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SOFTWARE AND SIGNAL PROCESSING UPGRADES FOR THE NATIONAL WEATHER RADAR TESTBED PHASED-ARRAY RADAR

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1. 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 (9.38 cm), agile-beam, phased-array radar located in Norman, Oklahoma that was established to demonstrate the MPAR concept (Zrnić et al. 2007). Since its inception in 2003, 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 (Forsyth et al. 2011). 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 coupled with advanced signal processing, allows for adaptive algorithms to produce higher temporal resolution data without sacrificing quality or spatial resolution through more efficient use of radar resources.

This paper focuses on the software and signal processing upgrades aimed at improving the scan control capabilities of the NWRT PAR by enabling the implementation of evolutionary scanning strategies that suit this unique instrument.

2. THE NWRT PAR

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° 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° at boresite (i.e., perpendicular to the array plane) and gradually increases to 2.1° at ±45° 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 replacement of WSR-88D radars, 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, software infrastructure, and signal processing upgrades have been accomplished to support the NWRT mission as a demonstrator system for the MPAR concept. The deployment of a new signal processing hardware (Forsyth et al. 2007) marked the beginning of a series of engineering upgrades. Using a path of continuous software development with an average of two releases every year, new and improved capabilities have been made available on the NWRT PAR (Torres et al. 2009, 2010). The need for these 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. A prime example of the latter is the use of adaptive scanning strategies to perform focused observations of the atmosphere, which is the focus of this work. Whereas this is not unique to PAR, update times can be greatly reduced by using PAR's electronic beam steering capabilities because scanning strategies are not constrained by the inherent mechanical inertia of reflector antennas.

3. DEMONSTRATING FASTER SCANS

In a 2008 survey about scanning strategy improvements for the WSR-88D conducted by the US

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National Weather Service (NWS), 62% of forecasters indicated the need for faster updates. High-temporal resolution data (~1 min) is expected to improve the understanding, detection, and warning of hazardous weather phenomena and is driving several radar research and demonstration initiatives (e.g., VORTEX2, CASA). As mentioned before, one of the strongest advantages of PAR compared to existing technology is its potential to produce data with very high temporal resolution. Naturally, this has been a major research and development thrust on the NWRT PAR. As such, the NWRT PAR can operate with phenomenon-specific scanning strategies that share the common goal of increasing the temporal resolution of weather data (Heinselman and Torres 2011). Two methods are currently exploited to reduce scan times without sacrificing data precision or spatial sampling: adaptive range oversampling and focused observations. These are summarized next.

3.1. Adaptive range oversampling

Range oversampling is family of signal acquisition and processing techniques that can be used to reduce data collection times (dwell times) while maintaining the desired data quality (Torres and Zrnic 2003). Compared to conventional matched-filter processing, range oversampling can be used to reduce scan update times by a factor of two while producing meteorological data with similar quality. The adaptive range oversampling algorithm implemented on the NWRT PAR (Curtis and Torres 2011) uses moment-specific transformations to minimize the variance of meteorological variable estimates. Thus, through signal processing, a new dimension is added to the traditional trade-off triangle that includes variance of estimates, spatial coverage, and update time. In other words, by trading an increase in computational complexity, the NWRT PAR is able to collect data both with higher-temporal resolution and improved variance of estimates without affecting the spatial coverage.

3.2. Focused observations

Another way to improve the temporal resolution of data collected with the NWRT PAR without loss in data quality is by reducing the number of beam positions in a given scanning strategy. Naturally, this makes sense if the radar can perform focused observations of the regions of interest (e.g., storms). A problem with this approach is that new developments outside the targeted scanned regions 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 while, at the same time, performing periodic (fast) surveillance to capture new storm developments.

In addition to focusing the radar beams to areas of interest, better and faster observations can be achieved by adaptively changing radar acquisition parameters and signal processing for different weather phenomena. For example, consider the different dwell times required by the weather surveillance[1] and tracking functions. That is, data collected for the surveillance function does not need to meet the stringent quality requirements of typical weather data. Hence, the number of samples collected by the radar for surveillance can be drastically reduced. Note that these samples must go through a different processing pipeline customized for detection, not estimation. As a result, even when executing the surveillance and tracking functions simultaneously, reduced update times are possible because the former only takes a fraction of the typical acquisition time.

The ultimate adaptive scanning scenario for faster updates combines focused observations with adaptive acquisition and processing parameters. In this scenario, individual storm cells can be targeted and scanned with particular parameters. Storm-specific update times can be met within a schedule-based scanning framework (e.g., Reinoso-Rondinel et al. 2010). In such framework, a storm identification and tracking algorithm is needed to define the “tasks” for the scheduler, which determines the best execution sequence to maximize the benefits of adaptive scanning.

The next section summarizes recent and planned upgrades of the scan control infrastructure to support the implementation of fast adaptive scanning on the NWRT PAR as outlined above.

