P6.5A PHASED ARRAY RADAR INNOVATIVE SENSING EXPERIMENT

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1. INTRODUCTION

The year 2008 marked the 20th anniversary of the final design for the Weather Surveillance Radar-1988 Doppler (WSR-88D). This design milestone was preceded by a ~30 yr effort focused on the research and development of Doppler weather radars (Whiton et al. 1998). Continuous improvements to the WSR-88D system hardware and products (Crum et al. 1998; Serafin and Wilson 2000) have resulted in significant service improvements, including increased mean warning lead time for tornadoes from 6 to 13 min, and reduced tornado-related injuries (40%) and fatalities (45%; Simmons and Sutter 2005). However, the approach of this system toward its 20-yr design life cycle (Zrnić et al. 2007), advances in radar technology since the early 1980s, and the lead time involved in the research, development, acquisition, and deployment of new systems have motivated the consideration of a replacement system or family of systems (National Academies 2002, 2008).

As a leader in the development of new weather surveillance capabilities, the National Severe Storms Laboratory (NSSL) and its partners have acquired and fielded an S-band Phased Array Radar (PAR), which is located on the north campus of the University of Oklahoma. This facility is known as the National Weather Radar Testbed (NWRT). This radar system is unique in that it provides targeted, high-temporal resolution, electronic scanning of storms within a 90°- azimuthal sector. The PAR's electronic scanning supports focused sampling of weather echoes without rotating the antenna. A description of this and other PAR capabilities is given in section 2.

Since spring 2007, the NSSL has run PAR experiments as a part of the Experiment Warning Program (Stumpf et al. 2008) in the NOAA Hazardous Weather Testbed. These experiments are designed to demonstrate the latest PAR sampling capabilities and attain user feedback from National Weather Service (NWS) participants (Heinselman et al. 2007; Heinselman 2008). The data collected during the experiments are used to study storm processes sampled at high-temporal resolution. The 2007 and 2008 experiments focused on the operational use of high-temporal resolution data on the analysis and warning of severe storms. During the 2009 Phased Array Radar Innovative Sensing Experiment (PARISE), this focus was enhanced by the implementation of adaptive scanning of weather echoes.

The PARISE ran from 27 April – 14 June 2009, with the exception of Memorial Day week. During that period, 16 National Weather Service (NWS) forecasters evaluated the operational utility of PAR technology during real-time operational warning situations and playback of archived cases. The two key objectives of PARISE were to demonstrate and obtain feedback on: 1) basic adaptive electronic scanning of weather echoes and 2) three scanning strategies for surveillance of storms. Forecaster evaluations of PAR weather data were obtained through an eight-item questionnaire.

The purpose of this paper is to describe key components of the experiment, document two severe weather events sampled by the PAR, and summarize the feedback provided by forecasters for two playback cases. The key technical components of PARISE, described in sections 2–4, are the PAR, the adaptive scanning software, and scanning strategies. An overview of forecaster activities is given in section 5. Section 6 documents 2 of the 3 severe weather events observed during real-time operations and section 7 summarizes

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common threads found within forecaster evaluations.

2. NWRT PAR

The NWRT PAR is an electronically steered, S-band radar (for a detailed description, see Zrnić et al. 2007) that was once mounted on a Navy ship. Its SPY1A antenna forms a beam electronically by controlling the phase of 4,352 transmit/receive elements. The steering of the beam is also accomplished electronically by fixing the beam in a set direction while data is collected along a radial, and then instantly switching the beam to another position. Because the NWRT PAR was originally developed to track military missiles and airplanes, rather than to detect weather echoes, the radar system transmits vertically polarized electromagnetic waves. Given that a raindrop becomes flatter with increasing size, the magnitude of reflectivity returns may be less than those measured from a horizontally polarized beam.

A basic characteristic of phased array radars is variation of the beamwidth in azimuth. For the NWRT PAR, in the direction perpendicular to the antenna face, i.e., broadside, the beamwidth is 1.5°, which is similar to the effective beamwidth of the WSR-88D without super-resolution (Brown et al. 2005). Between broadside and a 45° angle from broadside, the beamwidth increases gradually to 2.1°. During data collection, overlapped azimuths provide finer sampling of the increasingly degraded data toward the edges of the sector scan. In an operational system, the beamwidth specifications would match or exceed those of the WSR-88D.

Currently, the NWRT PAR is a single-faced phased array system which scans a 90° sector while stationary. As a result, the PAR can collect data with a VCP 12 scanning strategy, for example, within 58 s rather than 258 s (90° sector vs 360° sector, respectively). The reduction in time required for volumetric updates produces more realistic evolution of storm structures (Heinselman et al. 2008) and eliminates smearing of the beam due to rotation of the antenna. In the future, an operational PAR configuration, however, would have 4 independent faces capable of scanning a complete 360° sweep. In essence, a 4-faced PAR would be like having 4 radars in one location, each scanning its own 90° sector. Because the NWRT PAR has only one face, it is mounted on a pedestal to facilitate data collection within the 90° sector of greatest meteorological interest.

Owing to its different antenna design, the NWRT PAR has some unique capabilities compared to the WSR-88D. Most importantly, electronic steering of the beam supports targeted scanning of weather echoes. In spring 2009, targeted scanning of storms was accomplished using new adaptive scanning software developed by NSSL, called ADAPTS. The purpose of this software is to concentrate data collection on areas with significant weather echoes to provide users with more timely, needs-driven data. As described in the next section, the key radar need afforded by ADAPTS is higher-temporal resolution; an important radar capability reported in several recent studies (OFCM 2006; Steadham 2008; Newman et al. 2008).

