Wind Speeds in Two Tornadic Storms and a Tornado, Deduced from Doppler Spectra

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ABSTRACT

Doppler spectra of a tornado were collected with a radar having a large unambiguous velocity range, ± 91 m s^{-1}. Thus for the first time a presentation of nonaliased spectra was possible, showing direct measurement of radial velocities. By fitting the tornado model spectrum to data, the radius of maximum winds and tornado center location are deduced. Tornado spectral signature is defined as a double peak, symmetric with respect to the mean wind spectrum. Histograms of maximum measured wind speeds (from spectrum skirts) for two tornadic storms are obtained, and the histograms of velocity difference (between the left and right spectrum skirt) suggest that smaller scale turbulence (<500 m) is principally responsible for spectrum broadness.

1. Introduction

Maximum velocities that tornadoes generate have intrigued researchers from the very beginning of tornado studies. In recent years, the increased interest in assessment of tornado speeds has been spurred by the U.S. Nuclear Regulatory Commission and the Department of Energy largely because of a need for information relative to nuclear power station safety. A survey report by Golden[1] contains a table with photogrammetrically-derived maximum wind speeds for 33 tornadoes that occurred within the last 25 years. Typical maxima are of the order of 70–110 m s^{-1} with a mean value equal to 85 m s^{-1} and standard deviation of 38 m s^{-1}. Remote detection and tornado speed measurement with radar were first attempted by Smith and Holmes (1961) who used a continuous waveform (CW) Doppler radar. They show a velocity of 90 m s^{-1}.

It was not until the early 1970's that a successful systematic detection of tornadoes with a pulse Doppler radar was accomplished at the National Severe Storms Laboratory (NSSL). Tornado vortex signature (TVS) (Brown *et al.*, 1978), defined as a localized large shear with vertical continuity, is believed to be one characteristic identifiable feature. Here we define another feature, the tornado spectral signature (TSS) which is a broad bimodal spectrum measured by a Doppler radar. Estimate of maximum wind speeds from Doppler spectra is very attractive because it is done remotely and it presents velocities throughout the funnel cloud. Still there are a few drawbacks of which one should be aware when utilizing Doppler spectra: 1) only the radial velocity component can be measured, and 2) tracers, be it debris, precipitation or refractive index fluctuations, need to be present. Those tracers that follow maximum wind speeds may be such weak scatterers as to be totally obscured in the spectrum by noise or other signals and processing effects.

Zrnić *et al.* (1977) inferred indirectly from aliased spectra, maximum speeds between 85 and 92 m s^{-1} in two tornadoes; the unambiguous velocity interval of ± 34 m s^{-1} was totally filled with a bimodal tornado spectral signature, and the maximum velocity was estimated by fitting a folded model spectrum to data. For the purpose of high speed measurements and in order to remove the inherent uncertainty, a second transmitter at NSSL in Norman with a large unambiguous velocity interval, ± 91 m s^{-1}, was instrumented and sporadic data collection began in 1975. Pertinent characteristics of the modified high pulse repetition frequency (prf) system are listed in Table 1.

In this article we report direct observations (i.e., on spectral peaks and skirts) of velocities in a tornadic storm that was probed by the high prf system. From the tornado spectra the maximum velocity is determined. The position of a tornado within the radar resolution volume is deduced together with its radius by fitting the model (Zrnić and Doviak, 1975) to the data.

2. Data reduction

Digital radar samples were recorded and Fourier analyzed. A von Hann weight (raised cosine) was applied to data prior to a 128-point discrete Fourier

[1] A report on "Assessment of Wind Speeds in Tornadoes" by J. H. Golden, 1976. *Proceedings of the Symposium on Tornadoes*, June 1976, Texas Tech University, Lubbock, 5–42.

TABLE 1. Parameters of the high prf system.

Parameter	Value
Antenna	
Half power beamwidth	0.81°
Gain	46.8 dB
First side lobe level	21 dB
Transmitter	
Wavelength	10.52 cm
Pulse repetition time	288 μs
Pulse width	0.3 μs
Peak power	200 kW
Receiver	
Bandwidth 3 dB; 6 dB	0.45 MHz; 0.63 MHz
Minimum detectable signal (SNR = 1)	−111 dBm
General features	
Maximum unambiguous range	43 km
Maximum unambiguous velocity	±91 m s^{-1}

transform. This weight offers a good compromise between the width of spectral main peak and the size of sidelobes. Specifically, the rapid sidelobe decay reduces contamination of high velocity peaks by strong low velocity components.

In order to locate spectra (on tape) with high velocities, an adaptive algorithm to search for maximum velocities was developed. The algorithm starts by finding the noise level in each spectrum. This is accomplished from averages of spectral powers starting at the positive and negative extremes (i.e., Nyquist velocities). It is assumed that the signal power does not extend that far. Powers are adaptively averaged, i.e., after an average of 4 is calculated, the algorithm compares the level of the next three coefficients with the average. If two out of the three spectral powers exceed the average by more than 2.5 times, these coefficients are declared not to be noise. If the level is not exceeded, a five-point average of noise is made and comparison with the next three spectral points continues. The probability that noise alone will exceed the 2.5 threshold is only 0.019. In this manner, two noise estimates are generated: the left and right estimates; those two are averaged to give a unique noise level estimate.

Calculation of the maximum left (from the spectrum peak) and right velocities proceeds from the mean velocity of the signal spectrum. A three-point running average of the spectrum is taken to the left and right from the mean. When the three-point average drops below the level that is 2.5 times above the calculated noise, a maximum left or right velocity is declared. The rationale behind this method is to advantageously use the continuity of the main spectrum shape and to hopefully screen the spurious peaks.

The described automated procedure is capable of estimating the noise level and maximum velocities for most cases. However, there are times when the algorithm is erroneous; for instance, when a spectral peak is situated right at the maximum unambiguous velocity. Hopefully, such situations are rare. Because spectra with high velocities are grouped together, even if some of them are missed, chances are the other nearby spectra will be detected. Then it suffices to examine manually spectra from adjacent range and azimuth locations. This methodology was successfully used on data from two tornadic storms.

