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PROGRESS TOWARD IMPROVED GROUND-BASED VELOCITY TRACK DISPLAY (GBVTD) ANALYSIS OF MOBILE RADAR DATA COLLECTED IN TORNADOES

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1. INTRODUCTION

Mobile Doppler radar measurements collected in tornadoes have yielded many valuable insights concerning the 2D and 3D velocity structure of tornadoes. Use of the Ground Based Velocity Track Display (GBVTD) technique (Lee *et al.* 1999) allows for reconstruction of the full 2D or 3D wind field of an atmospheric vortex based upon only the along-beam velocities measured by a Doppler radar. The GBVTD analysis technique has been applied to radar data collected in multiple tornadoes (Bluestein *et al.* 2003; Lee and Wurman 2005; Tanamachi *et al.* 2006). It has been observed that the GBVTD analysis often includes a prominent wavenumber-2 component of azimuthal velocity (hereafter "wavenumber-2 feature", e.g. Fig. 1), even when data from different radars are analyzed.

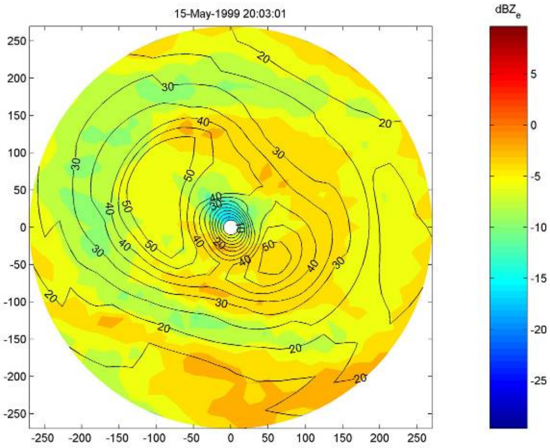

Fig. 1. Reflectivity (filled color contours, dBZ$_e$) and GBVTD-analyzed azimuthal velocity (sum of wavenumbers 0 through 3, in contour intervals of 5 m s^{-1}), in the Stockton, Kansas tornado of 15 May 1999, showing a prominent wavenumber-2 feature. The radar is located 4.5 km east-southeast of the center of the tornado.

The appearance of the wavenumber-2 component in GBVTD analyses of data collected by different radars was suggestive of a physical wavenumber-2 feature. However, Tanamachi *et al.* (2006) posited that the appearance of wavenumber-2 features in azimuthal velocities analyzed from W-band radar data of the 15 May 1999 Stockton, Kansas tornado (hereafter "the Stockton tornado") was primarily an artifact caused by translational distortion of the vortex during the time required to scan the sector. As the GBVTD technique was originally formulated (Lee *et al.* 1999), it was implicitly assumed that the analyzed vortex was stationary during the time interval over which the scan was collected. Tanamachi *et al.* (2006) argued that such distortion would likely manifest as a wavenumber-2 feature due to the apparent elongation of the tornado into an ellipse, and provided examples in which wavenumber-2 features were produced from GBVTD analyses of simulated radar scans of a horizontally translating Burgers-Rott vortex.

The following study is a follow-up to Tanamachi *et al.* (2006), and attends to a number of GBVTD analysis quality issues that were not specifically addressed in Tanamachi *et al.* (2006). Herein, examples of the wavenumber-2 feature analyzed from the radar data are presented, possible sources of this feature and its impact on GBVTD analyses are discussed, and a number of methods are investigated which could potentially minimize artificial or analysis-related sources of the wavenumber-2 feature.

2. OBJECTIVE ANALYSIS

As currently formulated, the GBVTD analysis technique employs a bilinear

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interpolation scheme to objectively analyze the radar data from a radar-centered polar coordinate system to a constant-altitude Cartesian coordinate system. Trapp and Doswell (2000), in surveying numerous radar data objective analysis schemes, found that bilinear interpolation can potentially introduce spurious higher-wavenumber features, particularly at long range from the radar.

Trapp and Doswell (2000) also recommended that for objective analysis of radar data, the Barnes (1964) objective analysis scheme be used, with its nondimensional smoothing parameter κ^* calculated, as Trapp and Doswell (2000) recommended, from the "maximum data spacing affecting the analysis domain." In the case of the Stockton tornado, the range of the tornado from the radar increased from 4.5 to 6.8 km, and W-band radar data collected in the tornado had an azimuthal resolution of 0.22°[†] - thus the "maximum data spacing" was ~ 20 m. From these figures, it can be deduced that the horizontal smoothing parameter κ should be approximately 10^{-4} km^2. The W-band radar data in the Stockton tornado were objectively analyzed using the Barnes scheme, using the above values.

