THE MULTIPLE VORTEX STRUCTURE OF A TORNADO

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1. Introduction

Conceptual models (Davies-Jones 1976), and computer (Rotunno 1984, Lewellen 1993, Lewellen et al 1997, Fiedler 1998) and laboratory simulations (Ward 1972, Church and Snow 1993, Church et al. 1979) of tornado structure predict that, under certain conditions, a primary tornado vortex will break down into several sub-tornadic scale multiple vortices (hereinafter "multiple-vortices"). Multiple vortices have been observed visually and in patterns of damage for decades (Fujita 1970, Pauley and Snow 1988). Direct radar evidence of sub-tornado-scale wind maxima probably associated with multiple-vortices was first obtained in a large tornado that destroyed much of the small town of Spencer, SD in 1998 (Wurman 1999, Fig. 1). The tornado was observed at ranges of 1.7-5 km (to center). The vortices were weaker than the tornadic flow, with perturbations of ~ 20-30 ms-1 on a parent flow of ~ 85-95 ms-1. The vortices caused a degradation of the typical clear eye structure observed frequently in received power data obtained in tornadoes not exhibiting strong multiple vortices (Wurman and Gill 2000, Burgess et al 2001. Sometimes, several "eyes" were evident.

Subsequently, observations from a 3-mm wavelength mobile radar revealed more evidence of multiple vortices in one of the tornadoes that occurred during the 3 May 1999 OK tornado outbreak. It observed windfield reversals and perturbations to the received power field probably associated with multiple vortices.

Until recently, however, quantitative, three-dimensional radar observations permitting a detailed characterization and mapping of the structure and behavior of multiple-vortices have been nonexistent.

On 3 May 1999, several dozen tornadoes occurred over Oklahoma and Kansas. One of these was observed by a DOW to exhibit pronounced multiple vortex structure.

2. Data collection strategy and data processing

Scanning was conducted through at 12 stepped elevation angles resulting in scans through the tornado center at 30-1500 m agl every 80-260 m. Each scan required ~ 4-5 s. A staggered PRT resulted in a Nyquist interval of about 260 ms-1. Integration periods were 0.16 s. 167 ns pulses and rapid sampling produced

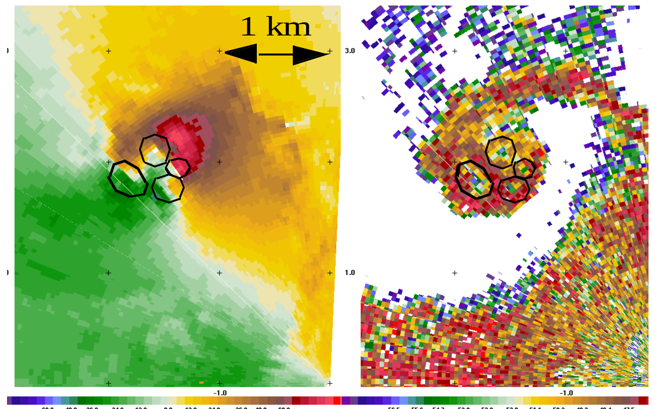
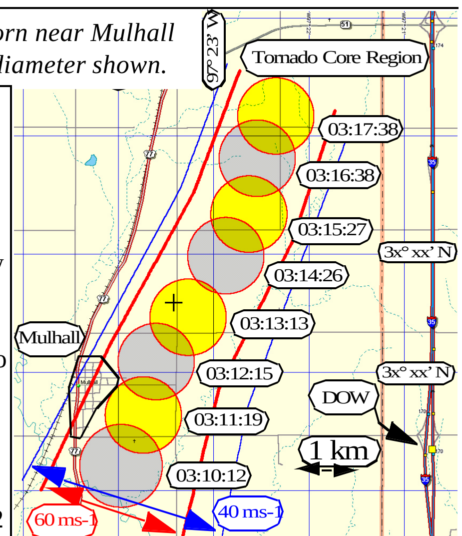


Figure 1.Doppler Velocity and Power in Spencer SD tornado illustrating multiple vortices (black ovals).

