16A.6 **An Examination of the Structure of Two Tornadoes Using Mobile Ka-band Doppler Radar**

Ryan S. Metzger* and Christopher C. Weiss
Texas Tech University, Lubbock, TX

1. INTRODUCTION

Knowledge of the vertical structure of tornadoes is of great importance to meteorologists and civil engineers alike, albeit for different reasons. Meteorologists' interest in the vertical structure of tornadoes stems from a desire to better understand and predict the genesis, movement and dissipation of tornadoes, while the engineering community is interested in building structures that are better suited to withstand the winds of a tornado. The scientific communities' current understanding of tornado structure is based on simulations conducted in the laboratory as well as numerical simulations (e.g., Lewellen et al. 2000). Both the laboratory experiments as well as the numerical simulations have shown that the structure of the tornado is highly dependent on the swirl ratio. More recently, fine-scale radar studies of tornado structure have added to the collection of knowledge about the structure of the tornado vortex (e.g., Bluestein et al. 2004). The aim of this study is to use fine-scale Ka-band radar observations to better understand tornado structure through comparisons with results from other platforms.

2. THE TTUKa RADARS

The Texas Tech University Ka-band radars (TTUKa; Weiss et al. 2009) are two new platforms that are well suited to the study of tornado vortex structure at a very fine-scale spatial resolution. The first radar (Fig. 1) was completed in the spring of 2009 in time to participate in the first year of the VORTEX2 field project. The second radar was finished

Figure 1- A photograph of a Texas Tech University Ka-band radar.

in late winter 2010 and was available for the second year of the project. During the course of the project, the TTUKa radars successfully scanned multiple tornadoes. Key specifications for the TTUKa radar system are listed in Table 1 below (adapted from Weiss et al. 2009)

Transmitter Frequency:	34,860 MHz (λ=8.6 mm)
Transmit Power:	200 W peak, 100 W average
Transmitter Type:	TWTA
Duty Cycle:	up to 50%
Antenna Gain:	50 dB
Antenna Type:	Cassegrain feed, epoxy reflector
Antenna Beamwidth:	0.49 deg
Polarization:	Linear, horizontal
Waveguide:	WR-28, pressurized
PRF:	Variable, up to 20 KHz
Gate Spacing:	15 m
Receiver:	MDS: -118 dBm
IF Frequency:	60 MHz
Pedestal:	Orbit AL-4016
DSP:	Sigmet RVP-8
Vehicle:	Chevy C5500 Crewcab
Moments:	Reflectivity, radial velocity, spectrum width

Table 1 – Specifications of the TTUKa radar system.

3. THE JUNE 13, 2010 BOOKER, TX TORNADO

On June 13, 2010 the VORTEX2 armada successfully intercepted a tornado in the eastern Oklahoma panhandle about 10 km

*Corresponding author address: Ryan S. Metzger, Texas Tech University, Atmospheric Science Group, Department of Geosciences, Lubbock, TX, 79409; e-mail: Ryan.Metzger@ttu.edu

northeast of the town of Booker, TX. The tornado was on the ground from approximately 2052 UTC to 2106 UTC and was rated an EF0 tornado by the National Weather Service.

One of the two TTUKa radars participating in the VORTEX2 project was able to perform both plan-position indicator (PPI) and range height indicator (RHI) scans of this tornado from a range of between 5 and 9 km. The Booker tornado was rain-wrapped as viewed from the vantage point of the TTUKa radar making it impossible for the radar crew to see the tornado from the radar. This precipitation at times attenuated the radar data; thus, not all of the PPI scans collected by the radar could be used in the analysis of this case.

i. VERTICAL STRUCTURE

A unique aspect of the June 13, 2010 dataset is a coordinated series of RHI scans of the tornado vortex. These RHI scans were performed at a constant azimuth allowing the vortex to traverse through the RHI plane. Thus, scans were conducted on both the inbound and outbound sides of the vortex as well as through the center (Fig.2). A schematic of the position of the various RHI planes relative to the center of the vortex is presented in figure 2. These RHI scans were relatively free of attenuation.

