5A.7 FEASIBILITY OF EARLIER TORNADO DETECTION USING DOPPLER SPECTRA

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1 Introduction

The accurate detection of severe and hazardous weather such as thunderstorms, downbursts, mesocyclones and tornadoes is of primary interest to researchers and forecasters. Doppler radar such as Weather Surveillance Radar- 1988 Doppler (WSR-88D) has proved to be a unique and important tool to observe such phenomena remotely, and to provide operational forecasters prompt information of rapidly evolving weather. Early and accurate identification of tornadic vortices can increase the lead time for tornado warning to benefit the general public. In this work, simulation results demonstrate that atmospheric vortices have a distinct signature in the Doppler spectrum that differs from typical weather Gaussian-shaped spectrum. The feasibility of tornado detection using tornado spectral signature (TSS) (Zrnić et al. 1985) is discussed.

The first milestone in the detection of tornadoes using radar was the recognition of the so-called hook echo on radar display. However, it was later shown that hook echoes in the radar reflectivity field may fail to identify tornadoes in many cases (Forbes 1981). A revolutionary improvement of vortex detection is the implementation of pulsed Doppler radar such as the WSR-88D. Currently, two improved algorithms are used for identifying vortices in the fields of Doppler velocities (e.g., Stumpf et al. 1998; Mitchell et al. 1998). The current mesocyclone detection algorithms associate localized (in azimuth and range) regions of Doppler velocities that increase with azimuth (azimuthal shear of radial wind). Continuity in time and height are used as well as threshold criteria for the shear strength and size of the rotating core, and other parameters to separate mesocyclones from benign shears. The tornado detection algorithm is similar except it searches for strong localized shears between two adjacent gates along azimuth, i.e., strong gate-to-gate shear (or azimuthal shear). The performance of current tornado detection algorithms depends on the interplay between the radius of maximum wind, the strength of the maximum wind, the transverse dimension of the radar beam, and the radar range resolution. Brown et al. (1978) suggested guidelines for the identification of tornado signatures in the field of Doppler velocities based on the appearance of tornadic vortex signature (TVS). One of these criteria is the observation of distinct azimuthal shear. However, azimuthal shear would be smoothed out significantly by the radar weighting function when a tornado is smaller than the radar beam (which would likely occur for tornadoes away from the radar). Due to radar discrete sampling in angle, the observed azimuthal shear is further degraded. Therefore, the detection of vortex signatures in the fields of mean radial velocity is limited when the size of tornadoes is small compared to radar resolution volume. This occurs very often when a tornado is formed at far range. In this work, preliminary results show cases that TSS deteriorate at a slower rate with range than azimuthal shear signatures in radial velocity data. As a result, such spectral signature can be used to improve tornado detection at far range.

2 Tornado Spectral Signature

2.1 Overview

A pioneering work in the measurement of tornado Doppler spectra was done by Smith and Holmes (1961) using a 3-cm continuous wave (CW) radar. Although the history of tornado spectrum measurements is long, there have been only a few successes. This is largely because neither the technology to process spectra nor the technology to record voluminous amounts of time series data were available. In the 1970s and 1980s, a few tornado spectra were recorded by a pulsed Doppler radar developed at

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National Severe Storms Laboratory (NSSL) (e.g., Zrnić and Doviak, 1975; Zrnić et al. 1985).

Doppler spectra of tornadoes have a distinct character that sets these apart from other spectra. Atlas (1963) expected a broad and flat spectrum to be observed by a pulsed Doppler radar when a tornado is within the radar resolution volume. A bimodal spectral signatures of tornadoes were observed by pulsed Doppler radar (Zrnić and Doviak 1975; Zrnić et al. 1985).

2.2 Simulation Scheme

All the time series data of tornadoes collected by NSSL in the 1970s and 1980s have been destroyed. Therefore, an analytic model introduced by Zrnić and Doviak (1975) was implemented to study tornado spectral signatures in a controlled manner. It is assumed that a tornado is centered at the origin with a maximum wind of V_{max} and the radius of maximum wind r_t. The radar is located at far enough from tornado such that the observed radial velocity only has a component in y direction (beam pointing direction). In addition, the two-way antenna beam pattern is approximated by the following equation as a function of x (transverse direction of radar beam).

$$f_b^2(x) = \frac{\ln 4}{\pi W^2} \exp^{-\frac{\ln 4}{W^2}(x-x_0)^2} \tag{1}$$

where $2W$ is the horizontal distance of 3 dB beamwidth normalized to r_t. A Doppler spectrum is simulated using the following two-dimensional approach (Zrnić and Doviak 1975).

