# 8.2 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. Because the total number of required radars would be reduced, maintenance and logistics infrastructure would be simplified.

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, scientists and engineers at the National Severe Storms Laboratory (NSSL) have been improving the quality of data produced by this system and, more importantly, demonstrating 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 latest improvements to the adaptive scanning capabilities of the NWRT PAR.

## 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 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 exploiting electronic beam steering. 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).

The deployment of new signal processing hardware (Forsyth et al. 2007) marked the beginning of a series of engineering upgrades. Since then, significant hardware, software infrastructure, and signal processing upgrades have been completed to support the NWRT mission as a demonstrator system for the MPAR concept. Using a path of continuous software development with an average of two software 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 data with quality as close as possible to that of the WSR-88D. High data quality leads to better data interpretation and is conducive to the development of more effective automatic algorithms. On the other hand, improvements are needed to demonstrate new capabilities, some of which are applicable to both conventional and phased-array radars, 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. 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.

## 3. ADAPTS: FASTER UPDATES THROUGH ADAPTIVE FOCUSED OBSERVATIONS

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 mutually coupled criteria in the design of scanning

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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 devoting less radar time to regions of reduced interest (e.g., clear air), thus reducing the total scan time. The concept of focused observations can be applied to both reflector and phased-array antenna 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 PAR 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. Active-beam-position determination*

Detecting regions with significant weather returns is the key for adaptive focused observations. ADAPTS works in real time by classifying individual beam positions within a scanning strategy as active or inactive based on two criteria: return significance and neighborhood.

The first 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$^2$) of 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 steering angle).

The second 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. By default, ADAPTS employs a crosshair mask of dimensions ±2.2° in azimuth and ±1° in elevation (Fig. 2), but at least one beam position is added in each azimuthal and elevation direction, even if they fall outside the neighborhood mask. 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.

### *3.2. Scanning-strategy adaptation*

In ADAPTS, the classification of beam positions into active or inactive is used to redefine the scanning strategy that the radar will use next. This process repeats until a new scanning strategy is added to the task schedule or the pedestal is moved (e.g., to keep storms of interest in the antenna's 90° azimuthal sector). Otherwise, the system can keep ADAPTS active-beam-position tables for up to 10 different scanning strategies in the task schedule.

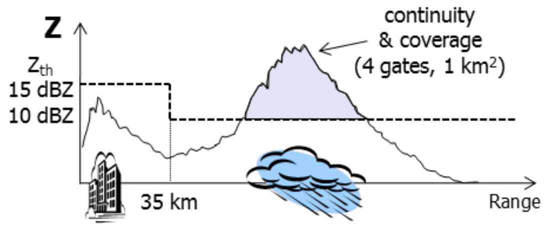

Fig. 1. Significance criterion for ADAPTS. A range-dependent reflectivity threshold is used to identify range gates with significant returns. A beam is activated if both continuity and coverage requirements are met on a given set of range gates with significant returns.

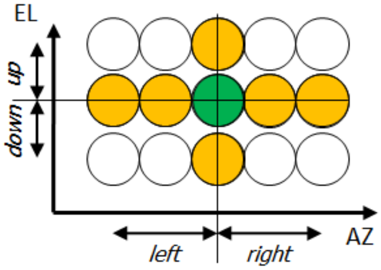

Fig. 2. Neighborhood criterion for ADAPTS. The neighborhood mask is centered on significant beam positions (first criterion). Each significant beam position (green circle) and its neighboring beam positions (orange circles) are activated.

In the initial implementation of ADAPTS, subsequent scanning strategies were redefined based only on active beam positions (Torres et al. 2012). That is, following an initial full scan (i.e., all active beam positions), only the active beam positions were scheduled to be scanned next, so data collection continued only on the set of active beam positions (Fig. 3). In this scenario, subsequent determinations of active beam positions could only "dilate" or "erode" the previous set. Thus, to detect new developments in areas corresponding to inactive beam positions, a full scan (i.e., activating all beam positions) was required to be scheduled periodically (by default every 5 min). Because of this potentially longer time between observations in certain areas and the need to maintain continuous low-level coverage, an additional activation criterion was deemed necessary so that all beam positions below a given elevation angle (by default 2.5°) were always active.

Whereas the initial implementation of ADAPTS (herein referred to as ADAPTS I) 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 because inactive beam positions were only scanned once every 5-10 min.

