REPORT TO CONGRESS

FEASIBILITY AND CAPABILITY OF A ROTATING PHASED ARRAY RADAR

Developed pursuant to: Title I of Division B of the Joint Explanatory Statement accompanying the Consolidated Appropriations Act, 2022 (Public Law 117-103)

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THE JOINT EXPLANATORY STATEMENT ACCOMPANYING THE CONSOLIDATED APPROPRIATIONS ACT, 2022 (PUBLIC LAW 117-103) INCLUDED THE FOLLOWING LANGUAGE

Next Generation Phased Array Weather Radars.— Within Tornado Severe Storm Research/ Phased Array Radar, the agreement provides an increase of $2,500,000 above the fiscal year 2021 enacted level, as requested, to develop advanced phased array weather radar systems and to strengthen NOAA's collaboration with current Cl partners with expertise in this area. This investment should also work in parallel to provide complementary research and development to meet National Weather Service requirements and to reduce long-term operations and maintenance costs of the future national radar network. Further, no later than 270 days after enactment of this Act, NOAA is directed, through its intramural radar research center of excellence at the National Severe Storm Lab and its affiliated academic partner, to provide a report on the feasibility and capability for a single-face rotating phased array radar to improve NOAA's weather prediction.

THIS REPORT RESPONDS TO THE COMMITTEE'S REQUEST.

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I. EXECUTIVE SUMMARY

To fully determine the feasibility and capability of a single-face rotating Phased Array Radar (PAR) to improve NOAA's weather prediction, the National Oceanic and Atmospheric Administration (NOAA) will perform research and development (R&D) with a single-face rotating PAR Test Article. NOAA's single-face rotating PAR Test Article was partially funded in FY 2023, with additional funds requested in the FY 2024 President's Budget Request. With the necessary funding, the acquisition of the PAR Test Article is planned to begin in FY 2024, delivered and installed in FY 2027 with a final report on the feasibility and capability of this technology completed by 2029. The report will inform an Analysis of Alternatives (AoA) which will determine the most viable, and potentially cost effective, alternative for the current National radar network, Weather Surveillance Radar – 1988 Doppler (WSR-88D, or NEXRAD).

NOAA has led the nation and the world in the development of weather surveillance radars. The current National radar network, the NEXRAD system, was developed and improved over the past 30 years by NOAA research. This network, which was developed jointly with the Federal Aviation Administration (FAA) and the Department of Defense, is critical in the detection and forecasting of tornadoes, thunderstorms, flash flooding, hail, and other hazards to aviation.

The NEXRAD network has been kept up to date with technology using information technology refresh, science upgrades, and sustaining engineering projects. In addition, NOAA's National Weather Service (NWS) implemented Service Life Extension Program (SLEP) activities to extend the operational capability of the WSR-88D system. The SLEP will be complete in 2024 and, with other maintenance and engineering efforts, will sustain the operation of the NEXRAD network into the 2030s. NOAA is currently investigating the best path forward for the operational system and has identified three options in the "Weather Radar Follow on Plan: Research and Risk Reduction to Inform Acquisition Decisions[1]": 1) sustain the current WSR-88D system with an additional SLEP to extend the operational capability; 2) replace WSR-88D with a new reflector dish, mechanically rotating radar system; or 3) replace WSR-88D with the promising Phased Array Radar (PAR) technology currently being investigated by NOAA. As a part of any future major acquisition program to replace the current NEXRAD network, NOAA will conduct an AoA to ensure that any other capability options to meet the observing requirements that may exist are also considered.

PAR technology has been used since at least the 1970s in the defense sector, but has not been widely used in the weather enterprise. The National Severe Storms Laboratory (NSSL) has been investigating PAR technology since 2003 to meet evolving radar requirements to support improved and enhanced weather warnings. PAR is a promising technology that has demonstrated great potential to improve warnings for various types of severe weather. Initial weather studies have highlighted increased volume scan update rates as the major benefit of PAR technology. More recent studies conducted on the Advanced Technology Demonstrator (ATD) have demonstrated the ability to obtain dual polarization capabilities for a fixed planar PAR

[1] Weather Radar Follow-on Plan: Research and Risk Reduction to Inform Acquisition Decisions

concept, which has moved dual polarization PAR technology to Readiness Level[2] (RL) 5 for weather radar application.

Prior research has primarily focused on a fixed 4-face planar PAR system to meet multiagency requirements for which a rotating PAR concept was not feasible. However, now a proof-of-concept rotating single-face PAR is needed for research and development (R&D) for weather surveillance requirements. This single-face rotating PAR concept could substantially reduce the NWS' potential future acquisition and operating costs of PAR compared to the previous PAR concepts, (e.g., cylindrical or fixed 4-face planar array). PAR technology will continue to be evaluated as a potential replacement technology for the WSR-88D system unless the ongoing research, development, and evaluation determines it is technically unsuitable or too costly for implementation. The proposed single-face rotating PAR would also be highly valuable for further evaluation of the stationary 4-face PAR configuration, which remains a viable solution in consideration.

