Rapid-Scan DOW 3D GBVTD and Traditional Analysis of Tornadogenesis

Joshua Wurman, Paul Robinson, Curtis Alexander, and Karen Kosiba,
Center for Severe Weather Research, Boulder, CO, *jwurman@cswr.org*,
Wen-Chau Lee, National Center for Atmospheric Research

1. The need and difficulty of seeing sharply

Narrow-beam scanning remote sensing tools such as radars and lidars have improved qualitatively our ability to observe the atmosphere. However, powerful as they are, radars and lidars are all limited by their ability to observe both fine spatial and temporal scales. Furthermore, ground-based systems are limited in their ability to observe near-ground phenomena that are not proximate to the radars themselves.

It is easily demonstrated that the spatial sampling limitations of radars are quite severe. Figure 1 illustrates, comparatively, the observable spatial scales of typical ~1° beam width radars, such as the current WSR-88D network, and the Norman Phased Array (NPA), and one proposed new technology, exemplified by the CASA network. As is well known, due to beam spreading, fine scale phenomena are not observable throughout much or most of the radars' survey domains. A comparison of several different operational and research radar system is shown in Figure 2 (next page). (The figure is plotted logarithmically, and the numerical values chosen for the scales of the observations and of the phenomena are quali-

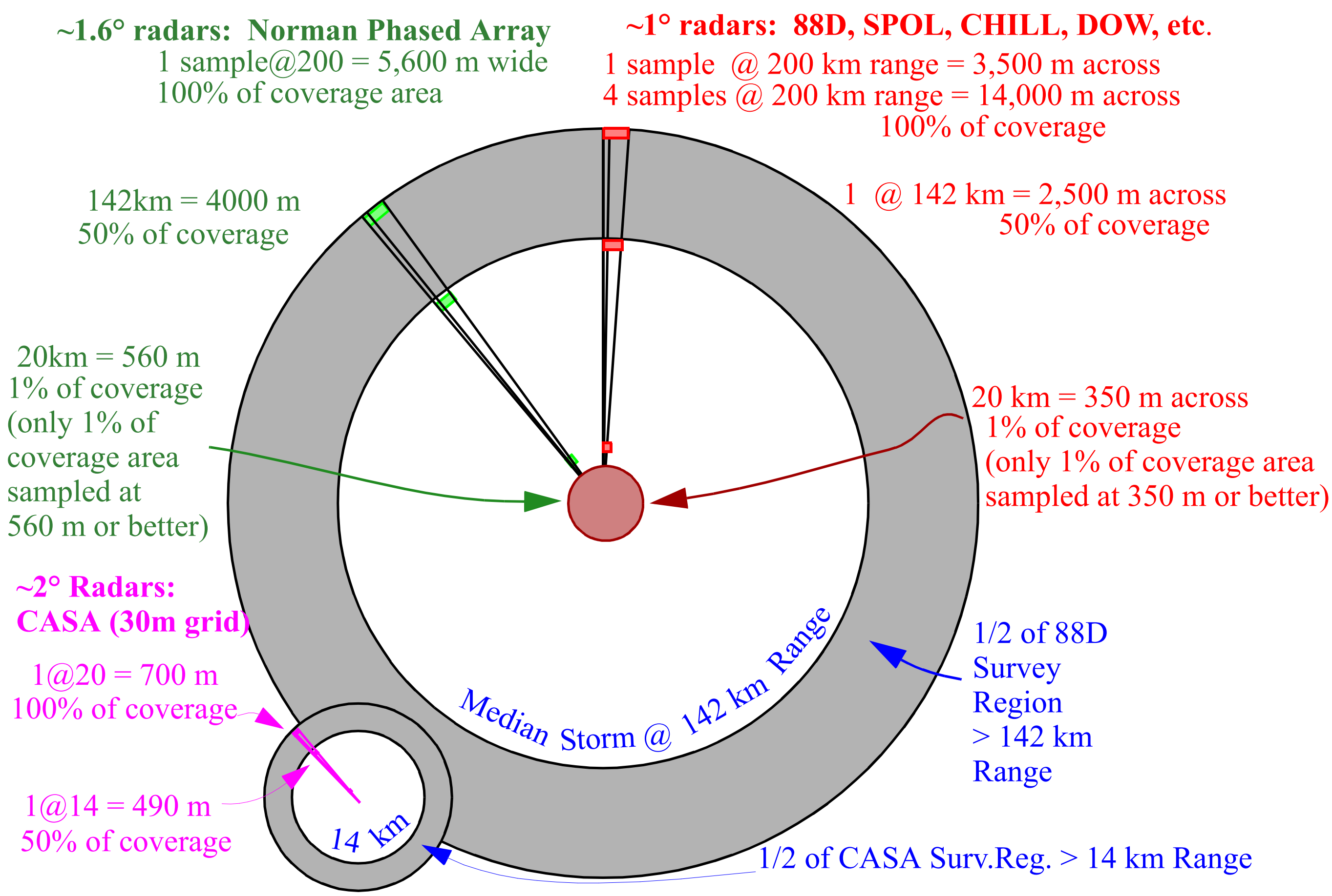


Figure 1. Sample size over the observation domain of some typical radars. Only a miniscule portion of the 88D or NPA domains sampled at ~500 m or better resolution. Only 1/2 of CASA domain sampled at ~500 m or better resolution.

tative.). The beam width of WSR-88D radars are greater than 350 m over 99% of the observable domain of the radars, and over 2.5 km over 50% of this area. This greatly limits the ability to resolve accurately the intensity of small scale phenomena such as mesocyclones and tornadoes. Oversampling by reducing integration times, and pulse compression methods provide some, but not qualitative, relief to these limitations. Recall that the sampling theorem, as described by *Carbone, et al., 1985, requires between six and eight samples before the amplitude of a phenomena is resolved within 20% of its true intensity.*

Phenomena can be merely detected, without intensity being accurately resolved, from just beam-to-beam shears and the like. Phenomena that are approximately one to two beam-widths in scale can be marginally detected at the optimistic ranges illustrated in Figure 2.

