A COMPARISION OF WIND ESTIMATES FROM CASA AND NEXRAD RADARS DURING SEVERE WIND EVENTS

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ABSTRACT

The Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) Oklahoma test bed has proven the usefulness of a high-resolution, rapidly updating network of radars for a variety of applications. The aim of this project is to quantify the value of the CASA network for the detection of severe wind events. A comparison is made between the performance of Next Generation Doppler Weather Radar (NEXRAD) and CASA radial wind measurements in relation to Oklahoma Mesonet reports of high wind gusts. Two factors inhibit the accurate measurement of winds from weather radar: (1) The viewing angle of the radial velocity beam, and (2) the beam height above ground level. Results show that the CASA radar network performed better overall for detecting and analyzing high wind events within the test bed. CASA dual-Doppler data improved the measurement of winds by 7.27 m/s over all NEXRAD measurements.

1. THE NEXRAD AND CASA RADAR NETWORKS

The Next Generation Doppler Weather Radar (NEXRAD) network has greatly improved forecasters abilities to detect and analyze hazardous weather events in real time (Serafin and Wilson, 2000). Yet a few distinct weaknesses in the NEXRAD network remain. First, terrain blockage and the curvature of the earth limit the ability of the network to detect atmospheric winds in the lowest portion of the atmosphere (<1km). More than 70% of the atmosphere below 1-km is not observed by the NEXRAD network (McLaughlin et al. 2009). Second, weather radars are limited to measuring radial velocity. Winds within a thunderstorm are rarely parallel with the beam; true wind velocity can only be found using two or more radars. The final weakness of the NEXRAD network is the temporal resolution of a full volume scan (Junyent et al. 2010). Severe storms rapidly evolve and update times are a serious limitation when trying to understand and predict transient severe weather events, especially those involving severe wind gusts.

The Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) McLaughlin et al. (2009) was founded to address some of the shortcomings of the NEXRAD network. CASA aims to develop a network of collaborative small, radars that can be deployed at low cost compared to the NEXRAD network. These radars have a much shorter range than the larger NEXRAD radars, but can be arranged in a manner that allows them to collaboratively scan storms by sharing data (McLaughlin et al. 2009). The organization of a network of radars provides much greater coverage for the lower portion of the troposphere. In summary, CASA radars are able to provide users with improved spatial and temporal resolution over existing systems.

The CASA network should be able to help forecasters improve their ability to detect severe wind events in a variety of ways. First, spatial and temporal resolution improvements will allow

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forecasters to see the fine details in storm evolution. Second, the geometry of the network should work to eliminate the viewing angle problem so common to operational forecasters. Finally, the radars will scan lower to the ground and give a better estimate of actual surface wind speeds.

The CASA radars have been shown to improve forecasters ability to assess wind speeds and increase their confidence in those assessments (Rude et al. 2011). The increase in spatial and temporal resolution has also allowed for routine observations of severe storm characteristics often not visible on NEXRAD network (Brotzge et al. 2010).

CASA radars do have a few shortcomings. Due to their small wavelength (3cm), attenuation is a problem in areas of heavy precipitation. Forecasters may also be overloaded with data due to the number of radars and faster scan rates. Instead of a full volume scan from one radar every four to five minutes, forecasters will have sector scans from multiple radars every minute (Brotzge et al. 2010).

The main purpose of this research is to quantify the differences between the estimates of CASA and NEXRAD radars during strong to severe wind events. By understanding the advantages and limitations of each radar system, forecasters will be able to better analyze and predict how strong winds will impact the surface. Corrections were also applied to the CASA data to see how they could improve the performance of CASA radars.

This paper is organized as follows Section 2 focuses on the collection, quality control, and processing of the data. Section 3 focuses on how each network performed and how height and viewing angle impacted the results. Also in section 3 dual Doppler analysis is performed and corrections are applied to the data. Section 4 is a discussion of the implication of the results.

2. DATA COLLECTION AND PROCESSING

Since the fall of 2006 the CASA Integrated Project 1 (IP1) test bed has been collecting a variety of standard and polarimetric radar data. For this research, only raw radial velocity and attenuated reflectivity were used from each of the radar sites. Radars are located in or near the towns of Chickasha (KSAO), Cyril (KCYR), Rush Springs (KRSP) and Lawton (KLWE); a map of the radar network is shown in Fig. 1. In addition to the four CASA radars, data from two NEXRAD radars, Fredrick (KFDR) and Twin Lakes (KTLX) were available for comparison

The Oklahoma Mesonet (Brock et al. 1999) provides an excellent network of sensors to measure low-level winds across Oklahoma. The Mesonet measures a variety of surface parameters every five minutes. The exact time and location of strong wind reports were sampled at seven Mesonet stations across the IP1 test bed. In this study variables sampled included maximum 3-second wind speed and average wind direction at 10m above ground level. For this study, all instances of a 3 second maximum wind gust of over 22.35 m/s (50mph) on days with thunderstorms were examined.

