GBVTD-retrieved near-surface vortex structure in a tornado and tornado-like vortices observed by a W-band radar during VORTEX2

Robin L. Tanamachi¹, Mingjun Wang¹, Ming Xue¹, Howard B. Bluestein², Krzysztof A. Orzel³, Stephen J. Frasier³

¹Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, Oklahoma, U.S.A.
²School of Meteorology, University of Oklahoma, Norman, Oklahoma, U.S.A.
³Microwave Remote Sensing Laboratory, University of Massachusetts – Amherst, Amherst, Massachusetts, U.S.A.

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1. Introduction

Retrieval of the near-surface tangential and radial winds in tornadoes remains a challenging problem. Although mobile Doppler radars can provide measurements of wind speeds, they only observe the along-beam component of the flow (Doppler velocity, denoted \( V_r \)). Retrieval of the full 2D or 3D wind field in a tornado requires an analytical method such as the Ground-Based Velocity Track Display (GBVTD; Lee et al. 1999) technique. In previous studies, radial and tangential winds in tornadoes were retrieved using GBVTD (Bluestein et al. 2003; Lee and Wurman 2005; Bluestein et al. 2007; Tanamachi et al. 2007; Kosiba et al. 2008; Kosiba and Wurman 2010; Metzger et al. 2011; Chan et al. 2012; Wakimoto et al. 2012) and dust devils (Snyder et al. 2006) observed by mobile and/or high-resolution Doppler radar.

In this study, we apply the GBVTD technique to retrieve winds in high-resolution Doppler velocity observations of a tornado and tornado-like vortices (TLVs) observed during Project VORTEX2 (Wurman et al. 2012). As in Bluestein et al. (2003) and Tanamachi et al. (2007), these data were collected by researchers from the University of Oklahoma (OU) and the University of Massachusetts – Amherst (UMass) using the UMass W-band, mobile Doppler radar (UMass W-band hereafter; Table 1) (Tsai et al. 2008).

This radar, which has an exceptionally narrow beamwidth (0.18°) and a range resolution of 30 m, collected near-surface, single-elevation scans in tornadic supercells on 25 and 26 May 2010. In contrast to the two previous case studies in which the GBVTD technique was applied to UMass W-band data, these retrievals cover the geneses of the tornado and TLVs.

Table 1. Characteristics of the UMass W-band radar in 2010.

<table>
<thead>
<tr>
<th>Radar</th>
<th>UMass W-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mobile</td>
</tr>
<tr>
<td>Wavelength</td>
<td>3 mm</td>
</tr>
<tr>
<td>Half-power beamwidth</td>
<td>0.18°</td>
</tr>
<tr>
<td>Peak transmitted power</td>
<td>600 W</td>
</tr>
<tr>
<td>Maximum range</td>
<td>12 km</td>
</tr>
<tr>
<td>Maximum unambiguous velocity (using staggered PRT technique)</td>
<td>±38 m s⁻¹</td>
</tr>
<tr>
<td>Range gate spacing</td>
<td>30 m</td>
</tr>
<tr>
<td>Pulse length</td>
<td>200 – 800 ns</td>
</tr>
<tr>
<td>PRF</td>
<td>5-7 kHz</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

Fig. 1. The UMass W-band radar collects reflectivity and Doppler velocity data in (a) an EF-0 tornado in the Tribune, Kansas supercell at 2316 UTC on 25 May 2010, and (b) the hook echo region of the Prospect Valley, Colorado supercell at 2215 UTC on 26 May 2010. The view is toward (a) the north, and (b) the west.

2. Data collection by the UMass W-band radar

The mission of UMass W-band, which had the highest spatial resolution data collection capability of all the radars in the VORTEX2 “armada,” was to collect near-surface Doppler radar observations in hook echoes. Since W-band electromagnetic waves attenuate rapidly in precipitation, the UMass W-band maximum range was limited to 12 km. The
effective unambiguous velocity of the UMass W-band was expanded to $\pm 38 \text{ m s}^{-1}$ via use of a dual pulse repetition frequency (PRF) or dual pulse repetition time (PRT) technique (Doviak et al. 1976; Sirmans et al. 1976). The update time ($\sim 20 \text{ s}$) was a function of the sector width (typically $-90^\circ$) and scan speed, both of which were manually controlled by the radar operator.

