The Quantitative Precipitation Estimation System for Dallas-Fort Worth (DFW) Urban Remote Sensing Network

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Abstract

The Dallas-Fort Worth (DFW) urban radar network consists of a combination of high resolution X band radars and a standard National Weather Service (NWS) Next-Generation Radar (NEXRAD) system operating at S band frequency. High spatiotemporal-resolution quantitative precipitation estimation (QPE) is one of the important applications of such a network. This paper presents a real-time QPE system developed by the Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center for the DFW urban region using both the high resolution X band radar network and the NWS S band radar observations. The specific dual-polarization radar rainfall algorithms at different frequencies (i.e., S- and X-band) and the fusion methodology combining observations at different temporal resolution are described. Radar and rain gauge observations from four rainfall events in 2013 that are characterized by different meteorological phenomena are used to demonstrate the capability of rainfall estimation of the CASA DFW QPE system. This high-resolution QPE system is used for urban flash flood mitigations when coupled with hydrological models.

Keywords: CASA, Radar, WSR-88DP, QPE, urban flooding, DFW

1. Introduction

Urban flash flooding is one of the most commonly encountered hazardous weather phenomena. Unfortunately, the rapid urbanization has made the densely populated areas even more vulnerable to flood risks. Therefore, accurate and timely estimation of precipitation and streamflow at high spatiotemporal resolution is critical for civil defense, especially in urban areas. To this end, numerous infrastructures have been deployed to directly or indirectly measure rainfall rate and amounts, such as rainfall gauges and weather radar networks. Among these tools, radar has shown great advantages to conduct spatially continuous observations over a large area with small temporal sampling intervals (e.g., Bringi and Chandrasekar, 2001; Cifelli and Chandrasekar, 2010). Hence, it is the primary system for quantitative precipitation estimation (QPE) in many nations. In addition, the point measurements of rainfall from rain gauges are often used for evaluation and bias correction of radar rainfall products (e.g., Seo et al., 1999; Seo and Breidenbach, 2002; Zhang et al., 2011; Willie et al., 2013), and/or for merging with radar rainfall products (e.g., Seo, 1998; Chumchean et al., 2006; Seo et al., 2010; Zhang et al., 2011; Habib et al., 2013; Zhang et al., 2014).

Traditionally, radar rainfall estimators start with the radar reflectivity (Z) and rainfall rate (R) relationships, which are also known as $Z - R$ relations. Nevertheless, the uncertainty factors make the $Z - R$ relations imprecise to capture the complex spatial and temporal variability of rainfall, especially in geographic areas with diverse topographies. These uncertainty factors may include radar partial beam blockage, radar signal attenuation due to propagation in rainfall, as well as absolute calibration errors of radar system, etc. (Wilson and Brandes, 1979; Kitchen et al., 1994; Fulton et al., 1998). Subsequently, the use of single-polarization radar based QPE as input to flash flood models is fairly limited in scope, especially for urban basins with rapid

70 response to short-term precipitation (Emmanuel et al., 2012). Moreover, the commonly used
71 power law relationship ($Z = aR^b$) greatly relies on the rain drop size distribution (DSD), which
72 can be very different for different climatological regions, even within a single storm. It is often a
73 nontrivial task to find an ideal $Z - R$ relation to satisfy the rain microphysical properties for all
74 the storms. Since the introduction of dual-polarization concept (Seliga and Bringi, 1976; Seliga
75 and Bringi, 1978), considerable research effort has been devoted to polarimetric radar systems
76 and QPE methodologies based on dual-polarization radar measurements (e.g., Park et al., 2005;
77 Ryzhkov et al., 2005; Giangrande and Ryzhkov, 2008; Wang and Chandrasekar, 2010; Cifelli et
78 al., 2011; Emmanuel et al., 2012; Figueras i Ventura and Tabary, 2013; Bechini et al., 2013). The
79 dual-polarization radar observations offer a number of advantages over single-polarization radar
80 by gleaning more information about rain DSD and providing more indicative characteristics for
81 discriminating precipitation echoes from non-precipitation echoes. The combination of dual-
82 polarization radar measurements and environmental temperature is also capable of identifying
83 different hydrometeor types over the illuminated scanning volumes to further improve the
84 precipitation estimation (e.g. Liu and Chandrasekar, 2000; Lim et al., 2005; Dolan and Rutledge,
85 2009; Chandrasekar et al., 2013a; Bechini and Chandrasekar, 2015). Since 2011, the U.S.
86 National Oceanic and Atmospheric Administration (NOAA)’s National Weather Service (NWS)
87 had initiated the effort to upgrade the S-band (wavelength $\lambda \approx 10 - 11\text{cm}$) Weather
88 Surveillance Radar-1988 Doppler (WSR-88DP) network to include dual-polarization
89 capabilities. One of the main drivers for dual-polarization upgrade is better rainfall estimation.
90 Now, all the WSR-88DP sites in the Contiguous United States (CONUS) are operating in dual-
91 polarization mode (<https://www.roc.noaa.gov>).

