network. *Bulletin of the American Meteorological Society* 88(11): 1,739–1,751.

Westrick K.J., C.F. Mass, and B.A. Colle. 1999. The limitations of the WSR-88D radar network for quantitative precipitation measurement over the coastal western United States. *Bulletin of the American Meteorological Society* 80: 2,289–2,298.

Whiton, R.C., P.L. Smith, S.G. Bigler, K.E. Wilk, and A.C. Harbuck. 1998. History of Operational Use of Weather Radar by U.S. Weather Services. Part II: Development of Operational Doppler Weather Radars. *Weather and Forecasting* 13: 219–252.

Wiliamson S., Weadon M. and Welshinger M. 2008. Evaluation of the Multifunction Phased Array Radar Planning Process. Presentation to the NRC committee, Washington, DC, January 14, 2008.

Yu, T., M. B. Orescanin, C. D. Curtis, D. S. Zrnic, and D. E. Forsyth. 2007. Beam multiplexing using the phased-array weather radar. *Journal of Atmospheric and Oceanic Technology* 24: 103–118.

Zhang, G. and R.J. Doviak. 2007. Spaced-antenna interferometry to measure crossbeam wind, shear, and turbulence: Theory and Formulation. *Journal of Atmospheric and Oceanic Technology* 24: 791-805.

Zhang, G. and R.J. Doviak. 2008. Spaced-antenna interferometry to detect and locate sub-volume inhomogeneities of reflectivity: an analogy with monpulse radar. *Journal of Atmospheric and Oceanic Technology*, in press.

Zhang, G., R.J. Doviak, D. Zrnic, J. Crain. 2008. Phased array radar polarimetry for weather sensing: Challenges and opportunities, IGARS, Boston, MA, July 6-11, 2008.

Zrnic, D.S., J. F. Kimpel, D.E. Forsyth, A. Shapiro, G. Crain, R. Ferek, J. Heimmer, W. Benner, T.J. McNellis, R.J. Vogt. 2007. Agile beam phased array radar for weather observations. *Bulletin of the American Meteorological Society* 88: 1,753-1,766.

Appendixes

Appendix A

STATEMENT OF TASK

The study committee will evaluate the planning to date related to continued development of multifunction phased array radar (MPAR). The committee will consider the report *Federal Research and Development Needs and Priorities for Phased Array Radar* issue in June 2006 by a Joint Action Group (JAG) of the Office of the Federal Coordinator for Meteorology (OFCM); information from an MPAR Symposium to be hosted in part by the OFCM in October 2007; and other information about the MPAR planning process. Examples of the issues to be addressed include:

- Has the planning process to date been comprehensive and inclusive?
- Does the JAG report identify the full range of benefits, costs, challenges, and potential participants (weather information as well as information useful to other purposes such as observations of dust, smoke, hazardous dispersions, aircraft surveillance)?
- Are the cost estimates provided to date realistic? Do they represent the best available information? Are there any potential life-cycle benefits or costs that are not considered?
- Are there are any significant gaps or errors in the initial planning?
- Have appropriate areas of uncertainty been identified and follow-on risk assessments conducted?
- Based on the information available, should the MPAR planning process go forward and, if so, what improvements might be recommended?

The committee will prepare a concise report of its evaluation of the MPAR planning process to date, as evidenced through briefings, the JAG report, the MPAR October 2007 symposium, and other information, and will include guidance on future directions.

Appendix B

ACRONYM LIST

ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance- Broadcast
AESA	Active Electronically Steered Array
AGL	Above Ground Level
AMS	American Meteorological Society
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
BMX	Beam Multiplexing
CAIV	Cost as an Independent Variable
CASA	Center for Collaborative Adaptive Sensing of the Atmosphere
CBA	cost-benefit analysis
CONUS	Contiguous United States
CRAFT	Collaborative Radar Acquisition Field Test
DHS	Department of Homeland Security
DOD	Department of Defense
DOD/AF	Department of Defense/ Air Force
DOE	Department of Energy
FAA	Federal Aviation Administration
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FHWA	Federal Highway Administration
GAO	Government Accountability Office
ITT	International Telephone & Telegraph
JAG	Joint Action Group
JAWG	Joint Agency Working Group
LRU	Line Replaceable Unit
MPAR	Multi-function Phased Array Radar
MRCR	mechanically rotating conventional radar
NAS	National Air Space
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Radar
NOAA	National Oceanographic and Atmospheric Administration
NORAD	North American Air Defense
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
NSSL	National Severe Storms Laboratory
NSTC	National Science and Technology Council
NWP	Numerical Weather Prediction
NWRT	National Weather Radar Testbed