Fig 2. Path of torn near Mulhall OK. Core flow diameter shown.



25m and 37.5m non-oversampled range resolution. The core flow region of the tornado approached to within ~ 3.5-4.5 km, resulting in a radar bw of 65 m, with 32 m apparent resolution due to azimuthal oversampling. Volumes of 25x 32x32m permitted scales of motion < 100 m to be resolved.

3. Overview of the tornado

A large disk of high reflectivity debris and rain, centered at 4.2-5.7 km range, demarked the tornado. The tornado moved in a generally NNE direction at 13.5 ms-1. The center of the tornado passed just to the SE of Mulhall, OK. It is estimated that parts of Mulhall experienced winds well in excess of 60 ms-1 (Fig 5). The high power observed throughout the core flow region of the tornado was similar in appearance to that of the Spencer, SD tornado of 1998 that might have contained multiple vortices (Fig 1), but contrasted sharply with the distinct low reflectivity eye visible tornadoes in which no multiple vortices were observed (WG, B, Wurman et al

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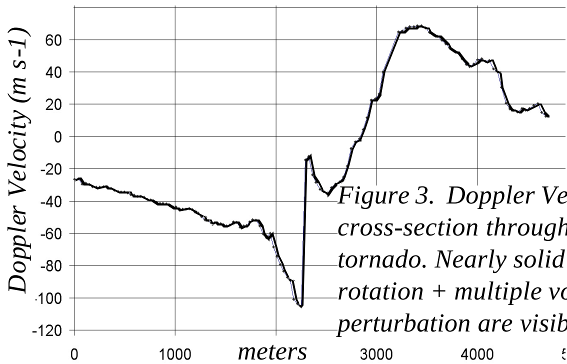

Figure 3. Doppler Velocity cross-section through tornado. Nearly solid body rotation + multiple vortex perturbation are visible.

1995). The high reflectivity debris disk was generally about 1.2 km in diameter near the surface. The ring with the highest power had a diameter of 0.8-1.0 km.

The low level tornadic circulation of this tornado was the largest ever mapped by radar. The distance between the peak inbound and peak outbound velocities, was ~1.2 km near the ground and as large as 1.75 km aloft. Winds > 50 ms-1 extended across a 2.5 km diameter region. Winds in > 30 ms-1 extended across 4.5 km. Doppler velocities occasionally exceeded 109ms-1, and a typical cross-sections through the velocity field of the tornado is illustrated in Figure3. The core flow region, exhibiting nearly solid body rotation with a shear of (160 ms-1 / 1200 m) = 0.13 s-1, and the outer velocity decay region are evident. A perturbation in the core flow due to a multiple vortex can be seen.

4. Multiple vortex structure

Several multiple vortices revolved around the tornado.

The velocity differences across these vortices sometimes exceeded 100 ms-1 (peaking at over 120 ms-1) over distances sometimes less than 100 m, but more typically 200-300 m, representing ~ 50% of the total azimuthal shear present in the tornado. Peak Doppler velocities in the vortices were as high as 109 ms-1, about 1.2-1.5 times the estimated peak azimuthally averaged tangential velocities (Vatp) (Lee and Wurman 2001) well below the largest predicted to exist by some models. This comparison is imprecise since the radar observed one component of the wind vector, so observed Doppler velocities were actually lower bounds on true wind speeds. However, Doppler velocity differences of about 80-100 ms-1 across the multiple vortices implied ~ +/- 40-50 ms-1 perturbations to the background flow. 40-50 ms-1 perturbations added to the 70-80 ms-1 Vatp calculated in LW would result in peak windspeeds of 110-130 ms-1, or about 1.5 times Vatp. However, it is possible that much higher windspeeds occurred on scales not resolvable by the DOW. Peak shear values were 2-4 s-1, implying extreme vertical vorticities of 4-8 s-1, by far the largest ever measured by radar in tornadic flows. While the

