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Mobile, X-band, polarimetric Doppler radar observations of the 23 May 2016 Woodward, Oklahoma tornadoes

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1. Introduction

On 23 May 2016, a group of three faculty and six undergraduate students from the Earth, Atmospheric, and Planetary Sciences (EAPS) department at Purdue University, participating in a summer course (Students of Purdue Observing Tornadic Thunderstorms for Research, or SPOTTR), observed at least two tornadoes north of Woodward, Oklahoma, around sunset (0144 UTC on 24 May 2016). One team used the University of Massachusetts (UMass) mobile, X-band (3 cm wavelength), polarimetric Doppler radar (UMass X-Pol) (Junyent 2003; Bluestein et al. 2007; Tanamachi et al. 2012) to collect observations in both tornadoes (Fig. 1).

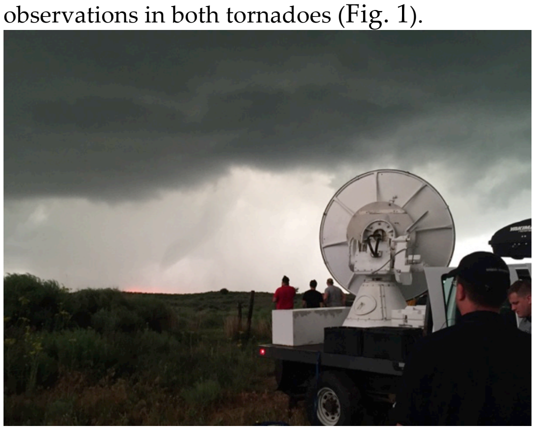

Fig. 1. UMass X-Pol deployed and scanning the first of two tornadoes near Woodward, Oklahoma on 23 May 2016. This image was taken at 0140 UTC, just before the tornado dissipated.

The National Weather Service (NWS) office in Norman, Oklahoma (which covers Woodward) contacted the first author for radar information regarding the duration, path, and intensity of the Woodward tornadoes. The purpose of this document is to summarize the deployment and relate preliminary findings based upon the UMass X-Pol observations collected. Because the NWS is particularly interested in wind speeds close to ground level, we have elected to focus primarily on the radar observations collected at the lowest available elevation angle (2.4°).

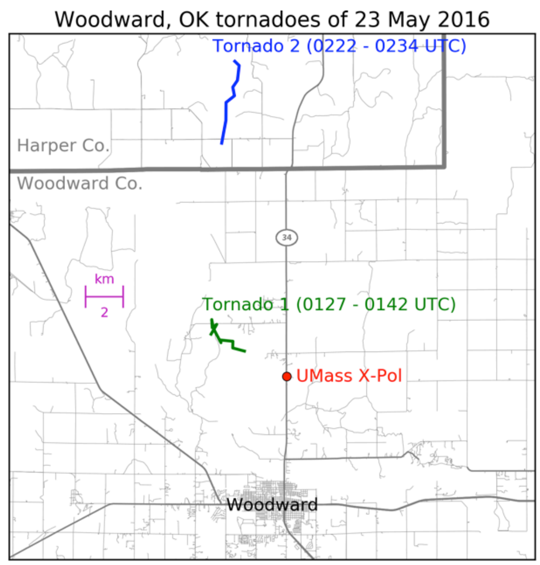

Fig. 2. Estimated tornado tracks for the two tornadoes (green and blue lines, respectively) detected by UMass X-Pol (red dot) on the evening of 23 May 2016 (local time). The times for each tornado are given in UTC time on 24 May 2016. Heavy gray lines outline county boundaries, medium-thickness gray lines are primary roads, and thin gray lines denote secondary roads. The primary north-south road upon which UMass X-Pol was deployed is Oklahoma State Road 34 (hereafter OK-34).

2. Deployment description

On 23 May 2016, the SPOTTR group traveled to southwest Kansas in anticipation of convective initiation along a dryline stretching from south central Kansas to southwest Texas (NWS Storm Prediction Center 2016). A low-level moist axis east of the dryline contributed to analyzed CAPE values in excess of 3000 J kg^{-1}, while a shortwave trough approaching from the west was expected to furnish sufficient low-level shear for supercell

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formation. After storms formed, but failed to mature into supercells in the Dodge City, Kansas area, the SPOTTR group migrated south toward Woodward. Just before sunset (0144 UTC), a cluster of developing storms moved northeast from the Texas panhandle into Woodward County, Oklahoma, and was projected to pass a few miles north of the city of Woodward. Although the storm cluster appeared initially to be relatively disorganized, intermittent low-level rotation and was noted on the 0.5° Doppler velocity observations from the Vance Air Force Base WSR-88D. Eventually, the storm cluster began to assume supercellular characteristics including a hook echo and cyclonically-curved, forward-flank reflectivity gradient, possibly reflecting the effects of an intensifying diurnal low-level jet (not shown) over the region.