2. The need and difficulty of seeing sharply and quickly.

Figure 2 also illustrates, very schematically, the temporal detectability of three classes of phenomena, mesocyclones, tornadoes, and tornadic multiple vortices and the smallest scales of near-ground hurricane boundary layer rolls,

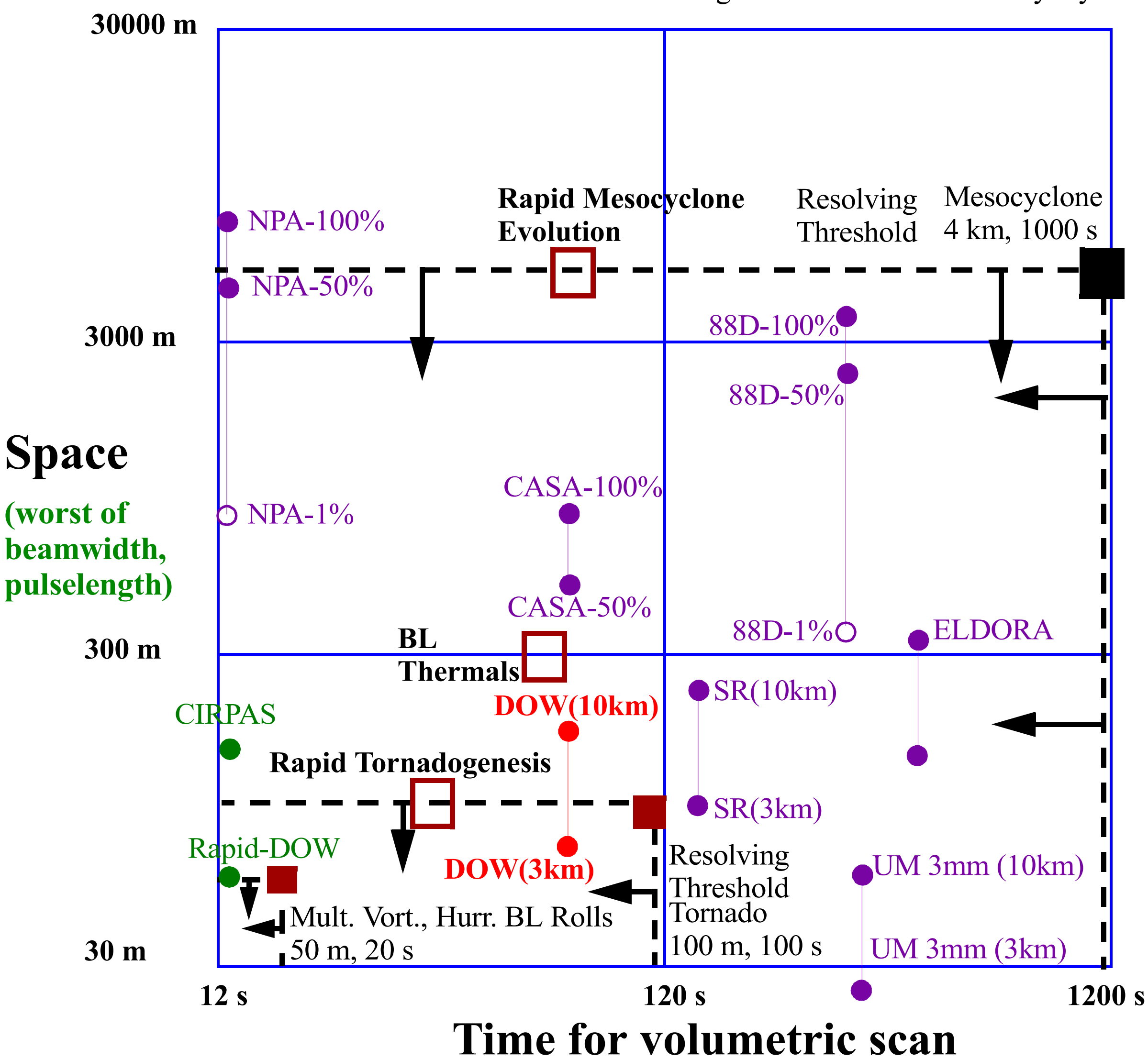


Figure 2. Temporal and Spatial Observability of various phenomena by different radars. For example, a tornado is detectable if resolution is < 100 m and 100 s, while resolution of tornadogenesis requires resolution of < 100 m and 30 s.

by various radar systems. Both operational and research radars are compared, though their missions are significantly different.

In Figure 2, it is assumed that, to resolve a mesocyclone, observations at 4km and 1000 s scale are required. Similarly, observations at 100 m and 100 s are required to resolve a tornado (based on recent DOW-radar based tornado-size climatology). Observations of 100 m and 30 s scale are required to observe the rapid evolution of the wind field during tornadogenesis. Observations of 50 m scale and 20 s are required for multiple-vortices. (Again, we note that the scale is logarithmic and that these values are chosen qualitatively for illustration.)

