Multifunction Phased-Array Radar for Weather Surveillance

Sebastián M. Torres[1] and Pamela L. Heinselman[2]
[1]*Cooperative Institute for Mesoscale Meteorological Studies, The University of Oklahoma and NOAA/National Severe Storms Laboratory, Norman, OK, USA, sebastian.torres@noaa.gov*
[2]*NOAA/National Severe Storms Laboratory, Norman, OK, USA, pam.heinselman@noaa.gov*
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Sebastián Torres

Introduction

The U.S. Government operates seven distinct radar networks providing weather and aircraft surveillance for public weather services, air traffic control, and homeland defense. A next-generation, multifunction phased array radar (MPAR) concept has been proposed that could provide enhanced weather and aircraft surveillance services with potentially lower life-cycle costs than multiple single-function radar networks. If critical technology costs decrease sufficiently, MPAR radars might prove to be a cost-effective alternative to current surveillance radars, since the number of required radars would be reduced, and maintenance and logistics infrastructure would be consolidated.

The National Weather Radar Testbed Phased-Array Radar (NWRT PAR) is an S-band phased-array radar located in Norman Oklahoma that was established to demonstrate the MPAR concept. Since its inception, a team of scientists and engineers at the National Severe Storms Laboratory (NSSL) has enhanced the functionality of the NWRT PAR to bring it up to operational weather radar standards (such as those in the operational NEXRAD network) and, more importantly, to demonstrate new capabilities. Unlike conventional radars, which are constrained by inertial limitations of mechanical scanning, the NWRT PAR can exploit electronic beam steering to focus weather observations solely on areas of interest without having to collect data contiguously. This capability, termed adaptive scanning, produces higher temporal resolution data without sacrificing data quality or spatial resolution through more efficient use of radar resources.

Every year, the NSSL conducts the Phased Array Radar Innovative Sensing Experiment (PARISE) to explore how to best capitalize on PAR capabilities to address 21st century forecast and warning needs (Heinselman et al. 2009). National Weather Service (NWS) forecasters are invited to participate in experiments designed to demonstrate and obtain user feedback on PAR weather surveillance capabilities. During PARISE, participants are asked to evaluate the operational utility of PAR technology during real-time operational warning situations as well as through playback of archived cases. The evaluations of PAR data given by PARISE participants positively impact meteorological research and engineering development on the NWRT PAR and are a very important component of the MPAR risk-reduction effort.

This paper presents the technical and signal processing capabilities of the NWRT PAR, evolutionary scanning strategy developments that suit this unique instrument, and results from PARISE that have led to the advancement of a SPY-1A antenna from military-surveillance radar to a weather-surveillance radar with unique capabilities. Individual weather events sampled by the NWRT PAR will be used at the conference to illustrate the advantages of the high-temporal sampling capabilities provided by adaptive scanning. Finally, we present a plan for future enhancements that will continue to provide researchers and users with an optimum platform for demonstrating and evaluating the MPAR concept.

The NWRT PAR

The NWRT PAR is an S-band (9.38 cm), agile-beam, PAR system (Zrnić et al. 2007). In a nutshell, the NWRT PAR exploits a passive, 4352-element phased-array antenna to provide stationary, two-dimensional electronic scanning of weather echoes within a given 90 deg azimuthal sector. The antenna is mounted on a pedestal so that the best orientation can be selected *prior* to any data collection. The antenna beamwidth is 1.5 deg at boresite (i.e., perpendicular to the array plane) and gradually increases to 2.1 deg at ±45 deg from boresite. The peak transmitted power is 750 kW and the range resolution provided by this system is 240 m. In some aspects, such as beamwidth and sensitivity, the NWRT PAR is inferior compared to operational radars such as the Weather Surveillance Radar-1988 Doppler (WSR-88D). However, the purpose of this system is not to achieve operational-like performance or to serve as a prototype for the MPAR, but to demonstrate the operational utility of some of the unique capabilities offered by PAR technology that may eventually drive the design of future operational weather radars. Significant hardware and software upgrades have been and are needed to support the NWRT mission as a demonstrator system for the MPAR concept. Since 2007, scientists and engineers at NSSL have been improving the functionality and capabilities of the NWRT PAR to support scientific goals (Heinselman et al. 2008). These upgrades are summarized next.