3. VORTEX CENTER LOCATION

As currently formulated, the GBVTD analysis technique employs a vorticity-maximizing simplex method (Nelder and Mead 1965; see Lee *et al.* 1999) to ascertain the location of the center of the vortex. In the present study, a different center-seeking algorithm was tested (C. Alexander, personal communication). In the Alexander technique, a user-specified maximum velocity differential (Δv) and maximum corresponding distance (Δd) were specified. Vortex centers were reported as the median coordinate position between the upper and lower 70th percentiles of Doppler velocity in the domain (within one distance increment Δd) around each potential vortex center.

In order for the Alexander technique to be applied successfully to the relatively noisy W-band Doppler velocity data, some editing of the data was necessary. First, as in Tanamachi *et al.* (2006), Doppler velocity data associated with reflectivities of -18 dBZ$_e$ or less were removed. Second, a "despeckling" routine removed isolated gates of data surrounded by gates of missing data.

While the simplex and Alexander techniques produced vortex centers that were very similar in location, for none of the 35 scans did the two techniques report exactly the same vortex center. The average separation between the reported vortex centers was 48 m, or approximately two-and-a-half grid spaces on the Cartesian grid. It was observed that the Alexander technique consistently reported vortex centers with a shorter range from the radar than the simplex algorithm, and generally along the edge of the low-reflectivity "eye" closest to the radar. Lee and Marks (2000) and Bluestein *et al.* (2003) demonstrated that errors in vortex center location with magnitude of two or more grid points would likely produce a conspicuous, spurious wavenumber-1 component of the resultant GBVTD-analyzed azimuthal velocities. Such wavenumber-1 features were observed more frequently in the azimuthal velocities analyzed around the vortex center reported by the Alexander technique than those from the simplex algorithm. A reason for this difference has not yet been determined. Based on these results, the simplex center-finding algorithm was retained for the remainder of the experiments.

4. RADAR HYSTERESIS

Tanamachi *et al.* (2006) noted that the track of the vortex center contained "wiggles" (Fig. 2) that resulted from hysteresis of the radar scanning mechanism. These apparent wiggles can significantly impact the apparent translation speed and direction of the vortex, complicating further efforts to compensate for translational distortion of the vortex.

To ameliorate the wiggling, the TclDORADE radar data manipulation package (http://tkradar.tkgeomap.org) was employed. The package contains a "dejiggling" function that calculates the azimuthal shift necessary to minimize the root mean square reflectivity difference between successive scans. The function indicated that alternate scans should be shifted azimuthally by +0.1 and -0.1 degrees in order to minimize the hysteresis effect. The track of the vortex center was thereby "smoothed" when the azimuth shifts were applied (Fig. 2). The kurtosis of the direction of motion of the tornado (generally west of north) was also reduced (Fig. 3).

[†] Note: The beamwidth of the W-band radar is 0.18°.

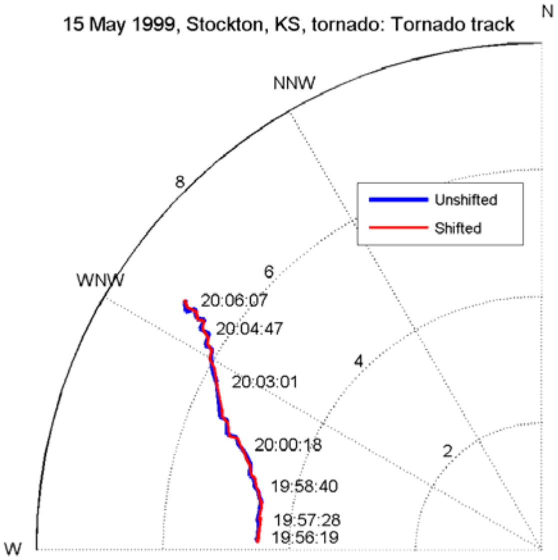

Fig. 2. Unshifted (blue) and azimuth-shifted (red) track of the Stockton tornado relative to the W-band radar. Range rings are in km, times are in CDT.

