Deployment of the X-band dual polarization phased array radar in the Dallas-Forth Worth Urban Demonstration Network

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1. Introduction

The Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts has developed an X-band dual polarization Phase Tilt Weather Radar (PTWR) (Orzel et al., 2013; Salazar et al., 2008) in an effort towards more reliable, scalable, low-cost weather radar networks. Phased-array systems have received substantial attention in the weather community due to the potential benefits, such as smart scanning and high temporal resolution (Zrnic et al., 2007). Major challenges to operational use of this technology are a direction-dependent beam and polarization characteristics. There are known sensitivity losses and also measurement biases in the polarimetric radar products when the beam is directed away from the principle planes of the array aperture (Zhang et al., 2009).

During spring 2014, the PTWR was deployed as a fixed roof installation in Arlington, TX (see Figure 1b). The direct proximity (250 meters away) of XUTA, a magnetron-based radar, allowed for a qualitative and quantitative data comparison. XUTA is an X-band dual polarization radar, which is part of the Dallas-Fort Worth Urban Demonstration Network (Chandrasekar et al., 2013) (Bajaj and Philips, 2012) operated by the Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA). The DFW test bed is the first demonstration of a short-range weather radar network deployed in a metropolitan area. The biggest advantage of this sensor network is an improvement in temporal and spatial resolution, along with availability of observations close to the ground. As a consequence, it is expected to generate more accurate detections and forecasts of low altitude wind, tornado, hail, ice, and flash flood hazards. The provided weather hazard information can be validated using a set of existing sensors, such as NEXRAD WSR-88D and TDWR radars, and rain gauges. Figure 1a presents the locations of all available weather radars in the Dallas-Fort Worth area during the spring 2014 deployment. The specifications of the radar systems are listed in Table 1.

2. Severe weather observations

The PTWR performed an observation of an evening severe thunderstorm passing over Fort Worth, TX area on 3 April 2014. The radar operated in volume scan mode, collecting data at five elevation angles between 2° and 18°. The maximum observation range was set to 45 km, while the unambiguous velocity was within $\pm 48 m/s$ using a staggered PRT technique. The radar illuminated a 90° sector facing northwest. The use of a $20 \mu s/3 MHz$ non-linear frequency modulated waveform resulted in a 3 km blind range and a range resolution of 60 m.

For qualitative comparison, a PPI of reflectivity collected by the WSR-88D radar (KFWS) at 01:11:21 UTC and the TDWR

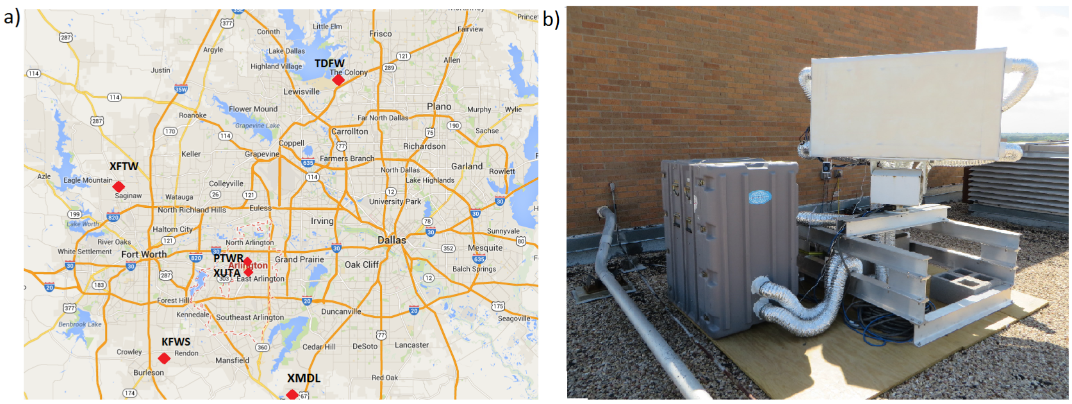

Figure 1: a) Map of the Dallas-Fort Worth radar network during the spring 2014 deployment. The PTWR was installed in direct proximity to the CASA XUTA X-band radar. Additionally, the data can be compared against a NEXRAD S-band WSR-88D radar (KFWS) located 25 km to the southwest and a C-band TDWR radar (TDFW) located 40 km to the northeast. The CASA network at the time of PTWR deployment consisted of two additional X-band radars (XFTW and XMDL). b) The PTWR deployed on a roof at the University of Texas Arlington.

