Verification of Beam Blockage Correction by
Comparison between Radar QPE and Rain Gage Measurement

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1. Introduction

The dual-polarimetric partial beam blockage correction algorithm (PBBCA) has been developed and examined by using S band dual-polarimetric S-POL radar observations on June 2008 in Taiwan. The correction results had been compared with results obtained from the digital elevation map (DEM) around the radar site. Advantages were observed at locations with high rising buildings, trees, and other human-made objects that are not included in the DEM. This has been reported in the previous report.

2. Z-R Relationship and Statistic Measures

To examine the performance of PBBCA on radar QPE, rain gage measurements in the partially blocked area are used for the comparison. Tropical Z-R relationship (i.e. Eq.(1)) is selected to estimate rainfall amount in the Taiwan cases.

$$R(Z) = 1.21\times 10^{-2} Z^{0.833} \tag{1}$$

Within the range of 148 km of the SPOL radar there are 135 rain gage stations. At 0.5^{o} elevation the radar beams pointing at 39 gauges are not blocked. The beams pointing at the rest 96 stations are partially or totally blockage. The radar QPE obtained from the tropical Z-R relation is compared with the measurements by the 135 rain gages. Four different measures of the quality of radar rainfall estimates are examined.

Bias ratio is defined as

$$BR = \frac{\sum_i T_R(i)}{\sum_i T_G(i)} \tag{2}$$

Correlation coefficient between radar storm total T_R and gage storm total T_G

$$\rho = \frac{\sum_i (T_R(i) - \langle T_R \rangle)(T_G(i) - \langle T_G \rangle)}{[\sum_i (T_R(i) - \langle T_R \rangle)^2 \sum_i (T_G(i) - \langle T_G \rangle)^2]^{1/2}} \tag{3}$$

Fractional rms error is defined as

$$FRMSE = \frac{(\frac{1}{N}\sum_i [T_R(i) - T_G(i)]^2)^{1/2}}{\frac{1}{N}\sum_i T_G(i)} \tag{4}$$

Median fractional rms error is determined as

$$MFRMSE = \frac{Median(|T_R(i) - T_G(i)|)}{< T_G >} \tag{5}$$

where $T_R(i)$and $T_G(i)$ are radar and gage estimates rain totals for i^{th} gage, $<T_R>$ and $<T_G>$ are average rain totals from radar and gages respectively.

The radar QPE at a rain gage site is calculated by using the average of rain rate at 20 gates (10 each at two adjacent azimuths) over a rain gage site. The spacing in range of the resolution volumes is 150 m. To mitigate contamination of the radar reflectivity measurements by ground clutter, correlation coefficient ρ_{HV} is used as follows. Only the radar measurements with ρ_{HV} larger than 0.95 within the 20 gates are selected to make the QPE. Also if the average ρ_{HV} from the 20 range locations is less than 0.9 then the radar QPE data is censored from the comparison.

3. QPE and Rain Gage Comparison

The rain event from 10:00 to 13:00 UTC on 14 June 2008 over SPOL radar is taken to evaluate the performance of dual-polarimetric PBBCA in term of radar QPE. Here DEM is used to determine which radar beam is blocked, and the blockage percentage is estimated by using dual-polarimetric PBBCA. The 3 hour rainfall accumulation obtained using radar QPE is compared with rain gage measurements (Fig.1). The four measures and the number of rain gages in the non-blockage and blockage areas are listed in the Table 1.

The four statistical measures in the non-blockage area are intended to be the ground truth to evaluate the performance of QPE after the beam blockage correction. In this area (1st row in Table 1), the bias ratio is close to 1, equal to 0.96. The correlation coefficient is about 0.89. The FRMSE and MFRMSE are 0.23 and 0.18. Thus, the radar QPE with tropical R(Z) relation properly matches the rain gage measurements. It means this relationship is an appropriate one at least for this precipitation event. The QPE using this tropical R(Z) after beam blockage correction should match the statistical measures obtained in the non blocked region.

In the blockage area (2nd and 3rd rows in Table 1), as blockage fraction increases, the bias ratio dramatically drops from 0.96 to 0.60, then to 0.23, the correlation coefficient decreases to 0.63 and 0.60, the FRMSE and MFRMSE increase. It means that reduced reflectivity caused by radar beam blockage strongly affects the QPE resulting in underestimate of the rainfall amount.