3. Maximum measured velocities

The Waurika storm occurred in late afternoon on 30 May 1976, ~130 km south-southwest of Norman.[2] A mesocyclone was identified in real time on a multimoment display (Burgess *et al.*, 1976), and data collection began. Intermittently low and high prf data were collected. We focused our attention only to 11 664 high prf spectra from data collected in a mesocyclone during a 3 min interval. Data were collected in a scan sequence over elevation angles spaced 0.5°; the range extent was 3 km and azimuthal distance 14 km. Radial separation in azimuth was 1°, and range gates were spaced 300 m apart. Histograms of maximum measured velocities (Fig. 1) show mean left velocity of −34 m s^{-1} with standard deviation (SD) of 13 m s^{-1}, mean right velocity of 22 m s^{-1}, SD of 14 m s^{-1} and a mean difference between the two velocities of 56 m s^{-1}, SD = 21 m s^{-1}. Note that there are almost no velocities above 50 m s^{-1} or below −65 m s^{-1}. The few cases of indicated very high velocities were individually examined, together with spectra from adjacent spacial locations. Those spectra and others throughout the mesocyclone did not reveal characteristics we would associate with a tornadic vortex. A short-lived tornado descended during the time of low prf data collection. It is not known whether tornado size vortices existed aloft during the time of high prf data, but even if they did, detection would have been very hard among the broad spectra due to coarse azimuthal sampling and poor resolution.

The Del City storm provided good spectral data for the analysis. It occurred early Friday evening, 20 May 1977.[3] All morning indications were that a major tornado outbreak was imminent for most of Oklahoma and portions of northern Texas. The 0600 CST rawinsonde data from throughout the region revealed an extremely unstable air mass (lifted index of −6) and strong vertical wind shears (4

[2] Synoptic situation and description of data collection for this day can be found in "Spring Program 76" by Alberty *et al.*, NOAA Tech. Memo. ERL-NSSL-83.

[3] Detailed "1977 Spring Program Summary" by Peter Ray and John Weaver is available as NOAA Tech. Memo. ERL-NSSL-84.

$\times 10^{-3}$ s^{-1} at Oklahoma City). Southeasterly, low-level flow continued to bring warm, moist air into southwestern Oklahoma and northern Texas. A major short wave, approaching from the southwest, reached Western Oklahoma by early afternoon.

By 1830 CST low-level, warm, moist air was present throughout most of Oklahoma accompanied with strong vertical wind shear. The wind veered from southeast at the surface to west-southwest (50 m s^{-1}) at 200 mb. Above 650 mb the air was dry. Throughout the day strong activity was occurring along an advancing forward left portion of a 200 mb jet stream. This combination of low-

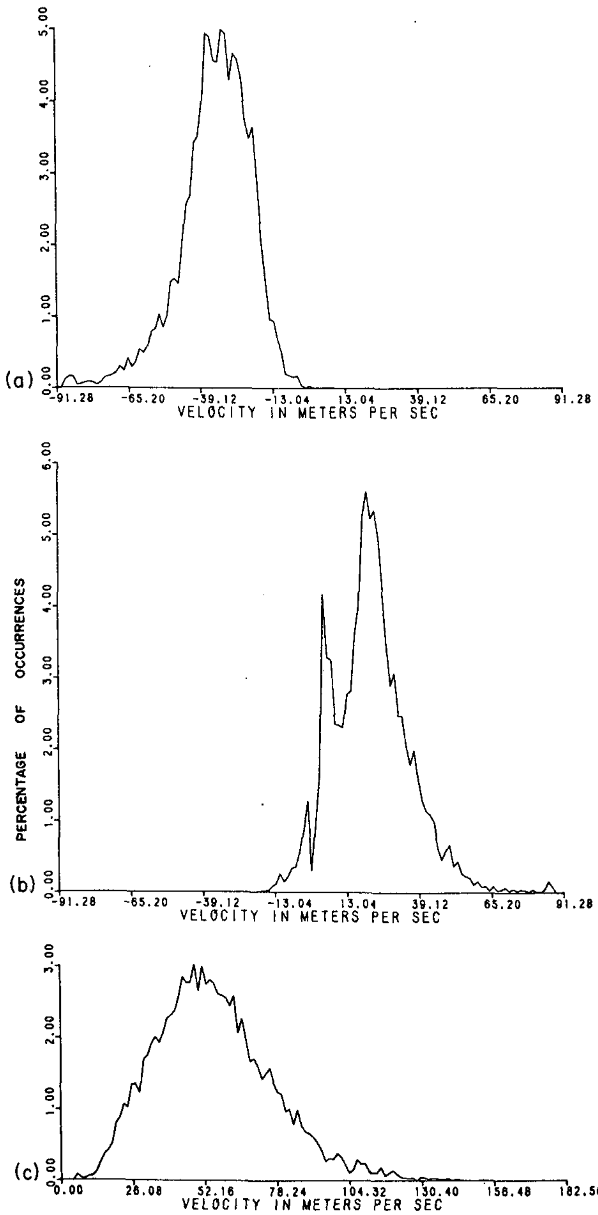


FIG. 1. Histograms of maximum measured velocities from the Waurika storm, category width −1.5 m s^{-1}: a) maximum left velocities, mean = −34 m s^{-1}, SD = 13 m s^{-1}; b) maximum right velocities, mean = 22 m s^{-1}, SD = 14 m s^{-1}; c) differences between right and left velocities, mean = 56 m s^{-1}, SD = 21 m s^{-1}.

