Integrating Quantitative Precipitation Estimation Products Concurrently from S- and C-band Dual-polarimetric Radars over Norther Taiwan

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Abstract

The quantitative precipitation estimation (QPE) from S- and C-band dual-polarimetric radars have different advantages and disadvantages. This study investigates the performance and integration of the RCWF (S-band) and the NCU C-Pol (C-band) dual-polarimetric radar QPEs over northern Taiwan. Four different QPE relationships [$R-Z$, $R-K_{DP}$, $R-(Z, Z_{DR})$ and $R-(K_{DP}, Z_{DR})$] of each rain types, namely spring rain, Mei-Yu, summer convection, typhoon and cold-front, are obtained from six years NCU 2D-Video disdrometer data and applied to several events observed by both radars from March of 2014 to August of 2015. The performances of radar-based QPE are validated by comparing with 96 rain gauges. Compensating the wet radome effect has pronounced improvements in QPEs from both NCU C-Pol and RCWF radars. Overall, KDP-based relationships which combine with $R-Z$ are most accurate. The normalized root-mean-square-error (NRMSE) of QPEs can be further reduced when Lagrangian-Evoluation Adjustment (LEA) QPEs are applied with respect to traditional discrete QPEs. Combining S- and C-band dual-pol QPEs provides the lowest NRMSE by capturing DSD variation.

Key word: dual-ppolarimetric radar, quantitative precipitation estimation

1. Introduction

Accurate radar-based quantitative precipitation estimation (QPE) has been a longstanding goal of meteorological radar. Marshall and Palmer (1948) utilized the measured raindrop size distribution (RSD), the simulated reflectivity (Z, mm^6m^{-3}) and a power-law relation, $Z=aR^b$ (Z-R), to estimate rainfall rate (R, mm hr^{-1}). However, the Z-R relation varies vastly in convective, startiform precipitation, and different climatological regions due to natural variability in RSD (Battan 1973). Seliga and Bringi (1976) proposed utilizing the dual-polarization radar (dual-pol) which is capable of transmitting horizontal and vertical electromagnetic signals. Consequently, the QPE has been greatly improved (Seliga et al. 1981; Gorgucci et al. 1995; Ryzhkov and Zrnić 1995).

Various forms of "power-law" QPE use one to three parameters [$R(K_{DP})$, $R(Z_{HH}, Z_{DR})$, $R(K_{DP}, Z_{DR})$, $R(Z_{HH}, K_{DP})$ and $R(Z_{HH}, K_{DP}, Z_{DR})$]. These various forms of dual-pol QPE algorithm have shown pronounced improvements compared to Z-R relations.Nevertheless, dual-pol QPE is still suffered from measurement error of radar variables and variability of RSD. The study from Lee (2006) has shown that the RSD variability is one of the major sources of error in radar-based QPE. Chang et al. (2009) has shown the unique RSD of typhoon systems. Chang et al. (2016) further utilized the variational-based algorithm to obtain optimal QPE by adjust the coefficient "a" of Z-R relationship. Despite the fact that the variational QPE may outperform "power-law" QPE by adapting the information from dual-pol variables and background climatology of "a", the "power-law" QPE algorithms are relatively easy and robust for operational implementation.

In the foreseeing future, the radar network in Taiwan will consist of 14 Doppler and dual-polarimetric radar in S- and C-band frequencies. These radars have two main purposes: weather surveillance and QPE. Consequently, there radars will have different scanning strategy with different spatiotemporal resolution. Furthermore, each dual-pol variable has distinct advantages and dis-advantages in terms of QPE. Jou et al. (2015) has first examined the performance of dual-pol QPE in northern Taiwan using RCWF S-band radar. The pro and con have been summarized in their study. They found $R(K_{DP})$ has higher error in low rain region. The QPE error from measurement error issue (e.g., attenuation effect, wet random effect) also reduce accuracy of dual-pol QPE. In addition, the noisy Z_{DR} significantly jeopardizes the dual-pol QPE.

In this study, the power-law dual-pol QPEs, namely $R(K_{DP})$, $R(Z_{HH}, Z_{DR})$, $R(K_{DP}, Z_{DR})$ and conventional $R(Z)$ will be investigated from S-band (RCWF) and C-band (National Central University C-band Dual-Polarimetric radar, NCU CPOL) dual-polarimetric radars. In Jou et al. (2015), the coefficients of dual-pol QPEs are not tuned for Taiwan RSD characteristics. The impact of QC procedures is not investigated. In this study, three key factors will be investigated. The sensitivity of dual-pol QPEs to the power-law coefficients, quality control procedures and combination procedures from multiple radars.

