REPORT TO CONGRESS

WEATHER RADAR FOLLOW-ON PLAN: RESEARCH AND RISK REDUCTION TO INFORM ACQUISITION DECISIONS

Developed pursuant to: Title 1, Division C of the Joint Explanatory Statement accompanying the Consolidated Appropriations Act, 2019 (Public Law 116-6)

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TITLE 1, DIVISION C OF THE JOINT EXPLANATORY STATEMENT ACCOMPANYING THE CONSOLIDATED APPROPRIATIONS ACT, 2019 (PUBLIC LAW 116-6) INCLUDED THE FOLLOWING LANGUAGE

Multi-Function Phased Array Radar (MPAR) Program.—The fiscal year 2018 appropriations Act directed the National Oceanic and Atmospheric Administration (NOAA) to maintain its leadership in the Spectrum Efficient National Surveillance Radar (SENSR) Program. There is frustration with the decision to de-scope the SENSR program by removing the high-resolution weather sensing requirements, and concern that NOAA is unprepared to execute a weather radar follow-on program. In lieu of Senate language, the agreement directs the Office of Oceanic and Atmospheric Research (OAR), in coordination with the National Weather Service (NWS), to develop and submit to the House and Senate Appropriations Committees, within 90 days of enactment of this Act, a weather radar follow-on research-to-operations transition plan, in accordance with the requirements for agency transition plans set forth under NOAA Administrative Order 216-105B, section 3.06.

THIS REPORT RESPONDS TO THE COMMITTEES' REQUEST.

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I. EXECUTIVE SUMMARY

The National Oceanic and Atmospheric Administration (NOAA) has been a leader in developing weather radar technology, which has gained widespread use in the government and commercial sectors around the world. NOAA research has led to the development of the Weather Surveillance Radar – 1988 Doppler (WSR-88D, or NEXRAD), which is arguably the premier operational weather radar in existence today. WSR-88D is the primary tool used by weather forecasters to provide warnings for severe weather (e.g., tornadoes, hail, strong winds), flash flooding, winter weather, and other hazards to aviation.

The NOAA National Weather Service (NWS) is conducting Service Life Extension Program (SLEP) activities to extend the operational capability of the system until an approximate timeframe of 2035 and on-going information technology refresh and sustaining engineering programs will support the continued operation of the NEXRAD network through the 2040 timeframe. NOAA will need to make a key decision by 2028 to continue maintaining the current system or to replace it with a new radar network. The WSR-88D underlying technology will be over 50 years old by 2040, although it has undergone multiple technology refreshes and upgrades, such as the addition of dual polarization capability that was completed in 2013. Dual polarization, the ability to transmit and receive both horizontal and vertical polarizations, provides for improved observations of precipitation rates and types, as well as cloud circulation patterns and debris detection to better isolate potential tornadic events.

NOAA's Office of Oceanic and Atmospheric Research (OAR) has been investigating Phased Array Radar (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. However, there are many technological risks that must be addressed before PAR technology can serve as a replacement for the WSR-88D system. Chief among these technology risks is the addition of dual polarization with PAR technology.

NOAA, in partnership with the Federal Aviation Administration (FAA), has developed the Advanced Technology Demonstrator (ATD), which is the first dual polarization PAR developed specifically for weather applications. The ATD is a proof-of-concept system that was installed at NOAA's National Severe Storms Laboratory (NSSL) in Norman, Oklahoma in 2018 to evaluate dual polarization calibration and performance on PAR technology and to demonstrate advanced scanning techniques for weather radars using PAR. The ATD is undergoing initial calibration evaluation and will provide experimental demonstrations in the spring of 2020.

Development of the ATD has moved PAR technology to Readiness Level (RL) 5 for dual polarization meteorological applications.[1] Further research and development is needed before NOAA can make a high-confidence decision regarding PAR technology as an appropriate replacement for WSR-88D. The research plan described herein considers the NWS

[1] NOAA, 2016. NAO 216-105B: Policy on Research and Development Transitions. (https://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/216-105B.html)

requirements, capabilities of various radar technologies, affordability, cost of maintenance, as well as benefits of different alternatives.

NOAA has developed a research plan to enable the technological progress needed to prepare for a formal Radar Acquisition Management Program (RAMP) beginning in 2028. RAMP will compare the cost-benefit analysis of: 1) sustaining the current system through an additional SLEP; 2) replacing WSR-88D with a new reflector dish, mechanically rotating radar system; or 3) replacing WSR-88D with the promising PAR technology currently being investigated by OAR. PAR technology will continue to be evaluated as a potential replacement technology for WSR-88D unless the ongoing research, development, and evaluation determines it is unsuitable or too costly for implementation.

II. INTRODUCTION

NOAA has long pioneered the research, development, procurement, transition, sustained operation, and maintenance of evolutionary advancements in weather surveillance radar technology. The foundations of these advancements are supported through collaboration between NWS and OAR and its strategic investments in operations and research. The resulting WSR-88D network is a cornerstone of NOAA's weather mission.

This report is in response to the Joint Explanatory Statement charge to submit "... *a weather radar follow-on research-to-operations transition plan, in accordance with the requirements for agency transition plans set forth under NOAA Administrative Order 216-105B, section 3 .06*" and describes NOAA's strategy to continue radar improvements through research, development, and integrated risk management. The content describes NOAA's sustained and innovative leadership in radar advancement, operations, and service delivery. Furthermore, significant recent progress by NOAA towards resolving key questions for meteorological PAR has motivated several accelerated risk reduction activities that will help identify the architecture needed for future radar replacement.