NWS	National Weather Service
O&M	Operations and Maintenance
OFCM	Office of the Federal Coordinator for Meteorology
OMB	Office of Management and Budget
OU	University of Oklahoma
PAR	Phased Array Radar
PARP	Phased Array Radar Project
QPE	Quantitative Precipitation Estimation
R&D	Research and Development
RF	radio frequency
SAI	Space Antenna Interferometry
SLC	Sidelobe Clutter Cancellation
SNR	Signal-to-noise Ratio
TASS	Terminal Area Surveillance System
TDWR	Terminal Doppler Weather Radar
T/R	transmit/receive
WG	Working Group
WSR-88D	Weather Surveillance Radar-1988 Doppler

Appendix C

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS AND STAFF

Committee Members

Dr. Paul Smith (Chair) has been at the School of Mines since 1966. He started as a research engineer in IAS, working his way up the ladder as chief engineer to engineering group head and senior scientist, to become the Director of the Institute in 1981. He served in that position until 1996, at which time he retired from full-time duties. Dr. Smith also was named the Facility Manager for the National Science Foundation supported T-28 Research Aircraft Facility, which was housed at the Institute of Atmospheric Sciences, and served in that position from 1985 to 2005. He has taught radar meteorology, physical meteorology, and microwave engineering. Dr. Smith's major research interests are in Radar Meteorology, Cloud Physics, and Weather Modification. He chaired the NRC's Committee to Assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain, California and also the Committee on Weather Radar Technology Beyond NEXRAD. Paul Smith has received the Award for Meritorious Civilian Service, USAF Air Weather Service (1975); the Editor's Award, Journal of Applied Meteorology, American Meteorological Society (1992); the Thunderbird Award, Weather Modification Association (1995), and was named a National Associate by the National Research Council (2004). He was selected as the American Meteorological Society's Remote Sensing Lecturer for 2006. Dr. Smith has more than 70 refereed publications in engineering and scientific journals or books and presented more than 100 papers at professional society meetings.

Mr. James Frost Davis is a Senior Project Engineer with The Aerospace Corporation in Chantilly, Virginia. He has spent 27 years in various positions in the private and academic sectors engaging in engineering research, testing and development, strategic planning, market research, technology assessment, and project management. Prior to joining The Aerospace Corporation, he held positions at Arthur D. Little, Inc., MIT Lincoln Laboratory, and IBM Corp. In his current position, he focuses on systems engineering and analysis of distributed electronic sensor systems, advanced concept development, experimental satellite architecture and payload development, systems architecture for space- and ground-based systems and services, and civil and commercial business development. Mr. Davis holds a B.Sc. (Hons) in Mechanical Engineering from the Imperial College of Science and Technology, University of London (UK, 1980), M.S. Degrees from the Georgia Institute of Technology in Mechanical Engineering (1983) and Electrical Engineering (1986), and a Master of Science in Management Degree from the Arthur D. Little School of Management (1996).

Dr. Eastwood Im is currently the Manager of the Earth Science Instruments and Technology Office at NASA's Jet Propulsion Laboratory. He has extensive experience in spaceborne meteorological radar science remote sensing, radar design and advanced technology. Dr. Im was the first instrument architect of the multi-functional radar for the Cassini Mission to Saturn during the pre-project phase (1987-1991), and went on to become the system engineer of that instrument until its launch in 1997. He was the CloudSat radar instrument manager from inception through the end of the first year of flight operations (1998-2007). Dr. Im has been a member of NASA's Tropical Rainfall Measuring Mission Science Team and the Precipitation Measurement Missions Science Team, focusing on the studies of advanced radar techniques and algorithms for precipitation and cloud parameter retrievals and calibration. Since 1998, Dr. Im has been the Principal Investigator of several NASA studies, developing new radar technologies for future spaceborne atmospheric science missions. Dr. Im is an Institute of Electrical and Electronics Engineers (IEEE) Fellow. He is recipient of the NASA's Exceptional Technology Achievement and Exceptional Engineering Achievement Medals, and JPL's Explorer Award and Awards of Technical Excellence. He received his Ph.D. from University of Illinois in electrical engineering.

