Presented at the Special Symposium on Meteorological Observations and Instrumentation,
97th AMS Annual Meeting, Seattle, WA, January 22-26, 2017,
Amer. Meteor. Soc., Paper 1027

1027 CASA DALLAS-FORT WORTH URBAN TESTBED OBSERVATIONS: NETWORK OF NETWORKS AT WORK

Keith A. Brewster[1], Apoorva Bajaj[3], Brenda J. Philips[3],
David L. Pepyne[3], Eric Lyons[3] and Frederick H. Carr[1,2]

[1]Center for Analysis and Prediction of Storms
[2]School of Meteorology
University of Oklahoma
Norman, OK 73072

[3]University of Massachusetts
Amherst, MA 01003

1. CASA X-BAND RADAR CONCEPT

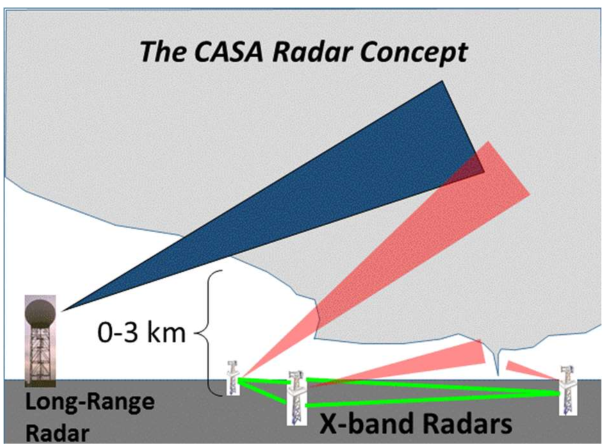


Figure 1. Schematic of CASA concept of gap filling radars covering lower levels of the atmosphere.

The Collaborative-Adaptive Sensing of the Atmosphere (CASA) project was originally established as a National Science Foundation Engineering Research Center (ERC) with the idea of deploying low-cost X-band (3 cm wavelength) dual-polarization Doppler weather radars that could scan the low-levels of the atmosphere in an adaptive fashion to precisely identify and track weather hazards such as tornadoes, strong winds and localized heavy rainfall (McLaughlin et al. 2009). The CASA ERC was based at the University of Massachusetts (UMass) and originally included three other academic institutions (University of Oklahoma, Colorado State University and the University of Puerto Rico-Mayaguez) with two others added later (University of Delaware and University of Virginia).

CASA's Integrated Project-1 (IP1) was established in 2006 in southwestern Oklahoma with four X-band dual-polarization Doppler weather radars. The radars were sited to maximize low-level coverage under the WSR-88D surveillance umbrella while providing overlapping coverage to provide good dual-Doppler winds (Brewster et al., 2005). CASA IP1 had a number of notable successes in Oklahoma including identification and tracking of several tornadoes, most notably the Chickasha-Newcastle tornado of 24 May 2011.

2. A PUBLIC-PRIVATE PARTNERSHIP

Toward the end of the ten-year CASA ERC it was decided to relocate the radars to the Dallas-Fort Worth Metroplex, an urban area with more than 6 million residents, several key transportation hubs, and a number of large sports and entertainment venues. The area experiences numerous severe thunderstorms, including some hail, flash flooding and tornadoes, in a typical year, as well as an occasional visit from a tropical storm.

The North Central Texas Council of Governments (NCTCOG) and CASA have developed a multisector partnership to install and operate the radars, provide radar sites, communication

*Corresponding author address: Keith Brewster,
120 David L. Boren Blvd., Suite 2500,
Norman, OK 73072, kbrewster@ou.edu

Figure 2. Schematic illustrating partnerships supporting the CASA DFW Testbed, including several private companies, academic institutions, federal, state and local governments. Trademarks property of respective companies.

and other support for the radar network (Bajaj and Philips, 2012). At the same time the U.S. National Weather Service (NWS) began exploring a National Mesonet that would include data from several government and private weather data sources based on the Network of Networks concept, spawned by a National Research Council report (NRC, 2009). These ensuing public-private partnerships (Fig. 2) comprise the CASA Dallas-Ft Worth Urban Testbed (CASA DFW Testbed, hereafter).

Siting for the radar network followed the principles discussed in Brewster et al. (2005b) while being constrained by more complex logistical issues than in Oklahoma. Site locations, power and communication had to be identified and arranged with various hosting institutions that included the University of North Texas, University of Texas-Arlington, Johnson County and the cities of Fort Worth, Addison, Midlothian, and Mesquite. Radars deployed included the original CASA radars from UMass, plus radars from EWR Weather Radar, Ridgeline Instruments, Furuno, and Enterprise Electronics Corporation. Figure 3 shows the layout of the X-band radar network overlaid on the county boundaries of the NCTCOG. Seven of eight planned radars have been deployed to date, and the urbanized area of the Metroplex is well covered by the network.

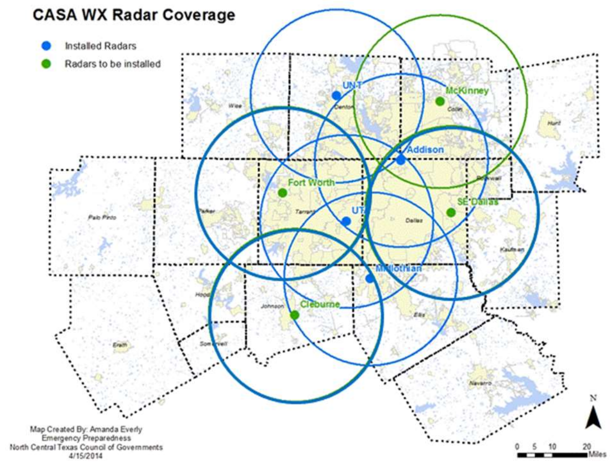


Figure 3. CASA X-band radar network. 40-km range rings for planned (green) and installed (blue) radars. Map of counties of NCTCOG, including urban areas in beige shading. Map courtesy of NCTCOG.