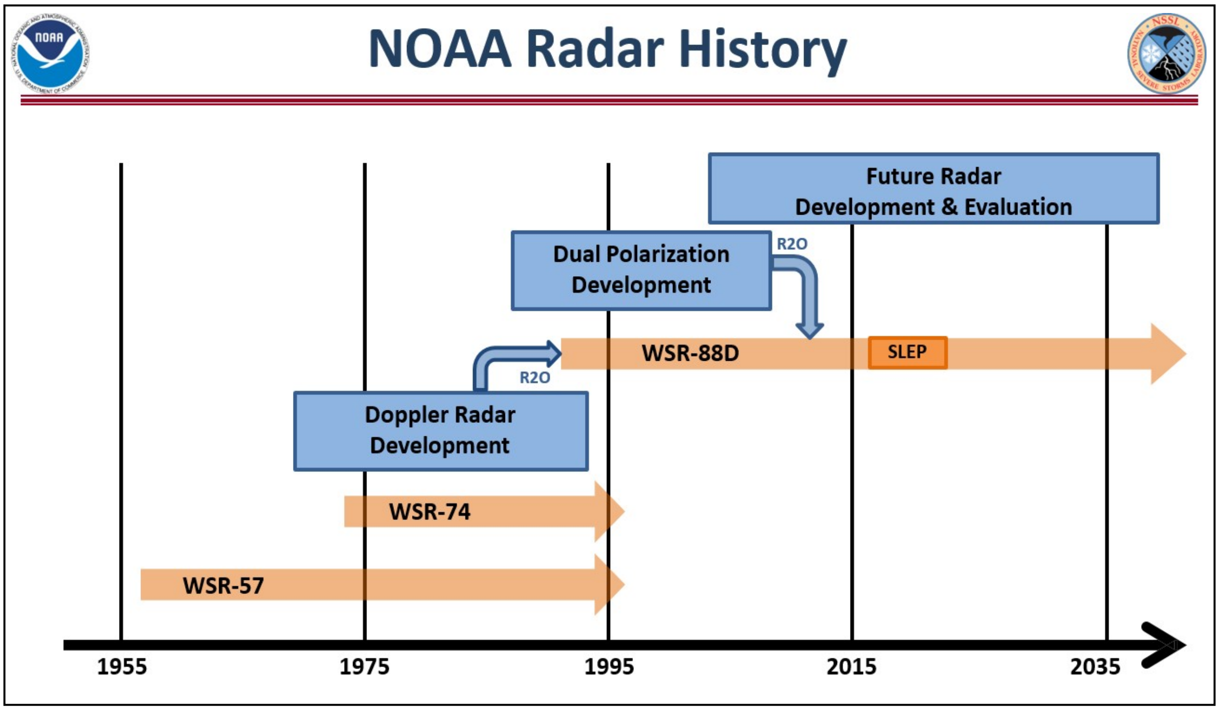
The report begins with a review of NOAA's leadership role in advancing weather radar, the current weather radar system, and charting the path ahead. Central to the strategic path forward is implementing a cohesive suite of research, development, and risk management elements that ensure the best investment decisions are made, and the best weather forecasts and warnings are provided to the Nation. For example, assessing NOAA's research and development in PAR is critical in determining if the rapid, adaptive scanning enabled by this technology can improve severe weather warning performance achieved with dual polarization WSR-88D. Subsequent sections of the report lay out the significant integrated elements of risk management and reduction that will position NOAA to make key investment decisions in 2028.

III. NOAA RADAR BACKGROUND

A. The Evolution of Weather Radar

NWS provides weather, water, and climate data, forecasts and warnings for the protection of life and property, and enhancement of the national economy. Since 1959, core observing data for forecasts and warnings have been provided by WSR systems. Throughout this period, OAR and NWS have pioneered the research, development, procurement, transition, sustained operation, and maintenance of evolutionary advancements in WSR technology (Figure 1). Each of these systems was a response to the recognition of new needs, opportunities and/or limitations of the prior generation radar.[2]

Figure 1. Timeline of Major Advancements in WSR Systems



(Tan = previous and ongoing operational NOAA Radars; Blue = previous and ongoing NOAA Radar research and development focus areas)

The successful outcomes of NOAA's leadership in WSR are carefully tracked. For example, the precipitation estimates from the radar have vastly improved NWS flash flood warning prediction, and the lead time has increased from about 7 minutes in the late 1980s, to 62 minutes today. In addition, until the WSR-88D network was deployed in the 1990s, the most intense, deadly, Enhanced Fujita (or EF)-3 and greater tornadoes were

[2] National Research Council, 2002. Weather Radar Technology, Beyond NEXRAD. Washington, DC. National Academy Press; Whiton, R. et al., 1998. History of Operational Use of Weather Radar by the U.S. Weather Services. Part I: The Pre-NEXRAD Era, Americana Meteorological Society.

typically only warned for after touchdown was observed. These intense tornadoes are now warned with average lead times ranging from 15 to 25 minutes.[3]

NOAA's Observing System Integrated Analysis quantified the significant impact of its current operational radar for the agency's weather mission service areas (Table 1). These data indicate that radar is the second most impactful observing system for the overall weather mission, and the highest impactful observing system for three mission service areas – fire weather, hydrology, and severe thunderstorms.

