Principles of High-Resolution Radar Network for Hazard Mitigation and Disaster Management in an Urban Environment

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Abstract

The center for the Collaborative Adaptive Sensing of the Atmosphere (CASA) Dallas–Fort Worth (DFW) Urban Demonstration Network consists of a high-resolution X-band radar network and a National Weather Service S-band radar system (i.e., KFWS radar). On the basis of these radars, CASA has developed an end-to-end warning system that includes sensors, software architecture, products, data dissemination and visualization, and user decision-making modules. This paper presents a technical summary of the DFW radar network for urban weather disaster detection and mitigation from the perspective of the tracking and warning of hails, tornadoes, and floods. Particularly, an overview of the design trade-offs of the X-band radar network is presented. The architecture and associated algorithms for various product systems are described, including the real-time hail detection system, the multiple Doppler vector wind retrieval system, and the high-resolution quantitative precipitation estimation system. Sample products in the presence of high wind, tornado, hail, and flash flood are provided, and the system performance is demonstrated by cross-validation with ground observations and weather reports.

Keywords CASA; DFW; dual-polarization; radar network; remote sensing; urban hazard mitigation

1. Urban hazard mitigation and disaster management

Currently, most parts of the world are becoming increasingly urbanized. The world’s urban population has grown from 746 million in 1950 to 3.9 billion in 2014. This number is expected to surpass six billion by 2045 (United Nations 2014). Figure 1 illustrates the growth rates of urban agglomerations by size class in 2014 (United Nations 2014). The rapid urbanization has made densely populated areas more vulnerable to natural disasters, such as urban flash floods. Therefore, monitoring the weather conditions in a timely manner at a good spatial resolution is critical in terms of protecting personal and property safety.

Radars have been used for weather applications over many decades. Nowadays, long-range microwave (e.g., S- or C-band) radar networks are considered by many nations as an integral part of their weather sensing and forecasting infrastructures. With the introduction of new technologies, such as dual-polarization, the sensing capabilities of these networks have been improved considerably over the past 30 years (Bringi and Chandrasekar 2001). However, one limitation of
today’s large weather radar installations is their inability to cover the lower part of the atmosphere because of the Earth’s curvature and terrain blockage. For the network of Weather Surveillance Radar-1988 Doppler (WSR-88DP) of the United States (also known as Next-Generation Radar), the S-band radars (wavelength ~10 cm) constituting the WSR-88DP network are spaced approximately 230 km apart in the eastern United States and 345 km in the western United States. At the maximum coverage range of 230 km, the lowest (0.5 degree) beam is approximately 5.4 km above ground level (AGL). The incomplete low-level coverage, limited spatial resolution at long distance, and slow scan rate impede the ability of such system to identify and detect fine-scale weather features, such as tornadoes (National Research Council 1995).

Aimed at enhancing weather sensing in the lower troposphere (1–3 km AGL), the US National Science Foundation Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) introduced an innovative, collaborative, and dynamic sensing paradigm called Distributed Collaborative Adaptive Sensing (DCAS) to overcome the resolution and coverage limitations of traditional weather radar networks (McLaughlin et al. 2009). The DCAS system utilizes a number of low-power (and lower cost) densely networked radar systems to observe, forecast, and respond to hazardous weather phenomena. The first research test bed of such kind, which consisted of four radar nodes, was deployed in the “Tornado Alley” over southwestern Oklahoma to study extreme precipitation and hazardous winds. This four-node DCAS system was operated in a tight loop with an end-user group comprising CASA researchers, the Weather Forecast Office (WFO) in Norman, Oklahoma, as well as emergency managers who have jurisdictional authority in the upstream counties over the test-bed area. The high-resolution observations, post-event case studies, and fundamental multidisciplinary research during five years of operation have demonstrated the viability of the DCAS concept (McLaughlin et al. 2009; Chandrasekar et al. 2012). Since the spring of 2012, CASA, in collaboration with NWS and the North Central Texas Council of Governments (NCTCOG), has initiated the effort to develop its first urban demonstration network in the Dallas–Fort Worth (DFW) area, one of the largest inland metropolitan areas in the United States. Every year, the DFW area experiences a wide range of natural hazardous weather events such as high winds, flash floods, tornadoes, and hail. It is an ideal location to demonstrate the DCAS concept in a densely populated urban environment. New product research and the transition of research to operations in the DFW remote sensing network occur in a quasi-operational environment in terms of urban hazard mitigation and disaster management. The real-time products are used and evaluated by a variety of users, including NWS forecasters, emergency managers, and users from transportation, utilities, regional airports, arenas, and the media. In this way,
the multidisciplinary team of CASA—radar engineers, computer scientists, meteorologists, hydrologists, and social scientists—will conduct “end-to-end” research from sensor observations to product development and validation linked to end-user decision making and response.

This paper presents the principles of a high-resolution weather radar network for urban hazard detection and mitigation with more of an emphasis on the application products. Section 2 presents an overview of the DFW dense urban radar network and the principles of short-wavelength radar technology and networking. Section 3 describes the hail detection system developed for the DFW radar network. Section 4 details the real-time multi-Doppler wind-retrieval system for tornado and high-wind detection. Section 5 presents the DFW quantitative precipitation estimation (QPE) system, with particular attention to the quantitative evaluation of QPE system products. Section 6 summarizes the main accomplishments during the operation of the DFW urban remote sensing network.

