Tornado Detection by Pulsed Doppler Radar

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ABSTRACT

Doppler radar measurements in the Union City, Okla., tornado storm of 24 May 1973 led to discovery of a unique tornado vortex signature (TVS) in the field of mean Doppler velocity data. The distinct character of this signature and its association with the tornado are verified using a model that simulates Doppler velocity measurements through a tornado. Temporal and spatial variations of the TVS reveal previously unknown tornado characteristics. The TVS originates at storm mid-levels within a parent mesocyclone, descends to the ground with the tornado (extending vertically at least 10 km), and finally dissipates at all heights when the tornado dissipates. NSSL Doppler radar data from 1973 through 1976 reveal 10 signatures; eight were associated with tornadoes or funnel clouds, while no reports are available for the other two. Since the TVS first appears aloft tens of minutes before tornado touchdown, the signature has decided potential for real-time warning.

1. Introduction

A promise of meteorological Doppler radar has been tornado detection and determination of tornado wind speeds (e.g., Atlas, 1963). In fact, the first Doppler radar built for weather purposes in the United States—a 3 cm continuous wave (CW) unit—was designed specifically to measure tornadic wind speeds (Brantley and Barczys, 1957; Smith and Holmes, 1961). On 10 June 1958 the Doppler velocity spectrum from the radar indicated velocities up to 92 m s⁻¹ in the developing funnel of a major tornado that struck El Dorado, Kans. (41 km from the radar). After several years of field experiments this radar was modified into a pulsed Doppler radar (Lhermitte and Kessler, 1964).

A pulsed Doppler radar with a high pulse repetition frequency (PRF)—having very large velocity capability—is well-suited for tornado studies. Atlas (1963) and Lhermitte (1964) contemplated what the pulsed Doppler velocity spectrum would be like when the beam from a high PRF radar is centered on a tornado. Atlas stated that "great spectrum width and roughly equal spread across zero velocity are the two distinguishing characteristics of a tornado." Using a simple annulus model, Lhermitte computed a broad velocity spectrum with a peak followed by a sharp drop-off at each end of the spectrum.

For a given wavelength (λ), the maximum radar-induced velocity (vmax) is proportional to the PRF

\[ v_{\text{max}} = \frac{\lambda}{4 PRF} \]

(Battan, 1973):

Few Doppler radars are set to measure high velocities because a high pulse repetition frequency results in a limited roundtrip distance for one pulse before the next pulse is transmitted; i.e., maximum range (rmax) is inversely proportional to PRF:

\[ r_{\text{max}} = \frac{0.5c}{PRF} \]

where c is the speed of electromagnetic wave propagation. A reduced range interval means that echoes at integer multiples of rmax all will appear on top of each other in the first trip interval (range is referenced from the time that each new pulse is transmitted). Thus there are distinct range disadvantages with a high PRF radar; on the other hand, there are corresponding velocity measuring ambiguities with a low PRF radar.

For the more typical long-range (lower PRF) Doppler radar with limited velocity resolution, tornadic wind speeds are aliased into the measurable velocity interval. The resulting broad spectrum fills the entire interval, making it extremely difficult to unscramble the maximum tornadic speeds. Using the 5.4 cm Air Force Cambridge Research Laboratories' Doppler radar, Kraus (1973) found filled spectra (±12.5 m s⁻¹) in the vicinity of the Brookline, Mass., tornado of 9 August 1972. Zrnic et al. (1977) have attempted to esti-
mate maximum speeds by comparing numerical simulations with aliased spectra measured by the two 10 cm National Severe Storms Laboratory (NSSL) Doppler radars (±34 to ±36 m s⁻¹ velocity interval, 0.8° beamwidth, 150 m pulse depth, 115 km first trip range, PRF of 1302 pulses s⁻¹). With low PRF data collection, one would expect the mean of the Doppler velocity spectrum to be near zero whenever the radar beam is centered on a tornado. The theoretical distribution of mean velocity values in the immediate vicinity of a tornado vortex has not been considered. Prior to the NSSL Doppler velocity measurements in the Union City, Okla., tornado storm of 24 May 1973 (see Brown, 1976), there was little reason to expect that a tornado could be detected without detailed scrutiny of Doppler velocity spectra. However, in the data collected in that storm, a unique mean Doppler velocity signature, the tornadic vortex signature (TVS)², was discovered (Burgess et al., 1975b). This signature also has been found in a number of more recent tornadic storms. Detected aloft near the center of the parent mesocyclone, the TVS signals an incipient tornado; if seen at 0° elevation as well as at higher levels, there is high probability that a tornado is on the ground. The TVS holds great promise for real-time tornado detection and warning. In this paper, we establish a theoretical relationship between Doppler velocity spectra near a tornado and the tornadic vortex signature. The TVS then is used to describe new spatial and temporal tornado characteristics.