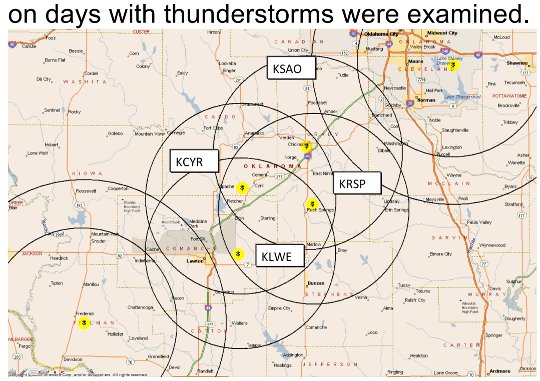

Fig. 1 The CASA IP1 test bed with 40km range rings for CASA radars and 40km and 60km NEXRAD range Rings

For each wind event, two scans from each NEXRAD site and five scans from each CASA site were examined. The two volume scans that were the closest to the reported Mesonet observation time were examined for NEXRAD and the five scans leading up to the Mesonet report were examined in the CASA scans. In the NEXRAD scans, the maximum radial velocity measurement was extracted along with the height above radar level (ARL), angle of the scan, and distance of measurement from the radar in the location of the maximum measurement. For CASA data, the maximum radial velocity measurement from the five scans was extracted from each of the CASA radars along with the height, angle, and distance measurements. The maximum measurement in each of these cases was the one that fell within the range of the latitude and longitude of the Mesonet station. Care was taken to avoid collection of data that fell within noisy regions or other areas where it appeared that the radar was not correctly measuring radial velocity. After this quality control was applied, 48 events were available for comparison with Mesonet data.

The main method for determining performance was subtracting the Mesonet velocity from the measured or computed velocity from the radar. This gives insight whether the radar is over or under estimating wind speeds. Another measurement used to determine performance was percent error. The percent error was determined for each measurement using a basic calculation:

$$Error = \frac{|Radial\ Velocity - Mesonet\ Velocity|}{Mesonet\ Velocity} * 100\ (1)$$

In addition to calculating error for each measurement, a minimum error for each network was also determined for each case. Minimum error is defined as the scan with the lowest error out of any measurement for that network. This minimum error was then used to determine the velocity of the best scan for that network during the time frame.

In order to quantify how height and viewing angle were related to error, all the observations were sorted by both height and viewing angle. Height above radar was considered. For the CASA radars, measurements were grouped into 3 levels: 0-.5km, .5-1.0km, and >1km ARL. NEXRAD was split into 3 height levels: <1km, 1-1.5km and >1.5km ARL. Measurements also were sorted by viewing angle relative to the mean surface wind direction. For each radar network the radial velocity measurements were split into 3 categories: <30 degrees, 30-60 degrees, and >60 degrees. Basic statistical variables were calculated for each of these groupings.

Dual-Doppler analysis was calculated for each case where two or more CASA radars measured radial velocity at an angle difference of more than 30 degrees relative to one another. This provided a more accurate analysis of the wind field than single radar could measure.

Finally, a wind profile was applied to account for frictional effects near the surface. The profile correction was applied to all of the measurements and the dual-Doppler analysis. A simplified version of the log law was used. The formula used was:

$$U_{z1} = U_{z2}\frac{\ln\left({}^{z1}/_{z0}\right)}{\ln\left({}^{z2}/_{z0}\right)}\ (2)$$

Where U_{z1} is the wind speed at 10m, U_{z2} is the measured wind speed, and the roughness (Z_0) is estimated to be .01 m for all of the cases. Since friction has the greatest effect in the 0-100m range, z_2 is treated as 100m in every case and z_1 is 10m. Wind speed is assumed constant above 100m AGL. After applying these assumptions our formula for estimating surface winds becomes:

$$U_{Z1} = U_{Z2} * .75\ (3)$$

This formula offers a simple way to provide a relatively accurate estimate of 10m winds.

3. RESULTS

3.1 NEXRAD Performance

Fig. 2 shows the NEXRAD measured velocity minus Mesonet velocity for the best NEXRAD Scan for each case. While Fig. 3 shows all of the NEXRAD scans. The mean difference between Mesonet and NEXRAD measurements was -5.31 m/s and the standard deviation was 6.71 m/s. Including every measurement the mean difference rises to -7.74 m/s and standard deviation increases to 9.69 m/s. This is more representative of the situation facing an operational forecaster. A forecaster does not know which measurement is the correct one.

The mean minimum percentage error for NEXRAD is 23.88%. Including all measurements this error rises to 39.82%. The data are also very variable. The standard deviation of all measurements was 27.09% and for minimum error is 22.52%. A forecaster armed with only NEXRAD data has a large error to account for and this poses a real challenge.