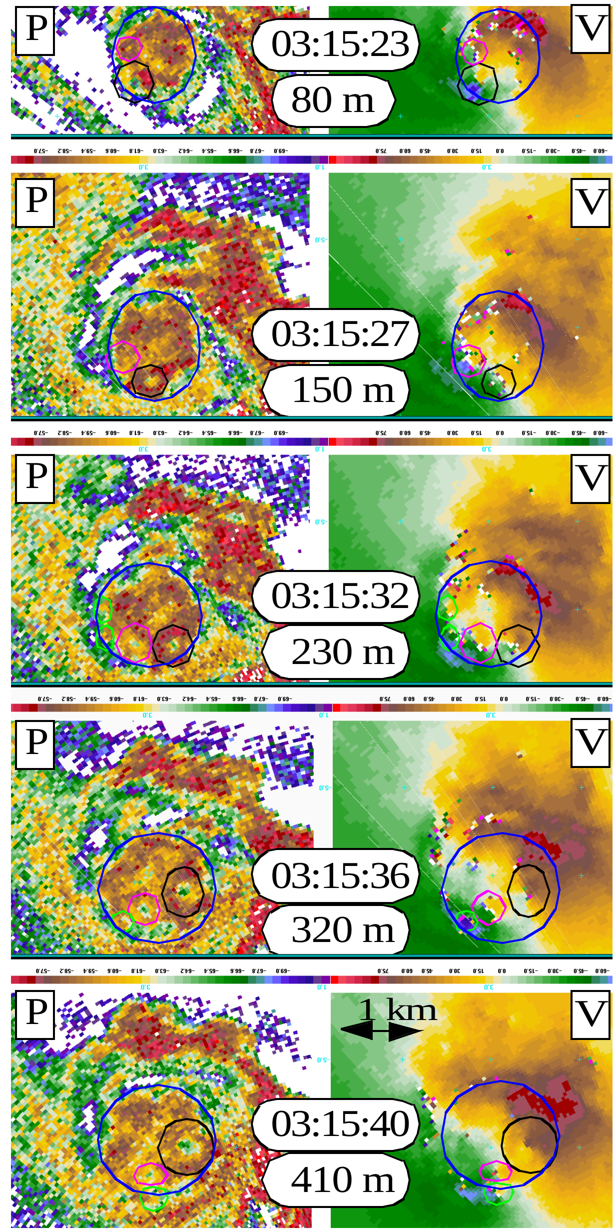

Figure 4. Tracking of Multiple Vortices. Black oval is Vortex A. Grey are vortices B and B' (not discussed). Vortices revolve about the center of the tornado.

peak windfield perturbations indicated a vortex scale of 200-300 m, much of the shear in the vortices was concentrated in regions of 40-100 m or less (gate-to-gate shear observations) indicating a windfield structure very different form that observed in tornadic circulations (Fig. 3).

The typical horizontal scale of the vortices was ~ 100-500m. The amplitude of the vortices decreased with altitude, and the size increased. The vortices propagated upstream in the parent tornadic flow at ~ 0.5-0.9 of the peak speed of the parent tornado, consistent with laboratory and numerical modelling studies. The characteristics of some individual vortices will be discussed in the next section.

Multiple low power eyes were associated with individual vortices above about 200 m agl. Some of the vortices existed at the outer edge of the central Z disk and were associated with miniature hook-like reflectivity structures rather than enclosed eyes. Some existed just inside the high power region, suggesting that they were in the corner flow region where inwardly moving air was turning upwards, somewhat inconsistent with some numerical simulations. A few vortices, did occur well within the debris cloud.

Spectral width observations also revealed the multiple vortex structure of the tornado.

5. Tracking individual vortices

Several vortices were trackable; one is discussed below.