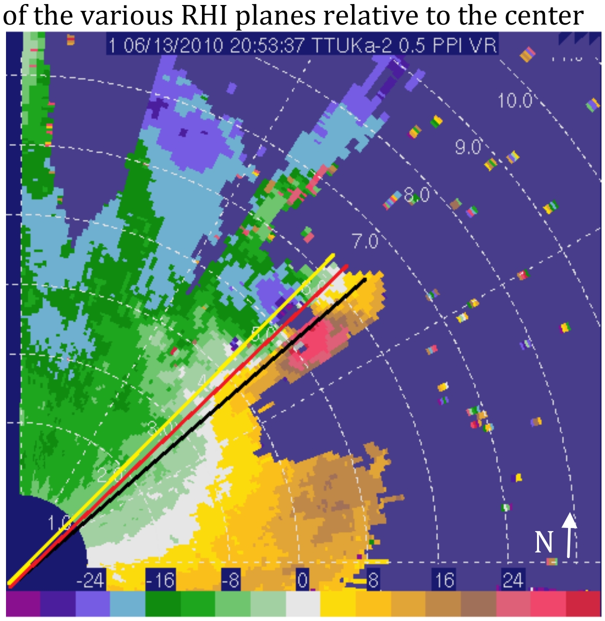

Figure 2- The position of the plane of RHI scans relative to the center of the tornado at 21:03:16 UTC (black line), 21:03:42 UTC (red line), and 21:03:54 UTC (yellow line)

Prior to analysis, the scans were edited using the SOLO software package (Oye et al. 1995) to unfold aliased velocities. Data were also threshold on returned power to ensure that robust assigned velocities were used in the analysis.

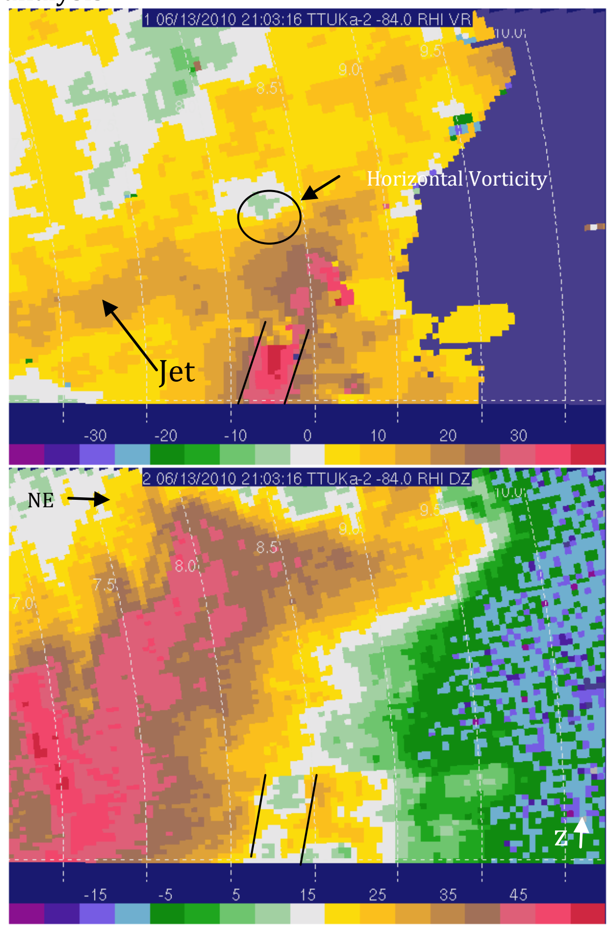

Figure 3- RHI of radial velocity (top, m s^{-1}) and reflectivity (dBZ) at 21:03:16 UTC. RHI is looking northeast from the radar.

The first RHI in the series is from 21:03:16 UTC (Fig. 3). This RHI was taken on the outbound side of the tornado vortex (outlined in black). In this scan the tornado manifests itself as the area of very high outbound velocities (on the order of 40 m s^{-1}) A few interesting features are present in this scan. An elevated jet of inflow is evident approaching the tornado vortex. Such a feature has been noted in previous RHI studies of tornadoes (e.g., Bluestein et al. 2004). This jet appears in close proximity to heavy precipitation that is evident in the reflectivity plane. It is suggested that the elevated nature of this inflow is due to the air being forced over a cold pool-perhaps associated with this precipitation-as it flow towards the tornado. Areas of horizontal vorticity are present close to the tornado.