92 In order to overcome the WSR-88DP coverage limitations due to terrain blockage and
93 Earth's curvature effect at long ranges, the U.S. National Science Foundation Engineering Center
94 (NSF-ERC) for Collaborative Adaptive Sensing of the Atmosphere (CASA) has been dedicated
95 to enhance the ability to observe, understand, predict and respond to hazardous weather events
96 using a dense network of small, low-power X-band dual-polarization radars (wavelength $\lambda \approx$
97 3cm) that can sense the lower atmosphere (McLaughlin et al., 2009). These smaller and less
98 expensive radars can serve as gap fillers of WSR-88DP network by providing enhanced
99 sampling of precipitation and winds near the ground. A new observation paradigm termed
100 Distributed Collaborative Adapting Sensing (DCAS) was proposed to collaboratively operate the
101 radar networks and adapt them to changing atmospheric conditions. The overall goal of the
102 DCAS sensing methodology is to save lives and reduce property losses through improving QPE
103 for flood prediction, reducing the tornado false alarm rate, and improving severe weather
104 forecast, etc. The first end-to-end DCAS system test bed with four radar nodes was deployed in
105 the tornado prone Southwestern Oklahoma at the locations of Cyril, Lawton, Rush Springs, and
106 Chickasha (McLaughlin et al., 2009). The high resolution radar observations, post-event
107 analysis, and fundamental multi-disciplinary research during the five-year (2007-2011) operation
108 had demonstrated the success of CASA concepts (Chandrasekar et al., 2010). In order to study
109 and mitigate the urban weather disasters, CASA, in collaboration with the North Central Texas
110 Council of Governments (NCTCOG) and NWS, has embarked on the development of the first
111 urban test bed in Dallas-Fort Worth (DFW) Metroplex, the largest land-locked metropolitan area
112 in the U. S. This urban remote sensing network, centered by the deployment of eight boundary-
113 layer observing, dual-polarization X-band radars and a WSR-88DP site (i.e., KFWS radar), is
114 expected to provide flash flood warnings and response in a densely populated urban environment

(Chandrasekar et al., 2013b). In this study, we present and evaluate the QPE system developed for this urban remote sensing network, which is built based upon the S-band polarimetric KFWS WSR-88DP radar and CASA DFW X-band dual-polarization radars.

The paper is organized as follows. In section 2, an overview of the CASA DFW urban remote sensing network is provided. Section 3 details the S- and X-band dual-polarization radar QPE methodologies and the rainfall merging based on radar observations from S- and X-band radar systems. Section 4 describes the four meteorological events selected for QPE evaluation. Section 5 presents the results of case studies, with particular attention paid to the radar-rain gauge comparisons. In section 6, we summarize the main findings of this paper.

2. Overview of the CASA DFW Urban Remote Sensing Network

Being one of the largest inland metropolitan areas in the U.S., the DFW Metroplex is home to over 6.5 million people according to the NCTCOG. It experiences a wide range of natural weather hazards, including urban flash flooding, high wind, tornado, and hail, etc. Successful monitoring of the rapid changing meteorological conditions in such a region is necessary for emergency management and decision making. Therefore, it is an ideal location to investigate the impacts of hazardous weather phenomena in an urban setting and demonstrate the CASA concept in a densely populated urban environment. Since 2012, CASA and the NCTCOG have initiated the five-year project to create the DFW Urban Demonstration Network. It covers 12 out of the 16 counties in the Metroplex, and majority of the 6.5 million people in this area.

The major goals of the development of this end-to-end test bed are to:

- develop high-resolution, two- and three-dimensional mapping of current atmospheric conditions for hazardous weather detection and mitigation.
- demonstrate the value of a dense network of dual-polarization X-band radars to existing sensors and assess optimal combinations of different observing systems.

- create impacts-based, neighborhood-scale warnings and forecasts in real-time for benefit of the public safety and economy.
- develop models for federal/municipal/private partnerships to introduce new observation technologies for on-going operational and interdisciplinary weather system research.

The research and research-to-operation topics include but not limited to:

- quantitative precipitation estimation (QPE) and forecasting (QPF)
- urban flooding and hydrologic modelling
- hydrometeor identification
- 3-D multi-Doppler wind retrieval

Centered in this urban remote sensing test bed is the deployment of a dense network of CASA X-band dual-polarization radars. Fig. 1 shows an example layout of the CASA X-band radars and their relative location to the local S-band KFWS WSR-88DP radar. Fig. 2 shows the overview of dataflow architecture in the DFW urban remote sensing network. Through internet and Local Data Manager (LDM) publish-subscribe protocols, the real-time polarimetric radar variables from the networked radars will be transferred to the DFW Radar Operations Center (DROC) housed in the building of NWS Southern Region Headquarters (SRH), where the data is archived. The Meteorological Command and Control (MC&C) system is also installed in DROC, which detects the meteorological features and adaptively adjusts the radar scanning strategies to optimize the allocation of system resources (i.e., sensing, computation and bandwidth) according to the end-users' feedback (Pepyne et al., 2008).

In addition, CASA will take advantage of existing sensors, such as WSR-88DP and rain gauges, for creating new products and for validation purposes. In this paper, the CASA X-band radar installed at the University of Texas-Arlington (hereafter referred to as XUTA) and S-band KFWS WSR88DP radar will be used extensively for demonstrating the QPE system for this local

region. The high-resolution rainfall products from the CASA DFW QPE system can serve as input of flash flood models (Rafieeinasab et al., 2014; Rafieeinasab et al., 2015 in review). Fig. 3 summarizes the key perspectives of this urban radar network in the context of QPE and flash flood warning.

3. Methodologies

3.1. A review of the dual-polarization radar observations

The dual-polarization radar measurements are derived from the back scattering matrix of the radar return signals (Bringi and Chandrasekar, 2001). In this section, four polarimetric radar variables commonly used in rainfall applications are briefly reviewed, namely, the reflectivity factor (Z_h), differential reflectivity (Z_{dr}), the specific differential propagation phase (K_{dp}), and the copolar correlation coefficient (ρ_{hv}). The interested reader may find more comprehensive reviews of the polarimetric radar variables in Bringi and Chandrasekar (2001) and Kumjian (2013). Among the four variables, Z_h , Z_{dr} , and ρ_{hv} can be directly measured by a dual-polarization radar system, whereas K_{dp} is estimated as the range derivative of the differential phase shift (Φ_{dp}).

