Evaluation of rapid sampling rates using the National Weather Radar Testbed Phased-Array Radar

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1. Introduction

Tornadoes often develop on time scales of 10 s or less (Bluestein et al. 2010), thus requiring rapid volumetric updates to adequately sample their evolution. In the United States, the operational radar system with the fastest lowest-elevation update time (1-min) is the Terminal Doppler Weather Radar. These C-band radars are located only at major airports in the U.S., so only a few regions are covered by them. Meanwhile, the National Weather Service’s Weather Surveillance Radar – 1988 Doppler (WSR-88D) obtains volume scans at update times of 240 s or longer. Thus, for short-lived tornadoes (i.e. ~5 min), velocity signatures that indicate tornado development may not be adequately sampled, possibly leading to delays when issuing tornado warnings (Brotzge and Erickson 2009). Thus, other radar technologies should be examined in order to obtain sufficient update times for detecting rapidly developing tornadoes and other severe weather.

The National Weather Radar Testbed Phased-Array Radar (NWRT PAR; Zrnić et al. 2007) has been used to obtain rapid volumetric updates for several severe storm types, including tornadic supercells (Heinselman et al. 2008; Heinselman et al. 2009). NWRT PAR uses a 90° scanning sector which allows for faster updates than a conventional 360° sector. A smaller scan sector is frequently used by mechanically scanning mobile radars to reduce sampling time. However, the NWRT PAR is better suited for sector scanning, since phased-array radar uses an electronically steered antenna. In addition, customized strategies may be used to prioritize scans toward specific target regions (Heinselman and Torres 2010). Such strategies may be designed to provide more frequent updates at low altitudes where circulations may contribute to tornado development.

This paper presents a test case for evaluating the update rate when using NWRT PAR to sample a rapidly developing tornado. On 07 May 2008, a mesoscale convective vortex (MCV) was sampled with the NWRT PAR over Oklahoma City, Oklahoma. A tornado developed rapidly along the western edge of this MCV and persisted for 5 min. The scanning strategy for NWRT PAR was designed to obtain data from the lowest elevation (0.5°) at approximately 30-s intervals and a complete volume scan every 60 s. The depiction and temporal evolution of circulations resulting from analyses of the NWRT PAR data are compared with those resulting from analyses of a near-by WSR-88D. This comparison demonstrates the capability of the NWRT PAR to provide rapid updates when sampling tornadic storms.

2. Radar sampling methods

During this event, the NWRT PAR used a scanning strategy with 14 elevations ranging from 0.5–38.8°. The scanning strategy was designed to progress upward through the lowest seven elevations, and then repeat the 0.5° elevation scan before completing the remaining upper elevations. As a result, the lowest elevation was sampled every 32 s, while all other elevations were sampled approximately every 61 s. The large range of elevations was selected to reduce the cone of silence close to the radar. Meanwhile, a WSR-88D located at Twin Lakes, Oklahoma (KTLX) used Volume Coverage Pattern (VCP) 212, which contains 14 elevations sampled over a 360° sector. Using this pattern, complete volume scans were obtained in approximately 270 s. The WSR-88D scanned elevations ranging from 0.5–19.5°, which allowed for better vertical sampling near the ground in exchange for a larger cone of silence.

3. Event overview

In the morning of 07 May 2008, a surface cyclone moved from northwestern Texas into central Oklahoma, producing large regions of showers and thunderstorms. The closest available sounding at 1200 UTC was from Lamont, Oklahoma, which showed that the environment was favorable for severe thunderstorm development with 2000 J kg⁻¹ of CAPE and moderate vertical wind shear (not shown). Early on this day, the National Weather Service’s Storm Prediction Center issued a severe thunderstorm watch for eastern Oklahoma from 1230–1800 UTC, and a tornado watch for eastern and northeastern Oklahoma from 1830–0100 UTC. Beginning around 1700 UTC, several clusters of severe thunderstorms moved across central Oklahoma, producing hail up to 4.4 cm in diameter along with wind gusts to 31 m s⁻¹. Multiple cases of tree and
property damage were reported with these storms. Around 2200 UTC, a tornado developed along a cold front in south-central Oklahoma, causing one injury. Further north, two more tornadoes briefly formed southwest of the cyclone core over the western Oklahoma City metropolitan area. Though these tornadoes were short-lived (10 min), they each produced EF-1 damage. Since storm surveys and damage paths were not available to compare with radar observations, these tornadoes are not analyzed in this paper.

