Multi-function Phased Array Radar and Cylindrical Polarized Phased Array Radar

Report to Congress

Prepared by National Oceanic and Atmospheric Administration
National Severe Storms Laboratory

The U.S. House of Representatives Committee on Appropriations issued House Report 113-171, which accompanied the Consolidated Appropriations Act, 2014 (P.L. 113-76). The report states, "…The Committee understands that NOAA [National Oceanic and Atmospheric Administration]'s MPAR [Multi-function Phased Array Radar] research, and in particular the dual polarization combined with phased array technology, is critical to the future of weather forecasting. The recommendation includes $13,000,000 for these activities. Within this amount, NOAA is encouraged to continue research on cylindrical polarimetric phased array radar (CPAR) and provide a report to the Committee no later than 180 days after the enactment of this Act on research activities related to MPAR and CPAR."

The U.S. Senate Committee on Appropriations issued Senate Report 113-78, which accompanied the Consolidated Appropriations Act, 2014 (P.L. 113-76). The report states, "…The bill includes $13,024,000 for continued development of the multi-function phased array radar [MPAR], the same as the budget request. When completed, this system has the potential to significantly extend lead times for detecting severe and hazardous weather. A promising MPAR design that combines dual polarization with phased arrays is the Cylindrical Polarimetric Phased Array Radar [CPPAR]. The Committee directs NOAA to submit a report to the Committees on Appropriations within 120 days after enactment of this act that provides a research plan for developing a full-scale prototype of CPPAR including the full cost of the project, detailed research goals, and a plan and timeline for possibly transitioning the technology from research to operations."

Introduction

The MPAR program is an initiative to combine the operational radar functions of several national networks and have them served by a single radar system delivering the required performance for aircraft and weather surveillance. Phased array radars are considerably more complex than the typical reflector dish antenna in widespread use today. A phased array radar is an array of antenna elements that is able to direct the radiation pattern by electronically changing the timing of the respective signals feeding the antenna elements. Phased array radars provide many performance and operational benefits, which are detailed below, over the mechanically steered dish antenna radars.

Phased array radar technology was developed for military applications and has been around for decades. The MPAR program began over 10 years ago when a military SPY-1A phased array radar was installed at NOAA's National Severe Storms Laboratory (NSSL). This National Weather Radar Testbed Phased Array Radar (NWRT/PAR) has been modified to provide faster updates and perform adaptive scanning strategies to demonstrate the value of improved radar observations. Recent research has demonstrated the potential benefits of rapid scan radar data when issuing warnings for severe and hazardous weather[1]. The NWRT/PAR has recently been modified to perform simultaneous aircraft and weather surveillance, demonstrating multi-function operation.

There has been an ongoing collaboration between NOAA and the Federal Aviation Administration (FAA) for over 10 years to perform research activities and related concept and technology development. These activities have concentrated on dual polarization capability for phased array radars, investigating how to meet the simultaneous multi-function mission performance requirements and reducing the cost.

Benefits of MPAR

MPAR will combine the different functions of various radar networks into a single multi-function network. There are separate radar networks for terminal-area aircraft surveillance (the Air Surveillance Radar (ASR) family), terminal-area weather (the Terminal Doppler Weather Radar (TDWR)), long-range aircraft surveillance (the Air Route Surveillance Radar (ARSR) family), and finally long-range weather (Weather Surveillance Radar – 1988 Doppler (WSR-88D)). Each of these radar networks performs a single mission and has its own management, maintenance, training, and supply logistics programs. There are roughly 550 radars (approximately 230 ASRs, approximately 45 TDWRs, approximately 120 ARSRs, and approximately 155 WSR-88Ds) in these combined networks, and that number would increase if Department of Defense (DOD) terminal aircraft surveillance radars were added.

Phased array radar technology is the only known technology available that could possibly meet the combined requirements of all the existing radar networks and any evolutionary requirements throughout its lifecycle. The working concept is that the approximately 550 current radars of multiple designs would be replaced by a single radar network of approximately 365 MPAR radars providing the same or better coverage for all missions. A fewer number of MPAR radars would be required since many of the existing single-function radars are nearly co-located with overlapping coverage areas. As the existing radars become obsolete and/or require extensive service life extension programs to maintain operations, it is expected that a reduced capital expenditure will be required to replace the legacy infrastructure with MPAR[2].

An MPAR deployment would also eliminate redundant maintenance, training, and supply logistics programs of multiple networks. The reduced operations and maintenance costs of a single phased array radar network (due to factors such as no moving parts) could also reduce the overall system life-cycle costs of the radar program and improve radar availability. Earlier analysis by the Office of the Federal Coordinator for Meteorology (OFCM) estimated that MPAR could save nearly $2 billion in radar procurement costs and $3 billion in life-cycle savings over 30 years of operation if MPAR is used to replace the legacy radar networks[2]. These

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[1] Heinselman, P. L., D. S. LaDue, H. Lazrus, 2012: Exploring Impacts of Rapid-Scan Radar Data on NWS Warning Decisions. *Weather and Forecasting*, **27**, p1031–1044.

[2] OFCM, 2006: Federal research and development needs and priorities for phased array radar. Rep. FMC-R25-2006, Interdepartmental Committee for Meteorological Services and Supporting Research, Committee for Cooperative Research Joint Action Group for Phased Array Radar Project, 62 pp. [Available online at www.ofcm.gov/r25-mpar/fcm-r25.htm]

potential cost savings do not factor in the increased performance benefits of MPAR over the current radar networks, which would add even greater value for an MPAR deployment.