Cloud base rotation intensified around 0050 UTC northwest of Woodward, prompting the SPOTTR group to stop 6.2 km north of Woodward to take observations. UMass X-Pol began collecting volume scans at 0057 UTC in a west-through-northeast sector (Fig. 1, Table 1).

Table 1. Selected parameters of the UMass X-Pol data collection on 23 May 2016.

Parameter	**Value**
Frequency	9.41 GHz
Half-power beam width	1.2°
Maximum unambiguous range	62.5 km
Maximum unambiguous velocity (PRT1)	19.0 m s^{-1}
Time of deployment	0057 through 0252 UTC (24 May 2016)
Azimuthal sector	270° through 45°
Elevation angles	2.4° to 14.4° every 2.0°
Volume update time	2 min

3. Data quality and processing

UMass X-Pol's onboard computer compass recorded a pitch (front to back) of 1.8° ± 1.0°, and roll (side-to-side) of 0.2° ± 1.0°. The pitch has been accounted for in the calculated altitudes of UMass X-Pol observations, but the roll has not.

The city of Woodward itself was located at the same altitude (610 m MSL) as UMass X-Pol. In post-processing, the azimuth of each ray was adjusted to match clutter targets with the locations of known stationary targets in and around Woodward. In particular, clutter targets along OK-34 (presumably metallic vehicles) matched closely the mapped location of OK-34, along which UMass X-Pol was parked. In addition, a large area of ground clutter was observed south of the UMass X-Pol that corresponded with the urban extent of the city of Woodward.

Doppler velocity (V_r) observations were dealiased automatically using a dual-PRT algorithm. Additional manual dealiasing was not deemed necessary for the purposes of this study.

4. Tornado 1 (0125 to 0141 UTC)

Fig. 3. Genesis, at 0125 UTC, of Tornado 1.

Duration: 0125 to 0141 UTC
Path length: 4.5 km
Direction of motion: Generally NWward
Maximum intensity: 38 m s^{-1} ± 3 m s^{-1}, estimated from UMass X-Pol velocities measured at a height of 140 m (± 20 m) AGL at 0129 UTC
Description: This tornado was observed by all members of the SPOTTR group, as well as numerous storm chasers and spotters located along OK-34. A rotating wall cloud was first noted at 0120 UTC, northwest of the UMass X-Pol deployment site. A funnel cloud was first observed at 0122 UTC, and this funnel first attained ground contact at 0125 UTC (Fig. 3). From the vantage point of UMass X-Pol, the tornado appeared to move first toward the right (east/northeast), then retrograde back to the left (west/northwest) slightly. It then became enshrouded in rain before roping out around 0142 UTC (Fig. 1). Ground contact by the condensation funnel was intermittent, suggesting either variations in tornado intensity, variability in dew point depression of the air converging at the tornado's base, or both.

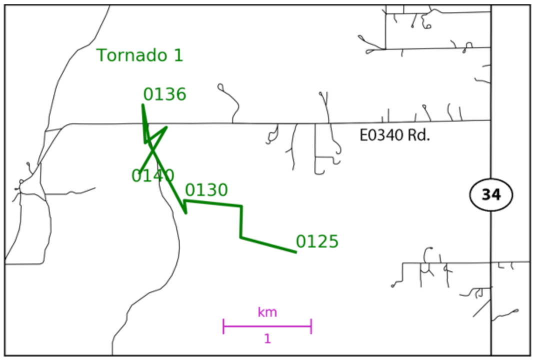

Fig. 4. Enlargement of Fig. 2 showing the detailed track of Tornado 1's TVS (green line). Times shown are in UTC on 24 May 2016.

Owing to the developing tornado's distance of approximately 2.4 km from UMass X-Pol, the 2.4° elevation beam intersected the vortex at a height of approximately 140 m AGL ± 20 m. Overall motion of the vortex was toward the northwest, with a short clockwise loop back toward the southeast prior to dissipation (Fig. 4). The tip of the Woodward storm's hook echo initially exhibited a double-hook structure, with two velocity couplets separated by approximately 0.5 km (Fig. 6a, b). The eastern couplet eventually became stronger, and the western couplet dissipated. A weak-echo hole appeared at 0125 UTC (Fig. 6c, d), coinciding with the first visible condensation funnel contact with the ground (Fig. 3). Peak Doppler velocities (+38 m s^{-1} ± 3 m s^{-1}) were observed by UMass X-Pol at 0129 UTC (Fig. 6e, f). The condensation funnel appeared to dissipate at 0141 UTC, shortly after the image in Fig. 1 was taken. Between volume scans at 0140 UTC (not shown) and 0142 UTC (Fig. 6g, h) the weak-echo hole closed, and the vortex signature transitioned to a divergence signature.