It can be seen that spatial observing scale of the WSR-88D is marginally suitable for detecting (not quantifying intensity) mesocyclones throughout its domain. Increased spatial resolution would certainly be beneficial. The WSR-88D can detect easily the temporal existence of mesocyclones with even the current 300 s volumetric sampling interval. Of course, the mere detection of mesocyclones is not sufficient for timely warning purposes. In order to provide detection of intensification that may occur at the 60-120 s temporal scale, temporal updates of at most 60 s would be beneficial.

a. Rapid-sampling using low spatial resolution radars has diminished value:

Sampling by radars with WSR-88D type spatial resolution at intervals much finer than 60 s results in diminishing returns over most of the coverage domain. Mesocyclone intensification is well resolved, temporally, with 60 second updates; ~10 s updates are not necessary. But, the rapid evolution of smaller and more quickly evolving phenomena cannot be observed by distant rapid-scan radars due to spatial observing limitations. Tornadoes themselves, are not observable by any practical sparsely distributed network except very close to the individual radars. As can be seen in Figure 2, actual tornadoes are not resolvable, typically, over 99% of the WSR-88D domain. Similarly spaced phased array radars of the NPA type would suffer even worse spatial resolution limitations over nearly their entire observational domain.

A radar network that provides both temporal sampling of about 60 s and spatial sampling better than 500 m throughout most of its survey domain would be the most efficacious at providing warnings related to mesocyclone intensity changes. Some proposed operational technologies move towards this criteria, while others do not, as can be seen in Figure 2. The CASA-type approach offers more hope of observing the combined spatial and temporal scale of small, quickly evolving, phenomena, including the rapid evolution of mesocyclones. However, even the CASA approach does not result in beam widths, through a majority of the radars' domains, sufficient to quantify accurately most tornado wind fields.

3. Mobile rapid-scan radars.

The above analysis paints a rather dismal portrait of the potential for accurate measurements of tornadoes, hurricane boundary layer structures, or other small-scale and quick-scale phenomena by stationary radar networks. While likely not a practical solution to the above operational problem, mobile rapid-scan radars offer a method of obtaining both fine temporal ***and*** spatial observations. Efforts towards mobile rapidly scanning radars have been described in Wurman and Randall 2001 (the Rapid-Scan DOW) and in Bluestein et al. 2007 (CIRPAS). One of the major goals of the Rapid-Scan DOW was to develop and field an inexpensive and rugged mobile system. While phased array radars can cost upwards of $\$10^7$, the Rapid-Scan DOW program required only

$1.5x10^6 to both develop and field test the radar, and with the technology now developed, future systems can be constructed for only about $5x10^5, bringing the technology within reach of small to medium sized research programs. Additionally, the technology is designed to be easily operable by lightly trained crew, including graduate students.

The Rapid-DOW, along with the single-beam DOWs, have recently become a National Science Facility National Facility. They can be requested by PI's from NSF and supported by Deployment Pool funds for educational and research projects.

4. The Rapid-Scan DOW

The Rapid-Scan DOW concept (described in more technical detail in Wurman and Randall 2001) is to transmit a rapid series of pulses at staggered elevation angles, then listen with a multi-channel receiver to all these channels. Effectively, data from six (or any number) of elevation angles is measured simultaneously. This is achieved using a slotted wave guide array antenna and a multi-channel receiver. Azimuth is scanned traditionally, resulting in 12 tilt sector scans in about 9 s and 12 tilt 360 degree volumes in about 14 s. (Figure 3).

The Rapid-Scan DOW was field tested in 2003 and 2005 with support from NSF. Initial tests