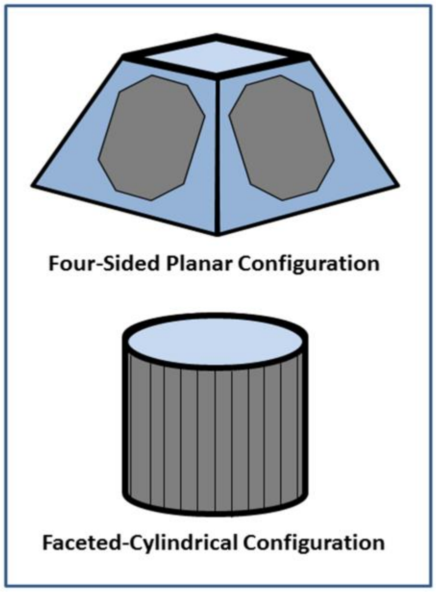
MPAR Partners

The MPAR program research activities are jointly planned, funded, managed, and executed by NOAA and FAA. In addition, there are several academic research institutions (including the University of Oklahoma Advanced Radar Research Center (OU/ARRC), Georgia Tech Research Institute, and Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL)) performing research, developing technology, or providing support to the government in current research activities. The NOAA and FAA research program has also funded activities with several radar development companies (Ball Aerospace, Lockheed Martin Corporation, Northrop Grumman Corporation, Raytheon Company, and Saab Sensis Corporation) to perform engineering studies and develop conceptual designs.

The MPAR Executive Council and MPAR Working Group is comprised of representatives from NOAA, FAA, DOD and the U.S. Department of Homeland Security (DHS) and supported and administered by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM). The Executive Council and Working Group meet quarterly to discuss progress and plans regarding MPAR.

MPAR Geometry

The MPAR program is still conducting research to determine which physical geometry would be better suited to meet MPAR performance requirements. The gray areas represent the location of the phased array antennas. The antennas are made up of many smaller panels.



The four-sided configuration has a planar array on each side of the truncated pyramid. Each face of the array may be operated independently during scanning.

The faceted-cylindrical configuration has antenna panels on each facet surrounding the structure. Four phased array antennas can be electronically formed by dividing the cylinder into arbitrary quadrants during scanning.

Recent and Planned Research Activities

The NWRT/PAR system is based on phased array radar technology that is several decades old, so the MPAR program has been funding research into developing and employing more modern technology. Dual polarization is one of the new technologies that is being implemented on phased array radars and is a critical element for MPAR based on NOAA's experience with the recent upgrade of the WSR-88D to dual polarization. Phased array radars may be configured in many different geometries, but the MPAR program has determined that either a four-sided planar array or a faceted-cylindrical array would provide the best overall performance versus cost. The MPAR program has funded the development of two small-scale engineering technology demonstration systems (one planar array and one cylindrical array) that will be evaluated in early 2015. These demonstration systems will be used to evaluate dual polarization performance, calibration techniques, and scanning strategy development for planar and cylindrical array configurations.

A budget increase in Fiscal Year (FY) 2014 was provided to replace the older technology of the NWRT/PAR system with modern dual polarization phased array radar technology. This Advanced Technology Demonstrator (NWRT/ATD) will be a single-face planar array capable of demonstrating multi-function operation using modern, dual polarization technology and allow the MPAR program to perform the analysis necessary to make key investment decisions. This three-year development effort is jointly funded by NOAA and FAA and is estimated to cost approximately $18 million. The NWRT/ATD should be ready for evaluation and testing in FY 2017.

The concept of a Cylindrical Polarized Phased Array Radar (CPPAR) was first proposed by Zhang et al. in 2011[3]. A preliminary conceptual design for a full-scale CPPAR demonstrator has been proposed by OU/ARRC but is not feasible within the current program budget and time-line. The CPPAR proposal is a four-year effort with a cost estimate between $28 million and $32 million for a full-scale demonstrator that incorporates an advanced, all-digital system architecture. A smaller effort to develop a single panel of the all-digital design would be beneficial to evaluate the capabilities of the all-digital design prior to considering a full-scale demonstrator, but additional funding would still be needed to complete the development and evaluation before the key investment decisions are planned. There are other advantages and challenges of the cylindrical geometry, as well as the all-digital system architecture that need further investigation. Nevertheless, a full-scale demonstrator of the CPPAR design would be necessary to resolve all issues with the cylindrical concept prior to production.

A more in-depth review of the current and ongoing MPAR research activities are discussed in the addendum. There are research questions remaining surrounding the preferred geometry (four-sided planar vs. faceted cylindrical) of the array and other system architecture details that are still being investigated.

Considerations for MPAR Deployment

The MPAR program is still in the risk reduction and research and development phase. There are many design decisions that must be made before baseline architecture and system design can be defined. Many of the final design decisions will not be made until all of the participating agencies define their operational requirements and begin an acquisition program in or around 2020. Phased array radar technology promises enhanced benefits compared to the reflector dish radar technology employed by current radars, but there remain technical considerations and cost/performance trade-offs that will have a significant impact on the affordability of an MPAR system.

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[3] Zhang, G., R. J. Doviak, D. S. Zrnic, R. Palmer, L. Lei, 2011: Polarimetric Phased Array Radar for Weather Measurement: A Planar or Cylindrical Configuration? *Journal of Atmospheric and Oceanic Technology*, **28**, p63–73.

The MPAR program continues to investigate the performance and cost trade-offs associated with the physical geometry (multi-face planar versus faceted-cylindrical), system architecture (analog sub-array beamforming versus all-digital beamforming), and performance characteristics (such as peak power, sensitivity, antenna beamwidth and side-lobes, mission specific update times, etc.). These factors contribute to the cost of phased array radar technology, and the trade-offs between performance and cost will impact the final MPAR design.