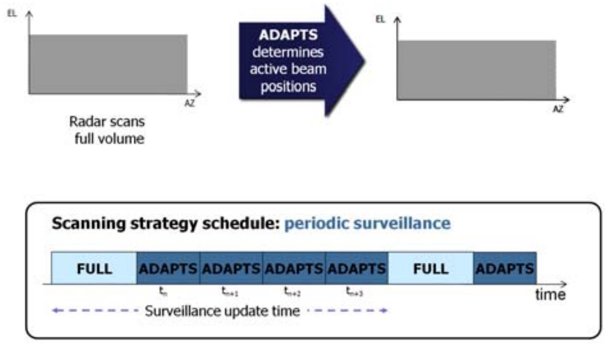

Fig. 3. Typical scanning-strategy schedule with ADAPTS I. A full scan (FULL) is scheduled periodically to detect newly developed storms in inactive areas. Otherwise, only active beam positions (ADAPTS) are scanned.

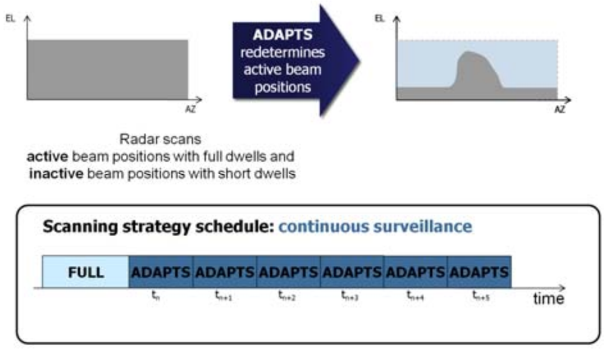

Fig. 4. Typical scanning-strategy schedule with ADAPTS II. After an initial full scan (FULL), surveillance runs continuously in conjunction with the scanning of active beam positions (ADAPTS) to detect newly developed storms.

The new implementation of ADAPTS (ADAPTS II) was designed to mitigate the limitations of ADAPTS I in terms of timely detection of new developments. With ADAPTS II, subsequent scanning strategies are redefined as follows. Whereas active beam positions are scanned with full spatial resolution and full dwell times (as with ADAPTS I), areas of inactive beam positions are also scanned but with coarser spatial resolution (i.e., with azimuthal sampling equal to the beamwidth, instead of half the beamwidth as normally done for active beam positions) and shorter dwell times (i.e., fewer pulses, by default 4). Scanning inactive areas in this manner makes sense because data from inactive beam positions are not meant to be disseminated to users or algorithms; they are only needed 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 takes a fraction of the typical acquisition time. In this manner, ADAPTS II results in an effective 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 in a timely manner.

### *3.3. Detection-only processing*

Time-series data acquired at inactive beam positions with ADAPTS II are processed using a newly developed surveillance processing mode, which differs significantly from the processing mode used to generate meteorological-variable estimates for users and algorithms. The surveillance mode operates on very few samples (by default 4) per dwell and needs to determine the presence of significant returns in a robust manner. That is, a compromise must be achieved between the probability of detecting significance and the occurrence of false detections. The former is required to achieve timely detection of newly developed weather phenomena and the latter is needed to prevent adding beam positions with no significant weather returns to the set of active beam positions.

Processing in the surveillance mode exploits range averaging to reduce the variance of reflectivity estimates so that significance can be more robustly determined. Due to the small number of samples, ground clutter mitigation is very difficult. Therefore, the surveillance mode relies on a spatial database of ground clutter powers. These are subtracted from total power estimates at each range gate to produce an approximate weather-signal power from which significance is determined. The database of removed ground clutter powers is completely populated when the first (full) scan runs and is continuously updated with data from the active areas. The amount of power removed by the CLEAN-AP ground clutter filter (Warde and Torres 2010) is used as a proxy for ground clutter power.

Because significance determination is not robust when processing a small number of samples, a persistence criterion must be met before a beam position with significant returns (as determined by the surveillance mode) becomes active. That is, beams from inactive areas with significant returns are temporarily activated without using the neighborhood criterion. As such, a false detection only results in the addition of one beam to the set of active beam positions and minimizes the visual impact of false detections on the meteorological data. The neighborhood criterion is applied as usual once significance is confirmed using full dwell times. Table 1 summarizes the ADAPTS II logic for scanning, processing, and activating beam positions. Fig. 5 shows an example of the classification of beam positions with ADAPTS II. In this figure, the scanning strategy is represented as a projection on the azimuth-by-elevation plane; that is, each circle represents a beam position. Significant beam positions in established active areas are shown in dark green, and those activated based on neighborhood are shown in light green. Newly detected significant beam positions (using the surveillance processing mode) are shown in blue. Note that these do not have an active neighborhood associated with them. Finally, inactive areas are shown in yellow (scanned with shorter dwell times) and white (not scanned).

| Data Origin | Spatial Resolution | Dwell Times | Processing Mode | Neighborhood Criterion |
|---|---|---|---|---|
| inactive area | coarse | short | surveillance | no |
| newly detected active area | coarse | full | weather | no |
| established active area | full | full | weather | yes |

Table 1. ADAPTS II logic for scanning, processing, and activating beam positions.