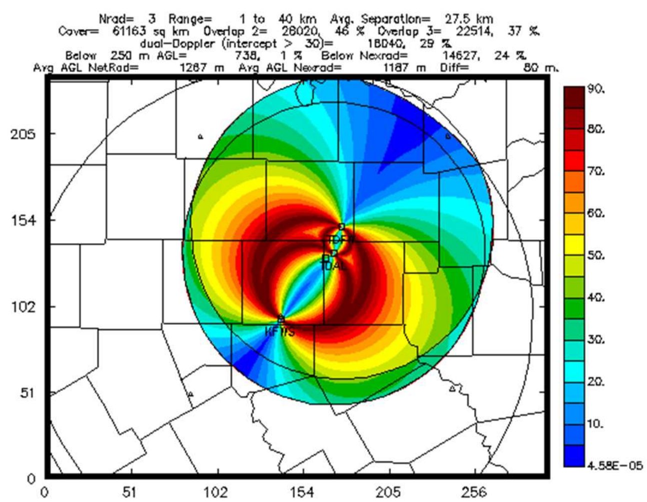


Figure 4. Dual-Doppler crossing angles (color fill, scale in degrees at right) for federal S-band (NEXRAD: KFWS) and C-band (TDWR: TDAL and TDFW) based in the Dallas-Ft Worth Metroplex.

Figure 4 shows the dual-Doppler intersection angle for the best pair of radars at each point considering the three federal radars in the testbed, namely the KFWS WSR-88D NEXRAD radar and the two FAA Terminal Doppler Weather Radars (TDWR) covering Dallas Love Field and DFW International Airport, respectively. The quality dual-Doppler coverage (orange and red colors in Fig. 4) is limited because the radars happen to be aligned in nearly a straight line.

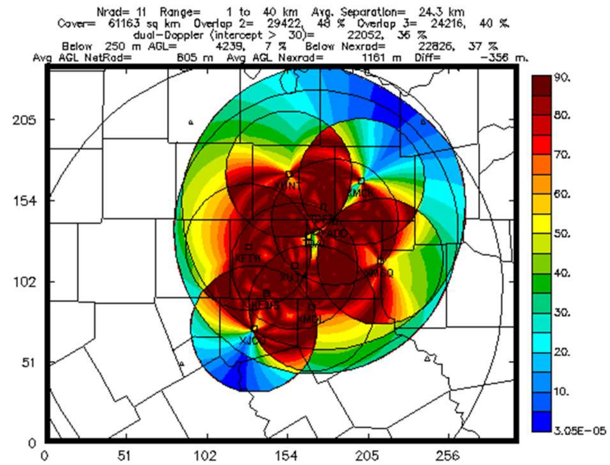


Figure 5. As in Fig. 3 but adding 8 X-band radars in the planned CASA radar network.

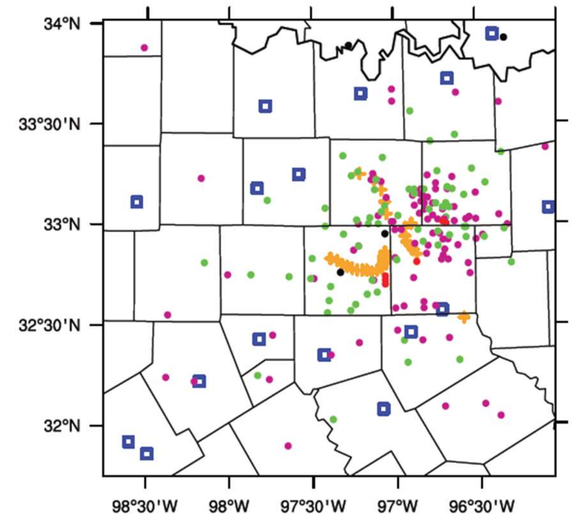


Figure 6. Sample observation distribution in the CASA DFW Testbed. Blue squares: ASOS & AWOS stations, Green Dots: CWOP sites, Magenta Dots: WxBug sites, Red Dots: MoPED truck observations, Black Dots: Other surface sites from MADIS, Orange Crosses: MDCRS aircraft observations.

Table 1. Observations and their sources for the CASA DFW Testbed

Observation	Type	Provider	Source
NEXRAD	S-Band Radar	NWS. FAA & DoD	IRADS via NWS
TDWR	C-Band Radar	FAA	FAA via NWS & NSSL
CASA	X-Band Radar	CASA, EWR, EEC, Ridgeline & Furuno	AWIPS-II via CASA
ASOS/AWOS	Surface	NWS & FAA	MADIS (Natl Mesonet)
CWOP	Surface	NWS	MADIS (Natl Mesonet)
Oklahoma	Surface	Oklahoma Climatological Survey	MADIS (Natl Mesonet)
West Texas	Surface	Texas Tech University	MADIS (Natl Mesonet)
WxBug	Surface	EarthNetworks	MADIS (Natl Mesonet)
Other Mesonets	Surface	Misc Federal & State Agencies	MADIS (Natl Mesonet)
High Freq. Pressure	Surface	ParoScientific	CASA
MoPED	Surface Mobile	GST	GST
Understory	Surface & Hail	Understory	Understory
SODAR	Wind Profiles	WeatherFlow	MADIS
Radiometer	Temp & RH	Radiometrics	MADIS
MDCRS/ACARS	Aircraft	Airlines via MDCRS/ACARS	MADIS
TAMDAR	Aircraft	Airlines via Panasonic	MADIS

Figure 5 shows the dual-Doppler crossing angles for the same area including the CASA radar network. The urban area within in the testbed is covered quite well with quality dual-Doppler crossing angles. In addition, the lowest radar beam height above ground is about 500 m compared to the NEXRAD coverage that has an average height of 1000 m in this domain.