2.1 25 May 2010: Tornado near Tribune, Kansas

On 25 May 2010, a supercell produced several tornadoes as it tracked from southeast Colorado into western Kansas (Monteverdi et al. 2010). The VORTEX2 team intercepted this storm near the town of Tribune, Kansas at around 2300 UTC. The crew deployed UMass W-band 23 km west of Tribune at 2310 UTC, and began scanning the hook region of the Tribune storm (which was about 8 km to north of UMass W-band) at an elevation angle of $0.7^\circ$. At 2314 UTC, a funnel cloud extended downward contact the ground, lasting three minutes before dissipating. It was followed by another cloud-to-ground condensation funnel at 2321 UTC that also lasted three minutes (Fig. 1a). A spiraling reflectivity pattern, Doppler velocity couplet, and weak-echo hole (WEH) likely generated by centrifuging (Dowell et al. 2005) are all present in the UMass W-band data continuously from 2314 UTC to 2324 UTC (Fig. 2). Therefore, we consider the two condensation funnels to be the same separate visual incarnations of the same tornado.

2.2 26 May 2010: TLVs in a tornadic supercell near Prospect Valley, Colorado

On 26 May 2010, a supercell formed near Denver, Colorado and tracked slowly toward the north-northeast over the town of Prospect Valley, Colorado. VORTEX2 operations targeting the Prospect Valley storm are described in more detail elsewhere in this volume (paper 379). The W-band radar was deployed about 12 km east of Prospect Valley and collected scans in the hook echo as it passed by to the northwest. No condensation funnel was observed by the VORTEX2 team, only a shallow, bowl-shaped lowering of the cloud base (Fig. 1b). In the W-band radar data, at least six small TLVs can be seen in the Prospect Valley supercell’s hook as it passed by the UMass W-band. The strongest and longest-lived of these TLVs (#4) appeared on the tip of the hook from 2234 UTC to 2242 UTC, at a range of 5 km (Fig. 3). This TLV bears a strong resemblance to Tribune tornado, with many similar features including Doppler velocity couplets and persistent WEHs. To the best of the authors’ knowledge, these are the first high-resolution Doppler radar data collected in such TLVs.

Fig. 2. (left) UMass W-band reflectivity and (right) Doppler velocity at an elevation angle of $0.7^\circ$ at 2316 UTC on 25 May, collected shortly after the Tribune tornado appeared. Range rings are every 5 km, azimuth spokes every $10^\circ$.

Fig. 3. Same as Fig. 2, but at an elevation angle of $1.9^\circ$ at 2235 UTC on 26 May, showing TLV #4. Range rings are every 2 km, azimuth spokes every $10^\circ$. 
3. Methodology

The maximum winds in the vortices never appeared to exceed the 38 m s\(^{-1}\) maximum unambiguous velocity, so no manual dealiasing of the data was necessary. After Doppler velocity data associated with low signal-to-noise ratio (SNR ≤ -18 dBZ) were removed, the UMass W-band data were objectively analyzed using a two-pass Barnes scheme (Majcen et al. 2008) to a Cartesian grid centered roughly on the vortex. The horizontal resolution of the grid was 30 m, in keeping with the 30 m range gate spacing of the W-band radar data and the azimuthal resolution of the radar data at the ranges of the tornado and TLVs (15-25 m). Because the UMass W-band radar data were collected at only one elevation angle, only one vertical grid level was used. Furthermore, because of the small dimensions of the objective analysis grid (2 km on a side) and shallow elevation angle (< 2.0°), vertical variation of the sweep surface (< 20 m) across the core width of the vortices (300-500 m) was ignored. During objective analysis, a time-to-space conversion was applied based on the estimated motion of the WEH, in order to minimize translational distortion of the vortex.

For the above grid spacing, a smoothing parameter \(\kappa = 0.0004 \text{ km}^2\) was calculated using the method of Trapp and Doswell (2000). This value of \(\kappa\) was used in the objective analyses of the 26 May data. However, it was found that the 25 May data collection suffered from an elevated noise floor, causing divergence of the vortex center-seeking algorithm in the subsequent step. The authors attribute the elevated noise floor to a temporary malfunction of the low-noise amplifier (LNA) in the receive chain. The first author subjectively evaluated several different values of \(\kappa\), seeking a value for which most of the grid-scale noise in the vortex was smoothed out, but for which the overall structure of the vortex was retained. A smoothing parameter of \(\kappa = 0.0020 \text{ km}^2\) was selected for the 25 May data. It is accepted that there will be errors in the GBVTD analyses of the 25 May data resulting from possible smoothing of the peak velocities in the Tribune tornado. However, the analyzed axisymmetric vortex structures appear credible, and we proceed to describe them in the next section.