2. Relationship of Doppler velocity spectra and the TVS

Tornado detection by Doppler radar is highly dependent on placement of the radar sampling volume (range gate) relative to tornado center. To understand this dependency, we have used a model developed by Zrnic that simulates a Doppler radar looking at a Rankine combined vortex (see Zrnic and Doviak, 1975). In a Rankine combined vortex (Rankine, 1901), the tangential velocity increases linearly from the center outward to a velocity maximum at the outer edge of the “solidly rotating” core, then decreases by an amount inversely proportional to distance from core center. The Rankine tangential velocity model seems appropriate for tornadoes based on in situ measurements in dust devils (e.g., Sinclair, 1973) and waterspouts (e.g., Levenson et al., 1975).

The radar sampling volume has a circular cross section normal to the radar beam (diameter specified by the nominal half-power beamwidth) and a finite depth in range (specified by the nominal pulse depth). These dimensions are nominal because a measurable amount of the returned power comes from outside the specified sampling volume. As range increases, the beam linearly widens while the pulse depth remains constant.

Understanding the influence of relative sampling volume size and shape on Doppler velocity measurements in a tornado can be facilitated by two examples using the Zrnic model. In the first example the beamwidth is four times the tornado's core radius and the pulse depth is equal to the core radius (Fig. 1). For the second example, beamwidth is ten times the core radius and pulse depth is four times the core radius (Fig. 2). Figs. 1 and 2 depict relative sizes and positions of the sampling volumes for incremental azimuthal sampling in one-quarter beamwidth steps and incremental range sampling in steps of one-half pulse depth. These two examples are used to illustrate the basic characteristics of measurements in a tornado.

a. Doppler velocity spectra in tornadoes

For a remote sensor like the Doppler radar, the tornado typically is smaller than the sampling volume. This situation precludes discrete point measurements.

\[ \text{BEAMWIDTH} \quad \text{CORE RADIUS} = 4 \]
\[ \begin{array}{c}
\frac{\Delta R}{\text{PD}} = 2.0 \\
\frac{\Delta A}{\text{BW}} = 1.0 \\
\end{array} \]
\[ \text{PULSE DEPTH} \quad \text{CORE RADIUS} = 1 \]
\[ \begin{array}{c}
\frac{\Delta R}{\text{PD}} = 1.5 \\
\frac{\Delta A}{\text{BW}} = 0.75 \\
\end{array} \]

Fig. 1. Relation of tornado's core radius (CR) to Doppler radar sampling volume. Numbered sampling volumes correspond to numbered spectra in Fig. 3 for various ratios of range increment to pulse depth (ΔR/PD) and ratios of azimuthal increment to beamwidth (ΔA/BW).

² This signature has been referred to by the interim descriptive name of "gate-to-gate shear" (GGS) by Burgess et al. (1975a, b) and Lemon et al. (1975).
in the tornado from which tangential velocity profiles through the vortex could be constructed. Instead, the radar measures the radial component (relative to the radar) of nearly the entire velocity distribution at one time, resulting in a spectrum of reflectivity-weighted Doppler velocities. When the sampling volume of a high PRF radar is centered on the tornado, the extreme spectral velocities should represent the extreme tangential velocities in the tornado, after corrections have been made for spectral broadening introduced in the radar receiver and during signal processing.