NOAA is considering two potential configurations for the PAR alternative: 1) a fixed 4-face planar system with a higher upfront procurement cost and operating cost, lower technical risk, and a higher degree of scanning flexibility; and 2) a rotating, single-face PAR with multiple simultaneous beams scanning strategies with a lower upfront procurement cost and operating cost, higher technical risk, and a lower degree of scanning flexibility relative to a fixed 4-face planar system. The proposed rotating PAR Test Article in the FY 2024 President's Budget Request is needed to perform R&D activities on scanning strategies and to better understand any scanning limitations compared to the 4-face planar concept.

This report is in response to the Joint Explanatory Statement passed by Congress on March 9, 2022. It summarizes the current knowledge of PAR systems to meet weather radar needs and describes the proposed plans to conduct additional R&D necessary to determine whether a single-face rotating PAR system is feasible and capable of improving NOAA's weather prediction.

II. INTRODUCTION

This report is in response to the fiscal year (FY) 2022 Joint Explanatory Statement directive to *provide a report on the feasibility and capability for a single-face rotating phased array radar to improve NOAA's weather prediction through its intramural radar research center of excellence at the National Severe Storm Lab and its affiliated academic partner*. To avoid a potential conflict of interest on the possible procurement,[3] NOAA consulted with NOAA Office of the General Counsel, Department of Commerce (DOC) Ethics, and the NOAA Budget Office on a suitable path forward for participation from academic partners involved in collaborative PAR R&D activities which include the University of Oklahoma (OU) Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO), the OU Advanced Radar

[2] NOAA Readiness Levels: www.noaa.gov/sites/default/files/legacy/document/2020/Mar/Handbook_NAO216-105B_03-21-17.pdf
[3] Advancements in Weather Surveillance Radar – Request for Information https://sam.gov/opp/fac5887de2aa4157a7fdef3caabe75c6/view

Research Center (ARRC), and Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL). To meet the congressional direction without impacting the future acquisition, NOAA solicited technical materials from OU CIWRO, ARRC, and MIT/LL based on their R&D activities. A Federal writing team was responsible for the preparation, review, and editing of this report.

NOAA's Office of Oceanic and Atmospheric Research (OAR) has been investigating PAR technology since 2003 to meet mission-driven expanded radar requirements that support improved and enhanced weather forecasts and warnings. PAR technology has demonstrated great potential to improve warnings for various types of severe weather, primarily through the use of faster updates and adaptive scanning capabilities. However, there are many technological challenges that must be addressed before PAR technology can serve as a cost-effective replacement of the WSR-88D system. Chief among these technological challenges needing additional R&D focus is the impact of a rotating dual polarization PAR system.

This report provides a review of NWS surveillance radar requirements. These requirements are instrumental in determining if any new technology, such as PAR, will be suitable for meeting the needs for the replacement of the dual polarization WSR-88D system. Following this section is an overview of the advancements in PAR technology highlighting NOAA's key findings, limitations, and next steps. Finally, the report discusses how the planned proof of concept single-face rotating PAR Test Article[4] could be used to demonstrate the potential for faster volume updates relative to the existing WSR-88D system while meeting NWS radar weather requirements for improved weather predictions.

III. NWS SURVEILLANCE RADAR REQUIREMENTS AND OPPORTUNITIES

NOAA's Observing System Integrated Analysis[5] quantified the significant impact of its current operational WSR-88D radar for the agency's weather mission service areas. This analysis indicates that radar is the second most impactful observing system for the overall weather mission, and the most impactful observing system for three mission service areas – fire weather, hydrology, and severe thunderstorms, which are projected to become more severe in the coming decades due to climate change.

As continuing to sustain the aging WSR-88D leads to increased reliability, maintainability, and availability challenges, NWS is preparing for an AoA to inform radar follow-on decisions. A requirement for this process is to determine how well new technologies like PAR perform weather surveillance for the objectives outlined in the NOAA NWS Functional Radar

[4] The 'Test Article' refers to a proof-of-concept radar that will be used in studies to determine the feasibility of rotating PAR technology for the NWS as a cost-effective replacement of the current WSR-88D system.
[5] United States, National Environmental Satellite, Data, and Information Service, NOAA Observing System Integrated Analysis (NOSIA-II) methodology report (2016) NOAA technical report NESDIS; 147 DOI:http://doi.org/10.7289/V52V2D1H

Requirements[6] and the NOAA Radar Surveillance Requirements: Weather,[7] including dual polarization performance, calibration techniques, and ability to perform rapid volume updates.

In addition, NWS has emerging objective requirements such as improved spatial resolution, mitigation of interference that affects radar data quality, and faster update rates (i.e., 60-90 second volume scans) that would improve weather prediction. By acquiring a single-face rotating PAR Test Article, NOAA will have the opportunity to perform studies to demonstrate the potential for this technology to meet emerging NWS requirements (e.g., faster update rates) with a lower initial capital investment than current 4-face planar PAR technology.