3. ADAPTS: Adaptive Data Signal Processing Algorithm for PAR Timely Scans

ADAPTS is a proof-of-concept implementation of adaptive scanning for the electronically steered NWRT PAR. As such, the algorithm is basic and limited to a certain type of scanning strategies. Still, preliminary evaluations of ADAPTS have shown that the performance improvement with adaptive scanning is quite significant compared to traditional scanning strategies. ADAPTS works by “turning on” or “turning 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 redetermine 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.

3.1 *Determination of active beam positions*

A beam position is said to be *active* if one or more of the following conditions are met:

1. The elevation angle is *low*,
2. A *neighboring* beam position is on, or
3. Reflectivities on gates along the beam meet *continuity*, *coverage*, and *significance* conditions.

The first criterion is used to ensure data collection at all beam positions for the lowest elevation angles. This is important from a meteorological point of view to constantly 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. However, note that due to the second criterion, there will always be an entire tilt above the specified threshold where ADAPTS will *activate* all beam positions.

The second criterion uses “neighboring” beam positions to expand the data collection footprint to allow for continuous adaptation in response to storm advection, growth, or decay. Nevertheless, new developments at midlevels may not be immediately sensed and therefore may not be timely added to the list of active beam positions. Neighboring beam positions are defined as those immediately above and below in elevation and two on either side in azimuth (i.e., there is a total of 6 neighbors for each beam position, unless the scanning domain boundaries are approached).

The third criterion uses continuity, coverage, and significance conditions to make a quantitative determination of the amount of significant weather returns at each beam position. In this context, a beam position is active if it contains:

1. a certain number of consecutive range gates (by default 4) with reflectivities exceeding a threshold (by default 10 dBZ), and

2. a total areal coverage (by default 1 km^2) with reflectivities exceeding the same threshold.

3.2 *Impact on scanning strategies*

Being in its infancy, ADAPTS only works with scanning strategies that have a certain structure. That is, the ADAPTS assumes that:

- There’s only one scanning strategy that repeats continuously,
- The scanning strategy runs in PPI mode,
- All tilts in the scanning strategy have beam positions at the same azimuths,
- Tilts are ordered in ascending elevation order,
- The azimuthal sector size is between 1–90°,
- The maximum azimuthal resolution is 0.5° (the max. number of beam positions in an elevation is 180).

3.3 *Monitoring ADAPTS performance*

Users at the Radar Control Interface (RCI; Priegnitz et al. 2009) can monitor the performance of the ADAPTS algorithm by looking at a graphical display of active beam positions (see Fig. 1). Beam positions are color-coded as follows: white beam positions are inactive, green and yellow beam positions are active. Green beam positions meet the third detection criterion, whereas yellow beam positions correspond to the “neighbor” footprint extension. The display updates every second and highlights in red the “current” beam position.

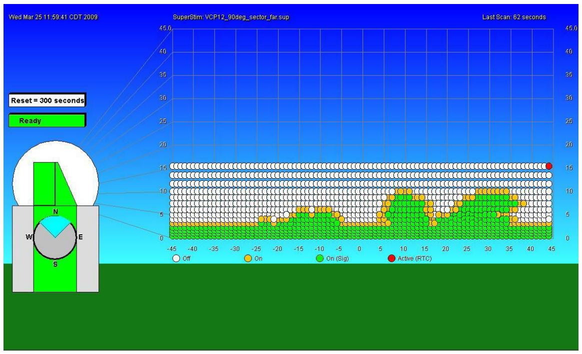

Fig. 1. Screen capture of the Radar Control Interface (RCI) graphical display of active beam positions with ADAPTS.

4. SCANNING STRATEGIES

An important objective of PARISE is the development and testing of scanning strategies designed to improve sampling and understanding of storm processes. The properties of the scanning strategies are chosen to provide either denser vertical or horizontal sampling than conventional scanning strategies, while maintaining temporal resolution higher than the fastest WSR-88D scan (4.2 min VCP-12 scanning strategy) and WSR-88D data quality requirements. During PARISE, the three scanning strategies implemented were 1) conventional 2) dense vertical, and 3) elevation-prioritized sampling.

Each scanning strategy has two versions: near and far (Table 1). In near scanning strategies, the elevation angles are spaced to provide improved sampling of mid and upper-levels of storms located within 70 km of the PAR. Rather than extending to the conventional 19.5° elevation angle, in most cases these scanning strategies extend to a 38° elevation angle. In contrast, far scanning strategies elevation angles are spaced to provide improved sampling of low-to-midlevels of storms located ~70 km or farther from the PAR. The far scanning strategies extend to only 15.5° to avoid sampling regions above storm top (i.e., 18 km). Both near and far scanning strategies use NEXRAD-like processing at lower elevations to provide velocity unfolding and the number of samples meet or exceed WSR-88D data accuracy requirements. An overview of each scanning strategy follows.