Spectra generated in the immediate vicinity of the modeled tornado are presented in Figs. 3 and 4. These spectra do not contain the artificial broadening effects just mentioned. A maximum tangential velocity of 100 m s\(^{-1}\) was used and measurements correspond to a simulated high-PRF Doppler radar having \(\pm 100\ m\ s^{-1}\) capability. Uniform reflectivity across the tornado was assumed. The actual reflectivity distribution in a tornado is unknown; there may well be an annulus of high reflectivity produced by centrifugal action on hydrometeors and debris. However, actual measurements across large tornadoes do not reveal significant varia-

tions in reflectivity from one sampling volume to the next.

The spectrum at the bottom left corner represents the sampling volume centered on the tornado. As expected, the spectra are broad and decrease quite rapidly as \(\pm 100\ m\ s^{-1}\) is approached. As the sampling volume moves away from the tornado in range the spectra narrow but remain symmetric about zero velocity. Had a component of translation been included in the simulation, the spectra would have shifted to the left (tornado approaching radar) or right (receding). As the sampling volume moves away from the tornado in an azimuthal direction, the spectra become asymmetric—reflecting the fact that the radar is sensing more and more of only one side of the circulation. In the absence of translation and radial flow, spectra to the left of tornado center are mirror images of these in Figs. 3 and 4.

b. Tornado vortex signature (TVS)

Real-time Doppler velocity processors, such as the pulse-pair processor (e.g., Miller and Rochwarger, 1972), compute the mean of the Doppler velocity spectrum without requiring the spectrum to be determined. The mean is computed directly from consecutive pairs of returned pulses. Real-time mean velocity processors do not permit determination of the maximum winds in a tornado (due to lack of spectra) but it is possible to detect the presence of a tornado from localized extreme azimuthal shear in the mean Doppler velocity measurements.

The spectra in Figs. 3 and 4 reveal the basis for a tornado vortex signature. Consider the bottom row of spectra in either figure (representing a scan at constant range through the tornado center). As the sampling volume moves past the center of the tornado, the positive portion of the spectrum (flow away from radar) increases and the negative portion (flow toward) decreases. By the time the sampling volume is one-quarter beamwidth from the center, the difference between positive and negative peaks is about 10 dB. When the sampling volume is one-half beamwidth from the center, the positive portion is 15–20 dB stronger than the other half; thus the mean of the spectrum essentially will be unaffected by the negative velocities. At greater azimuthal distances, the influence of negative velocities truly becomes negligible.

Means of the Doppler velocity spectra in Figs. 3 and 4 (as well as spectra not shown) are plotted in Figs. 5 and 6, respectively. These curves represent mean Doppler velocities as a function of azimuthal distance (normalized by beamwidth) from the center of the tornado. The individual curves indicate mean velocities within sampling volumes positioned at various ranges (normalized by pulse depth) from the tornado.

The most obvious features are the extreme mean Doppler velocity values that occur approximately one-
half beamwidth either side of the tornado when the sampling volume is centered at the same range as the tornado. For sampling volumes displaced one, two and three pulse depths in range, Figs. 5 and 6 reveal that the azimuthal separations of the extreme mean values increase while the magnitudes decrease. Thus the marked azimuthal changes in mean velocity quickly disappear at a range of a few pulse depths from the tornado.

If we consider only azimuthal scans (constant range) through the center of a tornado, we can compare tornadic vortex signatures produced for a variety of beamwidth-to-tornado-core-radius ratios (Fig. 7). The peak-to-peak spacing is not significantly affected by the size of the within-beam tornado. However, signature amplitude, which is affected, plays an important role in TVS detectability. The TVS cannot be resolved unless the peak-to-peak Doppler velocity shear is appreciably greater than the background cyclonic shear produced by the parent mesocyclone; typical threshold shear values are of the magnitude $1 \times 10^{-2}$ s$^{-1}$.