Dr. Jeffrey K. Lazo is Director of the Collaborative Program on the Societal and Economic Benefits of Weather Information (the Societal Impacts Program) at the National Center for Atmospheric Research (NCAR). The Societal Impacts Program aims to improve the societal gains from weather forecasting by infusing social science and economic research, methods, and capabilities into the planning, execution, and analysis of weather information, applications, and research directions. His research interests include nonmarket valuation, value of information, environmental economics, risk perception research, survey research, and econometric analysis. He received his Ph.D. in economics from the University of Colorado in 1993.

Dr. David McLaughlin is Professor of Electrical and Computer Engineering at the University of Massachusetts at Amherst and Director of the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA). He received his PhD from the University of Massachusetts in 1989, spent the period from 1989 through 1999 at Northeastern University, and joined the University of Massachusetts faculty in January of 2000, where he held the Armstrong Professorship in Engineering. His research interests include radar design, remote sensing and sensor networks.

Dr. Robert Palmer has a PhD in electrical engineering and holds the Tommy C. Craighead Chair in the School of Meteorology at the University of Oklahoma (OU). He is also an Adjunct Professor in the School of Electrical and Computer Engineering at OU. Dr. Palmer is Director of the interdisciplinary Atmospheric Radar Research Center (ARRC), which is the focal point for OU's weather radar research and education activities. His research interests have focused on the application of advanced radar signal processing techniques to observations of the atmosphere. Dr. Palmer has published widely in the area of radar remote sensing of the atmosphere, with an emphasis on generalized imaging problems, spatial filter design, and clutter mitigation using advanced array/signal processing techniques.

Dr. Steven A. Rutledge joined the CSU Department of Atmospheric Science in 1988 and served as the Department Head from July 1999 through December 2006. Prior to his arrival, he served on the academic faculty at Oregon State University. Professor Rutledge's research interests include mesoscale meteorology, cloud electricity, radar meteorology, and cloud physics. His current research focuses on the organization and structure of tropical convection, electrification processes in isolated convection and mesoscale convective systems, and the use of multi-parameter radar to infer hydrometeor distributions in clouds and to estimate rainfall. Professor Rutledge's research group addresses a broad range of issues associated with convection and remote sensing, including lightning in severe storms. He serves as the Scientific Director of the CSU-CHILL National Radar Facility. In 1995, he served as chair of the 27th American Meteorological Society (AMS) Conference on Radar Meteorology. He is a former member of the AMS Committees on Radar Meteorology and Cloud Physics and the NRC's Committee on Weather Radar Technology Beyond NEXRAD. He is a Fellow of the AMS and also an AMS Councilor. He also serves on the UCAR Board of Trustees and is Chair of the Board's Personnel Committee.

Dr. Scott Sandgathe has extensive experience in operational oceanography and meteorology including tropical meteorology, synoptic analysis and forecasting, and numerical weather prediction. He is a retired Navy Commander and has served onboard the USS Carl Vinson supporting battle group operations including meteorological support to radar operations and electromagnetic surveillance. Prior to joining the Applied Physics Laboratory at the University of Washington, he was the Team Leader for the Office of Naval Research Marine Meteorology and Atmospheric Effects Program where he supported research and technology development on electromagnetic propagation including support for the AEGIS SPY-1 program. His program sponsored the initial effort by Navy to develop a weather radar capability for the AEGIS SPY-1 tactical radar. He is currently technical advisor to the Navy's Tactical Weather Radar Program and Littoral Battlespace Sensing Program. His current research is in developing an automated forecast verification technique for mesoscale numerical weather prediction and working on automation and visualization tools for Navy meteorologists. Dr. Sandgathe is a Fellow of the American Meteorological Society and currently holds a top secret security clearance. Dr. Sandgathe joined the Laboratory in 2001.

Dr. Robert J. Serafin is the Director Emeritus of the National Center for Atmospheric Research (NCAR). NCAR has a staff of approximately 800, including over 200 PhD. scientists, and a budget of about $200 million annually. Serafin was responsible for the scientific and technical leadership, support programs, fiscal leadership, and management of the Center. Dr. Serafin began his career at Hazeltine Research Corporation where he worked on the design and development of high-resolution radar systems. This was followed by 10 years at the IIT Research Institute and Illinois Institute of Technology. He then joined NCAR as Manager of the Field Observing Facility in 1973 and in 1981 became director of the Atmospheric Technology Division, which is responsible for all of NCAR's observational research and research support facilities, used by scientists in universities and laboratories throughout the world. In 1989 he was appointed as NCAR's

