Response to the comments from the reviewer 3

Responses to the general comments:

We would like to thank the reviewer for the constructive comments and corrections, especially about the description of the polarimetric rainfall algorithms. The invaluable comments help improve our manuscript. Our responses are as follows.

In this document, for each comment (black font), we display an answer (blue font)

Responses to the specific comments:

Q1) Page 1, ll.19-21:It is not clear the link of the sentence starting with "therefore" with the previous one

A1) As your comments, the manuscript has been revised as follows:

After

"Polarimetric measurements are sensitive to size of raindrop, concentration, orientation and shape. Rainfall rates calculated from polarimetric radar are influenced by the shape of raindrop and canting. The shapes of raindrops play an important role in polarimetric rainfall algorithms based on differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}). However, the characteristics of raindrop are different depending on precipitation type, storm stage of development, and regional and climatological conditions.

Q2) Page 2, ll.16-18: Potential and actual advantages of polarimetry applied to radar systems have been analyzed in the literature. However, this sentence is not very precise.

A2) As your comments, we added the information of dual-polarization radar measurement, and we have modified the sentence as follows:

Added the sentence

"...because, more information about raindrop size distribution (DSD) is available, and dual-polarization radar can distinguish precipitation type."

Modified the sentence

Before

"Dual-polarization radar provides characteristics of the precipitation by backscatter and differential propagation phase of hydrometeors, and therefore can obtain more information about DSD”

After

“Dual-polarization radar provides characteristics of the precipitation by backscatter and differential propagation phase of hydrometeors and therefore can reveal uncertainty of rainfall estimation resulting from DSD variability”

Q3) Page 2, ll.20-21: Dual polarization rainfall algorithms used K_{DP} or combinations of Zh, Zdr, and K_{DP}.

A3) The manuscript has been revised as follows:

After

“Therefore, dual-polarization rainfall algorithms used K_{DP} or combinations of Z_H, Z_{DR}, and K_{DP} are better than using reflectivity factor only.”

Q4) Page 2, ll.24-25: This is wrong: maybe “allowing correct interpretation of polarimetric measurements in rain” or “an important feature of rain microphysics”.

A4) The sentence on ll.24-25 (“This is because…of the rain”) is misleading, so it was excluded from the paper. Instead, we added the following sentence

Added sentence

“Polarimetric radar measurements are sensitive to the DSD properties such as diameter, concentration, orientation, and shape. Rainfall rates derived from polarimetric radar measurements are affected by the mean shape of raindrops and canting (Brandes et al., 2002).

Q5) Page 2, ll.26-28: Authors should cite also more recent work on the drop-shape topic.

A5) As your comments, we added the recent reference (Brandes et al., 2002; Thural and Bringi, 2005; Marzuki et al., 2013)

Q6) Page 3, ll.1-3: “Thus,..”Again, I do not see how this conclusion follows from the previous sentence.

A6) As your comments, we have modified the manuscript.

After

"However, they are not frequently studied in Korea. Therefore, the shape of raindrop and polarimetric rainfall algorithm reflecting rainfall characteristics of the Korean peninsula studies are necessary to improve rainfall estimation."

Q7) Page 3, ll.14-17: Cited studies by Goddard et al. aimed at demonstrating the inadequacy of the Pruppacher and Beard shape-size relation.

A7) Goddard et al. (1982) suggest that the raindrop axis ratio relation from Pruppacher and Beard (1973) needs careful consideration. But, the overall agreement between the radar and disdrometer measurements was generally good.

Q8) Page 3, ll.19: Formulation of self-consistency by Gorgucci et al. (1992) was based on Zh, Z_{DR} and K_{DP} and not on Zh-K_{DP}.

A8) The calibration bias of radar reflectivity is calculated from the comparison of measured Φ_{DP_obs} with calculated Φ_{DP_cal} derived from Z_h using the Z_h-K_{DP} self-consistency relationship as following procedure (Lee and Zawadzki 2006).

1. Select the rain region to avoid the ground echoes and bright band contamination.
2. Calculate the K_{DP} at the rain region from the observed Z_h using the Z_h-K_{DP} relationship
3. Calculate Φ_{DP_cal} by integrating the calculated K_{DP} along the ray.
4. Find Φ_{DP_obs} measured in the same ray.
5. Calculate the calibration bias by comparing Φ_{DP_cal} and Φ_{DP_obs}.

Lee, G., and Zawadzki, I.: Radar calibration by gage, disdrometer, and polarimetry: Theoretical limit caused by the variability of drop size distribution and application to fast scanning operational radar data, J. Hydrol., 328, 83-97, 2006.