Several other practical limitations must be considered when attempting to identify tornadic vortex signatures from mean Doppler velocity measurement. First, when data are collected at discrete azimuthal increments, extreme values at tornado range may not be sampled when the sampling interval is greater than one beamwidth. Second, Zrnic and Doviak (1976) have shown that a radar antenna rotating rapidly relative to the sampling time produces an effectively broadened beamwidth. Thus, for a given maximum tangential velocity and tornado size, the amplitude of the TVS will decrease as the antenna rotation rate increases.

3. Signature of the Union City tornado

During the early afternoon of 24 May 1973, an isolated storm formed in west-central Oklahoma about 45 km ahead of a thunderstorm line (see Lemon et al.,
Fig. 4. As in Fig. 3, except that corresponding relative sampling volume positions are sketched in Fig. 2.

1978). When NSSL Doppler velocity measurements were made in the storm at 1515 CST, a TVS was present at mid-levels near the center of the parent mesoscale circulation. The Doppler radar in Norman collected data in the storm primarily with an azimuthal sampling interval of 1.0° (1.25 beamwidths).

It was in this storm that the tornadic vortex signa-

Fig. 5. Simulated azimuthal profiles of tornadic vortex signature at various normalized ranges from tornado center using same radar sampling and tornado characteristics as in Figs. 1 and 3. Ratio of pulse depth to beamwidth is 0.25.

Fig. 6. As in Fig. 5 except for radar sampling and tornado characteristics given in Figs. 2 and 4. Ratio of pulse depth to beamwidth is 0.4.
Figure 7. Simulated azimuthal profiles through center of tornadic vortex signature for various beamwidth to core radius ratios. Maximum tangential velocity in vortex is 100 m s\(^{-1}\). Ratio of pulse depth to beamwidth is 0.15.

Figure 8. Tornadic vortex signature (stippled) at 1545 CST on 24 May 1973 near ground within field of single-Doppler mean velocities (m s\(^{-1}\)). Velocities are relative to TVS motion (10 m s\(^{-1}\) from 283°). Velocities away from radar are positive, toward radar negative. Dark dot is surface tornado position. Dark rectangles (upper left) show relative radar sampling volume sizes. Azimuths and ranges are from NSSL Doppler radar in Norman.

Figure 9. Union City tornado at 1545 CST on 24 May 1973 during its organizing stage. Base of the lowered wall cloud (from which tornado is descending) is ~600 m above the ground. NSSL Doppler radar beamwidth is ~700 m at distance of tornado. View toward west-northwest. Photo courtesy of Steve Tegtmeier.
range of tornadic vortex size and maximum tangential velocity combinations. The three curves represent core radii varying from \( \frac{1}{3} \) to \( \frac{2}{3} \) beamwidth and maximum tangential velocities varying from 85 to 214 m s\(^{-1}\). Thus, the fitting of mean Doppler velocity measurements to theoretical curves cannot be used by itself to determine either the size or maximum velocity of the vortex that produces a TVS. However, if tornado size could be determined independently, the peak tangential velocity then could be estimated. For example, if core radius at 1546 is assumed to equal the visual tornado radius below cloud base (\( \sim 120 \) m), the ratio of beamwidth to core radius would be about 6. The corresponding tangential velocity would be about 135 m s\(^{-1}\). The highest photogrammetrically determined velocity in the outer edges of the surface debris cloud was 80 m s\(^{-1}\) (Golden and Purcell, 1978b).

A time-height profile of the maximum Doppler velocity value for each TVS pair (dot) is given in Fig. 12. Dots within the shaded regions represent data locations where a TVS could not be detected. The TVS originates aloft in the storm and descends to the ground at about the same time that the first damage occurs. The signature is strongest at all observed heights (extends to over 10 km) when the tornado funnel below cloud base is growing rapidly and is at near-maximum width

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**Fig. 11.** Theoretical Doppler velocity profiles through center of Union City tornadic vortex signature shown in Fig. 10. The three curves (from Fig. 7) represent vortices with various maximum tangential velocities \( (V_{\text{max}}) \) chosen to produce extreme TVS values of \( \pm 45 \) m s\(^{-1}\). Dots are observed Doppler velocity values.