2. Principles of short-wavelength radar technology and networking

2.1 X-band radar network design trade-offs

The radar sampling resolution is primarily determined by the transmitted pulse width, antenna beamwidth, and range from the radar. For an ideal uniformly illuminated parabolic reflector, the sampling resolution is given by the following:

\[
\text{Resolution cell length} \approx \frac{c T}{2}, \quad (1a)
\]

\[
\text{Resolution cell width} \approx \frac{\lambda R}{d}, \quad (1b)
\]

where \(c\) is the speed of light; \(T\) is the transmitted pulse width typically in the order of \(\mu s\); \(\lambda\) is the radar wavelength; \(d\) is the antenna aperture size; and \(R\) is the range from radar. McLaughlin et al. (2009) concluded that a reasonable antenna size for unobtrusive equipment deployment is of the order of 1 to 1.5 m. Assuming the frequency of the WSR-88DP system, operating a radar with a 1 m antenna will result in a resolution cell width of 3 km at a 30 km range. From a spatial resolution perspective, fine-scale weather features such as tornado and microburst cannot be resolved at this coarse resolution. In reality, each WSR-88DP system is equipped with a 9 m-diameter antenna. However, as aforementioned, the WSR-88DP radar coverage is non-overlapping (at very high altitudes if any), and the spacing between radars is approximately 230 km in the eastern United States and 345 km in the western United States. The illuminated volume will be tremendously expanded as the range from the radar increases. Furthermore, owing to the Earth’s curvature and terrain blockage, more than 70% of the atmosphere below 1 km altitude AGL cannot be observed (National Research Council 1995). From the temporal resolution perspective, individual radars in the WSR-88DP network are operated with a predefined volume coverage pattern (VCP) mode that is repeated. The update rate, which is the same for all areas under the radar umbrella, will decrease as the number of elevation angles of VCP increases. By taking the commonly used VCP12 precipitation mode (14 tilts with increasing elevation angles from 0.5° to 19.5°) as an example, it takes 5–6 min to finish a volume scan task. This is too long to capture the weather evolution details, particularly small-scale but high-impact meteorological phenomena such as tornadoes and urban flash floods that rapidly form and dissipate. Moreover, the deployment and maintenance of such high-power big radars (i.e., 12 m radomes) are extensive tasks in terms of cost efficiency and operational complexity.

By going to a shorter wavelength such as X band, higher spatial resolutions can be attained with a smaller antenna. The compact system can be readily deployed on small towers with small land footprints or on existing infrastructure elements such as rooftops and communication towers. Compared with the WSR-88DP radar, the easier manipulation of the X-band radar can provide us with higher temporal resolutions. Hence, the low-power, low-cost small X-band radar system is gaining increasing interest in recent years. To overcome the coverage and resolution limitations of the WSR-88DP radar network, the center of CASA proposed an innovative DCAS sensing concept by deploying dense X-band radar networks. The DCAS architecture designed by CASA includes distributed dual-polarization X-band radars; algorithms that dynamically process the collected data, detect ongoing weather features, and manage system resource allocations; and interfaces that enable end users to interact with the system. Figure 2 shows a conceptual diagram of the DCAS system that has operations determined by end users. In particular, the DCAS system uses a Meteorological Command and Control (MC&C) component (Zink et al. 2010) to collaboratively coordinate the scanning strategy of distributed radars in a network environment. By using a space–time adaptive, targeted sector-scanning approach or a collaborative processing approach, the network-level performance is superior to the capabilities of individual radars in terms of update rate on key weather features, minimum beam height, and spatial resolution (Junyent and Chandrasekar 2009). Furthermore, the requirement
on radar size and peak transmitter power is lower in DCAS mode than what it would need to be if the radars were operated independently to achieve a certain level of sensitivity. The research network deployed by CASA in southwestern Oklahoma demonstrated the feasibility of the DCAS concept (McLaughlin et al. 2009; Junyent et al. 2010; Chandrasekar et al. 2012). Since 2012, a collaborative agreement between CASA and local stakeholders has been made to establish its first urban radar network in the DFW Metroplex to demonstrate the feasibility of collaborative adaptive sensing paradigm in an urban environment.

However, moving to the X band did not come easily because technical solutions needed to be found for several basic issues such as attenuation and range velocity ambiguity. To this end, extensive research in CASA and elsewhere has been devoted to these matters; such research demonstrated that attenuation could be resolved using some modern attenuation correction techniques that included dual-polarization (Gorgucci and Chandrasekar 2005; Lim and Chandrasekar 2016; Shimamura et al. 2016). The range velocity ambiguity could be alleviated using modern pulsing schemes with advanced signal processing (details for CASA can be found in Bharadwaj et al. 2010). Furthermore, extra attention should be paid to clutter suppression during short-range operation in urban regions. CASA researchers invested heavily on this issue, and advanced clutter suppression techniques were developed to handle the high-clutter environment (Nguyen et al. 2008; Bharadwaj et al. 2010). The advanced clutter filtering techniques are working operationally in conjunction with other systems, such as that for range velocity mitigation. Overall, all the major technological advances developed through CASA have been put into operation in most of the radars in the DFW network, with a major focus on the demonstration of research to operations for the monitoring and warning of urban weather hazards.