NWRT PAR Hardware Upgrades

Soon after deployment of the NWRT PAR, it became apparent that proposed increasing needs for computational power and archiving of time-series and meteorological data were unsustainable with the original signal processing hardware. Accordingly, the radar signal processor was upgraded from a discontinued, proprietary cluster of multiprocessor boards manufactured by SKY Computers, Inc. to a Linux-based cluster of five dual-processor, dual-core nodes that communicate via a high-speed interconnect (Forsyth et al. 2007). The architecture of the new signal processor is based on distributed computing. That is, all nodes in the cluster work toward the common goal of real-time radar signal processing. The system is designed to optimally utilize the nodes (i.e., computational resources). Specifically, a load-balancing mechanism, in which nodes compete to read and process sets of radar data, tailors the data distribution to each node at a rate according to their capabilities. In this way, the system's scalability is facilitated by allowing a hybrid mixture of nodes in the cluster. The signal processor cluster is complemented by a 12-TB redundant storage system (RAID) that supports simultaneous, continuous recording of time-series and meteorological data for about 175 hours.

In addition to the in-house projects described above, we are collaborating with our university and private-industry partners on two other hardware upgrade projects. In partnership with the University of Oklahoma, a multi-channel digital receiver is currently being integrated with the NWRT PAR. This will allow access to additional antenna ports (Yeary et al. 2010). Sum and difference channels will be used to demonstrate both advanced aircraft tracking techniques and the spaced-antenna interferometry technique to measure cross-beam winds (Zhang and Doviak 2009). Additional auxiliary channels will be used to demonstrate spatial filtering techniques for clutter mitigation (Le et al. 2009).

Research continues to define a dual-polarized sub-array for demonstrating the feasibility and performance of phased-array dual polarization measurements in the context of weather observations (Forsyth et al. 2009). Several studies were completed by Basic Commerce Industries concerning radome effects, antenna pattern, calibration issues, and the design of the radiating elements to meet the cross-polarization isolation requirement of 30dB (Staiman 2009).

NWRT PAR Software Upgrades

The deployment of the new signal processing hardware marked the beginning of a series of software upgrades. Using a path of continuous upgrades with an average of two releases every year, we have been gradually incorporating new and improved functionality to the NWRT PAR. The need for software and signal processing improvements is twofold. On one hand, it is desirable that the NWRT PAR produces operational-like data with quality comparable to that of the WSR-88D. High data quality leads to better data interpretation and is conducive to the development of automatic algorithms. On the other hand, improvements are needed to demonstrate new capabilities, some of which are applicable to conventional and phased-array radars, and some that are unique or better suited to PAR technology. For example, the use of adaptive scanning strategies to perform focused observations of the atmosphere is not unique to PAR, but update times can be greatly reduced by using PAR's electronic beam steering capabilities as opposed to having the mechanical inertia inherent to reflector antennas.

.Infrastructure Upgrades

The software infrastructure was drastically revamped to support the implementation of new functionality in three major areas: the distributed computing environment, the user interface, and the real-time controller. The message-based, signal-processing-cluster infrastructure was modeled after the NEXRAD Open Radar Product Generation design (Jain et al. 1997). This type of design allows for seamless integration of nodes in the cluster, and provides the required computational power to implement traditional as well as advanced signal processing techniques.

The radar control interface (RCI) is a Java-based graphical user interface that provides radar control and status monitoring. The standard RCI functionality allows radar operators to complete tasks such as moving the antenna pedestal, selecting scanning strategies, turning the radar on and off, and controlling data archiving. In addition to these and many other basic control functions, the RCI has been significantly improved to demonstrate new capabilities (Priegnitz et al. 2009). For example, the system allows radar operators to dynamically select a sequence of scanning strategies and modify any of their parameters in real time. The dynamic selection of scanning characteristics is being evaluated as a manual capability, but will eventually lead to the design of new, advanced adaptive scanning algorithms. At the same time, the RCI provides a means to assess the performance of existing adaptive scanning algorithms in real time by providing a graphical display of active and inactive beam positions (Fig. 2; the current adaptive algorithm is described in a later section).