3.1.1. Reflectivity factor (Z_h)

The reflectivity factor at horizontal (Z_h) and vertical polarization (Z_v) is defined as (Bringi and Chandrasekar, 2001):

$$Z_h = \frac{\lambda^4}{\pi^5 |K_w|^2} \int \sigma_h(D) N(D) dD \quad (1a)$$

$$Z_v = \frac{\lambda^4}{\pi^5 |K_w|^2} \int \sigma_v(D) N(D) dD \quad (1b)$$

where λ is the radar wavelength; $|K_w|^2$ is the dielectric factor of water given by $|K_w|^2 = |(\epsilon_r - 1)/(\epsilon_r + 2)|^2$, here ϵ_r is the complex relative dielectric constant of water; D is the

particle equivalent diameter in mm; σ_h and σ_v are the radar cross section at horizontal and vertical polarization, respectively; $N(D)dD$ is the number of drops m^{-3} in the interval D to $D + dD$. The logarithmic transformation $10\log_{10}Z_h$ is often used and its units are in decibel of Z_h relative to $1 \text{ mm}^6\text{m}^{-3}$ (which corresponds to 0 dBZ).

3.1.2. Differential reflectivity (Z_{dr})

The differential reflectivity is the ratio of reflectivity factor at horizontal polarization to that at vertical polarization, and can be expressed as follows:

$$Z_{dr}(\text{dB}) = 10 \log_{10} \frac{Z_h}{Z_v} = 10 \log_{10} \frac{\int \sigma_h(D)N(D)dD}{\int \sigma_v(D)N(D)dD} \quad (2)$$

Z_{dr} directly relates to the axis ratio, size and canting effects of hydrometeors (Seliga and Bringi, 1976). Therefore, it is often used for DSD retrieval. Z_{dr} is positive for oblate particles such as raindrops, negative for prolate particles, and zero for particles that are ideally spherical. It is a critical dual-polarization radar variable utilized to identify rainfall intensities and different hydrometeor types. In addition, examining the Z_h and Z_{dr} space, we can separate large hailstones from raindrops because hailstones generally produce larger Z_h but smaller Z_{dr} relative to raindrops (Aydin et al., 1995; Ryzhkov et al., 2013).

3.1.3. Specific differential propagation phase (K_{dp})

The specific differential phase is defined as:

$$K_{dp} = \frac{180}{\pi} \lambda \text{Re} \int [f_h(D) - f_v(D)]N(D)dD \quad (3)$$

where f_h and f_v are the complex forward scattering amplitudes at horizontal and vertical polarization, respectively.

K_{dp} is estimated as the range derivative of the propagation phase difference (Φ_{dp}) between horizontal and vertical polarization channels.

$$\hat{K}_{dp} = \frac{\Phi_{dp}(r_2) - \Phi_{dp}(r_1)}{2(r_2 - r_1)} \quad (4)$$

3.1.4. Correlation coefficient (ρ_{hv})

The copolar correlation coefficient is a measure of the correlation between the reflected horizontal and vertical power returns. ρ_{hv} can be expressed in terms of the elements in the backscattering matrix as,

$$\rho_{hv}(0) = \frac{\langle S_{vv} S_{hh}^* \rangle}{\langle S_{hh}^2 \rangle^{1/2} \langle S_{vv}^2 \rangle^{1/2}} \quad (5)$$

where S_{hh} and S_{vv} refer to the elements of the backscattering matrix, the asterisk denotes the complex conjugate, and the angle brackets stand for sample average.

Though ρ_{hv} is not directly related to rainfall estimation, it is a good indicator of regions where there is a mixture of precipitation types, such as rain and ice mixture. It is also sensitive to particle axis ratio and shapes. In this paper, ρ_{hv} is used in the S-band radar hydrometeor classification algorithm (HCA).

3.2. QPE methodology for CASA DFW urban remote sensing network

3.2.1. Rainfall Algorithms

As the fundamental building block for deriving various rainfall algorithms, the DSD of rain describes the probability density of raindrop sizes. Generally, a water content normalized gamma DSD model can adequately represent the natural variations in the shape of rain DSD (Testud et al., 2000; Bringi and Chandrasekar, 2001):

$$N(D) = N_w f(\mu) \left(\frac{D}{D_0} \right)^\mu \exp \left[- (3.67 + \mu) \frac{D}{D_0} \right] \quad (6)$$

where D_0 is the median volume diameter in mm, μ is a distribution shape parameter, and N_w is the normalized intercept parameter of an equivalent exponential distribution with the same water content and D_0 . Both $N(D)$ and N_w are in the units of $\text{m}^{-3} \text{mm}^{-1}$, and,

$$f(\mu) = \frac{6}{(3.67)^4} \cdot \frac{(3.67+\mu)^{\mu+4}}{\Gamma(\mu+4)} \quad (7)$$

Based on the DSD, the rainfall rate (R) is defined as:

$$R = 0.6\pi \times 10^{-3} \int v(D)D^3N(D)dD \quad (8)$$

where $v(D)$ is the rain drop terminal velocity in m s^{-1} .

Various rainfall algorithms can be derived with respect to the dual-polarization radar measurements via the DSD information. An overview about the dual-polarization rainfall algorithms can be found in Bringi and Chandrasekar (2001). Generally, radar rainfall algorithms can be broadly classified into four categories, namely, $R(Z_h)$, $R(Z_h, Z_{dr})$, $R(K_{dp})$, and $R(Z_{dr}, K_{dp})$, in the following forms:

$$R(Z_h) = aZ_h^b \quad (9a)$$

$$R(Z_h, Z_{dr}) = aZ_h^b Z_{dr}^c \quad (9b)$$

$$R(K_{dp}) = aK_{dp}^b \quad (9c)$$

$$R(Z_{dr}, K_{dp}) = aZ_{dr}^b K_{dp}^c \quad (9d)$$

The generic constants a, b, c in the above equations are mainly determined by the natural distribution of rainfall type and radar operating frequency.