5. Tornado 2 (0222? – 0234 UTC)

Path length: Approximately 4.8 km
Direction of motion: Generally northward
Maximum intensity: 24 m s^{-1} ± 3 m s^{-1} at 0231 UTC, estimated from UMass X-Pol velocities measured at a height of 0.7 km (± 0.1 km) AGL
Description: This tornado occurred well after local sunset (0144 UTC) and was not visible to the UMass X-Pol crew. Tornado 2 was documented in video stills (not shown) by two off-duty NWS employees who were storm chasing in the area (J. and B. Boustead, 2016, pers. comm.). The tornado may also have been briefly observed by another SPOTTR instructor (D. Dawson) and two students, about 1.6 km north of UMass X-Pol's deployment site on OK-34.

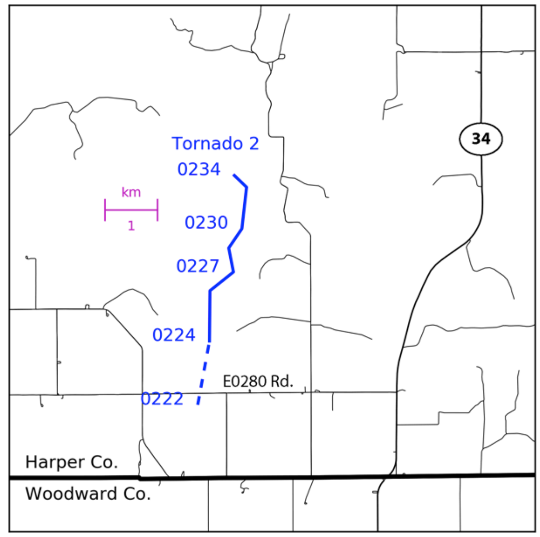

Fig. 5. Enlargement of Fig. 2 showing the detailed track of Tornado 2's TVS (blue line). Dashed blue lines indicate times when tornado strength winds were less certain.

Because of its longer range from UMass X-Pol (~ 15 km), the lowest-altitude Doppler velocity observations in Tornado 2 were collected at an altitude of approximately 0.7 km AGL. Considerably more uncertainty exists about the tornado location and intensity than were found for Tornado 1 as a result of this higher-altitude and coarser spatial sampling; radar-measured wind speeds in a tornado may not scale to the surface in a predictable way (e.g., Wurman et al. 2012; Snyder and Bluestein 2014).

A velocity couplet was first noted in the UMass X-Pol data at 0222 UTC (not shown), and generally tracked toward the north over the next 12 minutes (Fig. 5). An intermittent weak-echo hole (e.g., Fig. 7a) accompanied the velocity couplet. A peak inbound velocity of 24 m s^{-1} ± 7 m s^{-1} was observed at 0231 UTC (Fig. 7b). The couplet weakened and dissipated around 0234 UTC (not shown). Based upon the radar presentation, the UMass X-Pol crew alerted a collocated member of Woodward County Emergency Management and the NWS (via social media) to the probable location of the tornado.

6. Conclusions

Two tornadoes were sampled at relatively close range by the UMass X-Pol radar near Woodward, Oklahoma on 23 May 2016 (local time). These observations allowed detailed information about the tornado's position to be relayed to the National Weather Service and local emergency management personnel in near real time.

Tornado 1 occurred 2.4 km from UMass X-Pol, allowing low-altitude (~140 m AGL) sampling of the wind speeds. If its peak observed winds (38 m s^{-1} ± 3 m s^{-1}) were transposed to 3-sec surface gusts, they would have corresponded to a borderline EF-0/1 rating. Tornado 2 occurred after sunset, had questionable visual confirmation, and was sampled at a higher altitude (0.7 km AGL) by UMass X-Pol owing to greater range (15 km). Because of these factors, there is greater uncertainty in inferring tornado strength within this TVS. We infer that Tornado 2 was indeed a tornado because its radar presentation was similar to that of Tornado 1 (weak-echo hole, TVS), and because the condensation funnel was observed by two off-duty NWS employees. Its peak observed wind speeds (24 m s^{-1} ± 3 m s^{-1}), if transposed to 3-sec surface gusts, would have corresponded to an EF-0 rating.