Table 1. Impact of NOAA's WSR on Weather Mission Service Areas

Mission Service Areas	Impact Rank	Impact Description
Weather Mission (Overall)	2	**Very High**
Aviation Weather and Volcanic Ash	2	**Very High**
Fire Weather	1	**Very High**
Hurricanes/Tropical Storms	3	High
Hydrology and Water Resources/Integrated Water Prediction and Information	1	**Very High**
Marine Weather and Coastal Events	4	High
Public/Routine Weather	3	**Very High**
Severe Thunderstorms, Tornados, and Flash Floods	1	**Very High**
Space Weather	N/A	N/A
Tsunami	N/A	N/A
Weather-Ready Nation Science, Services, and Stewardship Advances	2	**Very High**
Winter Weather	3	**Very High**

B. The Current Weather Radar System

NOAA's current operational system comprises WSR-88D radars, also known as NEXt-generation RADar (NEXRAD). The first WSR-88D became operational in 1993 – and the last radar was installed in 1998 – with an existing Department of Defense (DoD) training radar moved to Langley Hill, Washington, in 2011 in response to Congressional direction. Throughout this time, numerous significant upgrades were transitioned from research to operations, such as the addition of dual polarization capabilities completed in 2013. NEXRAD continues to be the prime observing system for NWS, acquiring information about tornadoes and severe storms (storms containing damaging winds, hail, turbulence, and lightning). NEXRAD provides information on precipitation rates and types leading to better flash flooding with longer lead times and heavy snow warnings focused over smaller areas and is a key element in the forecasting of aviation-related weather events. The NEXRAD network is composed of 159 operational radars managed

[3] NOAA, 2018. National Weather Service Performance Management Portal (https://verification.nws.noaa.gov/services/gpra/NWS_GPRA_Metrics.pdf).

by NWS (122), FAA (12), and the U.S. Air Force (25), as well as 8 radars used for training and depot-level support. The radars are located throughout the United States and its territories, as well as several overseas locations (including two in South Korea and one in Okinawa).

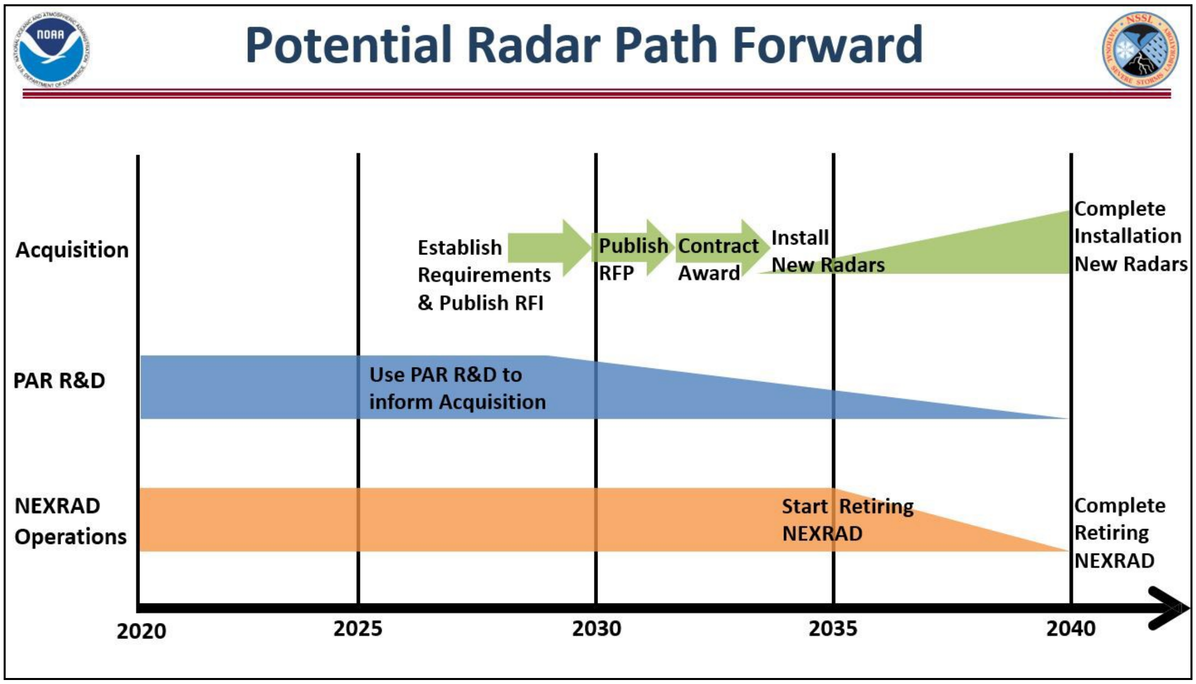
Three Federal Agencies

NOAA, FAA, and DoD support the costs of the Radar Operations Center that provides NEXRAD network operation and maintenance (O&M). The NEXRAD Program Management Committee is the tri-agency decision-making body, with each agency possessing one voting member. By tri-agency agreement, NWS is responsible for NEXRAD program management and implementing O&M support, including day-to-day operations, sustaining engineering, software maintenance, information technology security compliance, and system enhancements. The NEXRAD network is operated and maintained to meet overall the network tri-agency requirement of 96-percent service availability. Many components of the NEXRAD system are subject to technological obsolescence and require ongoing technology refresh to sustain service current design life. An aggressive SLEP is ongoing and provides continuous technology refreshment to ensure NEXRAD's high level of performance. SLEP is replacing obsolete transmitters – and refurbishing pedestals and shelters – that will extend the viability of these systems to an approximate timeframe of 2035 and continue operation to 2040 supported by ongoing sustaining engineering. SLEP is not only refurbishing the existing system, but also provides a cost-effective approach to preserving this $3.1 billion capital investment.