3. OTHER OBSERVATION NETWORKS

In addition to the X-band radar network there are other observation networks that cover the CASA DFW Testbed. Table 1 summarizes the observation networks within the testbed. Many are surface observation networks included in the NWS National Mesonet Program distributed via NOAA Meteorological Assimilation Data Ingest System (MADIS), but also includes truck data from the GST MoPED, surface and hail data from Understory Weather, wind profilers from WeatherFlow, surface-based radiometers from Radiometrics, aircraft data from MDCRS, as well as high-frequency pressure and GPS-Met data from CASA installed weather stations. Figure 6 shows a sample distribution of data (as indicated in the caption) for a selected 5-minute window.

4. REAL-TIME CASA RADAR OBSERVATIONS INTEGRATED WITH NWS TOOLS

CASA observations are used by the public safety community in North Texas as severe weather impacts North Texas. CASA has tools to display and animate the X-band radar data that are available to partners and subscribers as a way to support continuing operations. In order to better integrate the CASA data into the real-time warning and forecasting operations of the NWS, it was desirable to integrate the data into the AWIPS-II workstations used at the NWS Forecast Office in Fort Worth. To accomplish this, the UMass team worked with the NWS Southern Region to reformat the radar data and transmit them to appropriate NWS servers.

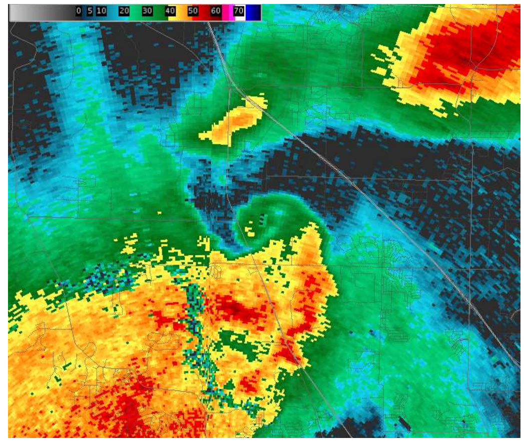


Figure 7. AWIPS-II display of Fort Worth X-band radar reflectivity (dBZ, color scale at top) of the Haslet tornado, 23 March 2016.

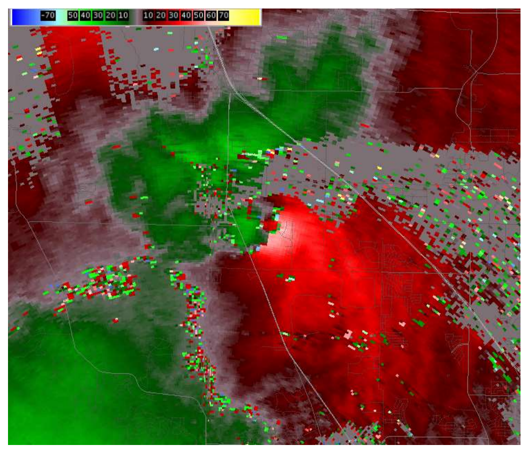


Figure 8. AWIPS-II display of Fort Worth X-band Doppler radial velocity (ms^{-1}, color scale at top) of the Haslet tornado, 23 March 2016.

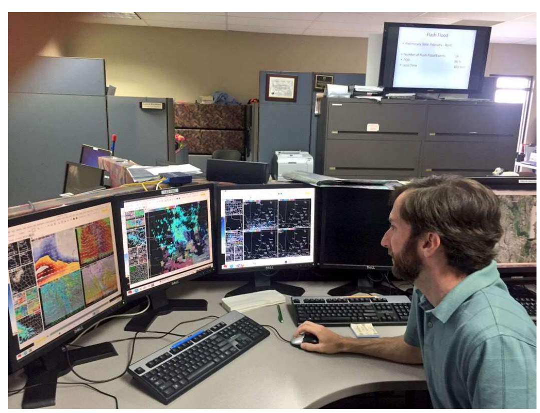


Figure 9. NWS forecaster viewing the CASA radar data on AWIPS-II display in the Fort Worth NWS Forecast Office.

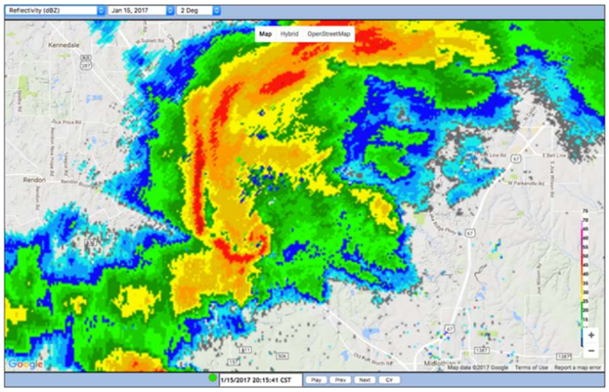


Figure 10. Reflectivity (dBZ, color scale at top) from the Midlothian X-band radar for the tornado of 15 January 2017.