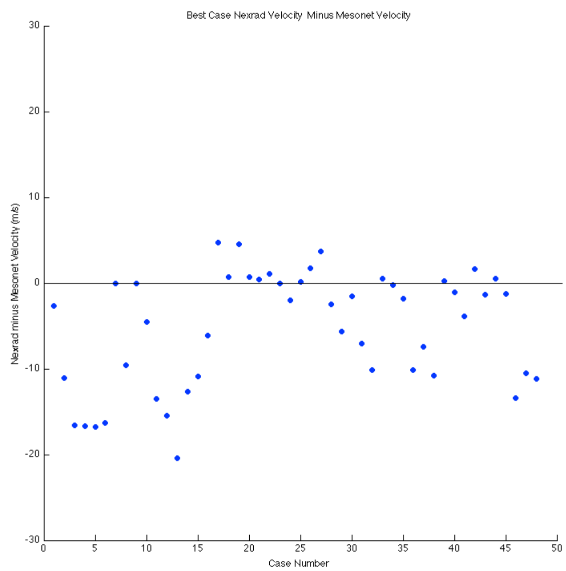

Fig. 2 NEXRAD Velocity with lowest error minus Mesonet Velocity for each case

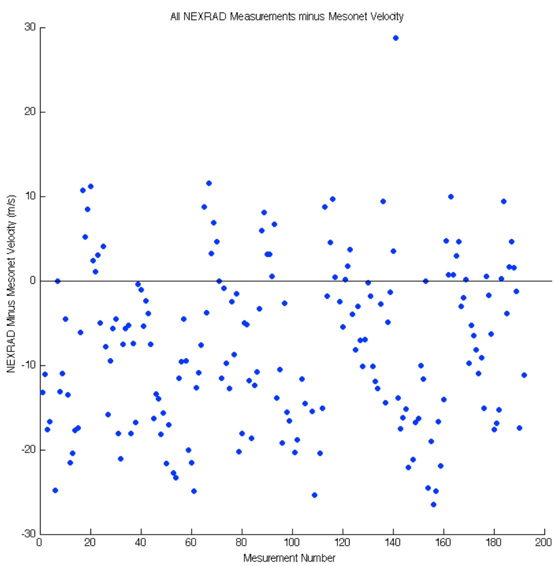

Fig. 3 All NEXRAD velocity Measurements minus Mesonet Velocity

3.2 CASA Performance

Fig. 4 is a plot of the reported Mesonet velocity subtracted from the CASA radial velocity with the lowest error for each case. Fig. 5 is the reported Mesonet velocity subtracted from all CASA measurements. The mean difference for the best case CASA scan is -2.11 m/s. When all measurements are included this difference increases to -4.21 m/s.

Examining error it is apparent that CASA error is less variable than NEXRAD error. The standard deviation of minimum errors was 7.00 m/s (17.41%) and 8.59 m/s (20.49%) including all CASA measurements.

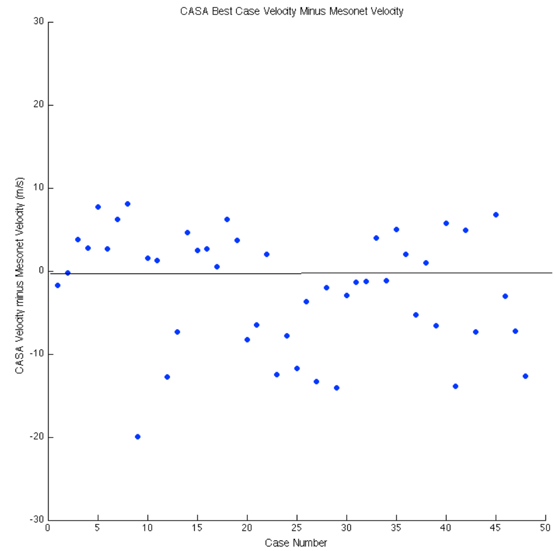

Fig. 4 CASA velocity with lowest error minus Mesonet Velocity for each case

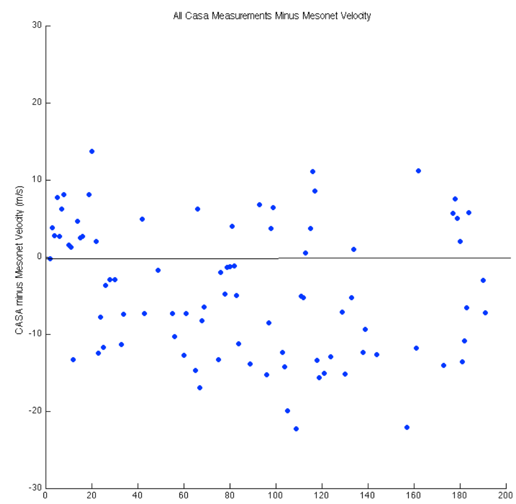

Fig. 5 All CASA measurements minus Mesonet velocity

3.3 Comparison of NEXRAD and CASA

The mean difference between CASA and Mesonet is slightly better than the mean difference between NEXRAD and Mesonet velocities, though the standard deviations are very close. For NEXRAD it is 6.71 m/s and 7.00 m/s for CASA. Both radars had problems underestimating wind speeds though this is to be expected from the viewing angle problem.

When examining percent error, CASA and NEXRAD are close in performance when using the best-case scenario. When all measurements are considered, the error in

CASA measurements is 7.55% better. This seems to be a better estimate of performance because forecasters will not know the scan with the best estimate of wind speed.