Agencies participating in an MPAR acquisition must finalize their radar requirements before any implementation design can be finalized. The NOAA National Weather Service (NWS) and the FAA have already begun documenting their anticipated future radar requirements. Agency requirements will impact design considerations and complexity of the system, which will then determine the ultimate cost of the MPAR production. Combining agency requirements into a single radar system will increase design complexity, but the associated cost concerns are expected to be mitigated by the reduced costs for operating and maintaining a network of phased array radars, in addition to the reduced number of radars needed to satisfy the radar coverage necessary to meet the requirements of all agencies.

The final decision on MPAR design is still several years in the future and will need to be coordinated with the agencies (to-be-determined) participating in the procurement contract. It is expected that there would then be a multi-year development effort for industry to build and test a prototype MPAR and ensure that it meets all the government requirements prior to making a decision on full deployment. Fabrication, assembly, and installation of approximately 365 MPAR radars could then take an additional 10-15 years based on current industry estimates.

Conclusion

The MPAR program has the ambitious goal of combining the operational radar missions of NOAA, FAA, DOD, and DHS into one scalable multi-function radar system to meet the requirements of all agencies. Phased array radar technology is the only known practical means for a single radar to perform both the weather surveillance and aircraft tracking missions simultaneously to the satisfaction of all agencies.

The NWRT/PAR has clearly demonstrated the potential for phased array radar to perform simultaneous weather surveillance and aircraft tracking. The evaluation and testing of the dual polarization technology demonstrations planned for 2015 will provide valuable insight toward the implementation of dual polarization technology on phased array radars. Additional studies or technology demonstrations may be required to mitigate any remaining risk with dual polarization on phased array radars.

Completion of the planned NWRT/ATD upgrade is also necessary to further MPAR development and testing. Furthermore, exploration of a full-scale CPPAR proof-of-concept system should be considered to further identify whether the comparative technical risks of both planar and cylindrical phased array radar designs have been mitigated.

Other design factors and cost-versus-performance trade-offs need to be evaluated before a final MPAR design can be made. The MPAR program is still in the research and development stage and it is premature to make the final design decisions before the participating agencies have defined their operational requirements.

Addendum

Technical Discussion of Multi-Function Phased Array Radar and Cylindrical Polarized Phased Array Radar Research Activities

Background

MPAR research has been aimed at answering some of the fundamental questions of how an MPAR system would be engineered to meet current and future mission requirements. This research has included work to determine the best physical geometry, system architecture and other system characteristics that define operational capability. Physical geometry of the system describes the arrangement of the antennas. For an MPAR system, either a four-sided planar or faceted cylindrical formation is expected to meet current and future mission requirements. The MPAR program has commissioned the development of small-scale technology demonstrators of both planar and cylindrical designs that will be evaluated in the coming year. Additional research activities are investigating the other design considerations. Figure 1 shows the recent and ongoing MPAR research and development activities that are further described in this report.

