Future U.S. Operational Weather Radar

Opportunities and Challenges for Its Next Generation

Key messages from "Towards the Next Generation Operational Meteorological Radar," by **Mark Weber** (University of Oklahoma, and NOAA/Office of Oceanic and Atmospheric Research/National Severe Storms Laboratory*), **Kurt Hondl, Nusrat Yussouf, Youngsun Jung, Derek Stratman, Bryan Putnam, Xuguang Wang, Terry Schuur, Charles Kuster, Yixin Wen, Juanzhen Sun, Jeff Keeler, Zhuming Ying, John Cho, James Kurdzo, Sebastian Torres, Chris Curtis, David Schvartzman, Jami Boettcher, Feng Nai, Henry Thomas, Dusan Zrnić, Igor Ivić, Djordje Mirković, Caleb Fulton, Jorge Salazar, Guifu Zhang, Robert Palmer, Mark Yeary, Kevin Cooley, Michael Istok,** and **Mark Vincent**. Published online in *BAMS*, July 2021. For the full, citable article, see https://doi.org/10.1175/BAMS-D-20-0067.1.

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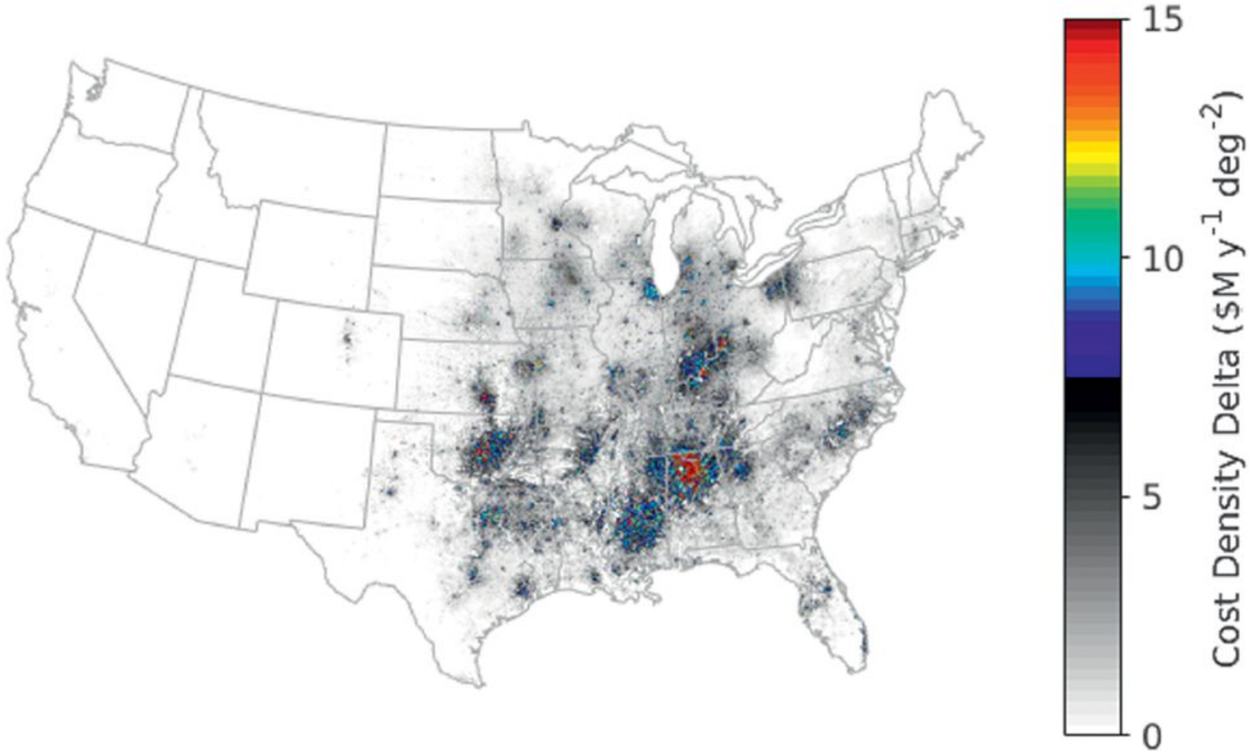
The National Oceanic and Atmospheric Administration (NOAA)'s current operational meteorological radar, the Weather Surveillance Radar 1988 Doppler (WSR-88D), was designed with the high sensitivity, angular resolution, transmit/receive stability, and pointing accuracy necessary to provide the excellent-quality observations required by its user community. Its upgrade to a dual-polarization configuration in 2013 enabled discrimination between different hydrometeor types; identification of nonmeteorological scatterers such as insects, birds, and chaff; and improvements to the accuracy of quantitative precipitation estimates (QPE). Analysis indicates that the WSR-88D has the highest operational impact of NOAA's weather observing systems for three critical mission areas—severe thunderstorms and tornadoes, hydrology, and fire weather. NOAA has recently begun evaluating alternative strategies for further sustaining or replacing the WSR-88D network after its current end-of-service life ca. 2035.