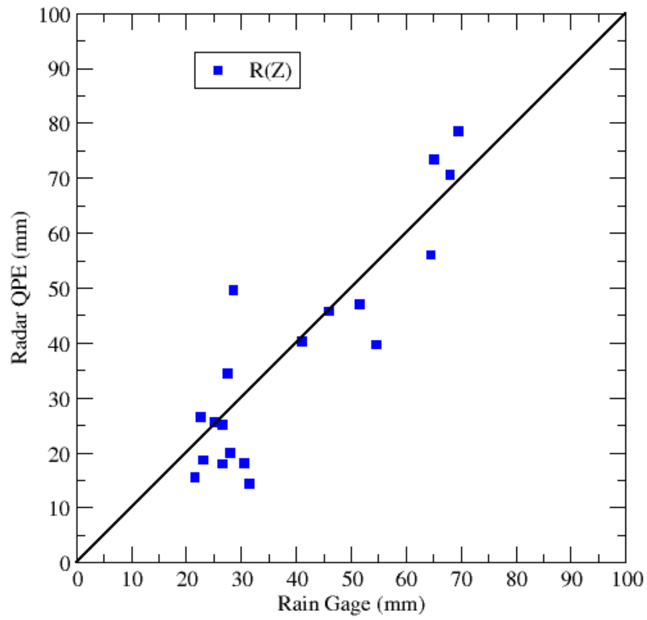

Fig.1. Scatterplot of 3 hour rainfall accumulation obtained from rain gage measurements vs. radar QPE in the area without beam blockage.

Table 1: Statistical measures of radar QPE without beam blockage correction for the 3 hour rainfall accumulation from 10:00 to 13:00 UTC on 14 June 2008. Number of rain gages in the non-blockage and blockage areas is indicated.

Beam Blockage Fraction (BBF)	Bias ratio	Correlation Coefficient	FRMSE	MFRMSE	No. of Gages
BBF=0	0.96	0.89	0.23	0.18	19
$0.0 < \text{BBF} \leq 0.5$	0.60	0.63	0.54	0.35	63
$0.5 < \text{BBF} \leq 1.0$	0.23	0.60	0.88	0.79	11

Table 2: Statistical measures of radar QPE with beam blockage correction in the partial beam blockage area for the 3 hour rainfall accumulation from 10:00 to 13:00 UTC on 14 June 2008.

Beam Blockage Fraction (BBF)	Bias ratio	Correlation Coefficient	FRMSE	MFRMSE	No. of Gages
$0.0 < \text{BBF} \leq 0.5$	0.81	0.77	0.38	0.22	63
$0.5 < \text{BBF} < 1.0$	0.85	0.90	0.48	0.32	11

With the correction of the reflectivity measurements using dual-polarimetric PBBCA (DPC thereafter), we found that the QPE in the partial blockage area has been greatly improved, especially in the area where BBF is larger than 0.5 (Table 2). The bias ratios has been improved from 0.60 without correction to 0.81 for BBF less than 0.5 and from 0.23 to 0.85 for BBF larger than 0.5 with correction. The rain is still underestimated by about 10~15% compared to the value in areas without blockage. All the four statistical measures are improved after the correction. Note that the correlation coefficient in the area with BBF lager than 0.5 increases from 0.6 to 0.9 which is larger than the value 0.89 in the non-blockage area. This indicates that the correction portion is reasonably proportional to the real blockage percentage. The scatterplots of rainfall accumulation measured by rain gages vs. radar QPE also show the QPE improvement after the correction (Fig.2).