4.1 *Conventional Scanning*

Conventional scanning is traditional, contiguous sampling using 14 elevation angles; the spacing between elevation angles increases with increasing height (Table 1). Similar to super-resolution sampling (Brown et al. 2005), 50% oversampling in azimuth is employed to improve the resolution of azimuthal signatures. Because the beamwidth varies across the sector, the 50% oversampling is adjusted accordingly (109 radials). The higher resolution azimuthal sampling is applied at all elevations, rather than on only the two lowest elevations, as done on the WSR-88D network. Velocity aliasing is minimized by employing the maximum available Nyquist velocity for the PAR: ~30 m s^{-1}. These sampling characteristics result in 1.4 min and 1.6 min updates for the near and far conventional scanning strategies, respectively.

During spring and summer 2009, the conventional scanning strategies sampled a nontornadic supercell and a few quasi-linear convective systems. These data collections provide the opportunity to investigate the impact of 50% azimuthal oversampling on the depiction of reflectivity and velocity signatures through storm depth.

4.2 *Dense Vertical Scanning*

Dense vertical scanning is accomplished using 25 elevation angles (Smith et al. 2009). Due to the high number of angles, 1° oversampling in azimuth is chosen to reduce sampling time. The highest elevation angles differ from the conventional and elevation-prioritized scanning strategies. Elevation angles for near scanning range from 0.5° to 28.5°, rather than up to 38°; elevation angles for far scanning range from 0.5° to 16.10° (vs 15.5°). Elevation angles for near scanning range from 0.5° to 28.5°, rather than up to 38°. The lowest tilts are very tightly spaced, resulting in vertical spacing finer than the beamwidth within 50 km of the PAR. The maximum Nyquist velocity and range are 26.1 m s^{-1} and 135 km, respectively. The high number of elevation angles produce volume update rates slower than the conventional scanning strategy: ~2 min to complete a 90° sector. The maximum Nyquist velocity and range are 26.1 m s^{-1} and 135 km, respectively. Further details are available in Smith et al. (2009).

During spring and summer 2009, the vertically dense scanning strategies (25 elevations) sampled primarily pulse storms, including a wide-spread heat burst event (Smith et al. 2009). These data provide the opportunity to investigate the impact of dense vertical sampling on the depiction of storm structures like three-body scatter spikes, vertical profiles of reflectivity, storm top height, indicators of strong updrafts, such as weak echo regions, and indicators of microbursts such as the magnitude of storm-top divergence, midlevel convergence, and low-altitude winds.

4.3 *Elevation-Prioritized Scanning*

Elevation-prioritized scanning is designed to provide the fastest update rate at low-elevation angles and the slowest update rate at high-elevation angles. In this case, 14 elevation angles are elevation-prioritized to accomplish the following within ~4.5 min (Fig. 2):

- 6 updates at the lowest 2 elevations,
- 3 updates at the next 5 elevations,
- 2 updates at the 6 highest elevations.

Owing to the interlaced nature of this scanning strategy, the temporal resolution at a fixed elevation angle varies. In the near elevation-prioritized scanning strategy (Fig. 2), for example, the time intervals between 0.5°-elevation scans range from 41–51 s, with a median time interval of 43.5 s. The median temporal resolution for each set of elevations is noted hereafter. Because the near elevation-prioritized scanning strategy sampled a storm described later, this section focuses on its temporal resolution.

Sampling the lowest two elevation angles most frequently provides 43.5 s (0.73 min) median updates of radar signatures that tend to evolve on very short time scales, such as high winds or tornadic vortex signatures. The second most frequently sampled elevation angles accomplish 87 s (1.45 min) median updates of midlevel storm structures like mesocyclones. The least frequently sampled upper-elevation angles provide 132.5 s (2.2 min) median updates of upper-level features such as storm-top divergence. Owing to the interlaced sampling, in spring 2009 this scanning strategy was incompatible with ADAPTS. However, ADAPTS is being enhanced to work with these scanning strategies during PARISE 2010.

The elevation-prioritized scanning strategy also implements 50% overlapped azimuthal sampling at all elevation angles. To further improve detection of tornadic vortex signatures and other hazardous weather signatures, velocity errors at the lowest two tilts are minimized by collecting a relatively high number of pulses (64). The accuracy of reflectivity data is also enhanced by collecting more than the traditional number of pulses (16) for all continuous surveillance scans above the second tilt. This is done to provide less noisy depictions of hook echoes, bounded weak echo regions, and other reflectivity signatures associated with potentially severe convective storms.

The far version of this scanning strategy provides denser vertical sampling than the near version: $\leq 0.75°$ spacing through 6.3°. This enhanced vertical sampling is implemented to provide improved estimates of the vertical extent of storm structures related to severe weather occurrence at distances 70 km and farther from the PAR.

In spring and summer 2009 the near elevation-prioritized scanning strategy sampled a tornadic cyclic supercell located within 50 km of the PAR. These data provide the opportunity to analyze the impact of interlaced sampling on the depiction of circulations and other supercell processes.

5. FORECASTER ACTIVITIES DURING PARISE

As stated in the introduction, PARISE ran for 6 of the 7 weeks during 27 April – 12 June 2009. At the beginning of each week, a new set of National Weather Service forecasters (2 – 4) began their participation in PARISE by attending a training session on the experiment and the Warning Decision Support System – Integrated Information (WDSSII) (Lakshmanan et al. 2007), which they used to display and interrogate the radar data.