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[6] www.roc.noaa.gov/WSR88D/PublicDocs/NOAA_Radar_Functional_Requirements_Final_Sept%202015.pdf

[7] https://sam.gov/api/prod/opps/v3/opportunities/resources/files/0166e05b01754e4d95e37bb2a94ecea9/download?&status=archived&token=

IV. HISTORY OF PAR USE AND RESEARCH

Building on PAR technology developed for military applications, NSSL has been investigating actual and planned PAR technology for weather radar application for the past 20 years (see Table 1).

PAR Technology	Impact	Questions Remaining
SPY - 1 2003 - 2016	The modified SPY-1 was able to **demonstrate benefits of rapid updates in a single polarization PAR** weather system.	What additional benefits will rapid updates provide for dual polarized radars?
MPAR/ SENSR 2008 - 2018	The multifunction PAR system was not feasible for aviation, weather, and surveillance simultaneously. **DOC/NOAA withdrew from the program in 2018.**	For weather applications, which design options (e.g., fixed 4-face planar array, rotating single-face planar array) would improve update times?
ATD 2014 - Pres.	The ATD was **able to demonstrate the calibration of a dual polarization PAR** weather system (as one face of a fixed 4-face planar array).	How can polarimetric calibration be maintained? ***Could a rotating PAR provide sufficiently rapid updates at a lower cost than a 4-face planar array?***
Horus 2016 - Pres.	Horus is **expected** to deliver an engineering demonstrator for an **all-digital polarimetric PAR** weather system.	What additional benefits will all-digital PAR architectures provide? ***Can this be scaled to a larger rotating PAR?***
Rotating PAR (Proposed)	*This new proposed test article will evaluate if a **highly digital, dual polarization rotating planar PAR** for weather is a feasible alternative (to a fixed 4-face planar array).*	***Will multiple simultaneous beams provide faster volumetric updates that meet data quality requirements?***

Table 1: Major PAR technologies analyzed by NSSL along with, impacts, and remaining research questions after the respective activity (including those to be investigated by a single-face rotating PAR test article in bold italics).

A. SPY-1

The SPY-1 is 1970s PAR technology that was originally developed for military use to track aircraft and missiles. The first PAR specifically modified for weather surveillance was the S-band SPY-1 radar on a U.S. Navy destroyer[8,9] in 1997. In 2003, NOAA's NSSL – with several private-sector, government, and university partners – developed the

[8]Maese, T., Melody, J., Katz, S., Olster, M., Sabin, W., Freedman, A., & Owen, H. (2001, May). Dual-use shipborne phased array radar technology and tactical environmental sensing. *Proceedings of the 2001 IEEE Radar Conference (Cat. No. 01CH37200)* (pp. 7-12). IEEE.

[9] Robinson, S. D. (2002). *Utility of tactical environmental processor (TEP) as a Doppler at-sea weather radar*. NAVAL POSTGRADUATE SCHOOL MONTEREY CA.

National Weather Radar Testbed (NWRT), which featured a SPY-1 antenna specifically modified to demonstrate the advantages of this new technology for weather surveillance.[10]

The NSSL operated the SPY-1 antenna from 2003-2016 and captured many different severe weather phenomena. The faster volume updates made possible by PAR technology demonstrated the potential for improved: 1) understanding of storm evolution[11]; 2) tornado and severe thunderstorm warning performance metrics[12,13]; and 3) data assimilation capabilities for high-resolution Convection Allowing Model numerical weather prediction systems.[14] Physical limitations of the SPY-1 system included its small aperture (antenna beamwidth was ~1.5 degrees compared to the WSR-88D beamwidth of 1.0 degrees) and passive analog array configuration, which prevented further beneficial research with the SPY-1.

The SPY-1 system also had several shortcomings that needed further investigation before NOAA could consider PAR technology for an operational replacement for the NEXRAD network. Primary among these was the fact that it did not have dual polarization capability, as required by the NWS. NOAA would need to invest in dual polarization PAR R&D to make it a viable alternative for the NEXRAD network replacement. In addition, the SPY-1 "passive" array technology was eclipsed by advances in "active" array technology.

