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Atmospheric Measurement Techniques Discussions

Interactive comment on "Retrieval of the raindrop size distribution from polarimetric radar data using double-moment normalisation" *by* Timothy H. Raupach and Alexis Berne

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This document provides responses to reviews of our manuscript AMT-2016-301-RC1. A version of the manuscript with text changes highlighted is attached as a supplement to this comment (changes to references, tables, and removed text are not highlighted). The main changes that have been made are summarised as follows:

1. Some relevant references were added to the introduction.
2. Relationships between radar variables, and the parameters of the generalised gamma distributions used for the double-normalised DSD models, are now trained using all three data sets combined. The result is better performance of the

suggested technique on the Payerne and Iowa data sets, and a slight reduction in performance for low-order moments in the HyMeX data set. In accordance, instead of training on HyMeX data and applying the technique to the other data sets, we now split all Parsivel data into training (60%) and validation (40%) sets.
3. A second power-law fit for prediction of DSD moment six from radar reflectivity when Z_H is low has been added, and both fits are now made using an orthogonal fitting procedure in log-log space.
4. The method for predicting moment three of the DSD has been updated for better accuracy. The updated method removes the requirement for a threshold on Z_H. In general, the new moment three and six predictions result in the DSD-retrieval technique performing better, especially for higher-order DSD moments.
5. The threshold value on Z_H for the prediction of DSD moment six has been updated and better justified in response to reviewer comments.
6. Instead of using the raindrop axis ratio of Thurai and Bringi (2005), we use the newer relationship of Thurai et al. (2007) in its place. The performance of SCOP-ME is better with this newer axis ratio function, and therefore comparisons between the proposed and existing techniques are fairer.
7. We now include all available Parsivel instruments instead of using only the best-performing station when instruments are collocated.

In the following sections we address all reviewer comments and explain which changes were made in response to each one.

1 Reviewer 1

We thank reviewer 1 for the constructive comments, and respond to each one below.

1. **Reviewer:** *In this paper, the authors present a new technique to estimate the raindrop size distribution and its parameters directly from polarimetric radar measurements. As already highlighted in the quick report, the present work can be of particular interest for the radar meteorologist scientific community. The logic flow of the conducted analysis is well exposed. The main revision points refer to the presentation of the results. The tables are very useful, while the figures are sometimes a bit small and it is difficult to easily distinguish dots, lines (i.e. in Figure 2 is difficult to distinguish the retrieved and measured rain rate time series). I suggest to increase the figure size where it is possible.*

   Response: We have reviewed the size of the figures, their text and symbols.

   Changes: Where possible we have increased the figure size and adjusted symbol sizes. The changes made to each manuscript figure are:

   - Figure 1: Text size and symbol size have been increased, and the threshold point has been made clearer.
   - Figure 2 has been removed, since the SCOP-ME and double-moment technique results are close enough to be difficult to distinguish.
   - Figure 3 (now Figure 2): all combinations of data set and axis ratio function are now shown. Text size and figure size have been increased.
   - Figure 4 (now Figure 3): instead of a scatter plot we now show densities of measured vs. recovered values. Because it is not possible to overlay two densities, and the differences between the two techniques are best shown using the regression lines, we show the densities only for the double-

     moment technique. Regression lines are then shown for both techniques. The figure size and text size have been increased.
   - Figure 5 (now Figure 4): Text size has been increased.
   - Figure 6 (now Figure 5): Text size has been increased, and now we show results for SCOP-ME using raw and noise-corrected data.
   - Figure 7 (now Figure 6) and Figure 8 (now Figure 7): Text size has been increased.

2. **Reviewer:** *As general comment, at least in one out of the three datasets (it is not well explained if the HyMeX dataset is provided by Parsivel first or second generation), the authors use the Parsivel first generation data. Has been demonstrated the better performance of Parsivel second generation (Parsivel2) with respect to the first generation (Tokay et al., 2014 ,JTECH). Even if the authors, using the Raupach and Berne 2016a,b approach to correct the Parsivel data, this could affect the goodness of the results.*

   Response: We agree that information on the HyMeX network was missing, and that the Parsivel^2 provides better performance than the first-generation Parsivels. The HyMeX data set is a mixture of the first-generation and Parsivel^2, the Payerne data set is composed only of first-generation instruments, and the Iowa data set includes only Parsivel^2. Our method is thus trained on a combination of first-generation and Parsivel^2 data. It is difficult to precisely determine the effect of our use of (corrected) first-generation Parsivel data on our results, but given that the technique is now trained on all three data sets combined we assume that the greater number of Parsivel^2 disdrometers now included will increase the representativeness of the trained approach.

