Overall Response: We sincerely thank you for the comments that help to improve our paper. The responses to the comments are as follow.

Comment 1): *Several challenges affect radar QPE besides calibration of radar moments: ground clutter, beam blockage in complex terrain, vertical structure of precipitation, partial beam filling. . . A discussion of these issues and how they are handled in the present study is required.*

Response 1) In this study, the ground clutter was removed by WRC's QC method based on fuzzy algorithm. We also cannot avoid the problem of the beam blockage because 70% of Korean territory is covered with mountains. However, the method in this study cannot solve the beam blockage and we give a description about the beam blockage in line 18 ~ 20 of page 7 and line 1 of page 10. Of problems caused by vertical structure of precipitation, the bright band of stratiform rain can overestimate radar rainfall. In this study, we try to avoid this problem by using 1.5km CAPPI and describe why we use 1.5km CAPPI in second paragraph of page 5. The problem of partial beam filling can be handled in the signal process. We cannot handle the partial beam filling because this study used the moment data after the signal process. We agree your comment that above sources of error can affect radar QPE. So we will give a description about the sources error and the QC method like below.

Revision 1a): (Second paragraph of section 3.1) QPE can be affected by ground clutter, beam blockage, vertical structure of precipitation in the case of stratification, beam filling, etc. The input data in this study therefore was made using post quality control (QC) processed data which is removed ground clutter, corrected beam blockage and identification of non/meteorological echoes by WRC's QC method based on fuzzy algorithms (WRC, 2015). In the empirical method, the primary input data for rainfall estimation was the CAPPI data of the YIT radar at 1.5 km in height. The CAPPI data was used as the main input data, because the impact of the bright band (or melting layer), which is often formed about 4–5 km in height for the cases considered in this study, can be avoided. In addition, it is assumed that hydrometeors at this height are purely rain because they are under the melting layer.

(First paragraph of section 4.1) Like the YIT radar data, the BRI, BSL and SBS radar data was also data quality controlled by WRC's QC method based on fuzzy algorithms, which includes removal of ground clutter, correction of beam blockage and identification of non/meteorological echoes (WRC, 2015).

Comment 2): *The methodology is not clear on how the adjustment of radar moments is performed and what constraints are used.*

Response 2): We have been working on enhancing the section 2 with further detail explanation and figures. Also the constraint of the method is explained in the section.

Revision 2):

(1) We will revise the figure 1 and also add below sentence.

-> Fig. 1 show each step of adjustment process in the empirical method.