During each week, the forecasters examined at least two playback cases run in simulated real time, and one or more real-time cases depending on weather conditions. When possible, playback cases were run prior to real-time operations to help familiarize forecasters with PAR data and WDSSII. Whether examining playback or real-time data, forecasters were asked to interrogate the PAR data and comparative data sets (e.g., Oklahoma City, OK WSR-88D data) as if they were in their own office. An “operational” mentality was encouraged by asking forecasters to issue severe weather warnings. Following each event, forecasters responded to an eight-item questionnaire designed to evaluate:

- strengths and limitations of high-temporal resolution PAR data in the analysis & understanding of severe storms,
- how characteristics of scanning strategies affected depiction of severe storms,
- how PAR data impacted warning decision making,
- performance of ADAPTS,
- forecaster radar needs, and
- overall experience with PAR capabilities.

Three real-time severe weather events occurred during the PARISE operations (1– 9 pm), including an isolated nontornadic supercell on 1 May, an isolated tornadic supercell on 13 May, and a quasi-linear convective system with wind damage on 10 June. Because they occurred early in the experiment, the 1 and 13 May events were added to the playback database. Two other playback events included a microburst (10 June 2006) and low-topped tornadic supercell (19 August 2007). Findings from an analysis of forecaster comments from these two events follow.

5.1. *Analysis methodology and findings*

The two playback cases were chosen because they were types of storms common elsewhere and atypical of Oklahoma. Thirty participants, at times working alone but usually in teams, evaluated the 10 July 2006 microburst and 19 August 2007 low-topped tornadic supercell case. PAR volumetrically sampled the microburst every 34 s and the low-topped tornadic supercell every 43 s. Forecaster participants were then asked to analyze the data and issue warnings as part of the simulated work environment; participants were asked to have a mental attitude of actually being on the job during evaluation to further simulate the pseudo-operational experience. At the end of each event, participants were asked to complete an evaluation questionnaire.

Data analyzed came from the following subset of participants: 10 senior/lead forecasters, 8 Science and Operations Officers (SOO), 6 forecasters, 3 Meteorologists (or Forecasters)-in-Charge, 1 meteorology instructor, 1 journeyman forecaster, and 1 Science Support Division Chief. Years of forecasting experience ranged from 5.5 to 30. A few teams included non-NWS meteorologists. Two researchers and one PhD student also participated, always on a team with someone from the NWS.

Since the questionnaire contained mostly open-ended questions, a data-driven thematic qualitative analysis method was employed (Boyatzis 1998; Patton 1990). The qualitative analysis was completed by coding written responses and then looking for themes among those codes. This analysis process was applied to each set of responses associated with each of the playback weather events. The themes that emerged from each event are discussed next.

5.1.1 Microburst

A central theme that arose was *benefits of high-resolution temporal sampling*. Words used by three different forecasters to describe their data interpretation experience with PAR data were “very useful”, “valuable”, and “extremely helpful.” These word choices represented their capability to identify key precursors to microburst development and subsequently monitor their evolution. The structural features noted by forecasters were updraft development and intensification of the reflectivity core aloft, descending high-reflectivity cores, divergence couplets associated with downdrafts, and the evolution of strong winds near the surface.

An important component in the analysis of microbursts is assessing the magnitude of the wind produced near the ground. Following the analysis of this microburst event, one forecaster remarked that, “High temporal resolution of PAR [data] allowed me to identify near-ground-level severe winds which were considerably under-played by KTLX: 27 kt vs 57 kt.” Though in this case the higher radial velocity attained from the PAR was due, in part, to closer sampling of the storm (~20 km), sampling more frequently increases the likelihood of better sampling maxima in the velocity field.

Forecasters also noted the benefit of a few minutes additional lead time in the warning of high winds from microbursts, owing to the capability to detect developing cores aloft earlier, and faster detection of features after they are sampled by the radar. Due to the relatively fast evolution of microbursts, and the current 4–5 min sampling of the WSR-88D, one forecaster stated that rapid updates “will help get the warning out period.” Similarly, another forecaster said that the rapid sampling of PAR “would definitely help us to improve pulse storm warnings. We have many missed pulse storm hail and wind warnings.”

Forecasters specifically expressed feelings of increased confidence during the simulation. They indicated that feelings of increased confidence arose due to their improved capability to interpret radar signatures and make decisions about whether or not to issue a warning. One forecaster described this experience as follows, “You can diagnose better what’s going on so you can have more confidence in issuing or not issuing warnings.”

Responses to the questionnaire also elicited specific recommendations from forecasters regarding scanning strategy needs for microbursts. Scanning strategy needs mentioned were fast update rates, scanning strategies with elevation angles adapted to better sample storms based on their distance from the radar, more near-surface sampling (i.e., below 0.5°), and rapid subsector scanning interspersed between basic scanning of the whole volume.

5.1.2 Low-topped supercell

Like the microburst case, a central theme that arose from forecaster responses to the questionnaire was *benefits of high-resolution temporal sampling*. All forecasters reported that the 43-s volumetric sampling by the PAR provided depictions of supercell storm structure and evolution superior to the WSR-88D's 4.1 min updates. They also found that the rapid updates resulted in quicker analysis of the development of circulations, including the rapid development of a short-lived tornadic vortex signature.

