8B.1 TORNADO SPECTRAL SIGNATURE OBSERVED BY WSR-88D

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1. Introduction

Weather Surveillance Radar- 1988 Doppler (WSR-88D) is an important tool to observe severe and hazardous weather remotely, and to provide operational forecasters prompt information of rapidly evolving phenomena such as microbursts, tornadoes, and mesocyclones. The most violent of these phenomena is the tornado which can produce destructive wind speed as high as 140 m s^{-1}(Davies-Jones et al. 2001). Early and accurate detection of tornadic vortices can increase the lead time for tornado warnings, thereby reducing injuries and loss of life. A key component of the current tornado detection algorithm on WSR-88D radars is a search for the presence of strong localized azimuthal shear of the radial winds (Stumpf et al. 1998). However, because the radar sample volume increases with distance from the radar, the shear signature deteriorates as the range of the tornado increases. In this work, an independent method of identifying tornado vortices in Doppler spectra data is proposed and investigated. Doppler spectrum reveals the weighted velocity distribution within the radar volume [Level II data (reflectivity, mean Doppler velocity, and spectrum width) is obtained by the first three moments of this distribution (Doviak and Zrnić 1993)]. Because of the unaveraged natural of information inherited in the Doppler spectrum data, a characteristic spectrum for tornadoes may still facilitate their identification when the Level II shear signature becomes difficult to identify.

Doppler spectra of tornadoes are distinctly different from the typical Gaussian-like spectra of most other atmospheric phenomena. Flat and bimodal tornado spectral signature (TSS) appeared in simulated data (Zrnić and Doviak 1975; Yu et al. 2003). A bimodal TSS was observed by pulsed Doppler radar with a radar configuration similar to the WSR-88D (Zrnić et al. 1977; Zrnić and Istok 1980; Zrnić et al. 1985). Doppler spectra of two more tornadoes from close range were obtained with a portable frequency modulated CW (FMCW) radar (Bluestein et al. 1993, 1997). Although the history of tornado measurements is long, there have been only a few successes in obtaining spectra data. This is largely because neither the technology to process spectra nor the technology to record voluminous amounts of time series data were available. However, recent advances in radar and computer technology will now permit a study of TSS in a systematic manner. The research WSR-88D (KOUN) operated by the National Severe Storm Laboratory (NSSL) has the unique capability of collecting massive volumes of Level I time series data over many hours. Doppler spectra can be obtained by processing these Level I data after the event. Doppler spectra from a tornado outbreak in central Oklahoma on May 10, 2003 are presented.

2. Tornado Spectrum

a. Doppler Spectrum

A Doppler spectrum $S(\mathbf{R}_0, v)$ as a function of radial velocity v and the location of the center of radar volume $\mathbf{R}_0$ can be as (Zrnić and Doviak 1975)

$$S(\mathbf{R}_0, v) = C \int_{v=\eta} f_b^2(x) W_r(y) Z(x,y) |\nabla v|^{-1} ds, \tag{1}$$

where C is a constant related to radar parameters, $Z(x,y)$ is the effective reflectivity factor, $f_b^2(x)$ is the radar beam pattern, $W_r(y)$ is the range weighting function, and $ds = \sqrt{dx^2 + dy^2}$. The gradient term is used to adjust the density of scatterers between the two surfaces of isodop. The integration is performed along each isodop of $v = \eta$ within the radar resolution volume. In other words, a Doppler

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*Corresponding Author: T.-Y. Yu (tyu@ou.edu), School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK 73019, USA spectrum reveals the reflectivity and radar weighting distribution of velocities within the radar volume. Here we assumed that the radar volume is located far enough from the radar that the azimuthal distance and range are well approximated by the Cartesian distance in the x and y direction, respectively. The reflectivity is assumed to be height invariant.