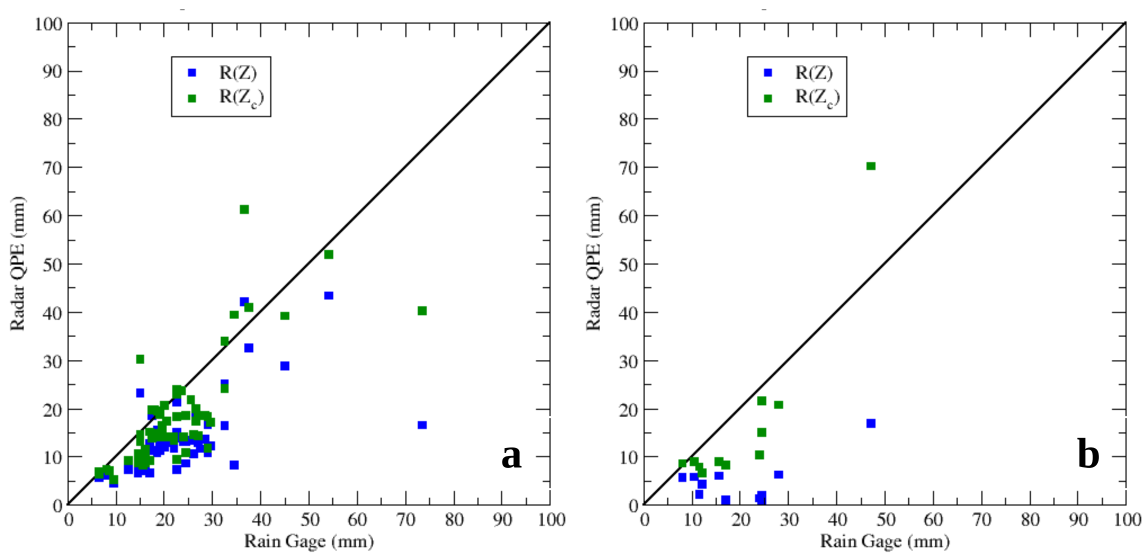

Fig.2. Scatterplots of 3 hour rainfall accumulation obtained from rain gage measurements vs. radar QPE in (a) the area with BBF less than 0.5 and (b) larger than 0.5. Blue squares represent the rainfall accumulation without correction, and green squares stand for the rainfall accumulation after correction.

The geometric method to correct reflectivity with DEM (Digital Elevation Map) is also applied. According to this methodology, the degree of radar beam occultation α is estimated from pure geometric considerations assuming standard atmospheric refraction. Then the corrected Z is computed from the formula

$$Z(\mathrm{dBZ}) = Z_{\mathrm{blocked}}(\mathrm{dBZ}) + 10\log(F_{\mathrm{shield}}) \quad (6)$$

where

$$F_{\mathrm{shield}} = 0.5\tanh[0.0277(50-\alpha)] + 0.5 \quad (7)$$

and the degree of blockage α (in %) is determined as

$$\alpha = 100\frac{\theta_b - \theta_0 + \Omega/2}{\Omega} \quad (8)$$

In Eq. (8), Ω is radar beamwidth, θ_0 is elevation angle of the beam axis, and θ_b is blockage elevation angle. Ω is set to 0.91° in Eq.(8).

Using the same R(Z) relation (Eq. 1), QPE is performed after geometric correction (GEOC thereafter). In can be seen that the radar QPEs after the geometric correction (green squares in Fig.3) have been compensated and are closer to the diagonal line than the uncorrected QPEs (blue squares). The improvements are also clearly observed in the Table 3. Both bias ratio and correlation coefficients have obviously improved, especially in the area where BBF is larger than 0.5. The FRMSE and MFRMSE become smaller as well.

Comparing the statistical measures of DPC and GEOC we conclude that DPC is slightly better than the GEOC. In the light rain region (< 20 mm) with BBF lager than 0.5, GEOC performs better than DPC (Fig.3b and 3b), because the later method depends on reliable Φ_{DP} measurements in that region. The change of Φ_{DP} along the radar beam in light rain is small, and may affect the accuracy of BBF estimate. In contrast, the DPC performs better in the moderate and heavy rain region where rainfall amount is larger than 20 mm (see Fig.3 and 4). It implies that in the moderate and heavy rain region, 1) reflectivity and Φ_{DP} measurements are more reliable; 2) the self-consistency relationship is more robust; and 3) the atmosphere deviates more from the standard condition that is used to derive DEM.

Table 3: Statistical measures of radar QPE with geometric beam blockage correction for the 3 hour rainfall accumulation from 10:00 to 13:00 UTC on 14 June 2008.