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

where $S(\mathbf{R}_0, v)$ is the Doppler spectrum as a function of normalized velocity v and the location of the center of radar volume $\mathbf{R}_0 = [x_0 \; y_0]$, $Z(x,y)$ is the effective reflectivity factor, $W_r(y)$ is the range weighting function, and $ds = \sqrt{dx^2 + dy^2}$. Note that all distances (x, y, x_0, y_0 etc) have been normalized to r_t and velocity is normalized to V_{max}. A Doppler spectrum is obtained by integrating (2) along each isodops of $v = \eta$ ($\eta = -1 \; - \; 1$) within the radar resolution volume. The radar resolution volume is defined by a rectangular box with length of $6W$ and dR in the x and y direction, respectively. dR is the radar range resolution ($c\tau/2$, τ is the pulse width) normalized to r_t. Isodop can be represented in the following form using the Rankine vortex model.

$$\begin{aligned} \eta &= r\cos(\phi - \alpha), & for \;\; r \leq 1 \\ &= r^{-1}\cos(\phi - \alpha), & for \;\; r \geq 1 \end{aligned} \tag{3}$$

where r is the distance measured from the center of vortex normalized by r_t, ϕ is the azimuth angle ($x = r\cos\phi$ and $y = r\sin\phi$), and $\tan\alpha$ is the ratio of maximum tangential speed to maximum radial speed. It is assumed that maximum tangential speed and maximum radial speed are coincided.

2.3 Simulation Results

In simulation, a range weighting function with a Gaussian profile was used. An independent reflectivity field with a donut shape was implemented using the following expression.

$$Z(r) = \exp^{-\frac{(r-r_m)^2}{2W_z^2}} \tag{4}$$

where r_m and W_z were set to 1.1 and 0.1, respectively. The radar sampling was simulated by locating the resolution volume at three angular locations of one beamwidth apart. In other words, three spectra were obtained by selecting proper $\mathbf{R}_0$ in (2) for a W and dR. Additionally, each spectrum with 128 points was generated.

Examples of tornado spectra with $dR = 4$ are shown in Figure 1. Each spectrum was normalized to its maximum value. For a fixed W, three spectra from left to right were obtained for the resolution volume was located at $x_0 = -2W$, 0, $2W$, respectively. The location of y_0 is zero for all three cases. It is evident that tornado spectrum is distinct and is different from typical Gaussian weather spectrum. Mean radial velocity of each spectrum is obtained using the first moment of spectrum and is denoted by arrow. Azimuthal shear is defined as the difference of mean velocity at $x = -2W$ and $x = 2W$. The resulting azimuthal shear includes smoothing effect caused by both radar weighting function and discrete sampling.

The deterioration of azimuthal shear as a function of W is shown in Figure 2(a). Note that for a fixed value of r_t and beamwidth, the larger value of W the further the range is. In other words, azimuthal shear becomes difficult to identify at far range. Furthermore, smoothing effect of radar range weighting function on shear increases with pulse width (large dR). In order to improve tornado detection at far range, it is expected to search for TSS which is less sensitive to range than azimuthal shear. In Figure 1, it is evident that broadened spectra are observed for $x_0 = 0$ and $W \geq 1$. Therefore, a simple and intuitive criterion to characterize tornado spectrum can be the spectrum width. It is shown Figure 2(b) that spectral width obtained at $x_0 = 0$ is still significant at far range. In practice, strong tornado often has