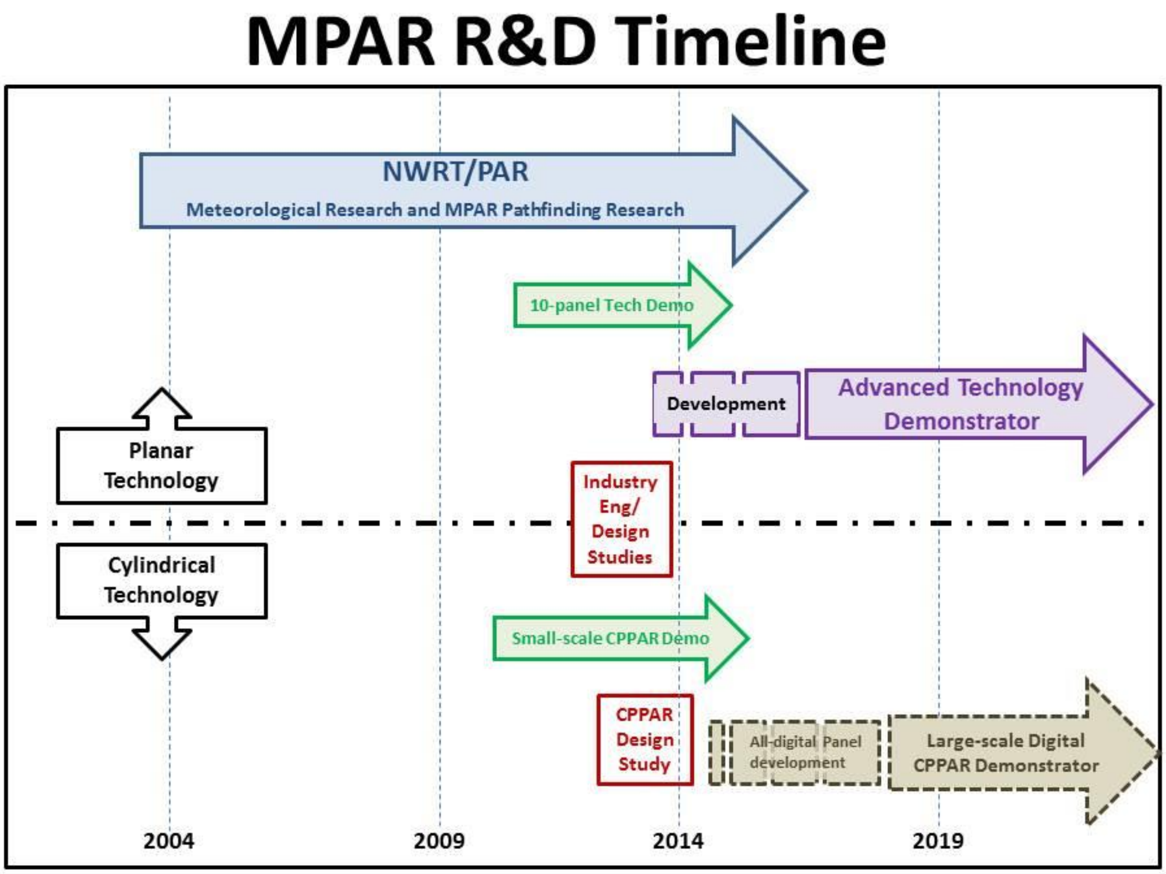

Figure 1: Recent and ongoing MPAR R&D activities that are described in this report. Arrows represent current and planned technology demonstrations (dashed arrow is not yet funded) on different scales and with different physical geometry and system architecture. Red boxes indicate paper-based engineering/design studies.

Many of the final design decisions will not be made until all the participating agencies define their operational requirements and begin an acquisition program in or around 2020. Once a contract award has been made it will take several years for industry to build candidate MPAR prototypes and demonstrate their performance. Deployment of MPAR production units may not begin until 2025 or later.

MPAR Research and Development Challenges

The MPAR Working Group has identified three key challenges in the development of MPAR: cost, dual polarization, and multi-function operation. Various activities, studies, contract awards, and technology development and demonstrations have been conducted to address these challenges.

Cost: Being able to meet expected MPAR performance measures at an affordable cost is the greatest challenge for the program. Current phased array radar technology would likely be able to meet the MPAR requirements if cost was not a concern. Potential cost reductions are being explored within the MPAR program and through collaboration with the private sector and other federal agencies. The MPAR program has funded the development and fabrication of antenna panels using commercial components and standard manufacturing technology. In addition, there has been substantial commercial activity (specifically in the smartphone/telecom sector) that has demonstrated cost reductions in production and packaging of enabling technology that would be employed by MPAR. Furthermore, the Defense Advanced Research Projects Agency (DARPA) has also recently initiated a study to develop low-cost phased array radar components that could benefit the MPAR program. There is also an effort underway at the Office of Naval Research (ONR) to develop Modular Open System Architecture technology that promises opportunities to share components across radar systems.

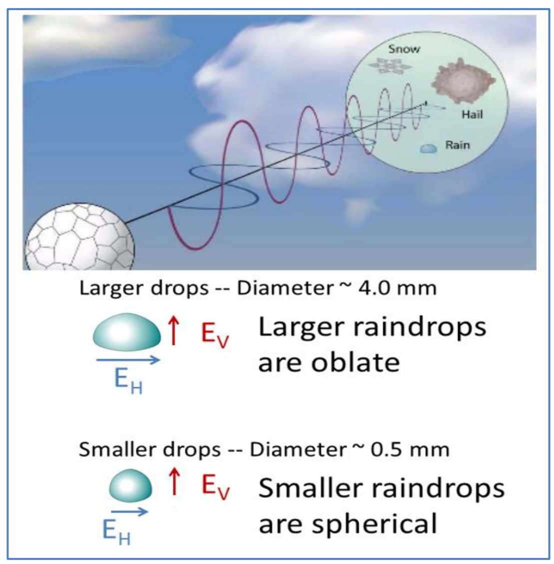

Figure 2: Dual polarization radars transmit and receive both horizontal (H, in blue) and vertical (V, in red) polarizations. The values of E_H are larger than E_V for larger drops, but they are nearly equal for smaller drops.

Dual polarization: The current long range weather radars (WSR-88D) have a dual polarization capability that has demonstrated significant contributions to weather forecasting, nowcasting, and warnings of severe and hazardous weather events. Dual polarization radars transmit energy in both the Horizontal (H) and Vertical (V) planes as illustrated in Figure 2. The signal returns from both polarizations must be isolated from each other so they do not interfere with the interpretation of the dual polarization radar data. The risk in implementing dual polarization on phased array radars is that isolating the H and V signals is much more difficult in such a large system of integrated electronics and circuitry. The information provided by dual polarization weather radar combined with other meteorological observations can provide details about the weather (such as the identification of frozen versus liquid precipitation, wet versus dry snow, and the size of hailstones) that are valuable to agency operations and public safety. For example, the ratio of the received H and V signals provides information about the size of raindrops (see Figure 2). Dual polarization data can provide additional benefits such as improved radar data quality, mitigation of ground clutter, and possible improvements to aircraft detection that would be of additional benefit to agency operations.

One of the key goals of the MPAR program is to implement dual polarization technology on phased array radars. This has not yet been demonstrated with the accuracy and precision required for weather surveillance, but is under investigation through the MPAR program. The MPAR program has funded both industry and academia to perform research directed towards the development of dual polarization technology for phased array radars. Two industry teams were awarded a dual polarization design study and another industry team was awarded a contract to develop a prototype transmit/receive element and a dual polarization antenna panel for a phased array radar. MPAR also funded two academic institutions to design dual polarization phased array radar antenna panels and to develop small-scale systems to demonstrate the technology.