4. NWRT PAR SCAN CONTROL FUNCTIONALITY

The scan control function of the NWRT PAR accepts high-level scanning strategy definitions and adaptive commands and generates real-time, low-level beam steering and sampling instructions. In other words, it controls the beam position at any given time and the corresponding timing for the transmitter pulses. Enhanced scan control capabilities have been made possible by an overhauled software infrastructure. This infrastructure and the evolution timeline for scan control capabilities are summarized next.

4.1. Software infrastructure

To support the enhanced scan control capabilities described later in this section, the software infrastructure was significantly upgraded in three major areas: the distributed computing environment, the user interface, and the real-time controller. These are briefly described next.

The architecture of the new signal processor (DSP cluster) 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., the computational resources). Specifically, a load-balancing mechanism, in which nodes compete to read and process sets of radar data, tailors the data distribution to

[1] Herein, the word *surveillance* is used in the context of weather observations. The *surveillance function* provides monitoring of the surrounding radar volume to detect new weather developments of interest. Once detected, these become part of the *tracking function*.

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. 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 message-based, DSP cluster infrastructure was modeled after the NEXRAD Open Radar Product Generation design (Jain et al. 1997).

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 the new adaptive scanning capabilities of the NWRT PAR (Priegnitz et al. 2009).

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 upgrades support multi-function capabilities by tagging received signals for function-specific processing. Also, the RTC receives commands from the DSP cluster to perform adaptive scanning by turning on and off selected beam positions. However, upgrades to the RTC's processing capabilities are limited because the software was not designed in house and any changes are prone to distort the precise timing required for real-time operations. Although initial scan control upgrades where implemented as modifications to the RTC code, current and future work relies on a migration of the scan control functionality to the DSP cluster.

4.2. Evolution of scan control functionality

One of the first enhancements to the NWRT PAR after its initial operation in 2003 was the addition of a user interface (RCI) to provide scan control functionality. Earlier versions of the RCI allowed the user to choose a radar scanning strategy to mimic the typical conventional scanning strategies that are operational on the WSR-88D. However, appropriate processing of some waveforms, such as batch pulse repetition time (PRT), was not feasible until after the signal processor upgrade in 2007. This initial upgrade allowed the implementation of new data processing modes, including the processing of batch PRTs. The next major upgrade in 2008 incorporated several data quality functions, such as ground clutter filtering, which made possible an almost perfect emulation of data obtained with operational scanning strategies on the WSR-88D.

Fast adaptive scanning with the NWRT PAR was first demonstrated in 2009 with the development and real-time implementation of ADAPTS (Adaptive Digital Signal Processing Algorithm for PAR Timely Scans). 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 2011). 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 (Fig. 1). 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. The active beam position determination function of ADAPTS was implemented on the DSP cluster. In addition, significant changes were made to the RTC to ingest this information and accordingly remove inactive beam positions from a given scanning strategy.

For 2010, scan control upgrades included the capability to perform manual scheduling and adaptation at the storm-scale level. With this upgrade, radar operators can dynamically select a sequence of scanning strategies and modify any of their parameters in real time through the RCI. 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.

In 2011, we plan to implement and test a surveillance function to run in conjunction with ADAPTS. That is, the surveillance and tracking functions will handle data collection for the ADAPTS-based inactive and active beam positions, respectively. A new processing mode will be added to the DSP cluster to handle the surveillance data processing. Weather tracking data processing will be done as usual with the current functionality.

For 2012 and beyond, we expect the system to begin supporting schedule-based scanning by migrating the scan processing functionality from the RTC to the DSP cluster. In this configuration, low-level beam information will be ingested by the RTC 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 lead to more advanced adaptive scanning schemes.

5. CONCLUSIONS

Under the umbrella of the MPAR initiative, scientists at the NSSL have been demonstrating unique PAR capabilities for weather observations. This paper described the software and signal processing upgrades to improve the scan control capabilities of the NWRT PAR. These enable the implementation of fast adaptive scanning and ultimately fulfill the instrument's mission as a demonstrator system for the MPAR concept.

Through continuous engineering upgrades, we have demonstrated 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.

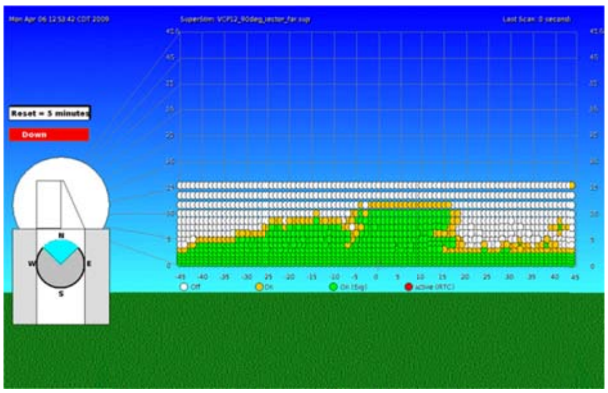

Fig. 1. Depiction of ADAPTS' real-time performance at the NWRT PAR user interface. Beam positions on an azimuth-by-elevation plane are color-coded as follows: white beam positions are inactive, green beam positions are active based on elevation and coverage criteria, and orange beam positions are active based on the neighborhood criterion.

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