C. The Path Forward

NOAA is actively preparing and planning for the analysis of alternatives and acquisition for a WSR-88D follow-on (Figure 2). A promising alternative is PAR technology, which has the potential to significantly advance NOAA's radar-based watches and warnings. Since 2003, OAR has been a leader in advancing and evaluating PAR weather surveillance radar capabilities. Based on the current state of technology and responses from industry to the Request for Information (RFI) other alternatives may include: 1) a second SLEP; or 2) acquisition of a center-fed parabolic antenna system (similar to NEXRAD technology). Central to this process is identifying, managing, and reducing risks related to operational and research requirements, technology maturity, performance, life-cycle costs, and spectrum availability. The following section describes integrated risk management and reduction elements NOAA is implementing to ensure continued world-class weather surveillance radar capabilities.

Figure 2. Tentative Timeline of the WSR Path Forward



(RFI = Request for Information; RFP = Request for Proposals)

IV. Integrated Risk Management and reduction Elements for NOAA's Future Radar

A. Validate Requirements

The foundation of any mature program is mission-based validated requirements. NOAA has developed a robust suite of validated current capabilities, threshold requirements, and objective requirements. These are described formally in the NOAA/NWS Radar Functional Requirements document.[4]

For completeness, NOAA also developed both a functional (technology independent) and technical requirements set. This enables NOAA to identify the minimum capabilities any replacement system must deliver (threshold) as well as the trade space (between threshold and objective) that new systems could potentially provide. NOAA has formally defined these requirement categories as the following:

1. Current: Present operational capabilities
2. Threshold: Expected operational capabilities in 2030 due to currently programmed activities such as SLEP, Technology Refresh, and Product Improvement programs
3. Objective: Beyond planned improvements but are NOAA observing requirements demonstrated by research and validated by the NOAA Observing Systems Council.

[4] NOAA, 2015. NOAA/National Weather Service Radar Functional Requirements (https://www.roc.noaa.gov/WSR88D/PublicDocs/NOAA_Radar_Functional_Requirements_Final_Sept%202015.pdf).

B. Sustain and Enhance NEXRAD

Through sustaining engineering and technology refresh investments, NEXRAD will continue to be upgradable, reliable, and maintainable through an approximate timeframe of 2040, given the SLEP investment that extends the current design life of critical NEXRAD components out to the 2035 timeframe. To maximize its reliability, increase performance, reduce operational costs during this period, and improve decision-making capacity for forecasters, several distinct risk reduction elements are being undertaken:

1. NEXRAD SLEP – to retrofit the core components of each NEXRAD including the pedestal, shelter, transmitter, and signal processor (SLEP was initiated in 2013 and is on track to be completed by 2023)
2. NEXRAD improvements during and after SLEP – This effort involves ongoing software, hardware, and system modifications to:

    a. Sustain technical requirements and functionality;
    b. Improve radar reliability;
    c. Address obsolescence;
    d. Integrate new technical capabilities;
    e. Improve the rate of the data processing; and
    f. Maintain security.

These activities advance expertise in radar fundamentals and position NOAA to evaluate existing and new technologies during the acquisition phase.

C. PAR Research and Development to Reduce Acquisition Risk

NOAA will continue its research, development and demonstration activities to determine which future weather radar architecture best meets current and future operational requirements, whether the underlying technology is mature, and whether it will be affordable from both acquisition and life-cycle support perspectives. NOAA is focusing on PAR because of its ability to address currently unrealized objective requirements for more rapid and adaptive volumetric scanning. Analyses and demonstrations at OAR's NSSL over the past 15 years have provided evidence that PAR has the potential to improve the accuracy and lead-time for severe weather warnings, and facilitate measurement of meteorological targets that are currently not well observed (e.g., clear air moisture and winds). Furthermore, the mitigation of interference such as wind-farm "clutter" and external radio frequency emissions are areas of newer inquiry that could have significant operational value. A dual polarization Advanced Technology Demonstrator (ATD) phased array radar was installed at NSSL in 2018 specifically to evaluate PAR technology as a weather radar. In parallel with PAR-focused risk reduction, work will continue to develop new scanning and processing techniques that can also optimize the operational capabilities of mechanically scanned, reflector radars, such as WSR-88D. This new PAR technology will ensure that NWS mission capability is maximized, should the NWS ultimately decide to replace WSR-88D with this class of radar.

The remainder of this section describes activities and decision points necessary to determine whether meteorological PAR can be advanced from its current RL 5 (validation through testing and prototyping) to RL 7 (functionality demonstrated in near-real-world environment) by 2028. If successful, these technology maturation activities and functional capability demonstrations will allow the NWS to make a high-confidence decision as to whether PAR is an appropriate technology for future replacement of the WSR-88D. A follow-on, NWS-led full-scale development and test contract with industry would then be required to complete the transition to RL 8 (finalized system development and testing).