2.2 CASA DFW dense urban radar network

The DFW Metroplex is one of the largest inland metropolitan areas in the United States and is also among the fastest growing major urban areas in the country. It is home to two major airports (one of which is DFW International Airport, the third busiest airport in the world), as well as numerous regional airports and many large sports complexes. It is an ideal place to demonstrate the application of dense radar network for urban weather disaster detection and mitigation. Centered in the DFW urban remote sensing network is the deployment of eight dual-polarization X-band radars that can provide coverage to most of the 6.5 million people in this region. Figure 3 shows the sample pictures of the installation of various DFW radars. Figure 4 illustrates the geographical deployment of the eight X-band radars and one S-band WSR-88DP radar deployed in the DFW area. The smaller blue circles in Fig. 4 correspond to the 40 km range from the X-band radars, and the larger circle in red corresponds to the 100 km range distance from the KFWS radar. The letter symbols (e.g., “XMDL”) in Figs. 3 and 4 correspond to the name of various radars. The specific location of each radar node, including the longitude, latitude, altitude, and county where the radar is installed, is listed in Table 1. The excessive overlapping

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**Fig. 2.** The simplified architecture of a DCAS system. The real-time data and products are disseminated to various end users. On the basis of MC&C, the radar network scan strategy is adapted according to feedback from end users.
Fig. 3. Installation of CASA DFW radars. The letter symbols, such as “XMDL”, correspond to the name of various radars. More information about DFW radar deployment can be found in Table 1.

Fig. 4. The layout of S-band KFWS WSR-88DP radar (100 km range ring in red) and the DFW dual-polarization X-band radars (40 km range rings in blue). The letter symbols, such as “XMDL”, correspond to the name of various radars.
regions where direct measurements of multiple Doppler velocities are available should be noted; this is the fundamental contrast to WSR-88DP deployment.

The DFW X-band radars sit atop a high-performance pedestal assembly that is capable of high accelerations and rapid back-and-forth plan position indicator (PPI) and range height indicator (RHI) scans. The radar systems deployed in this urban test bed are based on new technologies developed within the CASA program. The system specifications and base data products are listed in Table 2, which also shows the key specifications of a typical WSR-88DP radar system for cross-comparison purposes. There are two scan strategies designed for DFW radars. One strategy is the adaptive mode in the DCAS sensing paradigm, which can rapidly reconfigure each radar node in response to the changing atmospheric conditions and end-user needs (Chen and Chandrasekar 2018). The “heartbeat” for a volume scan in the DCAS mode is approximately 1 min. The other is a regular scan mode in which each radar typically conducts three full PPI scans at 1°, 2°, and 3° elevation angles within 1 min (i.e., scan speed is configured as 18° s\(^{-1}\)).

The dual-polarization radar measurements produced by DFW radars include but are not limited to reflectivity (\(Z_h\)), differential reflectivity (\(Z_{dr}\)), specific differential phase shift (\(K_{dp}\)), and copolar correlation coefficient (\(\rho_{hv}\)). These four polarimetric variables are used extensively for precipitation classification and estimation in the DFW network. Refer to Bringi and Chandrasekar (2001) for a detailed description of various dual-polarization observables.

The major objectives of DFW urban remote sensing network are as follows (Chen and Chandrasekar 2015):

- Develop high-resolution 3D mapping of the atmospheric conditions focusing on the boundary layer.
- Detect and forecast severe weather hazards including high-wind, tornado, hail, and flash flood.
- Create neighborhood-scale impact-based forecasts and warnings for a range of public and private sector decision makers that result in benefits to the economy and public safety; conduct comprehensive assessments of the early warning benefits.
- Demonstrate the added value of dense X-band radar network to existing and future NWS sensors, products, performance metrics, and decision-making strategies; assess the optimal combinations of observing systems.

Figure 5 shows the real-time dataflow architecture of the DFW urban radar network. The data and products transferred through the internet include single and multiradar data, vector winds, precipitation types, rainfall, data assimilation, and numerical weather prediction (NWP) products. In real time, the radar data from individual nodes are streamed to the DFW Radar Operations Center (DROC), which is physically located at the Southern Regional Headquarters of the National Oceanic and Atmospheric Administration (NOAA). The bandwidth of the network between DROC and individual radar nodes depends on the local environment and the “last mile” setup. Majority of the processes for range velocity ambiguity mitigation, clutter suppression, and attenuation correction are implemented at individual radar node computers. Other product generations such as reflectivity mosaic, hydrometeor classification, QPE, and multiple Doppler processing are performed on DROC servers. DROC also serves as the data archive center. The product-based forecasts and alerts are sent to a variety of end users

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Table 1. Longitude, latitude, and altitude above mean sea level (AMSL) of the eight dual-polarization X-band radars deployed in the DFW region, as well as the counties where the radars are deployed. The one marked with * (i.e., XMKN radar) is yet to be deployed.

<table>
<thead>
<tr>
<th>Radar Name</th>
<th>Lat (deg.)</th>
<th>Lon (deg.)</th>
<th>Altitude (m)</th>
<th>City, County</th>
</tr>
</thead>
<tbody>
<tr>
<td>XUTA</td>
<td>32.7306</td>
<td>-97.1125</td>
<td>300</td>
<td>Arlington, Tarrant County</td>
</tr>
<tr>
<td>XMDL</td>
<td>32.4921</td>
<td>-96.9973</td>
<td>250</td>
<td>Midlothian, Ellis County</td>
</tr>
<tr>
<td>XFTW</td>
<td>32.8385</td>
<td>-97.4257</td>
<td>300</td>
<td>Fort Worth, Tarrant, Denton, Parker, Wise Counties</td>
</tr>
<tr>
<td>XUNT</td>
<td>33.2536</td>
<td>-97.1520</td>
<td>224</td>
<td>Denton, Denton County</td>
</tr>
<tr>
<td>XJCO</td>
<td>32.3717</td>
<td>-97.3890</td>
<td>263</td>
<td>Cleburne, Johnson County</td>
</tr>
<tr>
<td>XADD</td>
<td>32.9814</td>
<td>-96.8391</td>
<td>210</td>
<td>Addison, Dallas County</td>
</tr>
<tr>
<td>XMSQ</td>
<td>32.7556</td>
<td>-96.3332</td>
<td>148</td>
<td>Mesquite, Dallas County</td>
</tr>
<tr>
<td>XMKN*</td>
<td>33.2118</td>
<td>-96.6572</td>
<td>225</td>
<td>McKinney, Collin County</td>
</tr>
</tbody>
</table>