Table 1: Radar system characteristics of the PTWR, XUTA, TDWR, and NEXRAD

Parameter	PTWR	XUTA	TDWR	NEXRAD
Peak power	$60W$	$10.8kW$	$250kW$	$500kW$
Frequency	$9.36GHz$	$9.41GHz$	$5.6GHz$	$3GHz$
Beam width (azimuth/elevation)	$1.8 - 2.6°/3.6°$	$1.8°$	$0.5°$	$1.25°$
Range resolution	$60m$	$60m$	$150m$	$1km$
Range coverage	$45km$	$40km$	$460km$	$460km$
PRF	$2000 - 3000Hz$	$1600 - 2400Hz$	$800 - 1120Hz$	$320 - 1300Hz$
Azimuthal resolution	$1°$	$0.5°$	$0.55°$	$1°$
Sector	$90°$	$360°/adaptive$	$360°$	$360°$
Pulse width	$20\mu s$	$0.6\mu s$	$1.1\mu s$	$1.57 - 4\mu s$
Pulse compression	yes	no	no	no

radar (TDFW) at 01:10:59 UTC on 4 April 2014 is presented in Figure 2. These radars are not co-located and utilize different antennas. Hence, shown reflectivity fields do not correspond to the same scattering volumes. Nevertheless, the measured reflectivity fields are roughly comparable. Both radars detected heavy precipitation in excess of 50 dBz. Furthermore, better spatial and range resolution provided by the TDWR radar is apparent.

To analyze the calibration accuracy and weather imaging capabilities of the PTWR, co-located measurements (in time and space) with XUTA were performed. Figure 3 presents radar polarimetric products generated by XUTA, while Figure 4 presents corresponding products generated by PTWR. There are six panels in each figure, showing attenuation corrected reflectivity, velocity, spectrum width, signal to noise ratio, differential phase, and correlation coefficient. Attenuation correction for the PTWR was performed using the relation shown in Equation 2.1 (Frasier et al., 2013). (Chen and Chandrasekar, 2012) demonstrated the excellent performance of the CASA QPE system by the cross comparison with rain gauges. Hence the radar products observed by XUTA are considered as the „truth“ and used to examine the bias in PTWR. The general comparison reveals that the storm structures illuminated by both radars are well matched. The differences between XUTA and PTWR are caused by two factors.

$$Z_{H,corr} = Z_H + 0.28\phi_{dp} \tag{2.1}$$

First, the PTWR is a solid-state low-power radar, and hence a lower SNR is to be expected. The measurements show the beam dependent SNR reduction in excess of 12 dB compared with XUTA. Due to lower sensitivity, the PTWR did not detect weak echoes seen in XUTA data between azimuth angles $0°$ and $15°$. The sensitivity of the PTWR can be improved by the modification of waveform parameters, by either increasing pulse duration or decreasing chirp bandwidth. The quality of the correlation coefficient, normalized coherent power (not shown), and spectrum width also degrades with decreasing SNR and is clearly visible in PTWR data. Cheong et al. (2013) has shown that this degradation can be significant in X-band solid-state weather radar and proposed a multilag moment processor, which does not utilize lag-0 auto-correlation estimates and performs well even if SNR is low ($< 20dB$).