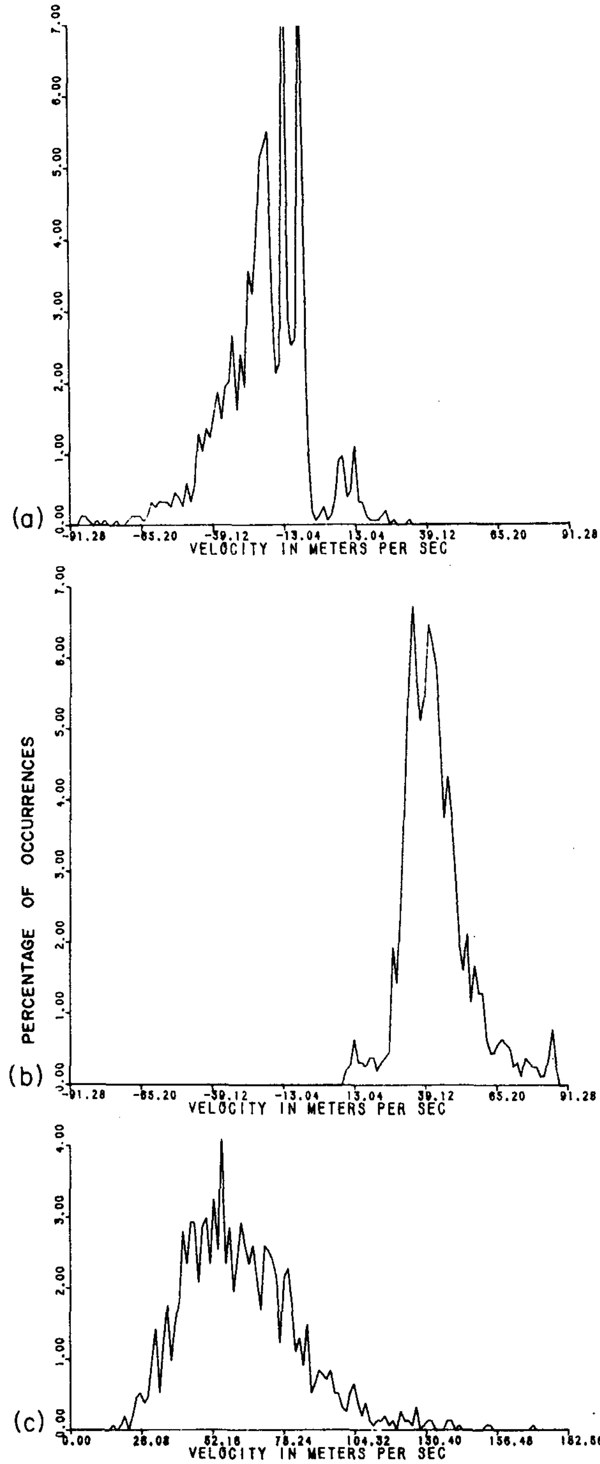
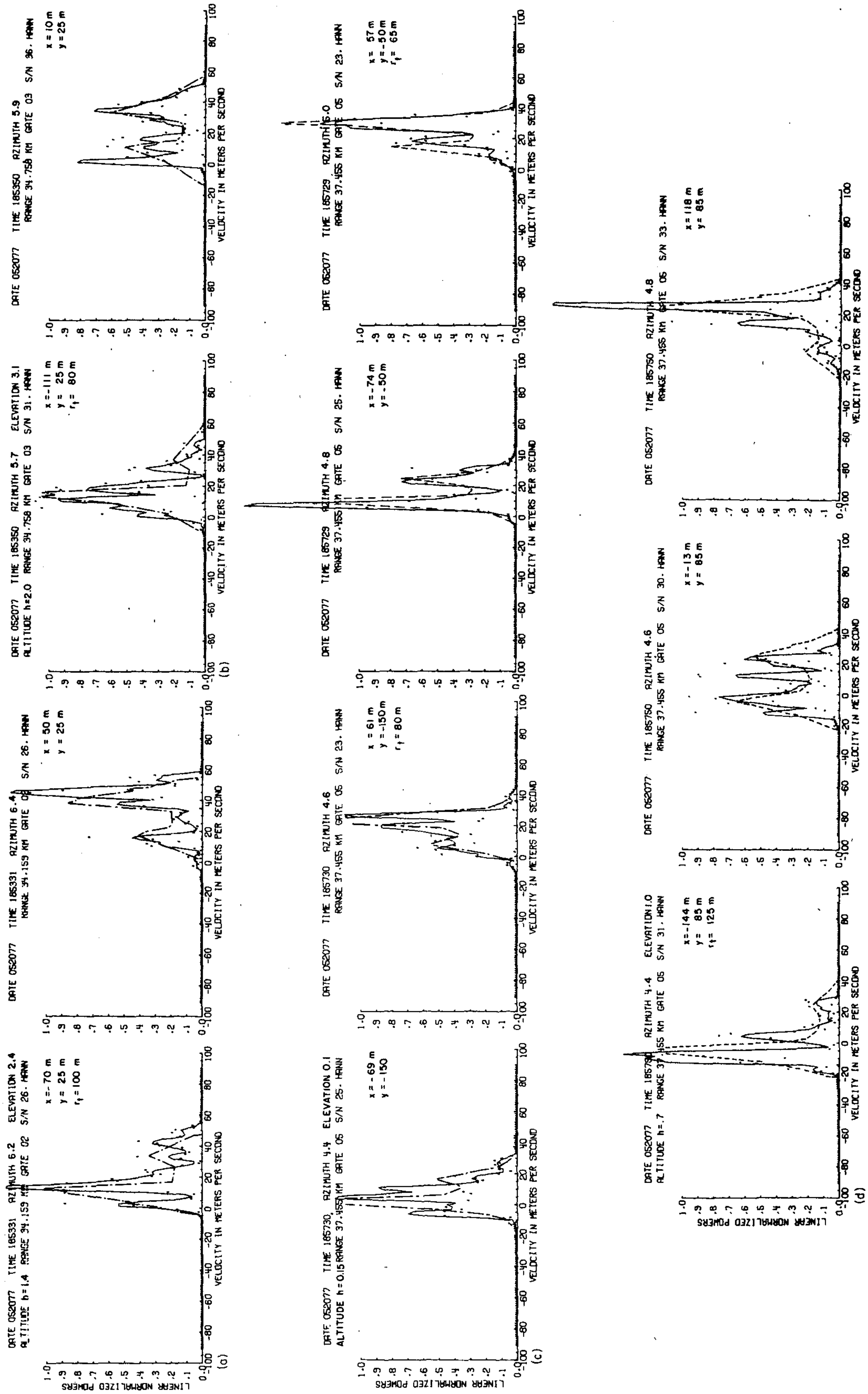


FIG. 2. Histograms from the Del City storm: a) left velocities, mean = −20 m s^{-1}, SD = 12 m s^{-1}; b) right velocities, mean = 42 m s^{-1}, SD = 15 m s^{-1}; c) difference right-left velocities, mean = 62 m s^{-1}, SD = 21 m s^{-1}.


DATE 052077 TIME 185331 AZIMUTH 6.2 ELEVATION 2.4
ALTITUDE h=1.4 RANGE 34.159 KM GATE 02 S/N 26. HANN
x = -70 m
y = 25 m
r_t = 100 m
DATE 052077 TIME 185331 AZIMUTH 6.4 GATE 02 S/N 26. HANN
RANGE 34.159 KM
x = 50 m
y = 25 m
DATE 052077 TIME 185350 AZIMUTH 5.7 ELEVATION 3.1
ALTITUDE h=2.0 RANGE 34.758 KM GATE 03 S/N 31. HANN
x = -111 m
y = 25 m
r_t = 80 m
DATE 052077 TIME 185350 AZIMUTH 5.9
RANGE 34.758 KM GATE 03 S/N 36. HANN
x = 10 m
y = 25 m
DATE 052077 TIME 185730 AZIMUTH 4.4 ELEVATION 0.1
ALTITUDE h=0.15 RANGE 37.455 KM GATE 05 S/N 25. HANN
x = -69 m
y = -150
DATE 052077 TIME 185730 AZIMUTH 4.6
RANGE 37.455 KM GATE 05 S/N 23. HANN
x = 61 m
y = -150 m
r_t = 80 m
DATE 052077 TIME 185729 AZIMUTH 4.8
RANGE 37.455 KM GATE 05 S/N 25. HANN
x = -74 m
y = -50 m
DATE 052077 TIME 185729 AZIMUTH 5.0
RANGE 37.455 KM GATE 05 S/N 23. HANN
x = 57 m
y = -50 m
r_t = 65 m
DATE 052077 TIME 185750 AZIMUTH 4.4 ELEVATION 1.0
ALTITUDE h=.7 RANGE 37.455 KM GATE 05 S/N 31. HANN
x = -144 m
y = 85 m
r_t = 125 m
DATE 052077 TIME 185750 AZIMUTH 4.6
RANGE 37.455 KM GATE 05 S/N 30. HANN
x = -13 m
y = 85 m
DATE 052077 TIME 185750 AZIMUTH 4.8
RANGE 37.455 KM GATE 05 S/N 33. HANN
x = 118 m
y = 85 m
LINEAR NORMALIZED POWERS
VELOCITY IN METERS PER SECOND
(a)
(b)
(c)
(d)