Research Background

Table 2 highlights key meteorological PAR research areas that have been the foundation for PAR research conducted since 2003, at NSSL. During the last 4 years, accelerated progress in addressing these has been possible through ongoing funding from OAR, and a feasibility study supporting the Spectrum Efficient National Surveillance Radar (SENSR) program.[5]

Table 2. Key Meteorological PAR Research Areas

Research Areas
Architecture (Array Geometry, Array Size, Level of Digitization)
Polarimetric Calibration and Compensation
Data Quality Differences Relative to WSR-88D
PAR Technology Evolution (Capability and Cost)
Concept of Operations (Scanning Strategies, Interface to Forecasters, NWP Assimilation Methods
Forecast and Warning Service Benefits
Radar Network Laydown and Supplementary Sensors

Array geometry, level of digitization, and array size have a critical impact on the complexity of calibration/compensation techniques for dual-polarization observations[6], flexibility and rate of scanning[7], and angular resolution. The engineering issues that will drive the choice of array architecture are being addressed using a number of PAR prototypes – the ATD described below, a cylindrical polarimetric PAR[8], and an all-digital planar PAR dubbed "Horus."[9] Ongoing experiments using near- and far-field calibration

[5] M. Weber, et al., "Assessing the Weather Observation Capabilities of a Spectrum Efficient National Surveillance Radar (SENSR)", 38th AMS Conference on Radar Meteorology, 28 August – 1 September, 2017, Chicago, IL.
[6] Zhang, G., R.J. Doviak, D.S. Zrnic, R. Palmer, L. Lei, and Y. Al-Rashid, "Polarimetric Phased-Array Radar for Weather Measurement: A Planar or Cylindrical Configuration?" Journal Atmos. Ocean. Tech., vol. 28, pp. 63-73, 2011.
[7] Fulton, C., M. Yeary, D. Thompson, J. Lake, and A. Mitchell, "Digital Phased Arrays: Challenges and Opportunities", Proc. IEEE, vol. 104, pp. 487-503, 2016.
[8] M. Galletti, D. Zrnic, G. Zhang, D. Doviak, J. Crain, "CPPAR – Cylindrical Polarimetric Phased Array Radar System Design", 2001 IEEE Radar Conference, Kansas City, MO, 2011.
[9] R.D. Palmer, "The 'Horus' Radar – An All-Digital Polarimetric Phased Array Radar for Multi-Mission Surveillance", AMS Phased Array Radar Conference, Paper 8A.6, Phoenix, AZ, 2019 (https://ams.confex.com/ams/2019Annual/webprogram/Paper349962.html).

sources and storm target-of-opportunity measurements[10] are designed to determine the strengths and limitations of these various architectures for meeting the observational requirements of the NWS mission.

A high-fidelity Signal Processing and Radar Characteristics (SPARC) simulator[11] has been developed to broaden these performance assessments to many different PAR configurations. SPARC is being used to assess architectures such as a rotating planar array, alternative spatial and temporal sampling techniques, and advanced signal processing techniques not readily emulated with our current hardware platforms. These simulations provide a critical method to assess tradeoffs between the scanning benefits of various PAR configurations and possible impacts on the quality of meteorological variable estimates, as well as improve the scanning rates, providing for decreased time and latency between observational data/information access for improved decisions.

Previous studies have documented the potential advantages of rapid-scan PAR data, both through direct presentation to forecasters[12], and through assimilation into high-resolution numerical weather prediction models.[13] Current research is focused on assimilation technique development for this latter paradigm, Warn on Forecast (WoF)[14] Observational studies using NSSL's experimental WSR-88D operating in a rapid sector-scan mode have documented the value of monitoring rapidly evolving, detailed storm features.[15] Finally, econometric studies of operational impacts of enhanced low altitude coverage for tornado warning and flash flood have shown that a more dense radar network would be beneficial[16], particularly for WoF efforts.

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[10] Fulton, C., J. Salazar, Y. Zhang, G. Zhang, R. Kelly, J. Meier, M. McCord, D. Schmidt, A. Byrd, L. Bhowmik, S. Karimkashi, **D.** Zrnic, R. Doviak, A. Zahrai, M. Yeary, and R. Palmer, "Cylindrical Polarimetric Phased Array Radar: Beamforming and Calibration for Weather Applications", IEEE Trans. Geoscience Remote Sensing, vol. 55, pp. 2827-2840, 2017.

[11] Schvartzman, D. and C. Curtis, "Signal Processing and Radar Characteristics (SPARC) Simulator: A Flexible Dual-Polarization Weather-Radar Signal Simulation Framework Based on Preexisting Radar-Variable Data", IEEE J. Selected Topics Appl. Earth Obs. Remote Sensing, vol. 12, pp. 135-150, 2018.

[12] Heinselman, P.L., D.S. LaDue, M. Kingfield, and R. Hoffman, 2015: Tornado warning decisions using phased-array radar data. Weather Forecasting, 30, pp. 57-78.

[13] N. Yussouf and D.J. Stensrud, "Impact of phased-array radar observations over a short assimilation period: Observing system simulation experiments using an ensemble Kalman filter", *Mon. Wea. Rev.*, vol. 138, no. 2, pp. 517-537, 2010.

[14] Huang, Y., X. Wang, C. A. Kerr, A. Mahre, T. Yu, and D. Bodine, "Impact of assimilating clear-air radar observation on the forecasting of supercell thunderstorm: An observing system simulation experiment study", Mon. Wea. Rev., to be submitted.

[15] Kuster, C.M., J.C. Snyder, T.J. Schuur, J.W. Brogden, R. Toomey, and P.L. Heinselman, "Rapid-Scan Radar Observations of Zdr Column Depth and Its Potential Use During the Warning Decision Process", *29th Conference on Weather Analysis and Forecasting*. Denver, CO, American Meteorological Society, Boston, 15A.7, 2018; Wen, Y., T. Schuur, H. Vergara, and C. Kuster, "Advancing flash flooding early warning using a rapid-scan polarimetric radar observations", *9th Workshop of International Precipitation Working Group*, Seoul, South Korea, 2018; Kuster, C. M., B. R. Bowers, T. J. Schuur, J. Brogden, and R. Toomey, "Identifying Downburst Precursor Signatures in K_{DP}", AMS Annual Meeting, Conference on Environmental Information Processing Technologies, Phoenix, AZ, American Meteorological Society, 8A.1, 2019; Wen, Y., T. Schuur, H. Vergara, and C. Kuster, "Advancing flash flooding early warning using a proxy of PAR observations", AMS Annual Meeting, Symposium on Phased Array Radar. Phoenix, AZ, American Meteorological Society, 2019.