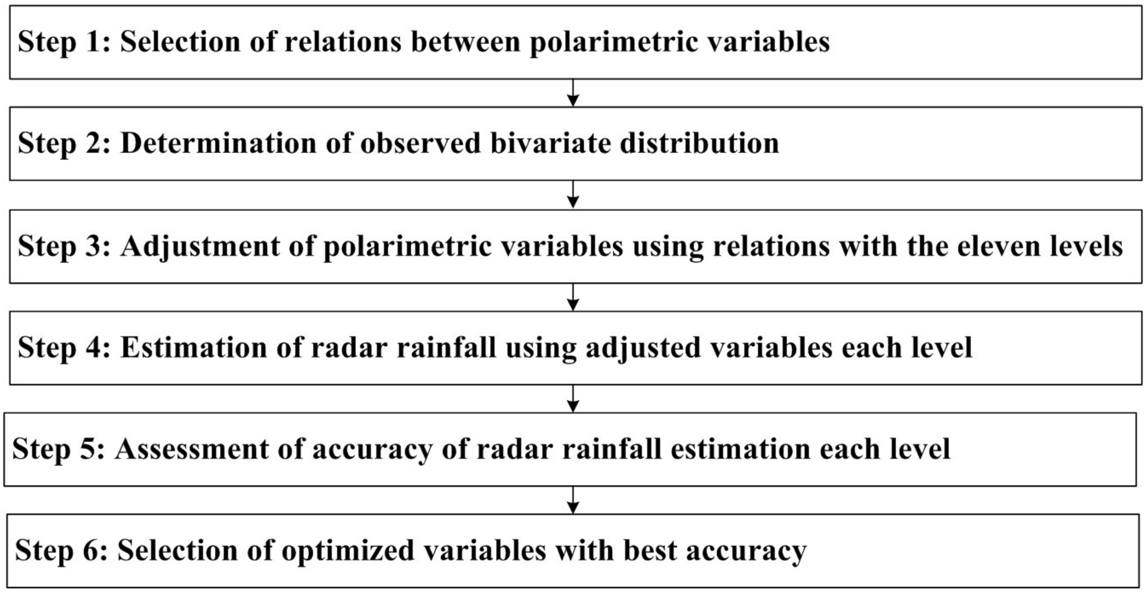


Figure 1. Flow chart of empirical method

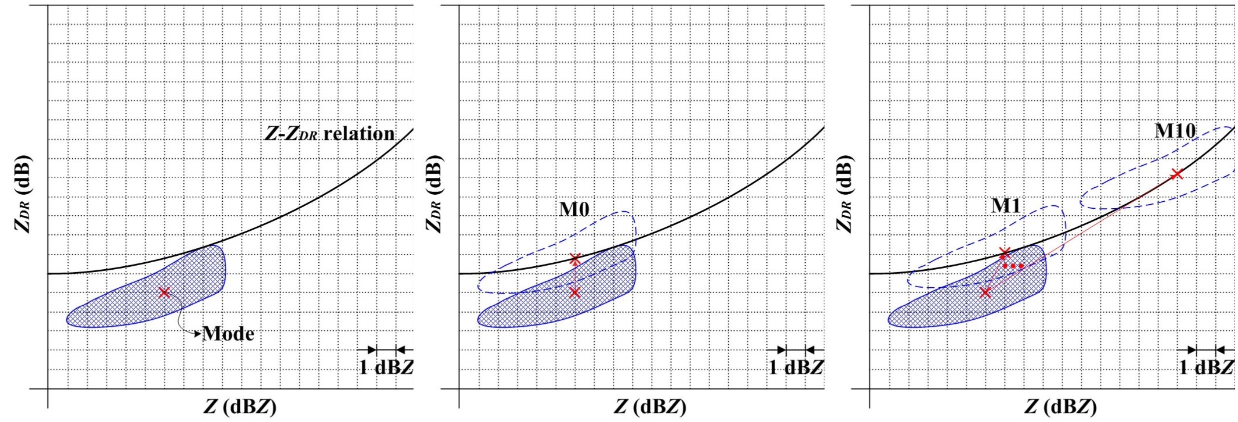
(2) We changed a word, 'derives' to 'selects' in Step 1. In fact, we just select derived reference lines in Step 1. Any reference lines can be selected but we choose the reference lines to reflect microphysics of precipitation in Korea. So we used the reference lines derived from the 2DVD in Korea. Therefore we will revise the first paragraph in Step 1 of section 2.

-> This step selects the relations between polarimetric variables from ground measurements. The WRC installed a two-dimensional video disdrometer (2DVD) at a ground observation station in Jincheon (hereafter Jincheon station). The 2DVD was installed to verify the polarimetric variables obtained by the YIT radar as well as to define microphysics of precipitation in Korea, particularly the its change due to climate change which has already shows changes on occurrence, intensity and features of precipitation, specifically during summer. The relations between polarimetric variables used in this study were derived using the 2DVD based on the first year observation. In order to derive these relations, the WRC (2014) conducted experiments for 22 storm events that occurred during the summer of 2014. Two relations, the $Z - Z_{DR}$ relation (Eq. (1)) and $Z - K_{DP}$ relation (Eq. (2)), were suggested by the WRC (2014) (Fig. 2). Any relations can be selected but below relations that reflect microphysics of precipitation in Korea are selected in this study.