For most forecasters, these improvements to operations produced feelings of increased confidence during their data analysis and/or warning decision making that they shared in their written responses. For instance, one forecaster stated, "PAR allows for increased confidence of storm feature evolution", while another said, "All warnings were high confidence." During the simulated warning operations, however, ~80% of forecasters recorded their warning information. Based on analysis of the PAR data, these forecasters issued a tornado warning on the storm about 3 min prior to the storm's development of an EF0 – EF1-rated tornado. Since a tornado vortex signature was sampled only once by the WSR-88D, it is unsurprising that a tornado warning was not issued during actual operations.

5.1.3 Concept of operations recommendations

Responses to the questionnaire also elicited specific recommendations from forecasters regarding scanning strategy needs for low-topped supercells. Most respondents voiced a need for rapid updates at low elevations. One specific suggestion was to "double [the] number of low-level tilts; attain [them] about every 1-min; upper tilts every 3 min." Another was to attain rapid updates of the lowest three tilts to "assess vertical continuity in wind/tornado situations", while sacrificing data collection at higher tilts. The need for rapid updates at low-elevation angles voiced by participants agrees with findings from a recent survey conducted by the Radar Operations Center on scanning strategy improvements needed by National Weather Service forecasters (Steadham 2008).

In their responses to the questionnaire, forecasters also provided feedback on initial challenges they think they would face if the current WSR-88D network was replaced with a network of PARs. A common theme voiced by forecasters was the idea that experience in analyzing rapid update data and making warning decisions from that analysis would be needed to "recalibrate" their warning decision process. A few forecasters explained that to recalibrate their warning process, they would need to gain experience as to how many consecutive scans needed to be examined prior to issuing a warning. In his own words, one forecaster explained, "Forecasters are typically trained to wait a couple of scans to see if [a feature] is persistent or real… [I] may need to wait 4–6 scans on PAR."

Several individual operational concerns were also noted by forecasters. Feeling overwhelmed by the 43 s update rate in this playback case, one forecaster shared his desire to have control over the update rate shown on the radar display**.** Another forecaster speculated that warning sectors would need to be made smaller and WARNGEN functionality better, to handle fast evolving hazardous weather situations. A different perspective given by another forecaster was that in this case, the higher temporal resolution of the data, and increased probability of detecting precursors to hazardous weather, raised the number of warnings he issued. Although he had high confidence in all of these warnings, he was concerned about the societal impact of the potential increase in information to the public. Though an interesting and relevant question, answering it is beyond the scope of this study.

6. 2009 REAL-TIME WEATHER EVENTS

A key part of PARISE is the demonstration and assessment of new sampling capabilities, which in 2009 included ADAPTS and elevation-prioritized sampling. This section provides an analysis the impact of each on the sampling of a spring 2009 severe weather event

6.1 *Impact of ADAPTS on temporal resolution and sampling*

During the evening on 1 May 2009 (004059 – 04403 UTC), data were collected on an isolated storm located in Custer County, Oklahoma (Fig. 1). The storm developed into a nontornadic supercell that, according to a preliminary Storm Data report, produced up to baseball size hail stones (2.75 in) at ~0200 UTC near Stafford, Oklahoma in south-central Custer County (http://www.spc.noaa.gov).

Because the storm was isolated, it was a good candidate for demonstrating and evaluating the utility of ADAPTS. Due to its distance from the PAR, 150 to 200 km, and a desire for rapid updates, the storm was sampled with the Conventional Far scanning strategy (1.4 min updates). On occasion there are gaps in data collection owing to rebooting the radar control interface (Priegnitz et al. 2009). A primary goal of ADAPTS is to reduce scan time by sampling only regions containing weather echoes, while capturing the growth, decay, and horizontal advection of existing storms. When ADAPTS is running, a full volume scan is completed at ~5-min intervals, with adaptive scanning occurring between.

Fig. 3 shows the improvement in temporal resolution attained from ADAPTS. As one expects, the highest temporal resolution sampling (~55 s) occurs early in the storm's life time: 0040:59 – 0052:44 UTC. Over the next hour, volume updates of 1 min or less are maintained between full volume scans (Fig. 3) owing mostly to lack of significant movement and vertical growth in storm top height (Fig. 4). The storm's vertical growth is well-captured by ADAPTS, as shown by the lack of additional elevation angles aloft following surveillance scans (Fig. 3).

Thereafter (015427 UTC), Fig. 3 shows a nearly linear increase in sampling time between 5 min intervals, which directly corresponds to an increase in the number of active beam positions. The factors contributing to longer sampling time are 1) an increase in the number of storms sampled, 2) horizontal and vertical storm growth, and 3) a concurrent increase in the number of radials and elevation angles that sample the storm as it advances toward the PAR. This event exemplifies the impacts of areal radar coverage and vertical extent of storms on improvements to temporal resolution resulting from ADAPTS.

b. *Evolution of TVS with elevation-prioritized sampling*

On the evening of 13 May 2009 (CDT) a cyclic, supercell moved across Oklahoma City, Oklahoma, within 10 km range of the PAR. Because tornado occurrence was a concern, high-temporal resolution sampling, especially at the lower elevations, was desired. Due to the storms' proximity to the PAR, the supercell was sampled with the near elevation-prioritized scanning strategy (Fig. 1), which provided 43.5 s median updates at the two lowest elevations: 0.5° and 1.5°. These data were collected while the supercell's hook echo and mesocyclone circulations were located within 20 km of the PAR: 0318:11–0348:26 UTC.