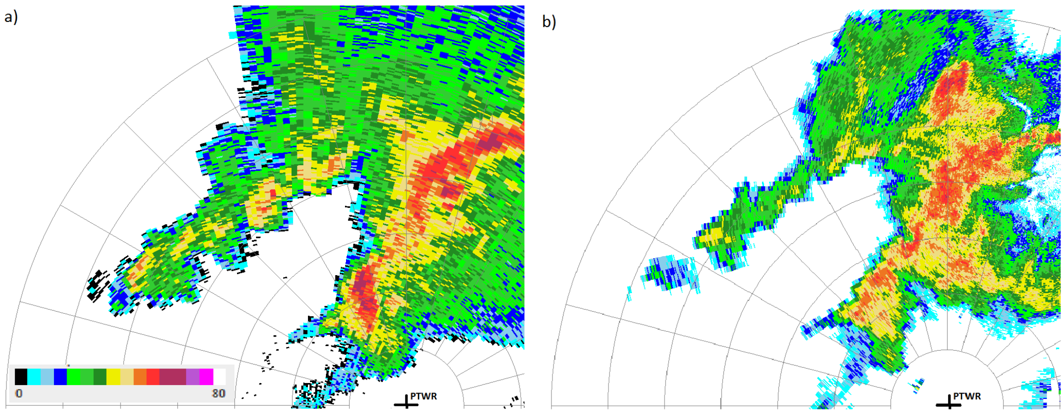

Figure 2: Comparison between a) the WSR-88D radar (KFWS) at 01:11:21 UTC and b) the TDWR radar (TDFW) at 01:10:59 UTC on 4 April 2014. Radars are not co-located and hence the reflectivity fields do not correspond to the same elevation above the ground. The better spatial resolution provided by the TDWR radar is apparent. The location of the PTWR is indicated with a black cross. The range rings are spaced 10 km apart.

