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ADAPTS IMPLEMENTATION: CAN WE EXPLOIT PHASED-ARRAY RADAR'S ELECTRONIC BEAM STEERING CAPABILITIES TO REDUCE UPDATE TIMES?

Sebastián Torres, Pam Heinselman, Ric Adams, Christopher Curtis, Eddie Forren, Igor Ivić, David Priegnitz, John Thompson, and David Warde

Cooperative Institute for Mesoscale Meteorological Studies, The University of Oklahoma and NOAA/OAR National Severe Storms Laboratory
Norman, Oklahoma

1. INTRODUCTION

It is well understood that high-temporal resolution data has the potential to improve the understanding, detection, and warning of hazardous weather phenomena. In fact, in a 2008 survey about scanning strategy improvements conducted by the US National Weather Service, 62% of forecasters indicated the need for faster updates. One of the strongest advantages of using phased-array radars for weather observations is their potential to produce data with very high temporal resolution. Naturally, this has been a major research and development thrust on the National Severe Storms Lab's (NSSL) National Weather Radar Testbed Phased-Array Radar (NWRT PAR).

One way to get faster updates without loss in data quality is by adaptively focusing observations to the regions of interest. This is the purpose of the Adaptive DSP Algorithm for Timely Scans (ADAPTS), which was first demonstrated in 2009. ADAPTS works by activating or deactivating individual beam positions within a scanning strategy based on elevation, significance, and neighborhood criteria. Preliminary evaluations of ADAPTS showed significant time savings, but also helped identify areas for further improvement. This paper describes the initial implementation of ADAPTS, its recent evolution, and outlines a plan for future enhancements towards obtaining the best weather observations in the shortest amount of time.

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 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 (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). 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 focus 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 initial implementation, present state, and future plans for adaptive scanning on the NWRT PAR.

3. ADAPTIVE DSP ALGORITHM FOR PHASED-ARRAY RADAR TIMELY SCANS (ADAPTS)

Fast adaptive scanning with the NWRT PAR was first demonstrated in 2009 with the development and real-time implementation of ADAPTS. 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

Corresponding *author address:* Sebastian M. Torres, NSSL, 120 David L. Boren Blvd., Norman, OK 73072; email: Sebastian.Torres@noaa.gov

criteria are met, the beam position is declared active; otherwise, the beam position is declared inactive. Active-beam-position (ABP) settings are applied and become valid on the next execution of a given scanning strategy. Additionally, ADAPTS periodically completes a full volumetric surveillance scan, which is used to detect newly formed weather echoes in regions of inactive beam positions. A user-defined parameter controls the time between full scans (by default this is set at 5 min). Following a full scan, data collection continues only on the active beam positions (Fig. 1). The ABP determination function of ADAPTS is described next.

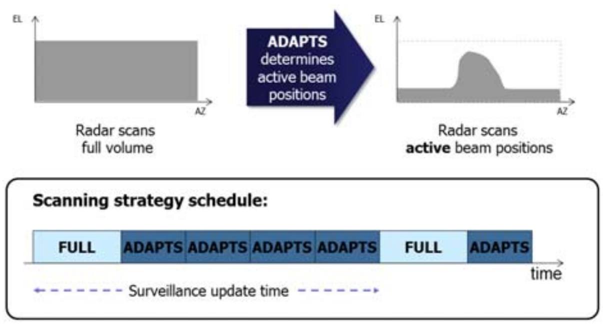

Fig. 1. Typical scanning-strategy schedule with ADAPTS. A full volume is scheduled periodically to detect newly developed storms. Otherwise, ADAPTS reduces the scan time by scanning only active beam positions.

3.1. Initial implementation

ADAPTS uses three criteria to determine the set of active beam positions in a scanning strategy: (1) elevation angle, (2) significance, and (3) neighborhood.

The first criterion provides data collection at all beam positions for the lowest elevation angles. This is necessary to continuously monitor low-altitude developments. A user-defined elevation threshold (2.5° by default) controls the lowest elevation angle where ADAPTS may begin to deactivate beam positions.