It is well known that each dual-polarization parameter based rainfall estimator has its own advantages and disadvantages. There are a few criteria that can be used for choosing the proper rainfall algorithms such as those depending on the rainfall rate values (e.g., Ryzhkov et al., 2005). In this paper, we use different methodologies for S- and X-band radar.

For the S-band KFWS WSR-88DP radar, we implement the algorithm described in Giangrande and Ryzhkov (2008) and Cifelli et al. (2011), where the blended rainfall algorithm is guided by the hydrometeor classification results. Fig. 4 shows a flowchart of the blended rainfall

rate retrieval algorithm (hereafter referred to as Colorado State University Dual-Polarization (CSU-DP) algorithm).

As shown in Fig. 4, a fuzzy logic based HCA is applied prior to rainfall estimation. The HCA is based on the radar measurement of Z_h , Z_{dr} , K_{dp} , ρ_{hv} , and the environmental temperature (T) (Liu and Chandrasekar, 2000; Lim et al., 2005). For the sake of rainfall estimation, only three hydrometeor categories are classified, namely, “Rain”, “Rain/Hail Mixture”, and “Others”. “Rain” includes drizzle and rain in Lim et al. (2005). “Others” includes wet snow, dry snow, and graupel, etc. The hydrometeor categories and thresholds on polarimetric radar variables (τ_1 , τ_2 , τ_3 in Fig. 4) are then used to direct the choice of specific rainfall algorithm. The rainfall relations used in the CSU-DP methodology, namely, $R(Z_h)$, $R(Z_h, Z_{dr})$, $R(K_{dp})$, $R(Z_{dr}, K_{dp})$, are from Bringi and Chandrasekar (2001) (see chapter 8 for S-band radar rainfall relations).

For the X-band CASA radars, the choice of rainfall algorithm is influenced by attenuation since Z_h and Z_{dr} must be first corrected for attenuation before using them for rainfall estimation. To this end, we consider only $R(K_{dp})$. At X-band, $R(K_{dp})$ is the only estimator not affected by attenuation. In addition, $R(K_{dp})$ is not sensitive to partial beam blockage, hail contamination, and the absolute calibration error of radar system (Aydin et al., 1995; Bringi and Chandrasekar, 2001). In this paper, we use the following relation for the X-band CASA radar rainfall estimation:

$$R = 18.15K_{dp}^{0.79} \quad (10)$$

Equation (10) is obtained based on the adjustment of one of the S-band KOUN’s $R(K_{dp})$ relations described in Ryzhkov et al. (2005), which is repeated here as:

$$R = 47.3K_{dp}^{0.791} \quad (11)$$

It should be noted that the relation in equation (10) is particularly for the region of Southern Oklahoma or Northern Texas.

3.2.2. Rainfall Merging

Multiple radar and radar-gauge QPE mosaicking has been studied extensively in the literature (e.g., Seo et al., 2010; Zhang et al., 2011; Habib et al., 2013). However, most of the operational multi-sensor QPE systems based on WSR-88DP radar network produce mosaicked QPE products typically on 1km by 1km spatial grids, and focus on rainfall accumulations at temporal scales of 1-hour, 3-hour, 6-hour, 12-hour, and/or 24-hour (daily). In this paper, we take advantage of the CASA high-resolution sampling strategy, which can produce high-resolution observations in both spatial and temporal domain. Fig. 5 shows a schematic diagram of the QPE system designed for the CASA DFW urban remote sensing network. The QPE system can produce real-time rainfall measurements at a 250m by 250m spatial scale, and temporally the various rainfall products are updated every minute.

As shown in Fig. 5, the S-band KFWS radar generates rainfall rate map every five to six minutes (Block 1 in Fig. 5), whereas the CASA X-band radar network creates rainfall rate updated every one minute (Block 2 in Fig. 5). To this end, a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) based interpolation methodology (Fritsch and Carlson, 1980) is implemented to interpolate the KFWS radar rainfall rate field into one-minute scale. Spatially, the KFWS radar observations in polar coordinates are mapped to 250m by 250m grids by Cressman interpolation (Cressman, 1959), in order to match the X-band QPE system resolution. Subsequently, the merged one-minute resolution rainfall rates are used for computing rainfall amounts at different time scales. It should be mentioned here that the investigation of different temporal interpolation methods for WSR-88DP radar is beyond the scope of this paper. There

might be more, and even better, interpolation schemes which can better reflect the temporal variability of precipitation. Interested readers can refer to, for example, Teegavarapu et al. (2009), Wagner et al. (2012), and Ruzanski and Chandrasekar (2015).

4. Rainfall Events

In order to evaluate the performance of CASA DFW QPE system, we select four rainfall cases characterized by different meteorological phenomena. In this section, we briefly describe the meteorological features of the four events. Table 1 presents an overview of the four events, including the number of gauges used in the validation analysis, and the archived hours when rainfall was passing over the gauge network. The data collected during the intense hours are used in the evaluation study.

18 April 2013

In the early morning of 18 April 2013, a squall line evolved ahead of a strong cold front and moved west-to-east in the DFW area. Wind gusts with the frontal passage were observed around 35 to 40 mph. Heavy rainfall was observed in the Metroplex around 09:00-1300UTC. Fig. 6 shows sample observations of Z_h , Z_{dr} , K_{dp} , and corresponding rainfall rate (R) map from the S-band KFWS WSR-88DP radar 0.5 degree elevation sweep at 08:47UTC, 18 April 2013. Particularly, near 09:40-10:40UTC, rainfall passed over the ground rain gauges deployed in the City of Grand Prairie. A severe thunderstorm watch was issued in north Texas for this event, but no significant severe weather was reported to the Storm Prediction Center (SPC). During this event, the CASA XUTA radar was conducting 2.0 degree elevation full Plan Position Indicator (PPI) scan every one minute, which is used for generating rainfall products.

