Quantitative Precipitation Estimation from C-band Dual-polarized radar for the July 08th 2013 Flood in Toronto, Canada.

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1 Introduction

A heavy rainfall event on July 08th 2013 caused significant flash flooding in Greater Toronto Area (GTA) of Canada. Areas of the city experienced more than 100 mm in 2 hours with the highest recorded amount of 126 mm at Toronto International Airport (CYYZ). The objective of this study is to evaluate quantitative precipitation estimates (QPE) from the Environment Canada (EC) King City C-band dual-polarized radar (WKR) located 30 km north of the airport.

Reflectivity (Z) derived rainfall estimates are known to be subject to significant errors (eg. Zawadski, 1984; Austin, 1987; Joss and Waldvogel, 1990; Tabary, 2007; Krajewski et al., 2010). Issues such as variability of the drop size distribution (DSD), attenuation, variation of the vertical reflectivity profile (VPR), wet radome, clutter, beam blocking and beam filling issues as well as radar mis-calibration must all be considered when deriving radar rainfall estimates. In addition to Z, dual-polarization radars also measure differential reflectivity (Z_{DR}), differential propagation phase (Φ_{DP}), specific differential phase (K_{DP}) and co-polar correlation coefficient (ρ_{HV}), which provide additional information to help mitigate issues with traditional Z only radar derived QPE.

For this study we used the WSR-88D (Fulton et. al., 1998) R(Z) convective relationship to derive Z only rain-rates. From the dual-polarimetric measurements path attenuation correction methods for Z and Z_{DR} were implemented which generally improved rainfall estimates over using uncorrected Z. Several dual-polarimetric rainfall rate estimators can be found in the literature (e.g. Bringi and Chandrasekar, 2001; Gorgucci, 2001; Ryzhkov et al. 2005; Illingworth and Thompson, 2005; Tabary et al. 2011) that are of the forms $R(Z, Z_{DR})$, $R(K_{DP}, Z_{DR})$ and $R(K_{DP})$. Recently Ryzhkov et al., 2014 developed an algorithm based on specific attenuation (A) to derive rainfall rates (herein R(A)) which is immune to radar mis-calibration and partial beam blockage. Some of these were evaluated for this study.

Precipitation estimates from the Buffalo New York, NEXRAD dual-polarimetric S-band radar and surface rain-gauges in the GTA were used to evaluate the relative performance of the various C-band derived estimates.

2 Data

2.1 *Rain Gauges*

Surface rainfall amounts were provided from 48 gauges of which 44 were tipping bucket rain-gauges (TBRG) operated and maintained by the Toronto and Region Conservation Authority (TRCA) and the City of Mississauga. Rainfall amounts in 5-minute increments were available from the 44 TBRG gauges. The remaining 4 gauges, operated by EC, only provided storm total accumulation. All of the gauges were distributed in the region of the heaviest rainfall for the event and all were within 55 km of the radar. The maximum rainfall total for the storm was 126.0 mm for the EC gauge located at the airport (CYYZ). Figure 1 shows the rain-gauge locations and storm total accumulations for the event over the Toronto area.

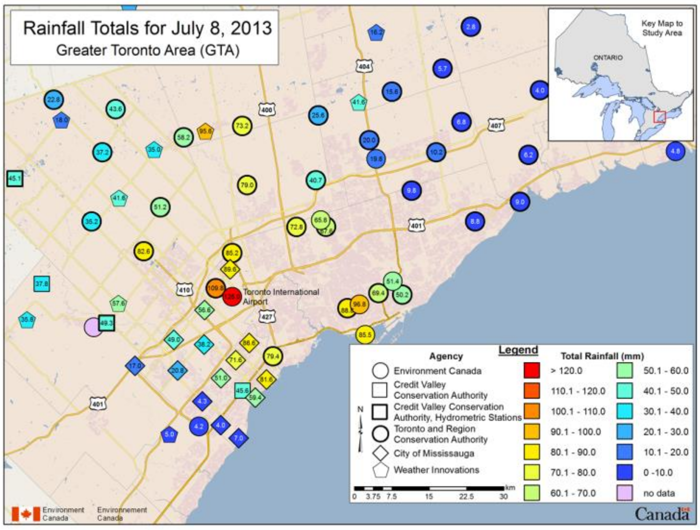

Figure 1: Rain-gauge locations and July 08th storm totals over Toronto, Canada.