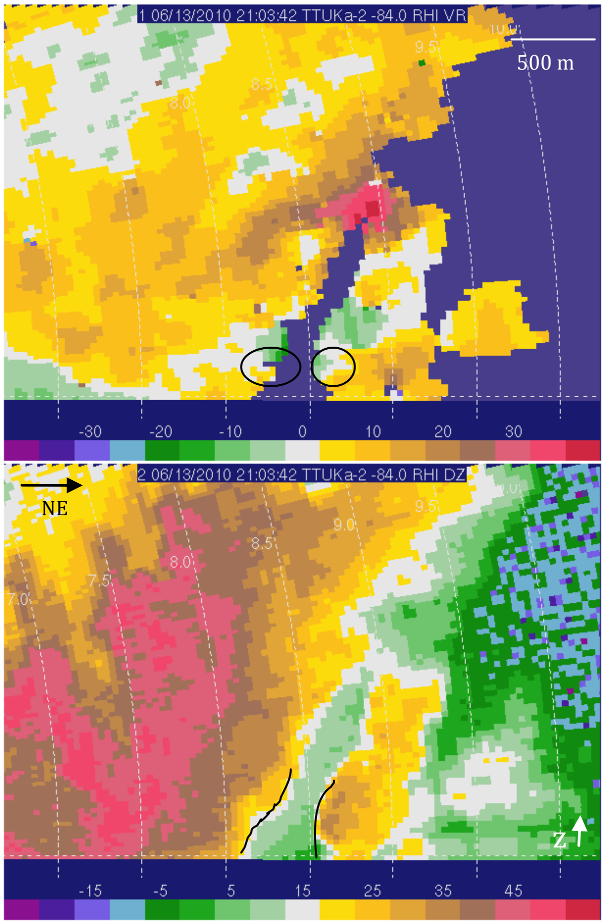

Figure 4- Same as Fig. 3 but for 21:03:42 UTC.

The next scan presented is from 21:03:42 UTC (Fig. 4). The plane of this scan traverses the center of the tornado. In this scan the low reflectivity center of the vortex is evident in the reflectivity field. The structure of the reflectivity field is similar to previous RHI studies of tornadoes (e.g., Bluestein et al. 2004). This area of weak reflectivity is broader closer to the surface than it is aloft. In the Bluestein et al. 2004 study, the authors found a thin band of high reflectivity below the weak echo hole. No such feature is evident in this dataset and it is speculated that the base of the RHI was too elevated to observe such a feature. In this case the base of the RHI is about 40m AGL. The area of weak reflectivity appears to tilt away from the radar in the vertical, likely due in part to the component of motion away from the radar along the plane of the RHI, as the antenna scanned upward.

Areas of horizontal vorticity (circled) are present on either side of the weak echo hole. While it is not surprising that such secondary circulations exist in the vicinity of a tornado, it is somewhat unexpected that the sense of the vorticity on either side of the vortex is the same (the vorticity vector is pointing in the same direction for both areas).

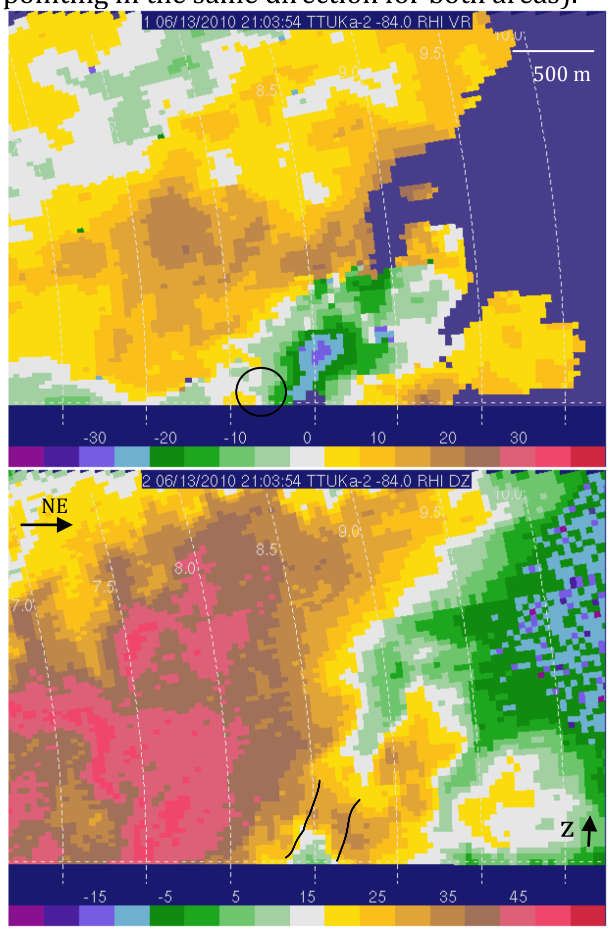

Figure 5- Same as Fig. 3 but for 21:03:54 UTC

The 21:03:54 UTC scan (Fig. 5) shows the inbound side of the tornado vortex. One interesting aspect of this scan is a small area of low-level convergence in front of the tornado (circled). The base of this RHI is about 40 m

