Response to the comments from the reviewer 2

Responses to the general comments:

We would like to thank the reviewer for the constructive comments and corrections on the paper. 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 remarks:

Q1) Page 6, ll.10: Why the Authors used the fall velocity-diameter relation of Brandes et al. (2002) to compute the rain rate and the one of Atlas et al. (1973) to filter out the outliers? Defend this choice or use the same relation.

A1) 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). So, 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.

Q2) Page 6, ll.12: How did the authors define an event? Please provide some information regarding the criterion used.

A2) We have divided rainfall event into three rainfall types such as stratiform, convective and mixed rainfall events using the radar reflectivity and one-hour rain rate calculated by rain gauge and 2DVD. We were referring to Chang et al. (2009), and rainfall rate was modified. The criterion of the rainfall events are as follows:

	Stratiform	Convective	Mixed(Str+Con)
Reflectivity [dBZ]	≤ 35	> 35	-
Rainfall rate[mm/hr]	≤ 5	> 5	-

Chang, W. Y., Wang, T. C., and Lin, P. L.: Characteristics of the Raindrop Size Distribution and Drop Shape Relation in Typhoon Systems in the Western Pacific from the 2D Video

Disdrometer and NCU C-Band polarimetric Radar, J. Atmos. Oceanic Technol., 26, 1973-1993, 2009.

Q3) Page 6, ll.26: How many events have been discarded by the quality control process?

A3) During the period from September 2011 to October 2012, total 38 rainfall events were measured by the 2DVD, five rainfall events were discarded by the quality control process. The excluded five rain events show that rainfall differences between 2DVD and rain gauge were mostly from 22% to 30%. A total of 33 rainfall events were analyzed and, the difference between 2DVD and rain gauge for the 33 rainfall events are listed in Table 2.

Q4) Page 7, ll.1-3: In the literature there are several different methods to distinguish between stratiform and convective rain. Can the Authors provide some information regarding the criterion used?

A4) As mentioned in A2), we have divided rainfall type into the stratiform and convective rain using the radar reflectivity and one-hour rain rate calculated by rain gauge and 2DVD. In addition, we distinguish precipitation type based on the dominant rainfall type over the observation time.

Q5) Page 7, ll.19: Can you provide some information regarding the choice of a third order polynomial? Did the Authors try also other relations (such as linear or a fourth order polynomial)? Can the Authors provide some information regarding the performance/goodness of the fitting (such as R^2)

A5) In order to produce the mean axis-ratio relation, a various fitting methods such as linear or polynomial (twice-, third-, fourth-order) fit were tried. As a result, the third-order polynomial relations were 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.

Q6) Page 8, ll.13: Can the Authors defend the choice of using Dmax=7 mm in the T-matrix simulation instead of using the maximum drop diameter measured by 2DVD in each DSD?

A6) The mean axis-ratio relation is necessary to calculate the complex scattering amplitudes of raindrops in the T-matrix simulation. This mean axis-ratio relation is based on 2DVD measurement data. Therefore, the effective diameter (D_{max} = 7 mm) of mean axis ratio relation is used for simulation of T-matrix.

Q7) Table 3: Please note that some correlation coefficients of Table 3 are very poor (0.01) please cheak this values.

A7) we change 0.10 to 1.00.

Q8) Page 10, ll.5-6: "This means that raindrops in South Korea are more oblate than the others." Please rewrite this sentence, it is "too strong". I think that there are not enough information to justify it.

A8) The manuscript has been revised as follows:

After

"These differences of raindrop shape can be caused by a variety of reasons, such as instrumental effects, fitting method, event selection, and different climatic regimes.

Q9) Page 10, ll.21: "Corr=0.01". Please check this value.

A9) The manuscript has been revised as follows: 0.10 ⇒ 1.00

Q10) Table 3: In terms of MAE, RMSE and corr., it seems that the use of different axis-ratio does not have a huge influence in particular the use of "new axis ratio" (that is optimized for the area) does not highly improve the three statistics. Can the Authors defend this issue?