Our research examines two critical questions that would drive the architecture of the WSR-88D's potential replacement: (1) Can improvements to the radars' temporal sampling rate (e.g., 1-min volume scans) and/or low-altitude coverage significantly enhance the utility of their data for severe weather warnings and forecasts? (2) Can the most plausible technology for improving the temporal sampling rate—phased-array radar (PAR)—provide the necessary data quality, particularly for the polarimetric variables? To address the first question, we applied storm observations and analysis, observing system simulation experiments, radar data assimilation (DA) studies, and geospatial analysis of forecaster warning performance in relation to radar coverage. Data from NSSL's Advanced Technology Demonstrator (ATD)—a 4-m diameter, 10-cm wavelength PAR—was used to examine the second question. High-level outcome examples from our work follow.

Phased array radar is synergistic with the Warn-on-Forecast System

Increasing severe thunderstorm, tornado, and flash-flood warning lead times is a key NOAA strategy for reducing casualties and



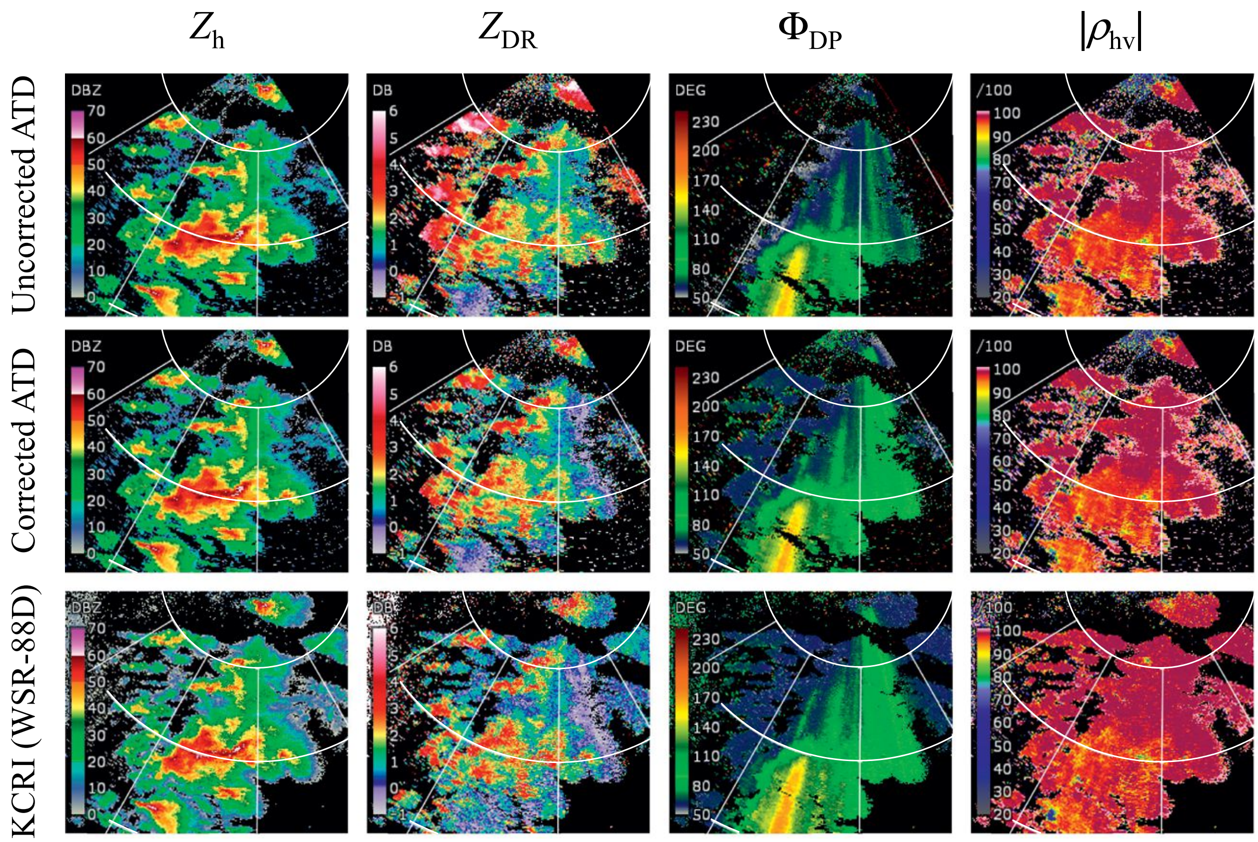
Geospatially resolved remaining cost benefits for tornado warnings from a "perfect" (versus today's) weather radar network. The "perfect" network assumes an extremely dense deployment grid (1-km spacing) so that low-altitude coverage and angular resolution are optimum. Rapid scan capability (1-min volume scans) is also assumed, with approximately one-half of the potential cost benefit attributed to rapid updates being applied to the existing radar network.