The centers of the vortices were located in the objective analyzed Doppler velocity data by applying the simplex center-seeking algorithm of Nelder and Mead (1965), as adapted by Lee and Marks (2000). Finally, the objectively analyzed Doppler velocity data and the objectively determined vortex center were fed into the GBVTD algorithm (Lee et al. 1999), which calculates wavenumber-0 (axisymmetric), -1, -2, and -3 tangential and radial velocity components around the vortex center.

4. Results

3.1 25 May 2010: Tornado near Tribune, Kansas

Most of the GBVTD analyses of the Tribune tornado exhibited highly asymmetric (wavenumber-1, -2, and -3) vortex structure, particularly in the inner radii where the analyses are least reliable (e.g., Fig. 4). Tanamachi et al. (2007) found that wavenumber-2 asymmetries could result from a number of causes, including the translation of the vortex. However, because the asymmetries are not consistent from scan to scan, their sources are less certain. We focus on the axisymmetric component of tangential velocity (\(V_{T0}\); Fig. 5), which would have been the least affected by grid-scale noise.

![Fig. 4. GBVTD-analyzed reflectivity (filled color contours in dBZ) and tangential velocity (solid black contours in m s\(^{-1}\)) in the Tribune tornado at 2320 UTC. The axes labels denote distance from the center of the vortex in m.](image)

![Fig. 5. Axisymmetric (wavenumber-0) tangential velocity (blue line, in m s\(^{-1}\)), axisymmetric radial velocity (green dashed line, in m s\(^{-1}\)), vorticity (red dotted line, in 10\(^{-1}\) s\(^{-1}\)), divergence (black dashed line, in 10\(^{-7}\) s\(^{-1}\)), and circulation (purple line, in 10\(^{3}\) m\(^2\) s\(^{-1}\)) for the GBVTD analysis depicted in Fig. 4.](image)

The axisymmetric vortex structure exhibits intensification and decay consistent with the appearance and disappearance of the tornado funnel. In general, both tangential velocities (Fig. 6) and circulation (not shown) increased (decreased) at all radii when the condensation funnels appeared (disappeared). Assuming the thermodynamic properties of ingested air remain relatively constant, a condensation funnel forms in response to increasing wind speeds and a dynamic pressure drop inside the vortex, where water vapor condenses into cloud droplets. The appearance of a condensation funnel,
therefore, serves as a visual indicator of vortex intensification.

Fig. 6. Hovmöller diagram of GBVTD-analyzed $V_T$ (in m s$^{-1}$) in the Tribune tornado. The appearances of condensation funnels are annotated on the vertical axis.

Fig. 7. Maximum axisymmetric tangential velocity (solid line, in m s$^{-1}$) and radius of maximum wind (dashed line, in m) for the Tribune tornado. The appearances of condensation funnels are annotated on the horizontal axis.

The radius of maximum wind (RMW), computed from $V_T$, appears to have decreased preceding the appearance of the first funnel (Fig. 7). However, because the area immediately around the developing tornado filled in with precipitation at genesis (2314 UTC), we have low confidence in the analyzed RMW prior to that time. The RMW fluctuated around 300 m as funnel #1 matured, then dissipated at 2317 UTC. The RMW then decreased to about 180 m just prior to the appearance of funnel #2 at 2220 UTC, and increased again to more than 300 m as funnel #2 dissipated. The trend of increasing RMW in weakening tornadoes is consistent with analyses of the 1999 Bassett, Nebraska tornado by Bluestein (2003), but contrasts with results from Tanamachi et al. (2007), who found that both RMW and $V_T$ decreased in the dissipating 1999 Stockton, Kansas tornado. We note that funnel #2 tilted with height as it dissipated (Fig. 1a), possibly leading to elongation of the vortex signature in the UMass W-band data. Such elongation may have resulted in a spurious increase in analyzed RMW. Some observed asymmetries may yet be the result of grid-remnant scale noise in the objective analyses. We cannot say with confidence which scenario is more likely.

In terms of peak $V_T$, the Tribune tornado (19 m s$^{-1}$) appears to have been both wider and weaker than either the Bassett (30 m s$^{-1}$; F0) or Stockton (45 m s$^{-1}$; F1) tornadoes. The additional complications imposed by the elevated noise floor, which necessitated extra smoothing during objective analysis, also made this a challenging case to analyze. However, the consistent association between changes in analyzed wind speeds and the appearance or disappearance of the condensation funnel lends confidence to the analyzed trends in $V_T$.