Q9) Page 3, ll.21: A recent paper by Chandrasekar et al. (2015) is more appropriate and update than Atlas et al. (2002).

A9) I appreciate your advice, after examining Chandrasekar et al. (2015), I'll consider your suggestion.

Q10) Page 3, ll.24: Replace "four" with "three"

A10) we change "four" to "three"

Q11) Page 4, ll.20: Please add the height ASL of the radar

A11) Sea level of antenna of BSL radar is 1,085 m, we added the ASL of radar.

Q12) Page 5, ll.1-2: A 0-deg elevation allows small distances between measurements aloft and ground measurements. For most installations measurements collected at such small elevation angles are prone to effects of nearby obstacles. Please demonstrate that for the Bislan radar, this elevation does not implies beam blocking/ground clutter effects or that they are negligible.

A12) 2DVD data are ground measurements and radar data are volume measurements. To compare polarimetric radar parameters, it is necessary to minimize the influence of height difference of 2DVD and radar, and effect by ground. If using high elevation, we can avoid effects from beam blocking and ground echoes on the measurements, however, this elevation is a very great difference in measurement height. Figure 1 show beam path of the BSL radar and 2DVD location. The 2DVD is located about 22.3 km (17°) away from the BSL radar. The 0.0° PPI radar data can avoid effect from beam blocking and ground echoes. Thus, the 0.0° PPI radar data were used.

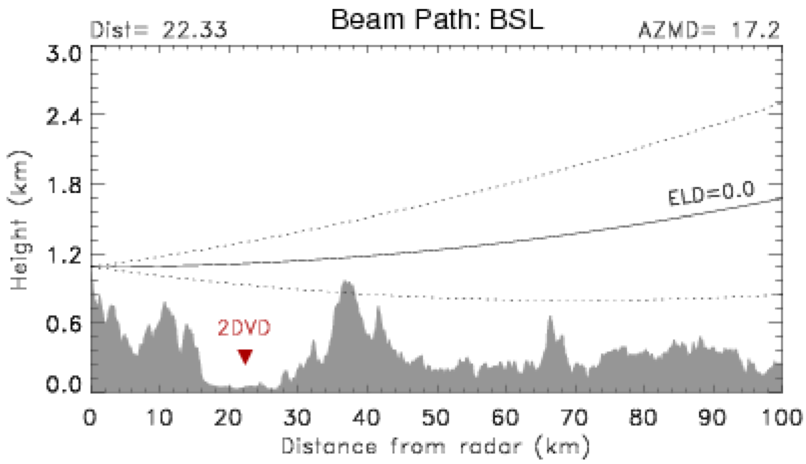

Figure 1. Beam path and terrain map in 17° azimuth angle of the BSL radar.

Q13) Page 5, ll.2-5: Please explain how averaging of PHIdp is obtained.

A13) We were wrong description, so the manuscript has been revised as follows. Φ_{DP} is measured by radar, and K_{DP} was calculated from the filtered Φ_{DP} (Φ_{DP} unfolding and FIR (Finite Impulse Response) filter were applied to the Φ_{DP} measurement data)

Before

"The Z_H, Z_{DR}, Φ_{DP}, and ρ_{hv} radar parameters were averaged …"

After

"The Z_H and Z_{DR} radar parameters were averaged …"

Q14) Page 5, ll.21: What does it mean "beyond the normal distribution"?

A14) "beyond the normal distribution….." sentence has been revised as follows:

Before

"Some of the outliers of fall velocity and oblateness distribution were beyond the normal distribution"

After

"Some particles have fall velocities beyond the terminal velocity of large raindrops.

Q15) Page 6, ll.10-11: Why do Authors use the velocity-size relation by Brandes et al. (2002) and Atlas et al. (1973) to filter 2DVD measurements? Note that, starting from 2DVD counts, such relation is not necessary for computing R.

A15) Atlas et al. (1973) fall velocity relation is derived as an exponential formula, and Brandes et al. (2002) fall velocity relation is computed as a polynomial function. For this reason, Brandes et al. (2002) relation is widely used for calculation of rain rates from the 2DVD data.

A number of hydrometeor fall velocity outliers measured by the 2DVD. Some particles have velocities well beyond the terminal velocity (≒ 12 m/s) of large raindrops (Kruger and krajewski, 2002). Therefore, we applied velocity-based filtering to reduce the effect of instrument errors. We use Atlas et al. (1973) fall velocity formula. This velocity relation has been widely used in many previous studies. In addition, the Atlas et al. (1973) velocity formula is used as a reference relation for comparison with measurement 2DVD data. Therefore, we use Atals et al. (1973) velocity model to filter the 2DVD data.

