Oscillations in Mesocyclone Signatures with Range Owing to Azimuthal Radar Sampling

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ABSTRACT

When a thunderstorm mesocyclone changes range relative to a Doppler radar, the deduced core diameter and mean rotational velocity of the Doppler velocity mesocyclone signature oscillate back and forth, even though the radar beam's physical width changes uniformly with range. The authors investigated the oscillations using a model mesocyclone and a simulated Doppler radar that collected data with an azimuthal sampling interval of 1°. They found that the oscillations are a consequence of changing data point separation with range relative to the Doppler velocity peaks of the mesocyclone signature.

1. Introduction

It is widely recognized that the magnitude of the single-Doppler velocity signature of a thunderstorm vortex (such as a mesocyclone) is dependent on the relationship between the vortex strength and size and the size of the radar sample volume (e.g., Donaldson 1970; Brown et al. 1978). Azimuthal profiles of Doppler velocity through a vortex degrade with range as the nominal diameter of the radar beam (distance between the half-power points) becomes progressively larger compared with the vortex core radius (Brown and Lemon 1976). However, Wood and Brown (1997) showed that varying degrees of degradation also can occur at a fixed range. The amount of degradation depends on the location of the Doppler velocity data points relative to the mesocyclone center. They calculated core diameter and mean rotational velocity for many different placements of the data points relative to the center of a typical mesocyclone. They found that at a given range there was considerable variation in the resulting apparent core diameters and mean rotational velocities depending on the actual locations of the data points.

Besides the variations at a given range, Wood and Brown showed that there are unexpected oscillations in the parameters with range when the radar collects discrete samples at 1° azimuthal intervals. However, they did not elaborate on the cause of the oscillations. The purpose of this note is simply to clarify the reasons for the oscillations. We use simulated nonnoisy radar data to reproduce the basic characteristics of the oscillations. In subsequent papers, we will relate more realistic noisy data to mesocyclone detection and discuss ways in which basic mesocyclone characteristics can be recovered from degraded measurements.

2. Doppler radar simulation

We used the analytical simulation of a WSR-88D (Weather Surveillance Radar-1998 Doppler) developed by Wood and Brown (1997) and a model mesocyclone to produce simulated Doppler velocity measurements. We assume that 1) the tangential velocity distribution across the mesocyclone is, to a good approximation, simulated using an axisymmetric Rankine (1901) combined vortex; 2) the tangential velocity field is uniform with height; 3) reflectivity is uniform across the mesocyclone; 4) the radar beam pattern is Gaussian shaped; 5) the beam axis is quasi-horizontal at 0.5° elevation angle; and 6) the effective beamwidth is 1.29° (broadened from a nominal 0.93° by the rapidly rotating antenna; see Wood and Brown 1997). Radar measurements were derived by scanning the simulated Doppler radar past the model mesocyclone. Doppler velocity values (weighted averages of velocity values distributed across the radar beam) were computed at azimuthal intervals of 1°. Noise was not added to the Doppler velocity values in this simulation because we wanted to investigate the inherent oscillations of core diameters and mean rotational velocities with range.

3. Oscillations of core diameters and mean rotational velocities with range

The width of the radar beam relative to a given-sized mesocyclone affects the sampling resolution. Since the physical width of the beam increases linearly with range

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from the radar, the peak Doppler velocity measurements gradually underestimate the peak rotational velocities of the mesocyclone (e.g., Donaldson 1970; Brown and Lemon 1976). In this section, we investigate how the Doppler velocity measurements change with range as the radar, collecting data at 1° azimuthal intervals, scans past a mesocyclone. We simulated three different situations, where 1) one of the Doppler velocity data points coincides with the mesocyclone center, 2) the mesocyclone center is midway between two Doppler velocity measurements, and 3) the Doppler velocity measurements are randomly positioned relative to the mesocyclone center. The model mesocyclone used in this study had a peak rotational velocity of 25 m s^{-1} and a core diameter of 5 km. The deduced mean rotational velocity is one-half the difference between the extreme positive and negative Doppler velocity values in the mesocyclone signature. The deduced core diameter is the distance between the extreme Doppler velocity values.