Vortex A exhibited a distinct and trackable doughnut-with-hole type power signature (Fig. 4) similar in some characteristics to that of a single cell vortex tornado with a low reflectivity eye surrounded by a ring of higher values. The diameter of the ring (from peak value to peak value) was ~ 200-300 m at the lowest levels. This is consistent with the size of the vortex inferred from the distance between the peak inbound and peak outbound radial velocities. The diameter of the reflectivity ring increased with altitude until it was 400 m in diameter at 415 m agl. During the 21.6 s between the observations at 78 m agl (03:15:25.8 UTC) and 611 m agl (03:15:47.4 UTC), the vortex had revolved from the southwest, through the south, east, and north side of the parent tornado. Above 611 m agl, the reflectivity signature was difficult to track and appeared to become split, with a double eye.

The difference in Doppler velocity (ΔV) across the vortex was in excess of 100 ms-1 at the lowest observed levels, but decreased substantially with height. ΔV across the vortex was over 50% of the ΔV across the entire tornado at the lowest levels, but proportionately less aloft. Vertical vorticity was approximated by the formula v=dv/dx-du/dy ~ 2 R dVr/dR. Vertical vorticity calculated using measurements across the entire vortex ranged from about 1.0-2.6 s-1 were several times higher than that calculated across the parent tornado (0.15 s-1 average shear implied 0.3 s-1 vertical vorticity). This vortex exhibited intense beam-to-beam shear at their centers. These intense shear zones were present in most every slice through the vortex. The Doppler velocity changed by 80 ms-1 in 0.4° in one sweep, with 60 ms-1 over 0.54° and 56 ms-1 over 0.6° observed in other sweeps, resulting in estimated vertical vorticity of 5.2, 2.8, and 2.2 s-1 respectively. Since the Doppler velocities reported from each beam really

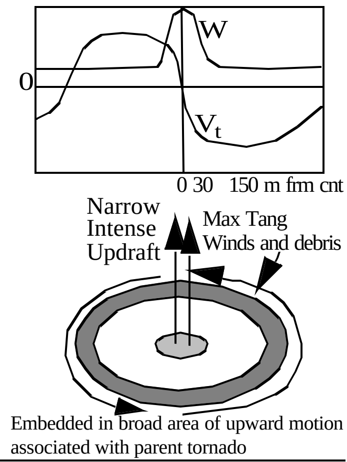

Figure 5.Hypothesized structure of multiple vortices. Rings of debris are centrifuged from the center of the vortices in the presence of perhaps slight upward motion possibly associated with the parent tornado. An intense, very narrow, updraft is associated with convergence and the strong gate-to-gate shear at the center.

reflected a weighted average across a beam width larger than the implied beam sampling intervals, these shear and vorticity values are likely *underestimates* of the true peak shear and vertical vorticity in the center of the vortex. The translational speed of the vortex was ~ 52 ms-1 with individual calculations based on the velocity and reflectivity centers ranging from 33 ms-1 to 76 ms-1 and 8 of 13 calculated values within +/-10 ms-1 of the mean. This was about 0.7- 0.8 times the Vatp, and indicated a propagation velocity upstream at about 0.2-0.3 of Vatp, somewhat consistent with predictions of propagation at 1/2 of the tornado tangential velocity. Since, upstream tilting of the vortex might have introduced some spurious apparent upstream propagation, these observations might also be consistent with the vortex simply being carried along passively at a speed of Vatp, with no upstream propagation.

6. Conceptual model of Vortex Structure

The velocity structure of these vortices differed significantly from that of tornadoes. The multiple vortices observed in this tornado exhibited extremely high shear and implied high vertical vorticity at their centers. Frequently, these regions contained half or more of the total shear observed across the vortices and vertical vorticity of several s-1.

It is possible that intense and horizontally very narrow (< 40 m) transient updrafts existed in the center of these vortices (Fig 5). This would have caused intense but transient horizontal convergence and resultant stretching of vorticity near the center of the vortices. It is hypothesized that the transient and narrow characteristics of the updrafts, and/or the rapid passage, at translational velocities of ~ 50 ms-1, of the small updrafts through particular regions of the tornado, did not allow the air in the vortices to reach states which exhibited the solid body rotation observed in this or other large tornadoes. Thus, comparatively high angular momentum (compared to what would occur in solid body rotation) reached close to the centers.