Fig. 6 is a plot of NEXRAD wind speed error against CASA wind speed error in the best case. NEXRAD underestimates a majority of the wind speeds while CASA is more evenly distributed.

The real advantage of CASA is apparent when viewing Fig. 7. From the plot it is apparent how NEXRAD is much more variable than CASA in terms of percentage error. For a few cases NEXRAD did an excellent job of measuring winds but there are also many cases were NEXRAD did a very poor job detecting winds. A majority of the CASA error falls below the 30% line in the figure. While CASA may not have as many cases with no error it has far fewer cases with extremely large error. The greater reliability is advantageous to forecasters when trying to determine the winds within a storm.

In order to better understand how each radar system performs, the next sections will examine how viewing angle and measurement height affect the errors of radial wind measurements and apply corrections to try and compensate for these errors.

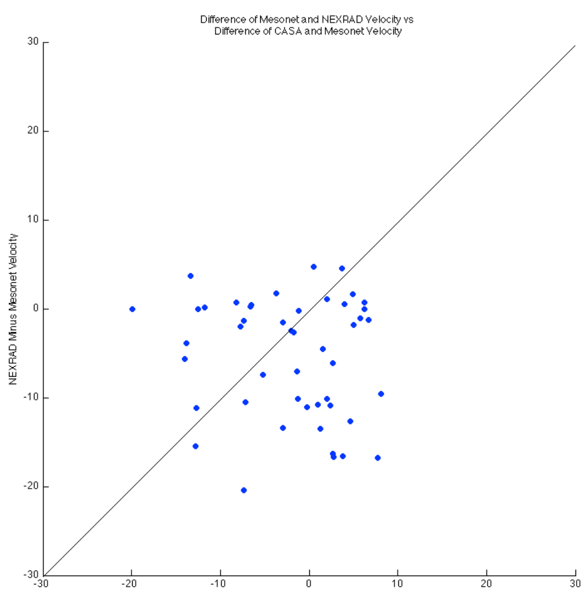

Fig. 6 NEXRAD vs. CASA wind speed errors in the best case

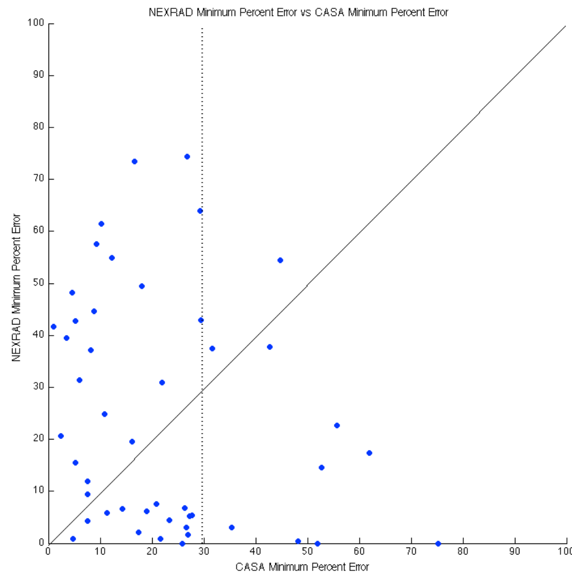

Fig. 7 NEXRAD vs. CASA minimum percent error

3.4 Errors from Viewing Angle

The main limitation of any radar wind measurement is the viewing angle of the beam in comparison to storm velocities. Figs. 8 and 9 plot velocity difference as a function of viewing angle for all measurements. As angle increases the radars go from an overestimation of the wind speeds to underestimating them. Angle presents a real problem to forecasters requiring the use of additional surface and model information to estimate the true wind direction and speed.

Table 1 (appendix) shows each radar system error when measurements were sorted by viewing angle. On average CASA performed very well in the 0-30 degree range. In fact, CASA performed better than NEXRAD in every category, especially when the viewing angle was between 30 and 60 degrees. Both radar systems performed poorly once the viewing angle relative to storm wind direction exceeded 60 degrees.

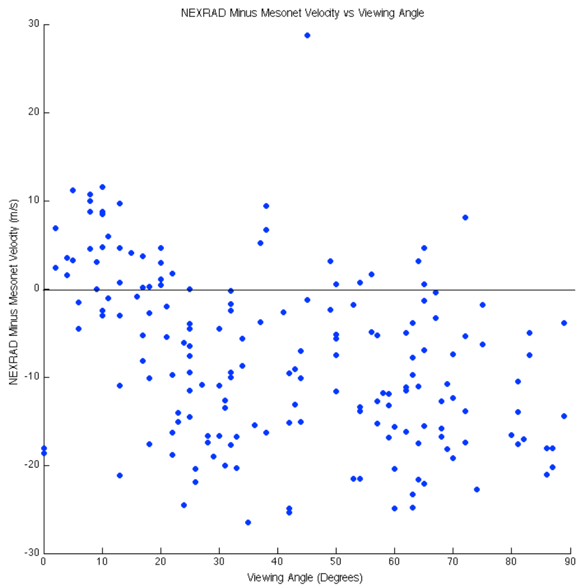

Fig. 8 Difference between NEXRAD and Mesonet velocity with respect to viewing angle difference