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[10] Zrnic, D. S., Kimpel, J. F., Forsyth, D. E., Shapiro, A., Crain, G., Ferek, R., … & Vogt, R. J. (2007). Agile-beam phased array radar for weather observations. *Bulletin of the American Meteorological Society*, *88*(11), 1753-1766.
[11] Heinselman, P. L., Priegnitz, D. L., Manross, K. L., Smith, T. M., & Adams, R. W. (2008). Rapid sampling of severe storms by the national weather radar testbed phased array radar. *Weather and Forecasting*, *23*(5), 808-824. 10.1175/2008WAF2007071.1.
[12]Heinselman, P., LaDue, D., Kingfield, D. M., & Hoffman, R. (2015). Tornado warning decisions using phased-array radar data. *Weather and Forecasting*, *30*(1), 57-78.
[13] Wilson, K. A., Heinselman, P. L., Kuster, C. M., Kingfield, D. M., & Kang, Z. (2017). Forecaster performance and workload: Does radar update time matter? *Weather and Forecasting*, *32*(1), 253-274.doi:10.1175/WAF-D-16-0157.1.
[14]Yussouf, N., & Stensrud, D. J. (2010). Impact of phased-array radar observations over a short assimilation period: Observing system simulation experiments using an ensemble Kalman filter. *Monthly weather review*, *138*(2), 517-538.

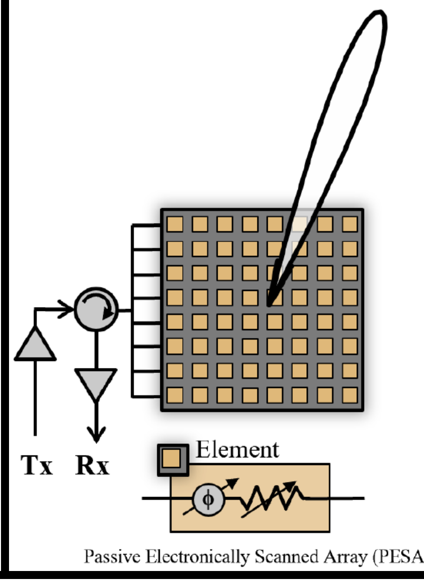
PAR Example	PAR Architecture Description	Planar Array Schematic
NWRT SPY - 1 2003 - 2016 	The SPY-1 system was a **"passive" analog beamforming array** with a single high power transmitter and phase shifters at the antenna elements that were used to electronically steer the radar beam. The antenna elements' receive signals are then combined (i.e., beamformed) via analog devices and output to a single digital receiver.	

Figure 1: The SPY-1 system is an example of an analog array with a single high-power transmitter with high-frequency power dividers and combiners designed to distribute power across the array. Planar Array Schematic is adapted from Palmer et al., 2022[15] *©American Meteorological Society. Used with permission.*

B. Multifunctional Phased Array Radar and Spectrum Efficient National Surveillance Radar

The Office of the Federal Coordinator for Meteorology convened a Multifunction Phased Array Radar (MPAR) symposium in 2007 to develop the requirements for a multi-agency R&D effort to examine PAR capabilities that needed additional focus. NOAA's concerns and efforts were focused on three areas: 1) the cost of PAR technology; 2) the development of dual polarization PAR technology; and 3) the multifunction concept of operations. The ongoing development of PAR technologies in support of military applications continued to drive costs downward with significant help from the telecommunications industry.

NOAA and the FAA invested heavily in the dual polarization PAR R&D efforts with special emphasis on the precision needed for a dual polarization weather radar. A cycle of design, development, and testing and evaluation with incremental advances in technology and scale were completed over the course of 10-plus years. The issue of the multifunction concept of operations concerned how the available radar resources could be utilized to fulfill each agency's mission without negatively impacting any agency's requirement, including even in target-rich environments (such as severe weather impacting arrival and departure flights of a busy airport while tracking a low-flying airplane that is not responding to air traffic controllers).

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[15] Palmer, R., Bodine, D., Kollias, P., Schvartzman, D., Zrnić, D., Kirstetter, P., ... & Yeary, M. (2022). A primer on phased array radar technology for the atmospheric sciences. *Bulletin of the American Meteorological Society*, *103*(10), 2391-2416. https://doi.org/10.1175/BAMS-D-21-0172.1.

The different update requirements for the various missions of the agencies removed the possibility of a rotating PAR from further multi-agency consideration. The agencies focused on other design alternatives such as a 4-face planar array or cylindrical array configurations to meet the MPAR functional requirements. Although there are advantages and disadvantages for either configuration, it was determined that the cylindrical configuration contained more technical risk[16] and would need substantially more investment.

Congress passed the Spectrum Pipeline Act of 2015 which made possible the use of Spectrum Relocation Funds (SRF) for R&D that could lead towards future spectrum auctions. The MPAR program had sought to move radar requirements from three different frequency bands into a common multi-agency MPAR. Thus, the MPAR program was eclipsed by the Spectrum Efficient National Surveillance Radar (SENSR) program in 2016 and received more robust multi-agency support. The agencies applied for and received SRF funding to continue R&D in preparation for a multi-agency radar.

The SENSR program engaged the radar industry to examine their current capabilities with regards to weather radar requirements. Although the radar industry had begun implementing dual polarization technology for military applications, its capabilities were untested or incompatible with NOAA's mission. NOAA ultimately withdrew from the SENSR program, primarily because the focus of each agency's driving mission and requirements suggested various PAR solutions. In addition, the time available prior to SENSR's planned contract award was insufficient for the research needed to determine whether PAR could meet NOAA's future high-resolution dual polarization weather radar requirements.