The second criterion tags beam positions as active if they contain significant weather echoes. Beam positions with significant echoes are those that contain range gates with reflectivity values above a threshold (by default 10 dBZ) that satisfy continuity and coverage requirements (Fig. 2). Continuity requires a certain number of consecutive range gates (by default 4) with significant reflectivities. Coverage requires a minimum total area (by default 1 km^2) with significant reflectivities (the areal coverage is computed as the product of the range 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 third criterion uses "neighboring" beam positions to expand the data collection 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. Beam positions within the neighborhood mask centered on each active beam position (based on the previous two criteria) are tagged as active, and at least one beam position is added in each direction, even if they do not fall within the neighborhood mask. The only exception to this rule occurs in a boundary condition (i.e., along the edges of the full sector). By default, ADAPTS employs a crosshair mask of dimensions ±2.2° in azimuth and ±1° in elevation. The typical spatial sampling of the NWRT PAR scanning strategies leads to a maximum of 6 neighbors for each beam position: one above, one below, and two on either side (Fig. 3).

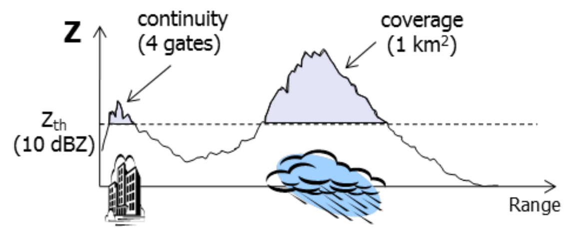

Fig. 2. Significance criterion in the old implementation of ADAPTS where continuity and coverage requirements are spatially decoupled.

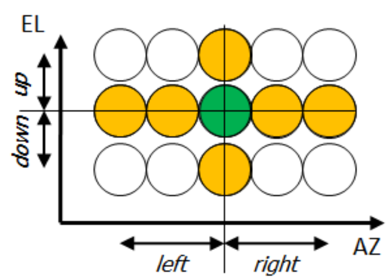

Fig. 3. Default neighborhood mask for ADAPTS. The mask is centered on every active beam position based on the first two criteria (green circle). Neighboring beam positions (orange circles) are added to the list of active beam positions.

Evidently, the time savings provided by ADAPTS depends on the distribution of weather echoes in the scan volume. For example, 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 of cases where ADAPTS may not reduce scan times significantly. Further, sampling, acquisition, and processing parameters can also impact the performance of ADAPTS. Such an impact is the reason behind the changes described next.

3.2. Limitations of the initial implementation

After the real-time implementation of range oversampling techniques on the NWRT PAR (Curtis and Torres 2011), operational scanning strategies were modified to employ about 50% shorter dwell times and make up in data quality by exploiting the reduction in variance of estimates provided by adaptive pseudowhitening. Dwell times were shortened at all elevation angles by reducing the number of pulses collected at each beam position (*M*). However, effective ground-clutter-filtering performance limits how small a number of pulses can be collected. Thus, a compromise was achieved by reducing *M* more at the intermediate and upper elevation angles and less at lower elevations where the likelihood of having ground clutter contamination is higher. As a result, current operational scanning strategies can only enable the ground clutter filter at elevations below 3°. This results in a small amount of ground clutter contamination close to the radar from the antenna sidelobes, which is not a significant distractor for users of NWRT PAR data but results in a large number of false detections for ADAPTS. In turn, this increases the scan time unnecessarily. Next, a solution to this problem is presented and illustrated through a case study.

3.3. A case study: June 5th, 2008

On June 5th, 2008, the NWRT PAR sampled storm initiation along a cold front that moved through central Oklahoma. To analyze the performance of ADAPTS, the event starts at 19:05 UTC with mostly clear-air echoes, and ends at 20:45 UTS with storms fully developed into a squall line. Fig. 4 shows three reflectivity PPI images at 2.4° elevation. They are representative of the three stages of the event: clear air, storm initiation, and their development at 20:02, 20:20, and 20:37 UTC, respectively.