2.2 *NEXRAD S-band Radar*

The Buffalo New York, NEXRAD S-band dual-polarimetric radar (KBUF) is located about 100 km south of Toronto and the distance between WKR and KBUF is approximately 130 km. The S-band dual-polarimetric moments from the Level II dataset were used to compare with the scans from WKR. Rain-rates were derived using the uncorrected S-band Z in the Fulton et al. 1998 algorithm. The dual-polarimetric QPE (DP-QPE) algorithm (Cocks et. al. 2012; Cunha et. al. 2013) provided the Level III storm total accumulation to compare with the C-band radar derived storm accumulations. A description of the NEXRAD Level II and Level III data is found at http://www.ncdc.noaa.gov/oa/radar/radarproducts.html.

2.3 EC King City C-band Radar

The King City C-band dual-polarimetric radar operates in simultaneous transmit/receive H/V mode and signal processing is done with a Sigmet RVP900 processor. Several scanning tasks are performed, one of which collects the dual-polarimetric data, collecting 64 samples with dual PRF of 1000/750 Hz at 0.5^o elevation (POLPPI). The task is completed in 1 minute with 0.25km x 0.5^o range and azimuthal resolution. Its maximum range is 150 km. Additional scans are performed that make up a 10 minute data collection cycle. Ground clutter returns from buildings, trees etc. are removed at the signal processor level using a fixed width clutter filter. Subsequently, thresholding by signal quality index (SQI), signal-to-noise ratio (LOG) and clutter-to-signal ratio (CSR) are applied to reflectivity and the dual-polarimetric data. The performance is good at removing most of the clutter in the urban environment as well as 2nd trip contamination.

The specific differential phase was calculated from the measured Φ_{DP} profiles. First, Φ_{DP} was de-aliased and noisy range gates were removed using a ρ_{HV} threshold of 0.9. The profile was smoothed over 6.0 km and interpolated to fill the gaps. From the processed Φ_{DP} profile K_{DP} was calculated using a simple least absolute deviation method over 6 range bins or 1.5 km. An example of this is shown in Figure 2 for the 180^o radial for the POLPPI scan at 2200Z. In Figure 2a the thin solid line is measured Φ_{DP} and the resulting smoothed Φ_{DP} profile is the dashed line. K_{DP} in Figure 2b ranged from about 0.5^o/km to 7^o/km along this radial.

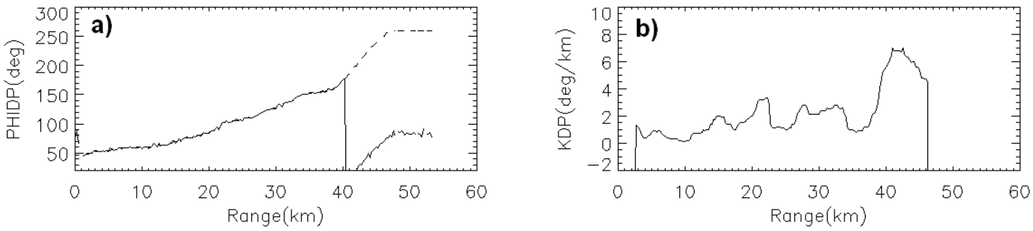

Figure 2: Radial profiles of a) Corrected (dashed) and uncorrected (solid) Φ_{DP} and b) K_{DP} for the 180^o POLPPI radial at 2200Z.