Multi-function Operation: The third challenge to the development of MPAR is the capability to perform both weather surveillance and aircraft tracking missions simultaneously. Phased array radars have a long proven track record of aircraft tracking and the NWRT/PAR has demonstrated their benefits for weather surveillance. However, the operation of the radar while performing weather surveillance is significantly different than its operation while performing aircraft surveillance. An MPAR capable of performing both weather and aircraft surveillance would have to share its resources to perform both functions in a timely manner without interfering or degrading the performance of the other. Academia, industry, and NOAA/NSSL have done some preliminary research and engineering studies into how an MPAR would be operated to meet both missions.

The National Weather Radar Testbed Phased Array Radar

NSSL has been investigating the use of phased array radar for weather surveillance since 2003. Phased array radar technology was developed for military applications and has been around for decades. A SPY-1A radar system, loaned by ONR and modified by Lockheed Martin Corporation, was installed at NSSL in Norman, OK in 2003 for weather research and observations (Figure 3). This system, the NWRT/PAR, collects weather observations and has been modified to provide faster updates and perform adaptive scanning strategies to demonstrate the value of improved radar data observations.

Figure 3: The Navy SPY-1A antenna is installed in the NWRT/PAR facility at Norman, OK in 2003.

In order to investigate multi-function operation, the NWRT/PAR has recently been modified to perform aircraft surveillance and tracking interleaved with weather surveillance scans. However, the NWRT/PAR system is based on obsolescent 1970’s technology and has limited capability compared to modern phased array radars and is unable to meet the multi-function operational performance specifications that would be expected of an MPAR system. Furthermore, the NWRT/PAR is not capable of dual polarization which is a necessary requirement for weather surveillance as established by the NWS recent upgrade to the WSR-88D. Nevertheless, this multi-function demonstration on the NWRT/PAR illustrates the possibility of simultaneously performing weather surveillance and aircraft tracking. This capability will be further explored with more advanced radar demonstrators in the future.

Dual Polarization Technology Demonstrations

Though the NWRT/PAR has served as a technology demonstrator for basic phased array radar operation for weather surveillance, it is not able to or meant to demonstrate all expected MPAR requirements. In order to test dual polarization phased array radar technology with actual hardware, the MPAR program has funded two (one planar and one cylindrical configuration) small-scale dual polarization phased array radar technology demonstrators. These systems will be evaluated in early 2105 to determine whether the dual polarization phased array radar technology has made satisfactory progress.

Dual polarization phased array radars must maintain electronic isolation between the H and V channels while scanning electronically in both azimuth (side to side) and elevation (up and down) directions. The H and V fields become coupled with each other when scanning off-broadside of a phased array (see Figure 4). That is, the H (or V) fields are no longer parallel (or perpendicular) to the surface of the earth and they interfere with each other. Planar arrays will need to correct and compensate for this dual polarization coupling in order to meet the performance requirements of MPAR.

Cylindrical phased array radar can steer the beam in azimuth by commutating (i.e. selectively turning on columns so that the radar beam points in a desired direction perpendicular to the cylinder). Thus, the beam can remain at broadside and avoid the calibration complexities

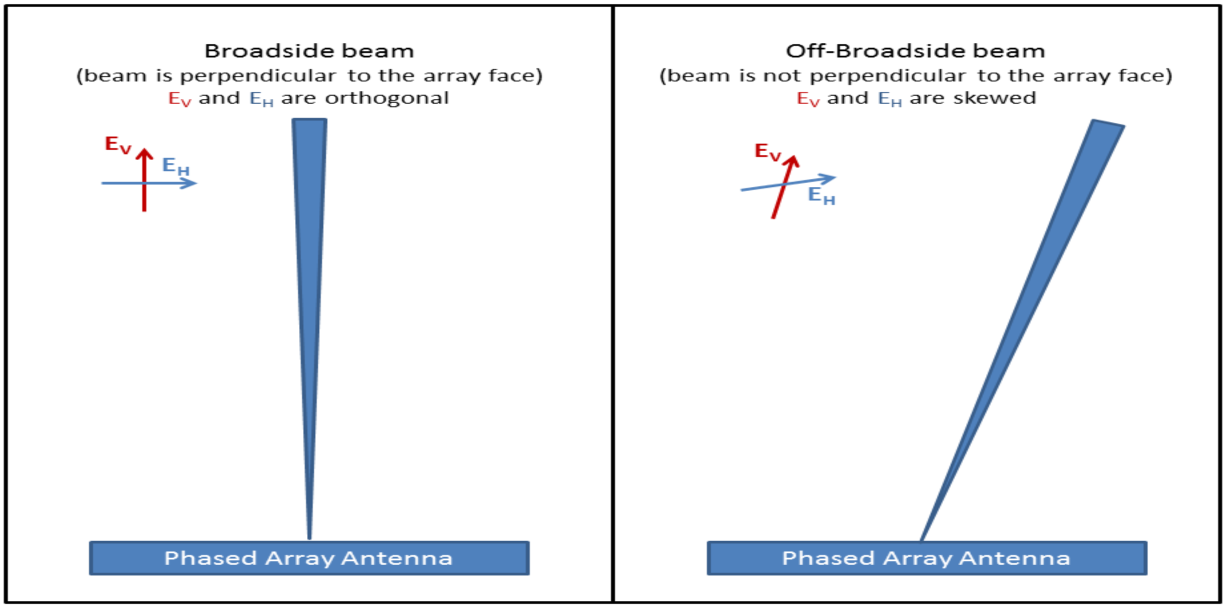

Figure 4: When the radar beam is broadside, the E_V and E_H fields are orthogonal. When the radar scans off-broadside, the E_V and E_H fields become distorted.

described above for planar arrays. However, there are other complexities with operating a cylindrical array (as discussed later) with multiple active sectors that need further investigation.