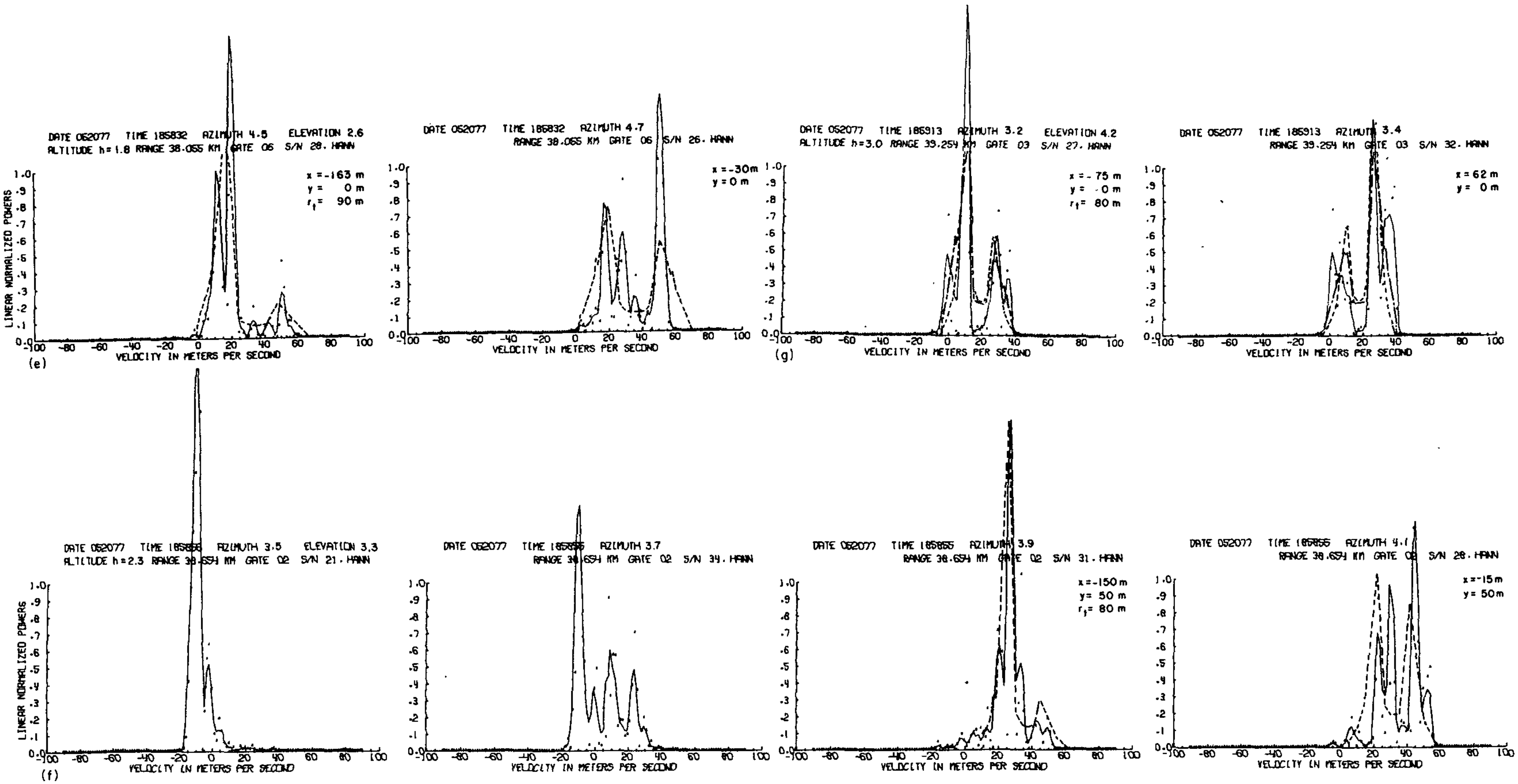


FIG. 3. Doppler spectra of the Del City tornado. Dots are magnitudes squared of Fourier coefficients for time series that were weighted with a von Hann window. Solid lines are three-point running averages. Dash-dot lines are best fit model spectra with uniform reflectivity *while the dash lines are for a donut of Gaussian-shaped reflectivity*. The signal-to-noise ratio is in dB, and x (azimuthal distance) and y (range distance) are coordinates of the tornado center with respect to the resolution volume center; r_t is the radius of maximum wind and the altitude (height) h is to beam center from the ground level in kilometers. On c) and f) are spectra that could have been produced by more than one vortex and/or point targets. On c), two vortices were fitted, but the one at az = 4.8° and 5.0° seems to have a more pronounced characteristic double peak; a peak appears on all four azimuths at about 20 m s^{-1} and perhaps is due to a point target. Spectrum on d) az = 4.6° indicates the vortex is almost centered on the beam axis. Best fitted model spectra for both the uniform and donut reflectivity are illustrated on g). (The indicated elevation angle is few tenths of a degree too high.)

level moisture, mid and upper-level dryness, strong wind shear and the upper level 50 m s^{-1} jet stream contributed to the formation of several tornadic storms. A strong mesocyclone cell developed south of Oklahoma City which produced two tornadoes.