a. Doppler velocity measurement coincident with mesocyclone center

Consider first the situation in which one of the Doppler velocity data points coincides with the center of the mesocyclone. With increasing range, one might expect the mean rotational velocity to decrease in a uniform manner and the core diameter to increase in a uniform manner. This type of variation, illustrated by the thin curves in Fig. 1, would be expected to occur if data were collected continuously with no gaps between data points as the radar scanned past the mesocyclone. In reality, WSR-88D data are collected discretely at 1° azimuthal increments. The discrete nature of the data collection produces the thick oscillating curves in Fig. 1. The hypothetical continuous sampling curves represent an upper limit for discretely obtained mean rotational velocity values and an approximate average for discretely obtained core diameter values.

The reasons for the abrupt changes in the discretely sampled data are illustrated in Fig. 2. Shown are azimuthal profiles of Doppler velocity values (black dots) through the mesocyclone at several different ranges from the radar. Between ranges (*R*) of 96 and 106 km, the extreme Doppler velocity values at B and F are separated by four azimuthal intervals, producing the large deduced values of core diameter for the mesocyclone signature (Figs. 1b and 2a,b). Over that range interval, the core diameter increases linearly from 6.7 to 7.4 km. Concurrently, the deduced mean rotational velocity decreases from 18.8 to 17.3 m s^{-1} (Figs. 1a and 2a,b). These changes are produced because data points B and F are moving away from the peaks of the signature, owing to the widening of 1° azimuthal intervals with increasing range.

When the mesocyclone moves from 106 to 107 km (Figs. 2b,c), the extreme Doppler velocity values jump from B and F to C and E. Thus, the number of azimuthal intervals between the extreme negative and positive Doppler velocity data points drops from four to two, yielding a sharp decrease in the size of the deduced core diameter (Fig. 1b). When the range increases from 107 to 117 km, the positions C and E continue to move apart (Figs. 2c,d). The deduced value of mean rotational velocity increases in magnitude beyond 107 km (Fig. 1a) as the extreme negative and positive Doppler velocity data points (C and E) approach the rounded peaks of the measured curve (Fig. 2d). After C and E reach the rounded peaks (that is, where the continuous and discrete curves are coincident in Figs. 1a,b), the extreme negative and positive Doppler velocity data points (not

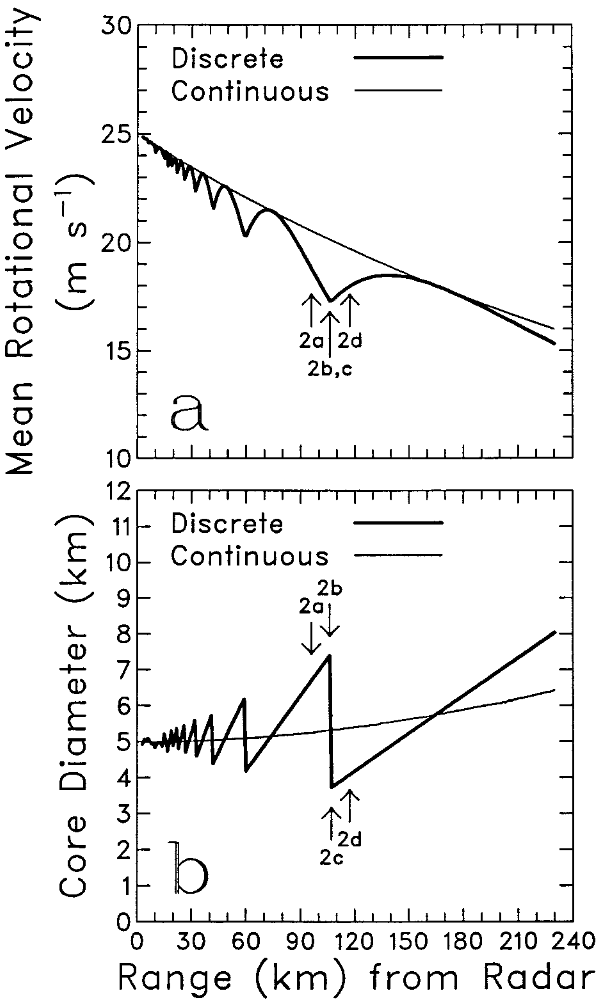

FIG. 1. Variations of (a) deduced mean rotational velocity and (b) deduced core diameter values as a function of range for a simulated mesocyclone having a typical rotational velocity peak of 25 m s^{-1} at a core diameter of 5 km. The thin curves represent the mean rotational velocities and core diameters of the mesocyclone signature if the simulated Doppler radar collected data continuously across the mesocyclone. The thick fluctuating curves represent 1° azimuthal sampling where one of the data points coincides with the mesocyclone center. Labels 2a–2d correspond to Figs. 2a–d, respectively.