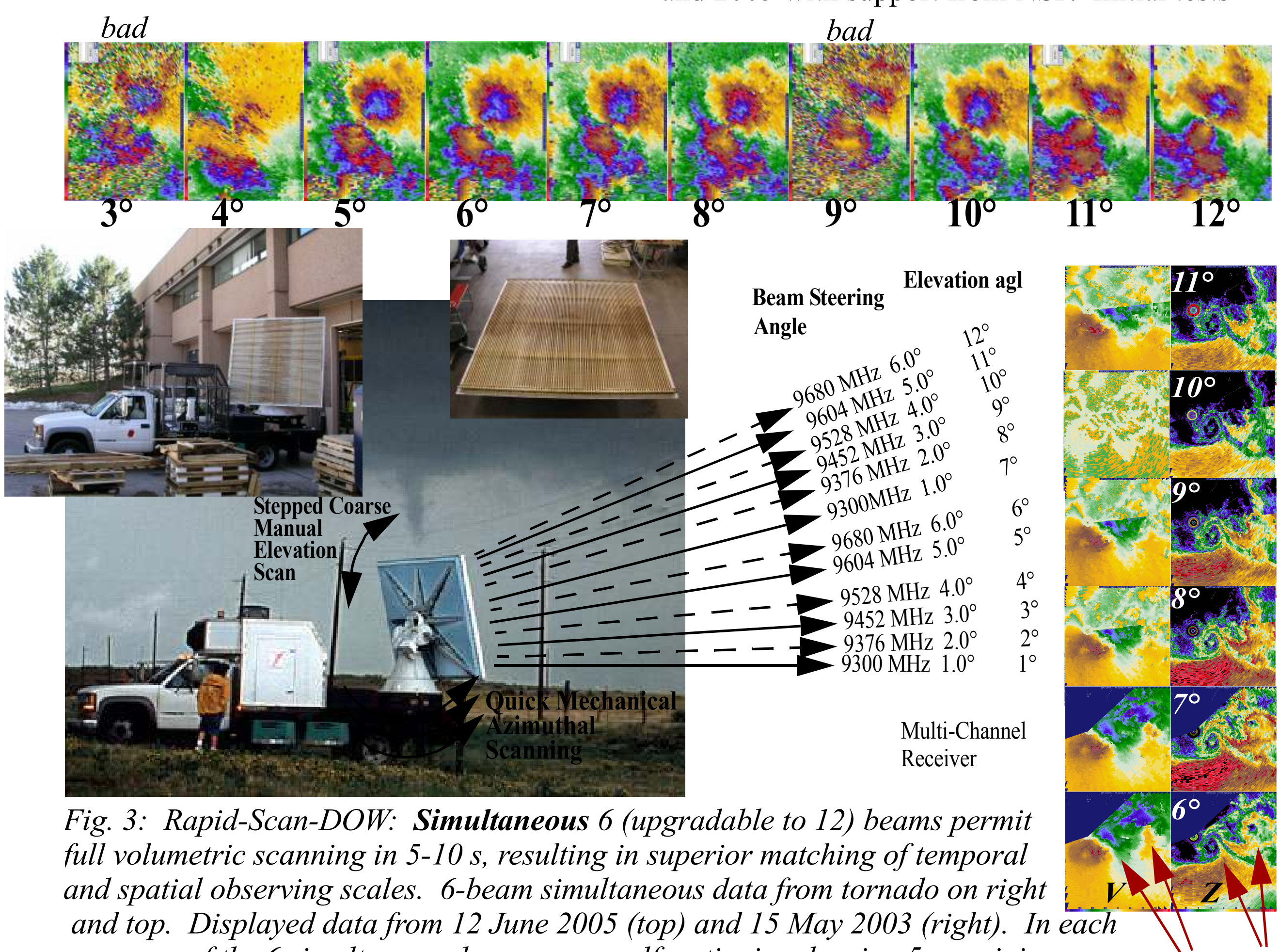


*Fig. 3: Rapid-Scan-DOW: **Simultaneous** 6 (upgradable to 12) beams permit full volumetric scanning in 5-10 s, resulting in superior matching of temporal and spatial observing scales. 6-beam simultaneous data from tornado on right and top. Displayed data from 12 June 2005 (top) and 15 May 2003 (right). In each case, one of the 6 simultaneous beams was malfunctioning, leaving 5 remaining. Doppler data have not been edited or dealiased. The tornado Doppler couplets are clearly discernible in the 12 June 2005 data. In the 9 June data, two distinct tornadic circulations are discernible, as indicated by red arrows.*

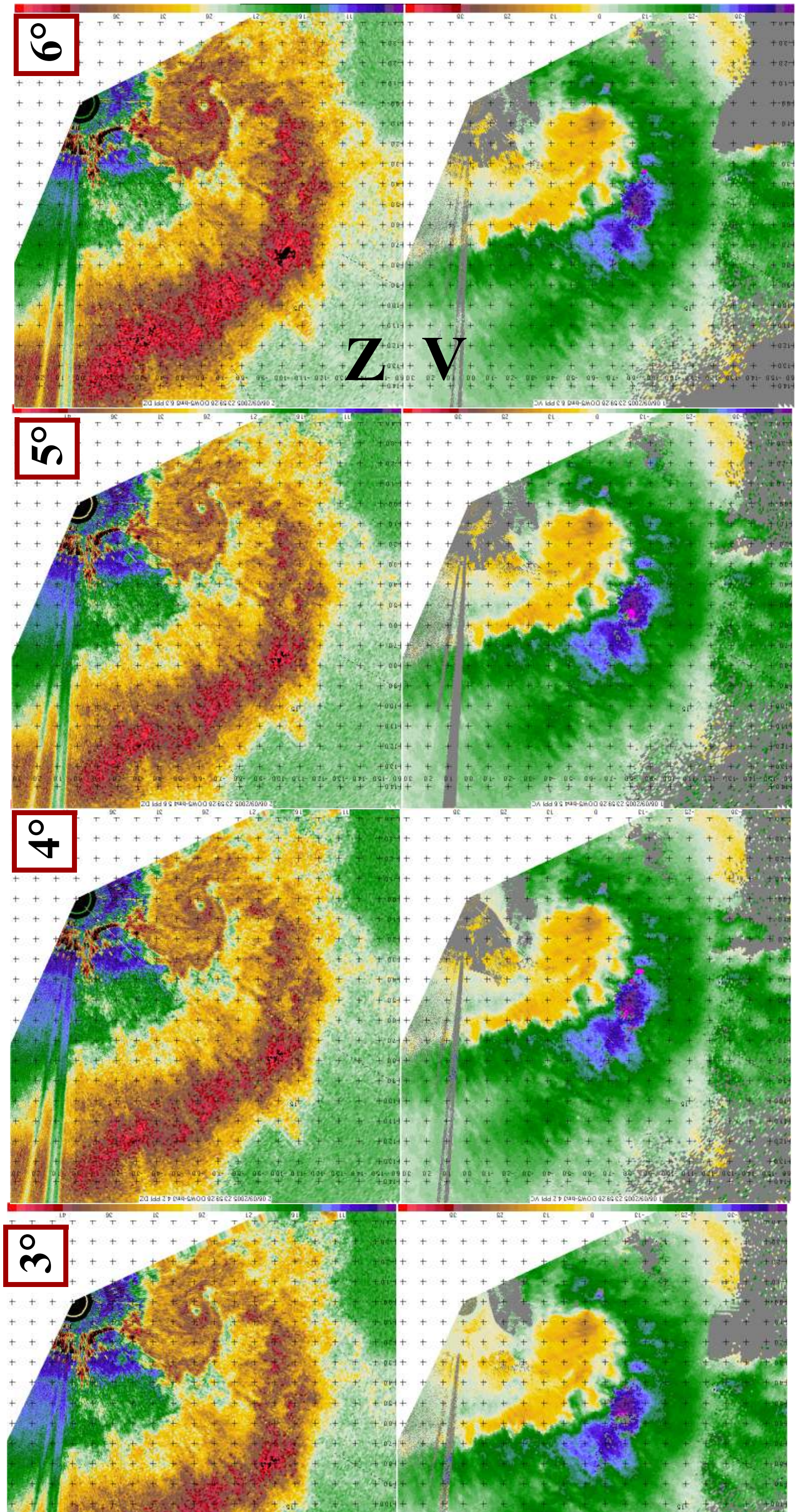


Figure 4. Four simultaneous slices of reflectivity (right) and Doppler velocity (left) through a tornado on 09 June 2005, observed by the Rapid-Scan DOW. Tick marks are 1 km.