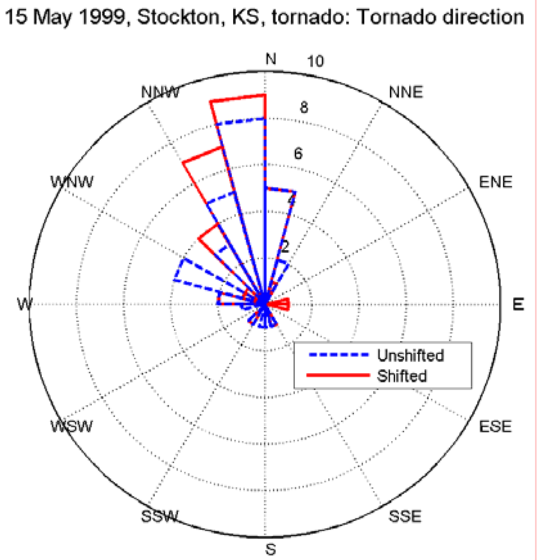

Fig. 3. Angle histogram ("rose" plot) of tornado translation direction for the unshifted (blue dashed) and shifted (red) tornado tracks in Fig. 2. "Petal" length is equal to the number of scans in which the tornado was moving in the corresponding direction.

5. TRANSLATIONAL DISTORTION

Once the tornado track was "smoothed" using TclDORADE, the tornado translation speeds and directions were calculated. A radar data objective analysis package (D. Dowell, personal communication) was then used to compensate for the distortion of each scan. Prior to Barnes analysis onto a Cartesian grid, the positions of each radar data gate were shifted according to the user-specified translation velocity and ray collection time offset from a reference time. The reference time was taken to be the time at which the first data ray in a given sweep was collected.

6. RESULTS AND RECOMMENDATIONS

Owing to lack of a "truth" data set, any "improvements" to the GBVTD analyses resulting from modifications made in this study had to be judged subjectively. The GBVTD analyses described in Tanamachi *et al.* (2006) were compared to GBVTD analyses of modified radar data (e.g., Appendix) in this study. The application of some modifications, particularly the correction for translation of the vortex, reduced but did not eliminate the wavenumber-2 component. It was noted that, in many of these cases, the "lobes" of highest azimuthal velocity were collocated with regions of relatively high reflectivity. A reason for this apparent correlation has not yet been determined.

Profiles of azimuthally-averaged azimuthal and radial velocity (e.g., Fig. 4 and Fig. 5) exhibited some variations, particularly at small radii where the GBVTD analysis is most sensitive to the reduced number of data points available for analysis. However, beyond a radius of 50 m, the overall shape and magnitude of the azimuthally-averaged azimuthal velocity profiles were largely unchanged.

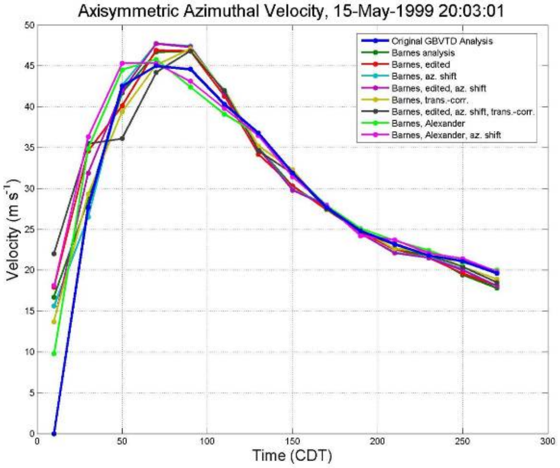

Fig. 4. Radial profiles of GBVTD-analyzed azimuthally-averaged azimuthal velocity in the Stockton tornado at 20:03:01 CDT, from Tanamachi *et al.* (2006, heavy blue line) and the modified analyses performed in the current study (color coding at upper right).

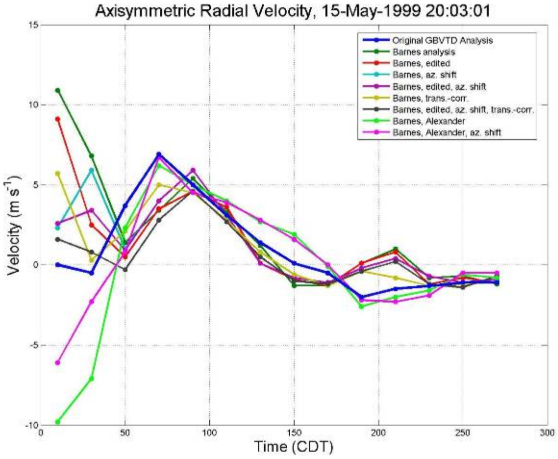

Fig. 5. As in Fig. 4, but for radial velocity.

It was noted in Section 3 that the vortex centers reported by the Alexander technique were displaced to the edge of the low-reflectivity "eye" of the tornado in many cases. The radial and azimuthal velocity profiles analyzed around such vortex centers were frequently very different from those analyzed around vortex centers produced by the simplex algorithm, probably because of the associated, likely-spurious wavenumber-1 component.

