Evaluation of Distributed Collaborative Adaptive Sensing for Detection of Low-Level Circulations and Implications for Severe Weather Warning Operations

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ABSTRACT

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA; McLaughlin et al. 2009) is a multiyear engineering research center established by the National Science Foundation for the development of small, inexpensive, low-power radars designed to improve the scanning of the lowest levels (<3 km AGL) of the atmosphere. Instead of sensing autonomously, CASA radars are designed to operate as a network, collectively adapting to the changing needs of end users and the environment; this network approach to scanning is known as distributed collaborative adaptive sensing (DCAS). DCAS optimizes the low-level volume coverage scanning and maximizes the utility of each scanning cycle. A test bed of four prototype CASA radars was deployed in southwestern Oklahoma in 2006 and operated continuously while in DCAS mode from March through June of 2007.

This paper analyzes three convective events observed during April–May 2007, during CASA’s intense operation period (IOP), with a special focus on evaluating the benefits and weaknesses of CASA radar system deployment and DCAS scanning strategy of detecting and tracking low-level circulations. Data collected from nearby Weather Surveillance Radar-1988 Doppler (WSR-88D) and CASA radars are compared for mesocyclones, misocyclones, and low-level vortices. Initial results indicate that the dense, overlapping coverage at low levels provided by the CASA radars and the high temporal (60 s) resolution provided by DCAS give forecasters more detailed feature continuity and tracking. Moreover, the CASA system is able to resolve a whole class of circulations—misocyclones—far better than the WSR-88Ds. In fact, many of these are probably missed completely by the WSR-88D. The impacts of this increased detail on severe weather warnings are under investigation. Ongoing efforts include enhancing the DCAS data quality and scanning strategy, improving the DCAS data visualization, and developing a robust infrastructure to better support forecast and warning operations.

1. Introduction

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA; McLaughlin et al. 2009) is a multiyear Engineering Research Center, funded by the National Science Foundation, for the development of small, inexpensive, low-power radars designed to improve scanning of the lowest levels (<3 km AGL) of the atmosphere. CASA radars are designed and deployed to operate as a network, providing dense, overlapping coverage to overcome the horizon problem common to large, long-range radars. Furthermore, the CASA radars scan collaboratively, collectively adapting to the changing needs of end users and the environment. This network approach to scanning, known as distributed collaborative adaptive sensing (DCAS; McLaughlin et al. 2009), optimizes the low-level volume coverage scanning and maximizes the utility of each scanning cycle for users (Philips et al. 2007). DCAS directs scanning on those
areas of greatest observational need, providing more frequent storm volume coverage than is possible using conventional volume coverage pattern (VCP) scanning. CASA’s long-term goal is to develop a new concept for low-cost, dense radar networks that provide comprehensive lower-tropospheric coverage that does not exist with today’s long-range radars.

CASA addresses an observational need in the operational forecasting community for more flexible and targeted radar scanning strategies. The Radar Operations Center Applications Branch previously conducted a survey of Weather Forecast Office, Central Weather Service Unit, and Department of Defense personnel and asked forecasters what improvements they would make to existing Weather Surveillance Radar-1988 Doppler (WSR-88D) scanning strategies (Steadham 2007). From a total of 128 responses, the top five requests were (i) faster scans (33%); (ii) more frequent, denser vertical scans at low levels (18%); (iii) elevation angle scans below 0.5° (16%); (iv) novel, adaptive scanning focusing on areas of interest (12%); and (v) more elevation scans (10%). Fortuitously, CASA is now testing many of the new scanning strategies requested in the survey. However, these often requested, yet novel approaches to sensing, such as rapid, adaptive scanning and dual-Doppler capabilities, introduce new challenges to the radar system designers as well as the operational forecaster.

To assess the CASA concept, a test bed of four prototype CASA radars was deployed in southwestern Oklahoma in 2006. During the spring of 2007, the system was operated continuously while in DCAS mode from March through June (Brotzge et al. 2007; Chandrasekar et al. 2007). This paper analyzes three case study events collected during April and May of 2007, with a special focus on evaluating DCAS scanning strategy for the detection and tracking of low-level circulations. Data collected from nearby WSR-88Ds and CASA radars are compared. A description of the CASA test bed in Oklahoma, the DCAS scanning strategy, the data collected, and the study methodology are presented in section 2. The three case studies are examined in section 3. Section 4 describes the opportunities and challenges presented by the CASA data to the operational forecaster.