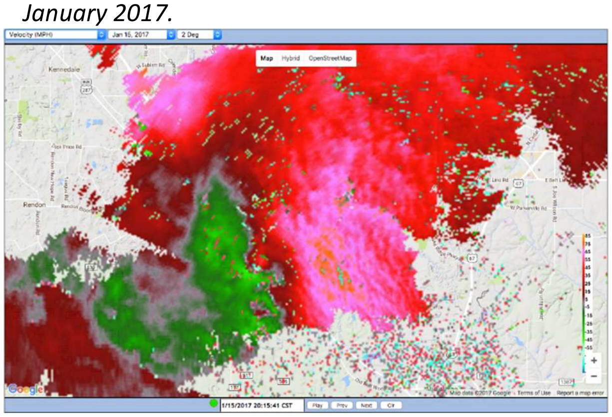
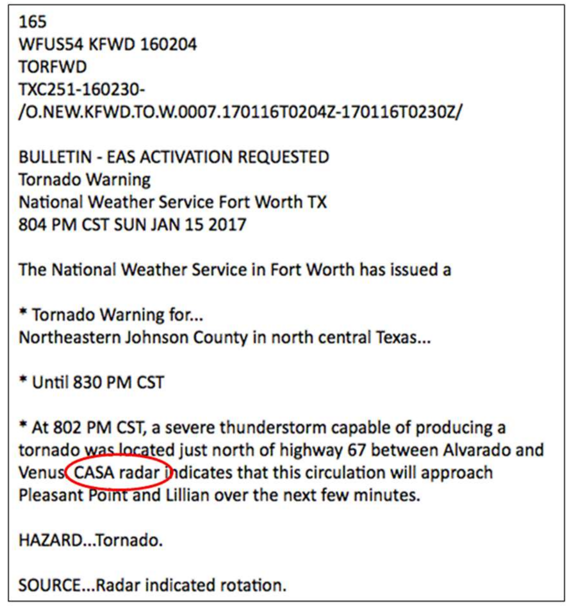


Figure 11. Doppler radial velocity (ms^{-1}, scale at top) from the Midlothian X-band radar on 15 January 2017.

As an example of the AWIPS-II display, the reflectivity and Doppler radial velocity from the X-band radar at Fort Worth for the 23-March-2016 Haslet tornado are shown in Figs 7 and 8, respectively. Figure 9 shows how the data are used on the AWIPS-II workstation at the Fort Worth NWS Forecast Office.

A notable success of this effort was when the CASA X-band radar data were used to pinpoint the location and movement of a compact F0 tornado that tracked near the border of Tarrant and Dallas Counties on the evening of 15 January 2017 (Figures 10 and 11). Knowing the precise location and movement of this feature was of increased importance on this evening because 100,000 NFL football fans were dispersing from AT&T Stadium in Arlington, Texas,



165
WFUS54 KFWD 160204
TORFWD
TXC251-160230-
/O.NEW.KFWD.TO.W.0007.170116T0204Z-170116T0230Z/

BULLETIN - EAS ACTIVATION REQUESTED
Tornado Warning
National Weather Service Fort Worth TX
804 PM CST SUN JAN 15 2017

The National Weather Service in Fort Worth has issued a

* Tornado Warning for...
Northeastern Johnson County in north central Texas...

* Until 830 PM CST

* At 802 PM CST, a severe thunderstorm capable of producing a tornado was located just north of highway 67 between Alvarado and Venus. CASA radar indicates that this circulation will approach Pleasant Point and Lillian over the next few minutes.

HAZARD...Tornado.

SOURCE...Radar indicated rotation.

Figure 12. Tornado warning text from Fort Worth showing the use of CASA radar to pinpoint tornado location and movement on 15 January 2017.

after the NFC Championship game that had just concluded. The warning product issued (Fig. 12) included those details from the CASA X-band radar.

5. CAPS REAL-TIME ANALYSES AND FORECASTS

In addition to the raw data displays, a real time high resolution analysis system (400-m grid spacing) and an efficient assimilation and Numerical Weather Prediction (NWP) system with 1-km grid spacing producing 0-to-2 hour forecasts with low latency are being run over the CASA DFW Testbed by the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (OU). Initially designed for the CASA IP1 domain (Brewster et al., 2007, Brewster et al., 2008, Brewster et al., 2010), the domain has since been moved to Texas.

The NWP system achieves very low latency on modest computing resources by utilitizing a 3DVAR analysis with complex cloud analysis (Gao et al., 2004, Brewster et al., 2005a, Hu et al., 2006, Brewster and Stratman, 2015). The analysis increments are assimilated into the ARPS (Xue et al, 2001, Xue et al., 2003) model using Incremental Analysis Updating (IAU, Bloom et al., 1996) with the recently-developed variable-dependent timing (IAU-VDT, Brewster et al., 2016). This allows production of the complete 2-hour thunderstorm-resolving forecast in about 20 minutes of wall-clock time on fewer than 200 cores of a Linux server cluster.

Data assimilation and short-term forecasting are run on a 350 x 320 km domain with 1-km grid spacing. 53 vertical grid levels are used with domain top at 20 km and enhanced vertical resolution near the ground (20 m minimum vertical grid spacing). Further details of the forecast and assimilation system can be found in Brewster et al., 2016.

6. GARLAND-ROWLETT, TX TORNADO

Example products from the assimilation and forecast system are presented from two recent tornado events in the Dallas-Ft. Worth region.