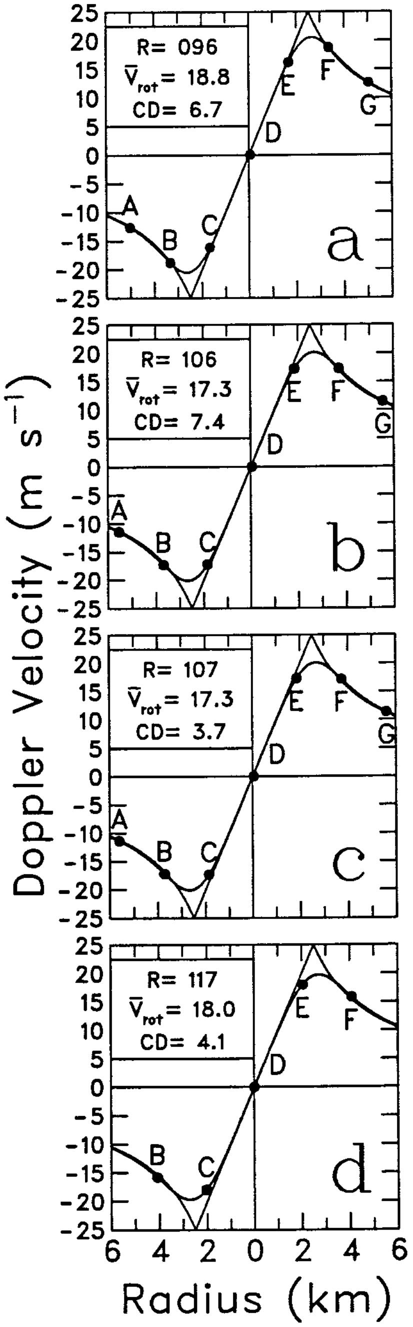

FIG. 2. Relationships of data points relative to the azimuthal profiles through the center of the mesocyclone as a function of range (R in km) when one of the data points (D) coincides with the mesocyclone center. The curve with rounded peaks (along which the data points fall) represents the Doppler velocity azimuthal profile of the mesocyclone signature if the radar were able to make measurements in a continuous manner across the mesocyclone. The curve with pointed peaks represents the Rankine combined velocity model for the mesocyclone having a peak rotational velocity of 25 m s^{-1} at a core diameter of 5 km. Data points at A–G represent the locations of successive Doppler velocity measurements collected at 1° azimuthal intervals as the radar beam scans across the mesocyclone. Deduced mean rotational velocity ($\overline{V}_{\text{rot}}$) in m s^{-1} and core diameter (CD) in km also are indicated.