2. System design and operation

The CASA radar system is an “engineered end-to-end test bed” that encompasses the entire process of moving information from the observing hardware to users of the data, and then moving information back from users to the observing hardware. CASA radar networks differ from conventional radar scanning in four significant ways: (i) an emphasis on lower-tropospheric scanning, as low as 275 m AGL; (ii) adaptive sector scanning that targets areas of importance; (iii) collaborative sensing providing multiple views of weather features, dual-Doppler wind analysis, and attenuation correction and mitigation; and (iv) inclusion of end-user input to drive the scanning system. These capabilities are enabled by the networked approach to deploying and operating the radars.

The CASA system comprises several modular components, including (i) radar hardware and signal processing, (ii) communications, and (iii) Meteorological Command and Control, which includes feature detection algorithms and scan optimization software (Kurose et al. 2006).

In 2007, CASA radars were low-power, dual-polarization, 3-cm (X band) radars with a beamwidth of 1.8° and azimuthal oversampling of 1° [with an effective beamwidth of about 2°; Brown et al. (2002)] and a range sampling of 100 m. For comparison, at the time of these study cases the data sampling of Next-Generation Doppler Radars (NEXRAD) was approximately 1° × 1 km for reflectivity (250 m for velocity). With the transition to high-resolution scanning, data sampling from NEXRAD is now approximately ½° × 250 m for reflectivity and velocity, and the CASA radars now oversample every 0.5° azimuth (instead of 1.0°). The CASA radars have a peak power of 25 kW and a mean power of 25 W. Signal processing is performed at the radar site and includes real-time clutter mitigation, attenuation correction, and dual-pulse repetition frequency (PRF) velocity processing that provides a Nyquist velocity of about 38 m s⁻¹. Attenuation is corrected in one of two ways. Single radar data are corrected using the dual-polarization variable specific differential phase (Gorgucci and Chandrasekar 2005), and data within multi-Doppler regions can be corrected by processing data from multiple radars (Lim et al. 2007). Radar specifications for both CASA and NEXRAD are listed in Table 1.

Moment data generated at the radar towers are transmitted via wireless microwave links to the Systems Operation Control Center, a central location for data processing and archiving. In the Meteorological Command and Control, data from all CASA radars are processed by a package of data-mining algorithms that search and tag features of interest [e.g., high reflectivity; Zink et al. (2008)]. Many of these algorithms operate within the Warning Decision Support System–Integrated Information (WDSS-II; Lakshmanan et al. 2007) framework. Any weather features identified are used by the optimization software to create a new scanning strategy for the next scanning cycle. The scanning cycle can vary and is user defined; a scanning cycle of 1 min was used for
all cases presented in this study. The optimization software considers sensing and weather information as well as the needs of various end users in developing each new set of radar scanning tasks (Philips et al. 2007).

The first CASA test bed (Fig. 1), known as Integrated Project One (IP1), is located in southwestern Oklahoma and is composed of four low-power, X-band radars. In 2007, each radar had a range of 30 km; the processing range was extended to 40 km in 2008. These four radars are located approximately 25 km apart in or near the towns of Cyril (KCYR), Lawton (KLWE), Rush Springs (KRSP), and Chickasha (KSAO), all of which are in Oklahoma. The radars are located midway between two existing WSR-88D radars in part to observe the atmosphere below that observed by the WSR-88D radar beams (Brewster et al. 2005) and with overlapping coverage to enable multi-Doppler analysis.

During 2007, the CASA radars were operated in DCAS mode. At the start of each 60-s scanning cycle, a new scanning strategy was transmitted to the radars from the System Operations Control Center. For the first 20 s, each radar completed a 360° scan at an elevation angle of 2°. These scans provide temporal continuity to the data and situational awareness across the entire domain. Each radar completed adaptive sector scanning for the remaining 40 s of the scanning cycle. Some radar tasks required only a single radar; others required two or more radars to scan collaboratively the same area in order to provide data for dual- or multi-Doppler analysis. Selectively scanning only the most high-value, targeted areas of the atmosphere reduces the need for time-consuming 360° scans. This methodology frees additional time to scan the volume of a specific storm of interest, at a rate of up to once per minute.