In the late afternoon and early evening of 26 December 2015 a total of 13 tornadoes were observed and damage tallied at more than $40 M (NWS, 2016, Marshall et al., 2016). Among the tornadoes in the Dallas area were an EF3 tornado near Ovilla around 0000 UTC 27 Dec., and 45 minutes later a large long-track tornado (approximately 20 km long, 500 m wide) with EF4 damage rating that touched down just south of Interstate-30 in Sunnyvale and passed through the portions of Garland and Rowlett in the northeast part of the metro area (Fig. 13). Following that, there were additional tornadoes to the north-northeast of Rowlett as the parent storm continued tracking in that direction.

The forecast system on this day was being run at 30 minute intervals. At the time five of the X-band radars in the DFW Testbed were installed; the radars at Ft. Worth and Mesquite were added later.

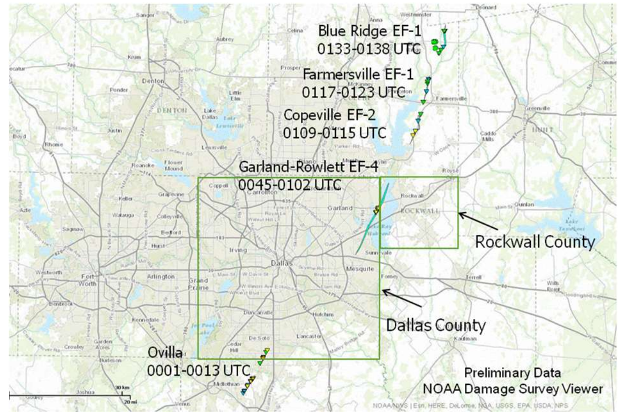


Figure 13 Tornado tracks near Dallas on 26-Dec-2015 (UTC Times 27-Dec-2015). Dallas and Rockwall Co. are highlighted to aid reader orientation with model output figures. From NOAA Damage Survey Viewer.

The forecasts were very successful in maintaining the storms and producing very strong rotation as indicated in the 1-6 km updraft helicity (UH) plots. Figure 14 shows four successive real-time forecasts (initialized 2300 to 0030) at the valid time for each where the forecast was indicating a strong UH field near the starting point of the Garland-Rowlett tornado. The tornado damage survey points are shown as the triangles in the plot, the contours are reflectivity in 10 dBZ intervals with the UH indicated in color contours, non-linear scale at right. The timing of the rotation center was a bit fast in each, with successive forecasts asymptotically approaching the 0045 actual estimated time of touchdown. Given that the latency for the 2-hour output is about 20-25 minutes the 2330 UTC forecast had nearly 1 hour actual lead time on the observed 0045 UTC touch down time.

As mentioned previously there was another tornadic storm 15 January 2017. On this date there was an issue with the real-time surface data, but after-the-fact the real-time system was rerun with all data sources and it was able to successfully predict the location and track of this storm to within 10 km. Figure 15 has sample forecast plots from the 15 January case.