The real-time controller (RTC) is the nexus with the rest of the radar hardware. The RTC provides control of antenna positioning, the transmitter, and the receiver. RTC updates support multi-function capabilities by tagging received signals for function-specific processing. Also, the RTC receives commands from the signal processor to perform adaptive scanning by turning on and off selected beam positions. In the fall of 2010, the system began to support schedule-based scanning by removing the scan processing functionality from the RTC and providing scan information directly from the signal processor. This will allow better real-time control of scanning strategies driven by an automatic scheduling algorithm (e.g., Reinoso-Rondinel et al. 2010) and will therefore enable more advanced adaptive scanning schemes.

.Signal Processing Upgrades

Signal processing enhancements are a fundamental part of the NWRT PAR upgrades with both traditional and advanced signal processing techniques being implemented and tested in a pseudo-operational environment. Traditional signal processing techniques are exploited to achieve performance similar to that of WSR-88D radars. This facilitates data analyses and comparisons with existing operational data. Additionally, we are able to transition our latest research into a radar system through the implementation of advanced signal processing techniques.

Signal processing techniques address needs in four major areas: calibration, artifact removal, range-and-velocity ambiguity mitigation, and data accuracy. As of the spring of 2010, the system runs a few automatic calibration routines such as noise power and direct-current (DC) bias measurements. Time-series data are filtered to mitigate contamination from radio-frequency interference, strong point targets such as airplanes, and stationary returns from the ground such as buildings or trees. Ground clutter detection and filtering is done automatically in real time. Detection is based on the autocorrelation spectral density and the filter's suppression is adjusted based on the strength of the contamination (Warde and Torres 2009). This mitigation technique, referred to as CLEAN-AP, has been shown to exceed the performance of standard operational methods (Warde and Torres 2010). To mitigate range and velocity ambiguities (Doviak and Zrnić 1993) the signal processor can ingest multiple-pulse-repetition-time (PRT) data such as "batch" or staggered PRT (Torres et al. 2004) and can perform range unfolding or velocity dealiasing, respectively. In addition, accuracy of meteorological data can be improved by using adaptive range oversampling techniques (Torres and Zrnić 2003, Curtis and Torres 2010) or beam multiplexing (BMX) (Yu et al. 2007). Typically, signal detection (a.k.a. censoring) in operational weather radars is performed using thresholds on estimated signal-to-noise ratio and/or magnitude of the autocorrelation coefficient. The NWRT PAR uses a novel approach based on coherency that leads to increased detection rates in the areas of weak reflectivity (Ivić and Torres 2009).

In upcoming upgrades, we plan to implement improved spectral moment estimators, additional automatic calibration routines, and advanced spectral processing techniques for improved data quality.

Scanning Strategies

Similarly to other operational weather radars, for NWRT PAR we have adopted phenomenon-specific scanning strategies. These achieve the best tradeoffs for a particular situation. Improved spatial resolution is achieved with scanning strategies employing higher-resolution vertical sampling and/or azimuthal sampling. Unique to the PAR is that the inherent beam broadening that occurs as the beam is electronically steered away from boresite can be exploited to reduce the number of beam positions and obtain faster updates (e.g., to completely cover a 90 deg sector, only 55 nonoverlapping radials are needed). For improved temporal resolution there are different options. BMX can be exploited to produce data with lower variance and faster updates. Yu et al. (2007) report it is possible to reduce the scan time by a factor of 2 to 4 without an increase in the errors of estimates at high signal-to-noise ratios. The tradeoff is in terms of data quality since effective ground clutter filters that are compatible with BMX have yet to be developed. More frequent updates for the lowest tilt are achievable by adding a low-elevation scan half way through the scanning strategy. This results in good data quality, but faster updates are only realized at the lowest tilt and this leads to slightly slower updates elsewhere. Through elevation-prioritized scanning different updates at different levels can be achieved. In general, the fastest updates occur at the lowest tilts for the best temporal resolution closer to the ground. Intermediate tilts are updated less frequently, enough to detect new storm developments with short latency. Finally, the upper tilts get the slowest updates. Another way to improve the temporal resolution of the NWRT PAR without loss in data quality is to scan less than the full 90 deg. However, new developments outside the reduced sector are likely to be missed. An optimum compromise to produce good-quality data with faster updates is to employ adaptive scanning techniques that automatically focus data collection on smaller areas of interest at the same time that periodic surveillance is performed to capture new storm developments. This automatic algorithm is described in the next section.