Data for this case was collected using conventional scanning. However, through playback, it is possible to simulate the performance of different implementations of ADAPTS. While faster updates are obviously not possible with playback, having the full-scan sampling is advantageous when assessing the performance of ADAPTS.

The first playback scenario runs the old implementation of ADAPTS described in the previous subsection. Fig. 5 shows active (green and orange circles) and inactive (white circles) beam positions for this scenario at a time when storms are yet to develop (19:17 UTC). From this figure, it is evident that ADAPTS produces a large number of false detections above 3°, which propagate to higher elevations via the neighborhood criterion. As mentioned before, the ground clutter contamination at these elevations is such that the continuity requirement is satisfied close to the radar and the coverage requirement is satisfied with one or two noisy range gates farther away from the radar. Thus, in this case, the performance of ADAPTS is not the best. Next, we describe the changes to the active-beam-position rules that were implemented to mitigate this problem.

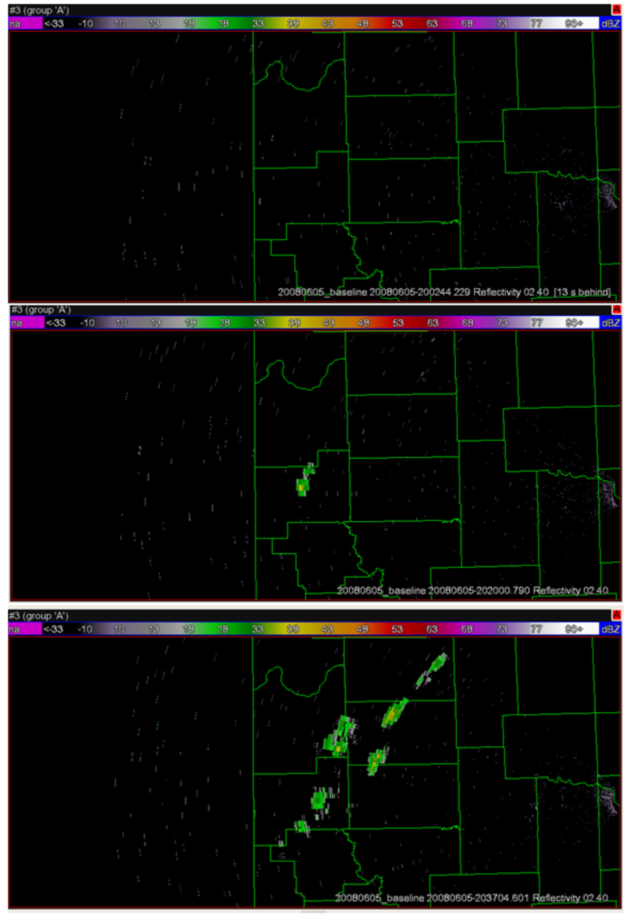

Fig. 4. Reflectivity PPI images at 2.4°. Data was collected with the NWRT PAR on June 5th, 2008. The event spans about 2 hours, from 19:05 to 21:07 UTC. The screen shots in this figure correspond to 20:02 (top), 20:20 (middle), and 20:37 (bottom) UTC, respectively.

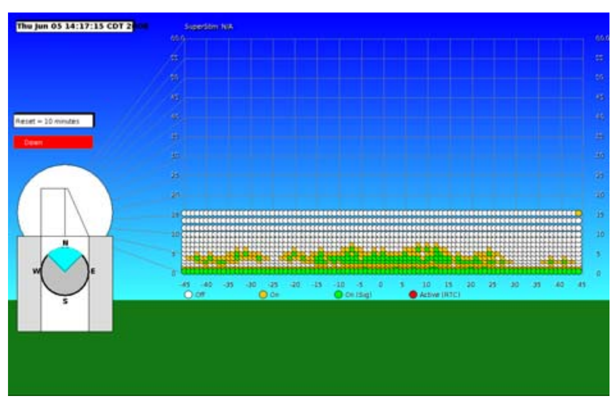

Fig 5. Performance of the initial implementation of ADAPTS. Beam positions on an azimuth-by-elevation plane are color-coded as follows: white beam positions are inactive, green beam positions are active based on elevation and significance criteria, and orange beam positions are active based on neighborhood.