16 May 2013

This event was characterized by supercells, flash flooding, lightning, and several tornadoes. In mid-May 2013, an upper-level shortwave trough causing tornado outbreak moved northeastward from Mexico into the Southern Plains states. The low-pressure area and atmospheric instability resulted in the formation of tornadoes across northern Texas and Oklahoma on May 15. This small but intense and deadly tornado outbreak produced several more damaging tornadoes in north and central Texas, Louisiana, and Alabama in the two days following May 15. In addition to tornadoes, large hail was reported, peaking at approximately 10 cm in diameter near Mineral Wells, Texas on May 15. Severe thunderstorms were observed in the DFW Metroplex and southern Oklahoma. For the sake of QPE validation, the S-band KFWS data and X-band CASA data collected during 01:00-05:00UTC, 16 May 2013, are used for producing rainfall products, when the strong thunderstorm passed over the Grand Prairie rain gauge network. Fig. 7 illustrates sample observations of Z_h , Z_{dr} , K_{dp} , and corresponding rainfall rate field from the S-band KFWS WSR-88DP radar 0.5 degree elevation sweep at 04:45UTC, 16 May 2013.

09 June 2013

A widespread severe thunderstorm moving from northwest to southeast entered the DFW area around 09:00UTC, 09 June 2013. A severe thunderstorm warning was issued by the NWS for several counties in northern Texas. The thunderstorm lasted a few hours and weakened around 13:00UTC. This event was a common summer rainfall case. The S-band KFWS and X-band CASA data collected around 11:35-12:35UTC, when the rainfall was passing over the gauge network, are used in the QPE validation analysis. Similar to Fig. 6 and Fig. 7, Fig. 8 shows the sample observations of Z_h , Z_{dr} , K_{dp} , and corresponding rainfall rate field from the S-band KFWS WSR-88DP radar 0.5 degree elevation sweep at 12:31UTC for this event.

27 October 2013

This event was characterized by large hail and lightning. On 26 October 2013, a cluster of severe storms extended from Eagle Mountain eastward to the DFW Metroplex. Golf ball size hail was reported in Eagle Mountain and Southlake around 01:20UTC, 27 October 2013. 95-115 km hr⁻¹ winds are also observed. A severe thunderstorm warning was in effect in DFW area until 02:30UTC, 27 October 2013. Fig. 9 shows the sample observations of Z_h , Z_{dr} , K_{dp} , and rainfall rate field from S-band KFWS WSR-88DP radar 0.5 degree elevation sweep at 02:39UTC, 27 October 2013.

5. Cross Validation with Rain Gauge Observations

In order to demonstrate the performance of the QPE system for CASA DFW urban remote sensing network, rainfall records from a rain gauge network, which consists of 20 gauges, are used for evaluation purposes. The gauge network is deployed and managed by the City of Grand Prairie. Figure 10 shows the location of this rainfall gauge network with respect to the S-band KFWS radar and CASA/DFW XUTA radar coverages.

At each rain gauge, rainfall data is archived based on the ALERT (Automated Local Evaluation in Real Time) transmission system. That is, each time one millimeter (0.04 inch) of rainfall occurs that information is transmitted to the base station and the data is stored to the nearest second. For the sake of cross comparisons, we aggregate the rainfall data to rainfall accumulations in 5-minute intervals over every 24-hour period. The 5-minute rainfall accumulations from 20 gauges are then used as the baseline for evaluating the CASA DFW radar rainfall products.

It is well known that radar observations represent a unit of illuminated resolution volume, whereas the gauges are providing point-wise measurements. Considerable literature exists documenting the scale mismatch between radar and gauge rainfall observations (e.g., Anagnostou et al., 1999; Steiner et al., 1999). In this paper, the radar measurements are spatially chosen at the location of rain gauges for validation. Temporally, the one-minute resolution radar rainfall rates are used for calculating the running accumulations of rainfall to match the gauge observation frequencies (i.e., five-minute interval). Rainfall amounts at longer time scales are then obtained by aggregating the five-minute rainfall data.

In order to quantify the accuracy of CASA DFW QPE system, the normalized mean bias (*NMB*) and normalized standard error (*NSE*) of rainfall amount at different time scales are computed for X-band network QPE, S-band QPE, as well as the merged rainfall products. Assuming the rain gauge measurements are the “ground truth”, the *NMB* and *NSE* can be defined as:

$$NMB = \frac{\sum_{n=1}^N (R_n - G_n)}{\sum_{n=1}^N G_n} \quad (12)$$

$$NSE = \frac{\sum_{n=1}^N |R_n - G_n|}{\sum_{n=1}^N G_n} \quad (13)$$

where R_n and G_n denote the radar and gauge rainfall measurement (mm) at time frame n , respectively. N is the total sample number.

NMB and *NSE* results, as well as the mean values of gauge rainfall measurement at different time scales (i.e., 5-min, 10-min, 15-min, 20-min, 30-min, and 60-min) for each of the events, are shown in Tables 2. In addition, the overall *NMB* and *NSE* are calculated, at each time scale, based on the entire observations combining all the four events. The results are shown in Table 3.