   Changes: Specified the details about the HyMeX network and added a note about the limitations of Parsivel instruments to Section 4.

3. **Reviewer:** *The simulation of the radar variable from disdrometric measurements to test the efficiency of the proposed technique with respect to the common used technique is particularly appreciated and useful. In the Section 5, they describe the difference between Rayleigh and Mie scattering region as function of the raindrop size at X-band frequency. They put a threshold at ZH=35 dBZ to discriminate the two regions by using the HyMeX Parsivel data only. What about the other two datasets? If they apply the say procedure, do they obtain the same threshold? There may be a climatic dependence on this threshold (i.e. the same reflectivity can be obtained by different DSD with a higher (lower) number of smaller (larger) drops respectively, which fall in the Rayleigh or Mie scattering region).*

   Response: To further generalise our proposed method, we now train the technique using combined data from the three training sets (HyMeX, Payerne, and Iowa). Also, moment six of the DSD is now predicted from Z_h on both sides of this threshold, instead of simply taking it to be equal to Z_h under the threshold. To choose the threshold we compared relative bias, IQR of relative bias, and squared correlation r^2 between Z_h [mm^6 m^{-3}] and M_6 by classes of Z_H [dBZ] between 10 and 40 dBZ with a class width of 2 dBZ. Z_h in all three regions departed from M_6 between 24-30 dBZ; HyMeX and Payerne data sets showed a drop in r^2 for the 24-26 dBZ class, while Iowa showed a sharp drop in r^2 in the 28-30 dBZ class. We used the threshold from the combined data, which showed a drop in r^2 at 28 dBZ. This particular threshold has been updated to 28 dBZ in the revised version of the paper.

   Changes: Threshold updated to 28 dBZ.

4. **Reviewer:** *From Figure 1 in linear scale, it is almost impossible to individuate*

ZH=35 dBZ (3.16e+03 mm^6 m^{-3}). I suggest to change the linear to dBZ scale.

   Response: We agree that the threshold point was too difficult to distinguish.

   Changes: The plot has been changed to radar reflectivity in dBZ, and the threshold point has been updated to 28 dBZ indicated with a larger symbol in blue and white.

5. **Reviewer:** *Figures 2-4. I suggest to increase the size of the plots. Even the dots size (especially for Figure 3) can be slightly decreased to a better interpretation of the figures.*

   Response: We have reviewed the figures and increased their sizes, and reduced the size of the points in Figure 3 (now Figure 2). Please see the response to point 1 above for details about each figure.

6. **Reviewer:** *Page 12. This is probably the most confusing part of the paper for the results interpretation. I clearly understand the summarize in only one figure the big amount of results is not easy, but some point arise reading this part. It could be useful for the reader, that the authors recall in the text the explanation of the Figure 5 and Table A1 and A2, which they give in the captions as well as the indicators used (relative bias, IQR of relative bias, correlation coefficient and slope of fit). They also show in Figure 5 the difference in performance between the double-moment technique and SCOPE-ME highlighting the cases where a method outperforms the other. On the other side, Table A1 reports also the absolute values of the considered indicators. I suggest to add this information at least in the Table A2. It is important to show which technique gives the best results, but it is equal (or more) important to know how far is the estimation from the measurement parameters.*

Response: We agree on the importance of showing the performance of each technique as well as their differences. In the previous version of the paper we tried to limit the number of tables by showing only differences for Payerne and Iowa datasets. In response to this reviewer's comment we now include all results in the appendix, thus showing the performance of both techniques in all three regions. The tables are provided in an appendix since differences are summarised in the text and Figure 5 (now Figure 4). The metrics used are explained in the text in Section 6, as well as in the table and figure captions.

Changes: Updated explanations of Figure 5 (now Figure 4) and the performance statistics used. Replaced Table A2 with two tables of results, for the Payerne and Iowa data sets respectively, which become Tables A2 and A3. Table A4 now contains all performance statistics instead of only differences.