Attenuation correction of Z and Z_{DR} used a modified version of the ZPHI profiling algorithm (Testud et al. 2000). The modified method relies on the identification of hotspots along radials, for which the α and β parameters of the algorithm varies with range as opposed to being constant in the traditional ZPHI method. A complete description and evaluation of the modified algorithm can be found in Ryzhkov et al. 2006, 2007 and Gu et al. 2011. Figure 3 shows the uncorrected and corrected profiles of Z and Z_{DR} using this method for the 180^o POLPPI radial at 2200Z.

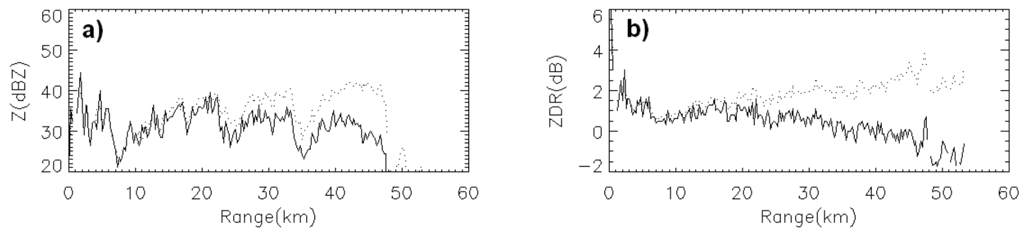

Figure 3: Radial profiles of a) Corrected (dashed) and Uncorrected (solid) Z and b) Uncorrected (solid) and Corrected Z_{DR} (dashed) for the 180^o POLPPI radial at 2200Z.

In Figure 3a there was heavy rain over the radome, with Z at close ranges up to 40 dBZ. Next, a heavy rain-cell along the radial extends from 8-25 km, and then another cell at 25-35 km, and a third cell at 35-48 km. The Z profile progressively decreases in intensity, but with attenuation correction (dashed) the loss is recovered. At the 3rd cell there is an approximate increase of 10 dBZ. In Figure 3b, the correction for Z_{DR} (dashed) shows recovery of about 1-2 dB for the 3rd rain-cell. Figure 4 shows the 2200Z PPI scans of a) uncorrected Z, b) corrected Z (Z_C), c) Φ_{DP} , d) uncorrected Z_{DR}, e) corrected Z_{DR} (Z_{DRC}), and f) K_{DP}. Heavy rain over the radome lasted for a prolonged period and compromised the attenuation correction methods.

