New Weather-Surveillance Capabilities for NSSL's 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. As critical technology costs decrease, MPAR radars could 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 been enhancing the functionality of this system to bring it up to operational weather radar standards (such as those in the operational NEXRAD network) and, more importantly, to demonstrate new capabilities in the context of weather and multifunction observations. 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 focused observations, produces higher temporal resolution data without sacrificing data quality or spatial resolution through more efficient use of radar resources.

This paper presents an overview of the adaptive weather-surveillance capabilities of the NWRT PAR, which continue to provide researchers and forecasters with an effective platform for demonstrating and evaluating the MPAR concept.

2. The National Weather Radar Testbed Phased-Array Radar (NWRT PAR)

In a nutshell, the NWRT PAR exploits a passive, 4352-element phased-array antenna to provide stationary, two-dimensional electronic scanning within a given 90° azimuthal sector. The antenna is mounted on a pedestal so that the best overall 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 (Zrnić et al. 2007).

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, 2011, 2012). 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 effective automatic algorithms. On the other hand, improvements are needed to demonstrate new capabilities, some of which are applicable to both conventional and PAR, and some that are unique or better suited to PAR. A prime example of the latter is the use of adaptive scanning strategies to perform focused observations of the atmosphere, which is the topic of this work. Whereas adaptive scanning 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. The rest of the paper describes the latest weather surveillance capabilities of the NWRT PAR based on adaptive scanning.

3. Achieving Faster Updates through Adaptive Scanning

The need for high-temporal resolution data (~1 min) to improve the understanding, detection, and warning of hazardous weather phenomena is driving several radar research and demonstration initiatives. In principle, update time (i.e., scan time), data quality (e.g., variance of meteorological-variable estimates), and spatial sampling (i.e., the number of beam positions to scan) are coupled criteria in the design of scanning strategies for weather radars. That is, if one is to be improved, one or both of the others must be sacrificed (Heinselman and Torres 2011). Focused observations provide a means to reduce update times with no sacrifice in data quality or spatial coverage by only scanning regions of interest (e.g., storms), thus reducing the number of beam positions to scan. The concept of focused observations can be applied to both reflector and phased-array antenna-based systems; however, a PAR using electronic beam steering is better suited for it since it is not constrained by mechanical inertia.

Scientists at the NSSL have been exploring the high-temporal resolution weather scanning capabilities of the agile-beam NWRT system for a number of years. Fast *adaptive* scanning with the NWRT PAR was first demonstrated in 2009 with the development and real-time implementation of the Adaptive DSP Algorithm for Phased-Array Radar Timely Scans (ADAPTS), which is described next.

3.1. Adaptive Focused Observations

Detecting regions with significant weather returns is at the core of adaptive focused observations. ADAPTS works in real time by classifying individual beam positions within a scanning strategy as *active* or *inactive* based on three criteria: (1) beam elevation angle, (2) return significance, and (3) neighborhood. The first criterion *activates* all beam positions for the lowest elevation angles (based on a user-defined threshold, by default 2.5 deg) to continuously provide coverage of low-altitude storm developments. The second criterion *activates* beam positions if they contain significant weather returns. Beam positions with significant returns are those that contain range gates with reflectivity values above a range-dependent threshold (by default 15 dBZ within 35 km of the radar and 10 dBZ outside this range) that satisfy *continuity* and *areal coverage* requirements (Fig. 1). Continuity requires a certain number of consecutive range gates (by default 4) with significant reflectivity values; coverage imposes a minimum total area (by default 1 km^2) to continuous significant reflectivity values (the areal coverage is computed as the product of the range-gate spacing and the gate width, which depends on the distance from the radar and the 2-way, 6-dB antenna beamwidth at the corresponding beam steering angle). The third criterion *activates* neighboring beam positions to expand the coverage footprint to allow for continuous adaptation in response to storm advection and growth. Neighboring beam positions are defined by either a crosshair or rectangular mask with predefined azimuthal and elevation dimensions. The neighborhood of beam positions activated based on the first two criteria is also *activated* (at least one beam position is added in each azimuthal and elevation direction, even if they do not fall within the neighborhood mask). By default, ADAPTS employs a crosshair mask of dimensions ±2.2° in azimuth and ±1° in elevation (Fig. 2). The typical spatial sampling of NWRT PAR scanning strategies leads to a maximum of 6 neighbors for each active beam position: one on either side in elevation, and two on either side in azimuth.

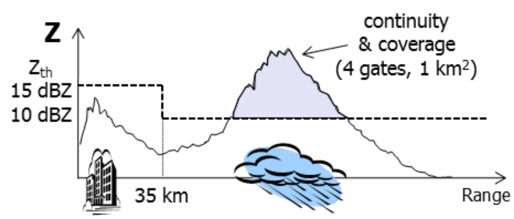

Fig. 1. Significance criterion for ADAPTS. A range-dependent reflectivity threshold is used to identify range gates with significant returns. A beam is activated if both continuity and coverage requirements are met on a given set of range gates with significant returns.