Around 2205 UTC, an MCV formed over extreme northwestern Oklahoma City. Fifteen minutes after the MCV was first observed, a fourth tornado developed within this mesoscale circulation (Fig. 1) that persisted from 2221–2226 UTC, and is the focus of this study. According to a storm survey conducted by the Severe Hazards Analysis and Verification Experiment (SHAVE; Ortega et al. 2009), the tornado traveled approximately 4.7 km and was as large as 68.6-m wide. A detailed damage track was constructed for this EF-0 tornado, which is used in conjunction with the radar data to complete an analysis of the associated circulation. Showers and thunderstorms persisted across central Oklahoma past 0000 UTC on 08 May, but no additional severe weather was reported after the fourth tornado dissipated.

Fig. 1: KTLX radial velocity obtained at 22:24 UTC during the fourth tornado. The light blue line indicates the approximate damage path of the tornado. A black box indicates the analysis region used to calculate maximum gate-to-gate for each KTLX elevation scan, while arrows indicate the spatial scale of the MCV.

4. Analysis of the TVS

To evaluate the impacts of rapid sampling on observations associated with the tornado, properties of a tornado vortex signature (TVS) are quantified to examine how the associated circulation evolves over time. A proxy measurement for assessing tornado development is gate-to-gate shear, which is defined as the difference in radial velocity calculated from two adjacent pixels in azimuth. Large values of gate-to-gate shear typically indicate locations where tornadic development may be imminent.

During the period 2213–2235 UTC, for both NWRT PAR and KTLX, an analysis region was defined based on the observed tornado track and known positions of the TVS signature (see Figs. 1–2). For each radar, the range to the tornado track is roughly equal (35–45 km), even though the radars are approximately 20 km apart. The maximum gate-to-gate shear was calculated within this region from both data sets, and the time and observed position of the maximum were recorded. (In the remainder of this paper, “shear” refers to the maximum gate-to-gate shear obtained at each elevation scan.) This procedure was repeated for each elevation scan, and the results were plotted in height and time to evaluate the evolution of shear both spatially and temporally. For all elevations, the heights of the maximum gate-to-gate shear changed with each volume scan, both due to storm movement and uncertainty in height estimates (Howard et al. 1997; Maddox et al. 1999).
Additional elevation scans can reduce the uncertainty of height estimates and improve the accuracy of measurements in the vertical (Heinselman and Torres 2010), but these sampling issues are not addressed in this paper.

Fig. 2: NWRT PAR radial velocity obtained at 2224 UTC during the fourth tornado. The light blue line indicates the approximate damage path of the tornado. A black box indicates the analysis region used to calculate maximum gate-to-gate for each elevation scan.

The evolution depicted from KTLX data is shown first (Fig. 3). During the analysis period, four volumes were completed with 276 s elapsing between consecutive scans at each elevation. Starting at 2215 UTC, only weak shear was detected through the volume scan, with a maximum magnitude of 20 m s$^{-1}$ between 0.5–0.8 km AGL and values less than 25 m s$^{-1}$ at higher altitudes. At 2219 UTC, the observed shear at the lowest two elevations remained relatively constant, while at 2.0–3.0 km AGL, the magnitude of shear increased to as large as 36.5 m s$^{-1}$. In the next volume scan (2224 UTC), the largest near-surface shear of 35.5 m s$^{-1}$ was observed, and maximum values between 0.4 km and 2.5 km increased to 30–35 m s$^{-1}$. During this time, the tornado was observed on the ground, but it dissipated by 2226 UTC. In this case, WSR-88D signatures suggesting tornado development were sampled about 2 min after the tornado began. By 2229 UTC, shear of 20 m s$^{-1}$ was detected at 0.5 km AGL with weaker magnitudes observed aloft. The vertical extent of the circulation (1.7 km) between 2225-2227 UTC was sampled over a period of 130 s, so rapid evolution of the circulation may not have been captured. This result indicates that the circulation associated with the tornado had weakened significantly, but the rate of weakening cannot be easily determined from the KTLX data.