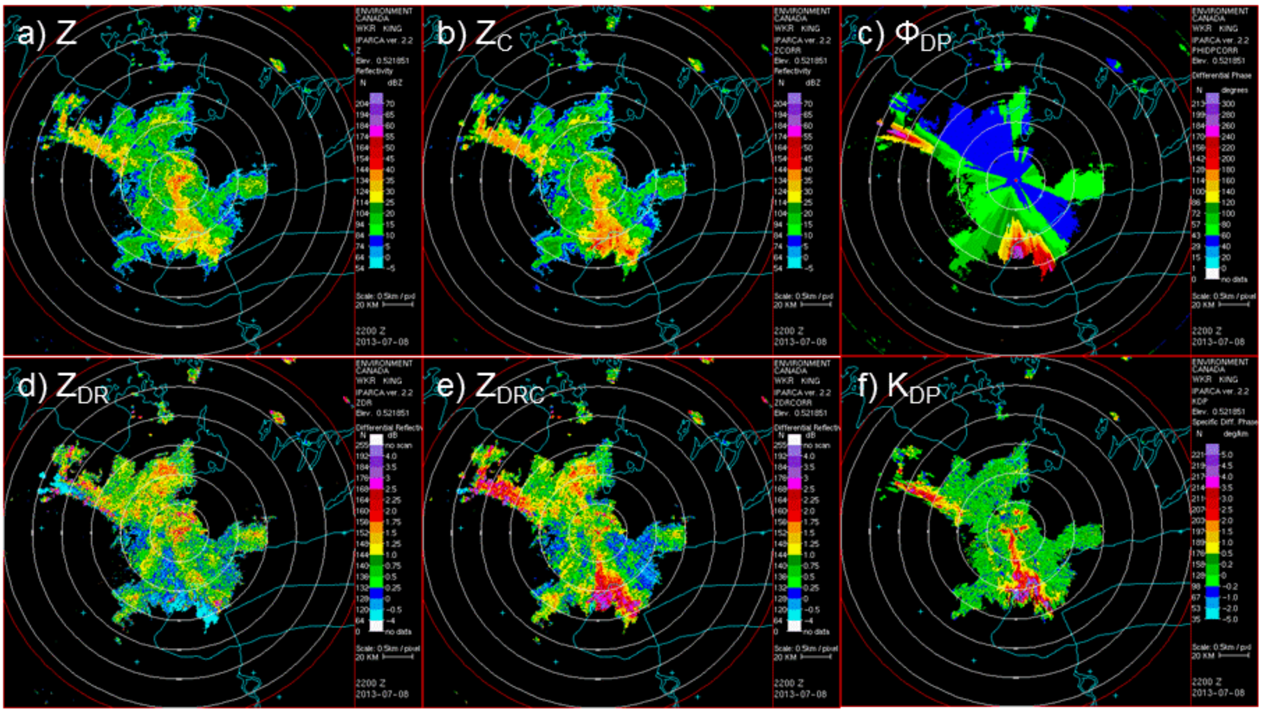

Figure 4: WKR PPI's of a) Z, b) Z_C, c) Φ_{DP}, d) Z_{DR}, e) Z_{DRC}, f) K_{DP} at 2200Z.

2.4 *Quantitative precipitation estimation*

Several rain-rate estimators of the forms R(Z), R(Z, Z_{DR}), R(K_{DP}, Z_{DR}), R(A) and R(K_{DP}) were evaluated using Z, Z_C and or Z_{DR} and Z_{DRC} where appropriate. Essentially there were 12 rate estimates from the C-band radar, however only the three presented in Table 1 are discussed in this paper. Note that only positive K_{DP} are used in the R(K_{DP}) algorithm.

Table 1: List of QPE estimators used for the King City Radar.

Source	Algorithm
Fulton et al. 1998. (WSR-88D)	$R=0.017Z^{0.714}$
Brandes et al. 2002.	$R = 33.8K_{DP}^{0.79}$
Ryzhkov et. al. 2014	R(A)

3 Results

The relative performances of the algorithms are evaluated against the storm total amounts from the gauge data. Additionally the rainfall accumulation fields were inter-compared to the spatial accumulation distributions of the KBUF dual-polarimetric radar. The storm total accumulation from the S-band DP-QPE algorithm (Berkowitz et. al. 2013) and the S-band Z only R(Z) (Fulton et. al.1998) are presented in Figure 5. The spatial distributions of the precipitation patterns are similar, however overall amounts are relatively higher with the DP-QPE algorithm compared to the R(Z) algorithm especially in areas north of the airport. This was attributed to path attenuation of the S-band Z over the precipitation period as indicated by large changes in the S-band Φ_{DP} (example not shown) along radials in this area. A local maximum of over 150 mm is also indicated in Figure 5a, just north-east of CYYZ that is not present in Figure 5b. Note that the DP-QPE product is of coarser resolution (0.24 km x 1^o) than the R(Z) accumulation (0.25 km x 0.5^o).

The C-band storm total accumulations for the algorithms in Table 1 are shown in Figure 6. Figure 6a is from the WSR-88D R(Z) using the attenuation corrected Z. Figure 6b and Figure 6c are for the R(K_{DP}) and R(A) algorithms, respectively. The C-band R(Z) accumulation is the worst of all the patterns showing very low accumulation in comparison to the other estimates. Even with attenuation corrected Z, the performance is poor. R(K_{DP}) and R(A) algorithms produced accumulation patterns very close to the S-band accumulations. However they are slightly noisier in appearance.