Histograms of maximum measured velocities from the Del City storm (20 May 1977, at 34 km north of Norman) are similar in shape and value to those from the Waurika storm in spite of the fact that the former was 3.5 times closer to the radar. Data were collected during a 5 min interval when a tornado had formed. The volume from which data are examined extends 3° in elevation; spectra are from radials spaced 1° in elevation, 0.2° in azimuth encompassing a sector of 6.6°, and extending in range for 3.6 km. Range gate spacing is 600 m. The more rugged shape of those histograms (Fig. 2) is due to a much smaller number of points (1614 spectra only). Mean values for the left and right velocities are −20 and 42 m s^{-1}; their standard deviations are 15 and 13 m s^{-1}, respectively (Fig. 2a, 2b). The difference between two velocity extremes has a mean of 62 m s^{-1} and SD of 21 m s^{-1} (Fig. 2c). The mean values of maximum measured velocities for the two storms differ mainly due to their different relative motion with respect to the radar. It is significant that the maximum velocity differences, which are a measure of spectral width, are very close. Somewhat lower differences for the more distant (Waurika) storm can be attributed to masking of weaker spectral skirts by noise. Since on the average the spectral widths are about the same for the case when the beam is 1.8 km wide as when the beam is 0.5 km wide, motions on the scales less than 0.5 km must in large part contribute to the spectral breadth. This conclusion is based upon the assumption that the contribution from turbulence of scales less than 500 m is dominant and identical in both cases. Similar findings based on histograms of spectrum widths from three storms were reported by Doviak *et al.* (1978).

4. Tornado spectra

Over a hundred spectra from the Del City storm were individually examined in order to find the tornado spectral signature. In all seven scans the tornado signature was identified. Spectra from two, three or four adjacent azimuthal locations where the signature was found are presented on Figs. 3a–3g. For example, when the antenna beam is not centered on the vortex the signature is as on 3a, while the second spectrum on 3b illustrates the case of centered beam. Superimposed on those figures are the best fitted model spectra. The model and the least squares fit are discussed in Zrnić and Doviak (1975) and Zrnić *et al.* (1977). The only modification in the present version is the weighting of the resolution volume in range, which is now Gaussian, to account for the transmitted pulse receiver filter effect (Zrnić and Doviak, 1978; Doviak and Zrnić, 1979). However, this change did not alter significantly the spectral shapes generated by the model. Both three-point running average and raw spectral points were fitted with occasional differences in the final result. The parameters deduced from the smoothed spectra had a better self-consistency; hence, those are reported here. Uniform and donut-type reflectivity profiles were tried. The reflectivity of the donut profile is a function of vortex radius only and in our case an offset (from tornado center) Gaussian curve is used to control the position and shape of reflectivity maximum (Zrnić and Doviak, 1975). More often the donut profile resulted in somewhat better fit. This is to be expected because the two "degrees of freedom" (position and width) allowed easier adaptation of reflectivity to nonuniformities caused by debris. Further support for such hypothesis comes from the fact that model spectra with donut reflectivity match better the data at lower altitudes (Figs. 3d and 3e). On our Fig. 3, the fitted model is for a profile that resulted in a better fit. To illustrate the small difference between the two profiles, both model spectra (uniform and a donut-shaped reflectivity) are shown in Fig. 3g.

Most often double peaks are present, but occasionally there are multiple peaks (Figs. 3a, 3d–f). Those are probably due to debris and point targets. It is doubtful that any more conclusions can be drawn about the funnel reflectivity structure because of the inherent limited resolution of the radar system.

Tornado location determined from the spectral fit is superimposed on the damage path obtained by survey teams (Fig. 4). Also on the figure are maximum measured velocities V_m, maximum rotational (tangential) velocities V_t and heights of the scans above ground. The velocities were obtained from points where smoothed spectra reach the noise level. Estimated radii of wind maxima range from 65 to 125 m; these are deduced from the model and drawn to scale on Fig. 4. The area between I-35 and the railroad tracks was not surveyed since it was not easily accessible to ground crews. Along the county road the damage stopped at Oakdale School, and the path was picked up NW from there.

The path deduced from Doppler spectra shows a gradual curving. It seems likely that the vortex responsible for the wide damage path weakened and lifted, but it is not clear if it touched down again or if a new one formed. The relative positions of the tornado with respect to the isodops of the mesocyclone are shown on Fig. 5. We note on Figs. 5a–5d how the tornado rotates cyclonically around the center of the parent circulation. This observation is similar to the one made by Ray *et al.* (1976). A photograph of the tornado taken a few minutes before the times of our observations contained multiple vortices. However, the spectral data concerning multiple vortices are inconclusive. Spectra on Figs. 3c and 3f could have originated from more than one vortex, yet we cannot rule out small-scale eddies and point targets in the mesocyclone.

We emphasize that the observed Del City tornado produced no more damage than F2.[4] Corresponding maximum rotational winds deduced from Doppler spectra were 35 m s^{-1}. With added storm motion the peak winds on the east side were no more than 65 m s^{-1}. Those are deduced from logarithmic plots of spectra (Fig. 6) obtained from windowed (von Hann) data. In this example, the sharp drop at 65 m s^{-1} (i.e., at the maximum velocity) is evident and agrees well with model predictions (Zrnić and Doviak, 1975). While higher wind speeds could not be ruled out on the basis of spectral measurements, the damage survey indicates that our values are quite realistic. The deduced radius of maximum winds (65–125 m) is much less certain because it relies heavily on the model. Nonuniformities in reflectivity, tilting of the vortex and variations with height, and targets in sidelobes are just a few effects that occur but cannot be accounted for.

Accuracy of measured velocities approximately equals the Doppler spectrum resolution which is 1.5 m s^{-1}. The pointing error of antenna beam is less than 0.1° which translates to about 50 m at the tornado location. Errors in slant range are quite small (<30 m), but the relative error (i.e., position of the tornado within the gate) could be 100 m. Errors in deduced radii of maximum winds are difficult to assess; however, the inferred radii between 65 and 125 m are plausible considering that the damage path width is between 200 and 500 m. A check for consistency was made by assuming that F0 (>18 m s^{-1}) and higher winds caused the damage. Then a 100 m assumed radius combined with measured maximum velocities and a Rankine profile resulted in a path width of about 500 m which is confirmed by the survey team in the first part of the path (Fig. 4). To illustrate the sensitivity of deduced radii, we present on Fig. 7 the rms differences of spectrum data (normalized powers) and the model spectrum versus the maximum wind radius for the case of Fig. 3g.