AGL and the convergence is visible in the lowest 50 m of the RHI.

ii. HORIZONTAL STRUCTURE

Although many of the PPI scans taken during this event had attenuation problems, there were nonetheless several good quality PPIs taken. In order to better understand the horizontal structure of this tornado the Ground Based Velocity Track Display technique (GBVTD) of Lee et al. (1999) was used. The GBVTD method was designed for use on tropical cyclones (Lee et al. 2000) but has since been used in a number of studies of tornadoes (Bluestein et al. 2003, 2007; Lee and Wurman 2005; Tanamachi et al. 2007; Kosiba and Wurman 2010). The GBVTD method was applied to the data at 20:53:37 UTC. The radar data were objectively analyzed using a bilinear interpolation scheme with grid spacing of $\Delta x=\Delta y=25$m, in order to create a Cartesian grid for use in the GBVTD process (Fig. 6). After the center of the vortex was identified using a simplex center algorithm (Lee and Marks 2000), the GBVTD technique was performed on the data (Fig. 7) to reveal the wave number zero (axisymmetric) components of the tornado relative velocities. The analysis identifies the radius of maximum wind at 175m. Maximum azimuthally averaged winds in this case are 34.4 m s^{-1}, in agreement with the EF0 rating assigned by the National Weather Service. Between the center of the vortex and the radius of maximum wind, the tangential velocity increases at a rate that is similar to that of solid body rotation. Away from the radius of maximum wind, the analyzed tangential velocity decreases at a rate similar to the function $r^{0.5}$ which is a slower rate of decay than the function of r^{-1} that is associated with the decay of tangential velocities in the theoretical Rankine vortex.

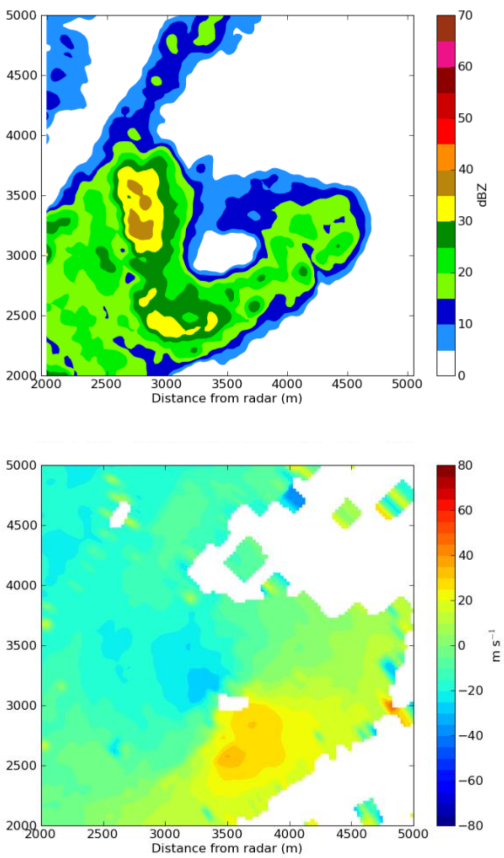

Figure 6- Objectively analyzed radar (top) reflectivity (dBZ) and (bottom) radial velocity (m s^{-1}) at 20:53:37 UTC.

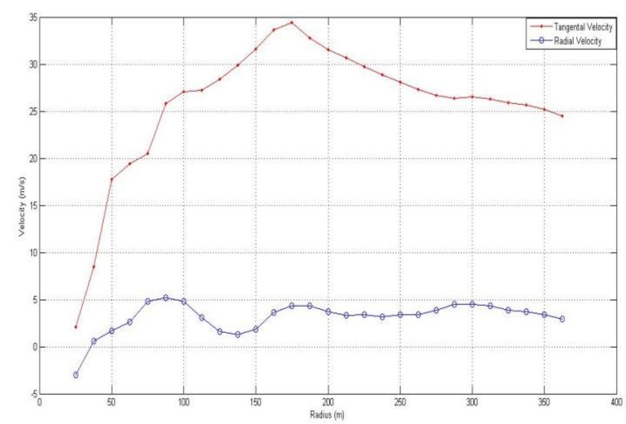

Figure 7- Results of the preliminary GBVTD analysis of the June 13, 2010 Booker, TX tornado.