The mean Doppler velocity $\bar{v}(\mathbf{R}_0)$ is defined by

$$\bar{v}(\mathbf{R}_0) = \int_{-\infty}^{\infty} v S_n(\mathbf{R}_0, v) dv, \tag{2}$$

where $S_n(\mathbf{R}_0, v)$ is the Doppler spectrum normalized by total power. Therefore, mean Doppler velocity represents a statistical average of the spectrum (i.e., first moment). The current operational tornado detection algorithm relies on the difference of mean Doppler velocity between adjacent radar volumes in azimuth. However, such a velocity difference will be smoothed out significantly by the statistical average when a tornado is smaller than the radar beam (which would likely occur for tornadoes far from the radar).

b. Tornado Spectrum

To further exploit TSS, (1) is simulated using a combined Rankine vortex model (Kundu and Cohen 2002). A detailed description of simulation scheme is given by Zrnić and Doviak (1975). An example of simulated tornado spectra at a signal-to-noise ratio (SNR) of 30 dB is presented in Figure 1. In this simulation, the idealized tornado has a radius of maximum wind of 0.25 km and was located at 40 km from the radar. A WSR-88D radar was simulated to scan through the tornado with one degree angular sampling and with a range resolution of 0.25 km. The columns and rows in Figure 1 denote the angular location and range with respect to the center of the tornado. All radial velocities in Figure 1 are normalized by the maximum wind of the tornado. Motion of rotation is apparent in Figure 1, i.e., spectra at region of negative angle is dominated by negative velocities (toward the radar), while spectra at right portion of the tornado is dominated by positive velocities (away from the radar). It is evident that the tornado spectrum deviates from ordinary Gaussian-like spectrum which is expected in non-tornadic regions of precipitations (Janssen and Spek 1985). A flat or bimodal spectrum is obtained when the radar beam passes through the center of the tornado. If the tornado radial velocity exceeds the radar unambiguous velocity, these aliased velocity will further flatten the spectrum. As a result, the bimodal signature can be difficult to identify.

3. Results

In this section, tornado spectra observed by the NSSL research WSR-88D (KOUN) located at Norman, Oklahoma on May 10, 2003 are analyzed. An F2-F3 tornado was reported during 0329-0406 UTC starting on the south of Edmond, Oklahoma (more details of the tornado can be found from NOAA National Climate Data Center NCDC, http://www.ncdc.noaa.gov/oa/ncdc.html). Level I time series data were collected during the entire period of tornado. Reflectivity and mean Doppler velocity were obtained every half degree in azimuth using an autocovariance method (Doviak and Zrnić 1993). A PPI of reflectivity and radial velocity form the lowest elevation angle (0.4^o) at 0343 UTC is given in Figure 2. A well-defined hook signature and strong azimuthal shear were observed at 6 km east and 39 km north of the radar, suggesting the existence of tornado. Three Doppler spectra in different regions of the flow (labeled 1-3 in Figure 2) are denoted by black lines in Figure 3. Each spectrum has 32 points and the radar unambiguous velocity is 32 m s^{-1}. The noise level, denoted by a blue solid line, is approximately at -50 dB. It is evident that the tornado spectrum (location 2) is flattened, while Gaussian-like spectra are obtained from non-tornadic regions. Equivalent Level II data can be obtained by Gaussian fitting the first three moments of spectrum (Doviak and Zrnić 1993). Reconstructed Gaussian spectra were indicated by a red line and the mean Doppler velocity is denoted by the location of a green arrow. Note that the mean Doppler velocity derived from a tornadic spectrum could be in substantial error since a slight change of the spectrum shape (due to noise and/or other effects) can result in a totally different value of radial velocity. As a result, shear derived from the field of radial velocity could be in error and the performance of the shear-based algorithm is limited.

From these analysis of simulated and real data, it is clear that tornados can produce a broad and flat spectrum which is similar to a white-noise spectrum. However, significant signal power was still present in the tornado spectrum, as shown in Figure 3b. In other words, one further criterion to identify TSS may be sufficient SNR. The signature of a broad spectrum can be characterized using spectrum width. Yu et al. (2003) have shown the spectral width of a tornado spectrum will deteriorate at a slower rate with range than azimuthal shear sig-