Sector scans were made from the lowest elevation to the highest as time permitted, starting at 1° elevation, followed by 3°, 5°, 7°, 9°, 11°, and 14° elevations (Fig. 2a). When minimal significant reflectivity was observed or when stratiform rain covered the domain, three 360° surveillance scans were performed by each radar at the lowest three elevation angles (Fig. 2b). When wider sector scans were required, fewer sector scans were completed (e.g., Fig. 2c). An example of this scanning technique, as shown in Fig. 3, demonstrates the ability to collect one 360° azimuthal scan (at the 2° elevation) and up to seven 60° azimuth sector scans, all within a 1-min time frame. An examination of this volume scan shows the vertical continuity of a cyclonic circulation from approximately 200 m to 2.7 km AGL.

The lowest elevation angle was chosen as a compromise between maximizing the observations at low levels and minimizing the clutter. Because of the 2° beamwidth of the CASA radars, the lowest elevation was set at 1° in an effort to minimize ground clutter. Due to the dense spacing of the radars, no point within the interior of the network is greater than 15 km from a radar. Thus, the center beam of the 1° elevation is no higher than 275 m AGL within the multi-Doppler region.

### Table 1. A list of CASA and WSR-88D radar specifications are shown for comparison.

<table>
<thead>
<tr>
<th></th>
<th>CASA</th>
<th>WSR-88D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>X band (9.41 GHz)</td>
<td>S band (2.9 GHz)</td>
</tr>
<tr>
<td>Peak power output</td>
<td>25 kW</td>
<td>750 kW</td>
</tr>
<tr>
<td>3-dB beamwidth</td>
<td>1.8°</td>
<td>0.92°</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>1.2 m (4 ft)</td>
<td>8.5 m (28 ft)</td>
</tr>
<tr>
<td>Dual polarization</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Clutter suppression</td>
<td>Real-time Gaussian model adaptive processing (GMAP)</td>
<td>GMAP</td>
</tr>
<tr>
<td>Ambiguity mitigation</td>
<td>Yes</td>
<td>Staggered pulse repetition time (PRT) upgrade planned for 2011</td>
</tr>
<tr>
<td>Range</td>
<td>30 km</td>
<td>460 km for reflectivity; 230 km for velocity, spectrum width</td>
</tr>
<tr>
<td>Range sampling</td>
<td>100 m</td>
<td>250 m</td>
</tr>
<tr>
<td>Data spacing</td>
<td>1° azimuth x 1° elevation x 100 m × 60 s</td>
<td>1.0° azimuth x 0.5° elevation x 250 m × 300 s (in 2007)</td>
</tr>
<tr>
<td>3-dB sample volume (m)</td>
<td>471 × 471 × 100</td>
<td>1847 × 1847 × 250</td>
</tr>
<tr>
<td>Domain with low-level radar coverage (%)</td>
<td>At 500 m 100</td>
<td>At 500 m 100</td>
</tr>
<tr>
<td></td>
<td>At 1 km 100</td>
<td>At 1 km 40</td>
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<tr>
<td></td>
<td>At 2 km 100</td>
<td>At 2 km 100</td>
</tr>
</tbody>
</table>

* Radar coverage percentages were estimated assuming an idealized network of radars with no terrain. A radar spacing of 35 km was assumed for CASA and a radar spacing of 225 km spacing for the WSR-88D (Brotzge et al. 2009).
3. Case studies

During April and May of 2007, three convective events observed by the CASA network captured three distinct low-level circulation features: supercell mesocyclones, nonsupercell misocyclones, and low-level vortices along the leading edge of a squall line. Each of these cases was observed by CASA researchers and NWS forecasters in real time while participating in the National Oceanic and Atmospheric Administration (NOAA) Hazardous Weather Testbed Experimental Warning Program (HWT/EWP; Stumpf et al. 2008).

![Map showing CASA network radars and WSR-88D radars.](image)

**FIG. 1.** The first CASA test bed is located in southwestern OK. The four radars are located in or near the towns of Chickasha (KSAO), Cyril (KCYR), Lawton (KLWE), and Rush Springs (KRSP). The nearest WSR-88Ds are the Frederick (KFDR) and Twin Lakes (KTLX) radars. Range rings of 30 km for the CASA and WSR-88D radars and 60 km for the WSR-88D radars are marked.