Because increased width of the Doppler spectrum can be an indicator of vortices in the resolution volume (Zrnić *et al.*, 1977), we have calculated widths from the periodograms at contiguous azimuthal and range locations. In every case local maxima of width occurred at the resolution volumes where a tornado was located. Those maxima ranged from 12 to 15 m s^{-1}. To illustrate the point, contours of width are drawn on Figs. 8a, 8b. At the lower elevation (2.4°, Fig. 8a) four regions of large widths (>12 m s^{-1}) are present. Only one contained the tornado vortex (indicated with T). Shear

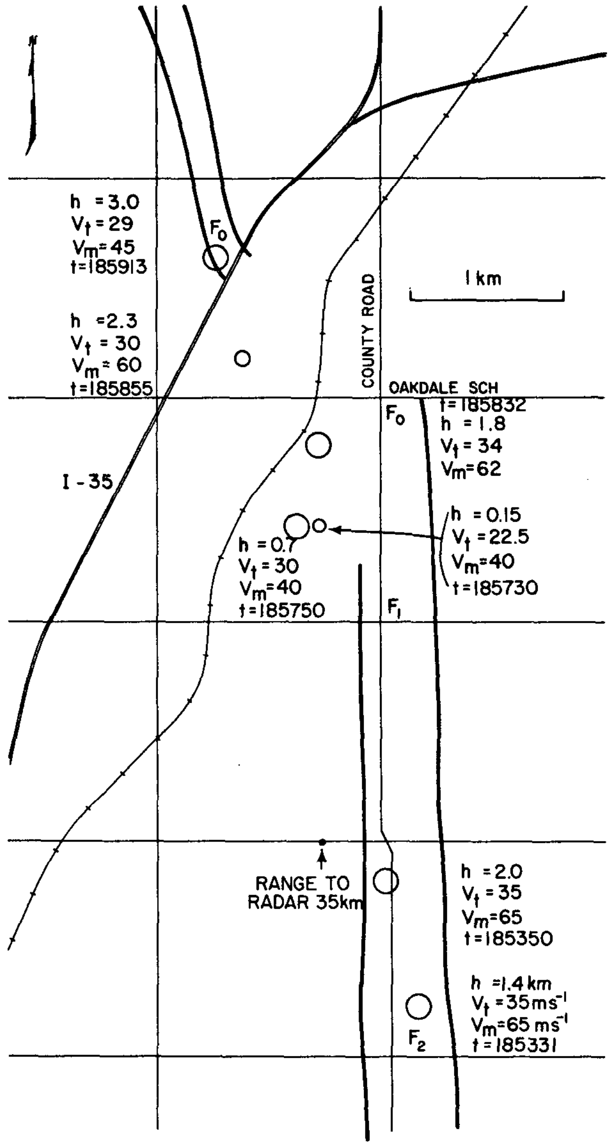
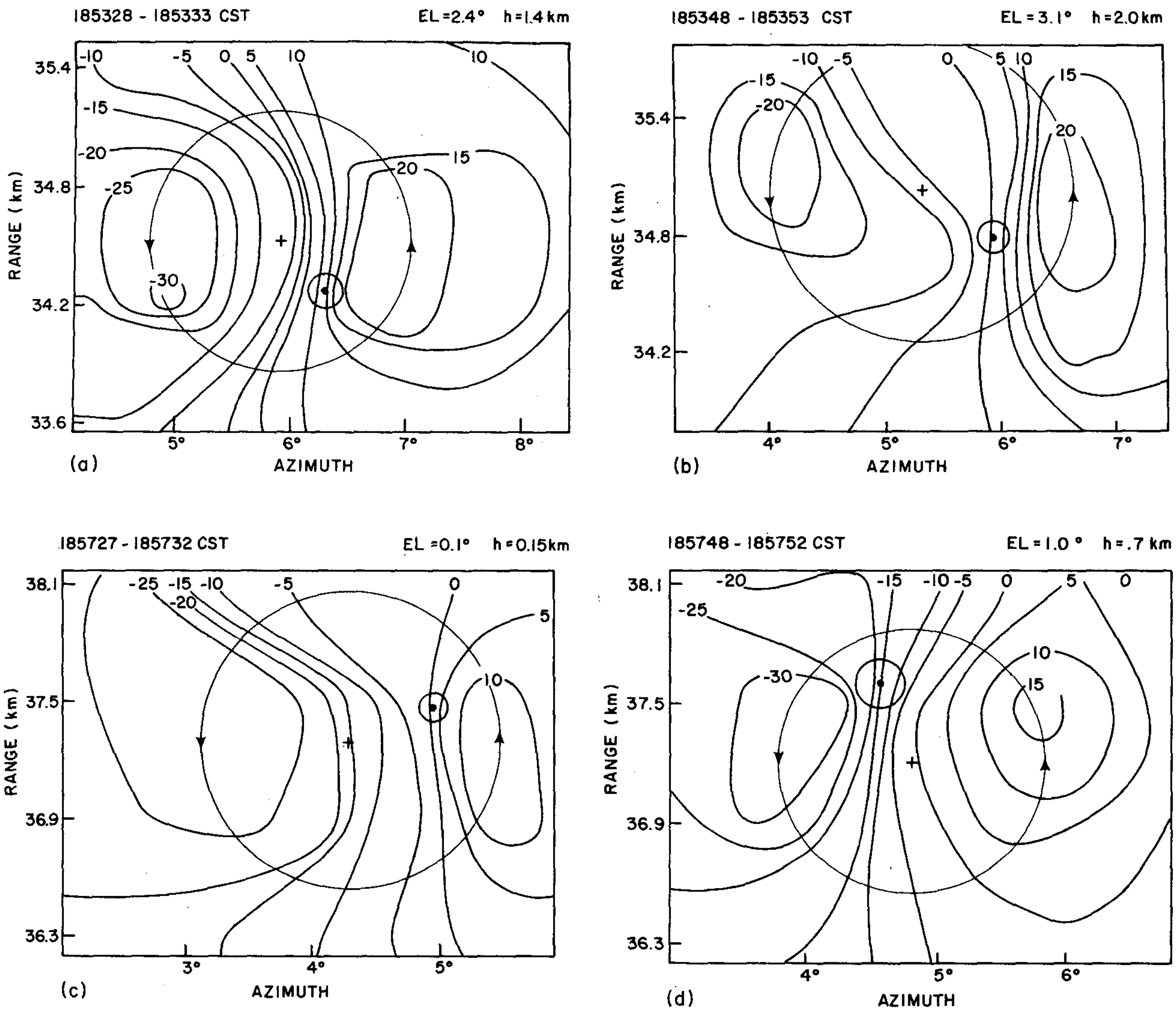


FIG. 4. Tornado position (circles drawn to scale) as deduced from the Doppler spectra is superimposed onto the damage path. Height (km) of beam center with respect to ground is h, V_t is the rotational speed (m s^{-1}) while V_m is the measured maximum speed which includes storm motion. The damage scale is according to Fujita. County roads (square grid) are 1.6 km (1 mi) apart.