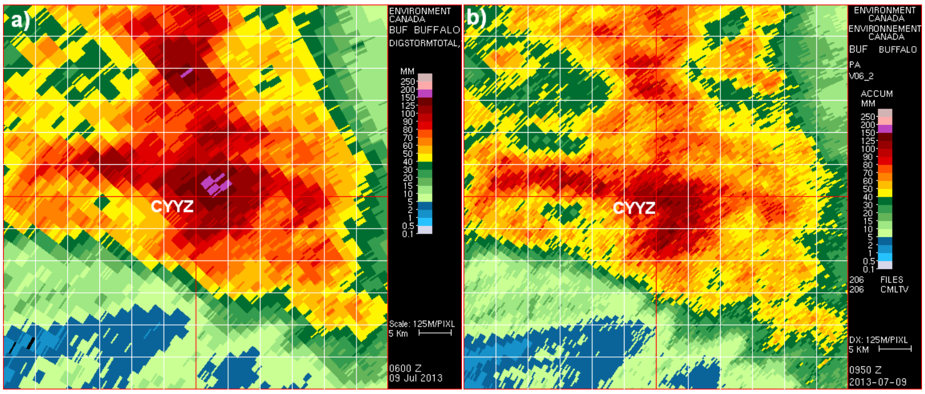

Figure 5: Total storm accumulation from the KBUF NEXRAD S-band a) DP-QPE algorithm and b) WSR-88D convective R(Z) algorithm. Toronto International Airport (CYYZ) is located at the red lines crossing in the center of the image.

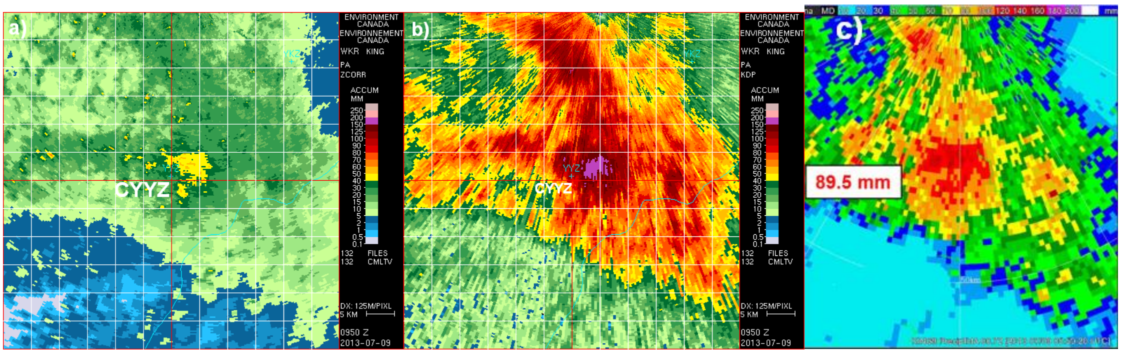

Figure 6: Total storm accumulation from the King City C-band radar using a) WSR-88D R(Z_C), b) Brandes et. al. 2002 R(K_{DP}) and c) Ryzhkov et. al. 2014 R(A) rain-rate algorithms. CYYZ is at the center of the images.

The maximum rainfall total from all the 48 gauges was 126 mm for the gauge at the airport. Table 2 lists the rainfall totals for the radar derived estimates for the 3 C-band and the 2 S-band algorithms at this location. As expected the R(Z_C) storm total for the C-band was severely under-estimated by about 80%. The other estimators also under-estimated the rainfall total at the airport by 13-25% and the S-band DP-QPE algorithm over-estimated the gauge total by 10%.

Table 2: CYYZ storm total accumulation and radar/gauge ratios for the C-band and S-band storm total estimates.