Acknowledgments
Dr. Indrajeet Chaubey (EAPS department head) generously sponsored travel for the SPOTTR class, and Purdue's College of Science funded the lease of the UMass X-Pol radar. Doug Speheger of the National Weather Service office in Norman, Oklahoma facilitated the addition of our observations into the National Center for Environmental Information (NCEI) Storm Events Database (https://www.ncdc.noaa.gov/stormevents/). Josh and Barbara Boustead (NWS – Omaha, Nebraska) confirmed the occurrence and location of Tornado 2. Radar plots were generated using Py-ART (Helmus and Collis 2016).

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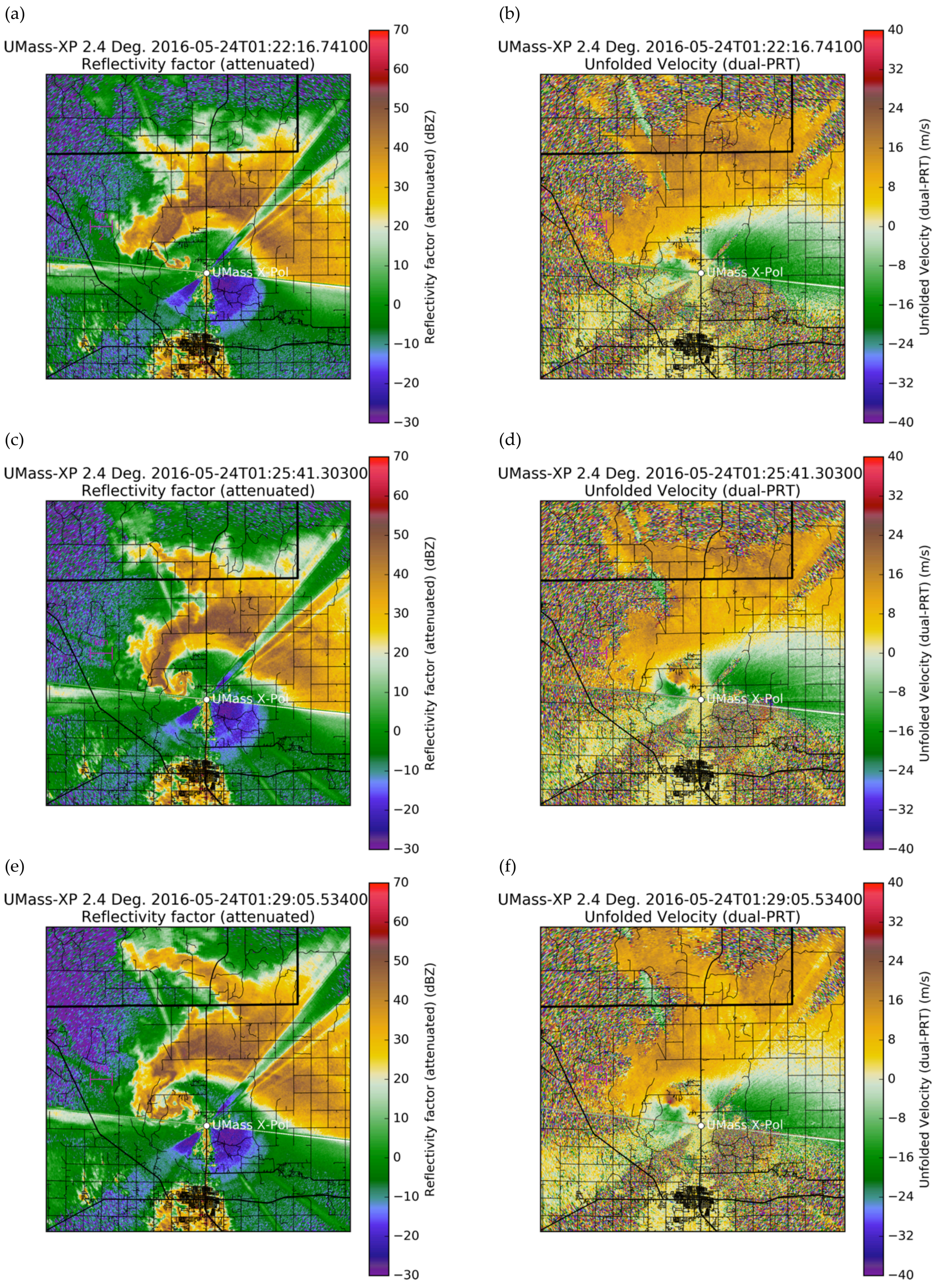

Fig. 6. (Left column) Reflectivity (in dBZ) and (right column) dealiased Doppler velocity (in m s^{-1}) measured by UMass X-Pol in the Woodward supercell at an elevation angle of 2.4°, showing (a, b) the double-hook structure at 0122 UTC; (c, d) 0125 UTC, when the visible condensation funnel in Fig. 3 appeared; (e, f) 0129 UTC, when the maximum Doppler velocity was recorded, and (g, h) 0142 UTC, as Tornado 1 dissipated (Fig. 1).