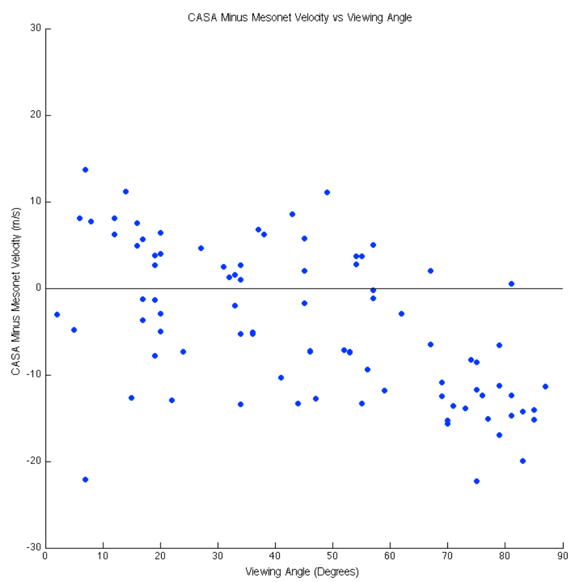

Fig. 9 Difference between CASA and Mesonet Velocity with respect to viewing angle differences

3.5 Dual Doppler Correction

In order to correct for angle errors within the CASA network, a dual-Doppler analysis was performed on all measurements where the angle difference between radar beams was over 30 degrees. Applying this analysis to CASA data caused CASA to overestimate Mesonet velocities by 7.52 m/s and *raised* the percentage error to 40.82%. This is because dual-Doppler analysis provides the winds at a relatively high height above ground where they are not slowed by friction and which would likely be expected to overestimate surface winds. Table 2 (appendix) sorts the dual-Doppler departure from Mesonet velocity by the average height of the two measurements. The error does not appear related to height as one may expect; most of the reduction in wind speed from friction is in the lowest 100m of the troposphere. The wind profile correction applied in section 3.8 will address this problem.

Fig. 10 is a plot of the difference between the Mesonet and dual-Doppler wind speeds of each event where it is applied. Applying dual-Doppler analysis overestimates most of the wind speeds; this is encouraging for applying a profile to the dual-Doppler analysis, which is done in section 3.9.

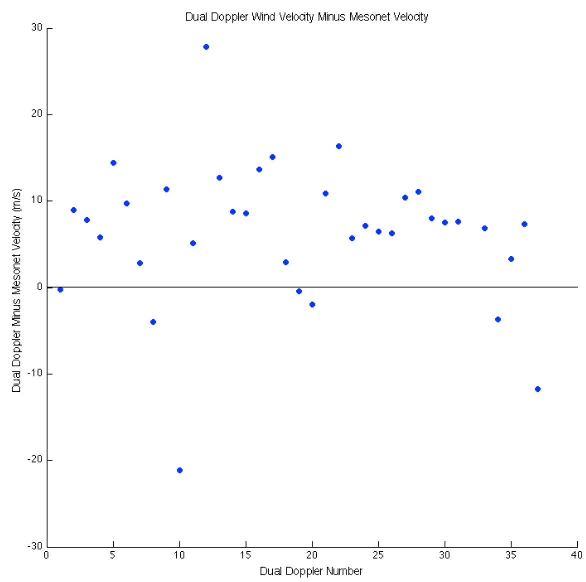

Fig. 10 Dual-Doppler analysis minus Mesonet velocity

3.6 Errors From Height

Beam height is a second important source of error in a radar's measurement of wind. Winds above ground level are higher than those experienced at the surface due to friction. Figs. 11 and 12 are plots of each network's wind speed error plotted against height. It is hard to extract a trend due to the clumping of height data. Tables 3 and 4 (appendix) show a breakdown of the difference from Mesonet measurements from each system sorted by height. CASA performs better than NEXRAD on average below 1km. Above 1km NEXRAD performs better but this may be due to the few CASA measurements above 1km.