ADAPTS: Adaptive Digital Signal Processing Algorithm for PAR Timely Scans

ADAPTS is a proof-of-concept implementation of spatially targeted adaptive scanning for the electronically steered NWRT PAR. Preliminary evaluations of ADAPTS have shown that the performance improvement with electronic adaptive scanning can be significant compared to conventional scanning strategies, especially when observing isolated storms (Heinselman and Torres 2010). ADAPTS works by turning "on" or "off" individual beam positions within a scanning strategy based on three criteria. If one or more criteria are met, the beam position is declared active. Otherwise, the beam position is declared inactive. Active beam position settings are applied and become valid on the next execution of a given scanning strategy. Additionally, ADAPTS periodically completes a complete volumetric surveillance scan, which is used to re-determine where weather echoes are located. A user-defined parameter controls the time between full scans (by default this is set at 5 min). Following a surveillance scan, data collection continues only on the active beam positions.

A beam position becomes active if one or more of the following criteria are met: (1) reflectivities on gates along the beam meet continuity, coverage, and significance conditions; (2) the elevation angle is below a predefined level; or (3) a neighboring beam position is active based on the first two criteria. The first criterion uses continuity, coverage, and significance conditions to make a quantitative determination of the amount of significant weather returns at each beam position (Fig. 1). In this context, a beam position is active if it contains: (a) a minimum number of consecutive range gates (by default 4) with reflectivities exceeding a threshold (by default 10 dBZ), and (b) a minimum total areal coverage (by default 1 km2) with reflectivities exceeding the same threshold. The second criterion provides data collection at all beam positions for the lowest elevation angles to monitor low-altitude developments. A user-defined elevation threshold (2.5° by default) controls the lowest elevation angle where ADAPTS may begin to inactivate beam positions. The third criterion uses "neighboring" beam positions to expand the data collection footprint to allow for continuous adaptation in response to storm advection, growth, or decay (Fig. 1). Nevertheless, new developments at midlevels may not be immediately sensed since additions to the list of active beam positions may be delayed until the next complete volume scan. Neighboring beam positions are defined as those immediately above and below in elevation and two on either side in azimuth of an active beam position (i.e., there are a total of 6 neighbors for each beam position, unless the scanning domain boundaries are approached). Even if no beam positions are defined active above the user-defined elevation threshold (criterion 2), ADAPTS will activate all beam positions at the tilt directly above the elevation threshold based on the neighboring criterion.

In its first release, ADAPTS only worked with scanning strategies that have a specific structure. ADAPTS assumed that there was only one PPI scanning strategy that repeated continuously. This prototype algorithm also expected tilts in ascending elevation order with the same azimuth beam positions and a minimum azimuthal spacing of 0.5° (i.e., the maximum number of beam positions in an elevation is 180). These limitations were removed with the next upgrade cycle for the spring of 2010.

Users at the RCI can monitor the performance of ADAPTS by looking at a graphical display of active beam positions (Fig. 2). Beam positions are color-coded as follows: white beam positions are inactive, green and yellow beam positions are active. Green beam positions meet the first and second detection criterion, whereas yellow beam positions correspond to the “neighboring” footprint extension (third criterion). The display updates every second and highlights in red the “current” beam position.