7. **Reviewer:** *Page 8-line 13 and page 10-line 15: the authors say that they simulate the radar variables "for the MXPol stacked PPI incidence angles" and "for an elevation angle of 4°". Is the radar incidence angle really a input parameter in the T-matrix code? I retain that the incidence angle does not infer the simulation of the radar variables from disdrometer data. Please clarify this point.*

   Response: The incidence angle is an important input to the calculation of polarimetric radar variables from the DSD. As one example, Z_{DR} at 90° (vertical incidence) is 0 dB because the reflectivity in horizontal and vertical polarisations is the same. At 0° incidence with larger raindrops present, the oblateness of the large drops is apparent and Z_{DR} is larger than 0 dB.

8. **Reviewer:** *Page 13. Table 3 summarizes the performance difference combining all the Parsivel data and the four axis ratios used. The authors are combining*

data collected from "different" instruments (same physical base but different version). It could have more sense combining the data collected from the same instruments. Moreover, as they report in lines 5-8, the different axis ratio gives different results (with the Thurai function, the double-moment outperforms the SCOPE-ME, while the opposite is true when the Brandes function is used, etc.). Averaging over the axis ratios, there may be a sort of compensation in the results. My opinion is that could be more interesting just to show the difference for each axis ratio but averaging over the three regions (much better if the considered data are collected by the same instrument as already said). This could give an indication about a climatological dependence of the results.

   Response: In Table 3 (now Table A4, the comparisons of DSDs retrieved from PPI data to MRR and Parsivel measured DSDs) there is no averaging over axis ratios. We chose to use one axis ratio that performed well (Thurai 2007) and use it for the double-moment technique in all PPI retrieval comparisons. Perhaps this was not made clear enough in the paper. We understand the reviewer's point about the different instrument types (or versions), but the two regions of Iowa and Payerne already split up the instruments into types, since the Iowa data was only Parsivel^2 and Payerne contained only first-generation Parsivel. The HyMeX data set contains both first-generation and Parsivel^2 disdrometers, but the correction procedure we apply to both is designed to make them more comparable (with reference to a 2DVD). The MRR data is always treated separately. Since we are not averaging over axis ratios, and since the two regions split the data into instrument types anyway, we prefer to leave the results in the same format.

   Changes: Table A4 now contains not just differences but all performance statistics for both techniques, in order to respond to this reviewer's point 6.

9. **Reviewer:** *Figure 8 and Table A3: the results show that when the double-*

moment technique is applied to the radar data, the improvements with respect to the SCOPE-ME are not so evident as much as when the technique is applied to the radar variable as simulated from disdrometers. Can the authors tell something about this?

Response: There are a large number of other factors at play when the DSDs are retrieved from real PPI data, as compared to simulated radar variables from disdrometers. Using real radar data, there is the change of support problem that increases the error bar size, vertical distance between PPI-measured locations and ground-based instruments, and the noise in the radar data. All these factors combine to effect the performance of both DSD retrieval techniques, leading to greater uncertainty around the comparisons made using real radar data than those made using simulated radar variables from disdrometer data. This larger uncertainty tends to smooth out the differences between the two methods.

Changes: Notes about the vertical distance and change-of-support problem were both in the paper, but were in separate places; these have been put together in the introduction to Section 8, together with a note about the greater uncertainty when using PPI data.

10. **Reviewer:** *Page 17-lines 2-4: please explain better the two sentences.*

    Response: These sentences related to the generalised gamma model parameters and drop size classes used for DSD retrieval to compare to MRR data.

    Changes: The sentences have been re-written to include new details and are, we hope, clearer.

2 Reviewer 2

We thank reviewer 2 for the useful comments and we respond to each one below.

1. **Reviewer:** *Fig. 3: The authors didn't justify the large values (larger than 5mm) of measured Dm in Fig. 3, which are probably erroneous. Such large values come to clear contradiction with the note from authors in another comment on the effect of truncation limits of DSD on results that drops above 7 mm in diameter are rare. By excluding such unrealistic large Dm values in Fig. 3 the correlation of the two estimation methods with measured values changes.*

   Response: We assume the reviewer was referring to Figure 4 (now Figure 3), the scatter plots. These large values of D_m are very rare. While rare, such values do arise when using empirical and not modelled DSDs, even when the DSDs are truncated at 7 mm. In the Parsivel data sets, there were 0.018%, 0.005%, and 0.014% of D_m values above 5 mm in the HyMex, Payerne, and Iowa data sets respectively. These DSDs passed our quality control procedures and therefore we have no reason to remove them; we thus leave them in the analyses.