Beam Blockage Fraction (BBF)	Bias ratio	Correlation Coefficient	FRMSE	MFRMSE	No. of Gages
$0.0 < BBF \leq 0.5$	0.80	0.65	0.42	0.19	63
$0.5 < BBF < 1.0$	0.71	0.85	0.41	0.40	11

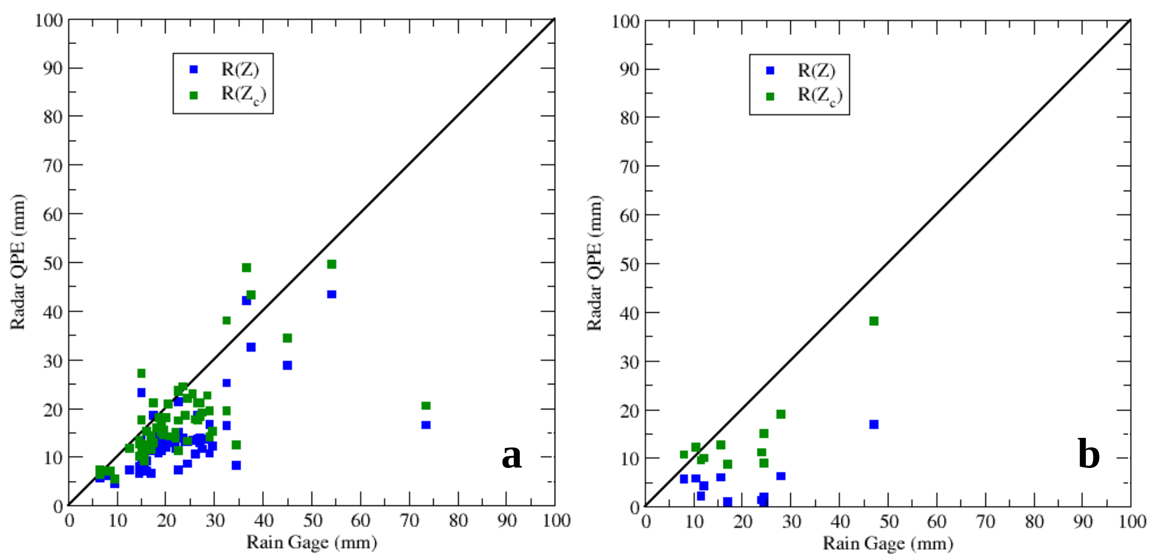

Fig.3. Scatterplots of 3 hour rainfall accumulation obtained from rain gage measurements vs. radar QPE in (a) the area with BBF less than 0.5 and (b) larger than 0.5. Blue squares represent the rainfall accumulation without geometric correction, and green squares stand for the rainfall accumulation after geometric correction.

4. R(K_{DP}) Estimator

For the purpose of radar QPE in mountainous area, using the relations between rainfall rate R and specific differential phase K_{DP} is an alternative and straightforward choice because the K_{DP} is immune to the beam blockage and defective radar calibration. A tropical R(K_{DP}) relation is obtained via simulations of K_{DP} for T = 20°C using drop size distributions measured in the tropical rain events in central Oklahoma. The tropical R(K_{DP}) relation we obtained is

$$R(K_{DP}) = 57.0\,|K_{DP}|^{0.743}\, sgn(K_{DP}) \;. \qquad (9)$$

The scatterplots of 3 hour rainfall accumulation obtained from rain gage measurements vs. radar QPE using R(Z) and R(K_{DP}) are in Fig.4. The statistical measures of the R(K_{DP}) estimator are listed on Table 4. It can be seen that the four statistical measures do not change much as BBF increases suggesting that the beam blockage does not affect QPE obtained from K_{DP}.

Comparing the rainfall accumulations using tropical R(Z) and R(K_{DP}), in the area without blockage indicates that both relations perform well (Fig.4a) as their bias ratios are close to 1. But in the blockage area, R(Z) clearly underestimates rain as mentioned in the previous section(Fig.4b and c). On the other hand, R(K_{DP}) shows good agreement with rain gage measurements, especially in the area with BBF larger than 0.5. The bias ratio is 0.99 and correlation coefficient is 0.9. These results demonstrate the immunity of K_{DP} to beam blockage and the advantage of application of R(K_{DP}) over R(Z) for QPE in the mountainous area.

Table 4: Statistical measures of radar QPE using R(K_{DP}) in the non-blockage and partial beam blockage area for the 3 hour rainfall accumulation from 10:00 to 13:00 UTC on 14 June 2008.