Algorithm	Storm Total (mm)	Radar/Gauge ratio
C-band WSR-88D R(Z_c)	27.2	0.22
R(K_{DP})	94.0	0.75
R(A)	89.5	0.71
S-Band WSR-88D R(Z)	109.2	0.87
S-band DP-QPE	138.4	1.1

Scatterplots of the radar derived amounts against the rainfall total for the 48 gauge locations are presented in Figure 7. The radar pixels were averaged over a 5x5 window centered at each gauge pixel to produce the radar amounts.

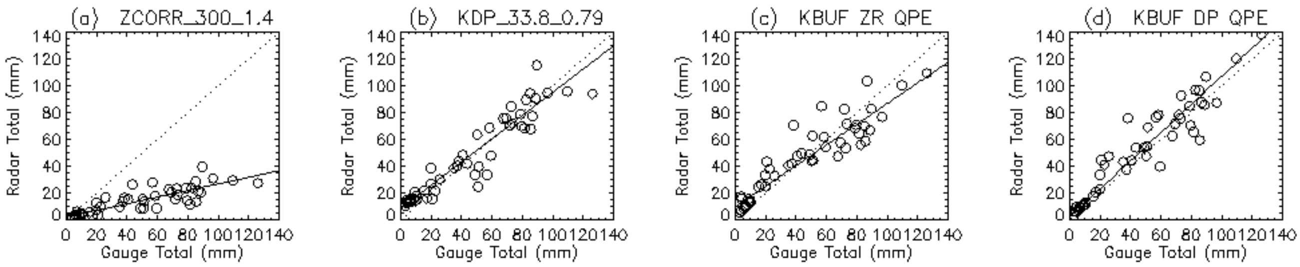

Figure 7: Scatterplots of radar vs. gauge storm totals for a) R(Z_C), b) R(K_{DP}), c) S-band R(Z) and d) S-band DP-QPE. Solid lines are least absolute deviation fits to the data pairs.

Spatial averaging helped reduce some of the errors due to mismatch of radar and gauge sampling. Note that all the gauges were within 60 km of the WKR radar and at 0.5° elevation the sampling heights were a few hundred meters above ground for the furthest gauge. R(A) scatter plots are not presented here, however they are expected to be similar to the R(K_{DP}) scatterplot in Figure 7b, because of the similarity of the spatial accumulation distribution between R(K_{DP}) in Figure 6b and R(A) accumulation in Figure 6c. A least absolute deviation fit for radar-gauge pairs are indicated by the solid lines in Figures 7a through 7d. Overall the fits for R(K_{DP}) in Figure 7b, and DP-QPE in Figure7d are better than the other algorithms. To assess the relative performance of the 4 radar derived storm total estimates with the gauge amounts the root mean square error (RMSE), normalized mean bias (NMB) and the Pearson correlation coefficient (CORR) were calculated. The results are summarized in Table 3.

Table 3: CYYZ storm total accumulation and radar/gauge ratios for the C-band and S-band storm total estimates.

Algorithm	RMSE (mm)	NMB (%)	CORR
C-band WSR-88D R(Z_c)	41.9	-70	0.84
R(K_{DP})	11.5	2.0	0.94
S-Band WSR-88D R(Z)	13.4	0.6	0.92
S-band DP-QPE	12.3	11.1	0.95

The RMSE for the R(Z) algorithm was about 4 times as large as the RMSE from the R(K_{DP}) algorithm for the C-band radar (11.5 mm). The S-band R(Z) RMSE was 13 mm, compared to the DP-QPE of just over 12 mm. NMB for C-band R(Z) is largely negative(-70%), reflecting the poor overall performance of the algorithm. There was only a very small improvement in using corrected Z relative to using the uncorrected Z in the R(Z) algorithm. The small difference in the accumulation between these two estimates is a direct result of radome wetting not being accounted for in the attenuation correction. The NMB for R(K_{DP}) was only 2% a large improvement over R(Z) at C-band. The NMB for S-band R(Z) was less than 1% compared to 11% bias for DP-QPE. Attenuation at S-band would have resulted in lower R(Z) amounts than DP-QPE and relative to the gauges the S-band R(Z) NMB is 10 times smaller than DP-QPE. The highest correlation coefficient was for DP-QPE (0.95) algorithm followed by R(K_{DP}) at 0.94. Slightly lower correlations were found for the R(Z) algorithm.