4. THE JUNE 5, 2009 LAGRANGE, WY TORNADO

On June 5, 2009 the first TTUKa radar intercepted a tornado in Goshen County, Wyoming near the town of Lagrange. The Lagrange tornado touched down at 22:07 UTC and dissipated at 22:31 UTC. The storm was rated as an EF-2 on the Enhanced Fujita scale. Due to poor road networks the TTUKa radar sampled the storm from a range of 16 km instead of the optimal range of 2-3 km. In spite of the larger than ideal distance, the TTUKa was able to obtain numerous PPI and RHI scans of the storm.

i. VERTICAL STRUCTURE

Despite the range to the tornado from the radar the RHI scan at 22:14:26 UTC (Fig. 8) reveals the low level wind field near the tornado. The radar was positioned on high ground relative to the surrounding land as determined using Google Earth™ software. The lowest elevation of the RHI plane was a slightly negative angle. At the range of the tornado the lowest elevation of the RHI was calculated to be at a height of approximately 70 m above the surface which is still well within the boundary layer. An area of convergence is clear in this layer (Fig. 8b, c) associated with the weak echo region (Fig. 8a). This suggests that the low level convergence around the tornado is still present at a depth of over 70 m. Analysis is ongoing to explore whether the corner flow region is indeed present in these data.

5. SUMMARY AND FUTURE PLANS

We have considered the structure of two different tornadoes observed by the Texas Tech University Ka-band radars during the course of the VORTEX2 project. A series of quality RHI scans of a tornado north of Booker, TX on June 13, 2010 illustrate the vertical structure of the vortex. These scans show an elevated jet of inflow to the tornado, as well as some interesting secondary circulations. A GBVTD analysis is presented to illustrate the horizontal structure of the Booker case. An RHI scan of the June 5, 2009 Goshen County, WY case reveals the nature and the depth of the boundary layer inflow to that tornado.

Further analysis of both of these cases is ongoing. A GVBTD analysis of the Lagrange tornado is planned. In addition, analysis of other VORTEX2 cases that were observed by TTUKa radar is planned. These analyses will help in the estimation of swirl ratio, by which these two cases can be compared.

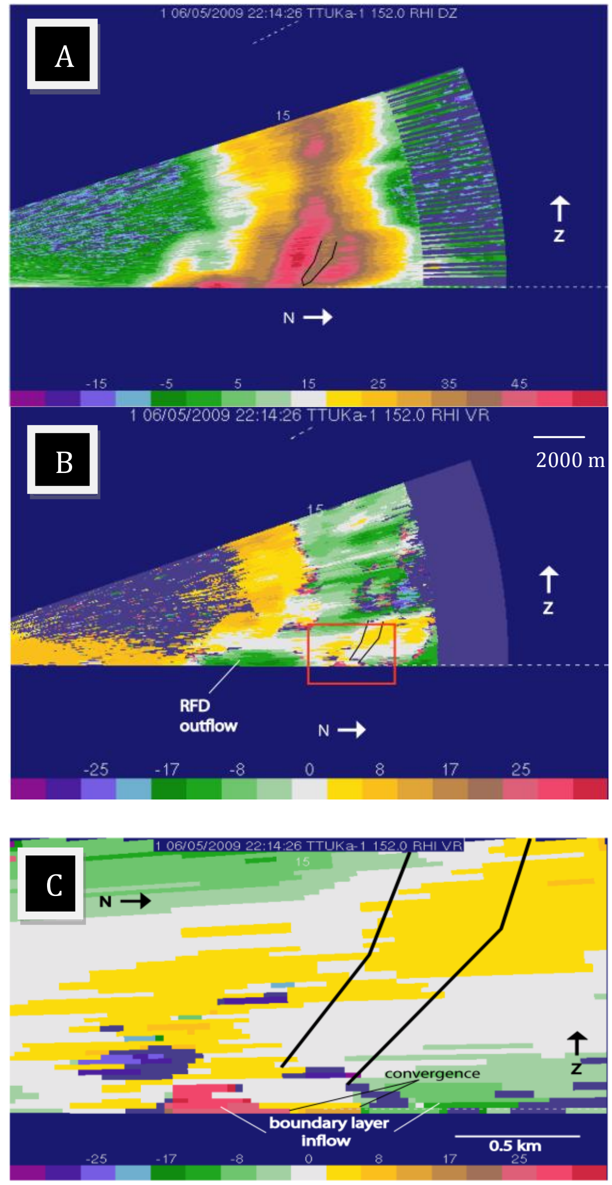

Figure 8- A wide presentation of a) reflectivity (dBZ) and b) radial velocity (m s^{-1}) and a zoomed presentation of c) radial velocity (m s^{-1}) from RHIs taken at 22:14:26 UTC. The outline of the weak echo region is common to all plots