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1A bandwidth of 10 mbps is requested from each radar node to DROC, but it is different for different radar nodes. Generally, it is much higher than 10 mbps (e.g., XUNT & XUTA are 60–70 mbps, XMDL is 25–50 mbps, XADD is 10–12 mbps). In theory the bandwidth from DROC to WFO is 45 mbps.
users including the NWS Forecast Office, emergency managers, and flood control district. The end users depending on the level of interest have access to both individual radar-based products and networked products. On the basis of the end users’ feedback, the radar control commands are sent out from the DROC machine.

It is worth noting that the standard products, such as hail identification and rainfall rate, are available from multiple radars with multiple looks (views from different vantage points) such that enhanced observations can be made. This also provides a fault tolerant scheme in which the DFW network system can operate and reconfigure itself even if one of the radars is down. In this regard, the whole DFW test bed is fundamentally considered an integrated networked radar operation system. In addition to providing high-resolution radar data and products to users for real-time warning operations, the DFW test bed is also an ideal research platform, with major research thrusts in including convective initiation, nowcast, and data fusion from in-situ and remote sensors including radars, rain gauges, local profilers, and meteorological satellites.

2.3 Space–time integration of DFW observations and products

Data fusion between the high-resolution X-band radar network and other instrumentation is one of the critical research efforts in the development of the DFW urban remote sensing network. The integration of different data sources is also an indispensable step for creating high-quality networked products. In the
following, we take the S-band KFWS WSR-88DP radar as an example to illustrate the solution of CASA to the spatiotemporal sampling differences among various radar sensors. As aforementioned (see also Table 2), the S- and X-band radar systems operate very differently. From the observation resolution point of view, the KFWS radar generates an update every 5 to 6 min, whereas the X-band radar network produces observations every minute. Spatially, the KFWS radar sampling resolution is severely degraded because of beam broadening as the distance to the radar increases, whereas the X-band radar network has a higher resolution because the individual radar coverage range is limited to within 40 km. Figure 6 shows a conceptual diagram illustrating the space–time integration of DFW observations at different scales. Multiple X-band radars are combined first as a unitary network to produce high-resolution products (e.g., 250 m × 250 m × 1 min). To match the resolution of X-band network products, the S-band KFWS radar-based products (i.e., rainfall rate field) are temporally interpolated to 1 min resolutions by using piecewise cubic polynomial Hermite interpolation (Fritsch and Carlson 1980). Spatially, the KFWS radar products in polar coordinates within 100 km from the radar are mapped onto 250 m × 250 m grids by using Cressman weighting (Cressman 1959). The 100 km range is selected mainly because of the radar beam size and beam broadening effect. Subsequently, products at the same spatiotemporal scale from both KFWS radar and the X-band radar network are merged to generate network-level products. This scheme is particularly suitable for deriving networked rainfall rates and amounts, which will be detailed in Section 5. It should be noted that instead of interpolating radar data (e.g., \(Z\), \(Z_{\text{dr}}\), \(K_{\text{dp}}\)), we decide to interpolate products to avoid nonlinear error propagation. Furthermore, in the hail detection system (detailed in Section 3), the S-band products are not interpolated from a temporal perspective. Instead, whenever there is an S-band scan, we combine it to generate the networked product of hydrometeor types. In other words, the networked hail product is essentially updated according to the KFWS radar scan rate (i.e., 5–6 min).

3. Hail detection

Traditionally, fuzzy-logic based approaches are typically used for hydrometeor classification (Liu and Chandrasekar 2000; Lim et al. 2005; Chandrasekar et al. 2013). As sketched in Fig. 7a, the fuzzy-logic method has four general blocks, namely, fuzzification, inference, aggregation, and defuzzification. It works on each radar resolution cell represented by azimuthal angle and range gate. However, this bin-by-bin-based classification methodology has limitations when applied to “noisy” radar data due to ground clutter, partial
Fig. 6. Schematic diagram showing the space–time integration of DFW observations at different frequencies and time scales.