Q16) Page 7, Section "Raindrop axis ratio": There are a number of questions about the fitting (4). First, what is the accuracy of the fitting. Second, is this fitting more appropriate for certain events (i.e. is there an event-by-event variation?).

A16) · *First, what is the accuracy of the fitting* ⇒ We derived new raindrop axis ratio relation using 2DVD measurement. For reliability of the 2DVD data, we apply to the velocity-based filter for remove drop outliers (Thurai and Bringi, 2005), and compared the rain rate calculated from the 2DVD data to collocated rain gauges measurement. In addition, the oblateness data corresponding to raindrop diameters smaller than 0.5 mm were removed when we derived the new axis-ratio relation. Also, although the measured maximum diameter from the 2DVD could reach about 8.0 mm, the fitting was established to within 7 mm in order to obtain accurate information from the appropriate data.

In order to produce the mean axis-ratio relation, a various fitting methods such as linear and polynomial (twice-, third-, fourth-order) fit were tried. As a result, the third-order polynomial relation was the most suitable for the observation data. For instance, as the raindrop size increased, the difference of raindrop size from the linear and twice-, fourth-order polynomial fit increased when compared with the 2DVD measurement data.

· *Second, is this fitting more appropriate for certain events* ⇒ The mean raindrop axis-ratio relation is based on measurement data collected by 2DVD, a total of 33 rainfall events were used for deriving the empirical relation. The dataset consisted of 15 stratiform rainfall events, 12 convective rainfall events, and 6 mixed (str/con) rainfall events with 17,618 min DSD samples. The majority of rainfall events have 0-5 mm raindrop diameter. Comparison results according to rainfall type, the derived relation was appropriate in all rainfall types. There are no significant differences between the rainfall types.

However, Marzuki et al. (2013) derive axis-ratio relation for stratiform, mixed stratiform/convective and shallow convective. According to paper, axis ratio of deep convective is slightly larger than for other rain types.

Marzuki, M., Randeu, W. L., Kozu, T., Shimomai, T., Hashiguchi, H., and Schonhuber, M.: Raindrop axis ratios, fall velocities and size distribution over Sumatra from 2D-Video Disdrometer measurement, Atmos, Res., 119, 23-37, 2013.

Q17) Page 7, Section "Disdrometer-rainfall algorithms": I think it is more appropriate to Z_h, Z_{DR}, K_{DP} "variables" or "measurements" instead of "parameters"

A17) As your comment, we change "parameters" to "variables"

Q18) Page 8, ll.12: Likely values of mean and standard deviation are switched.

A18) I'd appreciate your input on this. The manuscript has been revised as follow:

After

"The terms $\overline{\emptyset}$ and σ are assumed to be 0° and 7°, respectively.

Q19) Page 9, Section 3.4: What is the point of using light rain? Z_{DR} near zero?. Please explain. What is the accuracy expected with this calibration?

A19) We chose a continuous rainfall event for the continuity of measurement data, and we also use stable light rainfall event in order to avoid the impact of the unstable rain (e.g. convective, short observation of time of storms, beginning or an end of the storms).

The BSL radar measured Z_H and Z_{DR} can be compared with theoretical Z_H-Z_{DR} relation (derived by disdormeter) to verify the measurement data. Comparison result of Z_{DR} using the theoretical Z_H-Z_{DR} relation, the measured Z_H and Z_{DR} showed a substantially lower than theoretical Z_H and Z_{DR}. Thus, the determination of the calibration bias of Z_H and Z_{DR} is essential to improve the accuracy of radar rainfall estimation.

Q20) Page 10: "Variability of DSD in rainfall estimation" I would like to see also some relative performance factors, such as the ratio of RMSE and average value of R.

A20) To investigate the variability of DSD in rainfall estimation, R derived from observed DSDs of 17,618 min are compared with R_e estimated from combinations of polarimetric measurement (Figure 6). All derived relationships and statistics are shown in Table 3. The mean absolute error (MAE), the root-mean-square error (RMSE), and correlation coefficient (Corr.) are used for evaluating the DSD variability. And the 17,618 min DSD data used here is 2DVD measurement data during 2011 to 2012.

Q21) Page 10, ll.21: Corr=0.1??