For a side-by-side peer comparison, the rainfall products generated by the NWS for S-band KFWS WSR-88DP radar (both single- and dual-polarization products) are also included in the

validation study. The NWS single-polarization rainfall algorithm is presented in Fulton et al. (1998), whereas the dual-polarization rainfall algorithms are described in Giangrande and Ryzhkov (2008). Both are generated on a polar grid centered on the radar, and are available from the National Climatic Data Center (NCDC). The single-pol product included in the validation study is one-hour precipitation (N1P), which has a spatial resolution of 2 km in range by 1.0 degree in azimuth. The dual-polarization based hourly rainfall accumulations are produced in two different formats, namely, One Hour Accumulation (OHA) and Digital Accumulation Array (DAA). The NWS/OHA product has 16 data levels (i.e. 4-bit) with the same spatial resolution of NWS/N1P, whereas the NWS/DAA product has 256 data levels (i.e. 8-bit) and a spatial resolution of 0.25 km by 1.0 degree (<http://www.ncdc.noaa.gov/oa/radar/radarproducts.html>). The DAA never has a rain gauge bias correction applied, but the OHA product can potentially have bias applied. Both N1P, OHA, and DAA are estimates of precipitation accumulation over the last hour, and are updated every five-six minutes (Istok et al., 2009). The *NMB* and *NSE* of NWS/N1P, NWS/OHA and NWS/DAA for each of the events, as well as for all events combined, are shown in Tables 2-3. The evaluation statistics for rainfall products at other time scales are not included because the higher temporal-resolution data is not available from NCDC.

The main findings from the evaluation results of different rainfall products, including CASA X-band network QPE, CASA S-band/NEXRAD QPE, NWS single- and dual-polarization QPE, are summarized as follows:

- 1) Among the six rainfall products (five dual-polarization products: namely, DFW CASA X-band network QPE, DFW S-band NEXRAD QPE, DFW merged QPE, NWS/OHA, and NWS/DAA; one single-polarization product: NWS/N1P), the CASA/DFW merged rainfall products have the best performance in terms of *NMB* and *NSE*, for all four cases

or four cases combined. For all of the events combined, the *NMBs* of the merged 5-min, 10-min, 15-min, 20-min, 30-min and hourly rainfall, are -5.69%, 0.28%, 1.38%, 1.95%, 1.54%, and 0.39%, respectively, and the *NSEs* are 35.38%, 28.99%, 25.57%, 22.56%, 18.81%, and 14.76%, respectively. The excellent performance is further demonstrated by the combined scatter plots shown in Fig. 11 and Fig. 12 (a).

2) As we expected, the five dual-polarization hourly rainfall products have better performance than the single-polarization products for all four events or four events combined.

3) Both the CASA/DFW X-band network and S-band NEXRAD QPE have better performance than the NWS dual-polarization rainfall products (i.e., OHA and DAA). And the CASA/DFW S-band QPE products have slightly better performance than the X-band network products, except for the case of 18 April 2013. However, this does not necessarily mean that the CASA/DFW S-band QPE has better performance than X-band network over the whole DFW Metroplex, especially in the areas far from the KFWS radar. We note that the validation gauge network used in this paper is close to KFWS radar (approximately 30 km). The S-band QPE performance may get deteriorated in far ranges due to the influence of beam broadening (Gorgucci and Baldini, 2015).

4) It is also seen that the *NSEs* of CASA/DFW X-band network, CASA/DFW NEXRAD, and CASA/DFW merged QPE products have a decreasing trend as the rainfall accumulation time increases from five minutes to one hour. This is because the random radar measurement errors are being reduced by temporal and spatial averaging.

5) For all four events or four events combined, the NWS N1P and OHA products are underestimating rainfall compared with the gauge network observations. This is further

demonstrated by the scatter plots shown in Figure 12 (b) and (c). The overall *NMB* and *NSE* for NWS/N1P are -30.74% and 34.11%, respectively, and -13.31% and 29.30% for NWS/OHA, respectively. Other than spatial resolution difference, the impact of data quantization on NWS N1P and OHA may have introduced significant errors to the products (Istok et al., 2009). Detailed investigation of the quantization error is beyond the scope of this paper. The interested reader is referred to documents about NEXRAD Open Radar Product Generator (ORPG) from <http://www.roc.noaa.gov/>.

- 6) Overall, the NWS/DAA products have better performance than OHA in terms of *NMB* and *NSE*. The overall *NMB* is about 1.19%, and *NSE* about 25.03%. Besides the aforementioned spatial averaging and degraded quantization, the worse performance of OHA may be attributable to the bias applied to it (Istok et al., 2009).

In addition, it should be noted that the errors associated with rain gauge measurements can also impact the radar QPE evaluation scores (Habib et al., 2001; Emmanuel et al., 2012).

6. Conclusions

High spatiotemporal resolution QPE is one of the essential requirements for the predication of urban flash floods, which are usually associated with heavy rainfall over a short time span. It has been shown in the literature that the dual-polarization radar techniques can improve the QPE accuracy over the traditional single-polarization radars by rendering more measurements to enhance the data quality, providing more information about rain DSD, and implying more characteristics of different hydrometeor types. However, it is still a big challenge to do QPE in complex terrain due to the sampling limitations of NWS radar. Spatially, the NWS radars are normally separated by distances over 100 km, and the radar resolution volume is continuously enlarged with increasing range. Subsequently, the QPE accuracy will suffer from beam

broadening, beam overshooting, and the Earth curvature effect. In addition, it is an overwhelming task to find proper infrastructure to support the large radar system in urban environments, and to avoid local terrain blockage. Temporally, the NWS radar observations are updated every five to six minutes in precipitation mode, which is too long for urban flash flood modeling and forecasting. CASA has proposed a solution to the sampling dilemma of NEXRAD by deploying a network of higher-frequency (i.e., X-band) dual-polarization radars to fill the gaps in the operational S-band weather radar coverage. This small X-band radar system is gaining an increasing interest in recent years due to the cost efficiency and compact configurations especially for the urban deployment and applications.