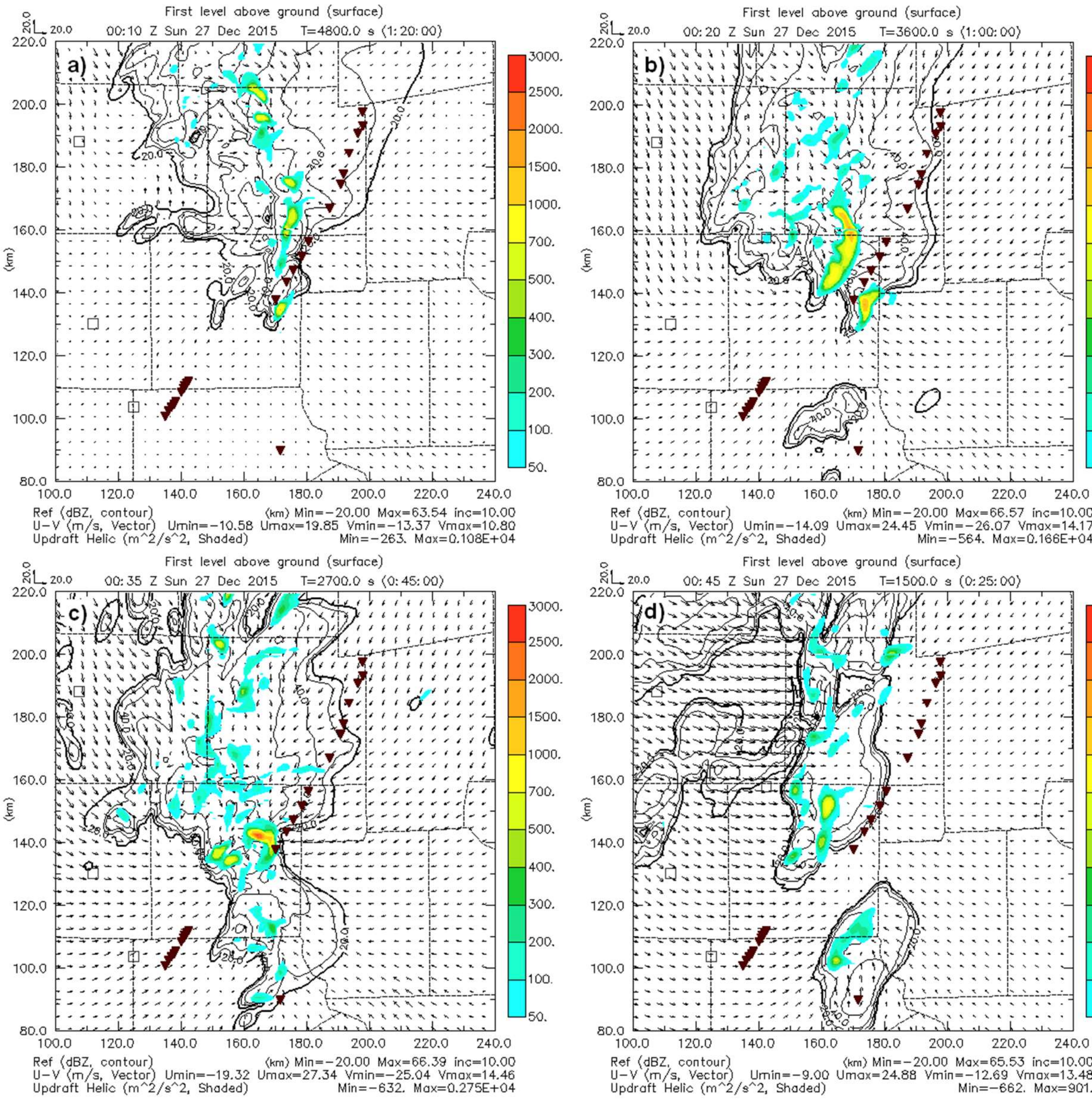


Figure 14. Four sequential real-time 1-km grid forecasts showing nearest forecast to the beginning of the 26 Dec 2015 Garland-Rowlett tornado track. Near surface perturbation winds and reflectivity (contours), 1-6 km integrated updraft helicity (color shading, $m^2\ s^{-2}$). Forecast initialized at: a) 2300 UTC, b) 2330 UTC, c) 0000 UTC, d) 0030 UTC.

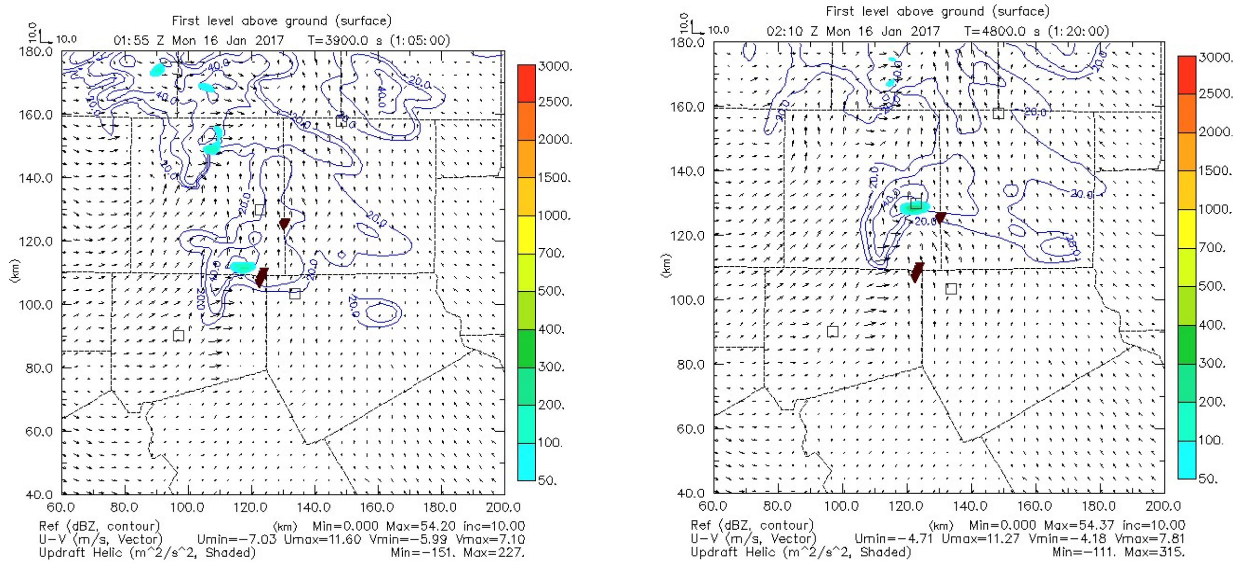


Figure 15. Forecast initiated at 0100 UTC for the 15 January 2017 tornado near Arlington. 55 minute forecast valid at 01:55 UTC 16 January (left) and forecast valid at 02:10 UTC (right).

7. HIGH-FREQUENCY PRESSURE AND PRECIPITABLE WATER VAPOR MEASUREMENTS

CASA built and installed two GPS-Meteorology stations in the DFW Testbed domain, one at the Univ. of Texas at Arlington, the other at the Fort Worth WFO (Nagarajan et al., 2015). In addition to a dual-frequency GPS receiver and weather station for temperature and relative humidity, each of these stations contains a Paroscientific Model 6000-16B barometer. These GPS-Met stations are being used to detect and investigate the forecast value of a number of phenomena.

Two experiments have to do with fast temporal sampling. Through fast sampling (>10 Hz) the pressure output of the Paroscientific barometers the rapid pressure drops associated with tornado vortices passing nearby the CASA GPS-Met stations can be detected and studied. By increasing the generation of GPS-Met precipitable water vapor (PWV) estimates from the typical 30 minutes between estimates to 5 minutes between estimates the water vapor gradients associated with convective initiation, growth, and decay can be detected and studied.