C. Advanced Technology Demonstrator

The ATD was developed by NOAA and the FAA under the above MPAR program to test and evaluate PAR technology's capability to meet the performance and calibration requirements for dual polarization. The initial design (based on prior NOAA-funded work) was started in 2014 and was developed and fabricated through 2018. The initial testing and evaluation of the system continued into 2021 before concluding that dual polarization could be implemented on PAR technology and calibrated to produce quality dual polarization weather products at the required electronic scanning angles. The ATD replaced the SPY-1 system in the NWRT and was similarly constrained in size, limiting the beamwidth to approximately 1.5 degrees.

The ATD was originally designed to represent a single face of a 4-face planar array, with a 90-degree field of view. To facilitate scanning in any direction, the ATD was installed on a rotating pedestal so the array could be repositioned in a direction of interest with suitable weather targets. As with the SPY-1 system, the intended use of the rotating pedestal was only to position the array in the general direction of interest, after which

[16] www.nssl.noaa.gov/publications/par_reports/FY14_MPAR_CPPAR_Congressional_Report.pdf

electronic scanning techniques would be used to observe the 90-degree sector within view of the antenna array. Although the rotating pedestal of the ATD may facilitate some basic demonstration of scanning while rotating, the ATD radar itself was designed for fixed operations and does not support some of the advanced techniques that would maximize the potential of a rotating PAR.

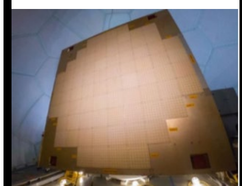
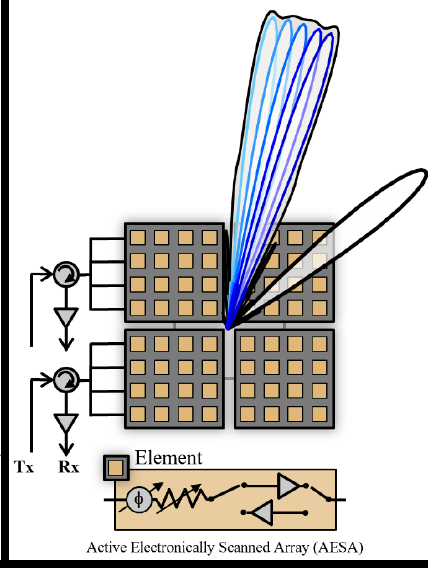
PAR Example	PAR Architecture Description	Planar Array Schematic
ATD 2014 - Pres.  	The ATD is an **"active" hybrid analog/digital sub-array beamformer** with low power transmitters at the antenna elements electronically steering the beam on transmission. The signals received from 512 antenna elements are combined via analog devices for 24 overlapping subarrays designed in the system. These 24 subarrays are processed by 24 digital receivers which are then combined digitally to form the beam. (Note: Since the ATD is a dual polarization radar, the subarrays have both a *Horizontal* and *Vertical* channel and are therefore processed by 48 digital receivers).	

Figure 2: NSSL's ATD shown as an example of an active hybrid analog/digital sub-array beamformer architecture with an Active Electronically Scanned Array. Planar Array Schematic is adapted from Palmer et al., 2022. ©American Meteorological Society. Used with permission.

V. ADVANCEMENTS IN DIGITAL PAR

In addition to the ATD demonstration of dual polarized PAR technology, NOAA R&D advancements in increasing the level of digitization of PAR technology have also been underway. An all-digital PAR means that transmit waveforms are generated, and receive waveforms digitized, at each of the thousands of individual elements. This architecture eliminates a large amount of analog Radio Frequency (RF) equipment associated with hybrid systems while having compelling benefits for radar processing. All-digital PAR offers maximum flexibility, enabling it to take advantage of capabilities that hybrid PARs cannot. This flexibility also allows all-digital PARs to maximize the benefit of PAR capabilities like beam agility, adaptive scanning, and digital beamforming.[17,18]

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[17] *Beam agility* refers to steering the radar beam to quickly observe different regions of interest almost instantaneously without mechanically rotating the antenna.
Adaptive scanning is the radar's ability to automatically tailor the scan strategy to the phenomena being observed, allowing it to selectively improve temporal resolution, spatial sampling, and/or data quality depending on need.
Digital beamforming enables simultaneously forming multiple receive beams within a large illuminated sector by digitally combining signals received from subarrays or antenna elements with digital outputs.

[18] Palmer, R., Bodine, D., Kollias, P., Schvartzman, D., Zrnić, D., Kirstetter, P., ... & Yeary, M. (2022). A primer on phased array radar technology for the atmospheric sciences. *Bulletin of the American Meteorological Society*, *103*(10), 2391-2416. https://doi.org/10.1175/BAMS-D-21-0172.1.