**FIG. 2.** DCAS scanning used by IP1 during 2007. DCAS scanning options include (a) narrow sector scanning, (b) low-level 360° surveillance scanning, and (c) wide sector scanning. Each option is completed within 60 s. The full 360° scan requires approximately 20 s to complete. [Figure adapted from Brewster et al. (2008).]
CASA data are compared with reflectivity and velocity data from nearby NEXRAD WSR-88Ds located near Frederick (KFDR) and Norman (KTLX), Oklahoma.

a. Supercell mesocyclone: 10 April 2007

On 10 April 2007, the second day the CASA radar system was operational, an upper-level trough approached the test bed from the west as a surface low developed in southwestern Oklahoma. An east–west-oriented warm front moved north across the test bed as the low pressure center continued to move eastward toward IP1 at 2000 UTC. A severe thunderstorm watch was issued for southwest Oklahoma at 2040 UTC, effective until 0300 UTC. A small complex of thunderstorms developed into a single cell along a boundary just east of the surface low by 2300 UTC and intensified rapidly as it entered the IP1 testbed coverage area. The National Weather Service (NWS) issued significant weather advisories for the storm at 2302 and 2316 UTC. A severe thunderstorm warning was issued at 2319 UTC, and...
FIG. 4. Radar data collected 10 Apr 2007. (left) The CASA merged reflectivity composites with 1-min refresh rates show a rapidly evolving v notch and an appendage. (right) As in the left panel but for the corresponding NEXRAD data with coarser spatial resolution and at a 5-min update cycle. A severe thunderstorm warning was issued by the NWS at 2319 UTC. The white circle indicates the area of the developing hooklike feature.
a tornado warning was issued for the storm at 2342 UTC. No tornado occurred, but severe hail and winds were observed within the test bed. Data were collected at all four IP1 sites in DCAS mode.

Severe storm characteristics were identified in the CASA reflectivity data minutes before such features were observed by NEXRAD. A series of images from the KLWE and KCYR radar sites, collected between 2315 and 2320 UTC, indicated that a strong thunderstorm was rapidly developing supercell characteristics (Fig. 4). Between 2316 and 2319 UTC, 1-min surveillance scans showed formation of a classic “V notch” in the reflectivity, indicating the presence of a strong updraft. By 2319 UTC, a small hooklike feature was observed in the reflectivity, possibly indicative of low-level rotation, as highlighted in the white circle in Fig. 4. Sector scans of the storm indicated vertical continuity of the hook structure up to 2.6 km AGL. Corresponding
data from KFDR indicated an increasing reflectivity gradient on the southern portion of the storm. However, a less distinct hooklike feature was observed by NEXRAD at 2319 UTC and no velocity couplet was detected by either CASA or NEXRAD.

An appendage persisted on the southwestern flank of the storm as observed by the CASA radars at 2323 UTC (Figs. 5a and 5b). Corresponding reflectivity data from KTLX and KFDR showed a strengthening weak echo region, but lacked the detail of CASA because of the greater distance of the storm from the WSR-88D and coarser resolution (Figs. 5c and 5d). However, neither NEXRAD nor CASA displayed a velocity couplet. At the same time, a professional storm chaser from KWTV, an Oklahoma City television station, observed a funnel cloud with this storm (Fig. 6). The funnel was 14 km from KCYR, but the signal was highly attenuated owing to the location of the precipitation core between the radar and the circulation. KLWE was 24 km from the circulation center, but either the rotation was simply too weak to be detected or the resolution provided by CASA could not fully resolve the feature at that range.

b. Supercell and misocyclones: 8 May 2007

During the day and evening of 8 May 2007, a surface low developed in southwest Oklahoma at the intersection of a stalled east–west frontal boundary and a surging cold front to the west. A mesoscale convective system formed along the cold front with a surging bow echo located along its leading edge. A mesoscale convective vortex (MCV; e.g., Davis and Trier 2007) formed on the northern end of the bow echo, just south of the Red River in northwest Texas. The MCV moved north and enhanced the low-level vertical wind shear to its northeast. The Storm Prediction Center (SPC) issued a tornado watch at 2230 UTC covering portions of northwest and north-central Texas and southwestern Oklahoma, including the IP1 test bed.

