1 INTRODUCTION

1.1 Historical Evolution of Radar Applications

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

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

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

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

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

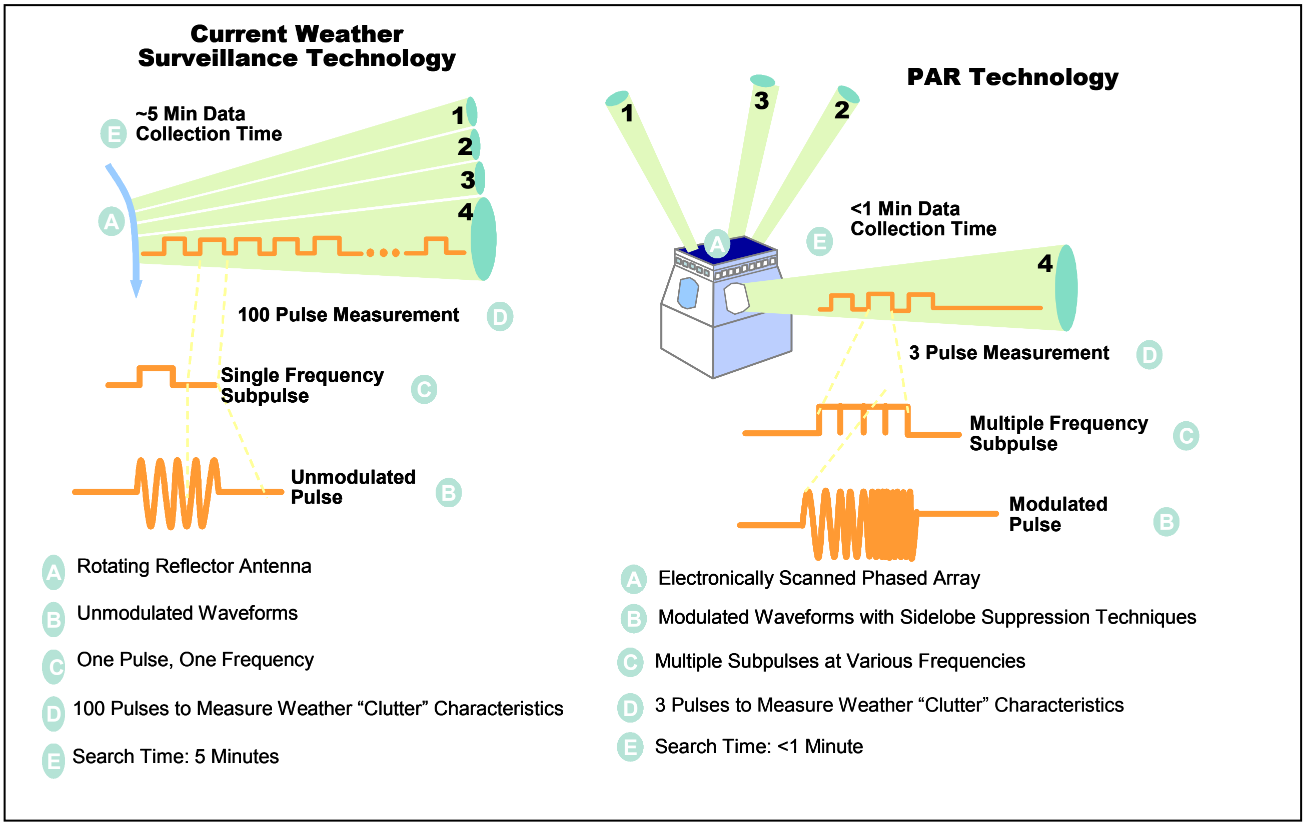

Figure 1-1. Basic differences between a mechanically rotating conventional radar (left) and MPAR (right).

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

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

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

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

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

1.2 Federal Civilian Agency Interest in Phased Array Radar

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

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

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

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

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

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

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

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

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

1.3 The Joint Action Group for the Phased Array Radar Project

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

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

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

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

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

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

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

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

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

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

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

1.4 Report Purpose and Structure

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

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

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

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

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