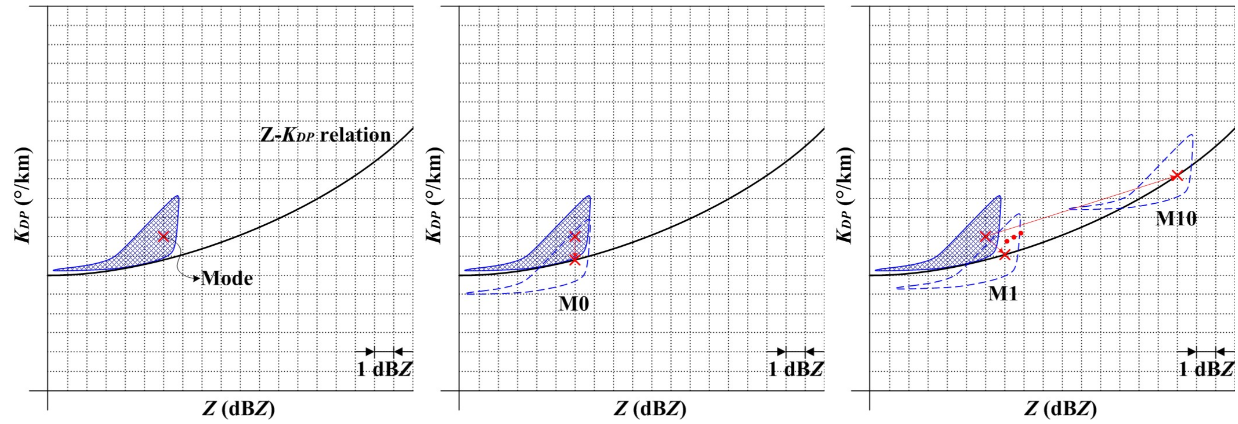
(3) We will revise Steps 2 and 3 of section 2 and add a figure as Fig. 3.

-> Step 2, which determines the observed bivariate distribution, and Step 3, which adjusts the polarimetric variables using the reference relations, are explained together as they are closely linked. Fig. 3 is a schematic diagram which show how to adjust the polarimetric variables. First, two bivariate distributions of $Z - Z_{DR}$ and $Z - K_{DP}$ observed by the radar are determined as a hatched area in Fig. 3(a). Next, the most frequent value (mode) in the observed bivariate distribution which is the mark of X in the hatched area has to be found. Then, the bivariate distributions move but the modes are constrained to be on the reference relations so that they occur in the dashed region.

It is, however, uncertain where the adjusted modes would occur on the line of the relations along the adjustment processes. Therefore, a degree of adjustment must be considered. Eleven levels of adjustment magnitude from 0 (M0) to 10 (M10) are used. At level M0, there is no bias in Z and the modes will vertically shift along the Y-axis (Fig. 3(b)). In this case, Z_{DR} and K_{DP} are either increased or decreased in order that the mode of the observed bivariate distribution falls on the reference relation. In other cases where Z has bias, this bias can vary because of environmental factors such as temperature or humidity that impact radar performance and measurements. In this case, Z is increased from 1 dBZ (M1) to 10 dBZ (M10) in intervals of 1 dBZ and also Z_{DR} and K_{DP} are either increased or decreased (Fig. 3(c)).



(a)



(b)

Figure 3. Schematic diagram of observed bivariate distribution (left panel) and bivariate distribution shift (middle panel: Z has no bias, right panel: Z has bias): (a) $Z - Z_{DR}$ space and (b) $Z - K_{DP}$ space

Comment 3)

Are the ground measurements from one disdrometer used to derive relations between polarimetric variables representative spatially and temporally (only one summer used)? Could we expect any variations in disdrometer-derived relations according to the precipitation microphysics associated with different seasons or rain types (convective, stratiform) for example?

Response 3): Recently, precipitation pattern in Korea changes due to climate chang. Therefore KMA installed the first 2DVD in 2014 to observe the change of precipitation microphysics and obtain the polarimetric variable relation. KMA will continuously develop the polarimetric relation in the mid-latitude region. We only consider summer season because the high rainfalls in Korea which can occur disaster are mostly concentrated in summer season. So, the variability due to the different seasons is not expected. The relations in section 3, however, were derived from the 2DVD data during only one summer (22 storms) and the relations in section 4 were complemented by adding the 2DVD data (73 storms). Naturally, the variability due to the rain type can occur because the relations were derived from only one or two year data and only one point data. More relations according to the rain type have to be derived by installing more 2DVD and accumulating the 2DVD data to solve this problem. Also, it needs to examine the variability due to the rain type in the future because the 2DVD in Korea is installed recently and the data is also not enough. We agree that the variability due to the rain type can occur as your comment. So, we will add below sentence in conclusions.

Revision 3): The variability due to the rain type can occur because the relations were derived from only one or two year data and only one point data. More relations according to the rain type have to be derived by installing more 2DVD and accumulating the 2DVD data to solve this problem. Also, it needs to examine the variability due to the rain type in the future because the 2DVD in Korea is installed recently and the data is also not enough.