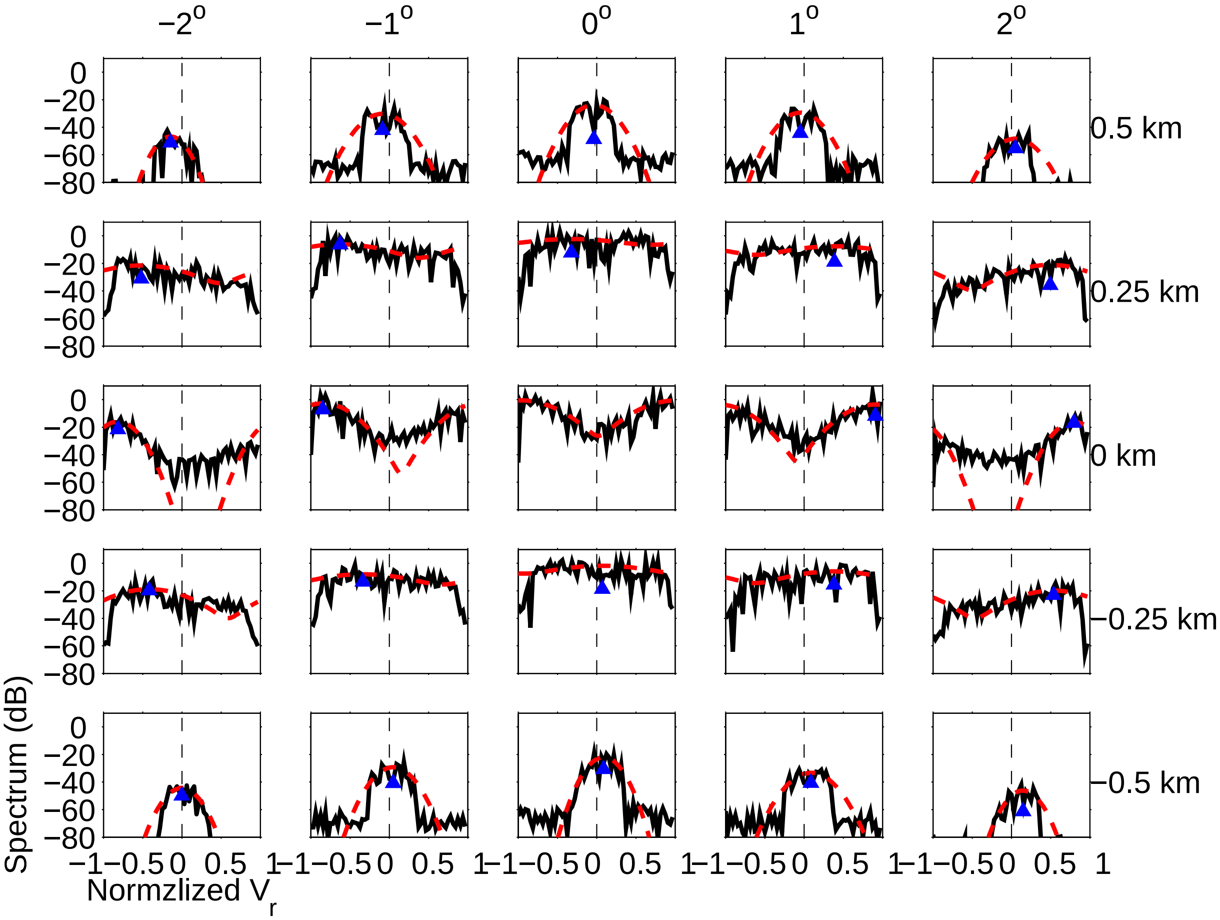

Figure 1: Simulated tornado spectra observed by a virtual WSR-88D.

natures in the field of mean Doppler velocity. Moreover, the flatness of the spectrum can be determined by the standard deviation (STD) of the spectrum values.

$$STD(S) = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(S_i - \mu_s)^2} \tag{3}$$

where S_i is the magnitude of Doppler spectrum in dB, M is the number of data points in a spectrum, and the mean of the spectrum values is defined as following.

$$\mu_s = \frac{1}{M}\sum_{i=1}^{M} S_i \tag{4}$$

Therefore, a flat tornado spectrum as shown in Figure 3b has a small STD compared to ordinary Gaussian-like spectra (Figure 3a and c). The mean of spectrum values is denoted by blue dash lines.