During this period, a tornado warning issued by the Norman, Oklahoma National Weather Service Forecast Office was in effect. Post-analysis revealed the development of several short-lived (i.e., few min) cyclonic circulations within 20 km of the PAR; all were sampled with a beamwidth of 0.47 km or less.

At 0339:25 UTC, a prominent circulation at the 0.5° elevation was sampled by a 0.45 km beamwidth at a height of 0.5 km above mean sea level (MSL; Fig. 4a). About 2 km north-northeast of this circulation was a cyclonic convergence zone. To track the intensity of these circulations, the maximum velocity difference within 1 km (2 gates in azimuth) on both sides of the center of the circulation was computed. Though the velocity difference associated with this first circulation was 23.5 m s^{-1} at 033925 UTC, it rapidly dissipated within the following 2 min. Within this same time frame, a new, stronger circulation developed ~1 km to the north of the former one, within the cyclonic convergence zone (0341:00 UTC, Fig. 4a). The initial velocity difference of this second circulation was 26 m s^{-1} (034100 UTC); this intensity was maintained or exceeded during the next 5 min.

A comparison of the locations of this velocity signature with a damage survey (completed by the first author and Les Lemon of the NWS/WDTB) concluded that a short-lived tornado producing EF0 damage occurred between 034224 and 034350 UTC. During its short lifetime, the maximum measured velocity difference was 31.5 m s^{-1} (0.5 km MSL) at 034350 UTC. Within its life time, it crossed the marina on the western shore of Lake Stanley Draper and proceeded southward across a picnic area, parking lot, and walking path just east of a small pond, producing an approximate 0.80 km path (Fig. 4b). Though short-lived, the tornado dislodged one dock in the marina, uprooted and broke branches off of several trees, and significantly damaged a port-a-potty.

7. Summary

This paper provided an overview of the 2009 Phased Array Radar Innovative Sensing Experiment (PARISE), including descriptions of

- the newly developed software Adaptive Data Signal Processing Algorithm for PAR Timely Scans (ADAPTS),
- three high-temporal resolution scanning strategies,
- the experiment goals, activities, and findings, and
- two severe weather events that occurred during the experiment.

Forecaster evaluations of two playback cases with high-temporal resolution PAR data (34 and 43 s updates) indicate that these data improved the depiction of severe weather precursors prior to a microburst and tornado produced by a low-topped supercell. The enhanced temporal continuity of storm structures increased forecaster confidence during the warning decision process. Forecasters also noted that, compared to the WSR-88D data they also observed during these events, the higher temporal resolution PAR data appeared to result in a few min earlier warning lead time.

The development of ADAPTS provided the first weather data collection with electronically steered adaptive scanning. ADAPTS ran while sampling the full lifetime of an isolated, hail-producing supercell on 1 May 2009 with the conventional scanning strategy. During the first 70 min of the storm's lifetime, the ADAPTS reduced the sampling time from 1.4 to 1 min between surveillance scans. The scanning time gradually increased thereafter in response to increases in number of storms, storm coverage and depth, and the resolution of the radar volumes as the storms moved closer to the PAR.

The 13 May 2009 tornadic supercell was the first storm sampled by the elevation-prioritized scanning strategy. This scanning strategy's median 4.3 s updates at the 0.5° and 1.5° elevation angles illustrate the need for high-temporal resolution data to identify and track short-lived circulations with the potential to produce tornadoes.

The 2010 PARISE will further capitalize upon the capabilities of the NWRT PAR. Enhancements to the ADAPTS are in progress to make it a more flexible and advanced adaptive scanning software. Concepts like elevation-prioritized scanning will be further exploited to improve temporal scanning of rapidly evolving features. Additionally, the PAR program will be infused with social science research focused on improving understanding of the impact of temporal sampling on the warning decision process.

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Near Scanning Strategy	**0.51**	**1.5**	**2.6**	**3.8**	**5.2**	**6.8**	**8.7**	**11.0**	**13.8**	**17.2**	**21.3**	**26.2**	**32.0**	**38.0**
Far Scanning Strategy	**0.51**	**1.1**	**1.7**	**2.4**	**3.2**	**4.1**	**5.1**	**6.2**	**7.4**	**8.7**	**10.1**	**11.7**	**13.5**	**15.5**

Table 1. Elevation angles used in the Near (≤ 70 km-range) and Far (> 70 km-range) Conventional Scanning Strategies.