A10) Although, correlation coefficient according to the different axis ratio assumption are not significantly different, MAE and RMSE are showing differences in the polarimetric rainfall algorithms based on Z_{DR} and K_{DP} related to raindrop shape. These statistical differences can lead to a difference in coefficients of polarimetric rainfall relations. As your say, the use of new axis ratio does not highly improve the three statistics, however, the statistic of scatter showed the best result when using the $R(K_{DP}, Z_{DR})$, and the $R(K_{DP}, Z_{DR})$ based on new axis ratio showed the best performance.

Q11) Page 11, ll.11: Why the statistical validation has been performed only on 18 events. How do you choses them?

A11) We chose a continuous rainfall event for the continuity of measurement data. In other words, time of observation is short and unstable rainfall events were excluded from the analysis.

Q12) Table 4: As for Table 3, also in this case the use of the "new axis ratio" does not produce a high improvement, in particular with respect to the relation of Pruppacher and Beard (1970). Please comment this issue.

A12) First, axis ratio relation from Pruppacher and Beard (1970) used here is a linear relation, and new axis-ratio experimental fit is derived as third-order polynomial function. As you say, Table 4 show that, 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 R from specific differential phase measured by dual-polarization radar, it is useful to have a linear equation between the mean axis ratio and drop diameter."

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.

Q13) Page 12, ll.1-2: the sentence is not clear to me. Which are the "DSD results"? How the Authors can say that, based on the results provided, "K_{DP} is less sensitive to DSD variation and uncertainties in raindrop shape"? Please explain in more detail

A13) The word "DSD results" means statistical results for 2DVD rainfall estimation, and we wanted to say that, the accuracy of the rainfall estimation improved when the K_{DP} parameter was used for 2DVD rainfall estimation. However, as your comments, this is misleading, so sentence has been revised as follows:

After

"In the single rainfall relation with Z_h (Figure 7a), an amount of scatter is present (MAE=0.95 mm h^{-1} and RMSE=1.23 mm h^{-1}), and the scatter decrease (MAE=0.70 mm h^{-1} and RMSE=0.92 mm h^{-1}) when the K_{DP} parameter was used for 2DVD rainfall estimation (Figure 7b). 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 $R(Z_h)$.