[4] Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. Satellite Mesometeor. Res. Proj., Res. Pap. No. 91, Dept. Geophys. Sci., University of Chicago, 44 pp.



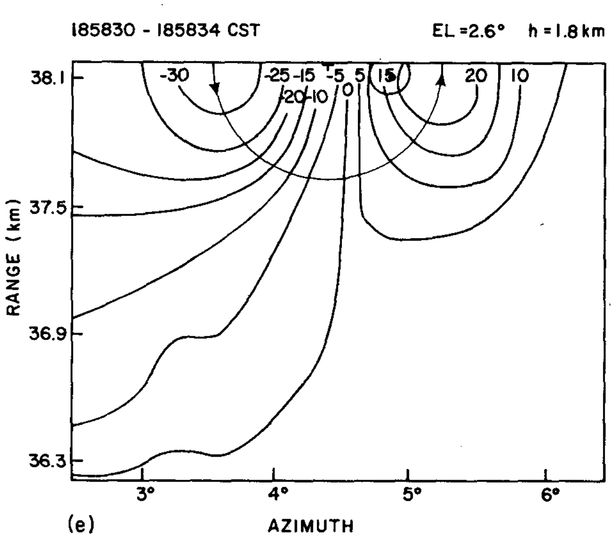


FIG. 5. Positions of the tornado (circles drawn to scale) with respect to the mesocyclone signature. Contours are drawn from data spaced 0.6 km in range and 0.2° in azimuth. Mean radial motion of the mesocyclone is removed. The notation and times correspond to the ones in Figs. 3 and 4.

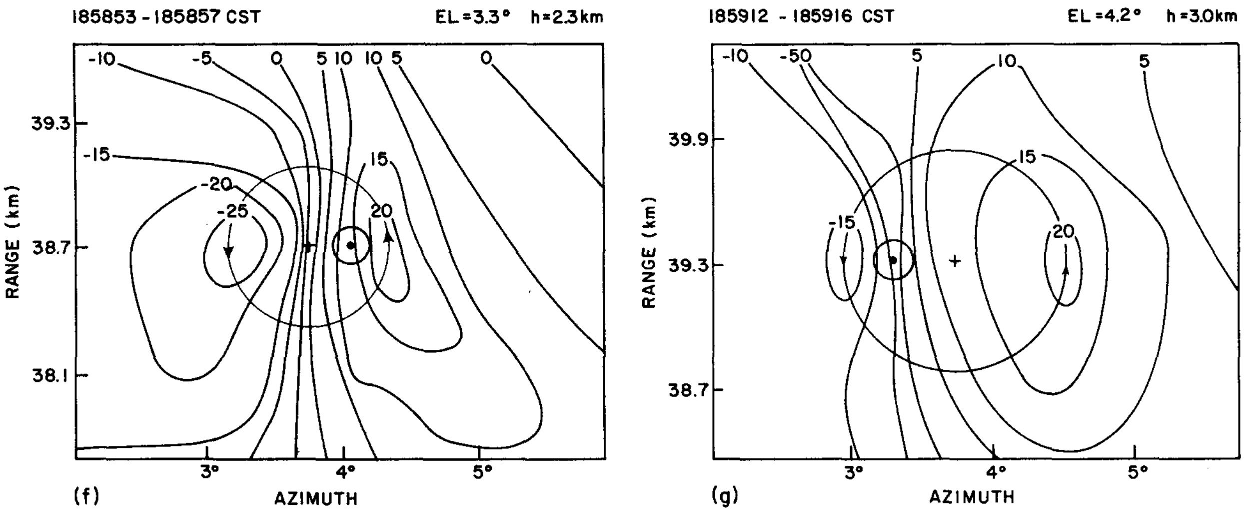


FIG. 5. (*Continued*)

and shear generated turbulence in the spiraling inflow at lower levels may have created those other large widths.[5] At higher elevation angles (4.2°, Fig. 8b) only the tornado region contained maxima greater than 12 m s^{-1}. Consequently, we conclude that large width is a necessary attribute of the vortex in a resolution volume. But by itself broad spectra are not a sufficient condition to ascertain the presence of tornadoes since other phenomena cannot be excluded.

5. Summary and conclusions

Maximum velocities are estimated from spectral skirts on data of two tornadic storms. Analysis of spectra is focused to a small volume containing the mesocyclone. Although one storm was only 34 km from the radar and the other 124 km, the histograms of maximum velocities and maximum velocity differences are quite similar in both storms. Mean magnitudes of maximum velocity range from 20 m s^{-1} to 43 m s^{-1} while the mean difference is 61 m s^{-1} for the closer storm and 55 m s^{-1} for the more distant one. The latter finding suggests non-isotropic turbulence and eddies on scale size less than 500 m to be the dominant spectrum broadening mechanisms.

The large unambiguous velocity range of ±91 m s^{-1} revealed for the first time the full extent of spectral broadness and shapes in a mesocyclone. To prevent contamination of high velocity spectral components by stronger powers at lower velocities, data windowing was essential. A simple von Hann window proved to be quite adequate.

[5] The detailed flow structure of this mesocyclone is described by E. A. Brandes in "Tornadic Mesocyclone finestructure and implications for tornadogenesis", *Preprints 11th Conf. Severe Local Storms*, Kansas City, Amer. Meteor. Soc., 549–557.

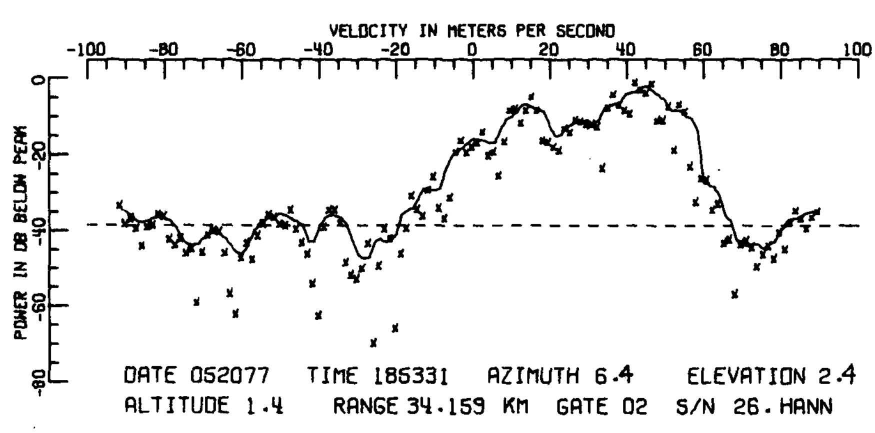


FIG. 6. Plot on a logarithmic scale of a tornado spectrum. This spectrum is the same as on Fig. 3a. Spectral powers are marked with ×'s and a 5-point running average is drawn for visual clarity. The dash line, 40 dB below the spectrum peak, is a noise-level estimate.