Fig. 7. (a) General blocks of traditional fuzzy-logic-based hydrometeor classification approach. (b) Diagram of the hydrometeor classification and hail detection system for the DFW urban radar network.
beam blockage, and/or bright band contamination. For example, the radar beam can partially overshoot precipitation, particularly during stratiform events. In regions where it is close to or within the melting layer, the bin-by-bin-based classification approach is not able to properly identify the mixed-phase precipitation because no physical constraints are applied. As a result, the hydrometeor classification products will be noisy. To overcome these issues, a region-based hydrometeor classification approach has been implemented in the DFW radar network. The overall structure of this region-based classification methodology is depicted in Fig. 7b. The input data include radar observed $Z_h$, $Z_{dr}$, $K_{dp}$, and $\rho_{hv}$, as well as the vertical profile of temperature ($T$) attained from a nearby sounding station. First, traditional bin-based fuzzy-logic approach is applied to obtain the initial classification results. The temperature profile is then adjusted on the basis of the quality of wet ice classification, which is essentially the average confidence of all the bins identified as wet ice based on the inference rule (Bechini and Chandrasekar 2015). Second, a modified $K$-means clustering technique is applied to incorporate the spatial contiguity and microphysical constraints. Thereafter, the connected component labeling algorithm (Gonzalez and Woods 2001) is employed to identify and label regions populated with adjacent bins assigned to the same hydrometeor type; the final classification is performed over connected regions by exploiting the statistical distribution of dual-polarization and temperature observations within the regions (for details, see Bechini and Chandrasekar 2015). In total, 11 hydrometeor types are classified, namely, “Large Drops (LD)”, “Drizzle (DR)”, “Rain (RA)”, “Heavy Rain (HR)”, “Rain Hail Mixture (RH)”, “Hail (HA)”, “Graupel (GR)”, “Wet Ice (WI)”, “Dry Ice (DI)”, “Crystals (CR)”, and “Dendrites (DN)”. Ground clutter and nonmeteorological echoes are also identified and labeled as “Clutter (CL)”. Compared with the conventional fuzzy-logic method, this region-based approach is appealing in terms of operational application and easy interpretation. For illustration purposes, Fig. 8 shows the dual-polarization observations from a CASA X-band radar and the corresponding hydrometeor classification results at 04:15 UTC on May 20, 2011. Overall, the classification product shown in Fig. 8e looks reasonable with a few well-defined regions. It is interesting to note that at approximately 2–3 km height and 30 km range where high reflectivity values are present, rain hail mixtures are identified. Some negative $Z_{dr}$ values are observed beyond the rain plus hail region; these values are possibly due to the under-
estimation of the difference of the path-integrated attenuation between two polarization channels. This also sheds light on the importance of coupling the hydrometeor classification for attenuation correction at X band. However, the negative $Z_{dr}$ values at approximately 10 km height and 30 km range are considered to be real, which implies the existence of vertically oriented ice crystals associated with electrical activity inside the storm (Carey and Rutledge 1996; Caylor and Chandrasekar 1996).

For the sake of operational interpretation and clean hail product generation, the hydrometeor classes from individual DFW radar nodes are merged together by using clustering analysis to produce a network-level product. In addition, the number of hydrometeor types is narrowed down to five categories, namely, “Drizzle”, “Rain”, “Rain+Hail”, “Hail”, and “Snow”. In particular, “LD”, “RA”, “HR”, and “WI” are grouped as Rain; “DI”, “CR”, and “DN” are grouped as snow; “HA” and “GR” are grouped as hail. These five categories are essential determined based on the requests of a variety of end users. In the following, the hailstorm that occurred on May 12, 2014, is used as an example to illustrate the hail detection and hail path product for operational warning applications in the DFW area.

A strong line of thunderstorms stretching from Brownwood northeast to Tulsa, Oklahoma, began pushing east-northeast through the DFW area shortly before 15:00 UTC on May 12, 2014. In a very short time span, the storm produced more than 30 mm of rain with hails as large as golf balls at many locations in North Texas. Power outage to more than 60,000 people was reported, with hundreds of flights at the two major airports of North Texas being delayed or canceled. Figure 9 shows the dual-polarization measurements of $Z_h$, $Z_{dr}$, $\rho_{hv}$, and $K_{dp}$ from a DFW X-band radar (i.e., XUTA radar) at 20:50 UTC, May 12, 2014. The $Z_h$ and $Z_{dr}$ shown in Fig. 9 are after attenuation correction. The high $Z_h$ but low $\rho_{hv}$ values near (10 km, −10 km) indicate that the precipitation is not purely liquid, which is identified as rain hail mixture in the DFW hail system product shown in Fig. 9e. With the hail products, a hail path is generated based on the duration of hailfall at the given location. Figure 10 shows the estimated hail path from 20:37 UTC to 20:57 UTC, from which it is observed that dense hail occurred near the Joe Pool Lake. Figure 10 also shows hail pictures and screenshots of ground hail reports from social media. The reported location and time demonstrate the good performance of the DFW hail

![Fig. 9. Sample DFW radar (i.e., XUTA) dual-polarization observations and corresponding hydrometeor classification result at 20:50 UTC, May 12, 2014: (a) $Z_h$, (b) $Z_{dr}$, (c) $K_{dp}$, (d) $\rho_{hv}$, and (e) classified hydrometeor types. The $Z_h$ and $Z_{dr}$ fields shown here are after attenuation correction.](image-url)
system. Although extensive efforts have been devoted by CASA to ground hail report collection and in-situ instrument deployment for hail observations over the DFW Metroplex, it should be noted that the verification of hydrometeor classification (hail) products has never become a straightforward task, particularly when the mix-phased precipitation is observed.

4. Tornado and high-wind detection

Close to the “Tornado Alley”, the topology of the DFW radar network allows for high-resolution observations of the lower troposphere while providing large areas of overlapping coverage (see also Fig. 4). In addition, either under the DCAS scan strategy or the regular scan mode, each radar node is able to finish a volume scan within 1 min, thus making the high-resolution X-band radar network more appealing for retrieving Doppler velocity information and subsequently issuing tornado or high-wind warnings. In this section, the fundamental concept of vector wind velocity retrieval using Doppler radar network is described. The real-time multi-Doppler system designed for the dense urban radar network of DFW is detailed, including the multi-Doppler scan strategy, system integration of high-resolution observations, and sample real-time products generated during tornado and high-wind events.