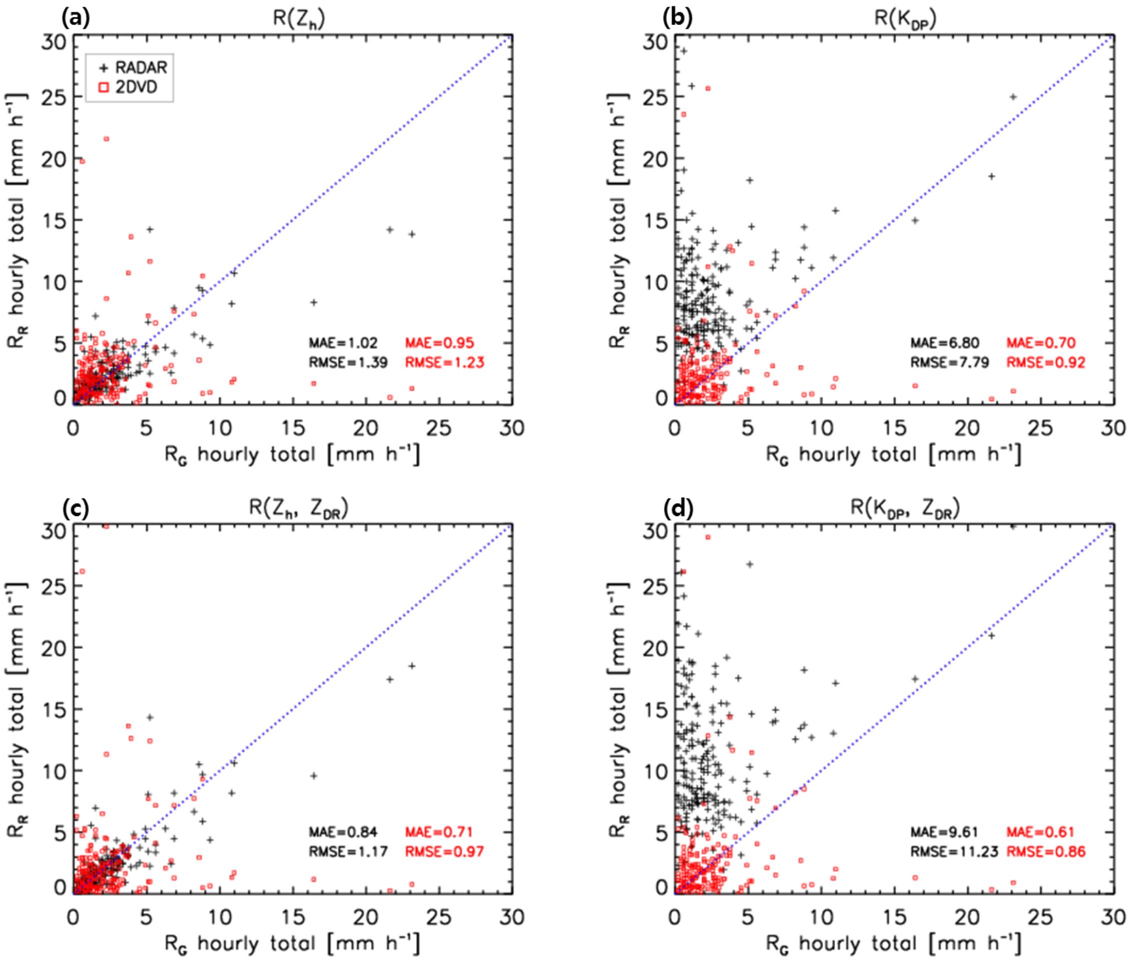

Figure 7. Scatter plot of one-hour rain rate from rain gauge (RG) and BSL S-Band radar (or 2DVD) based on Eq. (4) for 18 rainfall cases: The pluses represents one-hour gauge rain rate versus radar hourly rain rate from polarimetric rainfall algorithms, and squares indicate gauge and 2DVD rain rate by different polarimetric rainfall algorithms.

Q14) Page 12, ll.7: I suggest to shows some plots regarding the performance of the algorithms for R > 5 mm/h

A14) We tried to explain the phenomena K_{DP} noise is reduced as rain rate increases (> 5 mm/hr), and combined polarimetric rainfall algorithm using K_{DP} better than $R(Z_H)$ and $R(Z_H, Z_{DR})$ for estimated rainfall at higher rain rates (> 15 mm/hr). However, this sentence is misleading it was excluded from the paper. Also, the manuscript has been modified.

Q15) Page 12, ll.9-10: This is known in the literature (such as Vulpiani et al. 2015 among others), please provide some reference.

A15) I have attached one reference: Ryzhkov et al. (2005), Vulpiani et al. 2015

Q16) Page 12, ll. 11-15: "The polarimetirc rainfall relations based on the new axis-ratio relation also were better than the others". Please explain how you can say that they are better. I think that this paragraph is about a crucial issue however it is not clear to me. I suggest to rewrite in order to explain the improvement of the new axis ratio in the rainfall retrieval.

A16) The manuscript has been revised as follows:

When using the new mean axis-ratio relation, R(K_{DP}, Z_{DR}) is showing good results on 2DVD rainfall estimation and R(Z_H, Z_{DR}) is showing best performances on radar rainfall estimation. However, 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). Althought the difference in the value of the statistics seems small according to mean axis-ratio relations, it can lead to significant errors in the estimated DSD and rainfall rates (Bringi and Chandrasekar 2001). Therefore, consideration of rainfall characteristics is necessary to improve the polarimetric rainfall algorithm.

Q17) Section 4.2.3: I think that the world "calibration" is misleading, the procedure explained in the paragraph is not really a calibration procedure, in my opinion it is more an adjustment of radar variables based on a ground truth (2DVD data). Pleas reformulate it. Moreover, the Authors did not compute the "calibration bias" for K_{DP} why?