   Changes: A note about the rarity of these large values of D_m has been added to the caption for Figure 4 (now Figure 3).

2. **Reviewer:** *p. 15, l. 27-28: As it was mentioned in the comments on the original manuscript, the threshold of 35 dBZ for ZH to replace radar measured ZDR and KDP with expected values in order to avoid noise effects is too high. At X-band it corresponds on average to a value of 1.5 mm for Dm and values in ZDR and KDP higher than the corresponding thresholds of 0.2 dB and 0.3 deg/km, which they authors additionally use and are acceptable values. For example, the average*

relation at X-band between ZH and ZDR (Park et al. 2005, JTECH) shows that a value of 35 dBZ for ZH corresponds on average to 1.2 dB for ZDR, which is clearly a value that is above noise for all polarimetric radars.. A 15 dBZ threshold for ZH would be more realistic. The 35 dBZ threshold reported in the paper of Bringi et al. (2002) that the author use a reference for such a high value corresponds to S-band radar data (lower ZDR than X-band) and it used to discriminate light rain (usually stratiform) from more intense rain in order to use a different retrieval method in this case. Similar use for the 35 dBZ threshold is made by Part et al. (2005) in rainfall estimator (with or without KDP). This does not mean that 35 dBZ correspond to noisy ZDR or KDP in order to replace them with expected values, but simply that the specific polarimetric rainfall estimators fail below this threshold.

Response: We thank the reviewer for this helpful comment. We have re-examined the choice of thresholds we use for Z_H when deciding whether to replace possibly noisy values of Z_{DR} and K_{dp}, with reference to this comment and the previous paper mentioned (Park et al., 2005). We have concluded that although the reviewer is correct that a value of $Z_H = 35$ corresponds to a higher value of Z_{DR} than 0.2 dB, in the real radar data we used there are so many noisy values of Z_{DR} and K_{dp} below about 37 dBZ that the noise correction still needs to be applied in this range of Z_H values.

Looking first at Z_{DR}, Fig. 1 of this comment shows the relationship between Z_H and Z_{DR} in the training data set we use, with a dotted line shows $Z_{\mathrm{DR}} = 0.2$ dB. Horizontal lines show medians, vertical lines show 10th to 90th quantile ranges, boxes show interquartile ranges. There are differences between the relationship found here and that shown in Park et al. (2005) Figure 5, which we hypothesise are due to the differences in disdrometer used (including the correction we apply to some of our DSD measurements which tends to reduce the concentrations of small drops) and the climatology (Europe/USA vs. Japan). However, the plot

shows that if we assume (as per Bringi et al. (2002)) that $Z_{\mathrm{DR}} = 0.2$ dB is a reasonable noise threshold, then 15-18 dBZ is a reasonable equivalent value for Z_H at X-band, as the reviewer suggests. In our training data, the median value of Z_H for values of Z_{DR} between 0.19 and 0.21 is 18 dBZ. However, in real radar data Z_{DR} is noisy for values of Z_H below about 35-37 dBZ, as shown in Fig. 2 of this comment, which uses PPI data from the three studied regions and shows outlier points as dots. We therefore keep the Z_H threshold at a higher value, and use 37 dBZ. The result of the correction on Z_{DR} is shown in Fig 3 here, and the cleaned Z_{DR} values are clearly closer to the theoretical values shown above.

Regarding K_{dp}, Fig. 4 of this comment shows the relationship between K_{dp} and Z_H in our training data. A dotted line showing $K_{\mathrm{dp}} = 0.3\ ^\circ$ km^{-1}. Again, horizontal lines show medians, vertical lines show 10th to 90th quantile ranges, boxes show interquartile ranges. The y-axis is in logarithmic scale to better distinguish $K_{\mathrm{dp}} = 0.3\ ^\circ$ km^{-1}. In this case, our threshold of $Z_H = 35$ dBZ seems reasonable, although some values of $K_{\mathrm{dp}} < 0.3\ ^\circ$ km^{-1} fall into the class containing Z_H up to 42.5 dBZ. For K_{dp} between 0.29 and 0.31 $^\circ$ km^{-1} in our training data, the median value of Z_H is 36.4 dBZ. To ensure we treat most noisy values we use an updated threshold value of 37 dBZ, which matches the threshold used for Z_{DR}. For $36.99 < Z_H < 37.01$ in our training data, the mean and median values of K_{dp} are both 0.32 $^\circ$ km^{-1}. Fig. 5 of this comment shows the observed PPI values for Z_H vs. K_{dp}, in which noise is observed below about 37 dBZ. The noise-treated values of K_{dp} are shown in Fig. 6 here. The treated values more closely match the theoretical relationship expected.