We now examine what information is gained by the 32 s updates provided by the NWRT PAR at the lowest elevation, and associated volume scans every 61 s. As shown in Fig. 4, at 2214 UTC, the initial gate-to-gate shear below 1.5 km AGL was around 20 m s$^{-1}$, with values of 10–15 m s$^{-1}$ aloft. These values closely match the initial shear profile detected by KTLX. However, within 2.5 min, shear at 0.5 km AGL intensified from 25 to 35 m s$^{-1}$. At 1.4 km, the shear increased more dramatically from 20 m s$^{-1}$ to 40 m s$^{-1}$, indicating that a strong circulation developed aloft between 2215 and 2217 UTC. By 2219 UTC, shear near the ground increased to 40 m s$^{-1}$ but remained relatively unchanged at 1.5 km. This analysis suggests that between 2215 and 2219 UTC, a strong circulation developed aloft, then descended toward the surface, contributing to strong intensification of shear at 0.5 km AGL. In this case, NWRT PAR sampled signatures suggesting tornado development three minutes before the tornado was observed at the ground.
Fig. 3: Time, height and magnitude of maximum gate-to-gate shear detected by KTLX from 2213—2235 UTC. The tornado was on the ground from 2221—2226 UTC (solid black bar). Colors indicate the magnitude of maximum gate-to-gate shear detected at each elevation scan. The update time for all scans was 276 s.

Shortly after the tornado was first observed (2221 UTC), the strongest value of gate-to-gate shear (51.5 m s\(^{-1}\)) was observed at 0.5 km AGL. Aloft, values of shear greater than 30 m s\(^{-1}\) were detected as high as 2.3 km AGL. This evolution indicates that the circulation was ascending, leading to weakening shear near the surface and brief intensification aloft. The layer from 0.5–2.2 km AGL was sampled in approximately 13 s, thus providing a consistent vertical snapshot of the shear profile at 2224 UTC. At 2226 UTC, the tornado dissipated at the ground, and the mesoscale circulation weakened significantly. After this time, shear at 0.5 km AGL decreased from 30 m s\(^{-1}\) to 20 m s\(^{-1}\), while shear between 1.0 and 3.0 km AGL weakened to below 30 m s\(^{-1}\). By 2032 UTC, shear had decreased to less than 15 m s\(^{-1}\) at all levels, indicating the circulation had dissipated.

5. Conclusions

This paper examined the effects of the temporal update rate on the depiction and evolution of a tornadic vortex signature associated with a short-lived tornado sampled on 07 May 2008. The maximum gate-to-gate shear was calculated for each elevation scan obtained from the NWRT PAR and KTLX, and the values were plotted in altitude and time to provide a means of examining the circulation’s evolution. Results from KTLX showed only one volume scan with a strong circulation; the start time of the scan was two min after the tornado began. Based on these data, the depth of the measured parent circulation from 2224–2227 UTC was 1.7 km and the maximum gate-to-gate shear at 0.5° was 35.5 m s\(^{-1}\). The 30-s updates at the lowest tilt (0.5°) and 1-min volumetric updates from NWRT PAR provided earlier and more complete information regarding the tornado vortex signature’s evolution. Results showed that a strong parent circulation developed at 1.0–1.5 km AGL then descended to 0.5 km AGL in a 3-min period just prior to tornado development. Strong gate-to-gate shear, as high as 51.5 m s\(^{-1}\), persisted near the ground as the tornado was observed on the ground. The depth of the circulation at 2224 UTC was initially 1.75 km and increased to 2.4 km at 2227 UTC, coinciding with the tornado’s observed dissipation. This case shows that the NWRT PAR’s rapid temporal observations have strong potential to sample parent circulations associated with developing tornadoes, especially those located close to the radar. Furthermore, the results suggest that the more frequent sampling may provide better estimates of the circulation’s strength throughout its life cycle.

Acknowledgments

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Fig. 4: Time, height and magnitude of maximum gate-to-gate shear detected by NWRT PAR from 2213—2235 UTC. The tornado was on the ground from 2221–2226 UTC (solid black bar). Colors indicate the magnitude of maximum gate-to-gate shear detected at each elevation scan. Elevation scans at the lowest elevation (0.5°) had an update time of 32 s, and all other elevation scans had an update time of 61 s.

References