The MCV moved north from Texas into Oklahoma and spawned one supercell and three minisupercells [each approximately 5 km in diameter; Suzuki et al. (2000)] within the CASA test bed. Four circulations, including three misocyclones (as defined by Kessinger et al. 1988), were observed by the CASA radars between 0000 and 0400 UTC (Fig. 7). One brief tornado, which was rated as an EF0 on the enhanced Fujita scale, was reported northwest of Lawton in association with circulation 1 by a television storm chaser, but this report could not be confirmed by a follow-up damage survey team. One EF1 tornado was confirmed near Minco, Oklahoma, associated with circulation 4. See Fig. 7 caption for more information on the numbered circulations.

Severe storms entered the CASA network from the south at approximately 0000 UTC 9 May and exited the network to the north at about 0400 UTC 9 May. This storm event occurred in two distinct phases. First, a supercell was observed by the CASA radar KLWE between 0000 and 0100 UTC. Low-level rotation was observed with this supercell with both NEXRAD and CASA. Second, a series of three misocyclones was observed by the CASA radar KSAO between 0300 and 0400 UTC. Unfortunately, both storm episodes remained
largely within the single-radar coverage of CASA and many of the advantages of the CASA test bed (e.g., dual-Doppler analysis, multi-Doppler attenuation correction) could not be realized. Nevertheless, the high temporal and spatial resolutions and low-level coverage of the CASA radars provided additional insight into the development and progression of this particular event.

1) Supercell Near Lawton: 0000–0100 UTC

As the developing supercell entered IP1 at about 0000 UTC, the CASA feature detection software recognized the storm as a “feature of interest” due to its high reflectivity (>50 dBZ) and began scanning the storm in DCAS mode. This storm could only be observed from the KLWE radar, so KLWE was instructed by the Meteorological Command and Control algorithms to scan the storm in an approximate 60° azimuth sector encompassing the storm at 1°, 2°, 3°, 5°, 7°, 9°, 11°, and 14° elevations, similar to the pattern shown in Fig. 2a.

Low-level rotation could be seen from KLWE as the storm entered the network at 0000 UTC with gate-to-gate shear of 11 m s⁻¹ observed at 1 km AGL coincident with a developing hook echo. By 0015 UTC, low-level rotation was observed in the CASA velocity data coincident with an appendage observed in the CASA reflectivity. An NWS tornado warning was issued at 0016 UTC. A hook echo formed between 0015 and 0020 UTC, as can be seen from the KLWE data, and by 0033 UTC a pronounced hook was observed (Fig. 8a). By 0045 UTC the hook and appendage dissipated,
though broad weak rotation persisted (azimuthal shear <0.006 s$^{-1}$).

Data collected from the WSR-88D radar near KFDR between 0034 and 0039 UTC are shown in Fig. 8b. Data from KFDR were available from the lowest elevation angle only every 5–6 min, compared with every minute from CASA. In addition, the range resolution provided by the KFDR reflectivity was about 1 km compared with 100 m for KLWE. Finally, KFDR was about 50 km from the circulation area compared with about 22 km for KLWE. Given these distances, the center of the 1° elevation angle beam from KLWE was at approximately 400 m AGL while the center of the ½° elevation angle beam from KFDR was at approximately 580 m AGL.

One distinctive feature observed in the KLWE data is what appears to be an anticyclonic circulation. Between 0030 and 0041 UTC, a cyclonic–anticyclonic pair of circulations was inferred from the lowest levels of reflectivity near the hook echo (Fig. 9). Unfortunately, low-level anticyclonic rotation could not be confirmed due to noise in the velocity data. Similar cases have been documented in the literature (e.g., Brown and Knupp 1980; Rasmussen et al. 2006) and with the phased-array radar of the National Weather Radar Testbed (Zrnić et al. 2007).