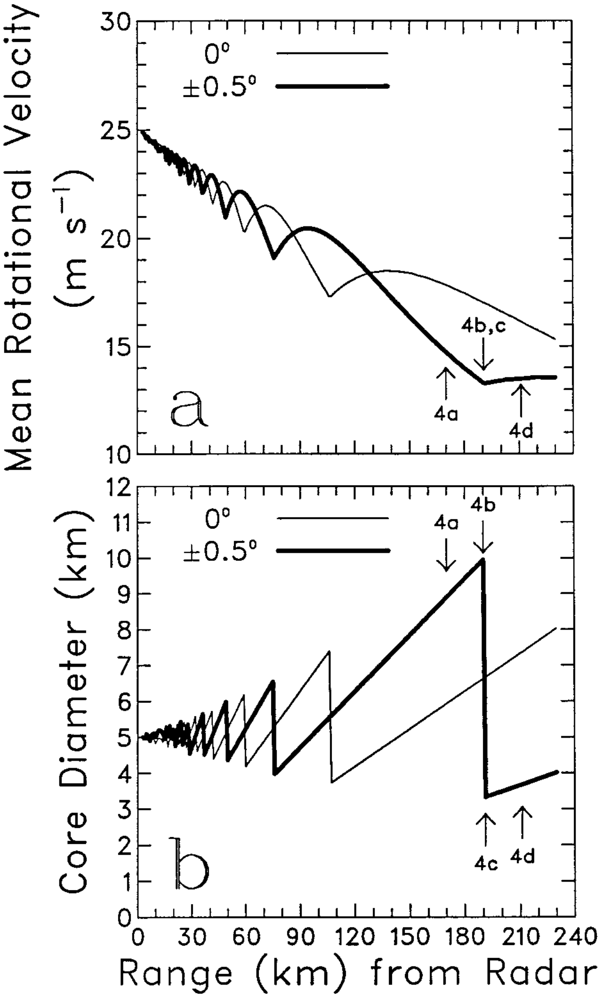

FIG. 3. Variations of (a) deduced mean rotational velocity and (b) deduced core diameter with range. The thin curves are the discrete 0° separation curves from Fig. 1. The thick curves represent variations when the closest data points are equidistant (±0.5°) from the mesocyclone center. Labels 4a–4d correspond to Figs. 4a–d, respectively.

shown) begin to decrease in magnitude. However, the core diameter continues to increase as C and E move farther apart.

b. *Mesocyclone positioned midway between two Doppler velocity measurements*

In the examples shown thus far, the deduced values of mean rotational velocity and core diameter have been computed only when one of the data points coincides with the center of the mesocyclone. When the closest data points are equidistant from the mesocyclone center (azimuthal separation of ±0.5°), the deduced values shown in Fig. 3 (thick curves) undergo oscillations that are offset from the ones with 0° separation (thin curves) that are reproduced from Fig. 1. The explanations for such oscillations are straightforward. When the meso-

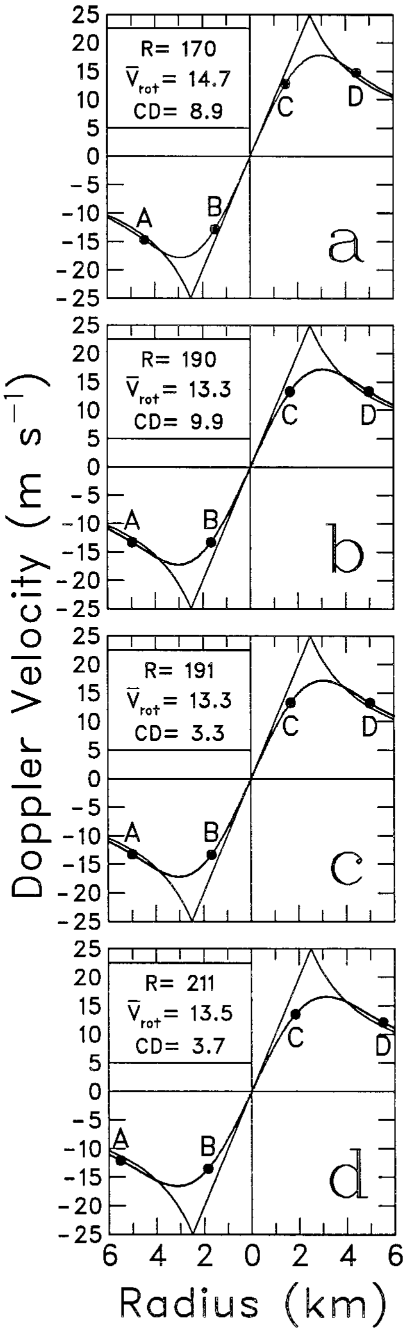

FIG. 4. Same as Fig. 2, except that the mesocyclone is at a farther range and its center is midway between two data points.

cyclone moves from 170 to 190 km (Figs. 4a,b), the extreme negative and positive Doppler velocity data points A and D are located outside the mesocyclone core and are separated by three azimuthal intervals. Between 170 and 190 km, the increasing separation distance causes the mean rotational velocity value to decrease from 14.7 to 13.3 m s^{-1} (Figs. 3a and 4a,b). At the same time, the deduced core diameter increased from 8.9 to 9.9 km (Figs. 3b and 4a,b).