were conducted to verify that the antenna was focused and steered correctly, and could, in fact, produce the 6 desired simultaneous beams as designed. The 3dB beam width was verified as designed at 0.8° and elevation steering of 1° per 76 MHz was confirmed using a cw remote signal generator source. Focusing and steering were also confirmed through ground clutter and blockage measurements. *Despite the normal focusing and steering of the beam, the system had much lower sensitivity than designed (see later discussion).*

Figure 4 shows several simultaneous slices through a tornado on 09 June 2005. High quality reflectivity and Doppler velocity measurements were obtained. The data clearly are different at each level, and strong gradients are seen in both reflectivity and Doppler fields, indicating that the radar beams are well focused and steered. Sensitivity was sufficient to image much of the hook echo. Attenuation typical of X-band systems, extinguished the beam in the core of the parent supercell.

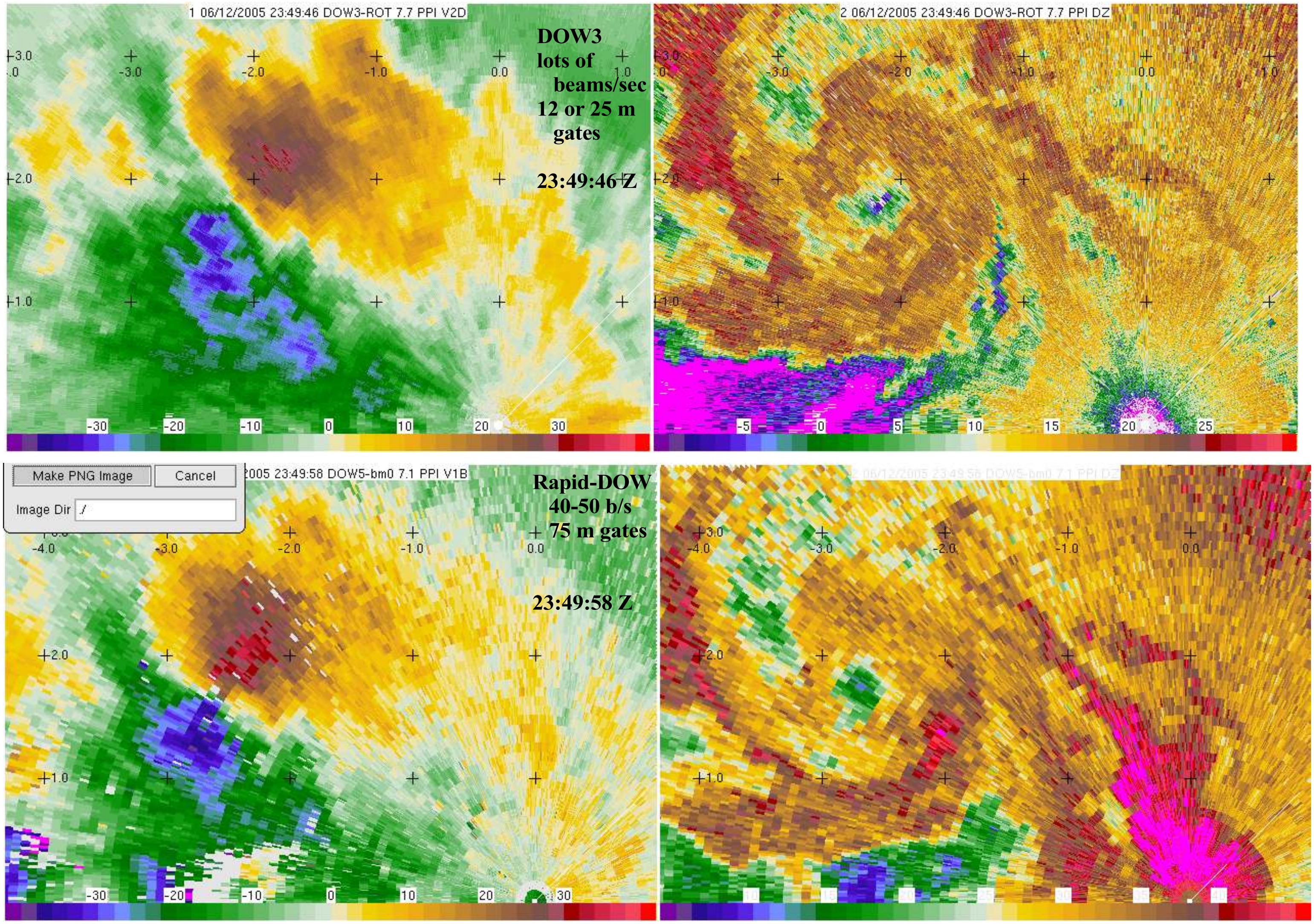


Figure 5. Rapid-Scan-DOW seems to see same features as 'ground truth' DOW3. Some differences may be due to 12 second difference in observation time and/or slight differences in observation elevation and location. DOW3 and Rapid-DOW are not exactly co-located. Rapid-Scan-DOW DZ may not be range corrected correctly resulting in high values near radar. Similarly DOW3 DZ data are too low near the radar due to receiver saturation. In this tornado, data are obtained by the Rapid-Scan-DOW through the tornado core/eye.