2) MINISUPERCILLS NEAR CHICKASHA: 0300–0400 UTC

As the mesoscale convective vortex moved north, a series of minisupercells developed just to the northwest of the CASA radar KSAO. At least three distinct circulations were identified between 0300 and 0400 UTC within range of the KSAO radar. The observations of these circulations from the Twin Lakes, Oklahoma (KTLX), WSR-88D radar and the CASA KSAO radar were compared directly. The distance from KSAO to the circulations ranged from 16 to 30 km, yielding a minimum scanning height of approximately 400 m to 1.1 km at the 2.0° elevation angle. The range from KTLX was approximately 70 km, yielding a minimum scanning height of approximately 900 m at the 0.5° elevation angle.

FIG. 8. (a) Reflectivity data collected at 2.0° elevation from the CASA radar KLWE between 0033 and 0039 UTC 9 May 2007. (b) Level 3 reflectivity data collected at 0.5° elevation from the WSR-88D radar KFDR between 0034 and 0039 UTC 9 May 2007.
The first circulation developed by 0304 UTC (Fig. 10). The azimuthal shear was approximately 0.0144 s\(^{-2}\), observed by KSAO at 0313 UTC at a height of 300 m AGL, and drifted to the northwest and dissipated by 0322 UTC (Fig. 11a). Data from KTLX at 0.5° elevation shows a broad and persistent shear region with a gate-to-gate shear velocity of 19 m s\(^{-1}\) (azimuthal shear of 0.0171 s\(^{-2}\)) at 0313 UTC at 1.0 km AGL moving to the north (Fig. 11b). Observations at multiple elevations indicate that the CASA and WSR-88D radars are observing the same features but at different levels. This suggests that the CASA system, with its increased temporal and spatial resolutions and a larger percentage of the observational domain below 1 km AGL, is capable of tracking the details of phenomena that would not otherwise be detected.

A second circulation pattern formed directly to the north of KSAO by 0331 UTC (Fig. 12a). The gate-to-gate wind shear as estimated from KSAO had increased to 34.2 m s\(^{-1}\) at 400 m and 32.0 m s\(^{-1}\) at 700 m AGL, whereas the gate-to-gate shear from KTLX was estimated as 19.9 m s\(^{-1}\) at 800 m AGL. The wind shear estimates appeared to increase significantly as measured by KSAO, just prior to tornadogenesis, which occurred a short time later at approximately 0355 UTC from the same storm cell (Fig. 7).

The shear estimate differences between CASA and NEXRAD cannot be readily explained. The CASA wind estimates represent a much smaller pixel volume compared with that of NEXRAD, and so estimates from CASA tend to vary more widely due to the smaller averaging volume. In addition, the radial velocity estimates from CASA also had some moderate amount of uncertainty associated with the noise and aliasing of the data at the time these data were collected. A number of improvements have been made to the signal processing and quality control of the data since 2007. Clutter suppression and attenuation correction algorithms have been improved, an automated radar calibration has been added, and networked reflectivity retrieval is now being tested.

One disadvantage of the CASA system is attenuation, as noted by the speckled areas to the northwest of the shear signature (Figs. 11a and 12a). In fact, a second shear signature, observed about 20 km to the northwest of the main circulation area (both were observed by KTLX; see Fig. 11b), is unobserved by KSAO, owing to the attenuation from the nearer storm. In a much larger operational network, overlapping coverage from neighboring radars would be able to fill in these gaps, and in most cases complete attenuation would be limited to the edges of the network domain. The attenuation is caused largely by the use of short-wavelength (X band) technology, a problem much reduced when using longer-wavelength (e.g., S band) radars. The advantage of X-band radars is that much finer structures can be observed.

c. Vortices along a squall line: 30 May 2007

During the evening of 29 May 2007, an intense squall line developed in eastern Colorado and western Kansas along a cold front pushing south-southeastward. By 0500 UTC 30 May, the squall line had entered northwestern Oklahoma; at this time, the squall line began to evolve into a bow echo. The SPC issued a severe thunderstorm watch at 0949 UTC for portions of southwestern Oklahoma including the CASA test bed. The line began to enter the test bed at 1000 UTC. The NWS issued a severe thunderstorm warning at 1001 UTC for the northern half of the test bed and soon extended the warning across the southern half of the test bed at 1009 UTC.