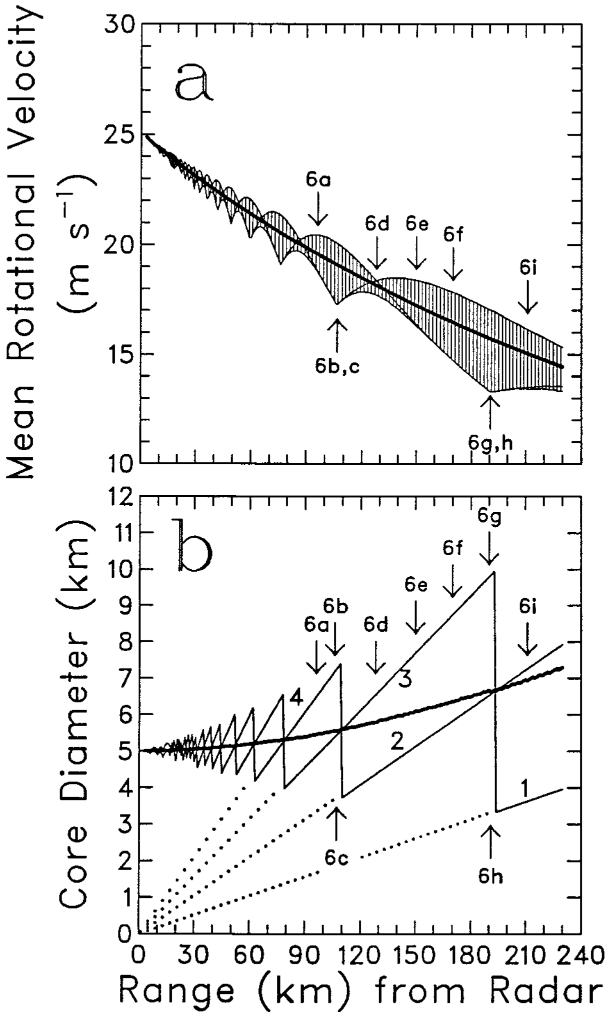

FIG. 5. Variations of (a) deduced mean rotational velocity and (b) deduced core diameter as a function of range. The thick curve in the middle of the data curves represents the average of the values at each range. Shading in (a) represents the full spread of mean rotational velocity values for all possible azimuthal sampling offsets between the data points and mesocyclone center. In (b), the dotted lines radiating from the origin illustrate that the sloping lines (labeled by the number of azimuthal intervals between extreme data point values) represent the linear increase of data point separation with increasing range. Labels 6a–6i correspond to Figs. 6a–i, respectively.

When the mesocyclone moves from 190 to 191 km, the extreme negative and positive Doppler velocity values suddenly change from points A and D to points B and C. Consequently, the number of azimuthal intervals separating the extreme values decreases from three to one (Figs. 3b and 4b,c), producing a deduced core diameter one-third of the previous value. Beyond 191 km, the number of azimuthal intervals between the extreme data points remains at one, no matter how far apart B and C become. Also beyond 191 km, the deduced values of rotational velocity will increase as long as B and C are approaching the peaks of the mesocyclone signature curve (Figs. 3a and 4d). However, after they pass the