10 Panel Planar Array Demonstrator: The MPAR program has funded Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) to develop a dual polarization antenna panel design beginning over five years ago. More recently, the program has funded MIT/LL to develop a 10-panel demonstrator based on their panel design. The single face planar antenna aperture will be approximately one meter by two meters in size. The planar array will have the ability to collect dual polarization weather data while scanning electronically in both azimuth and elevation.

The 10-panel demonstrator array will be used to test and evaluate the ability to correct and compensate for the distortions when scanning off-broadside. A unique ability of the 10-panel demonstrator is that it may also be oriented to be facing upward such that both the H and V fields will be parallel to the surface of the earth, which provides a robust means to calibrate the dual polarization measurements. The 10-panel dual polarized phased array radar demonstrator is being assembled at the MIT/LL facilities and should be ready for transportation to NSSL during early 2015 for testing and evaluation.

Cylindrical Polarized Phased Array Radar Demonstrator: The MPAR program has also funded University of Oklahoma Advanced Radar Research Center (OU/ARRC) to develop a small-scale cylindrical demonstrator to investigate dual polarization performance and cylindrical array operation (Figure 5). The two meter diameter cylinder has 48 dual polarization column antennae covering approximately 180 degrees of the cylinder.

The small-scale CPPAR demonstrator scans in azimuth by selectively activating the appropriate sectors of the cylindrical array. The software to perform the scanning strategy and collect data is currently being prepared and the small-scale CPPAR demonstrator should be available for testing and evaluation in early 2015.

Industry-developed demonstrator: Raytheon Company has developed (using their own Internal Research and Development funding) an X-band (short-range) dual polarization planar phased array radar that has been collecting some observational weather data. Discussion between the government and Raytheon to coordinate access to their weather data for analysis by the MPAR program are ongoing.

These three demonstrators are the first attempts aiming to collect quality dual polarization weather data with phased array radar. It is important to note that none of these systems is considered to be a final design for an MPAR system nor are they expected to meet all the MPAR performance requirements. Nevertheless, these demonstrators will provide valuable information on a path forward and are an essential part of the research and development process for MPAR.

Figure 5: Photo of OU/ARRC Cylindrical Polarized Phased Array Radar (CPPAR) during assembly.

NWRT Advanced Technology Demonstrator

The current NWRT/PAR system is based on older passive phased array radar technology that has limited capability compared to the newer active phased array radar technology. Passive array radar has a single high-power transmitter whose energy is distributed to all the elements on the array antenna, whereas active array radar has a low-power transmit/receive chip located at each element in the array. Active array architecture gives the radar the ability to perform advanced beamforming and shaping to improve performance. The primary limitation with a passive array is that, with its single transmit and receive path, it can form only one beam. In order to meet the multi-mission functionality of MPAR an active array will be required to form multiple simultaneous beams. Because the current testbed radar is limited by the technology of the system, as well as its advanced age, an upgraded system is necessary for further development and evaluation of MPAR.

The NOAA MPAR program received a $3 million budget increase in the Consolidated Appropriations Act of 2014 (Public Law 113-76) for a total of $13 million. Over the next three years the additional NOAA MPAR funds (with matching FAA funds) are planned to replace the NWRT/PAR SPY-1A antenna with a dual polarized active array antenna. The development of this NWRT/ Advanced Technology Demonstrator (ATD) will take approximately three years with NOAA and FAA sharing the costs (total cost estimate approximately $18 million). Other ongoing MPAR research activities will continue in the meantime. The current plan is to upgrade the NWRT/ATD with dual polarization panels of the MIT/LL design (pending successful evaluation of their 10-panel demonstrator). The larger NWRT/ATD array would consist of 76 panels giving the demonstrator a 1.5 degree beamwidth. The NWRT/ATD could then serve as an MPAR proof-of-concept system providing radar data with the quality necessary for meteorological research and further insight into the concept of operations for a future MPAR system.

Developing the NWRT/ATD will also involve replacement of digital signal processing equipment with modern hardware and software to control the new NWRT/ATD. The NWRT facility will also require substantial upgrades to the power and cooling systems to handle the new radar. The MPAR program hopes to leverage existing software and hardware developed under sponsorship of ONR for reuse with the NWRT/ATD. Current plans for the NWRT/ATD activity are scheduled to allow testing and evaluation during FY 2017.

Industry Engineering Study

The FAA and NOAA jointly awarded four separate engineering studies (to vendors Ball Aerospace, Lockheed Martin Corporation, Northrop Grumman Corporation, and Raytheon Company) to develop a conceptual phased array radar antenna and system design that meets the MPAR Notional Functional Requirements (NFR). The NFR (attached) is based on the current agency radar capabilities and likely future requirements being driven by other agency programs. Examples of these potential future requirements include faster weather updates to support planned Warn-On-Forecast objectives of NOAA, lower radar cross section detection requirements to support new entrants into the National Airspace System (e.g. Unmanned Aircraft Systems), and an ability to mitigate the impacts of clutter due to wind turbine farms. Another core objective for the antenna design was that it be scalable such that a large (high resolution, long range) and small (low resolution, short range) variant could be assembled from the same building blocks.

The industry-provided responses for the conceptual antenna and system design study were not intended to be proposals or offers by industry to build an MPAR prototype. The intent of the study was for industry to provide their experience in radar design and production such that the MPAR program could refine its assumptions regarding the technical and cost factors to consider in specifying a multi-function phased array radar. The industry teams were asked to provide the rationale behind the various technical trade-off decisions they made within their conceptual design and provide the associated impact on cost and performance. The MPAR requirements were defined with full awareness that in their entirety, the vendors would face significant challenges in their design process.