**Fig. 12.** Time-height profile of the magnitude of the largest Doppler velocity value within each TVS (adjusted for TVS motion). Dots indicate data points and dashed lines represent the limits of data collection. Velocity shears below the TVS detectability level are lightly shaded. The black region at bottom center is the diameter (using ordinate scale) of the Union City tornado funnel near cloud base.
velocity. It is impossible to know whether changes in TVS magnitude are due to size changes, velocity changes, or both. For the case of the Union City TVS, one might speculate that the signature magnitude was primarily influenced by vortex size because its magnitude and the observed tornado diameter varied together, while damage intensity remained unchanged.

A horizontal projection of the TVS data points (Fig. 13) reveals that the signature consistently tilts toward the north-northeast at an average angle of 25° from the vertical. Relative to the direction of storm motion, TVS tilt is to the left consistent with the observed tilt of the tornado funnel below cloud base.

4. Signature of the Stillwater tornado

During the late morning of 13 June 1975, thunderstorms formed in a convergence area in north central Oklahoma ahead of a weak cold front. The storms became severe as they spread slowly southeastward during the afternoon and evening. Around 1730, NSSL Doppler data collection (0.6 beamwidth azimuthal spacing) began on an intensifying echo about 105 km from the Norman radar. A TVS was detectable aloft within the parent mesocyclone but only the parent circulation was evident near the ground.

By the time of the next low-level Doppler velocity measurements (1743), the TVS was detectable at the lowest levels and the tornado was inflicting damage on the ground. The intense shear of the TVS was at mesocyclone center, coincident with the reported tornado location. The anomalous character of the Stillwater TVS, like the Union City TVS, made it stand out in the Doppler velocity field. For example, at a height of 0.6 km, the indicated velocity changed over an azimuthal distance of 0.5° (0.6 beamwidth) from 18 m s\(^{-1}\) toward the radar on the left side to 25 m s\(^{-1}\) away from the radar on the right.

At 1748 the radar sampling volume apparently passed through the tornado center at a height of 9.1 km above the ground. The measurements were compared with various simulated Doppler velocity curves and found to have best agreement with TVS curves peaking at 40 m s\(^{-1}\) (Fig. 14). Since tornado vortex size at the height of the measurements is unknown, no estimate can be made of maximum tangential velocities.

The two low-level Doppler velocity measurements during the tornado lifetime reveal tornadic vortex signatures that coincide with the surface damage path (Fig. 13). At 1753 the tornado was in its shrinking and decaying stage and velocity difference across the TVS was reduced from nearly 45 to 30 m s\(^{-1}\). Burgess et al. (1976) discuss the measurements in more detail and show examples of the TVS as it was identified in real-time on a Doppler radar multimoment display. Low PRF Doppler velocity spectra in the vicinity of the tornado are presented by Zrnic et al. (1977).

5. TVS statistics

Objective criteria for defining a tornadic vortex signature have not yet been established. A thorough search of the NSSL Doppler radar archives now is underway to identify all possible signatures. An outcome of that study should be a set of objective identifying criteria. In the meantime, we have been using some tentative guidelines that work quite well. These guidelines are as follows:

1) An azimuthal shear of at least 20 m s\(^{-1}\) over an azimuthal distance of approximately one beamwidth (typically greater than 1\(\times\)10\(^{-2}\) s\(^{-1}\)).
2) Signature with extreme Doppler velocity values of opposite sign, after TVS translation has been removed.

3) Anomalous shear region not more than about 1 km in range extent (otherwise it would indicate a shear line rather than a small-scale vortex).

4) Shear region at least several kilometers in vertical extent.

5) Persistent anomalous shear region at the same general heights for about 10 min or more.

Using these tentative criteria, we thus far have identified ten signatures in the 1973–76 data set. Since TVS detection is a function of tornado size and strength as well as radar sampling volume and spatial density, not all tornadoes produce noticeable signatures.