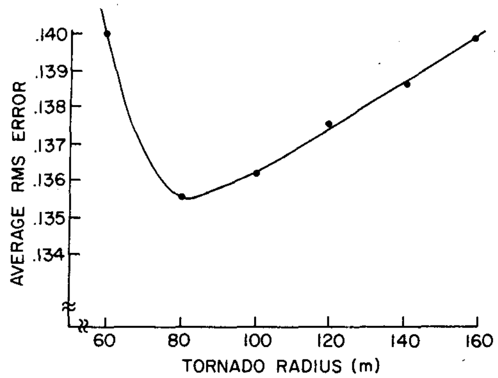


FIG. 7. Behavior of the rms error between fitted spectra and data as a function of tornado radius. A change by a factor of 2 in radius results in less than 3.6% change in error. Because this minimum is broad, spurious effects can easily shift it. Thus the uncertainty in radius could be tens of meters.

Tornado spectral signatures were found in seven scans during the Del City storm. Deduced tornado locations coincided with the path determined from the damage survey. A least-squares fit between smoothed spectra and the model was accomplished in order to estimate the radius of maximum winds and the position within the resolution volume. Obtained values range from 65–125 m and are consistent with the damage path width. The rotational velocities measured from spectral skirts are 35 m s^{-1}; with storm motion superimposed the maximum measured wind speed is 65 m s^{-1}. Light damage on the ground indicates that radar-deduced velocities are realistic. There is evidence of point targets and a hint of multiple vortices in the spectra, but those could not be independently confirmed.

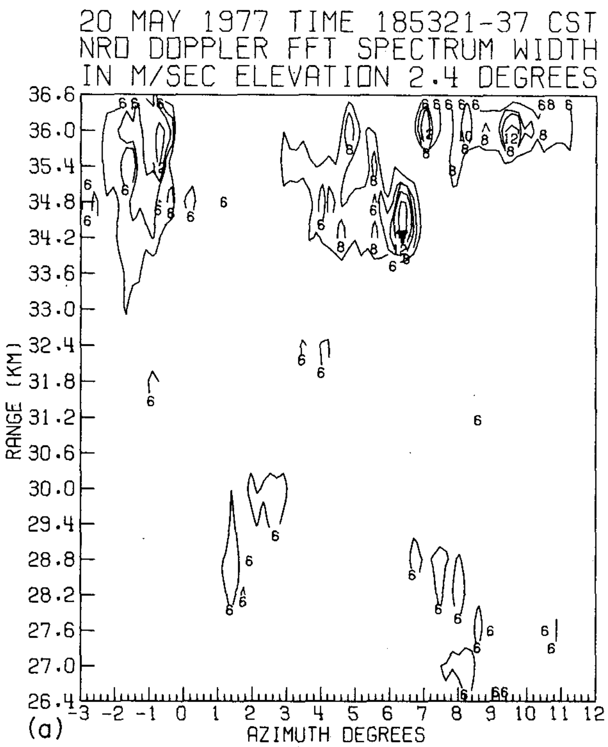


FIG. 8a. Contours of spectrum width for the Del City tornado at 2.4° in elevation. Only values larger than 6 m s^{-1} are presented in steps of 2 m s^{-1}. Tornado location is indicated with T. This figure corresponds to the isodops on Fig. 5a.

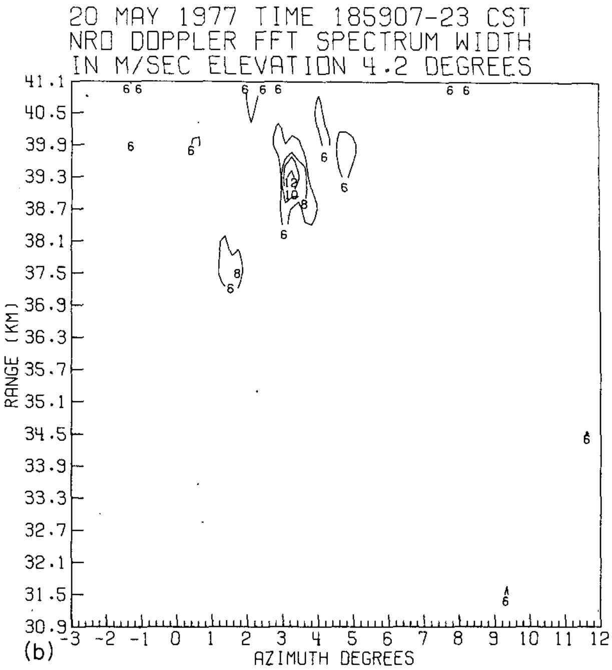


FIG. 8b. As in Fig. 8a but the elevation angle is 4.2°. The tornado is located exactly at a 12 m s^{-1} contour. The isodop field on Fig. 5g corresponds to this width field.

Identification of tornado spectra and measurement of maximum velocities is a complicated task. Data collection must be made on a very densely spaced grid in azimuth and range (one-fourth beamwidth spacing and one pulse depth); also to follow the evolution of a vortex and map trajectories of scatterers and debris, one should collect consecutive spectra from adjacent azimuths and elevations simultaneously. This cannot be done with a mechanical antenna; rather an electronically steerable multibeam radar is called for.

As far as automated data analysis goes, there are too many variables and unknowns; therefore, examination of individual spectra must be made. Perhaps the biggest obstacle to automated maximum velocity measurement is that one needs to rule out all spectral artifacts.

Acknowledgments. The authors appreciate the efforts of NSSL personnel who provided the data. Don Burgess directed our attention to the Waurika storm, and together with Bob Davies-Jones provided damage survey information; Larry Hennington developed the tracking technique and collected Del City storm data; Glen Anderson and Dale Sirmans developed the high prf transmitter, and Bill Bumgarner preprocessed the tapes. Dr. R. J. Doviak reviewed the paper and together with Ed Brandes provided valuable advice; Mickey Tyo and Connie Hall typed the manuscript. Mr. E. S. Gillespie, Jr., from California State University, Northridge, developed the software for histogram calculations. Measurement of tornado velocities is supported at NSSL by the U.S. Nuclear Regulatory Commission under Interagency Agreement AT(49-25)-1004 and U.S. Energy Research and Development Administration, Interagency Agreement E(49-5)-1289. While at California State University, Northridge, Dr. Zrnić was supported by the Atmospheric Research Section, National Science Foundation, under Grant ATM76-22974.

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