Two of the vendor teams provided plans for a four-faced planar array and the other two vendor teams provided plans for a faceted-cylindrical array conceptual design. There were some commonalities among the designs such as peak power of the transmit elements and size of the array that were driven by the NFR. Other design elements, such as their dual polarization implementation strategy or system architecture, differed from team to team and were likely influenced by their prior work and experience in phased array radar development. All four teams identified varying design features in an effort to design an affordable system that would meet MPAR requirements.

The engineering studies also showed that the ability to calibrate the phased array radar and the procedure to maintain calibration during operation must be considered during the design stage. Reflector dish radars in use today mechanically steer the antenna to point the radar beam in a given direction so the characteristics and calibration of the beam are always the same. The beam characteristics of an electronically steered phased array radar changes depending on the beam position and the performance of the distributed transmit/receive elements. The calibration for each beam position of a phased array radar must be considered and routinely monitored to assure correct operation.

The industry responses indicated that some MPAR requirements drove costs upward (e.g. high sensitivity, faster update rates, narrower beamwidth, dual polarization accuracy, and low antenna side-lobes). While each industry team provided valuable insight into the technical challenges facing the MPAR program, no team was able to complete an affordable conceptual design and scanning strategy that met all the MPAR requirements at the current state of phased array radar technology. As a result, the government team is reviewing the requirements in the NFR to determine where performance trades can be made to relax certain specifications, but so as not to impact overall mission and functional capabilities.

CPPAR Design Study

OU/ARRC has been the lead academic institution conducting research into the benefits of a cylindrical geometry for phased array weather radar applications. The majority of commercial or military phased array radar designs are planar arrays (either multi-faced or rotating arrays). A team comprised of OU/ARRC and NSSL personnel was established in early 2013 to look specifically at a cylindrical design with the objective to meet the requirements documented in the MPAR NFR. The team met regularly to discuss the potential design implications and trade-offs, and the various technical risks that would need to be mitigated to determine if the CPPAR concept could potentially meet the expected MPAR requirements. Once consensus was reached on a conceptual CPPAR design, the task of estimating costs to build a proof-of-concept system began and followed through the writing and review of the design study report, which was completed in March 2014.

The team identified advantages and disadvantages with both planar and cylindrical phased array radar designs. The list in Figure 6 shows how the advantages for one show up as disadvantages for the other in a comparison between the two geometries. Other design considerations were included in the CPPAR design study, but the list in Figure 6 shows the primary comparison between planar and cylindrical arrays.

Faceted-Cylindrical Array	Multi-face Planar Array
• Sector commutates to scan different azimuths	• Each face uses electronic beam steering to scan in azimuth
– Beams are locked together in azimuth	+ Each face may operate independently
+ Beam shape is invariant with azimuth	– Beam gets wider when scanning off broadside
+ Polarization is always pure H & V since always scanning on principal planes	– Results in skewed polarization when scanning off principal planes
– Difficult to isolate sectors due to continuous ground plane around cylinder	+ Easier to isolate sectors due to physically separated array faces

Figure 6: Comparison showing the advantages (plus sign) and disadvantages (minus sign) of planar and cylindrical arrays.

A major component of the CPPAR design study was to identify the technical risks associated with a cylindrical design. There are some electromagnetic effects that can cause interference in other sectors of the antenna when transmitting in another direction. A similar problem exists on multi-faced planar arrays but due to the separation between faces there are well established techniques to mitigate the interference between antenna faces. The impacts of this electromagnetic interference is highly dependent on the array element spacing and other design considerations and will need to be analyzed, modeled and demonstrated to determine the optimal configuration for CPPAR. Techniques may be available to prevent or mitigate this interference and will require further study.

Previous design studies have also looked at the trade-offs between the analog sub-array beamforming and all-digital beamforming architectures. The NWRT/PAR system is a passive analog array which means that the electromagnetic signals from every element are combined (beamformed) and passed through one receiver to an analog-to-digital converter (ADC). The analog sub-array architecture may combine electromagnetic signals from several elements or a single panel and pass them through a receiver and ADC before combining the digital signals from all the sub-arrays into a radar beam.

An all-digital beamforming architecture has a receiver and ADC for each radiating element and the digital signals are then combined to form the radar beam. The all-digital architecture offers maximum flexibility allowing on-the-fly reconfiguration of the number of radar beams and/or their shape (referred to as adaptive beamforming) depending on the operational situation. The additional flexibility allows the same radar to be operated differently at different times as the operational circumstances change or as new processing techniques are developed. Realization of the all-digital design would require some engineering development costs to design the integrated circuitry necessary to make the demonstrator practical, unless commercial-off-the-shelf chips become available.

Figure 7 summarizes the differences between analog sub-array and all-digital beamforming architectures and the physical geometry of current and proposed investments. The planned NWRT/ATD will be a planar array geometry and have an analog sub-array beamforming architecture. The OU/ARRC proposed CPPAR demonstrator would be an all-digital system architecture if funded.