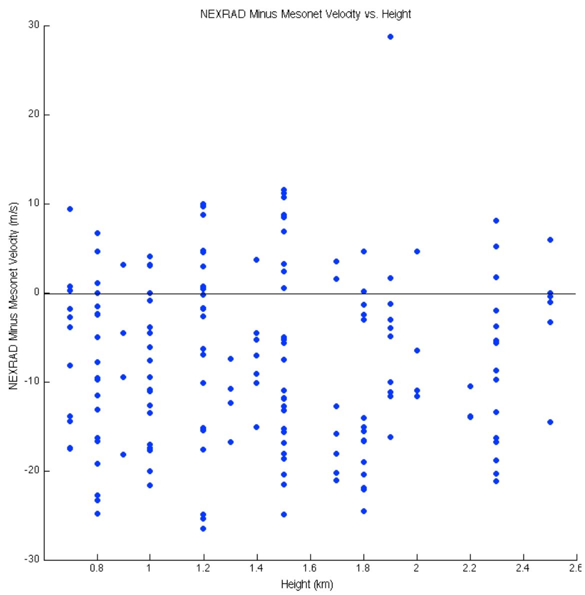

Fig. 11 NEXRAD minus Mesonet with respect to Height Above Radar Level

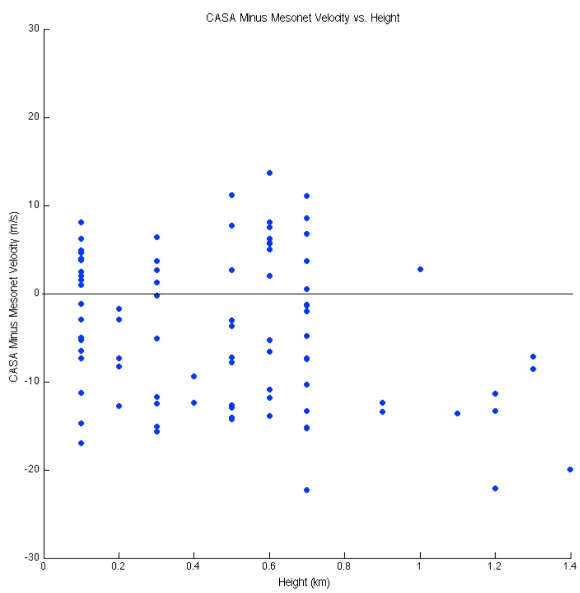

Fig. 12 CASA minus Mesonet Velocity with respect to height above radar level

3.7 Profile Correction

Appling the profile correction to raw data did not provide an improvement for measuring wind speeds. When the profile was applied and the best scan chosen departure from the Mesonet velocity was -7.05 m/s and was -9.09m/s for NEXRAD. Figs. 13 and 14 show the difference on a case-by-case basis for each system. Table 5 (appendix) sorts the profile corrected error by categories according to viewing angle. The profile does not seem to offer any improvement at lower angles and fails at higher angle measurements. CASA performs better in the 30 to 60 degree range with the profile correction applied than NEXRAD does.

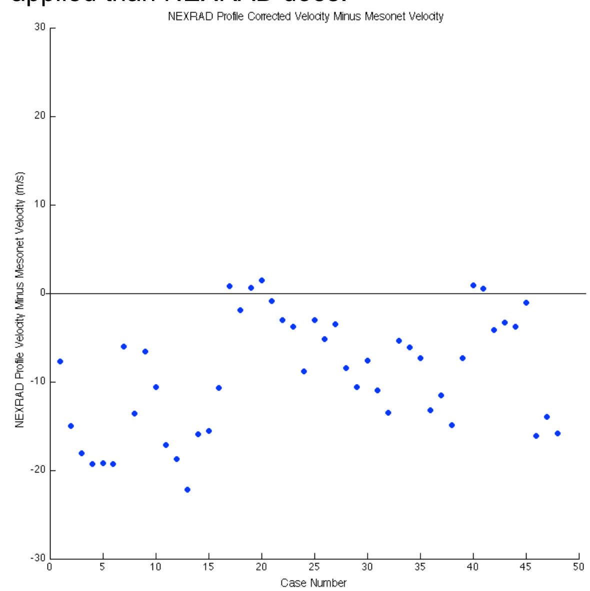

Fig. 13 NEXRAD velocity measurements with profile correction minus Mesonet velocity

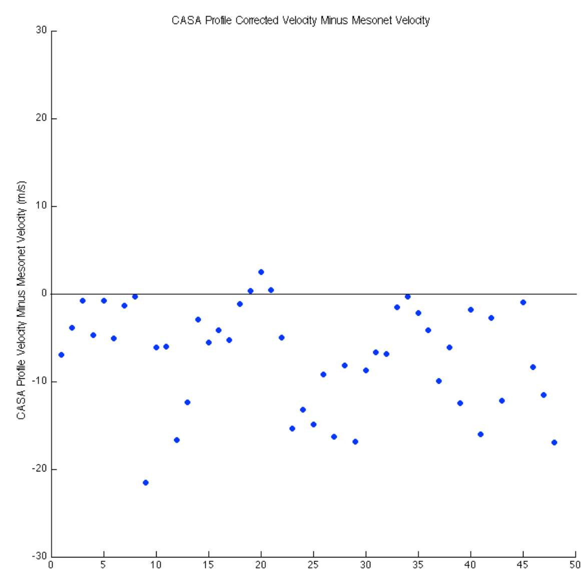

Fig. 14 CASA velocity measurements with profile correction minus Mesonet velocity

3.8 Errors From Height and Viewing Angle

Tables 6 and 7 (appendix) are NEXRAD and CASA data sorted by both angle and beam height. Tables 8 and 9 (appendix) are the standard deviation of each of these groupings. NEXRAD performed reasonably well in the upper left categories but got progressively worse as height and viewing angle increased. CASA performed very well when the beam was at a height of less than 1 km and the angle was less than 60 degrees. CASA had a small standard deviation in the lowest .5km of the atmosphere. The smallest deviation was when the beam was very low and measuring winds at a small angle. To address the problems of viewing angle and beam height, both dual-Doppler analysis and a profile correction were applied to CASA data in the next section.