6. ACKNOWLEDGEMENTS

The funding to build the radars was provided by a grant from the Texas Tech Vice President for Research. Funding for the 2009 season pilot study was provided by the Texas Tech University Vice President for Research, the TTU Department of Geosciences as well as the TTU Wind Science and Engineering Research Center. The National Science

Foundation provided funding for the radars to participate in the 2010 portion of the VORTEX2 field campaign through NSF grant AGS-0964088. Robin Tanamachi provided the GBVTD code as well as information on how to conduct the GBVTD analysis. Anthony Reinhart provided technical assistance for this study. Ryan Hastings provided photos that were helpful in the RHI analysis of the Booker tornado. Patrick Skinner, Brad Charboneau and Scott Gunter also provided assistance with this study. The authors are grateful for the assistance of all of the faculty and students from Texas Tech University and the University of Michigan who assisted in the data collection during the VORTEX2 project.

7. REFERENCES

Bluestein, H. B., W-C. Lee, M. Bell, C. C. Weiss, A. L. Pazmany, 2003: Mobile Doppler radar observations of a tornado in a supercell near Bassett, Nebraska, on 5 June 1999. Part II: Tornado-Vortex structure. *Mon. Wea. Rev.*, **131**, 2968–2984.

---., C. C. Weiss, and A. L. Pazmany, 2004: The vertical structure of a tornado near Happy, Texas on 5 May 2002: High-resolution, mobile, W-band, Doppler radar observations. *Mon. Wea. Rev.,* **132***,* 2325-2337*.*

---,---,M.M. French, E.M. Holthaus, R.L. Tanamachi, S. Frasier, and A.L. Pazmany, 2007: The structure of tornadoes near Attica, Kansas on May 2004: High-resolution mobile, Doppler radar observations. *Mon. Wea. Rev*., **135**, 475-506

Kosiba, K. and J. Wurman, 2010: The three-dimensional axisymmetric wind field structure of the Spencer, South Dakota (1998) tornado. *J. Atmos. Sci.*, in press. [Available via AMS Journals Early Online Release.]

Lee, W.-C, and F.D. Marks, 2000: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part II: The GBVTD-Simplex center finding algorithm. *Mon. Wea. Rev.*, **128**, 1925–1936.

---, and J. Wurman, 2005: Diagnosed three-dimensional axisymmetric structure of the Mulhall tornado on 3 May 1999. *J. Atmos. Sci.*, **62**, 2373–2393.

---, B. Jou, P.-L. Chang, and S.-M. Deng, 1999: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part I: Interpretation of Doppler velocity patterns and the GBVTD technique. *Mon. Wea. Rev.*, **127**, 2419–2439.

---, ---, ---, and F.D. Marks, 2000: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part III: Evolution and structures of Typhoon Alex (1987). *Mon. Wea. Rev.*, **128**, 3982–4001.

Lewellen, D. C., W. S. Lewellen, and J. Xia, 2000: The influence of a local swirl ratio on tornado intensification near the surface. *J. Atmos. Sci.,* ***57,*** *527–544.*

Oye, R., C. K. Mueller, and S. Smith, 1995: Software for radar translation, visualization, editing, and interpolation. Preprints, *27th Conf. on Radar Meteorology,* Vail, CO, Amer. Meteor. Soc., 359–361.

Tanamachi, R. L., H. B. Bluestein, W.-C. Lee, M. Bell, A. Pazmany, 2007: Ground-Based Velocity Track Display (GBVTD) analysis of W-Band Doppler radar data in a tornado near Stockton, Kansas, on 15 May 1999. *Mon. Wea. Rev.*, **135**, 783–800.

Weiss, C.C., J.L. Schroeder, J. Guynes, P. Skinner, and J. Beck, 2009: The TTUKa mobile radar: Coordinated radar and in situ measurements of supercell thunderstorms during project VORTEX2. 34th AMS Radar Conference, Williamsburg, Virginia, October, 2009