5. Verification of Rapid-Scan Data and GBVTD comparisons.

While the Rapid-Scan DOW data appeared to be of good quality, verification with conventional, single-beam data from DOW3 was critical in order to have confidence in the system.

On 12 June 2005, the DOW3 and the Rapid-Scan DOW were nearly co-located (500 m range from each other) while observing a tornado from close range (about 2-3 km). Figure 5 shows a slice through the tornado with each system. Data spacing in the DOW3 is finer due to smaller gate lengths and azimuthal oversampling. However, the qualitative appearance of the fields are quite similar. The effects of finer sampling and sensitivity are evident in Figure 6, showing data collected in a very rain wrapped and therefore attenuated tornado. The DOW3 data reveal a much stronger velocity couplet compared to the Rapid-Scan DOW, with finer scale detail. The Rapid-Scan DOW was unable to measure winds in the relatively clear eye due to a sensitivity problem with the radar and to non-optimal tuning during the 2005 tests.

A broader range view of the same tornado shows that the Rapid-Scan and DOW3 Dop-

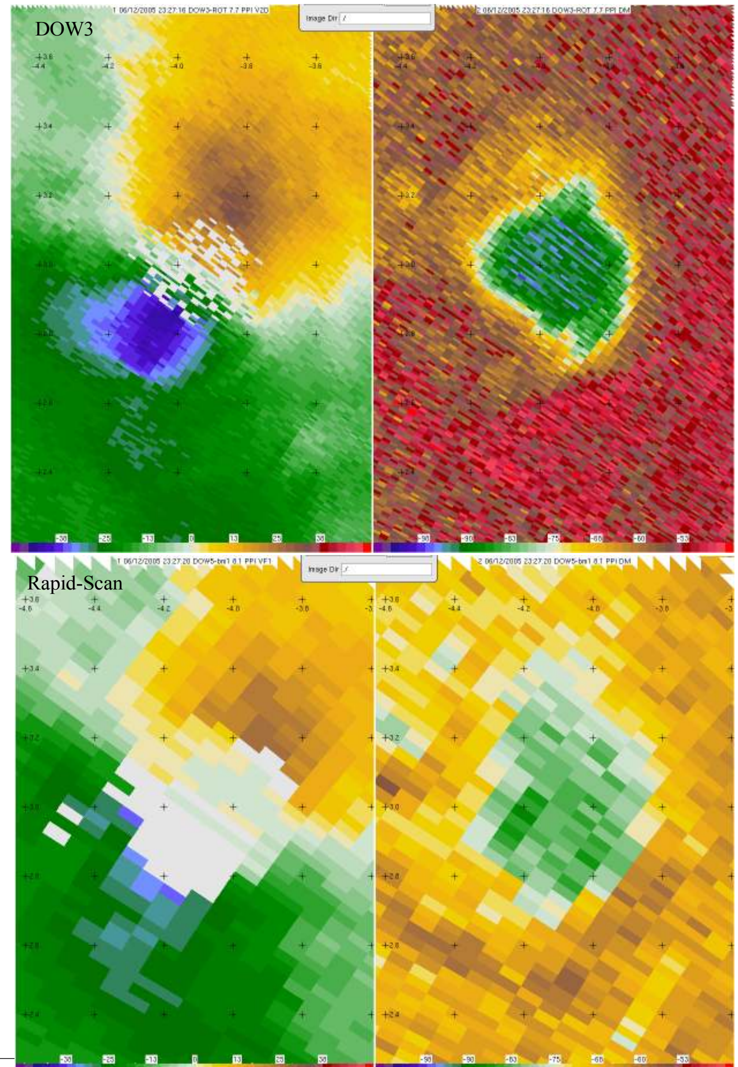


Figure 6. Comparison of Rapid-Scan and DOW3 data in tornado core with substantial attenuation and clear eye. Rapid-Scan DOW used 50 m gating and no oversampling while DOW3 employed 12.5 m gating and a high degree of oversampling.

pler fields agree in regions of higher returned signal (Figure 7). Except in a low signal area at the lower right of the plotter region, the Doppler velocities are in quite close agreement.

Basic tornado metrics, delta-V across the core flow region and core flow radius (rmw), as determined from both Rapid-Scan DOW and DOW data, in one tornado were compared. As illustrated in Fig. 7, the values agree closely. From T=48-51, the scale of the circulation shrinks, and delta-v increases, as tornagenesis occurs.