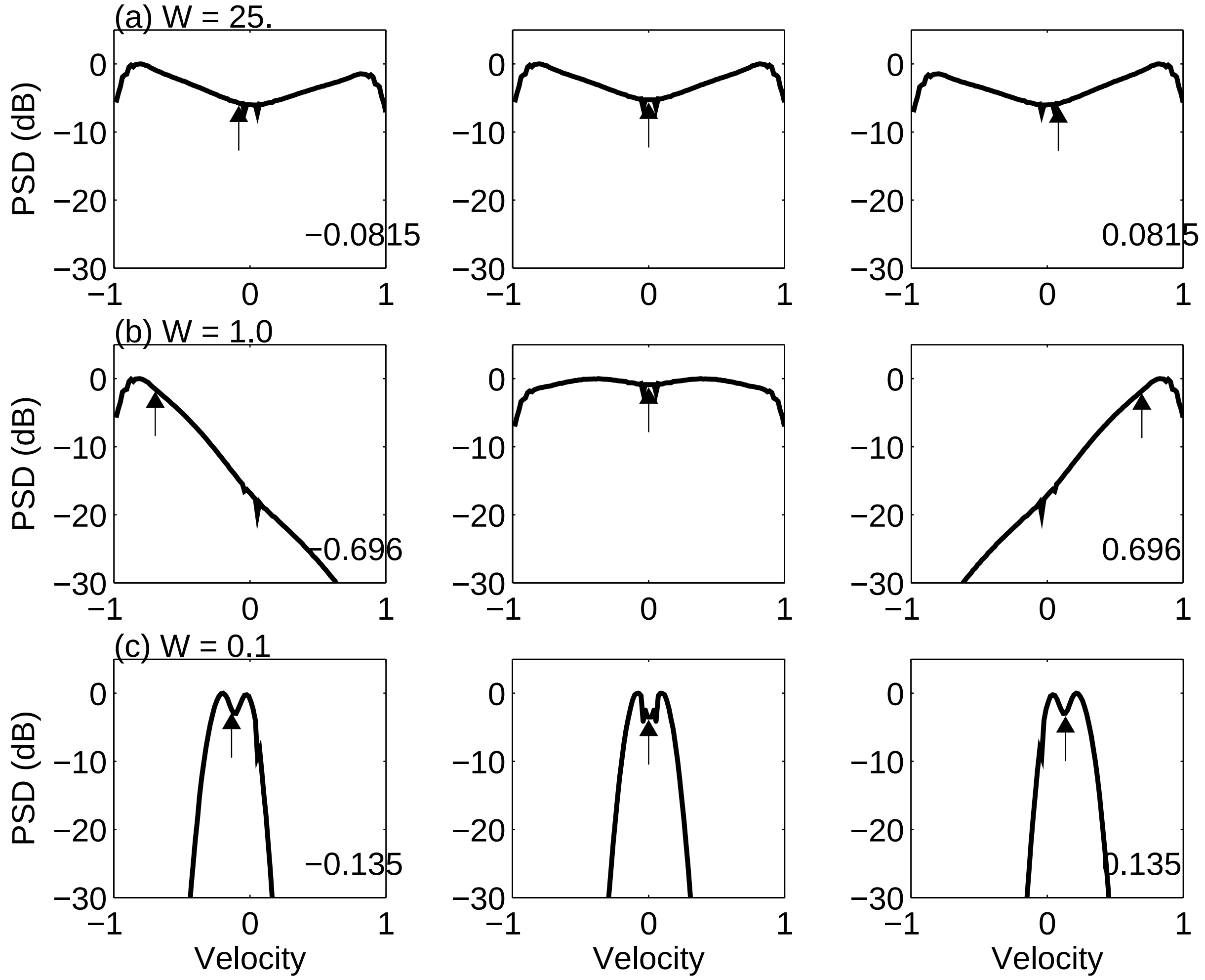

Figure 1: Tornado spectra from three discrete angular locations separated by one beamwidth for (a) $W = 25$, (b) $W = 1$, and (c) $W = 0.1$. The value of mean velocity is shown at lower bottom of each plot and the location of mean velocity is indicated by arrow.

maximum speed which exceeds the radar unambiguous velocity. These aliased velocities would further flatten the spectrum to make the criterion of wide spectral width even more favorable. Note that data from at least two angular location are needed for shear measurement, while a single characteristic spectrum could be sufficient for tornado identification.

3 Conclusions

Current algorithms of tornado detection search for vortex signatures in the field of mean Doppler velocities by identifying strong localized azimuthal shears. However, such shears become difficult to identify when a tornado is located at far ranges or when the size of tornado is small compared to the radar beam. It is shown that tornadic vortices have a distinct signature in the Doppler spectrum that deviates from ordinary weather signatures. Doppler spectrum is a measure of weighted velocity distribution within a radar beam while Doppler velocity represents a statistical average of the distribution. Therefore, a characteristic spectrum for tornadoes may facilitate their identification. In this work, a intuitive criterion of spectral width was used to demonstrate that tornado spectral signatures will deteriorate at a slower rate with range than azimuthal shear signatures in radial velocity data. Note that other effects such as strong shears occur within a radar volume or low signal-to-noise ratio can also produce wide spectra. Therefore, more robust and sophisticated criteria should be included in the identification procedure. A fuzzy logic approach of characterizing TSS is currently under