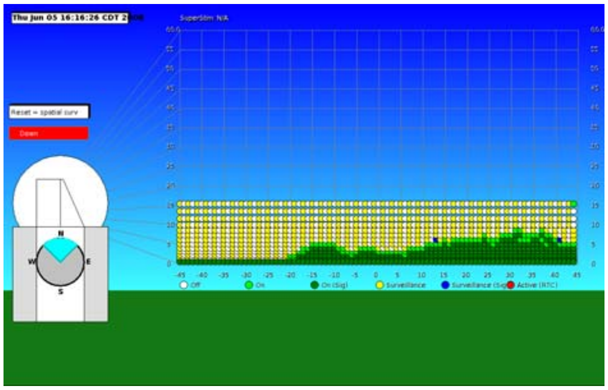

Fig. 5. Example of the classification of beam positions with ADAPTS II through the NWRT PAR user interface.

A new ground clutter filter for the surveillance mode is currently under testing. This filter was designed to remove most of the ground clutter at the cost of potentially removing a portion of the weather signal, which is not as detrimental as it seems because the surveillance mode does not produce meteorological variables, only significance flags. As such, it is not imperative to try to preserve the weather signal since determination of significance should not be substantially affected by excessive filtering in isolated range gates.

## 4. ADAPTS-II PERFORMANCE

The time savings afforded 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 elevation-angle 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 because longer PRTs are needed at the lowest elevation angles). New developments will be detected on time using the surveillance mode on inactive areas.

A theoretical comparison of update times as a function of storm coverage is given next to illustrate the benefits that can be realized with ADAPTS II. For this analysis, it is assumed that the scanning strategy is defined as the operational WSR-88D volume coverage pattern (VCP) 12 given in Table 2, and that beam positions are activated in azimuthal sectors equally for all elevation angles in the scanning strategy. Although ADAPTS does not work in this way, this simplification allows for a simpler definition of coverage. Herein, coverage (*C*) is computed relative to the 90° sector that the NWRT PAR is able to scan using electronic beam steering. Thus, a storm that covers a 45° azimuthal sector (including all elevation angles) represents 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° azimuthal sector (recall that on the NWRT PAR, the beamwidth is the narrowest at boresite, 1.5°, and increases up to 2.1°at ±45° 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.

| *El* (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 2. 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.

Using ADAPTS I (i.e., *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 elevation criterion using a threshold of 2.5°. 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 can be computed as $\bar{U}_a = (k\ U_a + U_s)/(k + 1)$, where $k$ is the number of times ADAPTS runs in between full scans.

Using ADAPTS II (i.e., *with* continuous surveillance), the scan time as a function of coverage is given by $U_{a+s} = C/100 \times 109 \times 645.16$ ms + $(1 – C/100) \times 109/2 \times 105.41$ ms, where 105.41 ms is the total single-azimuth dwell time for surveillance using $M = 4$ samples (the longer PRT is used for multi-PRT elevations such as split and batch cuts), and the total number of azimuthal beam positions for surveillance is halved to account for the coarser spatial sampling on the inactive areas. Note that in this case, the elevation activation criterion is disabled, and a periodic full scan is not needed. Fig. 6 shows the average update times for conventional scanning, ADAPTS I (with different $T_r$ times), and ADAPTS II. It is clear that the greatest time savings are realized with ADAPTS II and for small storm coverage. As storms grow in size or get closer to the radar, the coverage increases and no time savings are possible using adaptive focused observations.

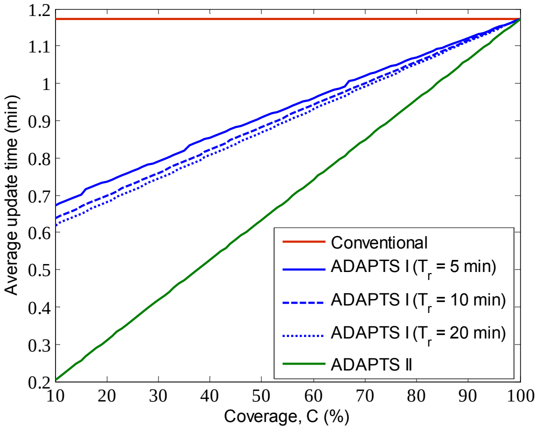

Fig. 6. Average update times (in seconds) for conventional scanning ($U_c$), ADAPTS I with different $T_r$ times ($\bar{U}_a$), and ADAPTS II with surveillance ($U_{a+s}$) as a function of the percentage of azimuthal coverage ($C$) with respect to a full 90° sector.

## 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 not feasible 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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