Changes: We use an updated $Z_H = 37$ dBZ threshold for treatment of noisy data. We are aware that changing the input data may change the relationships between observed radar variables, and therefore unduly penalise the SCOP-ME technique. To be fair in our comparisons we show the Parsivel results with no noise cleaning, and we also show the difference made by the noise cleaning in the comparison with the MRR data in Figure 5 in the article. For the other results we show performance statistics for the techniques using cleaned radar data.

References

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Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2016-301/amt-2016-301-AC1-supplement.pdf

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-301, 2016.

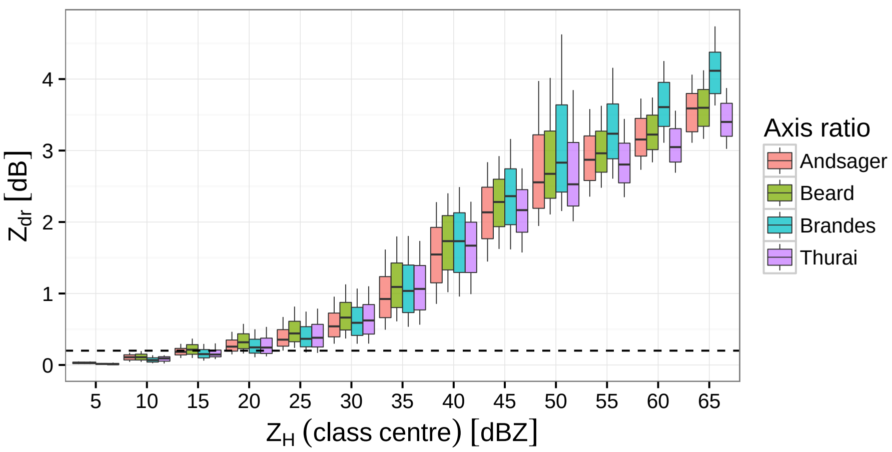

Fig. 1. Horizontal reflectivity to differential reflectivity relationship.

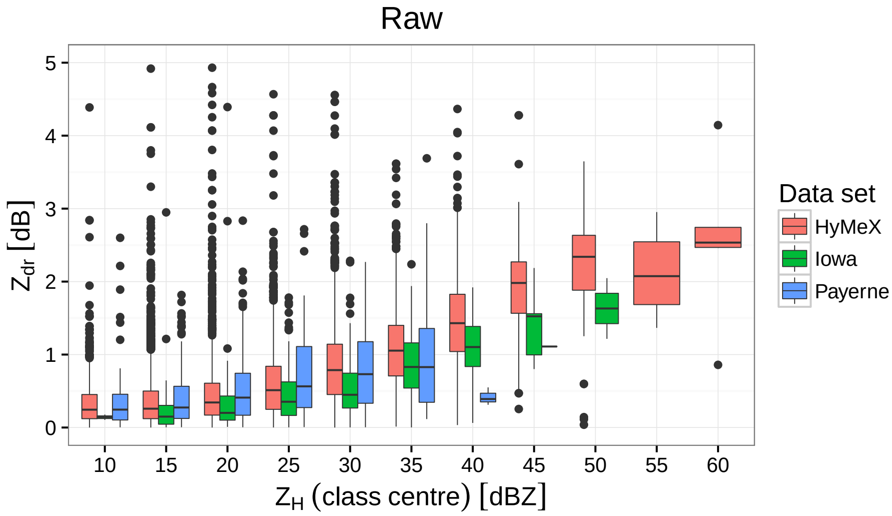

Fig. 2. Horizontal reflectivity to differential reflectivity measured relationship.