Another experiment is applying state-of-the-art machine learning methods to the problem of nowcasting precipitation 1-hour in the future. Noting that precipitation is generally preceded by a localized build-up of atmospheric water vapor, the machine learning methods seek to nowcast the reflectivity field (a measure of precipitation intensity) over the DFW domain 1-hour in the future from a past history of PWV (a measure of atmospheric water vapor) and reflectivity fields. For the experiments, the reflectivity data comes from the KFWS NEXRAD radar in Fort-Worth and the PWV fields come from an interpolation of PWV estimates obtained using the GAMIT GPS-Met tools from the regional network of Texas Dept. of Transportation (TxDOT) GPS CORS stations and ASOS surface observation sites. Fig. 16 shows an interpolated PWV field as obtained from the TxDOT network. Fig. 17 shows a reflectivity field superimposed atop the associated PWV field. The figure is a snapshot of a storm moving to the east through

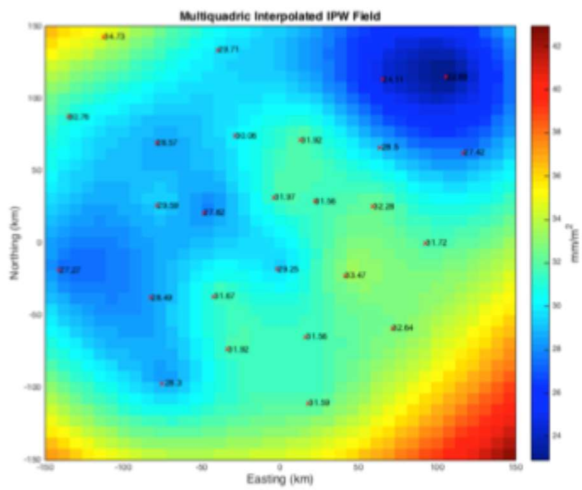


Figure 16. Field of integrated precipitable water vapor obtained by interpolation of GPS-Met data obtained from the network of TxDOT GPS CORS sites and ASOS stations in the coverage domain of the Fort-Worth KFWS NEXRAD radar.

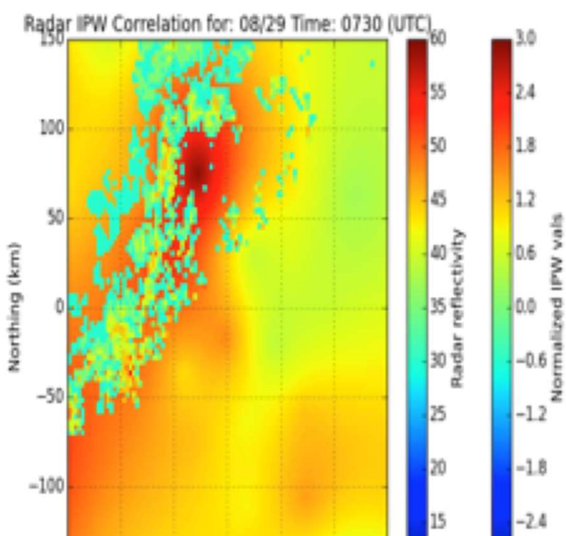


Figure 17. Reflectivity superimposed over standard anomaly of precipitable water vapor field showing how reflectivity (precipitation) often follows peaks in PWV.

the DFW region and illustrates how the reflectivity field often follows behind peaks in the PWV field. Nowcasting results using a variety of machine learning approaches to learn the PWV/reflectivity relationships show promising results (Nagarajan and Pepyne, 2016) and work is on-going to improve the learning performance using the recent "deep learning" approaches started in (Nagarajan, 2017).

8. ONGOING AND FUTURE WORK

We are performing Observing System Experiments (OSEs) to measure the sensitivity of the forecasts to various data sources within the DFW Testbed, for example, as described by Carr et al., 2016.

Formal quantitative evaluation is planned for the NWP precipitation forecasts using Equitable Threat Scores and object-based methods for tornadoes, following recent work of Stratman and Brewster (2015).

Training of forecasters and emergency managers in the use of these and other CASA tools will also be done in the coming year, with subjective evaluation by other stakeholders to follow, based on results.

Future work with pressure instruments will seek to extend the work of Bass et al. (1995) and Murray (2012) to develop a pressure-based vertical wind profiler for aviation applications.

9. ACKNOWLEDGMENTS

Thanks to Karen Cooper of NSSL for access to the real-time Level-II FAA TDWR data for the D/FW Testbed. Thanks to all private partners and municipalities who provide real-time radar and other data.

Oklahoma Mesonet data provided by the Oklahoma Climatological Survey. West Texas Mesonet data provided by Texas Tech University.

Supercomputing resources from the Oklahoma University Supercomputer Center for Education and Research (OSCER) were used for the analyses and forecasts in this study. Kevin W.

Thomas of CAPS is responsible for the CAPS real-time forecast system.

The DFW Testbed and CASA work is supported in part by the National Science Foundation (NSF) under EEC03-13747 and PFI-AIR 1237767, by the National Weather Service National Mesonet and Network of Networks Programs, and the North Central Texas Council of Governments. Funding for the work using the precipitable water and high frequency pressure measurements was provided by the Jerome M. Paros Fund for Measurement and Environmental Sciences Research.

Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the funding agencies nor the host universities. Mention of specific radar and measurement system brands does not constitute an endorsement by the authors or funding agencies.

10. REFERENCES

Bajaj, A.N. and Philips, B.J., 2012 Casting the Net – A revolutionary business model for deploying weather radar networks. *Meteorological Technology International*. 106-108.

Bass, H.E., R. Raspet, and J.O. Messer, 1995: Experimental determination of wind speed and direction using a three microphone array. *J. Acoust. Soc. Am.* **97**, 695.

Bloom, S. C., L. L. Takacs, A. M. da Silva, D. Ledvina, 1996: Data Assimilation Using Incremental Analysis Updates. *Mon. Wea. Rev.*, **124**, 1256–1271.

Brewster, K., M. Hu, M. Xue, and J. Gao, 2005a: Efficient assimilation of radar data at high resolution for short range numerical weather prediction. World Weather Research Program Symposium and Nowcasting and Very Short-Range Forecasting WSN05, Toulouse, France. WMO World Weather Research Program, Geneva, Switzerland. Symposium CD, Paper 3.06.