It was observed that the maximum azimuthally averaged azimuthal velocities did exhibit some variation (less than ±10 m s^{-1}) relative to the Tanamachi *et al.* (2006) GBVTD-analyzed velocities in a majority of the cases (Fig. 6), while the radius of maximum azimuthally averaged azimuthal velocity (or radius of maximum wind, RMW) fluctuated by as much as 60 m between scans, depending on what modifications were made (Fig. 7). However, the trends in RMW circulation (Fig. 8) exhibited a generally increasing trend during the Stockton tornado's intensification phase (19:56:19 – 20:03:01 CDT), a primary or secondary maximum at 20:03:01 CDT (identified by Tanamachi *et al.* [2006] as the time of greatest tornado intensity), and a generally decreasing trend between 20:03:01 CDT and the time at which the tornado decayed (20:06:07 CDT). From these results, it can be inferred that the primary conclusions of Tanamachi *et al.* (2006) remain largely unchanged, and are in fact reinforced, with the modifications to the GBVTD analyses.

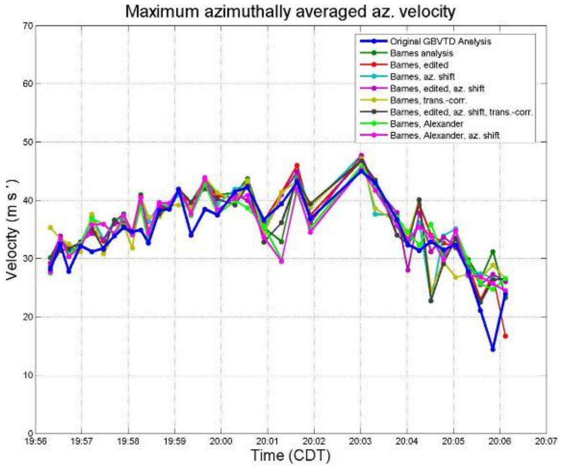

Fig. 6. Maximum GBVTD-analyzed azimuthally averaged azimuthal velocity as a function of time from Tanamachi *et al.* (2006, heavy blue line) and the modified analyses performed in the current study (color coding at upper right).

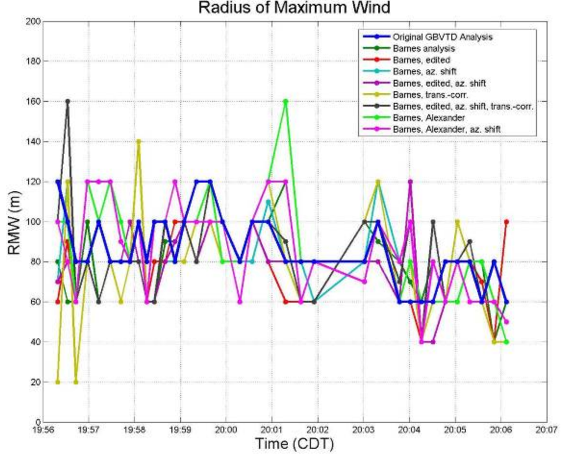

Fig. 7. As in Fig. 6, but for radius of maximum GBVTD-analyzed azimuthally averaged azimuthal velocity.

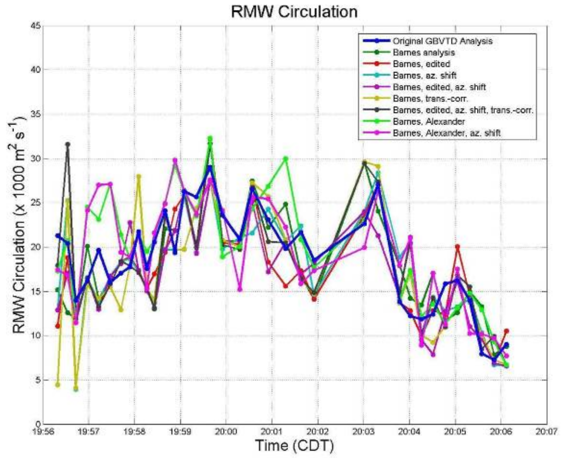

Fig. 8. As in Fig. 6, but for circulation around the vortex center at the radius of maximum aximuthally averaged azimuthal velocity.