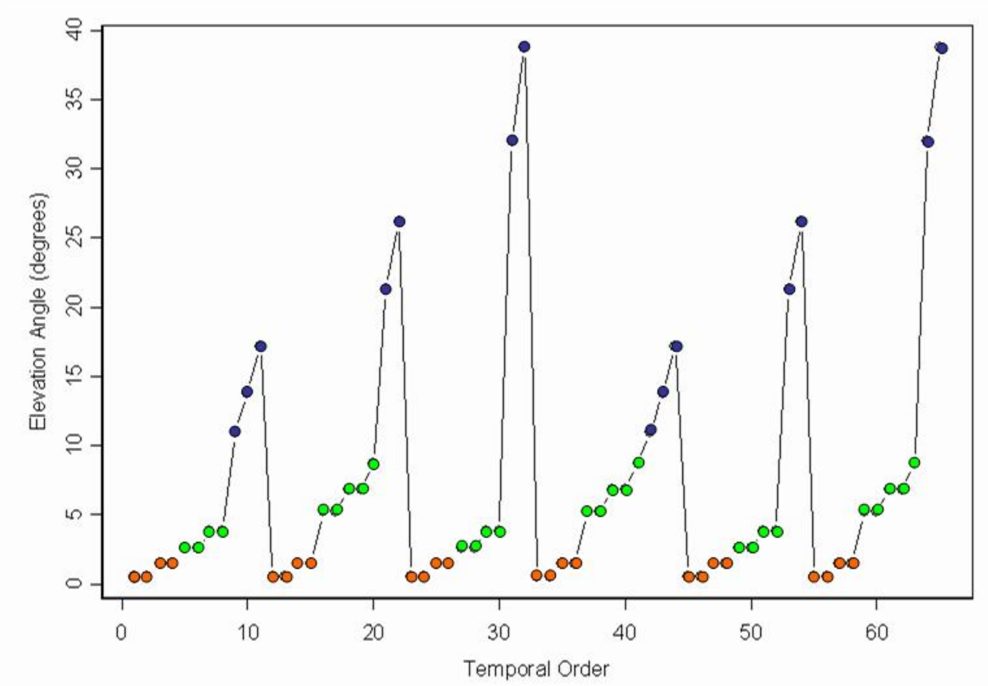

Fig. 2. Temporal order of elevation angles in near-version of elevation-prioritized scanning strategy. The median temporal resolution is indicated by the colored dots: orange: 43.5 s (0.73 min), green: 87s (1.45 min), blue: 132.5 s (2.2 min).

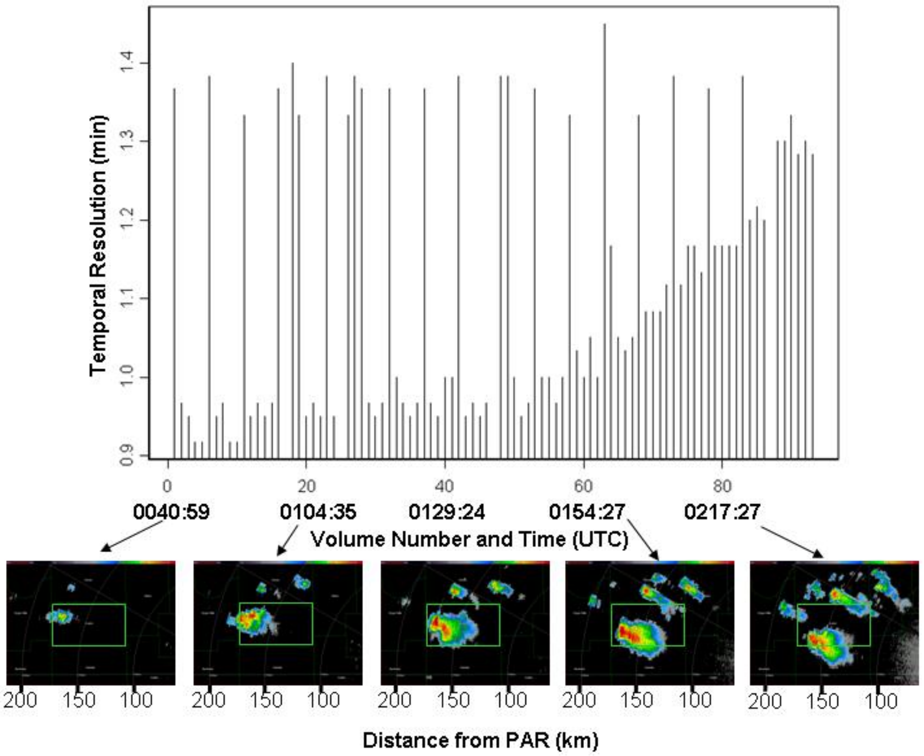

Fig. 3. Time series showing temporal resolution of 102 volume scans collected within 0040:59 – 024403 UTC 1 May 2009. Also shown are 0.5° elevation images at five times during the period. The green box outlines Custer County in west central Oklahoma.