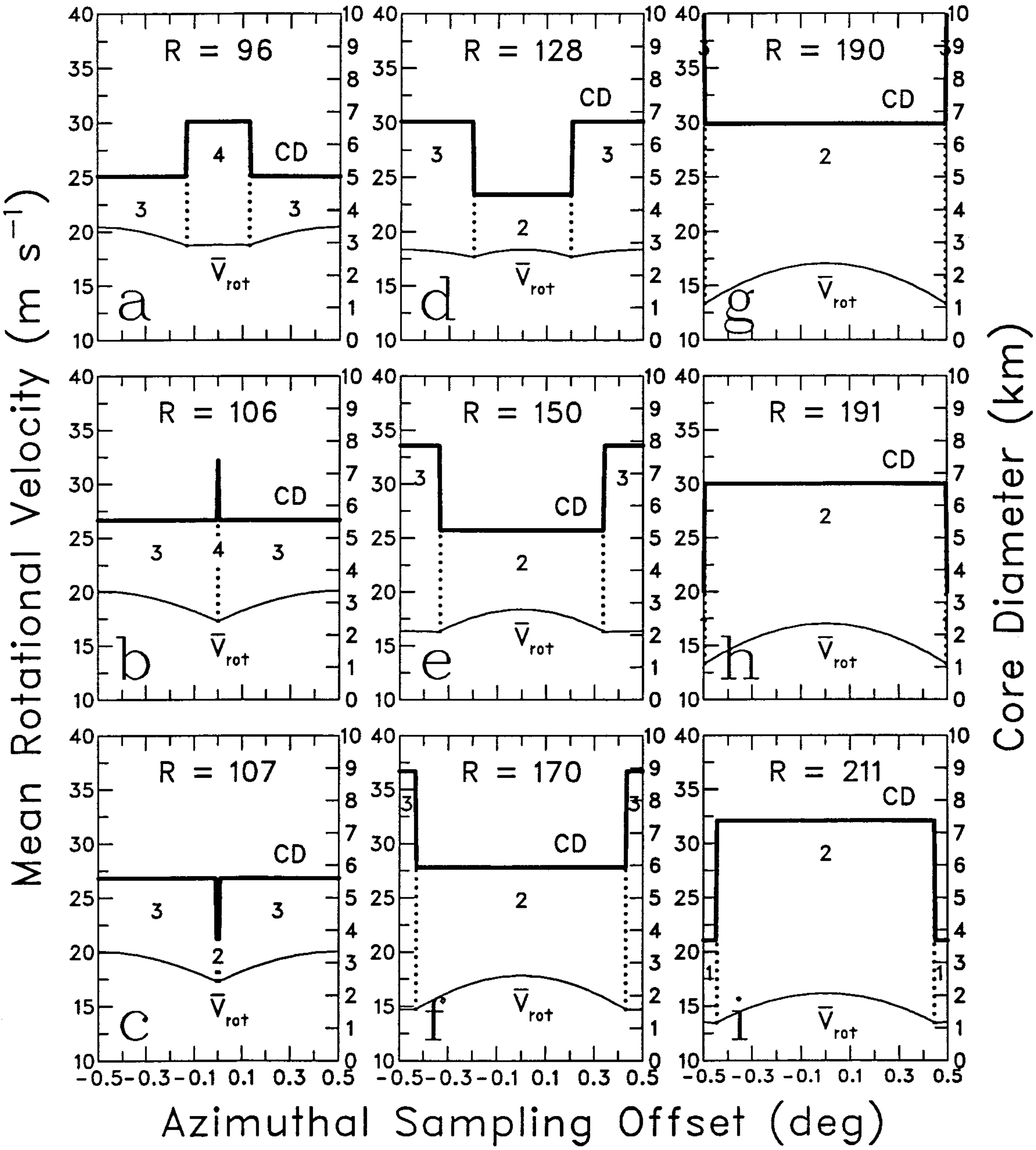

FIG. 6. Variations of deduced mean rotational velocity and core diameter as a function of azimuthal sampling offset (−0.5° to +0.5°) at several ranges from a WSR-88D radar. Thin and thick curves, respectively, represent deduced values of mean rotational velocity ($\bar{V}_{\rm rot}$) and core diameter (CD); their magnitudes, respectively, are given along the left and right sides of each panel. The vertical dotted lines represent the boundaries between the number of azimuthal intervals (labeled) separating the extreme positive and negative Doppler velocity data points of the mesocyclone signature.

peaks, the deduced mean rotational velocity will decrease.

c. *Doppler velocity measurements randomly positioned relative to mesocyclone center*

Up to this point, we have discussed what happens, as a function of range, when a Doppler velocity data point coincides with the mesocyclone center (0° azimuthal offset) or the two closest data points are equidistant from the center (±0.5° azimuthal offset). Now we discuss the situation where the closest data point is randomly positioned in the ±0.5° interval. To simulate all of the possible azimuthal offsets, we computed mean rotational velocities and core diameters at 0.02° intervals from 0.5° to the left of mesocyclone center to 0.5° to the right. The results of the computations are shown in Fig. 5. The shaded oscillating band in Fig. 5a represents the full spread of mean rotational velocities as a function of range.