3.4. New Implementation

The excessive number of false detections with the initial implementation of ADAPTS comes from the fact that the continuity and coverage requirements for significant returns are not spatially coupled. That is, the ground clutter near the radar meets continuity, while a few noisy range gates far away from the radar meet coverage.

A second playback scenario was run with the new implementation of ADAPTS whereby the continuity and coverage requirements are now spatially coupled; i.e., they have to be met on the same echo "feature". Fig. 6 shows a graphical depiction of the new significance criterion, and Fig. 7 shows the performance of ADAPTS with these changes. It is evident from this example that the new rules are effective at reducing the number of false alarms (compare Figs. 7 and 5). Still, a few false alarms remain. Deeper examination revealed that these are due to clutter contamination that spans a number of gates large enough to meet the significance criterion. In fact, close to the radar where the areal coverage of range gates is the smallest, about 14 contiguous range gates with clutter contamination close to the radar are needed to satisfy the significance criterion.

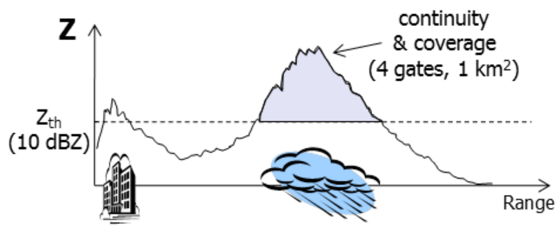

Fig. 6. Same as Fig. 2 but for the new implementation of ADAPTS with spatially coupled continuity and coverage requirements.

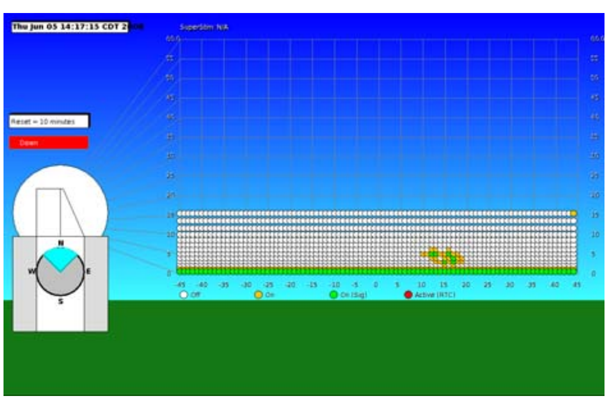

Fig. 7. Same as Fig. 5 but for the new implementation of ADAPTS.

To remove the few remaining false detections due to the clutter contamination close to the radar, the threshold for significance was modified to include a range dependency. Thus, the significant-reflectivity threshold was raised to 15 dBZ within 35 km of the radar and left at the default value of 10 dBZ elsewhere. Fig. 8 depicts this change and Fig. 9 shows the corresponding performance of ADAPTS. It is easy to see that the number of false detections is significantly reduced in this case (compare Figs. 5, 7 and 9).

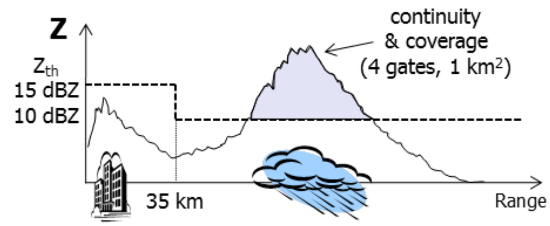

Fig. 8. Same as Fig. 6 but for the new reflectivity threshold for significance.