[16] Cho, J.Y.N. and J.M. Kurdzo, "Weather radar network benefit model for tornadoes", J. Appl. Met. and Climate, 2019, https://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-18-0205.1; Kurdzo. J.M, E.F. Clemons, J.Y.N. Cho, P.L. Heinselman and N. Yussouf, "Quantification of radar QPE performance based on SENSR network design possibilities", Conference Proc., IEEE Radar Conference, Oklahoma City, OK, 2018.

This significant recent progress towards resolving key questions for meteorological PAR motivates accelerated risk reduction activities that support the need for NWS to determine the architecture for its future WSR-88D replacement.

Planned Risk Reduction Activities

The ATD is a foundational asset for NOAA's planned acquisition risk reduction program. In 2020-2022, data collection, analysis and demonstration will determine whether PAR can meet NWS requirements for quality of observations, while increasing the overall temporal sampling rate and adaptively concentrating observations in volumes of high importance in comparison to current WSR-88D operationally available data. Two key determinations will be the effectiveness of PAR dual-polarization calibration techniques and the capability to realize desired scanning capabilities through transmit/receive/processing techniques tailored to PAR. In parallel, benefits for the assimilation of rapid update PAR observations in the WoF system will be assessed and tests with forecasters will be conducted to demonstrate operational suitability. At the end of 2024, a determination will be made as to whether – with reasonable expectations for ongoing technology maturation – PAR remains a promising operational candidate for the WSR-88D replacement network.

If this determination is positive, efforts in 2023-2025 will develop high-fidelity prototypes supporting operational evaluation of PAR. This reference architecture will include: 1) a "Generation 2 ATD" providing observational capabilities consistent with NWS objective requirements; 2) a real-time WoF-PAR probabilistic warning system matched to the observing capabilities of the Generation 2 ATD; and 3) appropriate forecaster Human-Machine Interface (HMI). HMI will likely include software interface based on developing artificial intelligence capabilities to view, manipulate, process, and integrate information provided by the PAR processing systems. Operational evaluations in 2025-2027 will assess the technical suitability of the prototype systems, their benefits for warning and forecast services, workload impacts, and the suitability of the overall concept of operations. These evaluations may also enable initial assessment of forecaster training issues for the new technology, as well as system maintainability in a quasi-operational configuration.

Acceptance Criteria

Through the applied research, demonstration, evaluation and documentation activities described above, NOAA will determine if PAR is a suitable operational replacement for the WSR-88D system. Key acceptance criteria are that PAR be shown to:

1) Replicate or improve the observational capabilities of the WSR-88D in terms of reliability, spatial resolution, sensitivity, meteorological variable detection, accuracy and volumetric coverage;
2) Enable volumetric scan rates sufficient to improve the lead-time and/or skill (e.g., critical success index) of severe weather warnings, in particular for tornadoes.

Research has shown that volumetric scan rates of once per minute achieve this objective;

3) Improve the ability to mitigate interference from wind turbines and other non-meteorological scatterers by means of adaptive scanning and beam shaping;
4) Improve the ability to measure winds and infer moisture through the use of adaptively scheduled, ultra-long dwell waveforms, and advanced data processing techniques; and
5) Be affordable, considering lifecycle costs, reliability requirements and benefits, program funding profile, and other agency needs.

In parallel, NOAA will continue interactions with industry, external research partners and relevant government acquisition programs (e.g., SENSR) to leverage knowledge that can also advance weather radars. These interactions are needed to assess whether the technology necessary for meteorological PAR is mature, affordable, deployable, and maintainable by the time an NWS acquisition review process and decision is required.

Milestones and Deliverables

Key milestones for the risk reduction program, including efforts underway or already completed are as follows:

▪ Jan. 2014	ATD development commences
▪ July 2015	Cylindrical polarimetric PAR evaluations commence
▪ July 2016	All Digital PAR prototype development commences
▪ Sept. 2017	SENSR feasibility study addressing meteorological PAR commences
▪ July 2018	ATD installed at NSSL
▪ Dec. 2019	SENSR feasibility study final report
▪ Mar. 2020	ATD Initial Operational Capability (IOC) achieved
▪ Apr. 2020 – Dec. 2022	ATD science studies and operational demonstrations
▪ Dec. 2024	Determine whether PAR remains a strong alternative for WSR-88D replacement system
▪ Dec. 2025	High-fidelity PAR operational evaluation system developed
▪ Dec. 2027	PAR operational evaluation completed
▪ Dec. 2028	PAR acquisition artifacts delivered to NWS

The acquisition artifacts derived from this sustained research and development effort will include:

- Mature radar technical requirements;
- Validated system-level concept of operations;

- Technical exhibits – the prototype systems and associated design and performance data – which could be provided to industry as government furnished information (GFI);
- Cost/benefit analysis; and
- Evaluation of radar network modifications relative to today's laydown (e.g., deployment of gap-fillers where cost/benefit analysis justifies this).