Director. The holder of three patents, Dr. Serafin has published more than 50 technical and scientific papers in the open literature. He has also written or contributed to many reports in the classified literature early in his career. And he has contributed to many reports published by the National Academies of Science Press. He established the Journal of Atmospheric and Oceanic Technology, and was its co-Editor for several years. He has served on and chaired many National Research Council (NRC) panels and committees. Serafin chaired the NRC committee on National Weather Service Modernization and a committee that provides advice to the National Weather Service, the Federal Aviation Administration, and the U.S. Air Force on their Doppler weather radar system. He recently served on the NRC's Space Studies Board and its Executive Committee and as chair of the NRC's Board on Atmospheric Science and Climate. The topics of recent NRC committee reports have been homeland security, weather modification science, NASA's strategy for earth system science, weather radar, and U.S. space science policy. He is a member of the National Academy of Engineering (NAE), a Fellow and Past-President of the American Meteorological Society (AMS), and a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). In the private sector Serafin has served on several boards and currently chairs the board of a small high tech company in Boulder, CO. He also serves on the board of the UCAR (University Corporation for Atmospheric Research) Foundation and two companies founded by the Foundation. Dr. Serafin received the BS, MS, and PhD degrees in Electrical Engineering from Notre Dame University, Northwestern University, and Illinois Institute of Technology, respectively.

Dr. Marilyn M. Wolfson holds the B.S. (honors) in Atmospheric and Oceanic Science from the University of Michigan and the S.M. from M.I.T., where she was named an Ida M. Green Fellow. She began work at Lincoln Laboratory in 1983 and later returned to M.I.T. as a Lincoln Staff Associate, graduating with the Ph.D. in 1990. She applied her thesis work in developing a real-time microburst prediction algorithm which is currently operational in the FAA's Integrated Terminal Weather System. Dr. Wolfson began development of automated short-term convective weather forecasts for air traffic management applications in 1996, as leader of the FAA Aviation Weather Research Program's Convective Weather Product Development Team. She has patented and licensed the technology needed to make accurate 1-2 hr storm forecasts, and has transferred this technology to FAA, having the pleasure of seeing it debut operationally in 2006 as part of the Integrated Terminal Weather System. She now serves as assistant leader of the Weather Sensing Group directing their weather research efforts. The group is currently operating the Corridor Integrated Weather System for the FAA and is interested in increasing the year-round accuracy of the forecast products, as well as increasing the lead time to 8 hrs and beyond. Understanding and anticipating the impact of the forecasts on air traffic capacity and demand are important next steps in her group's research, as is the eventual coupling of the forecasts to automated aids to traffic flow management. Dr. Wolfson has received the American Meteorological Society Editor's Award for her work on the Monthly Weather Review journal, and in 2005 received the Lincoln Laboratory Technical Excellence award for her work in the application of meteorology to the problem of improving air traffic control and for her national level role in the application of advanced convection weather forecasts for use in the aviation community. She has served on the NRC's National Weather Service Modernization Committee, the Committee on Meteorological Analysis, Prediction and Research, and the Committee for a Workshop on Weather Forecasting Accuracy for FAA Air Traffic Control.

NRC Staff

Dr. Curtis H. Marshall is a Program Officer with the Board on Atmospheric Sciences and Climate. He received B.S. (1995) and M.S. (1998) degrees in meteorology from the University of Oklahoma, and a Ph.D. (2004) in Atmospheric Science from Colorado State University. His Doctoral research, which examined the impact of anthropogenic land-use change on the mesoscale climate of the Florida peninsula, was featured in *Nature* and the *New York Times*. Prior to joining the staff of BASC in 2006, he was employed as a research scientist in the National Oceanic and Atmospheric Administration. Since joining the staff of BASC, he has directed peer reviews for the U.S. Climate Change Science Program and directed or supported a number of studies, including the development of mesoscale meteorological observing systems, multifunction phased array weather radar, the NPOESS spacecraft and ESAS Decadal Survey, and the impacts of climate change on human health.

Ms. Katherine Weller is a Senior Program Assistant for the Board on Atmospheric Sciences and Climate (BASC) and the Polar Research Board (PRB). In 2004, she received her B.S. from the University of Michigan in Biopsychology. Ms. Weller is currently working toward a master's degree in Environmental Science and Policy at Johns Hopkins University.