The azimuthal profile of SNR, radial velocity, spectrum width, and the STD of the spectrum are given in Figure 4 for three adjacent ranges. The tornado was located at approximately 9° and is denoted by a downward arrow. Strong SNR ensures the good quality estimate of spectrum and spectral moments. Strong azimuthal shear can be observed between 8° and 10° in azimuth for the three successive ranges (39.375-39.875 km). It is obvious that the mean radial velocity at 39.875 km and the azimuth of 9.5° is aliased. Therefore, de-aliasing of radial velocity is needed in order to obtain accurate shear values. A local minimum of STD and a maximum of spectrum width are evident close to the tornado center at 9° . Similar results were obtained at different time during the course of this tornado. A secondary minimum of STD and maximum of spectral width can be observed at approximately 5° , while the SNR is relatively low and no strong shear is appeared.

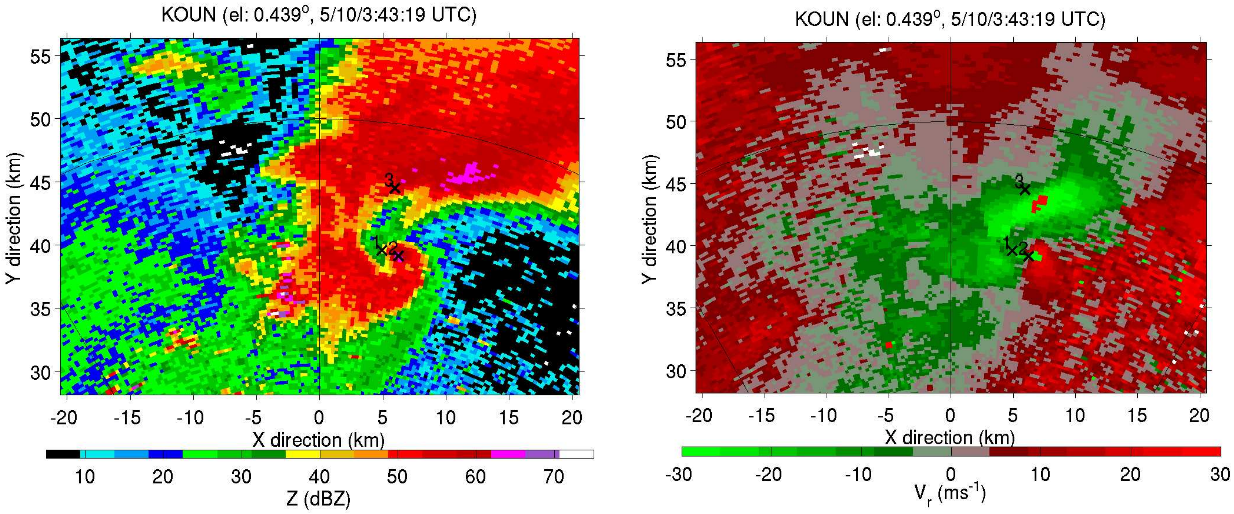

Figure 2: PPI of the reflectivity and velocity at 0343 UTC, May 10, 2003.

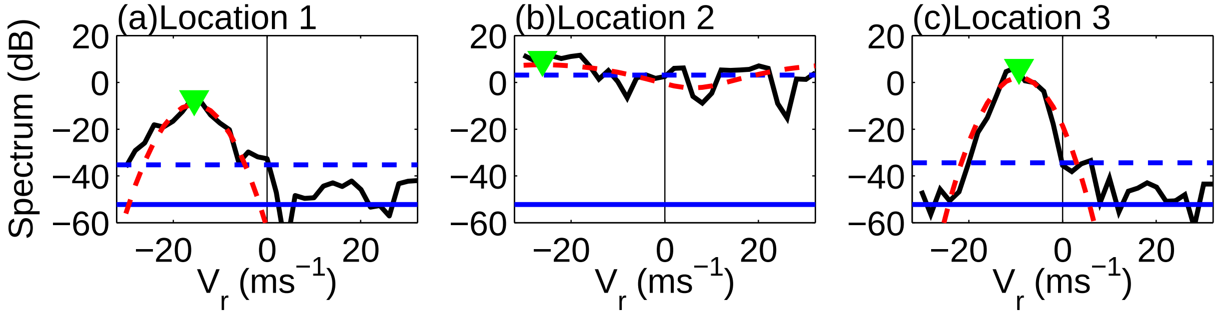

Figure 3: Spectra from the three regions labeled in Figure 2. It is clear that tornado (location 2) has a flat spectrum.