In this paper, we have presented the high-resolution (spatially ~250 meters, temporally ~1 minute) QPE system designed for CASA DFW urban radar network. This real-time QPE system is built based upon a local polarimetric S-band WSR-88DP radar (i.e., KFWS radar) and the CASA X-band radar network. The specific dual-polarization rainfall algorithms at different frequencies (i.e., S- and X-band) and the fusion methodology combining observations at different temporal resolution have been detailed. The performance of CASA DFW QPE system was evaluated in an operational environment during four precipitation events occurred in 2013. The four events were characterized by different meteorological phenomena. The evaluation results showed that this multiple-radar based QPE system had low overall biases of -5.69%, -0.28%, 1.38%, 1.95%, 1.54%, and 0.39%, and low overall normalized standard errors of 35.38%, 28.99%, 25.57%, 22.56%, 18.81%, and 14.76%, for 5-min, 10-min, 15-min, 20-min, 30-min and hourly rainfall accumulation products, respectively.

In addition, we also compared with the NWS hourly rainfall products (the NWS does not generate rainfall products in shorter time scales other than one-hour precipitation and storm total

precipitation). It has been shown that for the four events analyzed in this study the merged hourly rainfall product from CASA DFW QPE system has about 20% better *NSE* than the NWS single-polarization rainfall product, and more than 10% better *NSE* than the NWS dual-polarization rainfall products. By coupling with various hydrologic models, the high resolution CASA DFW QPE products are being used in downstream applications such as urban flash flood forecast for emergency management and warning operations.

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Table Captions

Table 1. Summary of the four precipitation events. Columns (from left to right) refer to the rainfall date, number of rain gauges used in the validation analysis, archived hours when rainfall was passing over the gauge network, and notes regarding the precipitation type and weather impact.

Table 2. Evaluation results (*NMB*: normalized mean bias, and *NSE*: normalized standard error) of various rainfall products at different time scales. ‘X’ indicates that data is not available from NWS.

Table 3. valuation results (*NMB*: normalized mean bias, and *NSE*: normalized standard error) of various rainfall products at different time scales for all events combined. ‘X’ indicates that data is not available from NWS.

Table 1

Summary of the four precipitation events. Columns (from left to right) refer to the rainfall date, number of rain gauges used in the validation analysis, archived hours when rainfall was passing over the gauge network, and notes regarding the precipitation type and weather impact.

Date	No. of gauges	Intense rain hours over gauges	Remarks
18 April 2013	19	09:40-10:40UTC	Squall line,
16 May 2013	20	01:15-02:15UTC, 04:00-05:00UTC	Supercells, tornadoes, lightning, flash flooding in north Texas
09 June 2013	20	11:35-12:35UTC	Classical summer storm
27 October 2013	20	01:55-02:55UTC	Winter storm, lightning

Table 2

Evaluation results (*NMB*: normalized mean bias, and *NSE*: normalized standard error) of various rainfall products at different time scales . ‘X’ indicates that data is not available from NWS.

Case	Time scale	Mean gauge rainfall (mm)	<i>NMB</i> (%)						<i>NSE</i> (%)					
			DFW CASA	DFW NEXRAD	DFW Merged	NWS NIP	NWS OHA	NWS DAA	DFW CASA	DFW NEXRAD	DFW Merged	NWS NIP	NWS OHA	NWS DAA
18 April 2013	5-min	1.7968	-11.36	-7.63	-2.80	X	X	X	31.72	35.79	30.83	X	X	X
	10-min	3.5714	-7.03	-8.31	-1.18	X	X	X	20.85	23.01	20.14	X	X	X
	15-min	5.2042	-5.74	-7.50	-0.52	X	X	X	18.73	20.86	17.70	X	X	X
	20-min	6.5977	-4.76	-7.45	-0.26	X	X	X	16.72	18.37	14.71	X	X	X
	30-min	8.9989	-4.45	-8.12	-0.63	X	X	X	15.33	17.25	13.86	X	X	X
	60-min	21.5618	-4.82	-8.21	-3.36	-42.74	-18.19	-1.56	11.31	13.50	10.60	42.74	22.51	16.21
16 May 2013	5-min	1.9923	-23.98	-14.25	-4.23	X	X	X	41.75	40.47	37.05	X	X	X
	10-min	4.1795	-19.16	-5.21	2.70	X	X	X	37.26	34.00	31.52	X	X	X
	15-min	6.5634	-17.86	-2.45	3.77	X	X	X	34.10	29.72	27.61	X	X	X
	20-min	9.0869	-17.49	-0.73	4.56	X	X	X	31.68	26.35	24.02	X	X	X
	30-min	14.3310	-18.79	0.25	4.43	X	X	X	29.17	21.92	19.69	X	X	X
	60-min	23.9078	-15.54	-1.73	1.96	-19.26	-1.8	11.32	24.67	16.07	14.69	25.42	24.61	27.44
09 June 2013	5-min	1.4827	-13.06	-10.48	-2.71	X	X	X	38.23	39.27	39.11	X	X	X
	10-min	3.1611	-0.20	-0.74	8.89	X	X	X	35.06	33.73	34.29	X	X	X
	15-min	5.0229	1.90	-1.01	10.57	X	X	X	32.25	28.92	30.49	X	X	X
	20-min	7.1233	2.11	1.29	10.24	X	X	X	28.72	24.90	27.27	X	X	X
	30-min	11.3828	0.95	1.53	9.01	X	X	X	23.80	18.87	20.71	X	X	X
	60-min	17.7927	9.81	2.78	11.14	-25.20	-1.37	7.75	20.55	12.60	15.50	28.20	29.73	22.91
27 October 2013	5-min	1.6447	-23.11	-17.00	-7.96	X	X	X	41.77	35.73	33.94	X	X	X
	10-min	3.1808	-22.72	-12.48	-5.09	X	X	X	37.23	29.46	26.58	X	X	X
	15-min	4.5657	-22.24	-12.06	-5.18	X	X	X	32.13	24.51	21.85	X	X	X
	20-min	5.8011	-21.53	-12.17	-5.57	X	X	X	29.27	21.88	19.22	X	X	X
	30-min	8.2568	-19.58	-13.92	-7.78	X	X	X	26.12	20.12	16.55	X	X	X
	60-min	19.7358	-13.83	-10.79	-2.39	-51.74	-46.91	-26.58	21.43	16.01	14.69	51.99	46.91	29.78