3.2 26 May 2010: TLVs in a tornadic supercell near Prospect Valley, Colorado

Fig. 8. As in Fig. 4, but in Prospect Valley TLV #4 at 2238 UTC.

Fig. 9. As in Fig. 5, but for the GBVTD analysis depicted in Fig. 8.
We were able to analyze the UMass W-band data collected in TLV #4 in exactly the same manner as we did previous UMass W-band tornado data sets (Fig. 8, Fig. 9). TLV #4 exhibited similar behavior to a tornado, intensifying and then weakening over its 8 min life cycle, and exhibiting a WEH (Fig. 3) during most of that time. Since no condensation funnel was observed, we take the WEH as an indicator of intense winds in the TLV core (Dowell et al. 2005). The appearance of this WEH coincides with some of the highest analyzed $V_{T0}$s in the TLV.

In contrast to the wavenumber-2 maxima in tangential velocity exhibited by previous tornadoes, Prospect Valley TLV #4 exhibited a strong wavenumber-1 component of velocity (e.g., Fig. 8). This feature was consistently embedded in a curtain of precipitation that wrapped around the far side of TLV #4 (with respect to the UMass W-band; Fig. 3). Three-dimensional analyses of the Prospect Valley storm with comparable spatial and temporal resolution would be needed to diagnose any angular momentum transport associated with this rain curtain; such an analysis is underway as of this writing.

Overall, weaker axisymmetric tangential velocities were analyzed in TLV #4 than in either the Basset or Stockton tornadoes. (The Tribune tornado would make a fairer comparison.) Peak analyzed $V_{T0}$, at 2338 UTC, was 15 m s$^{-1}$. The RMW shrank to less than 100 m as TLV #4 intensified from 2234-2238 UTC, then increased to greater than 200 m after the WEH closed at 2240 UTC. Somewhat paradoxically, circulation in the hook of the Prospect Valley storm appeared to increase after the demise of TLV #4. This increase in circulation, which resulted from a simultaneous increase in RMW and peak $V_{T0}$, may have been associated with another TLV (#6) that formed less than a minute after and within 2 km of where TLV #4 dissipated.

5. Summary

GBVTD analyses were conducted on two W-band radar data sets collected in tornadic supercells during Project VORTEX2. The two data sets, collected one day apart and less than 200 m above the surface, show the full life cycle of an EF-0 tornado in western Kansas and a TLV, which did not have an associated condensation funnel, in northeast Colorado. It was found that the Tribune tornado and Prospect Valley TLV #4 both had similar life spans (as measured by the appearance of WEHs, ~8 min), similar intensification and weakening phases (as seen in the evolution of the RMW), and similar axisymmetric vortex structure at peak intensity. The principal differences between these two vortices lay in the magnitude of the peak intensity (which was smaller for the TLV), the RMW (which was wider in the Tribune tornado), and the presence or absence of a condensation funnel.
The case of the 26 May 2010 TLVs raises an interesting question. The American Meteorological Society glossary defines a tornado as, “A violently rotating column of air, in contact with the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud.” (Glickman 2000). If this definition serves, it is not strictly necessary for the tornado to possess the funnel cloud that is its distinguishing visual characteristic. It is well known that a tornado with no visible condensation funnel can still inflict surface damage. A vortex velocity couplet with a weak-echo hole (WEH) is clearly visible in the UMass W-band data. However, over 100 VORTEX2 personnel, most of whom had at least some tornado field research experience, were present during the data collection on 26 May 2010. None reported a tornado or even a funnel cloud, only “suspicious lowering” of the cloud base.

While the peak analyzed $V_T$ in the Prospect Valley TLV #4 was only 15 m s$^{-1}$, peak analyzed $V_T$ in the Tribune, Bassett, and Stockton tornadoes all dipped below this value at some point during their life cycles. Therefore, the distinction between a tornado and a TLV may be merely a matter of moisture! We suspect that many such TLVs occur beneath High Plains supercells, but go unreported for the simple lack of a visual indicator such as a condensation funnel or debris cloud. It is only through the use of high-resolution radars such as the UMass W-band and Texas Tech University Ka-band mobile radars (Hirth et al. 2012) that such vortices can be detected.

Acknowledgments

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References


Monteverdi, J. P., M. M. Umscheid, and E. M. Bookbinder, 2010: Two tornadic thunderstorms in ostensibly weak deep layer shear environments in southeastern Colorado: cyclic supercells of May 25 (Kiowa County) and May 31 (Baca County) 2010. 25th Conf. on Severe Local Storms, American Meteorological Society, P10.14.