2. Data and QPE coefficients

The data of 2D-Video Disdrometer (2DVD) at NCU from October 2000 to June 2007 is collected to characterize the RSD of northern Taiwan. There are total 14314 quality-controlled 6-mins RSDs composing of a variety of precipitation types. These RSDs are categorized into 5 different types of precipitation system based on the climatology of the precipitation systems of Taiwan (Chen and Chen 2003). They are: spring (March–April), Mei-Yu (May–June), convection (July–September), cold front (October–February) and typhoon (manually selected). The rainfall rates of each type are up to 70 mm hr^{-1}. The Mei-Yu and Typhoon are even up to 90 mm hr^{-1}. The rainfall rates of cold front are mostly below 5 mm hr-1. These quality-controlled RSD data are consequently applied to calculate the QPE coefficients.

The radar variables (i.e., Z_{HH}, Z_{DR}, K_{DP}) are first simulated through T-Matrix scattering calculation (Barber and Yeh 1975) from RSDs. The rainfall rates are obtained from RSDs as well. The coefficients of the following QPE algorithms are derived consequently.

$$R = a_1 Z_{HH}^{b_1} \quad (1)$$
$$R = a_2 Z_{HH}^{b_2} Z_{DR}^{c_2} \quad (2)$$
$$R = a_3 K_{DP}^{b_3} \quad (3)$$
$$R = a_4 K_{DP}^{b_4} Z_{DR}^{c_4} \quad (4)$$

The coefficients of (1)-(4) of five types of precipitations (here after, seasonal coefficients) are obtained by Levenberg-marquardt algorithm (Rogers 2000) in both S- and C-band frequencies (Table 1 and 2). In addition, the coefficients without considering seasonal RSD variability were obtained by including all RSD data for comparison as well, here after, generalized coefficients.

S - band

		All data	Spring	MeiYu	Convection	Typhoon	NE front
R-Z	a	0.0279	0.0197	0.0244	0.0435	0.0282	0.0408
	b	0.6619	0.6874	0.6779	0.6233	0.6624	0.6173
R-KDP	a	47.5998	44.6864	48.0516	48.3448	64.3293	42.5163
	b	0.7605	0.7950	0.7915	0.7725	0.7278	0.7225
R-(Z,ZDR)	a	0.0046	0.0019	0.0018	0.0011	0.0013	0.0033
	b	0.8492	0.9452	0.9578	1.0017	0.949	0.8888
	c	-0.6193	-0.9734	-1.0434	-1.1240	-0.7988	-0.7439
R-(KDP,ZDR)	a	64.8411	61.9421	63.3873	62.3633	73.0964	60.2012
	b	0.988	0.9782	0.9766	0.9727	0.9476	0.9486
	c	-0.6921	-0.6445	-0.6403	-0.6196	-0.6039	-0.5836

Table 1: The coefficients of S-band dual-pol QPEs.

C - band

		All data	Spring	MeiYu	Convection	Typhoon	NE front
R-Z	a	0.0376	0.026	0.0316	0.0710	0.036	0.0434
	b	0.634	0.6630	0.6558	0.5761	0.6394	0.6138
R-KDP	a	26.2342	23.948	25.8619	26.4884	36.167	24.0925
	b	0.7485	0.7823	0.7784	0.7590	0.7158	0.7103
R-(Z,ZDR)	a	0.0035	0.0014	0.0014	0.0013	0.001	0.0028
	b	0.8886	0.9922	0.9952	1.0018	0.9812	0.9199
	c	-0.6575	-0.9840	-1.0031	-1.0239	-0.7714	-0.7474
R-(KDP,ZDR)	a	31.2514	29.8459	30.4106	29.9747	36.8965	30.3301
	b	0.9648	0.9563	0.9593	0.9381	0.9212	0.9500
	c	-0.5988	-0.5334	-0.5418	-0.5132	-0.5146	-0.5717

Table 2: The coefficients of C-band dual-pol QPEs.

The seasonal and generalized dual-pol QPE coefficients are first examined by validating against simulated radar variables and rainfall rate from RSDs. As shown in Fig. 1, the values of normalized mean bias (NMB) and normalized root mean square error (NRMSE) are lower when seasonal coefficients are used.