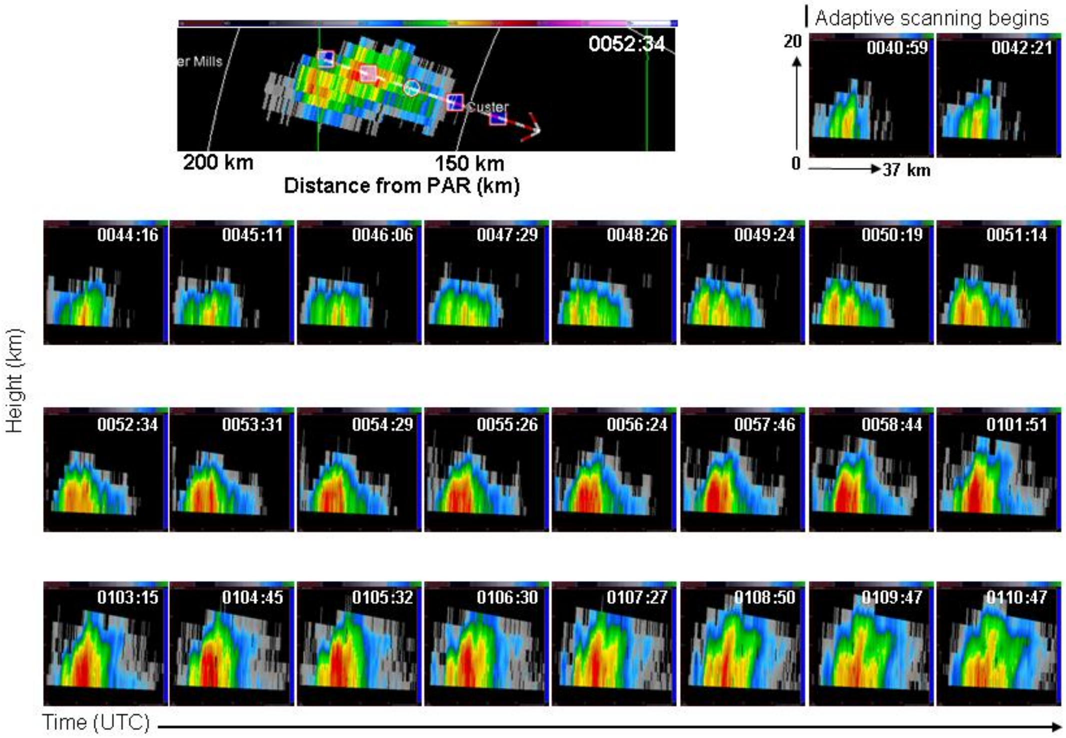

Fig. 4. Location of vertical cross sections of reflectivity on 1 May 2009 storm taken along a fixed radial while running ADAPTS (0052:34 UTC shown). The time series represents the storm's slow vertical growth during this ~30 min period.

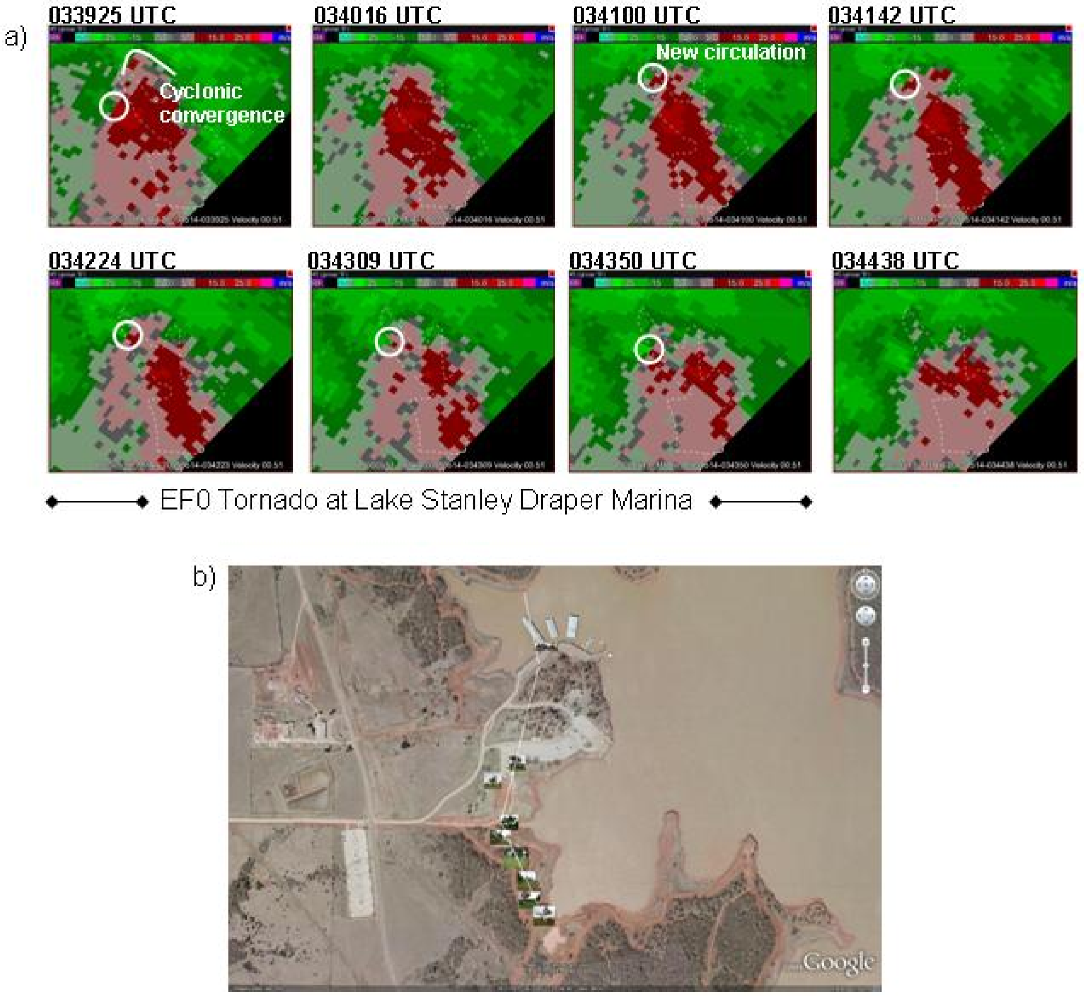

Fig. 5. a) A time series of PAR and KTLX 0.5° elevation radial velocity data prior to and during the EF0 tornado over Lake Stanley Draper. b) The white line shows the 0.8-km damage path of the EF0 tornado that occurred on the western shore of Lake Stanley Draper on 14 May 2009.

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