4. Conclusions

A Doppler spectrum can reveal the weighted velocity distribution of a tornadic vortex within the radar volume, while a mean Doppler velocity is a statistical average of such a distribution. Current algorithms of tornado detection search for vortex signatures in the field of mean Doppler velocities by identifying strong localized azimuthal shears. In this work, the tornado signature in Doppler spectrum is studied. Analysis of idealized (Rankine) vortex data and real tornado data have shown that the tornado spectrum has distinct signatures that differ from typical weather Gaussian-shaped spectrum. Tornado spectrum is often broad and flat, a feature that can possibly be characterized by spectrum width and the STD of spectrum values in decibels. A good agreement between spectral feature and azimuthal shear signature was obtained for the tornado in central Oklahoma on May 10, 2003.

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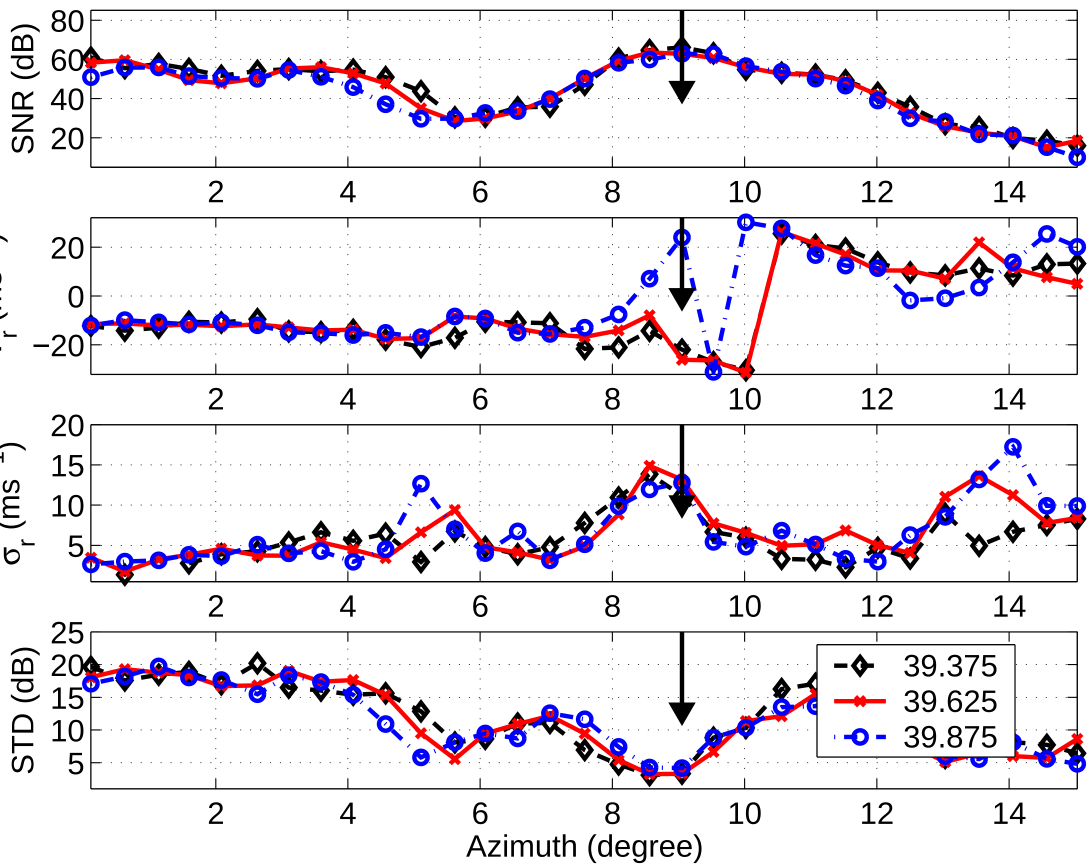

Figure 4: Azimuthal profiles of SNR, radial velocity, spectrum width, and the STD of the spectrum at 39.375, 39.625, and 39.875 km.

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