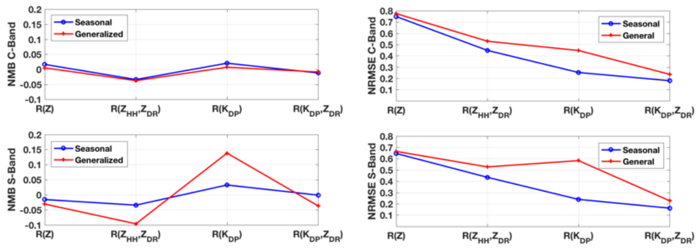

Figure 1: The values of NMB and NRMSE of seasonal and generalized coefficients for S- and C-band dual-pol QPEs from RSD data.

3. Quality Control

Both S- and C-band radar are suffered from attenuation and wet-random effects, the coefficients for Φ_{DP}-based attenuation correction algorithm for Z_{HH} and Z_{DR} are obtained from RSD data (Bringi and Chandrasekar 2001). The system bias and wet-random are estimated from self-consistency algorithm (Vivekanandan et al. 2003). As the rain accumulates above random and forms a thin water layer, the wet-random effect (WRE) will reduce the Z_{HH} along the beam (similar feature to system bias).

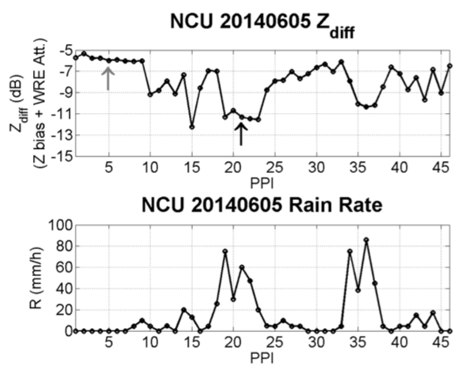

Figure 2: The time series of estimated bias values (including system bias and wet-random effect) of NCU CPOL and the rainfall rate from a rain gauge next to radar.

In Fig. 2, the time series of rainfall rate of a rain gauge next to NCU CPOL and the estimated bias (including system bias and WRE) are found in good agreement. For the first 8 PPI scans, the bias remains consistent (around -6 dB). As heavy precipitation system approach radar site (17^{th} to 24^{th} PPI scans), the bias further increases to -11 dB due to WRE. The results indicate that the self-consistency algorithm can estimate system bias and WRE properly.

The improvements of attenuation correction and WRF for S- and C-band radars are investigated by examining the performance of dual-pol QPE. In Fig. 3, The NCU CPOL has higher NRMSE values than RCWF after only system bias correction. While the attenuation correction is further applied to both radars, NCU and RCWF show comparable performance. Applying the WRE correction can further reduce the NRMSE of both radars.

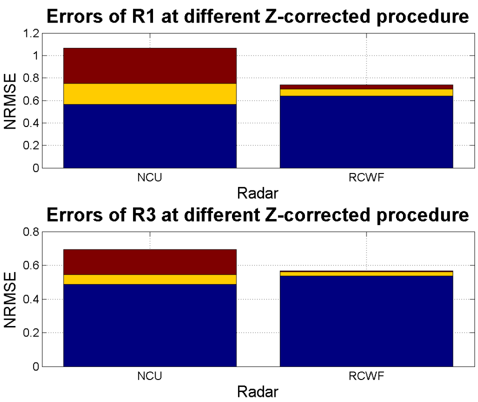

Figure 3: The values of NRMSE of dual-pol QPE R1 (from eq.1) and R3 (from eq. 3). The red, yellow and blue colors represent the NRMSE of system bias correction only, attenuation correction is added on and WRE is added on.

4. Comparison between S/C-band radars

After obtaining seasonal coefficients for dual-pol QPE and applying complete QC procedures, the performance of dual-pol QPE from S- and C-band radars is investigated.

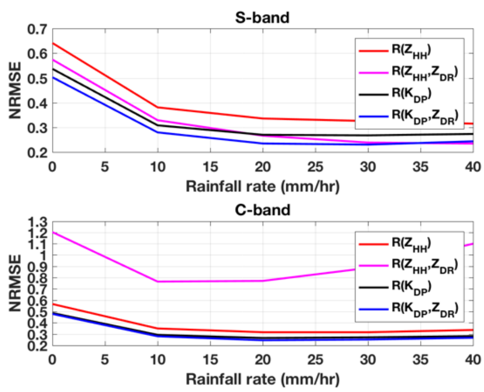

Figure 4: The values of NRMSE at different rainfall rate for four different power-law dual-pol QPE.