The available 5-minute resolution gauge data at 44 of the locations provides some insights into the accumulation and variability of the estimates at their respective locations. Figure 8 is a cumulative accumulation example for one of the gauges, located 2-3 km from the airport. In Figure 8, the black line with stars is for the 5-minute gauge data, red line is for R(Z) S-band, green line is for DP-QPE is green, thin black for C-band R(K_{DP}) and magenta for C-band R(Z) algorithms.

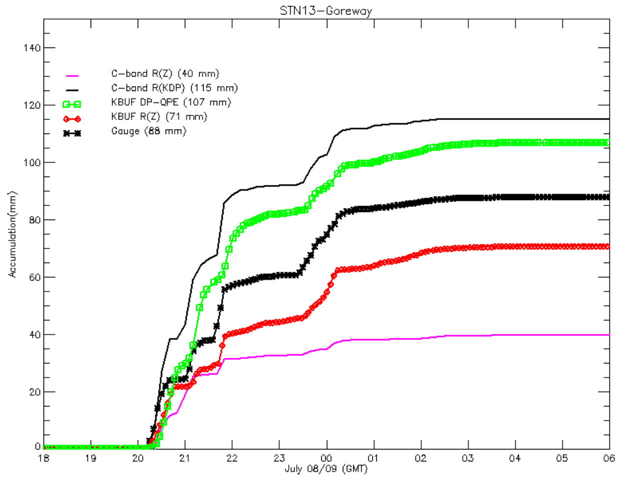

Figure 8: Cumulative accumulations from the 5-minute rain-gauge data (black stars), KBUF R(Z) (red), KBUF DP-QPE (green) and WKR C-band R(K_{DP}) (thin black) and C-band R(Z) (magenta) algorithms.

The rainfall totals from the various estimates are highly variable, ranging from 40 mm for C-band R(Z) to 115 mm for C-band R(K_{DP}). The S-band R(Z) was 71 mm and DP-QPE was 107 mm. The gauge recorded 88 mm rainfall total. The two estimates that were closest to each other were 115 mm and 107 mm, from the R(K_{DP}) and DP-QPE. It is suggested that the gauge may be may be biased lower than the actual rainfall at this location and the true accumulation is somewhat closer the R(K_{DP}) and DP-QPE amounts. Nonetheless, all the estimates whether biased or not from the true rainfall, captured the sub-hourly rainfall intensity at this location.

4 Summary and conclusions

The July 8th 2013 heavy rainfall event storm highlighted many issues associated with radar QPE for C-band. The rainfall was over a highly urbanized area with significant ground clutter contamination and the high resolution dual-polarimetric scans used were prone to second trip contamination. Since the gauges were relatively close to the radar, issues with vertical reflectivity profile correction and bright-band were not considered significant. The main factors affecting the radar derived rainfall estimates were path attenuation and most important for this event was the losses from heavy rainfall over the radome. The heavy rain at the King City radar resulted in radome wetting and this complicated and compromised attenuation correction techniques resulting in poor performance of the algorithms based on Z and Z_{DR} in general. $R(K_{DP})$ and R(A) performed much better in this situation and gave relatively low overall bias, but the root mean square, or variability of the estimates over the different gauge was still moderate at about 12 mm. Similar RMSE were found for the S-band estimates. In general, the C-band dual-polarimetric radar can provide reasonably good rain-fall estimation with some care, which is comparable to S-band.

At the King radar site a rain-rate sensor has been installed and future work involves building a dataset where radome wetting was significant. By using the rain-rate information and high resolution gauge data, hopefully a quantification of the radome loss can be achieved.

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