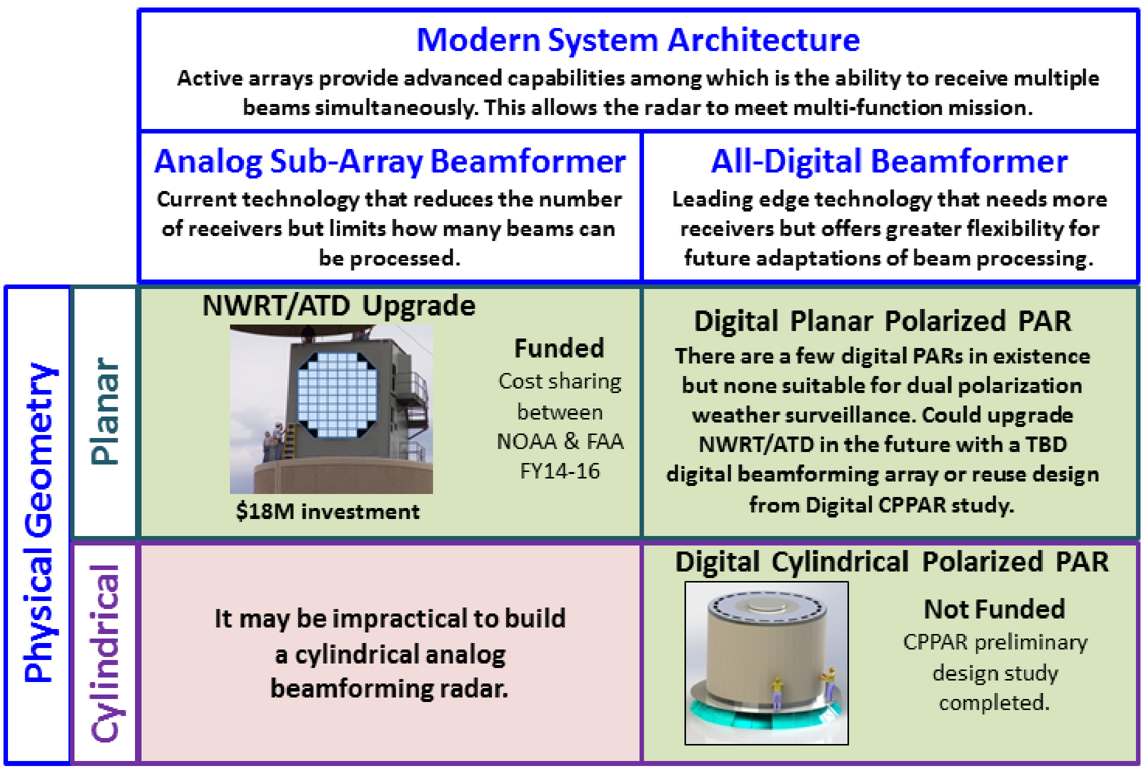

Figure 7: Matrix of system architecture versus physical geometry and the current investments in technology demonstrations.

The development of an all-digital architecture design is already in progress. The next phase of this endeavor would include the fabrication of an all-digital panel (a set of eight elements). Pending successful testing and evaluation of the all-digital panel, a small-scale demonstrator (approximately 1,000 elements) could then be built to further demonstrate the capabilities of the all-digital system architecture. The all-digital technology could be tested in a small-scale planar configuration prior to committing to a larger-scale cylindrical array.

CPPAR Demonstrator

The CPPAR design study proposes building an all-digital faceted-cylindrical demonstrator. This proof-of-concept system would have a diameter of approximately 6 meters and would be considerably larger than the current small-scale CPPAR demonstrator. The all-digital architecture of the large-scale CPPAR demonstrator would have much greater capabilities than the small-scale CPPAR demonstrator being developed. The CPPAR demonstrator would have a full 360 degree antenna surface partially populated with electronics that would allow scanning through about 90 degrees in azimuth (similar to a single-faced planar array) with a 2 degree beamwidth. The populated electronics panels could be reconfigured such that a ring of active panels would circle the full 360 degrees of the cylinder for evaluation of the electromagnetic interference issue that occurs with the cylindrical design.

The CPPAR demonstrator project plan proposes a four-year development effort to begin a detailed design, prototyping, fabrication and integration/assembly of a large-scale prototype. Additional efforts would include building a facility to house the radar and software development to control the radar and process data. The CPPAR design study team also looked at the projected cost of the various hardware components, software development, and labor costs to build the CPPAR demonstrator. The estimated cost of the demonstrator is between $28 million and $32 million and is not feasible within the current budget and schedule.

The only true method of determining if the risks associated with the CPPAR design have been overcome is through the development of a proof-of-concept demonstrator. Current modeling studies and research activities with the small-scale CPPAR are only a beginning of the research to determine if CPPAR is a viable alternative design to meet the MPAR mission. Further development of the CPPAR concept would be required to perform the analysis and evaluation necessary to determine if the technology risks identified in the design study have been sufficiently mitigated.

Conclusion

It is too early in the MPAR program to make final design decisions relative to physical geometry and other system design characteristics. MPAR research activities will continue to inform the government of the impact of its requirements, and the performance and cost trade-offs to be considered. The MPAR program anticipates that these design decisions will be made and documented as final baseline requirements are defined through ongoing research and operational demonstrations in the coming years. The production MPAR design will be determined during the evaluation of proposals subsequent to a government solicitation based on final MPAR requirements.

Appendix A
List of Acronyms

ADC	Analog to Digital Converter
ARSR	Air Route Surveillance Radar
ASR	Air Surveillance Radar
ATD	Advanced Technology Demonstrator
CPPAR	Cylindrical Polarized Phased Array Radar
DHS	Department of Homeland Security
DOD	Department of Defense
FAA	Federal Aviation Administration
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
MPAR	Multi-function Phased Array Radar
NFR	Notional Functional Requirements
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWRT	National Weather Radar Testbed
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
ONR	Office of Naval Research
OU/ARRC	University of Oklahoma Advanced Radar Research Center
PAR	Phased Array Radar
TDWR	Terminal Doppler Weather Radar
WSR-88D	Weather Surveillance Radar – 1988 Doppler