![Fig. 9. Reflectivity data collected at 2.0° elevation from the CASA radar KLWE at 0033 UTC 9 May 2007. Note the cyclonic and anticyclonic pair of hook echoes.](image-url)
As the squall line entered the testbed coverage area, a series of three to four hooklike features were noted in the reflectivity data along the leading edge of the line (Figs. 13a and 13b). An examination of the velocity associated with these reflectivity features revealed several areas of low-level cyclonic wind shear (Figs. 13c and 13d). These small vortices may be the result of vorticity stretching caused by updrafts that were located along the leading edge of the line of storms. Further examination of the features found regions of enhanced wind speeds where the translation speed of the storms and the tangential velocity of the circulations were additive.

Forecasters who reviewed the KCYR data and compared it to KTLX data felt that the additional spatial and temporal resolution afforded by CASA provided them additional confidence to identify regions of potentially severe winds.

This case demonstrates the potential value of DCAS, scanning near the surface, to provide advanced warning for both low-level, nonmesocyclone supported circulations and straight-line winds. Between 1015 and 1020 UTC, a bow echo was advancing toward an Oklahoma Mesonet station (McPherson et al. 2007) located near the town of Ninnekah (NINN; Fig. 14). Oklahoma Mesonet stations provide 5-min observations of wind speed and direction and maximum 3-s wind speed gusts collected at 10 m AGL. The NINN mesonet site recorded a 3-s gust of 26.6 m s\(^{-1}\) between 1015 and 1020 UTC. At 1019 UTC, the KRSP radar recorded a north-easterly radial velocity measurement of 28.6 m s\(^{-1}\) over the NINN mesonet site. The NINN mesonet site is 17 km from KRSP and the 1° elevation beam was at approximately 600 m AGL at this location. By comparison, the estimated radial velocity from KTLX for the same time, using the ½° elevation beam at approximately 1 km AGL, was 9 m s\(^{-1}\). The discrepancy between the NEXRAD measurement and that provided by CASA results from two issues: the NEXRAD measurement was from a higher altitude and was likely too high to sample the strong winds near the ground, and because the gust front translation and winds were nearly perpendicular to the radial of the radar beam. Similar results were found by comparing NEXRAD, CASA, and in situ measurements at two other mesonet site locations (Table 2).

4. Discussion and conclusions

Forecasters who participated in the Hazardous Weather Testbed evaluated these events either in real time or through archived case reviews. Forecasters used a “think aloud” protocol (Ericsson and Simon 1993) where they shared their reasoning, processing, and concerns as they analyzed cases and completed questionnaires on adaptive scanning patterns, data quality, important features recognized in CASA data, and the potential impacts on the warning decision-making process. Actual warning experiments were not conducted because 2007 was CASA’s first season of operation.
One key result from the forecaster evaluation is that CASA data confirmed current conceptual models of storm development and provided added detail within its operating range. Conceptual models are used to train forecasters to quickly evaluate developing storm scenarios. Forecasters reported it was easier to identify certain storm features with the faster, adaptive radar network and that the clarity in the details of the CASA radar presentation lessened the need for interpretation of data. High-resolution storm features observed in the CASA data included weak-echo regions, sharp reflectivity gradients, echo appendages, and outflow boundaries. For example, forecasters reviewing the 10 April case noted the ability with the CASA data to quickly identify areas of “strong reflectivity gradients” and to gain “a few minutes jump on the [storm] evolution.” Meso-scale rotations in the 8 May case were clear in the CASA data but not as evident in the NEXRAD data. Small-scale details such as the detection of low-level vortices from the 8 and 30 May cases could now be observed directly. As one forecaster noted while observing the mesocyclones of 8 May, “This is not gate-to-gate shear!,” emphasizing the differences posed by high-resolution data. In addition, forecasters repeatedly cited the “greater time continuity [sic]” of the storm features, where “conceptual models are realized.” The rapid update time allows for the smooth playback of radar features showing continuous storm formation and development.