Based on the results of this study, the authors recommend (1) that Barnes analysis be used to objectively analyze radar data to a Cartesian grid instead of bilinear interpolation, in line with the recommendations of Trapp and Doswell (2000); and (2) that the simplex algorithm be retained for determining location of the vortex center. For cases in which the phenomenon under investigation evolves on a timescale similar to the length of time required to collect a radar data sweep (e.g., both are ~10 s in the case of a tornado) it is recommended (3) that the TclDORADE package be used to ameliorate any hysteresis effects in the radar data; and (4) that the translational distortions in the data be compensated for prior to objective analysis to a Cartesian grid.

7. ACKNOWLEDGMENTS

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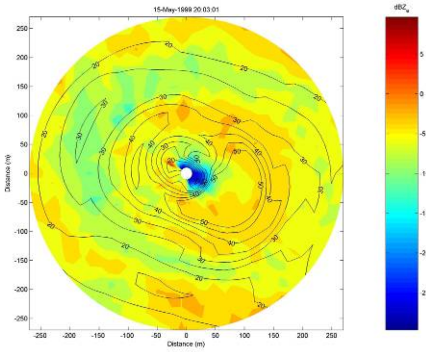
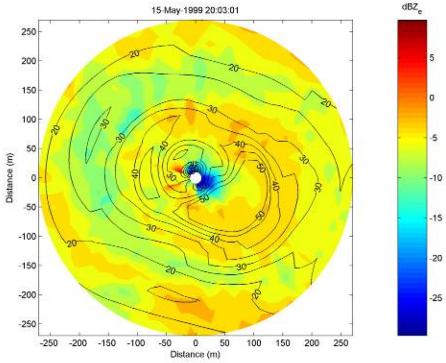
9. APPENDIX: MODIFIED GBVTD ANALYSIS EXAMPLES

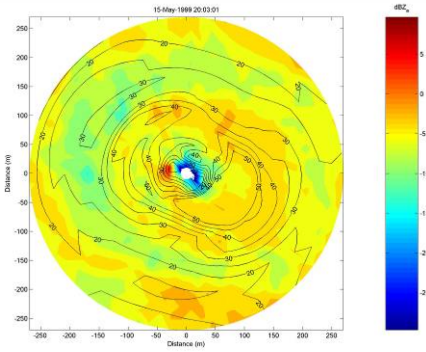
Barnes Analysis



Barnes, Edited



Barnes, Az. Shifted



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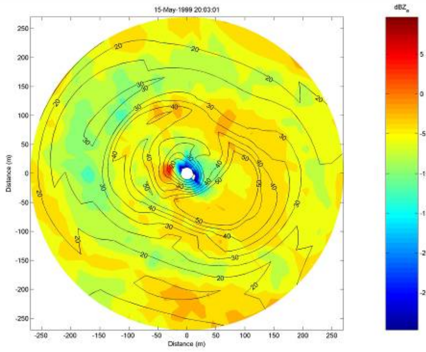
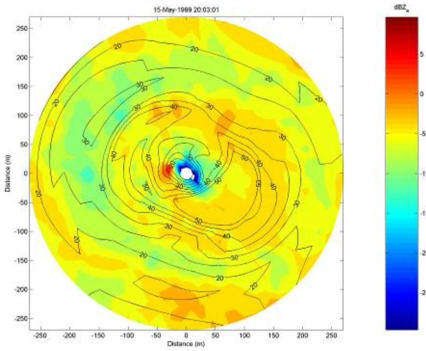
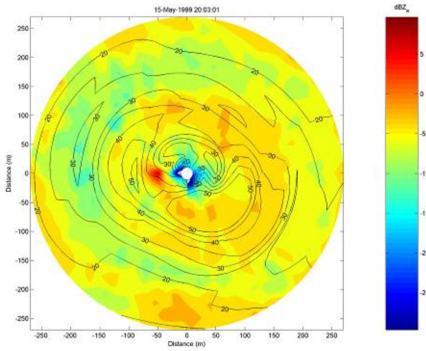


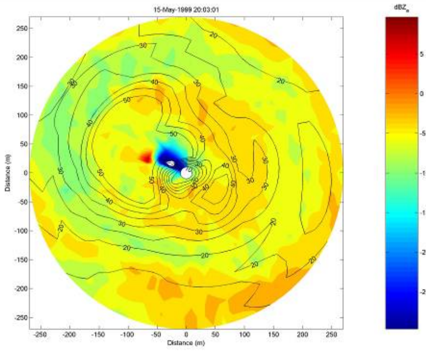
Barnes, Trans. Corrected



Barnes, Edited, Az. Shifted, Trans. Corrected



Barnes, Alexander Center



Barnes, Alexander Center, Az. Shifted