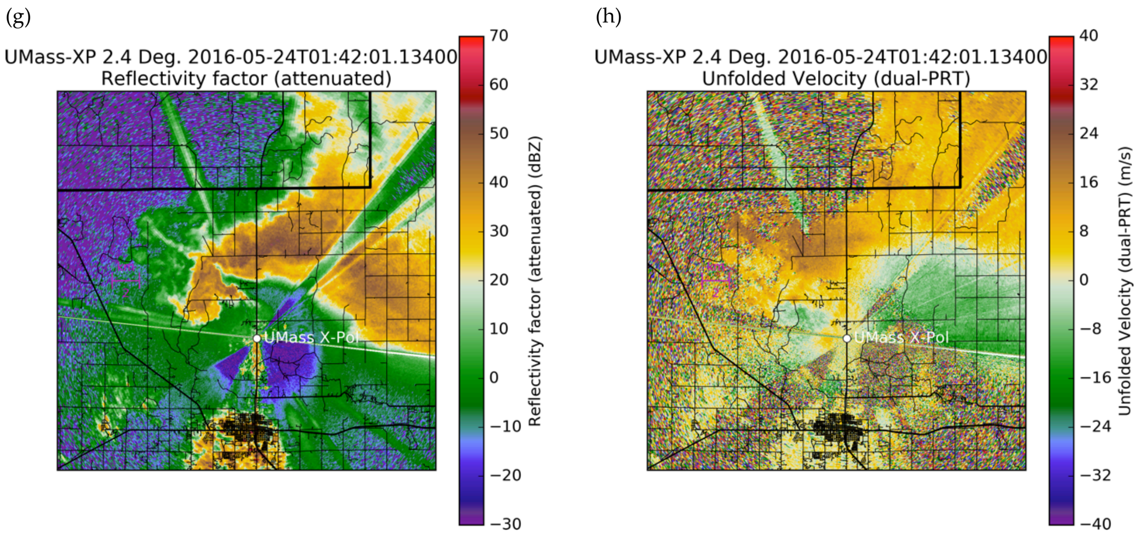

Fig. 5. (continued)

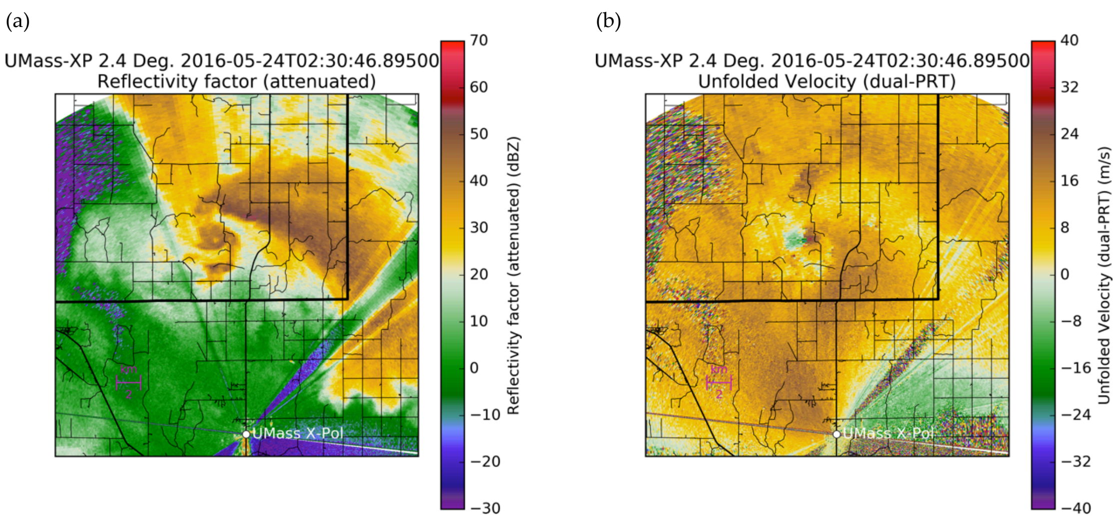

Fig. 7. As in Fig. 6, but at (a, b) 0231 UTC, when Tornado 2 reached peak intensity.