All-digital PARs can scan narrow pencil beams or wide imaging beams in any direction within the antenna's field of view without the constraints of a sub-array architecture like the ATD, allowing for a wide variety of synthesized beam patterns and scan strategies. Measurements from all-digital PARs would have higher accuracy with less beam contamination. Importantly, all-digital PAR also addresses one of the biggest challenges in dual-polarized PAR (calibration) by enabling a new polarimetric calibration technique based on measuring the mutual coupling of individual antenna elements.[19] Although the initial costs of all-digital PARs are higher than PAR systems with lower or no degrees of digitization, their ability to be reconfigured via software upgrades instead of hardware modifications has the potential to reduce lifetime operations and maintenance costs.

NOAA currently sponsors two complementary, all-digital PAR R&D efforts that use fundamentally different physical architectures and digital processing techniques. These collaborative efforts with NSSL and partners are at relatively low readiness levels, RLs, of "applied research" (RL2) or "proof of concept" (RL3) but are designed to be scalable with the ultimate goal of informing the NWS AoA. These efforts are the OU ARRC's Horus demonstrator (RL3) and MIT/LL's Digital Polarimetric Phased Array Radar (DPPAR) panel (RL2).

The Horus engineering demonstrator is the first-ever polarimetric S-band all-digital PAR for demonstrating weather observations.[20,21] Horus uses an 8x8-element "slat-based" building block, comprising a flat antenna panel with eight 1x8-element slats that slide into the panel frame and house the supporting radar electronics. This proof-of-concept system started collecting data with five panels in spring 2022 and is planned to have a complete 4x4 array (of 16 panels) during FY23 to demonstrate the engineering benefits of all-digital technology for weather observation. However, its coarse beamwidth of ~4.5 degrees will not produce high spatial resolution observations of precipitating systems which would be required to verify performance as a weather radar. Nevertheless, Horus has shown in a laboratory setting that polarimetric calibration can be robustly accomplished when digitizing at each element.

MIT/LL's DPPAR, in contrast, is comprised of an 8x8-element "tile-based" building block that includes all electronics in a set of two circuit boards: a digital control board and RF panel. This DPPAR panel, which heavily leverages the design, infrastructure, and lessons learned from the ATD, can operate as a self-contained, all-digital PAR building block. DPPAR moves most of the signal processing onto each panel instead of having multiple off-array connections. A two-panel proof-of-concept engineering demonstrator is under active development (as of fall 2022).

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[19] Lebrón, R. M., Tsai, P. S., Emmett, J. M., Fulton, C., & Salazar-Cerreno, J. L. (2020). Validation and testing of initial and in-situ mutual coupling-based calibration of a dual-polarized active phased array antenna. IEEE Access, 8, 78315-78329.
[20] Palmer, R. D., C. J. Fulton, J. Salazar, H. Sigmarsson, and M. Yeary, 2019: The "Horus" radar – An all-digital polarimetric phased array radar for multi-mission surveillance. *35th Conf. on Env. Info. Proc. Tech.*, Amer. Meteor. Soc., Ed., Phoenix, AZ.
[21] Yeary, M., R. Palmer, C. Fulton, J. Salazar, and H. Sigmarsson, 2021: Update on an S-band all-digital mobile phased array radar. 2021 IEEE Radar Conference (RadarConf21), 1–4, https://doi.org/10.1109/RadarConf2147009.2021.9455287.

Future research and development efforts into all-digital PAR technologies will need to address important questions about:

1. *Resolution*, or the possibility that the above digital PAR demonstrators can be scaled to a larger rotating PAR concept that will be discussed in the next section;
2. *Clutter mitigation*, or the potential for some beam and range sampling procedures to reduce wind turbine clutter for a relatively small number of turbines;
3. *Interference reduction techniques*, including the possibility of designing highly or all-digital PAR systems that are less susceptible to internal and external interference sources; and
4. *Managing high processing software complexity and large data throughput* generated by a highly or all-digital PAR system that is a few orders of magnitude greater than that generated by the existing WSR-88D, with data transmitted externally being increased by a factor of ~4. Fortunately, new processing software and protocols for transferring vast amounts of data have been and will continue to be developed for related industries (e.g., computer networks and wireless communications) to help reduce the monetary and computing cost.