If the acceptance criteria in the preceding subsection are demonstrated, NWS will be in a position in the late 2020s to release a Request for Information (RFI) and subsequent RFPs to industry. This industry contract for full scale development would be structured to bring meteorological PAR to RL 8.

Risks and Mitigations

The time-phased research and demonstration activities described above provide defined decision points and off-ramps should PAR be deemed at any point to pose unacceptable risks as a replacement for the WSR-88D. Table 3 summarizes high level risks and mitigations associated with this effort.

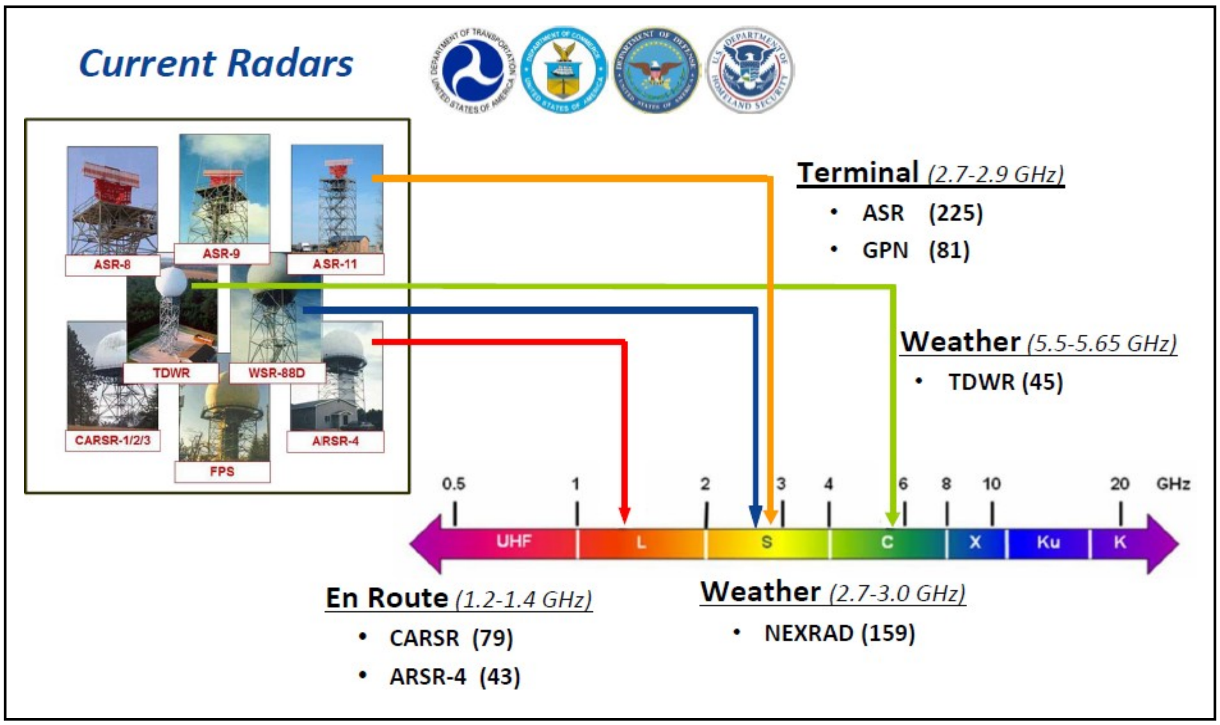
Table 3. PAR Risks and Mitigation Strategies

Risk	Mitigation Strategies
PAR cannot fully meet NWS Radar Functional Requirements owing to inherent differences relative to a mechanically scanned reflector antenna	Any requirements shortfalls will be identified during this transition plan. If these are unacceptable to NWS and cannot be mitigated, the transition process will be terminated.
Monetized operational benefits for PAR do not exceed the additional costs for acquisition and operation, relative to a mechanically scanned reflector antenna system	Cost benefit analysis will be a significant aspect of this transition. If the cost/benefit analysis is not viewed as acceptable, the transition process will be terminated.
PAR technology does not mature sufficiently to meet NWS requirements for manufacturability and maintainability for the WSR-88D replacement system	Industry engagement, and coordination with the highly relevant SENSR acquisition program will be significant throughout this transition project. If at any point, it appears that PAR technology maturation will be insufficient to meet NOAA needs, the transition process will be terminated.
Transition schedule is not achieved owing to unforeseen technical issues, delay in funding or other factors	NSSL will provide quarterly transition progress reports to OAR and NWS. These will identify schedule slippages, if any, and proposed mitigations.

D. Manage Spectrum

Spectrum has become a very valuable commodity and is highly regulated by the Federal Communications Commission for state/local government and private users and by the National Telecommunications and Information Administration for Federal Government users. There is a major interest in increasing utilization by the private sector which is limiting available spectrum for federally-supported observations. The S-band – which is used for NEXRAD (Figure 3) and is viewed as an essential basis for the success of the NEXRAD observations of reflectivity, precipitation type, and wind – is expected to be a targeted landing band by the SENSR Program. While NOAA will have a non-voting, advisory role in the SENSR Program, NOAA will be provided access to proposed SENSR solutions to ensure there are no impacts to NEXRAD. The interest in increasing spectrum utilization will require NOAA to engage in formal processes to defend its S-band allocation and possibly accommodate new users while also limiting opportunity for a bigger NOAA footprint.