Brewster, K.A., L. White, B. Johnson, and J. Brotzge, 2005b: Selecting the sites for CASA NetRad, a collaborative radar network. Ninth Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), 85th Amer. Meteor. Soc. Annual Meeting CD, Paper: P3.4.

Brewster, K.A., K. W. Thomas, J. Brotzge, Y. Wang, D. Weber, and M. Xue, 2007: High resolution assimilation of CASA X-band and NEXRAD radar data for thunderstorm forecasting. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred*., Salt Lake City, Utah, Amer. Meteor. Soc., Paper 1B.1

Brewster, K. A., J. Brotzge, K. W. Thomas, Y. Wang, M. Xue, J. Gao, D. Weber, and K. Howe, 2008: High resolution assimilation of CASA and NEXRAD radar data in near-real time: Results from Spring 2007 and plans for Spring of 2008. *12th Conf. IOAS-AOLS*, New Orleans, LA, Amer. Meteor. Soc.

Brewster, K., K. Thomas, J. Gao, J. Brotzge, M. Xue, and Y. Wang, 2010: A nowcasting system using full physics numerical weather prediction initialized with CASA and NEXRAD radar data. Preprints, *25th Conf. Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., Denver, CO, Paper 9.4.

Brewster, K.A. and D.R. Stratman, 2015: An updated high-resolution hydrometeor analysis system using radar and other data. Preprints, 27th Conference on Wea. Analysis and Forecasting and 23rd Conf. on Numerical Wea. Pred., Amer. Meteor. Soc., Paper 31.

Brewster, K.A., Brewster, K.A., D.R. Stratman, K.W. Thomas and F.H. Carr, 2016: Incremental analysis updating with variable-depending timing applied to a real-time high resolution forecast system. *28th Conf. on Severe Local Storms*, Portland, OR, Amer. Meteor. Soc., Paper 69.

Carr, F., M. Morris, A. Osborne, and K.A. Brewster, 2016: Observing System Experiments in the Dallas-Fort Worth Testbed, *Preprints, Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IAOS-AOLS),* New Orleans, LA, Amer. Meteor. Soc., Paper 262.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier 2004: A three-dimensional variational data assimilation method with recursive filter for single-Doppler radar, *J. Atmos. Oceanic. Technol.* 457-469.

Hu, M., M. Xue, and K. Brewster, 2006: 3DVAR and cloud analysis with WSR-88D Level-II Data for the Prediction of Fort Worth Tornadic Thunderstorms Part I: Cloud analysis and its impact. *Mon. Wea. Rev.*, **134**, 675-698.

Marshall, T.P., M. Fox, M. Huffman, and D. Cavanaugh, 2016: Damage survey of the North Texas Tornadoes: 26 December 2015, Extd Abstracts, 28th Conf. on Severe Local Storms, Amer. Meteor. Soc., Paper P1A.3.

McLaughlin, D. D. Pepyne, V. Chandrasekar, B. Philips, J. Kurose, M. Zink, K. Droegemeier, S. Cruz-Pol, F. Junyent, J. Brotzge, D. Westbrook, N. Bharadwaj, Y. Wang, E. Lyons, K. Hondl, Y. Liu, E. Knapp, M. Xue, A. Hopf, K. Kloesel, A. Defonzo, P. Kollias, K. Brewster, R. Contreras, B. Dolan, T. Djaferis, E. Insanic, S. Frasier, and F. Carr, 2009: Short-Wavelength Technology and the Potential For Distributed Networks of Small Radar Systems. *Bull. Amer. Meteor. Soc.*, 90, 1797-1817.

Murray, N.E., 2012: *Passive Acoustic Detection of Wind Turbine In-Flow*. DOE Project Report. Available on-line: http://www.osti.gov/scitech/biblio/1037463

Nagarajan, A., 2017: *Explorations into Machine Learning Techniques for Precipitation Nowcasting*. Masters Thesis, Dept. of Mechanical and Industrial Engineering, Univ. of Mass., Amherst, MA.

Nagarajan, A., M.C. Jacques, A. Lagace, D.L. Pepyne, M. Zink and D.J. McLaughlin, 2015: Lower-cost GPS-Met station design for use in dense network slant path GPS-Met estimates of tropospheric wet delay and precipitable water vapor. *AMS 19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface* (IOAS-AOLS), Pheonix, AZ.

Nagarajan, A. and D.L. Pepyne, 2016: On Learning Patterns Between GPS Derived Precipitable Water Fields and Radar Reflectivity Fields. AMS 14th Conf. on Artificial and Computation Intelligence and its Applications to the Environmental Sciences, New Orleans, LA.

National Weather Service, 2016: North and Central Texas December 26, 2015 Tornado Outbreak. NWS Fort Worth web product: http://www.weather.gov/fwd/dec26tornadoes

National Research Council, 2009, *Observing Weather and Climate from the Ground Up. A Nationwide Network of Networks.* The National Academies Press, Wash. DC, 250 pp. http://books.nap.edu/catalog/12540/

Stratman, D.R. and K.A. Brewster, 2015: Verification of 24 May 2011 simulated mesocyclones using various microphysics schemes at 1-km grid resolution. 27th Conf. on Wea. Analysis and Forecasting & 23rd Conf. on NWP, Chicago, IL, Amer. Meteor. Soc., Paper 13A.6.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D.-H. Wang, 2001: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. *Meteor. Atmos. Physics,* **76**, 143-165.

Xue, M., D.-H. Wang, J. Gao, K. Brewster, and K.K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS) – storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, **82**, 139-170.