A21) The manuscript has been revised as follows: 0.10 ⇒ 1.00

Q22) Page 11, ll.3:"A summary of…" The beaviour of the different algorithms with intrinsic dual-pol measurements is what is expected (e.g. Bringi and Chandrasekar, 2001). What is strange is that only $R(K_{DP}, Z_{DR})$ takes advantage from the new shape-size relation.

A22) ·First ⇒ As your comments, we added the following sentence and reference. "The reflectivity factor is affected by the absolute calibration error, and it require accurate knowledge of the radar constant. The differential reflectivity is independent of absolute radar calibration. Therefore it can be measured without begin affected by absolute calibration errors. However, Z_{DR}-based algorithm needs to be used in conjunction with Z_h or K_{DP}, because Z_{DR} is a relative power measurement. Unlike Z_h and Z_{DR}, K_{DP} is independent of the absolute calibration error, attenuation because it is related to the phase shift of the electromagnetic wave. However, K_{DP} is relatively noisy in light rain (low rain rate). Thus, the pros and cons of each polarimetric variable translate into the error of rainfall algorithms (Bringi and Chandrasekar, 2001)."

·Second ⇒ $R(K_{DP}, Z_{DR})$ is showing good results on 2DVD rainfall estimation when using new mean axis-ratio relation. These results are influenced by the variability of DSDs, and the effect of the DSD variability is declined in rainfall estimation with the $R(K_{DP})$ or $R(K_{DP}, Z_{DR})$ than that with the $R(Z_h)$. But, the accuracy of the rainfall estimation declined when the K_{DP} parameter was used for radar rainfall estimation. Whereas $R(Z_H, Z_{DR})$ is showing best performances on radar rainfall estimation. This was because K_{DP} measured by radar is noisy in low rain rate.

Using the polarimetric parameter K_{DP}, the accuracy of the radar rainfall estimation is improved in rain estimation with the Pruppacher and Beard (1970) than that with the new axis ratio. According to Marzuki et al. (2013), when inferring rainfall from K_{DP} measured by dual-polarization radar, it is useful to have a linear equation between the mean axis ratio and drop diameter. In addition, raindrop shapes are influenced by the temperature and pressure (Beard and Chuang 1987), and drop shape differences can be seen by the measurement errors, drop oscillation, dataset and fitting method (Thurai and Bringi 2005).

Q23) Page 11, ll.21-22: now, it is $R(Z_H, Z_{DR})$ the best algorithm and is the only one that take advantage from new shape-size relation. This is also not surprisingly. A simple exercise consisting in adding a properly modeled error to intrinsic measurements would reveal how algorithms are sensitive to random measurement fluctuation and/or calibration biases (see again Bringi and Chandrasekar, 2001). The bad performance of $R(K_{DP}, Z_{DR})$ can be ascribed to the an unappropriate K_{DP} estimation (see the increase in the error of radar $R(K_{DP})$. From figure 7 compared with figure 6, I would expect worst MAE and RMSE values than those in Table 3. Finally, it is not clear to me whether Zh and/or Z_{DR} bias correction was applied or not here.

A23) The invaluable comments help improve our manuscript. However, the purpose of this study was to examine the performance of polarimetric rainfall algorithm according to raindrop shapes. So, various errors such as radar measurement errors and error due to the parametric form (R) were equally applied to the algorithms. I appreciate the suggestion and we'll consider it in future research. And Table 4 is the uncorrected result, and the Table 5 shows the results of applying the daily Z_H and Z_{DR} biases.

Q24) Page 12, Section: "Correction of calibration bias": What is the accuracy of this calibration? Can the event-to event variability of the bias be related to variation of radar performance? Figure 9 shows clearly that the estimation of Zdr bias is extremely poor.

A24) Adaptive calibration is daily Z_h and Z_{DR} calibration biases, and the verification of rainfall estimation is performed by applying adaptive calibration biases that vary each rain event. In general the adaptive bias is more effective than the averaged bias in terms of reduction of random error in rainfall estimation. In addition, the application of adaptive calibration biases is the most effective in reducing radar rainfall errors in particular for rainfall estimators with both Z_H and Z_{DR} (Kwon et al., 2015).

The rainfall event on 23 August 2012 (Figure 9) is mixed rainfall event, and Z_{DR} biases in weak reflectivity were lower than biases in strong reflectivity. Therefore, low bias seems to be derived because daily Z_{DR} bias is calculated by average during the observation time.

References

E. Gorgucci, G, Scarchilli, and V. Chandrasekar, Calibration of radar using polarimetric techniques, IEEE Trans. Geosci. Remote Sens., vol. 30, no. 5, pp. 853-858, Sep. 1992

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