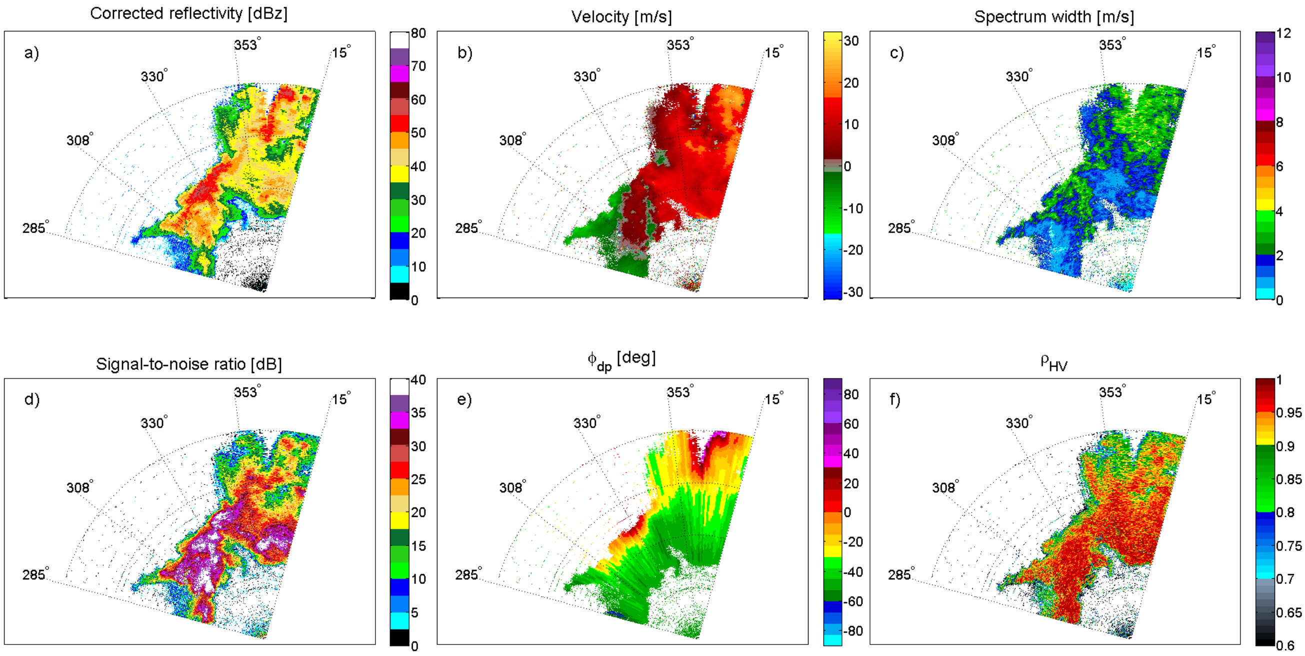

Figure 3: Severe weather observation by CASA XUTA radar at a 5.3° elevation angle over north Fort Worth, TX area on 4 April 2014 at 01:10:09 UTC. The range rings are spaced 10 km apart.

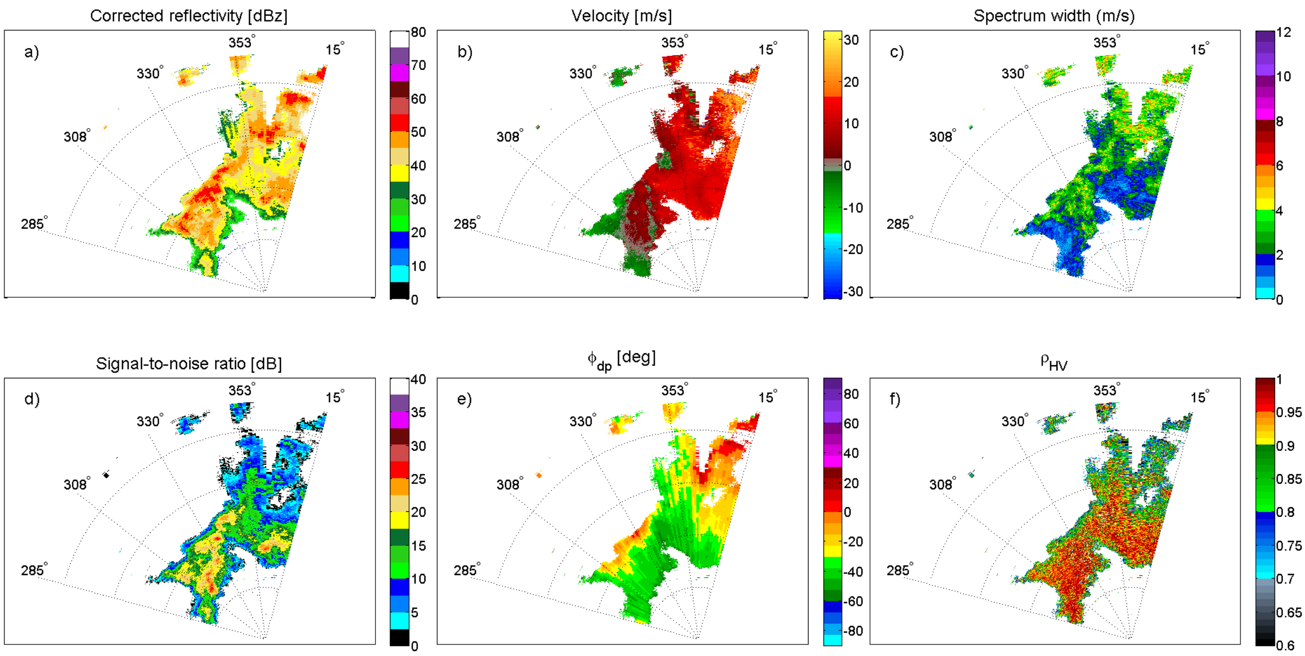

Figure 4: Severe weather observation by PTWR radar at a 6° elevation angle over north Fort Worth, TX area on 4 April 2014 at 01:10:07 UTC. The range rings are spaced 10 km apart.