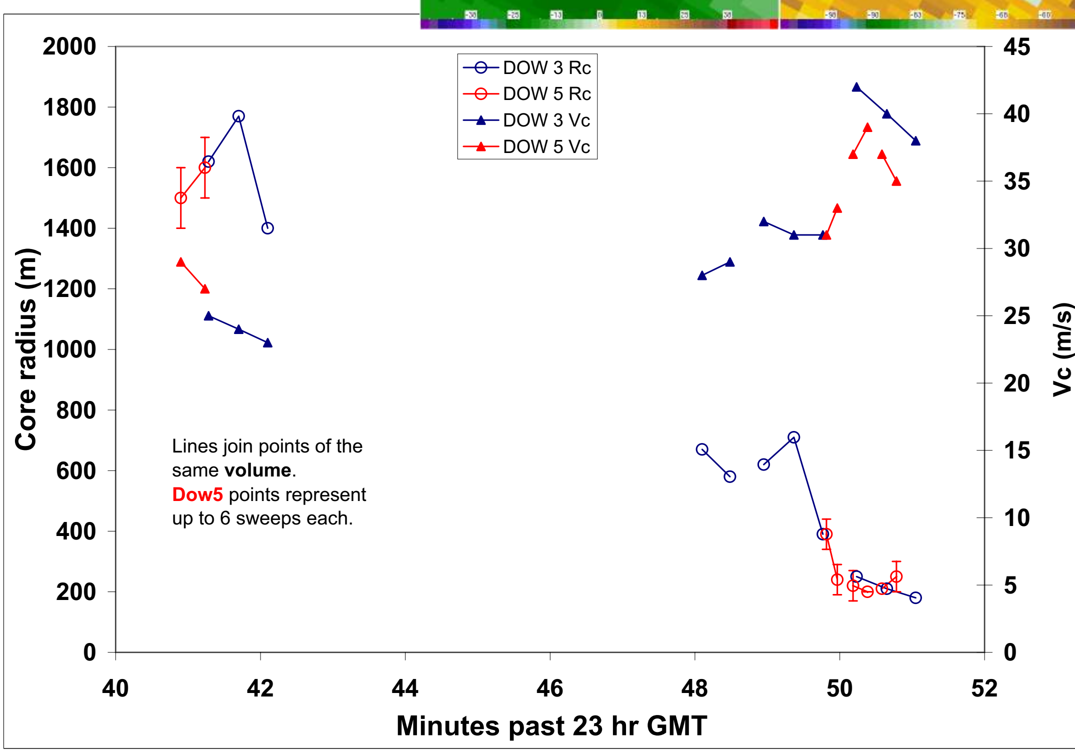


Figure 7. Core flow radius and maximum delta-V across a tornado as determined by both Rapid-Scan DOW and DOW3 measurements. Close agreement is seen, further validating the Rapid-Scan wind field measurements.

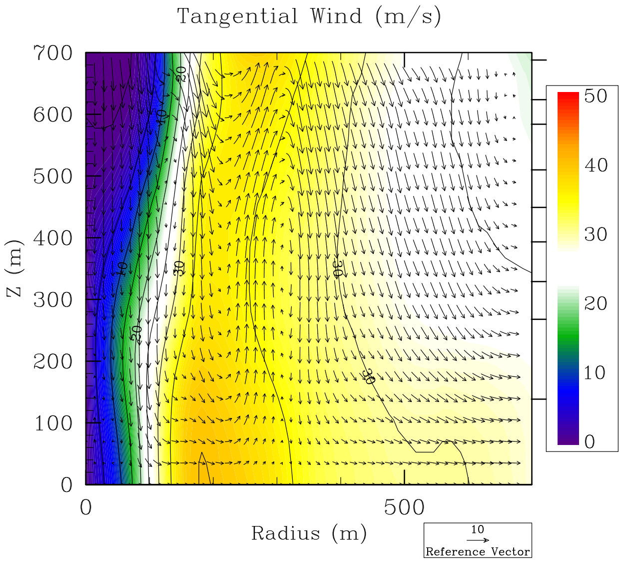


Figure 8 (left). GBVTD analysis of one of the tornadoes on 12 June 2005. A two cell structure with a central downdraft is revealed.

Figure 9 (below). Comparison of Hovmoller diagrams for a 12 June 2005 tornado with a clear eye and attenuation using DOW3 (left) and Rapid-Scan DOW (right) wind fields. Since the Rapid-Scan DOW was not able to measure winds in the clear eye, it missed the highest tornado winds. Therefore, inside the rmw (heavy black line) the GBVTD retrievals do not agree. But, outside the rmw, in regions with more precipitation, there is close agreement.