The 10 identified signatures are listed in Table 1. Eight signatures had tornadoes or funnel clouds associated with them. These occurrences were documented either from Storm Data (Department of Commerce, 1973–76) or from damage surveys conducted by NSSL meteorologists. The remaining two signatures had no tornadoes reported with them. Unfortunately, we do not know what occurred at these rural sparsely populated locations because damage surveys were not conducted at signature positions.

### Table 1. Tornadic vortex signatures and associated weather phenomena.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Associated phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 May 1973</td>
<td>Union City, Okla.</td>
<td>Tornado</td>
</tr>
<tr>
<td>23 May 1974</td>
<td>Yukon, Okla.</td>
<td>Tornado</td>
</tr>
<tr>
<td>6 June 1974</td>
<td>Tabler, Okla.</td>
<td>Tornado</td>
</tr>
<tr>
<td>8 June 1974</td>
<td>Oklahoma City, Okla.</td>
<td>[No reports]</td>
</tr>
<tr>
<td>9 June 1974</td>
<td>Harrab, Okla.</td>
<td>Tornado</td>
</tr>
<tr>
<td>13 June 1975</td>
<td>Stillwater, Okla.</td>
<td>Tornado</td>
</tr>
<tr>
<td>13 June 1975</td>
<td>Ripley, Okla.</td>
<td>Funnel aloft</td>
</tr>
<tr>
<td>13 June 1975</td>
<td>Cushing, Okla.</td>
<td>Funnel aloft</td>
</tr>
<tr>
<td>13 June 1975</td>
<td>Kendrick, Okla.</td>
<td>[No reports]</td>
</tr>
<tr>
<td>30 May 1976</td>
<td>Waurika, Okla.</td>
<td>Tornado</td>
</tr>
</tbody>
</table>

6. Summary

A pulsed Doppler radar can provide information about tornadoes in two different ways. If the radar has a sufficiently high-pulse repetition frequency to unambiguously measure tornadic velocities (≈100 m s⁻¹), maximum tangential velocities can be deduced from the extremes of the Doppler velocity spectrum. However, at low-pulse repetition frequencies, the high velocities are aliased into a limited velocity interval and velocity extremes are no longer detectable. Not all is lost, though—a unique tornadic vortex signature (TVS) is found in the spectral mean velocity values that reveals the presence of the tornado. The TVS is a qualitative signature. However, the signature can be used to crudely estimate quantitative tangential velocities when the tornado's core radius can be determined reliably.

The main feature of the tornadic vortex signature is mean Doppler velocity extrema (of opposite sign) that occur about one beamwidth apart, regardless of vortex size or strength. However, signature magnitude decreases as the sampling volume is displaced in range relative to tornado center and as vortex size and/or maximum tangential velocity decreases. Detectability of a TVS depends upon the Doppler velocity shear between the signature extremes being significantly greater than the surrounding shear.

Detection of a TVS in the Union City storm led to the first substantiated information about tornado behavior above cloud base. The tornadic vortex signature originated at storm mid-levels. It took at least 25 min for the signature to work its way down to the ground. During this time, the signature magnitude increased at all detectable heights and continued to increase until the tornado reached its maximum observed size. As the tornado progressed through its shrinking and de-

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**Fig. 15.** Stillwater tornado damage track with location of low-level mesocyclone (no TVS) and tornadic vortex signatures. Dashed damage boundaries indicate condensation funnel not touching the ground, but continuous damage. After Burgess et al. (1976).
caying stages, the signature magnitude gradually decreased at all heights (measurements from the surface to over 10 km height). The TVS was no longer detectable at any height after the tornado dissipated. Behavior of the Stillwater TVS was very similar to the Union City TVS (to the extent limited data permit a comparison).

Tornadoes or funnel clouds were associated with 8 of the 10 tornado vortex signatures identified in the 1973–76 NSSL Doppler radar data. Due to size and sampling limitations, not all reported have produced identifiable signatures.

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REFERENCES