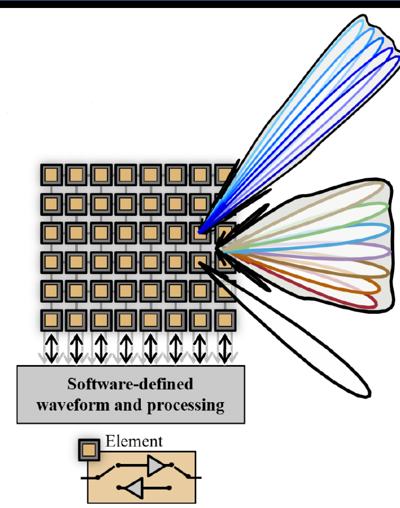
PAR Example	PAR Architecture Description	Planar Array Schematic
All-Digital PAR R&D Efforts *OU Horus* 	An **all-digital beamforming PAR** would have a low power transmitter and an analog to digital converter at each antenna element to convert the receive signals to digital. The digital element data would then be combined to construct/form the beam. In a **highly digital system**, the signals received from a small number (e.g., 4, or 8, or 16) of antenna elements could be combined before converting to digital to reduce the amount of data to be processed.	

Figure 3: The OU Horus radar is shown as an example of an all-digital array with the received energy being converted from analog to digital at every element. Planar Array Schematic is adapted from Palmer et al., 2022. ©American Meteorological Society. Used with permission.

VI. ROTATING PAR TEST ARTICLE

After withdrawing from the SENSR program in 2018, NOAA continued its research into dual polarization PAR technology and began exploring the concept of a single-face rotating planar PAR to further reduce costs compared to a 4-face planar PAR. A rotating PAR could meet the current 5 minute volume update rate of the WSR-88D but would require additional technology development and R&D to meet the faster update time (i.e., 60-90 seconds) possible on the 4-face planar PAR. The scanning strategy of a rotating PAR is restricted by the mechanical rotation and would require the technical implementation of multiple simultaneous beams (MSB) to achieve the faster update rates provided by a 4-face planar system. Several MSB strategies have been proposed and tested for point target (e.g., aircraft) detection but have encountered difficulties when proposed for distributed weather targets (e.g., raindrops) that require more quantitative measurements.

The simplest MSB technique would transmit a larger ("spoiled") beam and then use the digital receiver channels to form multiple receive beams within the larger transmit beam. However, this technique effectively reduces the power density of the radar beam and the one larger transmit beam may contaminate the smaller individual receive beams with power returned from other targets within the spoiled transmit beam, potentially obscuring important meteorological features. More precise and technically complex MSB techniques that need to be investigated with a single-face rotating PAR to increase volumetric update rates include:

1. Transmitting separate individual beams in multiple directions simultaneously and performing digital beamforming to receive in each of these directions simultaneously;
2. Transmitting multiple beams in rapid succession in different directions and performing digital beamforming upon receive to distinguish the different beams; and
3. Transmitting multiple beams in rapid succession at different frequencies to provide greater electronic isolation on receive to distinguish the different beams.

NOAA proposes to acquire a rotating planar array suitable for testing the various MSB strategies (Figure 4) to determine if they can produce weather radar data that is compatible with NWS radar requirements for data quality, resolution, and sensitivity. A higher number of MSB will result in faster update times. Four simultaneous beams would be required to match the volume update times of a similarly sized 4-face planar array. The primary advantage of a rotating single-face PAR would be lower production cost when compared to a 4-face PAR configuration. However, the rotating platform presents another potential single point of failure for the system that could increase maintenance costs and the mechanical rotation imposes some restrictions on scan adaptability.

The rotating PAR Test Article would be NOAA's most advanced technology demonstrator to date that could be used to evaluate performance of high-resolution weather radar applications. There still remains significant technical risk with the MSB strategy, but the rotating PAR Test Article could also be used to further evaluate the 4-face planar configuration with higher functioning hardware, including a more highly digital PAR architecture relative to the ATD.