In Fig. 4, the dual-pol QPEs are first examined in the same power-law algorithm. The results indicate that given the same dual-pol QPE, S- and C-band radars have comparable performance. Despite the fact that C-band is more vulnerable due to severe attenuation effect, C-band radar can provide comparable dual-pol QPE after proper QC procedures. Except C-band has much higher values of NRMSE in R(Z_{HH}, Z_{DR}) algorithm. The WRE of C-band radar Z_{DR} measurements cannot be properly corrected is the main reason. In addition, the R(K_{DP}) and R(K_{DP}, Z_{DR}) QPE algorithms slightly outperform R(Z_{HH}) and R(Z_{HH}, Z_{DR}) algorithms. The detailed analysis can be found in Chen et al. (2017).

5. Lagrangian-Eulerian Adjust (LEA) QPE

Conventionally, the radar-based QPE is obtained by integrating each radar scan discretely (time difference between two scans is ΔT). Each radar has different temporal resolution and scanning sequence, synchronizing the QPE products from multiple radars is very challenging in practice. However, it is crucial to obtain optimal QPE products from multiple radars. The study from Ventura et al. (2010) utilized the advection correction to reduce the error from low temporal resolution. Chen and Chandrasekar (2015) utilized a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) based interpolation methodology.

In this study, a Lagrangian-Eulerian Adjust technique is developed to mitigate the differences among radars. The domain mean advection of the precipitation is first obtained from two consecutive scans. The minutely QPEs (R_j) are thus obtained by combining the forward advection QPE from early scan (R_i) and backward advection QPE from later scan (R_{i+1}). Two scans are merged by the weighting determined by the time difference between early and later scans. The Δt_j represents the time difference between "j" minutely QPE and early QPE (R_i). As shown in eq. (5), The R_j has higher weighting of early QPE if Δt_j is small (closer to early scan), vice versa.

$$R_j = R_i \frac{\Delta T_i - \Delta t_j}{\Delta T_i} + R_{i+1} \frac{\Delta t_j}{\Delta T_i} \tag{5}$$

The results indicate that applying LEA to both S- and C-band radar mitigates the values of NRMSE pronouncedly. The most pronounced improvements can be noticed in C-band which has lower temporal resolution. The advantage of higher temporal resolution from S-band QPE is diminished by reducing the radar scans. The optimal QPE products is the combinations of S- and C-band radar QPEs with LEA technique.

6. Conclusion

In this study, the seasonal coefficients of dual-pol QPEs are derived from RSD data in northern Taiwan. The results have shown pronounced improvements when seasonal coefficients are applied. Moreover, detailed QC procedures and their impacts on dual-pol QPEs are investigated as well. The attenuation and WRE corrections for S- and C-band radar are applied as well. The results indicate that vulnerable C-band radar suffer from attenuation effect and WRE can be properly corrected. Consequently, the QPEs are comparable to S-band QPEs.

In practice, the QPE uncertainty due to different temporal resolution and scanning sequence from multiple radars can be reduced by apply the LEA technique developed in this study. The results indicate that the optimal QPE products is the combinations of S- and C-band radar QPEs with LEA technique.

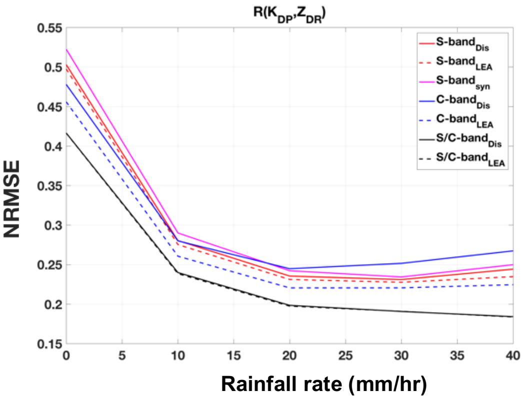

Figure 5: The values of NRMSE as function of rainfall rate. The solid (dash) lines represent discrete (LEA) QPEs. The QPEs from S-band (C-band) are red (blue) lines. The pink line is the S-band QPE with reduced temporal resolution. The black lines are QPEs from the combinations of S- and C-band.

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