FIG. 11. Single-Doppler velocity data collected 8 May 2007 north of Chickasha. (a) Velocity data collected from KSAO at 2° elevation at 0314, 0315, 0316, 0317, 0319, 0320, 0321, and 0322 UTC. (b) Velocity data collected from KTLX at 0.5° elevation at 0313, 0318, and 0322 UTC.
The eventual operational use of CASA data by forecasters will require the development of a new concept of operations for warnings as well as advances in existing display technology. These new approaches will become increasingly necessary as NOAA implements a multi-observational platform strategy and multiple sources of observations become available to forecasters, such as Terminal Doppler Weather Radar (TDWR), or the Multi-Purpose Phased-Array Radar. In addition, new NEXRAD capabilities and products, such as dual polarization and range velocity mitigation, will add to the information available to forecasters. Data overload, training, and effective visualization are issues that will need to be addressed by all forecast offices in the future.

CASA data will add to this increasingly complex stream of data. A new warning process for new features such as misocyclones will need to be developed. As forecasters observe greater numbers of velocity signatures at faster update rates and at lower altitudes, the number of small-scale circulations seen likely will increase dramatically. Initially, this could lead to an increase in the false alarm rate. Warning the public of small-scale circulations is particularly challenging due to the erratic paths and short durations of misocyclones and gustnadoes. Small, short-lived tornadoes in hurricane-prone regions may be the most comparable for creating warning methodologies.

Visualization of CASA’s multiple elevations will be a significant challenge. What is the best way to present to the forecaster multiple sector scans that are adaptively changing every minute? Interactive display visualization will become increasingly critical as observing tools become ever more adaptive and complex.

Supercell mesocyclones, nonsupercell misocyclones, and low-level vortices along a gust front were observed by CASA radars in three convective episodes observed during April and May of 2007. These storms were scanned using an automated, adaptive sensing technique known as DCAS. DCAS allows for faster, adaptive sector scanning of features of interest as identified by end users. For these three cases, the DCAS strategy for scanning proved to be beneficial for providing more focused volumetric scanning of storm features.

In part because of the DCAS strategy for scanning, several features were identified in the CASA data that were not observed in the WSR-88D data. Low-level circulations associated with a mesocyclone and a gust front were identified in the 10 April and 30 May events, respectively. On 8 May, a pair of cyclonic–anticyclonic circulations was inferred from the reflectivity in association
with a supercell storm near Lawton, Oklahoma, and rapid volume scans of this storm showed the vertical continuity of the cyclonic circulation up to 3.5 km. The development and evolution of smaller-scale vortices near Chickasha, Oklahoma, were identified and tracked, and were unable to be seen in the operational WSR-88D data. In fact, an entire class of vortices, seldom observed by conventional means, may now be resolved. Overall, the much higher

![FIG. 13.](image1)

**FIG. 13.** Single-Doppler reflectivity and velocity data collected 30 May 2007 northwest of Cyril. (a) Reflectivity data from KTLX at 0.5° elevation at 1001 UTC. (b) Reflectivity data from KCYR at 2.0° elevation at 1001 UTC. (c) Velocity data from KTLX at 0.5° elevation at 1002 UTC. (d) Velocity data from KCYR at 2.0° elevation at 1001 UTC.

![FIG. 14.](image2)

**FIG. 14.** Single-Doppler reflectivity and velocity data collected 30 May 2007 northwest of Rush Springs. (a) Reflectivity and (b) radial velocity data collected at 1019 UTC at 1° elevation from KRSP. The mesonet site near Ninnekah (NINN) is marked.
temporal and spatial resolutions of the CASA data, especially in densely populated networks where a much greater percentage of the domain is scanned below 500 m AGL than with the existing NEXRAD network, yield a unique tool for capturing the temporal and spatial scales associated with meso- to mesoscale features of the atmosphere.

The CASA test bed in Oklahoma continues to be operated each spring and fall during active weather periods. The signal processing and quality control have been upgraded since 2007, and data from the network now drive real-time surface analyses, nowcasting, and dynamic numerical weather prediction models. Forecast evaluations continue within the Hazardous Weather Testbed Experiment Warning Program and are being used to quantify the impacts of CASA data on the warning process. Current plans are to expand the size of the IP1 network within the next several years.

Operational challenges for the forecaster include data overload, visualization, revision of NEXRAD-era conceptual models, and greater temporal and spatial specificities in warning. Improved display interface technology combined with additional training and experience is critical. Integration of these new tools and techniques into the operational forecasting environment, together with the benefits of dual-polarization, multi-Doppler analysis and improved NWP, may be keys for further improvements to warnings for convective storms.

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