Beam Blockage Fraction (BBF)	Bias ratio	Correlation Coefficient	FRMSE	MFRMSE	No. of Gages
BBF = 0.0	1.03	0.83	0.27	0.20	18
0.0 < BBF ≤ 0.5	1.04	0.73	0.33	0.19	63
0.5 < BBF < 1.0	0.99	0.90	0.24	0.22	11

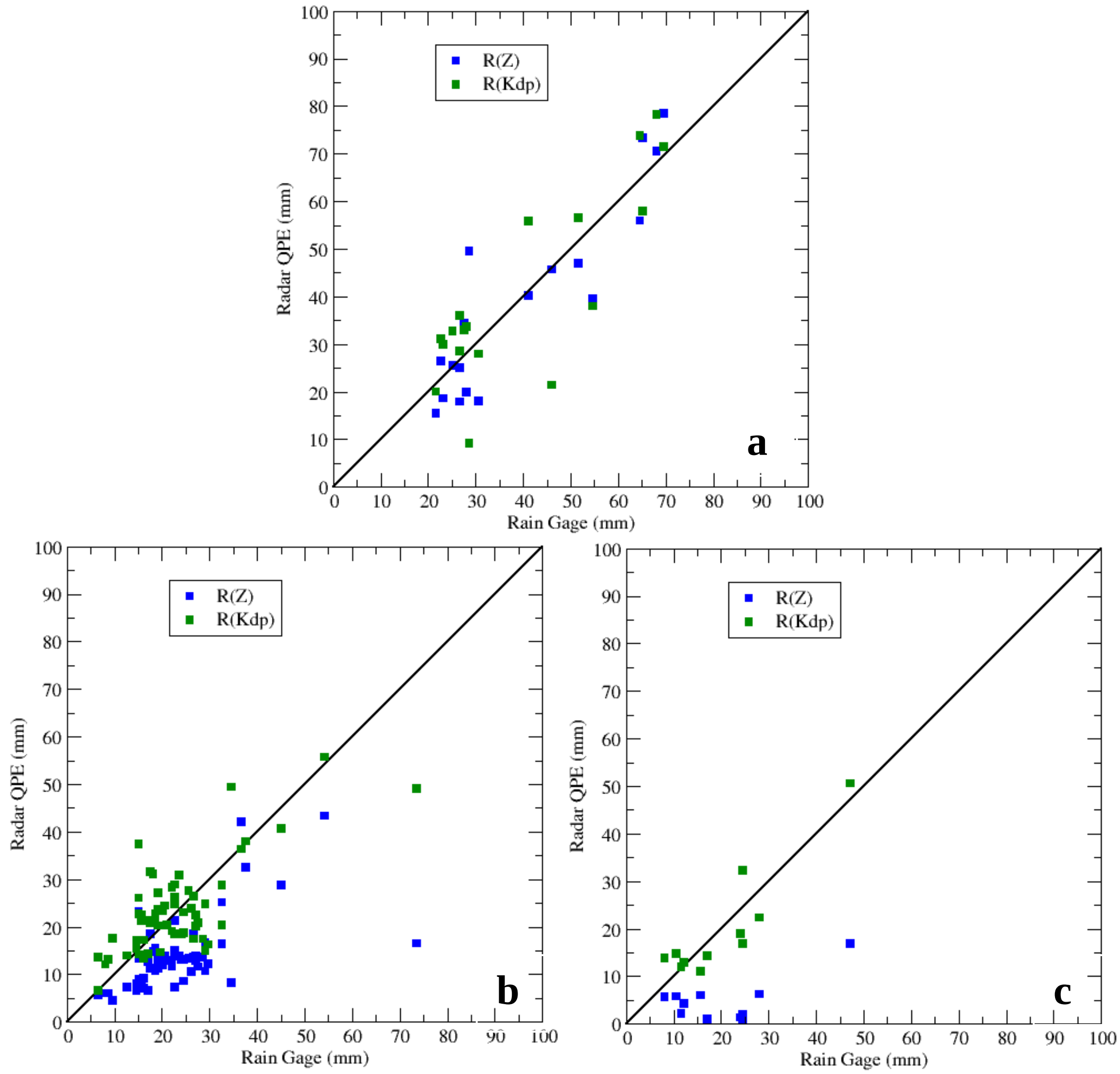

Fig.4. Scatterplots of 3 hour rainfall accumulation obtained from rain gage measurements vs. radar QPE using R(Z) and R(K_{DP}) in (a) the area without beam blockage, (b) with BBF less than 0.5, and (c) larger than 0.5 . Blue squares represent the rainfall accumulation using R(Z), and green squares stand for the rainfall accumulation using R(K_{DP}).