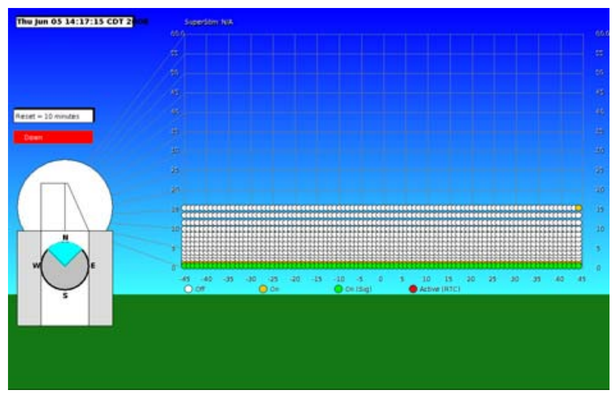

Fig. 9. Same as Fig. 7 but using the new reflectivity threshold for significance and the new ADAPTS.

Figs. 10 and 11 show reflectivity PPI panels depicting the storm sampling with conventional scanning and the new implementation of ADAPTS, respectively at 2.4°, 3.1°, 4.1°, and 5.1°. A qualitative comparison of these two figures reveals that whereas the new implementation significantly reduces the number of active beam positions, it does not sacrifice the sampling of the storms.

Fig. 12 shows zoomed-in reflectivity PPI panels comparing the performance of conventional scanning, the initial implementation of ADAPTS, the new implementation of ADAPTS, and the new implementation with range-dependent significant-reflectivity thresholds. It is evident here that each implementation improves on the previous one, with the latest version providing maximum scan time savings.

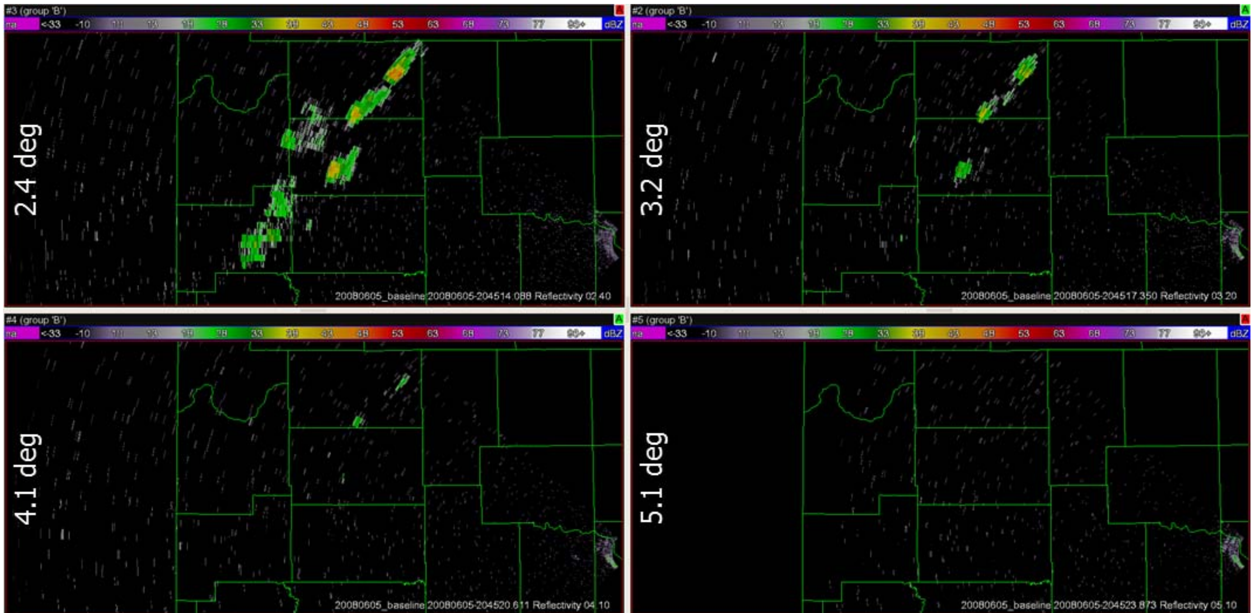

Fig. 10. Reflectivity PPI displays for data collected on June 5th, 2008 at 20:45 UTC with conventional scanning. The panels correspond to 2.4°, 3.2°, 4.1°, and 5.1° elevation angles.