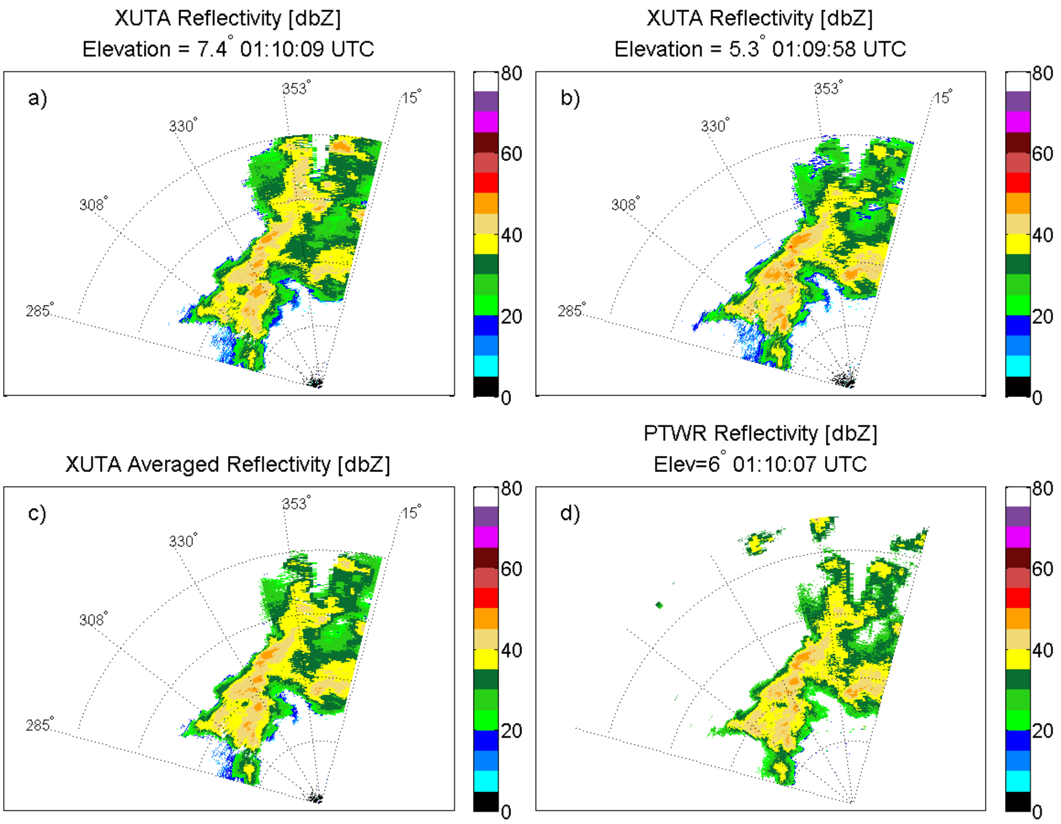

Figure 5: PPI of uncorrected reflectivity by a) XUTA at a $7.4°$ *elevation angle averaged in azimuth over* $2°$*, b) XUTA at a* $5.3°$ *elevation angle averaged in azimuth over* $2°$*, c) XUTA as an average of* $5.3°$ *and* $7.4°$ *elevation angles, d) PTWR at a* $6°$ *elevation angle.*

Second, PTWR illuminates a scattering volume more than 3 times larger than XUTA due to its wide antenna beamwidth. This is particularly disadvantageous at longer ranges, where a non-uniform beam filling effect can result in lower correlation coefficient values, noisier spectrum width, and a bias in specific attenuation estimate (Gosset and Zawadzki, 2001). The different scattering volumes between the radars is also evident in reflectivity fields. The strong reflectivity values are underestimated, and the weak reflectivity values tend to be slightly overestimated. This stands in agreement with findings presented by Wu and Liu (2014), who compared observations of an X-band radar utilizing a dish antenna against a 2-D single polarized phased array radar.

A qualitative evaluation of the wide beamwidth effect on uncorrected reflectivity is presented in Figure 5. To simplify comparison, the XUTA data was first averaged in azimuth over $2°$ (panels a and b) to roughly match with PTWR azimuthal resolution. Additionally, XUTA precipitation data from two available elevations ($5.3°$ and $7.4°$) were averaged in order to obtain reflectivity field of a comparable observation volume. The averaged PPI of XUTA (Figure 5c) is close to that observed by PTWR (Figure 5d). The improvement obtained by averaging is the most visible at long-range gates, since the beam mismatch effect between XUTA and PTWR increases with range.