economic costs from these high-impact weather phenomena. NSSL's Warn-on-Forecast System (WoFS) addresses this strategy using a probabilistic convective-scale ensemble analysis and forecast system that assimilates in-storm observations. We used real radar observations from a tornadic supercell event (31 May 2013 in El Reno, Oklahoma) to show that rapid-update PAR observations improve the performance of WoFS. DA experiments were conducted using 1-, 3-, 5-, and 15-min cycling intervals to produce very short-term forecasts of this storm. Subjective evaluations of low-level reflectivity (Z) and midlevel updraft helicity (UH), and objective metrics including ensemble Fractions Skill Score (eFSS), showed that the 1-min PAR data assimilation cycle outperformed those with lower DA-cycling frequencies. Analysis indicated that more frequent DA improved the forecasts by developing storms more quickly in the correct locations, while removing spurious storms.

We directly compared WoFS performance using 1-min PAR data versus 5-min volume scans from the Oklahoma City WSR-88D (KTLX). The PAR-based forecasts exhibited higher probability of strong UH within the validated midlevel rotation track and better represented a secondary mesocyclone that developed behind the initial mesocyclone. More accurate UH forecasts resulted because the PAR-based WoFS analysis indicated stronger updrafts and larger midlevel temperature anomalies that sustained these updrafts.

Radar network configuration impacts warning performance

We evaluated whether deployment of a denser future radar network, or supplemental radars where there are gaps in WSR-88D coverage, might enhance severe weather warning performance with positive societal benefits. Regression analysis on many years of historical forecaster warning performance data shows that better radar coverage and performance improve warning statistics (probability of detection, lead time, false-alarm ratio), which in turn reduces casualties. Using 21 years (1998–2018) of data, we developed a model linking geospatially resolved warning performance to radar capabilities (vertical coverage, cross-range resolution) as established by the current operational network. We then showed that casualty rate is statistically dependent on these warning performance metrics and other factors (e.g., population inside a tornado path, tornado surface dissipation energy, and the fraction of



ATD reflectivity and polarimetric variable fields on 1 May 2019, (top row) without and (middle row) with bias corrections derived from near-field array characterization. The bottom row is concurrent data from the colocated WSR-88D (KCRI) operated by NOAA's Radar Operations Center (ROC) in Norman, OK. ρ_{HV} is correlation coefficient. The ATD and KCRI data were collected at the same time (19:57:43 UTC) and elevation angle (0.5°). Range rings are at 50 km and 100 km.

population residing in mobile housing). This regression model can be used to estimate monetized casualty reduction opportunities on a geospatial grid (shown in the first figure here for tornadoes), thereby providing a means for evaluating the impact of additional radars in the future network. The potential casualty reduction benefit is large, increasing the $535 M per year tornado casualty reduction benefit of the current network (WSR-88D and FAA Terminal Doppler Weather Radar) by $676 M per year for a "perfect" radar network.

Initial exploration of the dual-polarization challenge is encouraging

When a PAR's beam is electronically steered away from the array normal, biases are introduced in the polarimetric variables due to angle-dependent variations in the horizontal (H) and vertical (V) antenna patterns. One of the major challenges for adoption of PAR for weather observations is the careful calibration and bias correction necessary to achieve polarimetric data quality comparable to that from reflector antenna radars such as the WSR-88D.