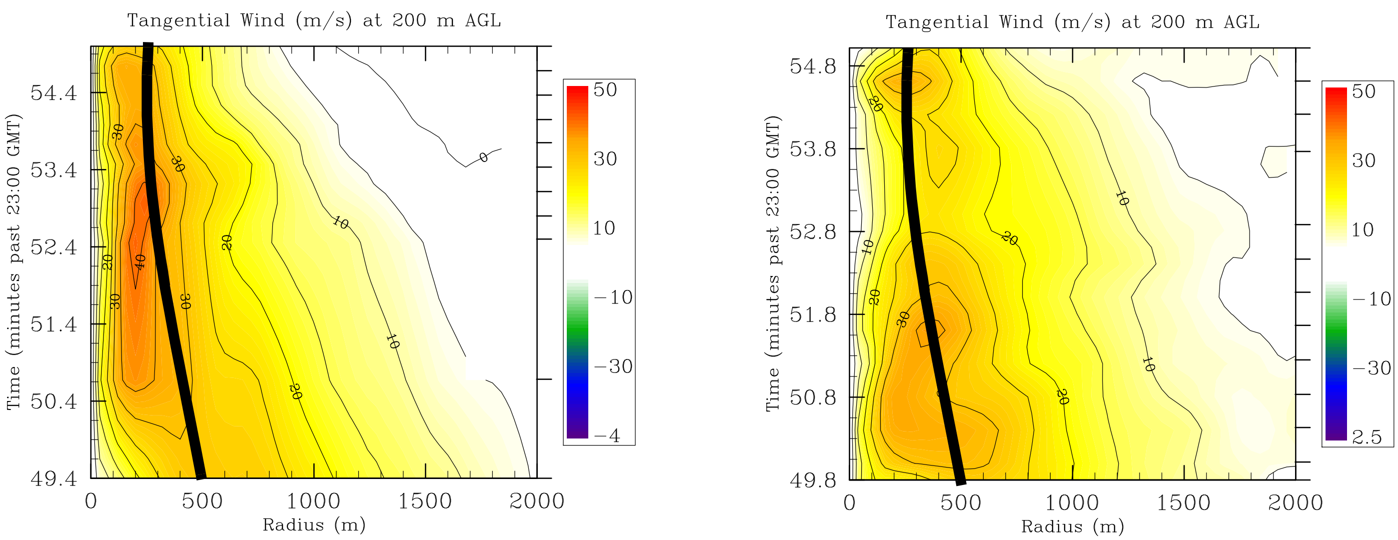
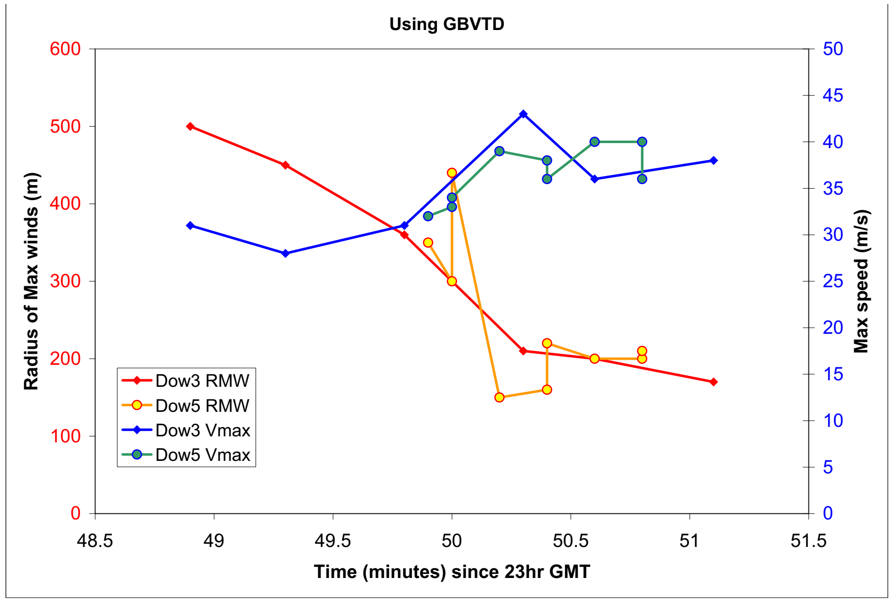


Figure 10. Comparison of GBVTD-derived tornado metrics from Rapid-Scan DOW and DOW3 radar wind fields. The maximum axisymmetric tangential winds and radius of maximum winds agree very closely during the tornadogenesis.



GBVTD analyses were conducted using both radars in order to compare objectively determined tornado metrics such as axisymmetric tangential winds and the radius of maximum winds. A sample of one of these analyses using Rapid-Scan data is shown in Figure 8. The retrival compares well with subjective analyses of this tornado, and appears similar in quality to those conducted in other tornadoes using traditional DOW data. A central downdraft penetrates to the ground inside a sloping updraft region surrounded by a convergent inflow. An additonal downdraft region is retrieved well beyond the radius of maximum winds. This may be an artifact of the retrieval or representative of a complex flow regime in this weak and short lived tornado. Hovmoller diagrams (Figure 9) reveal that the GBVTD retrievals of tangential wind field structure from the Rapid-Scan DOW and DOW3 data agree over a long time period and range of altitudes, outside the clear central eye region.

The GBVTD analyses of the Rapid-Scan DOW data produced reasonable and repeatable radius of maximum winds, up/downdraft structures, etc. in some tornadoes, but failed to resolve the maximum wind regions where clear eyes and attenuation were present in others. Tornado metrics extracted from the GBVTD analyses of the well resolved tornadoes using each radar's data were retrieved and compared very well, as illustrated for one case in Figure 10. During the 200 s of observation, the scale of the circulation collapses as a tornado forms as evidenced also by the increase in tangential velocity.

6. Sensitivity problems and antenna side lobes.

While the Rapid-Scan DOW was validated as a useful research tool, and the wind fields and reflectivity fields were verified favorably against 'ground truth' traditional high resolution DOW radar data, a significant limitation of the Rapid-Scan DOW was also revealed.

Laboratory and field tests revealed that, while the antenna focused well, and produced a well behaved, steerable, 0.8° beam, the sensitivity to received signals was about 20-30 dB lower than designed. It is believed that the problem is in the coupling between the feed waveguide and the radiating waveguides. This is borne out by the burning of a low power dummy load originally at the end of the feed waveguide. While designed to absorb only 20% of the energy, it appears that the bulk of the transmitted 50 kW was dissipated in this load, rather than coupling into the radiating elements. Additionally, a side lobe spaced about 30°

from the main lobe has been observed in tornado wind fields.

Diagnosis/correction of these issues is a high priority of the Rapid-Scan DOW program.

With low sensitivity, the Rapid-Scan DOW can perform its missions when observing areas with moderate to high echo intensity. Many to most tornado cores can be measured, so the system is suitable for tornado studies such as VORTEX2. Hurricane boundary layer rolls, since they occur in precipitation, have been well resolved with the Rapid-Scan DOW (which was deployed to Hurricane Isabel in 2003). Clear air sensitivity is limited, however, so studies of rapidly evolving boundary layer thermals and similar low reflectivity phenomena are problematical until the sensitivity issue is resolved.

The Rapid-Scan DOW will be participating in the VORTEX2 project in 2009-10, in its first use as an NSF National Facility