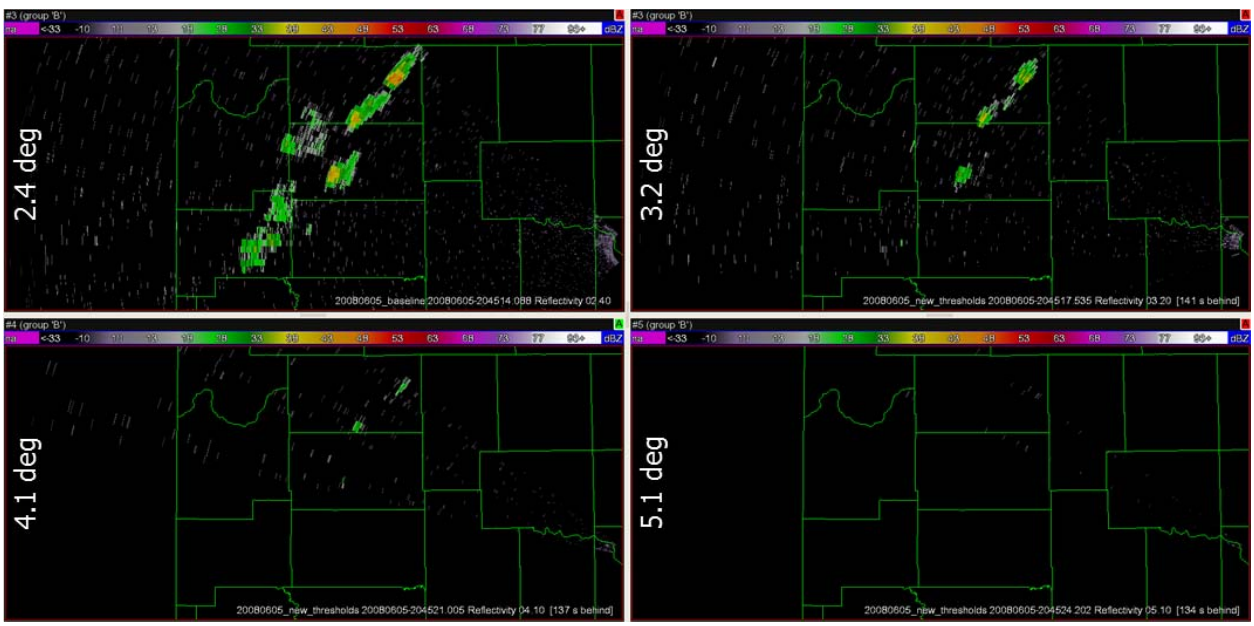

Fig. 11. Same as Fig. 10 but for the new implementation of ADAPTS with the new thresholds.