4.1 Fundamentals of multi-Doppler retrieval

The essence of multi-Doppler wind retrieval from a radar network is to obtain the 3D velocity components in Cartesian coordinate from the nonorthogonal radial velocities measured by individual radars (Miller and Strauch 1974; Ray et al. 1980). In the Cartesian coordinate system, the velocity of a particle at \((x, y, z)\) within a thunderstorm can be expressed by a triplet

![Hailfall Duration (minutes)](image)

Fig. 10. Hail product (path/duration) based on the DFW radar network over Joe Pool Lake from 20:37 to 20:57 UTC on May 12, 2014. The hailfall and hail path have been demonstrated by social media reports.
(u, v, w + wₖ), where u, v, and w are the velocity component eastward, northward, and vertical, respectively. wₖ is the particle fall speed. The projections of particle motion onto the line of sight of the radars are expressed as follows:

\[ V_{R}^{m} = \begin{bmatrix} u \sin \Phi_{m} \cos \theta_{m} + v \cos \Phi_{m} \cos \theta_{m} + (w + w_{k}) \sin \theta_{m} \\ \vdots \\ u \sin \Phi_{m} \cos \theta_{m} + v \cos \Phi_{m} \cos \theta_{m} + (w + w_{k}) \sin \theta_{m} \end{bmatrix}, \]

where \( V_{R}^{m} \) is the radial velocity measured by radar node \( m \); \( \Phi_{m} \) and \( \theta_{m} \) are the azimuth and elevation angles of the radial beam, respectively. By taking into account the geometric relation in Cartesian coordinates, Eq. (2) can also be expressed as follows:

\[ V_{R}^{m} = \frac{1}{r_{m}} \begin{bmatrix} u(x - x_{m}) + v(y - y_{m}) \\ (w + w_{k})(z - z_{m}) \end{bmatrix} \]

(3)

for a radar at \((x_{m}, y_{m}, z_{m})\) with slant range \( r_{m} = \sqrt{(x - x_{m})^{2} + (y - y_{m})^{2} + (z - z_{m})^{2}} \).

Putting the radial velocities into a vector form \( \mathbf{V}_{R} = [V_{R}^{1} \ldots V_{R}^{n}]^{T} \) and using the following matrix form:

\[ \mathbf{H} = \begin{bmatrix} \sin \Phi_{1} \cos \theta_{1} & \cos \Phi_{1} \cos \theta_{1} & \sin \theta_{1} \\ \vdots & \vdots & \vdots \\ \sin \Phi_{m} \cos \theta_{m} & \cos \Phi_{m} \cos \theta_{m} & \sin \theta_{m} \end{bmatrix}, \]

where \( \mathbf{H} \) is the mass continuity equation (Miller and Strauch 1974):

\[ \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0, \]

(8)

where \( \rho \) is the air density that is modeled as a function of the altitude in this study. Furthermore, its local variation is assumed to be negligible. In this paper, we focus more on the horizontal wind retrieval with an emphasis on the engineering issues and application products. Refer to Miller and Anderson (1991) and Zhang (2011) for more details on the vertical velocity component computation and boundary conditions applied when solving Eq. (8).

### 4.2 DFW multi-Doppler retrieval system

Simultaneous measurements from individual radar nodes are required to apply the multi-Doppler techniques. Therefore, effective and efficient scans should be conducted for multi-Doppler retrieval by taking into account the resource limitations such as time constraint and computational complexity. As aforementioned, the DFW network is designed with a small “heartbeat” for a volume scan to ensure data synchronization and meet the computational requirement. In addition, multiple candidate pairs may exist for dual-Doppler synthesis in the overlapping regions, and a choice has to be made to select the best pair. In the DFW network system, the selection is made according to the optimal radar beam-crossing angles for the target areas (Chen and Chandrasekar 2018). Figure 11 illustrates the real-time data flow and system operation for multi-Doppler retrieval. There are three major steps, namely,

1. Real-time data acquisition
2. Ingestor
3. Main processing for Doppler wind synthesis

On the basis of data transmission protocols, the moment data from each radar in compressed NetCDF format are streamed to the radar operation center (see also Fig. 5), which houses the rest of the processing sub-systems. In this step, radar data are also broken down into elevation denominated PPI sweeps. Thereafter, the “Ingestor” program will decompress the incoming data, extract their scanning information, and synchronize them to respective radars and volumes for subsequent Doppler synthesis. In the main processing, the data in radar polar coordinates are first mapped onto a common Cartesian space such that multi-Doppler wind synthesis can be conducted (Chen and Chandrasekar 2018). In the Doppler synthesis step, if data are available from only one radar node, no wind velocity information will be produced. If two or more radars are available, the horizontal components (i.e.,
and \( v \) of wind velocity will be retrieved. The whole system is automated, and the processing is continuously updated every minute, thus making it suitable for the real-time detection of sudden wind-related hazards, such as tornadoes and microbursts. The real-time wind products are immediately sent to the forecast and emergency management offices for issuing tornado and high-wind warnings.

4.3 Case studies

a. EF0 tornado on May 8, 2014

On May 8, 2014, the large-scale lift ahead of an upper level shortwave, combined with ample instability and adequate moisture, evolved in North Texas. Severe thunderstorms were observed moving through this area. Scattered convection developed in the afternoon, and a linear mesoscale convective system formed by late afternoon. Although there were no fatalities or injuries, the damaging downburst winds produced numerous damaged trees and brought down power lines across areas in and around the city of Dallas. An EF-0 tornado was reported in Cockrell Hill (32.757N, -96.889W) in Dallas County around 20:14 UTC on May 8, 2014. Figure 12 shows a screenshot of the NWS tornado report\(^2\) for this event. The tornado

\(^2\) Available at https://www.weather.gov/media/fwd/sd0514.pdf

Fig. 11. Framework of real-time Doppler wind retrieval system and application for DFW urban radar network.