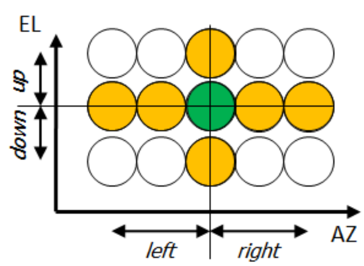

Fig. 2. Neighborhood criterion for ADAPTS. The neighborhood mask is centered on active beam positions based on the first two criteria (green circle). Neighboring beam positions (orange circles) are also activated.

It is important to note that the classification of beam positions as *active* or *inactive* only becomes valid on the next execution of the scanning strategy. In the initial implementation of ADAPTS, only active beam positions were scanned (Torres et al. 2012). Thus, to detect new developments that may occur on *inactive* beam positions, all beams in a scanning strategy are re-activated periodically (by default every 5 min). Following a full scan (i.e., all beam positions are active), data collection continues only on *active* beam positions (Fig. 3). In this implementation, the first activation criterion is necessary to maintain continuous low-level coverage.

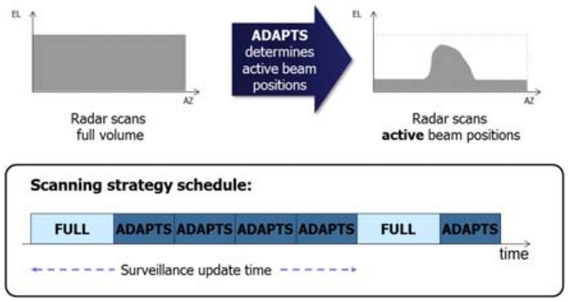

Fig. 3. Typical scanning-strategy schedule with the initial implementation of ADAPTS. A full scan (FULL) is scheduled periodically to detect newly developed storms. Otherwise, ADAPTS is used to reduce the scan time by performing adaptive focused observations.

3.2. Continuous Surveillance

Whereas the initial implementation of ADAPTS showed significant performance improvements compared to conventional scanning strategies, especially when observing isolated storms (Heinselman and Torres 2011), timely detection of new developments was not guaranteed, since *inactive* beam positions were only scanned once every 5 min (by default). As an improvement to this, *inactive* beam positions can be constantly monitored using shorter observation times (i.e., fewer samples, by default 4) and also a coarser spatial sampling (i.e., with azimuthal sampling equal to the beamwidth, instead of half the beamwidth). This makes sense because the meteorological data from *inactive* beam positions are not meant to be disseminated to users or algorithms, but only to detect new storm developments. As a result, even when continuously scanning both *active* and *inactive* beam positions, reduced update times are possible because the latter only take a fraction of the typical acquisition time. In this manner, adaptive focused observations results in an optimum compromise that produces good-quality data with faster updates on smaller areas of interest while, at the same time, performing continuous surveillance to capture new storm developments. This capability has been implemented on the NWRT PAR and is currently undergoing operational evaluation.

Signals acquired at *inactive* beam positions are processed using a *surveillance mode*, which differs significantly from the processing mode used to produce meteorological-variable estimates for users and algorithms. For example, the surveillance mode exploits range averaging to reduce the variance of reflectivity estimates so that new storms can be effectively detected. Due to the small number of samples, artifact removal (e.g., ground clutter) is not possible, so reflectivity thresholds used for significance must be adjusted to balance the ability to detect new storms and the occurrence of false alarms.

4. ADAPTS Evaluation

Evidently, the time savings provided by ADAPTS depends on the distribution of weather echoes in the scan volume. For example, it is not difficult to see that isolated storms at far distances from the radar lead to the greatest time savings, while widespread precipitation, squall lines, or storms close to the radar are examples where ADAPTS may not reduce scan times significantly. A great advantage of maintaining continuous surveillance is that the first criterion for activation of beam positions can be removed leading to significant time savings. That is, once continuous surveillance is maintained it is not necessary to provide continuous low-level coverage using full observation times (which are usually the longest in a typical scanning strategy) since new developments will be timely detected using the surveillance mode on inactive beam positions.

A theoretical comparison of update times is given next as a function of storm coverage to illustrate the benefits that can be realized with ADAPTS. For this analysis, assume that the scanning strategy is defined as the operational WSR-88D volume coverage pattern (VCP) 12 given in Table 1, and that beam positions are activated in azimuthal sectors including all elevation angles in the scanning strategy. Although ADAPTS does not work in this way, this simplification allows us to simplify the definition of coverage. Here, coverage is computed relative to the 90-deg sector that the NWRT PAR is able to scan using electronic beam steering. Thus, a storm that covers a 45-deg azimuthal sector (including all elevation angles) represents a 50% coverage in our analysis. Assuming oversampling in azimuth with 50% beam overlap, a total of 109 beam positions at each elevation are needed to cover a 90-deg azimuthal sector (recall that on a PAR, the beamwidth is the narrowest at boresite; i.e., perpendicular to the array plane, and increases with the inverse of the cosine of the steering angle away from boresite).