Illustrations of Sampling Tradeoffs with the NWRT PAR

One of the key advantages of NWRT PAR is the capability to produce the higher-temporal resolution data desired by NWS forecasters (e.g., Steadham 2008), broadcast meteorologists in the Southern Plains (LaDue et al. 2010), and several government agencies (OFCM 2006). Multipanel designs typical of PAR systems reduce sampling time by each panel scanning only part of a 360 deg sector (Brookner 1988). This type of design is demonstrated by the 90 deg sector scanned by the NWRT PAR. Depending on the situation, update time can be traded for spatial resolution and/or data quality. During the presentation at the conference we will use case examples to illustrate some of the sampling tradeoffs employed by the NWRT PAR for scanning storms.

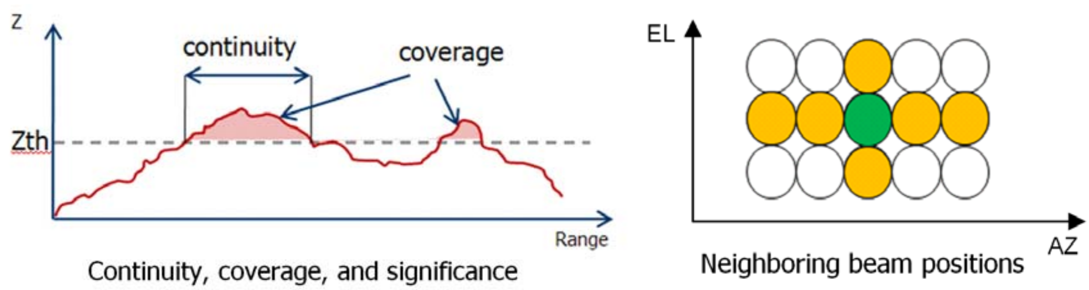

Fig. 1. Second and third criteria for active beam determination in ADAPTS. (left) Depiction of continuity, coverage, and significance conditions based on a range profile of reflectivity. (right) Depiction of neighboring beam positions (orange) for an active beam position based on first and/or second criteria (green).

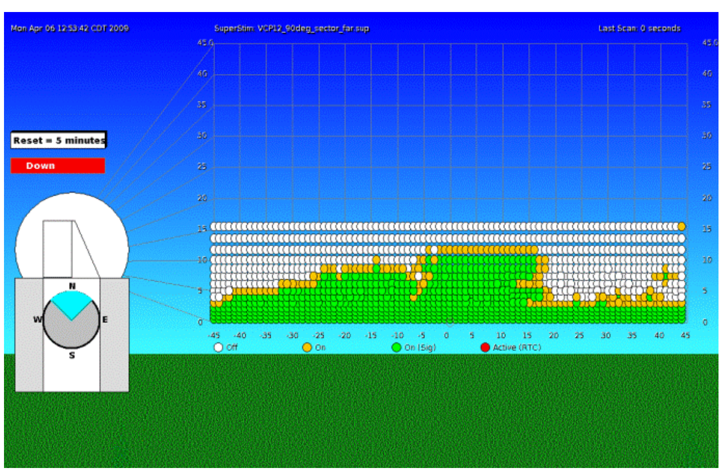

Fig. 2. Depiction of ADAPTS’ real-time performance at the NWRT PAR user interface. Beam positions on an azimuth-by-elevation plane are color-coded as follows: white beam positions are inactive, green beam positions are active based on elevation and coverage criteria, and orange beam positions are active based on the neighborhood criterion.

Conclusions

Under the umbrella of the MPAR initiative, scientists at the National Severe Storms Laboratory have been demonstrating unique PAR capabilities for weather observations. This paper described the hardware and software upgrades required to fulfill the NWRT PAR's mission as a demonstrator system for the MPAR concept. Through these continuous upgrades we have been demonstrating that PAR technology can be exploited to achieve performance levels that are unfeasible with current operational technology. Nonetheless, more research is needed to translate these improvements into concrete, measurable, and meaningful service improvements for the National Weather Service. As such, the NWRT PAR will continue to explore and demonstrate new capabilities to address 21st century weather forecast and warning needs.

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