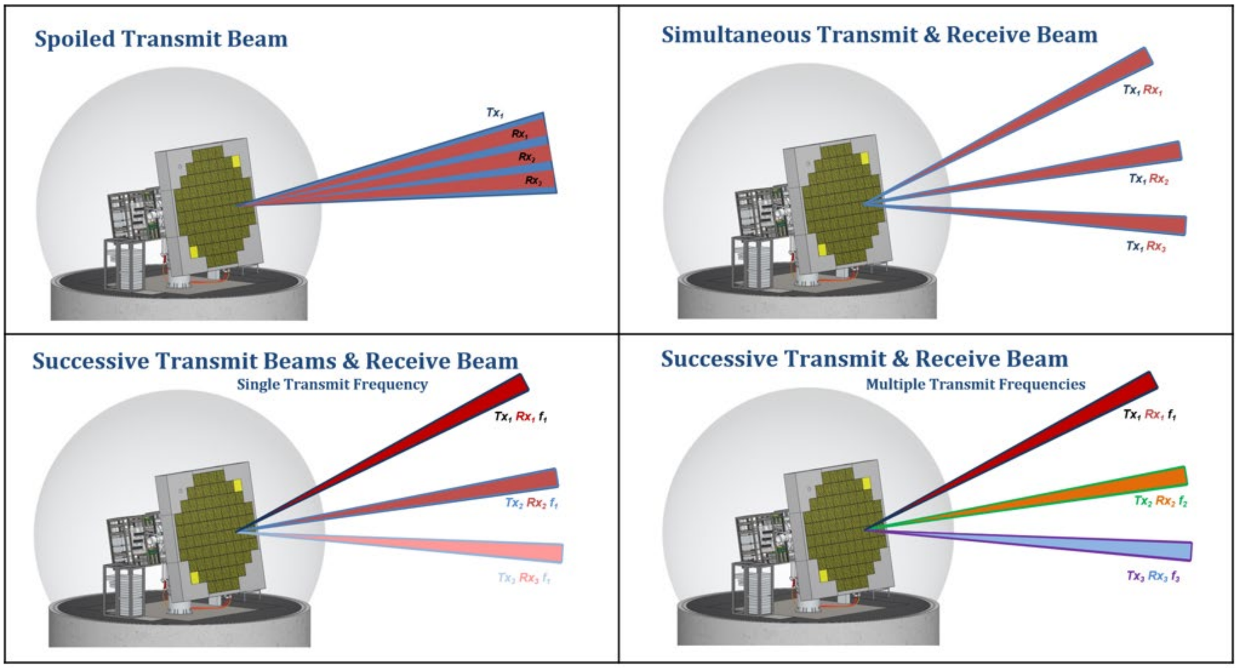


Figure 4: Conceptual drawings of the various multiple simultaneous beam (MSB) techniques to be examined using a Rotating PAR Test Article. Tx=Transmit Beam, Rx=Receive Beam, f=frequency

VII. CONCLUSION: FEASIBILITY AND CAPABILITY OF THE ROTATING PAR CONCEPT

With the additional funding requested in FY 2024, NOAA will be able to acquire the single-face rotating PAR Test Article necessary to determine the feasibility and capability of using rotating PAR to improve NOAA's weather prediction for the Nation. A report will be developed to document the findings of the R&D that will be completed with the PAR Test Article and this report will be used to inform NOAA's AoA. After completion of the AoA, NOAA will choose between the identified alternatives (i.e., SLEP, replacement dish radar, PAR) or other possible alternatives. Of these three currently known options, the PAR technology is the only alternative that could meet the NWS' emerging objective for faster volumetric updates (i.e., 60-90 seconds). NOAA is considering two potential configurations for the PAR alternative: 1) a fixed 4-face planar system with a higher upfront procurement cost and operating cost, less technical risk, and a high degree of scanning flexibility; and 2) a rotating PAR with MSB scanning strategies with a lower upfront procurement cost and operating cost, higher technical risk, and a lower degree of scanning flexibility. The acquisition costs and operational costs (e.g., electricity) of a single-face rotating PAR are expected to be three times less expensive than a 4-face stationary PAR configuration. The proposed rotating PAR Test Article is needed to perform R&D activities on the MSB scanning strategies and to better understand any scanning limitations compared to the 4-face planar concept.

Market research conducted over the past year indicates that industry is capable of delivering a single-face rotating PAR Test Article in the S-band, with multiple options, including various architectures, digitization, and polarimetric capabilities. Market research also indicates that industry should be able to deliver the planned rotating PAR Test Article within the anticipated time frame needed to conduct the MSB risk reduction if supply chain constraints do not increase. The proposed single-face rotating PAR Test Article with highly digital architectures will enable R&D for technical risk reduction of the rotating PAR concept that could result in significant savings relative to the 4-face planar system. The highly digital nature of the proposed system is also critical and would provide additional evaluation needed even for the 4-face planar configuration.

This proof-of-concept rotating PAR Test Article would focus on reducing the technical risks associated with MSB scanning strategies to obtain rapid volume update times. In addition research completed with this rotating PAR Test Article and the ATD will help inform the NWS' AoA to determine which alternative is more viable and potentially cost effective. The feasibility of the rotating PAR with MSB scanning strategies will only be fully known after demonstration and evaluation of the various MSB techniques inherent in the risk reduction activities. Meanwhile, NOAA will continue R&D activities with the available PAR assets (ATD and Horus) to better understand the performance benefits of digital arrays, performance tradeoffs of different scanning strategies, and pathfinding of rotating PAR concepts.

VIII. LIST OF ACRONYMS

AoA	Analysis of Alternatives
AESA	Active Electronically Scanned Array
ARRC	Advanced Radar Research Center
ATD	Advanced Technology Demonstrator
DPPAR	Digital Polarimetric Phased Array Radar
FAA	Federal Aviation Administration
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
MPAR	Multifunctional Phased Array Radar
MSB	Multiple Simultaneous Beams
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
NWRT	National Weather Radar Testbed
OAR	Oceanic and Atmospheric Research
PAR	Phased Array Radar
RL	Readiness Level
ROC	Radar Operations Center
SENSR	Spectrum Efficient National Surveillance Radar
SLEP	Service Life Extension Program
RL	Readiness Levels
WSR	Weather Surveillance Radar
WSR-88D	Weather Surveillance Radar – 1988 Doppler