3.9 CASA Dual Doppler Analyses and Wind Profile Correction

After applying the wind profile correction to the dual-Doppler data, the difference between the data and Mesonet velocities was very small. On average the mean error was .47 m/s with a median difference of -.265 m/s. Dual-Doppler analysis from the CASA network offers a very accurate estimate of the surface winds within a thunderstorm. Fig. 15 is a plot of the difference between corrected CASA data and Mesonet velocities. There are numerous data points close to zero difference.

Fig. 16 is a plot of profile corrected NEXRAD error and CASA data. This figure shows the importance of beam angle. Without knowing the true winds from dual-Doppler analysis, applying a profile to NEXRAD data will not help a forecaster determine surface wind speeds with any greater accuracy.

Fig. 17 is a plot of CASA corrected data error vs. the error from the best NEXRAD scan of each case. CASA error in many cases is quite low and most of the points are within 20% of the actual recorded surface wind. The median error for CASA dual-Doppler data is 9.94%. When available, dual-Doppler analysis with beam height correction offers an excellent tool for forecasters to use to determine surface winds.

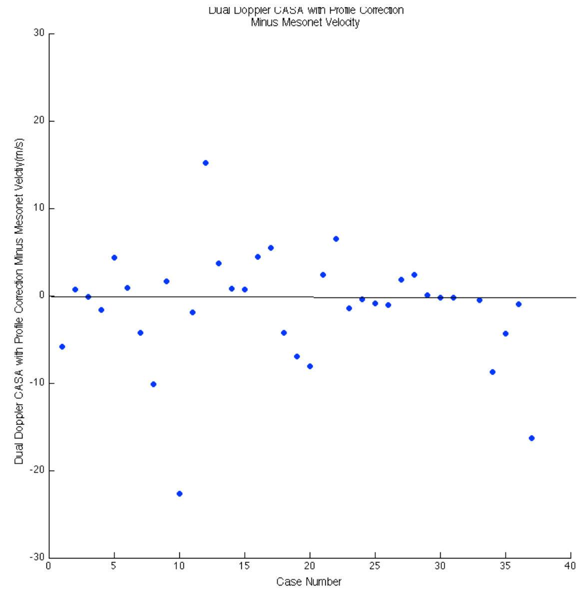

Fig. 15 Profile corrected dual-Doppler minus Mesonet Velocity. One data point outside of y axis range.

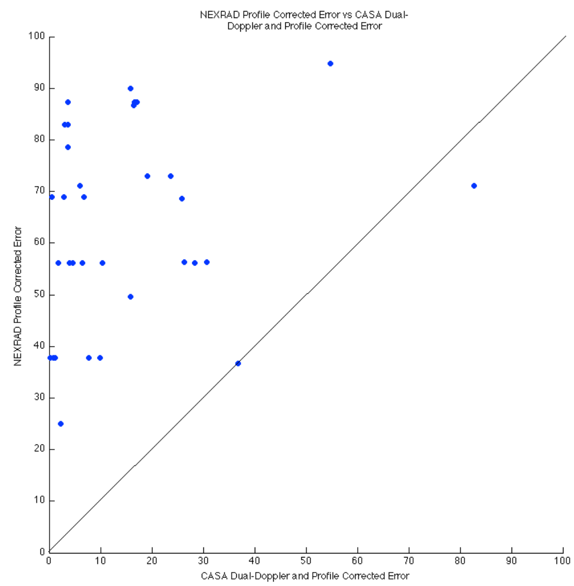

Fig. 16 NEXRAD best case profile correction plotted against CASA dual-Doppler with profile correction

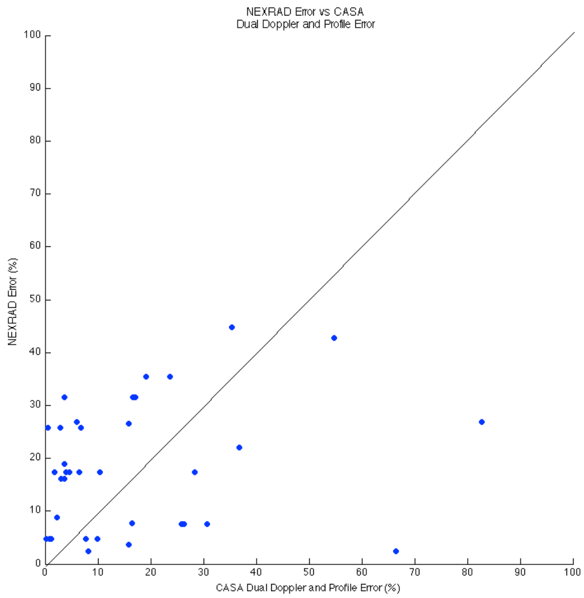

Fig. 17 Best NEXRAD error vs. CASA dual-Doppler with Profile Correction

4. DISCUSSION

The importance of viewing angle is very apparent from the results of this study. NEXRAD had trouble viewing storms that were moving from the northwest but did very well in estimating wind speeds in storms from the southwest. The ability of CASA to use multiple radars to obtain the best viewing angle is one of the main reasons for the smaller variability of CASA data. No matter the wind direction CASA will have a radar with a more accurate viewing angle. If more radars are added to a network this advantage will only increase.