Fig. 12. NWS tornado report for the EF0 tornado in Cockrell Hill on May 8, 2014.
path length was approximately 800 m, and the path width was approximately 137 m, according to the NWS report. Although the tornado only lasted 2 min (20:14–20:15 UTC), it caused damage to a warehouse building in Cockrell Hill. Several windows were blown out of the warehouse, and the building also suffered roof damage as the tornado moved from the southwest to northeast.

During the entire event, the DFW multi-Doppler wind retrieval system was continuously monitoring the weather conditions. Figure 13 shows the multi-Doppler velocity retrieval results at 1 km height during this EF0 tornado event. At 20:14 UTC, the retrieved maximum velocity is approximately 112.7 km h$^{-1}$ (31.3 m s$^{-1}$) and 119.0 km h$^{-1}$ (33.1 m s$^{-1}$) at 20:15 UTC. The color-coded field represents the vertical vorticity. The vortex locations agree fairly well with the NWS tornado report shown in Fig. 12.

![Figure 13](image-url)  
Fig. 13. Multi-Doppler wind velocity retrieval results based on the DFW radar network during the EF0 tornado event on May 8, 2014, at (a) 20:14 and (b) 20:15 UTC. The results are at 1 km height level. The arrows denote the magnitude and direction of the retrieved wind velocity. The reference speed of 100 km h$^{-1}$ corresponds to 27.8 m s$^{-1}$. The maximum velocity at 20:14 UTC is approximately 112.7 km h$^{-1}$ (31.3 m s$^{-1}$) and 119.0 km h$^{-1}$ (33.1 m s$^{-1}$) at 20:15 UTC. The color-coded field represents the vertical vorticity. The vortex locations agree fairly well with the NWS tornado report shown in Fig. 12.

b. High wind on October 2, 2014
Severe thunderstorms packing winds of up to 200 km h$^{-1}$ (55.6 m s$^{-1}$) tore through the DFW area on October 2, 2014. The severe storm began to develop shortly before 18:00 UTC, when a severe thunderstorm watch was issued for most of North Texas. The storms developed near Jack County, Wise County, and Parker County approximately 70 km to the northwest of Fort Worth before moving east. A severe thunderstorm warning was effective until 22:00 UTC for Dallas County. This fast-moving storm left widespread damage and power outages as winds downed utility poles and tree limbs. Many flights were canceled at DFW International Airport. It was concluded that the significant damage was not caused by rain (less than 10 mm of rain was observed in DFW airport) but by straight-line winds. The real-time DFW multi-Doppler wind retrieval system was operating during this high-wind event. Figure 14 shows the DFW network reflectivity observation and the retrieved wind speed and directions at 1 km height at 20:53 UTC, which was when the peak wind was reported. The peak wind speed reached approximately 200 km h$^{-1}$ (55.6 m s$^{-1}$) at the location near (-97.15W, 32.75N). The retrieved peak wind and corresponding location agree fairly well with the ground weather report (SPC 2014).

5. Quantitative precipitation estimation for DFW network
5.1 High-resolution DFW radar rainfall system
It is well known that both the dual-polarization radar measurements and rainfall rate can be related to raindrop size distribution (DSD). On the basis of the DSD information, various rainfall relations have been developed with respect to dual-polarization radar
namely, relations can be broadly classified into five categories, observables (e.g., Chen et al. 2017). In general, these relations can be broadly classified into five categories, namely, \( R(Z_a), R(Z_d, Z_d), R(K_{dp}), R(Z_{dp}, K_{dp}), \) and \( R(A_n) \), which is based on attenuation \( A_n \). Unfortunately, owing to spatiotemporal sampling limitations, the operational QPE products based on the WSR-88DP network are typically produced on \( 1 \text{ km} \times 1 \text{ km} \) spatial grids (e.g., Zhang et al. 2016) and focused on rainfall accumulations at temporal scales of 1, 3, 6, 12, and/or 24 h (daily). The coarse resolution hinders the WSR-88DP-based rainfall products for flash flood applications, particularly high-impact urban flash floods.

In the DFW network, we take advantage of the rapid radar scan strategy that can produce high-resolution observations in both space and time domains to create real-time high-quality rainfall products for flood applications. Figure 15 shows the schematic diagram of the real-time QPE system for the DFW urban radar network. The DFW QPE system consists of the dual-polarization S-band KFWS WSR-88DP radar and high-resolution X-band polarimetric radar network. As shown in Fig. 15, we use different rainfall methodologies for S-band KFWS radar and X-band DFW radars. For S-band, a blended rainfall algorithm is implemented where specific rainfall relations are guided by hydrometeor classification results (Chen et al. 2017). The estimated rainfall rates in radar’s native (polar) coordinates are then mapped onto Cartesian grids by using a Cressman weighting scheme to match the X-band network product resolution. For the X band, the choice of rainfall algorithm is influenced by attenuation because \( Z_a \) and \( Z_{dp} \) must be corrected for attenuation before using them for any quantitative application. Therefore, we consider only \( R(K_{dp}) \) at the X band. \( R(K_{dp}) \) is the only estimator not affected by attenuation, and it is not sensitive to partial beam blockage and hail contamination, as well as the absolute calibration error of the radar system (Aydin et al. 1995; Chandrasekar et al. 1990). In the DFW QPE system, the \( K_{dp} \) fields from synchronized X-band radar scans are projected onto the same Cartesian grids at first. Thereafter, they are merged together to produce \( R(K_{dp}) \)-based rainfall rates. Therein, for a given grid pixel, the closest radar has priority in the merging process to ensure high-resolution and low-level samples (Chandrasekar et al. 2012). The integration of measurements at different frequencies and time scales is described in Section 2.3. Overall, the DFW QPE system produces real-time rainfall rate estimates at \( 250 \text{ m} \times 250 \text{ m} \) scale spatially; temporally, the instantaneous rainfall rates are updated every minute (Chen and Chandrasekar 2015). Using the one-minute resolution rainfall rate field, running accumulations of rainfall at different time scales are produced in real time, including 5, 15, 30, 60 min rainfall amounts updated every minute. Furthermore, 3, 6, and 12 h rainfall products are generated at the top of the hour.