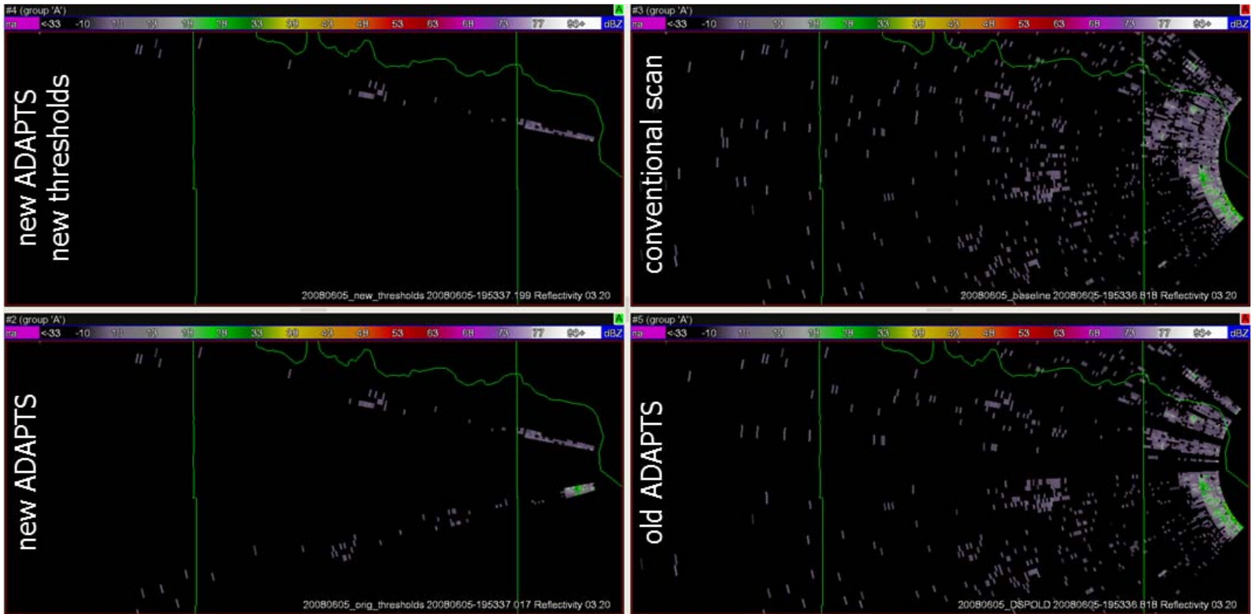

Fig. 12. Reflectivity PPI displays for data collected on June 5th, 2008 at 19:53 UTC at 3.2° sampled with conventional scanning (top right), the initial implementation of ADAPTS (bottom right), the new implementation of ADAPTS (bottom left), and new ADAPTS with new thresholds (top left).

The improvement realized by these changes can be quantified by computing the scan time for the different playback scenarios. Fig. 13 shows the scan time of the three playback scenarios (old ADAPTS, new ADAPTS, and new ADAPTS with new thresholds) as a percentage of the full scan time for the 110 scans comprising the 2-hour period under analysis. Whereas the old implementation of ADAPTS was able to reduce scan times to the 60-70% range for this case, more improvements are realized by the modifications outlined above. By spatially coupling the continuity and coverage requirements, an additional 15% of time savings can be seen with overall scan-time reductions in the 45-55% range. Furthermore, increasing the significant-reflectivity threshold near the radar can add up to 5% of additional time savings, resulting in the shortest scan times.

4. THE FUTURE OF ADAPTS

As discussed before, 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 surveillance to capture new storm developments. ADAPTS is a proof-of-concept algorithm that is implemented on the NWRT PAR and is used as the default mode of operation.

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, data collected for the weather-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. This capability is currently being implemented for operational use on the NWRT PAR and will be tested in the coming year.

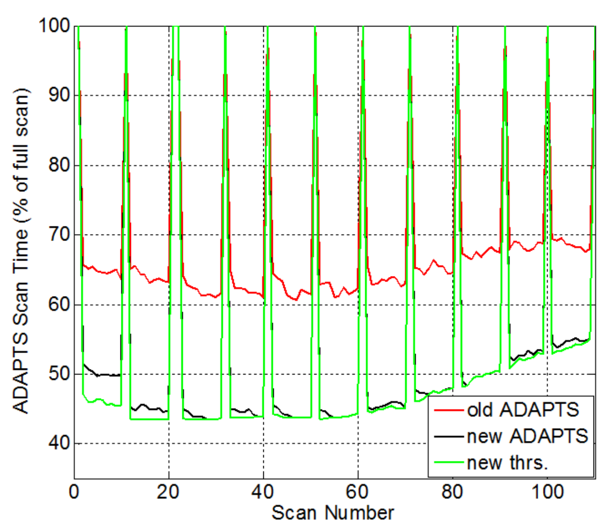

Fig. 13. ADAPTS scan times as a function of scan number. Scan times are given as a percentage of the full scan time for the old ADAPTS, new ADAPTS, and new ADAPTS with new thresholds. The 110 scans span the 2-hour interval of the June 5th, 2008 case. The periodic "jumps" are indicative of a full scan (about every 10 scans).

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. This capability is planned for future upgrades of the NWRT PAR.

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 an implementation of fast adaptive scanning to 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 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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