Proof-of-concept for the calibration process was accomplished by characterizing the ATD H and V antenna patterns in a near-field anechoic chamber at MIT Lincoln Laboratory, prior to its deployment at NOAA's National Severe Storms Laboratory. Co- and cross-polar transmit and receive patterns at a total of 2,859 electronic beam-steering positions were measured and used to estimate the co-polar biases in Z, differential reflectivity (Z_{DR}), and differential phase (Φ_{DP}) at each beam position. Corrections for these biases were applied to ATD data collected during a severe weather outbreak in central Oklahoma and compared with "truth" from a colocated WSR-88D. Resolution cell-by-cell comparisons of the two radars' data show small median differences and interquartile difference ranges consistent with the expected variance of the polarimetric variable estimators at high signal-to-noise ratio (SNR). There are, however, a greater number of large differences ("outliers") than would be expected for a normal distribution of the variable estimate errors, possibly the effect of the two radars' different beamwidths, antenna sidelobe levels, and sensitivities. While this initial comparison is encouraging, major challenges remain that must be addressed to verify the feasibility of PAR technology as a replacement for the WSR-88D. These are discussed in the full article.

Research-to-operations is underway

Ongoing progress in advancing the maturity of meteorological PAR makes it appropriate to initiate a research-to-operations (R2O) strategy for the PAR alternative, supporting a NOAA acquisition decision (ca. 2028) for the WSR-88D replacement network. In the near term, the ATD and other experimental assets will be used to refine concepts of operation for the future radar system and address technical risks. Development of a second-generation ATD is recommended to support additional risk reduction research and development to ensure PAR can provide observing capabilities more consistent with NWS future radar requirements. A real-time "Warn-on-Forecast–PAR" capability should be developed—adapted to and benefiting from the faster-update observations provided by PAR. Operational evaluations using these systems would demonstrate benefits for warning and forecast services and assess workload impacts and the suitability of the overall concept of operations. These activities will support NOAA's initial decision in 2028 as to whether the operational benefits and technical maturity of the PAR alternative make it appropriate for the WSR-88D replacement system.

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BAMS: What would you like readers to learn from this article?

Mark Weber (University of Oklahoma, and NOAA/Office of Oceanic and Atmospheric Research/National Severe Storms Laboratory): *We hope the article helps readers appreciate how changes to the architecture of the future (post-2035) NOAA weather radar system may enhance the operational missions for which it was deployed and, at the same time, better understand the technical and operational challenges associated with the most forward-looking technology alternative, polarimetric phased-array radar (PAR). PAR's electronically shaped and steered beams enable rapid, efficient scanning but raise the need to thoroughly understand possible impacts on the quality of the radar observations. Our work explores in depth the potential benefits of rapid scanning, methods needed to realize such scanning, and the significant data quality challenges that must be addressed through robust calibration and novel processing. NOAA's decision on the suitability of the PAR-alternative for its future operational radar will be based on ongoing, data-driven evaluation of the issues discussed in our article.*

BAMS: How did you become interested in the topic of this article?

MW: *Beginning in 2006, I became involved in collaboration between the FAA and NOAA's NSSL to explore the application of phased-array radar technology—developed primarily by the defense industry—for civil missions such as commercial aircraft surveillance and weather observation. We developed a multifunction phased-array radar concept that became the basis for a sustained FAA/NOAA research program exploring phased-array technology, its scientific and operational applications, and the mission benefits that might be realized. A novel, low-cost, phased-array panel developed under this program has provided the building block for NSSL's Advanced Technology Demonstrator (ATD), data from which are crucial in this article's initial assessment of the accuracy of phased-array radar dual-polarization observations.*

BAMS: What surprised you the most about the work you document in the article?

MW: *The manner in which the results obtained independently by the participating research teams fit together was a pleasant surprise. This was not preordained, as the PIs formulated and executed their research plans separately. To foster cross-collaboration, we met four times per year for in-depth technical exchanges among the research teams and shared progress monthly through an informal technical "letter." Equally important were the complementary interests, technical competencies, and organizational cultures of the participating researchers.*

BAMS: What was the biggest challenge you encountered while doing this work?

MW: *The answer to this question would be different, I'm sure, for each of the talented researchers listed as coauthors on this article. For example, for coauthor Kurt Hondl and myself, a major challenge arose from the circumstance that the opportunity for this large-scale research program arose suddenly and was associated with a relatively short (two-year) period of performance. Defining the overall scope of the program, coordinating as necessary within NOAA and other government agencies, and working with the PIs to define the individual projects with sufficient detail also were major challenges in getting this research underway in a timely manner.*

BAMS: How will you follow up?

MW: *The full article describes ongoing work to inform NOAA's decision on PAR as an alternative for future replacement of the WSR-88D network. This work is expected to include technology development, risk reduction research, and capability demonstrations that engage with the operational severe weather warning enterprise.*