The curves in Fig. 5b indicate that, at a given range, one of only two deduced core diameters is possible (except at the transition range). These two possibilities are those that occur for azimuthal offsets of 0° and ±0.5°. The dotted lines radiating from the origin (continuations of sloping portions of the curves) represent the linear increase of data point separation and its effect on core diameter with increasing range. The vertical portions of the curves in Fig. 5b simply represent the transition points illustrated in Figs. 2b,c and 4b,c, where the core diameter jumps to a smaller value and where the local minima in mean rotational velocity values also occur. The locations marked 6b, 6c, 6g, and 6h (representing Figs. 6b,c,g,h) in Figs. 5a,b represent these two transition points.

To further explain the oscillations in Fig. 5, the distributions of mean rotational velocity and core diameter as a function of azimuthal sampling offset are presented in Fig. 6. The full spread of offsets are presented at nine selected ranges. (Figures 2a–c are subsets of Figs. 6a–c at an offset of 0° and Figs. 4a–d are subsets of Figs. 6f–i at offsets of ±0.5°.)

All of the maximum rotational velocities along the top of the shaded band in Fig. 5a occur along either the 0° offset or the ±0.5° offset curve (cf. Fig. 3a). This situation is further illustrated in Fig. 6, where the highest portion of the mean rotational velocity curve (thin curve) is either at 0° offset or ±0.5° offset. Where the two offset curves cross in Fig. 5a (such as indicated by the 6d arrow in Fig. 5a), the maximum values at 0° and ±0.5° offsets are equal (see Fig. 6d).

On the other hand, the minimum rotational velocity values along the bottom of the shaded band in Fig. 5a represent the full range of azimuthal offset values. The pointed localized minima (such as the 6b,c and 6g,h arrows) occur alternately at offsets of 0° and ±0.5°. In between these points, the associated offset values change in a uniform manner from one extreme value to the other. This type of transition is shown in Fig. 6, where the minimum rotational velocity value moves from 0° offset at a range of 107 km (Fig. 6c) to ±0.5° offset at 190 km (Fig. 6g).

It is at the range of the pointed localized minima in mean rotational velocity that the marked transitions in core diameter occur (Fig. 5), as mentioned earlier. These transition points are indicated by the dotted vertical lines in Fig. 6. At the transition point at 106–107 km, the core diameter is equal to three azimuthal intervals, except at the 0° offset where the transition takes place. With increasing range, the fraction of the azimuthal offset interval equal to three azimuthal intervals decreases, while the fraction of offsets equal to two azimuthal intervals increases. At 190–191-km range, the core diameter is equal to two azimuthal increments at all but the ±0.5° offset. The thick mean diameter curve in Fig. 5b reflects the gradual change from three to two azimuthal intervals as range increases from 107 to 190 km.

4. Concluding discussion

In this note, we investigated the basic characteristics of oscillations in the strength and size of a mesocyclone signature that occur when the mesocyclone moves toward or away from a Doppler radar. The oscillations are a natural consequence of data points at constant azimuthal intervals changing their physical separation distances with changing range. As data point separation increases or decreases, the data points change their positions in a systematic manner relative to the Doppler velocity peaks of the mesocyclone signature. The deduced mean rotational velocity values oscillate as a continuous function of range. In contrast, the deduced core diameter undergoes discontinuous increases or decreases in size.

For actual Doppler velocity data, the oscillations discussed here are masked to some extent by the inherent uncertainties (noisiness) in the Doppler velocity estimates. However, abrupt changes still will be evident in deduced core diameters. Such changes, especially by a factor of 2 or 3 at farther ranges, can be very misleading during the real-time monitoring of mesocyclones. In subsequent papers, we will incorporate noisiness into our simulations and discuss ways in which basic mesocyclone characteristics can be recovered from range-degraded Doppler velocity mesocyclone signatures.

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