663 **Table 3**
664 Evaluation results (*NMB*: normalized mean bias, and *NSE*: normalized standard error) of various rainfall products at different time
665 scales for all events combined. ‘X’ indicates that data is not available from NWS.

Time scale	Mean gauge rainfall (mm)	<i>NMB</i> (%)						<i>NSE</i> (%)					
		DFW CASA	DFW NEXRAD	DFW Merged	NWS NIP	NWS OHA	NWS DAA	DFW CASA	DFW NEXRAD	DFW Merged	NWS NIP	NWS OHA	NWS DAA
5-min	1.7815	-23.71	-13.63	-5.69	X	X	X	39.93	37.77	35.38	X	X	X
10-min	3.6561	-18.70	-6.27	0.28	X	X	X	34.96	31.17	28.99	X	X	X
15-min	5.5916	-17.44	-4.28	1.38	X	X	X	32.10	27.19	25.57	X	X	X
20-min	7.5584	-16.89	-3.21	1.95	X	X	X	29.71	24.09	22.56	X	X	X
30-min	11.5103	-17.41	-2.77	1.54	X	X	X	27.19	20.37	18.81	X	X	X
60-min	21.3775	-13.56	-3.87	0.39	-30.74	-13.31	1.19	22.31	14.99	14.76	34.11	29.30	25.03

Figure Captions

Fig. 1. The example layout of eight CASA DFW dual-polarization X-band radars (40 km range rings in blue) and its relative location to S-band KFWS WSR-88DP radar (100 km range ring in red).

Fig. 2. The overview of dataflow architecture in CASA Dallas-Fort Worth (DFW) urban remote sensing network.

Fig. 3. Key features of the CASA DFW urban remote sensing network for rainfall estimation and hydrological applications.

Fig. 4. Flowchart of the CSU-DP rainfall rate retrieval algorithm for S-band KFWS WSR-88DP radar. τ_1 , τ_2 , τ_3 are thresholds on Z_h , Z_{dr} , and K_{dp} , respectively.

Fig. 5. Schematic diagram of the QPE system for CASA DFW urban remote sensing network.

Fig. 6. Sample observations from the S-band KFWS WSR-88DP radar 0.5 degree sweep at 08:47UTC, 18 April 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 7. Sample observations from the S-band KFWS WSR-88DP radar 0.5 degree sweep at 04:45UTC, 16 May 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 8. Sample observations from the S-band KFWS WSR-88DP radar 0.5 degree sweep at 12:31UTC, 09 June 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 9. Sample observations from the S-band KFWS WSR-88DP radar 0.5 degree sweep at 02:39UTC, 27 October 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 10. Locations of the Grand Prairie rain gauge network (20 rainfall gauges) under the coverage of X-band CASA/DFW XUTA radar and S-band KFWS WSR-88DP radar, where the blue dots denote the location of rain gauges.

Fig. 11. Scatterplots of merged (a) 5-min (b) 10-min (c) 15-min (d) 20-min (e) 30-min rainfall accumulations from CASA DFW QPE system vs rain gauge for all events combined.

Fig. 12. Scatterplots of hourly rainfall accumulations from radar vs rain gauge for all events combined. (a) CASA DFW merged product (b) NWS N1P product (c) NWS OHA product (d) NWS DAA product.

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 694 rings in blue) and its relative location to S-band KFWS WSR-88DP radar (100 km range ring in
 695 red).

^aMeteorological Command and Control

^bAdvanced Weather Interactive Processing System

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 701 radar. τ_1, τ_2, τ_3 are thresholds on Z_h, Z_{dr} , and K_{dp} , respectively.

Fig. 5. Schematic diagram of the QPE system for CASA DFW urban remote sensing network.

Fig. 6. Sample observations from the S-band KFS WSR-88DP radar 0.5 degree sweep at 08:47UTC, 18 April 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 7. Sample observations from the S-band KFS WSR-88DP radar 0.5 degree sweep at 04:45UTC, 16 May 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 8. Sample observations from the S-band KFS WSR-88DP radar 0.5 degree sweep at 12:31UTC, 09 June 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

Fig. 9. Sample observations from the S-band KFS WSR-88DP radar 0.5 degree sweep at 02:39UTC, 27 October 2013. (a) Z_h , (b) Z_{dr} , (c) K_{dp} , (d) corresponding rainfall rate (R) field.

715 Figure 10. Locations of the Grand Prairie rain gauge network (20 rainfall gauges) under the
 716 coverage of X-band CASA/DFW XUTA radar and S-band KFWS WSR-88DP radar, where the
 717 blue dots denote the location of rain gauges.

Fig. 11. Scatterplots of merged (a) 5-min (b) 10-min (c) 15-min (d) 20-min (e) 30-min rainfall accumulations from CASA DFW QPE system vs rain gauges for all events combined.

720 Fig. 12. Scatterplots of hourly rainfall accumulations from radar vs rain gauge for all events
 721 combined. (a) CASA DFW merged product (b) NWS N1P product (c) NWS OHA product (d)
 722 NWS DAA product.