Figure 3. Current Spectrum Usage for Various Radar Technologies



For future NOAA radars, NOAA will need to determine spectrum needs and coordinate with other incumbent and adjacent users, likely to include SENSR, to receive spectrum certification. A primary focus of the National Telecommunications and Information Administration (NTIA) spectrum certification and frequency assignment process will be an electromagnetic compatibility analysis that NOAA will conduct as part of the acquisition process in accordance with OMB A-11 and the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management. Research and development supporting the electromagnetic compatibility analysis will be required to ensure NOAA will not impact other users in and around the selected frequency band (presumably 2.7 to 3.0 GHz) and is well positioned to justify current and future spectrum requirements.

E. Organize for Success

The past and ongoing evolution of NOAA's weather radars has a foundation of strong intramural, extramural, and inter-agency collaborations. Within NOAA, the lead units are the NWS Office of Observations/Radar Operations Center (ROC) and OAR NSSL. The co-location of both in Norman, Oklahoma, allows for a continuous feedback loop of research to operations and operations to research activities. The high priority of NOAA's radar is emphasized by quarterly briefings of all major radar related programs (NEXRAD SLEP, PAR, and SENSR) to NOAA's Program Management Council. The governance and oversight proactively identifies and mitigates program risks and issues.

The ROC was established by the NEXRAD agencies in 1988 to provide centralized meteorological, software, maintenance, and engineering support for all WSR-88D systems. This role has been critical in creating the robust operational performance of the current system. This approach will be expanded during the 2028-2040 time frame to handle the additional responsibilities related to transition and parallel operations during deployment. During this time frame, NOAA will also establish a formal Radar Acquisition Management Plan (RAMP).

NOAA also continues to expand and strengthen partnerships with the radar community, including leading experts at federally funded research and development centers, national laboratories, academic departments, and industry. For example, NOAA is collaborating with the National Centers for Atmospheric Research to advance Airborne Phased Array Radar. These organizations will significantly contribute to the refinement of NOAA's research to operations strategy, as well as participate in its execution. NOAA also collaborates with the University of Oklahoma's Advanced Radar Research Center (ARRC) which is also located in Norman, Oklahoma. ARRC is a key partner on numerous PAR advancement projects. Another important collaboration is with the Massachusetts Institute of Technology Lincoln Laboratory that has been integral in the successful PAR ATD deployed at Norman, in 2018.

Federal partners play a key role in NOAA's current and future radar systems. As previously noted, the NEXRAD Program Management Committee is the tri-agency decision-making body, with each agency possessing one voting member. NOAA also continues to serve an important advisory role in the SENSR program in order to assess possible impacts on the protected spectrum band used by WSR-88D. A likely benefit of this engagement will be insight into the technical maturity of PAR technology, as compared to other systems, and the viability of large-scale manufacture, deployment, and operation of such radars.

Although the high resolution weather requirements have been removed from the SENSR program, NOAA has and will continue to engage industry to share findings and determine the current state of emerging radar technologies. NOAA participated in RFIs for weather surveillance radar in 2012, 2018, and 2019. Additional market surveys will also be conducted to inform the acquisition management process.

V. Budget and Preparation for Execution

NOAA's budget balances the investments in sustained operations, service life extension, refinement in existing capabilities, and long-term research and development. NOAA's current base annual appropriated funds for NEXRAD's total operations and maintenance is approximately $73 million. In addition, the FAA and DOD contribute a total of approximately $10 million annually to the Radar Operations Center (ROC) that contributes to the overall sustainment of NEXRAD. NOAA's investment in PAR research and development in FY 2020 is approximately $11.6 million from the Tornado and Severe Storm Research budget line and has been a total of about $133 million since the inception of the program in 2003. Recapitalization alternatives of the entire system in the 2035 to 2040 timeframe have an estimated cost on the order of $6 billion. This initial estimate is based on the acquisition of the original NEXRAD system (i.e. siting, land, infrastructure, equipment) adjusted for inflation. Refined costs will be available as the acquisition program conducts key steps including finalizing requirements and conducting the RFI and analysis of alternatives process in the 2026 to 2030 time frame.

VI. Summary

NOAA has pioneered the research, development, procurement, transition, sustained operation and maintenance of evolutionary advancements in weather surveillance radar technology. The foundation of these advancements is collaboration between NOAA's NWS and OAR, and its strategic investments in operations and research. The current WSR-88D network is the premier cornerstone of NOAA's weather mission, and the SLEP will extend the lifetime of this radar network supporting the NWS warning program through an approximate timeframe of 2035 with continued sustaining engineering and information technology refresh investment programs to support the network through 2040 when a replacement can be fielded. NOAA will continue to strategically advance the trajectory of radar improvements through research, development, and integrated risk management. Significant recent progress towards resolving key questions for meteorological PAR motivates accelerated risk reduction activities that support NWS's need to determine the architecture for its future WSR-88D replacement. This approach positions NOAA to make informed acquisition decisions in 2028, that will ensure the best weather forecasts and warnings are provided to the Nation.

List of Acronyms

ARRC	Advanced Radar Research Center
ADT	Advanced Technology Demonstrator
FAA	Federal Aviation Administration
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NTIA	National Telecommunications and Information Administration
NWS	National Weather Service
O&M	Operation and Maintenance
OAR	Oceanic and Atmospheric Research
PAR	Phased Array Radar
RL	Readiness Level
ROC	Radar Operations Center
RAMP	Radar Acquisition Management Program
SENSR	Spectrum Efficient National Surveillance Radar
SLEP	Service Life Extension Program
SPARC	Signal Processing and Radar Characteristics
WoF	Warn on Forecast
WSR	Weather Surveillance Radar
WSR-88D	Weather Surveillance Radar – 1988 Doppler

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