A17) The reflectivity factor is affected by the absolute calibration error, and it require accurate knowledge of the radar constant. And differential reflectivity is independent of absolute radar calibration. These calibration errors can be calculated by various ways (Atlas 2002), it is commonly referred to as the "calibration of radar". In this study, we calculate daily Z_h and Z_{DR} calibration biases using the 2DVD data. This is adaptive calibration, in general the adaptive bias is more effective 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). K_{DP} is independent of the absolute calibration error, attenuation because it is related to the phase shift of the electromagnetic wave. Therefore we did not compute the K_{DP} calibration bias.

Atlas, D.: Radar calibration: some simple approaches, Bull. Amer. Meteor. Soc., 83, 1013-1316, 2002.

Kwon, S., Lee, G. W., and Kim, G.: Rainfall Estimation from an Operational S-Band Dual-Polarization Radar: Effect of Radar Calibration, J. Meteor. Soc. Japan., 93, 65-79,2015.

Q18) Page 12, ll.18: Why do you use only 8 events for this analysis? Can you use all the 18 events selected for the validation? I noticed that in the 8 selected events there aren't convective events. Why?

A18) To achieve accurate calibration bias of radar, the process of calibration bias should be performed in continuous and stable rainfall systems. Therefore, time of observation is short and unstable rainfall events were excluded.

Q19) Page 12, ll.19-21: This is just a suggestion. Instead of doing two scatterplots for each event (namely Figure 8c and d for one event and Figure 9c and d for another one) the Authors can plot the results for all the events in two graphs (one for Z_h and one for Z_{DR})

A19) I appreciate the suggestion. I'll take it into account.

Editorial remarks:

Q1) Page 1, ll.16-17: "The shapes of raindrops have a direct impact on rainfall estimation". Although the sentence is correct in my opinion it is necessary to add that also the number, the dimension (diameter) and fall velocity of the raindrops play a central role.

A1) 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 1, ll.20: I suggest to write "raindrop size distribution". Instead of "raindrop shapes"

A2) We change "raindrop size distribution" to raindrop shapes

Q3) Page 2, ll.2: what does it means "DSD statistics"? There worlds are used several times in the manuscript, but it is not clear the exact meaning. Please clarify it.

A3) "DSD statistics" means the statistical results of the precipitation derived from the 2DVD data.

Q4) Page 2, ll.24-25: "This is because the shape of raindrops is one of the most sensitive parameters for representing the DSD properties of the rain". Please consider to reformulate this sentence or to put one or more reference. There are other important parameters (e.g. diameter, number of drops etc) that should be mentioned.

A4) The manuscript has been revised as follows:

After

"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 3, ll.7-10: Please check this sentence, single polarimetric radar does not provide Z_{dr}

A5) we change "single polarimetric radar" to "polarization radar"

Q6) Page 3, ll.24: I think that "four" should be substitute to "three"

A6) we change "four" to "three"

Q7) Page 6, ll.3-4: This sentence should be moved to page 5 line 25 after "...Atlas et al. 1973)". Furthermore it is not clear the meaning of "the normal distribution". Please reformulate it.

A7) As your comments, "The value outside…" sentence was moved to page 5 line 25, and "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.

Q8) Page 7, ll.13-14: similar to my previous comments, I think that the sentence "this relation is one of the most sensitive parameters for representing the rainfall properties" is "too strong". Can you provide some references or reformulate it?

A8) The manuscript has been revised as follows:

After

"The mean raindrop shape is related to the precipitation type, regional and climatological conditions, and it affects rainfall rates derived from polarimetric radar measurements.

Q9) Table 5: check the format of the date.

A9) We have modified the Table 5

References:

Vulpiani, G., L. Baldini, and N. Roberto. "Characterization of Mediterranean hail-bearing storms using an operational polarimetric X-band radar." Atmospheric Measurement Techniques 8.11(2015): 4681-4698