The main limiting factor for CASA data is attenuation. There were many cases where a CASA radar was in prime position to sample storm winds, but the data was too attenuated to use. Again adding more radars would address this problem. More radars offer more directions to look at the storm before the radar is shrouded in heavy precipitation.

CASA offers an excellent tool for forecasters to use when determining surface wind speeds. Rude et. al (2011) examined the effect of CASA data on forecasters performance in estimating the surface wind speed; forecasters improved their error in estimating wind speed by 30%. This study quantified how well CASA radars can be used to estimate surface wind speeds. CASA radar wind estimates were usually within 30% of ground truth. Using CASA forecasters should be able to more confidently predict where and when severe winds will strike at the surface. Rude et. al (2011) have shown that forecasters confidence did in fact increase when they were give both NEXRAD and CASA data to use.

A forecaster will not only get an improvement in wind speed estimates from CASA radars, but they will also get much better temporal resolution. Rude et al (2011) mention that an increase in the number of scans allow radars to sample higher winds in a storm. Though Mesonet stations do not give the time of the highest gust during the 5-minute sampling period, it was often easy to determine the exact time of the gust from the 5 one-minute CASA scans within the 5 minute time period. All of the available CASA scans showed the moment that maximum winds were occurring.

Applying dual-Doppler analysis and a wind profile correction only adds to the advantages that CASA provides. It offers a measurement around 10% more accurate than the best-case NEXRAD measurement and almost 25% over the average of all NEXRAD measurements. With CASA data, in addition to NEXRAD data, forecasters should be able to more confidently and accurately predict where strong winds will affect the surface.

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6. Appendix

Table 1 NEXRAD AND CASA - Mesonet Velocity Sorted by Viewing Angle

Angle (degrees)	<30	30-60	>60
NEXRAD – Mesonet Mean (m/s)	-3.87	-8.65	-11.99
CASA – Mesonet Mean (m/s)	.37	-2.28	-11.68
NEXRAD – Mesonet Median (m/s)	-2.00	-10.00	-13.35
CASA – Mesonet median (m/s)	3.19	-1.42	-12.43

Table 2 Dual-Doppler analysis minus Mesonet velocity sorted by average height sample size in parenthesis

Height (km)	0-.5	.5-1	>1
Mean (m/s)	10.96 (14)	4.94 (22)	16.35 (1)
Median (m/s)	8.16	6.67	16.35

Table 3 NEXRAD velocity minus Mesonet velocity sorted by height sample size in parenthesis

Height (km)	<1	1.1-1.5	<1.5
Mean (m/s)	-8.15 (57)	-6.68 (62)	-8.41 (63)
Median (m/s)	-8.2	-7.05	-10

Table 4 CASA velocity minus Mesonet sorted by height sample size in parenthesis

Height (km)	<.5	.5-1.0	>1
Mean Error (m/s)	-3.72 (36)	-3.44 (42)	-11.65 (8)
Median Error (m/s)	-2.97	-4.25	-12.34

Table 5 Errors with profile correction applied and Mesonet subtracted out sorted by angle sample size in parenthesis

	0-30	30-60	60-90
NEXRAD mean (m/s)	-9.27 (32)	-12.78 (27)	-15.28 (26)
CASA mean (m/s)	-5.97 (26)	-8.11 (34)	-14.94 (26)
NEXRAD median (m/s)	-7.88	-13.6	-16.2
CASA median (m/s)	-4.03	-6.89	-15.56

Table 6 NEXRAD errors (m/s) sorted by angle and height sample size in parenthesis.

	0-30	30-60	>60	Mean(m/s)
0-1 (km)	-4.63 (21)	-5.6(16)	-13.89(20)	8.15 (57)
1.1-1.5 (km)	1.76 (22)	-11.74 (27)	-10.42 (13)	-6.68 (62)
>1.5 (km)	-7.74 (28)	-6.45 (16)	-11.06 (19)	-8.41 (63)
Mean (m/s)	-9.27 (71)	-12.78 (59)	-15.28 (52)	

Table 7 Casa errors (m/s) sorted by angle and height sample size in parenthesis

	0-30	30-60	>60	Mean
0-.5	3.34 (9)	-2.24 (16)	-11.64 (11)	-3.72 (36)
.5-1.0	.09 (16)	-1.59 (15)	-11.11 (11)	-3.44 (42)
>1.0	-22.11 (1)	-5.90 (3)	-13.34 (4)	-12.34 (8)
Mean	.37 (26)	-2.28 (34)	-11.68 (26)	

Table 8 Standard Deviation of NEXRAD minus Mesonet (m/s)

	0-30	30-60	>60
0-1.0	6.33	9.73	7.53
1.1-1.5	9.67	7.69	7.37
>1.5	9.21	11.69	8.9

Table 9 Standard deviation of CASA Error (m/s)

	0-30	30-60	>60
0-.5	4.39	4.99	4.26
.5-1.0	8.25	8.68	7.18
>1.0	0	8.14	4.87