Comment 4): *How are these disdrometer-derived relations affected by the large resolution difference between the disdrometer and the radar observations?*

Response 4): We did not compare the polarimeric variables from 2DVD with the polarimeric variables from radar. We adjusted the polarimeric variables from radar on Z-ZDR and Z-KDP spaces using the disdrometer-derived relations. So, the resolution difference doesn't affect the relation. Naturally, the resolution of the radar can affect the magnitude of the best accuracy.

Revision 4): There is no revision.

Comment 5): *Comparison of radar estimates with raingauge measurements provides indication of the pertinence of the different processing techniques employed. However the evaluation is not well developed, for example classical criteria are not used (e.g. bias, correlation, root mean square error). The abstract mentions an improvement but only a number is provided without details on the score used to assess this improvement*

Response 5): We will add some criteria, mean error (ME), root mean square error (RMSE) and correlation (CC) and revise tables 4 and 6 like below.

Revision 5):

Table 4. Magnitude (M) obtains the best accuracy and statistical measures of radar rainfall estimations using the observed ("Before") and optimized ("After") polarimetric variables for three events

Event	Algorithm	M	1-NE (%)		ME (mm/hr)		RMSE(mm/hr)		CC	
			Before	After	Before	After	Before	After	Before	After
1	*R*1	4	56.9	66.9	-0.63	-0.22	1.17	0.90	0.75	0.77
	*R*2	5	62.8	71.4	-0.55	-0.24	1.01	0.81	0.80	0.83
	*R*3	5	49.3	70.6	-0.75	-0.18	1.27	0.82	0.74	0.82
2	*R*1	9	31.7	76.1	-3.61	-0.59	5.94	2.44	0.85	0.93
	*R*2	8	44.7	75.2	-2.95	-0.64	4.93	2.63	0.86	0.92
	*R*3	7	41.8	75.7	-3.21	-0.65	5.02	2.46	0.84	0.93
3	*R*1	9	40.6	72.8	-4.54	-0.00	9.01	4.05	0.79	0.92
	*R*2	8	38.9	68.5	-4.72	-0.50	9.27	4.94	0.74	0.88
	*R*3	7	57.9	73.6	-3.03	0.04	6.45	4.15	0.85	0.92

Table 6. Statistical measures of the radar rainfall before and after the adjustment (from May to Oct 2015)

Radar	Algorithm	1-NE (%)		ME (mm/hr)		RMSE(mm/hr)		CC	
		Before	After	Before	After	Before	After	Before	After
BRI	*R*1	40.8	65.7	-1.92	-0.54	3.96	2.46	0.70	0.84
	*R*2	33.3	66.0	-2.33	-0.46	4.34	2.48	0.69	0.84
	*R*3	37.9	67.6	-2.18	-0.46	3.90	2.37	0.75	0.85
BSL	*R*1	47.9	68.1	-1.52	-0.54	2.94	1.93	0.74	0.84
	*R*2	37.3	70.5	-2.00	-0.46	3.55	1.80	0.60	0.87
	*R*3	41.4	67.8	-1.84	-0.40	3.18	1.90	0.70	0.86
SBS	*R*1	38.6	69.4	-1.97	-0.60	3.70	2.18	0.75	0.87
	*R*2	57.8	68.9	-0.61	-0.38	2.95	2.23	0.77	0.86
	*R*3	38.5	70.0	-2.00	-0.41	3.59	2.05	0.74	0.89

Comment 6): *There is no mention of the sampling difference between radar and raingauges. For comparison it would be useful to give some elements about the spatial representativity of raingauges measurements at the considered time step, and how they match the QPE spatial resolution.*

Response 6): There is the sampling error because observing method of the radar differs from the gauge and many researcher examined the sampling error. In this study, we used 60 min accumulated rainfall to minimize the temporal sampling error. Also, rainfall estimation values of a centroid radar grid and eight surrounded grids were compared to the gauge rainfall to minimize the spatial sampling error. Among the nine values, the best matched value was taken accounted into the calculation of the rainfall estimation accuracy. So we will add a figure as figure 4 and give a description about the sampling error in Steps 4 and 5 of section 2.