5.2 Sample products and system performance

The DFW QPE system has been operating for a number of years. Overall, it is very robust and continues to work fine without any incident. In the following, an interesting flash flood event (i.e., Thanksgiving...
event) in 2015, which is the wettest year on record, is investigated to illustrate the real-time QPE products and system performance. Over the night of November 26, 2015, a slow-moving band of thunderstorms moved into the DFW area from the west and dumped more than 150 mm of rain. Later, a few isolated thunderstorm cells moved from the south and also merged with the line of storms, thus enhancing rainfall and leading to severe flooding. Dangerous flooding situations were reported all across the Metroplex. In Johnson County, more than 45 roads were closed. Figure 16 shows sample real-time rainfall products from the DFW QPE system for a flooded area (~40 km × 40 km) on November 27, 2015, at 12:00 UTC.

Chen and Chandrasekar (2015) quantitatively evaluated the performance of DFW rainfall system for several precipitation events in different seasons in 2013 using rainfall measurements from 20 high-quality gauges in Grand Prairie. It has been shown that the DFW QPE system product has superior performance to both WSR-88DP single- and dual-polarization rainfall products for the precipitation events presented in their study. To date, many gauge data have been made available to CASA. Figure 17 shows the layout of available validation gauges (red triangles) with respect to the location of several DFW radars. Therefore, we take this opportunity to revisit the case studies presented in Chen and Chandrasekar (2015) by using rainfall measurements from over 50 gauges as references. Figure 18 shows the rainfall performance as a function of rainfall accumulation time for the case studies reported in Chen and Chandrasekar (2015). The error bars in gray show the variation of rainfall performance at over 50 gauge locations. Generally, the variation is less than 7%. The quality of DFW QPE products is among the best results available in the literature. Nevertheless, it should be noted that the intention of this paper is not to provide an exhaustive evaluation of various rainfall products for a large number of precipitation events.

In the Thanksgiving 2015 case study, for the sake of cross-comparison, the 1 min DFW rainfall estimates are aggregated to produce rainfall accumulations at 15 min intervals. Figure 19 illustrates the 15 min rainfall from the DFW QPE system and gauges at sample gauge locations over a 24 h period. Rainfall accumulations during this 24 h period are also shown in Fig. 19 (cross comparisons at other gauge locations are not shown because they show essentially the similar results as those in Fig. 19). The radar network-based rainfall products agree very well with rain gauge observations, thus demonstrating the excellent performance of the DFW QPE system.

6. Summary and conclusions

Owing to the Earth’s curvature, complex terrain,
and urban deployment challenges, physically large, high-power, long-range radars in the current operational network have severe limitations in observing the lower part of the troposphere, where many hazardous weather events occur. Furthermore, the space–time resolutions of measurements and products based on the current operational radars are insufficient for monitoring high-impact localized weather phenomen-
Fig. 18. Rainfall performance as a function of rainfall integration time for the case studies in Chen and Chandrasekar (2015). The error bars show the variation of rainfall performance at over 50 different gauge locations. Generally, the variation is within 7%.

Fig. 19. The 15 min rainfall (thin lines) and rainfall accumulations (thick lines) from the DFW QPE system versus the rainfall observations from gauges at sample gauge locations over a 24 h period during the 2015 Thanksgiving flood event.

To this end, the center for CASA has developed an alternative weather sensing approach by deploying dense networks of low-power, small X-band dual-polarization radars. The new sensing paradigm proposed by CASA collaboratively and adaptively operates X-band radar nodes and adapts them to changing atmospheric conditions and the needs of multiple users. By observing and tracking the storm cells in an adaptive and dynamic manner, such networks can provide enhanced sampling of weather features near the ground, which is beyond the capability of state-of-the-art operational radars.

The CASA consortium has been operating its first urban high-resolution radar network in the DFW Metroplex for approximately five years. Centered around the deployment of a network of eight boundary-layer observing dual-polarization X-band radars, the DFW test bed is based on the new technologies.
and end-user research conducted by the CASA project. Furthermore, existing in-situ and remote sensors such as WSR-88DP radar and rain gauges are used to generate network-level weather products. Data products from the DFW network include single and multiradar data, vector wind, QPE, nowcasting, and analysis and NWP products. The overall goal is to save lives and reduce property losses due to urban weather disasters. The DFW urban radar network is also an ideal platform to demonstrate the new sensing paradigm advanced by CASA in a quasi-operational environment.

By using the DFW network as an example, this paper presented the principle of high-resolution radar network for urban hazard mitigation and disaster management. Particularly, the precipitation classification and estimation systems developed for DFW dense urban radar network were described for improving hail and flash flood prediction. The multiple Doppler wind retrieval system was also presented to improve the detection and tracking of high winds and tornadoes and reduce false alarm rates. The real-time products are integrated to operational platforms for evaluation by a variety of users, including NWS forecasters, emergency managers, and social media.

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References