Figure 6a shows a histogram of all available observations from averaged XUTA (Figure 5c) and PTWR (Figure 5d) data, thresholded at SNR_{PTWR} = 0 dB. These are calibrated X-band reflectivities without attenuation correction. The observations provided by both radars exhibit a high correlation coefficient of 0.90, a relative bias (XUTA/PTWR) of 0.75 dB, and a standard deviation of 2.58 dB. The less-than-unity slope of the least square fit line confirms an underestimation of higher reflectivities by PTWR. This is mostly due to the uncompensated signal extinction, which occurs earlier in the PTWR due to a lower transmit power than the XUTA radar. The overestimation of low reflectivities by the PTWR is a consequence of the larger antenna beamwidth and the rain reflectivity probability distribution (see Figure 6b). The deviation from XUTA=PTWR line increases if a non-averaged XUTA reflectivity field is used as a reference .

3. Conclusions

To verify the observational capabilities of the new X-band dual polarization Phase Tilt Weather Radar (PTWR), co-located precipitation observations with a CASA magnetron-based radar (XUTA) were performed in the Dallas-Forth Worth Urban Demonstration Network. A qualitative comparison shows that both radars can resolve similar reflectivity structures. The experiment proved that a low-cost, low-power, electronically-scanned radar, using an alternate-transmit alternate-receive mode of operation, can detect severe weather events up to 45 km away and provide a volume update on order of 1 minute. The

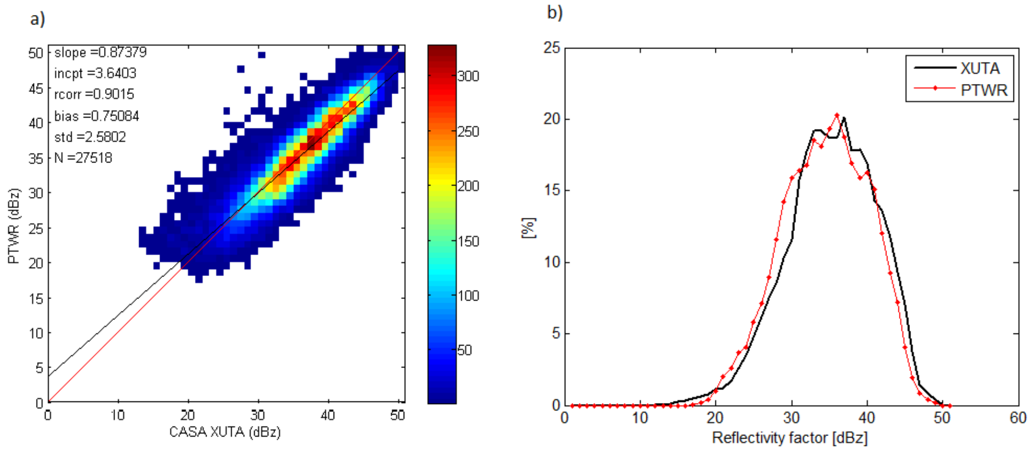

Figure 6: a) Histogram of uncorrected reflectivities observed over the Fort Worth area by XUTA and PTWR radars (Figures 5c and 5d). The black line is XUTA=PTWR and the red line is a least squares fit. An average bias over all observations is 0.75 dB. b) Corresponding probability distributions of reflectivity by XUTA and PTWR.

degradation of PTWR data quality compared to XUTA radar is mostly due to a significantly lower signal to noise ratio. The techniques to mitigate this problem, such as waveform modification and multilag and spectral processing, are currently investigated. The effect of beam width mismatch on reflectivity between XUTA and PTWR was analyzed. The quantitative analysis demonstrated a high correlation coefficient between both radars, which validates the usage of solid-state radars for weather observations.

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