With these assumptions, the full scan time corresponding to conventional scanning is given by U_c = 109 x 645.16 ms = 1.17 min. Using ADAPTS *without* continuous surveillance, the scan time as a function of storm coverage C (%) is given by U_a = 109 x 332.46 ms + C/100 x 109 x (645.16 ms – 332.46 ms), where 332.46 ms is the total single-azimuth dwell time for the lower elevation angles only, which are always activated with the first criterion using an elevation threshold of 2.5 deg. Here, time savings are only realized at the upper elevation angles, where, depending on coverage, a fraction of beam positions may be inactivated. In this case, a periodic full scan is also scheduled every T_r sec with a scan time given by U_c. The average update time in this case can be computed as $\overline{U}_a = (k\, U_a + U_s)/(k + 1)$, where k is the number of times ADAPTS runs in between full scans. Finally, using ADAPTS *with* continuous surveillance, the scan time as a function of coverage is given by U_{a+s} = C/100 x 109 x 645.16 ms + (1 – C/100) x 109/2 x 105.41 ms, where 105.41 ms is the total single-azimuth dwell time for surveillance using M = 4 samples of the longer PRT for multi-PRT elevations, and the total number of azimuthal beam positions for surveillance is divided by 2 to account for the coarser spatial sampling on the inactive beams positions. Note that in this case, the first activation criterion is disabled and a periodic full scan is not needed. Fig. 4 shows the average update times for conventional scanning, ADAPTS (with different T_r times), and ADAPTS with surveillance. It is clear that the greatest time savings are realized for small storm coverages. As storms grow in size or get closer to the radar, the coverage increases and no time savings are possible using adaptive focused observations.

Elevation (deg)	$T_{s,long}$ (μs)	M_{long}	$T_{s,short}$ (μs)	M_{short}	*Dwell Time* (ms)	
0.5	3106.7	15	986.7	40	86.07	Lower elevations
0.9	3106.7	15	986.7	40	86.07	
1.3	3106.7	15	986.7	40	86.07	
1.8	3106.7	3	986.7	29	37.93	
2.4	2240.0	3	986.7	30	36.32	
3.1	2240.0	3	986.7	30	36.32	Upper elevations
4.0	2240.0	3	986.7	30	36.32	
5.1	1553.3	3	986.7	30	34.26	
6.4	1553.3	3	986.7	30	34.26	
8.0			913.3	38	34.71	
10.0			846.7	40	33.87	
12.5			780.0	44	34.32	
15.6			780.0	44	34.32	
19.5			780.0	44	34.32	
			Total Single-Azimuth Dwell Time (ms) =		645.16	

Table 1. WSR-88D VCP-12 scanning strategy parameters. The total single-azimuth dwell time corresponds to an azimuthal sector one-beam-position wide (i.e., all elevations at a single azimuth). For the NWRT PAR employing oversampling in azimuth with a total of 109 beam positions per elevation angle, the total scan time with conventional scanning is 1.17 min.

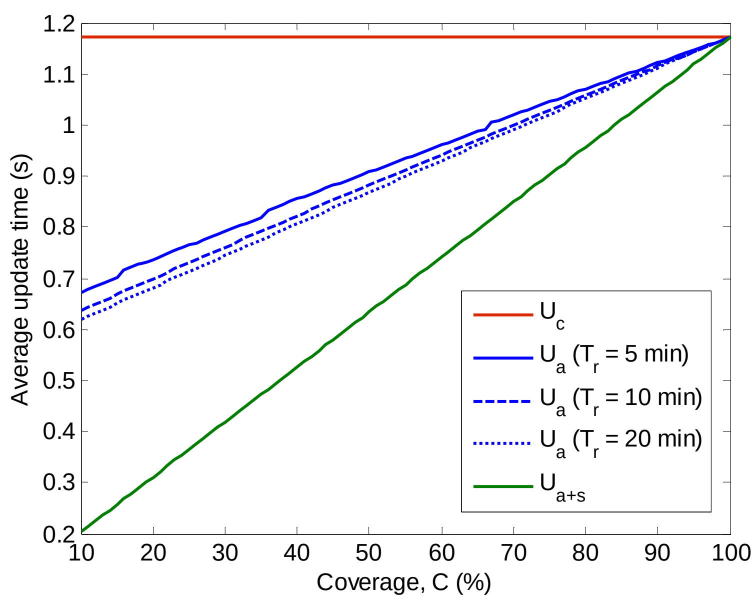

Fig. 4. Average update times (in seconds) for conventional scanning (U_c), ADAPTS with different T_r times ($\bar{U}_a$), and ADAPTS with surveillance (U_{a+s}) as a function of the percentage of azimuthal coverage (C) with respect to a full 90-deg sector.

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 latest weather-surveillance capabilities of the NWRT PAR based on adaptive focused observations. 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 and other government agencies. 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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