Revision 6): When the accuracy of the radar rainfall is assessed, temporal and spatial sampling error can occur because the accuracy of the radar rainfall was calculated in the comparison with rainfall records of the raingauges. In this study the rainfall rates estimated by the three algorithms accumulated for 60 minute to minimize the temporal sampling error. Also as precipitation echoes are moving and wind impacts on the direction of falling raindrops towards ground, it is not easy to have exactly matched value for each grid (1 km × 1 km) with rainfall record of the raingauge. With this reason, hourly rainfall values of a centroid grid and eight surrounded grids were compared to the rainfall record of the raingauge (Fig. 4). Among the nine values, the best matched value was taken accounted into the calculation of the hourly rainfall accuracy to minimize the spatial sampling error. The accuracy of the hourly rainfalls was assessed using the Eq. (3) for each magnitude. Values approaching 100 % indicate a better rainfall estimation. The normalized error (NE) quantifies the absolute error, and maximum $1 - \mathrm{NE}$ indicates minimized errors for both bias and random error.

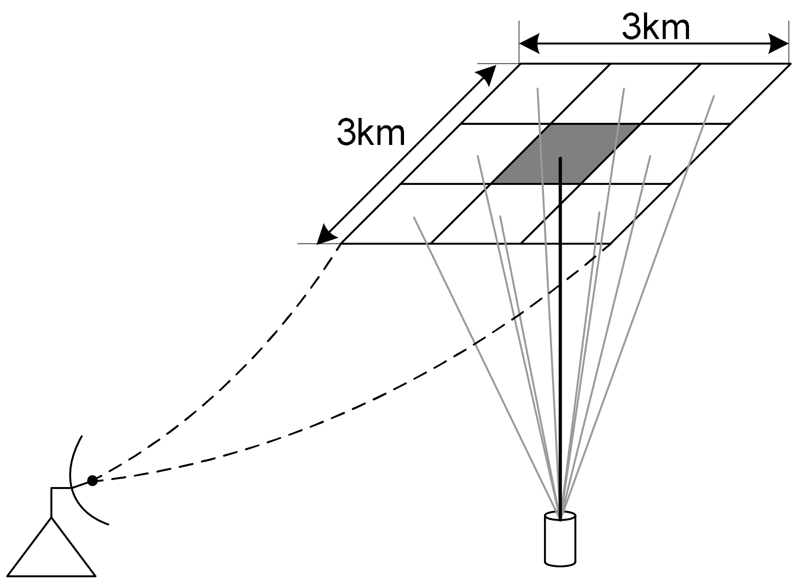


Figure 4. A centeroid grid matched to a raingauge and eight surrounded grid

Comment 7): *Regarding the raingauge data, is data control performed?*

Response 7): The gauge rainfall is quality controlled by KMA's method that uses the data of 95 percentile. So we will give a description about the KMA's method in sections 3.1 and 4.1 like below.

Revision 7): The used AWSs are only operated by KMA and all data were quality controlled by KMA's method (WRC, 2015).

WRC (Weather Radar Center): Development of application techniques for the harmonization of cross governmental radar (II), Seoul, Korea, 412 pp. , 2015.

Comment 8): *A discussion on the operational applicability of this method would be welcome.*

Response 8): The empirical method in this study is still being developed. We plan to develop the method until finishing KMA's dual-polarization radar network in 2019. Also, applicability of the method for the operational radar will be determined after overcoming the limitation of the method. So we will give a description about the operational applicability of the method in conclusion like below.

Revision 8) This study shows that the empirical method to adjust polarimetric variables using the referential relations suggested by WRC is a reliable method for overcoming measurement biases in dual-polarization radars for rainfall estimation. It will be useful for quantitatively improving the rainfall estimation of newly install radars, as establishing optimal or reliable quality control algorithms on new radars such as the YIT radar takes long time. In addition, the empirical method could be useful for improving the accuracy of radars operated by different agencies. Nevertheless, there is still much room for improvement in the method, particularly for radar measurements with partial beam blockage and severe systematic biases. The variability due to the rain type can occur because the relations were derived from only one or two year data and only one point data. More relations according to the rain type have to be derived by installing more 2DVD and accumulating the 2DVD data to solve this problem. Also, it needs to examine the variability due to the rain type in the future because the 2DVD in Korea is installed recently and the data is also not enough. Thus, this method will continue to be developed through applications to more varied precipitation types and real-time adjustment of the polarimetric variables in the near future.