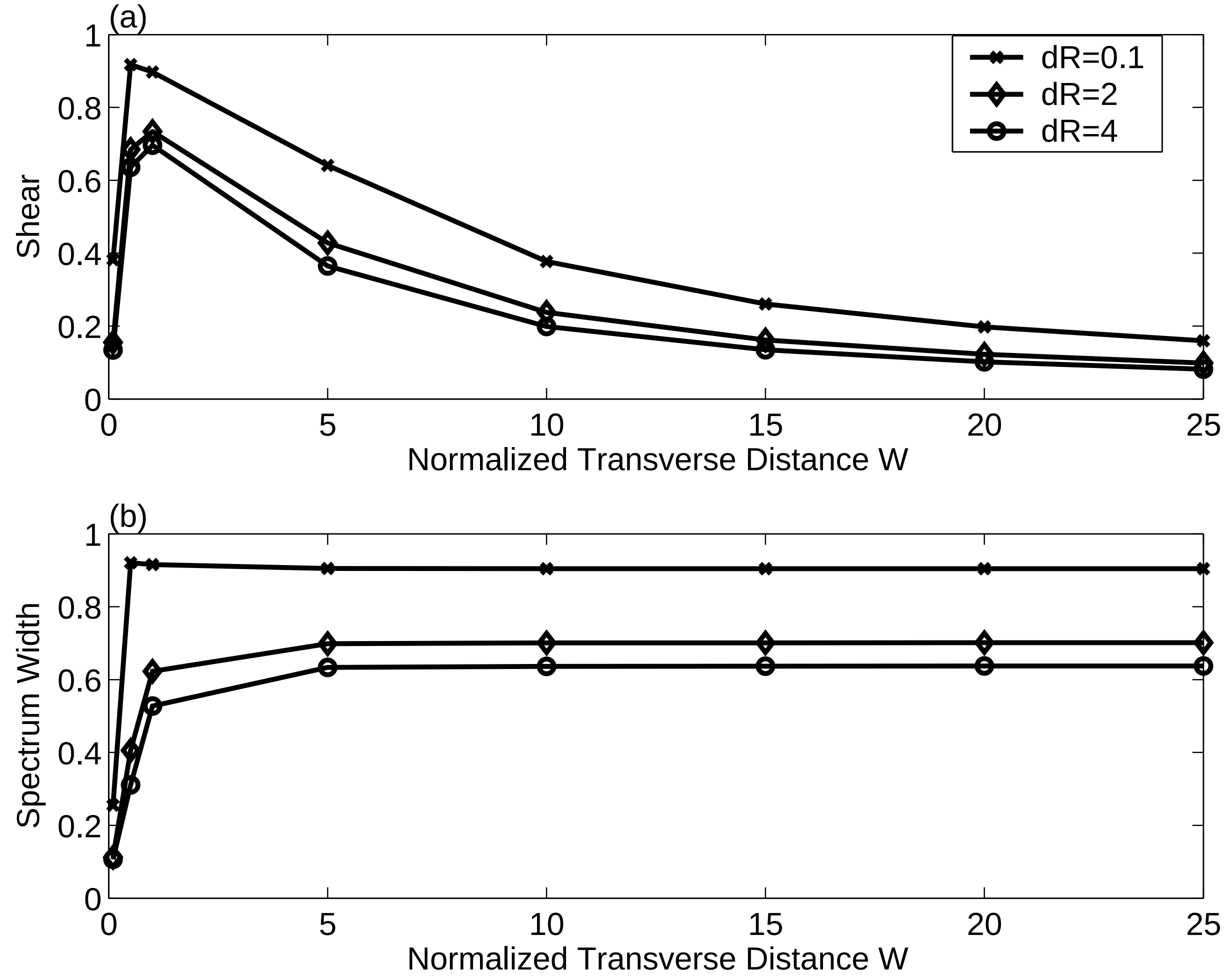

Figure 2: Deterioration of (a) Azimuthal shear, and (b) spectral width as a function of normalized transverse dimension of the radar beam W. Note that W is proportional to range given r_t and radar beamwidth.

investigation.

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