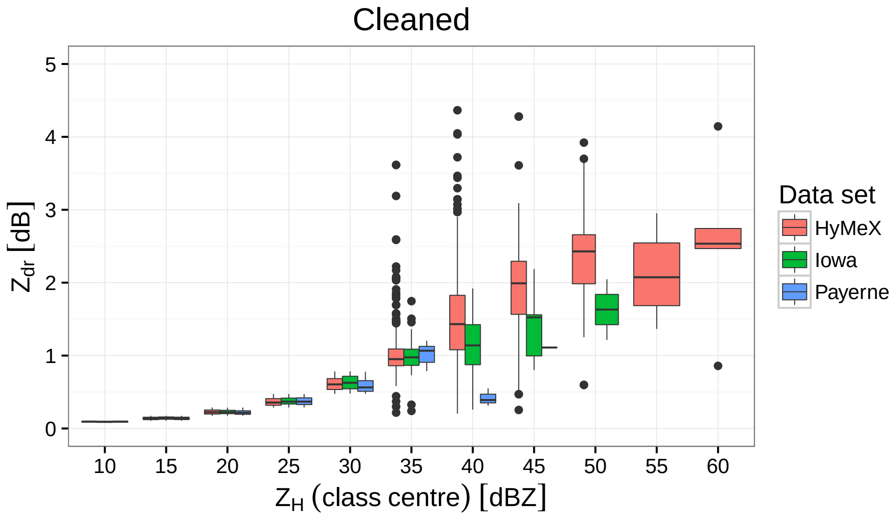

Fig. 3. Horizontal reflectivity to differential reflectivity relationship in cleaned radar data.

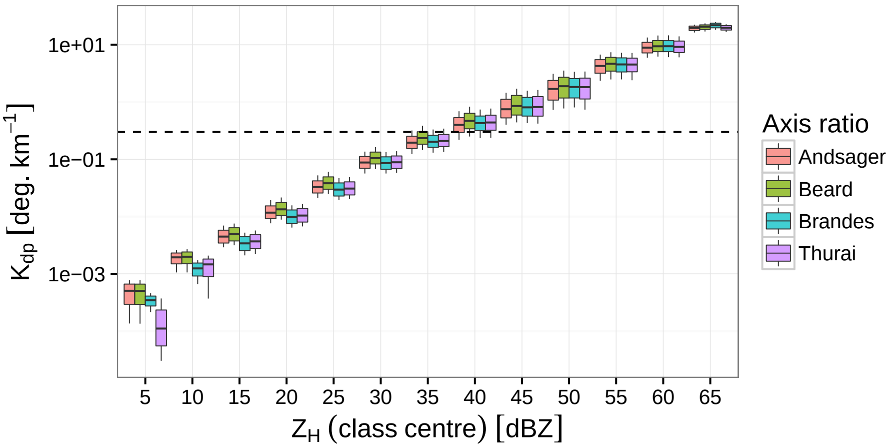

Fig. 4. Horizontal reflectivity to specific differential phase relationship.

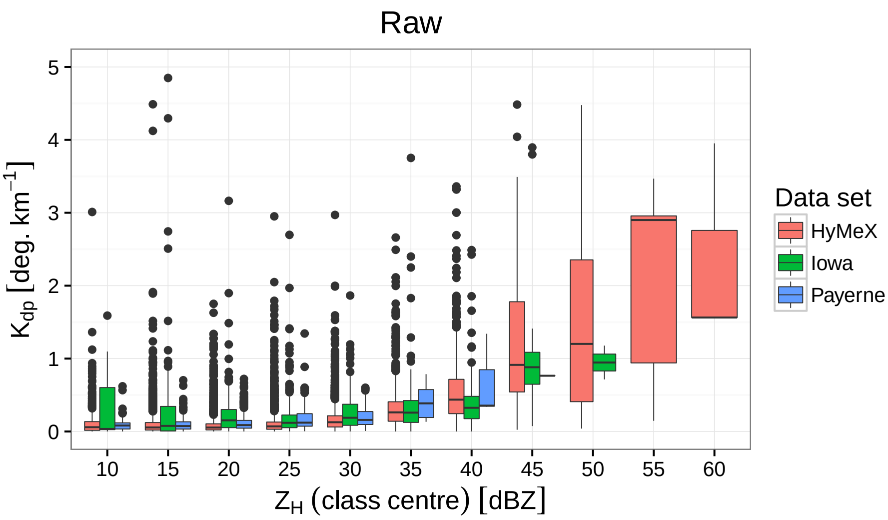

Fig. 5. Horizontal reflectivity to specific differential phase measured relationship.

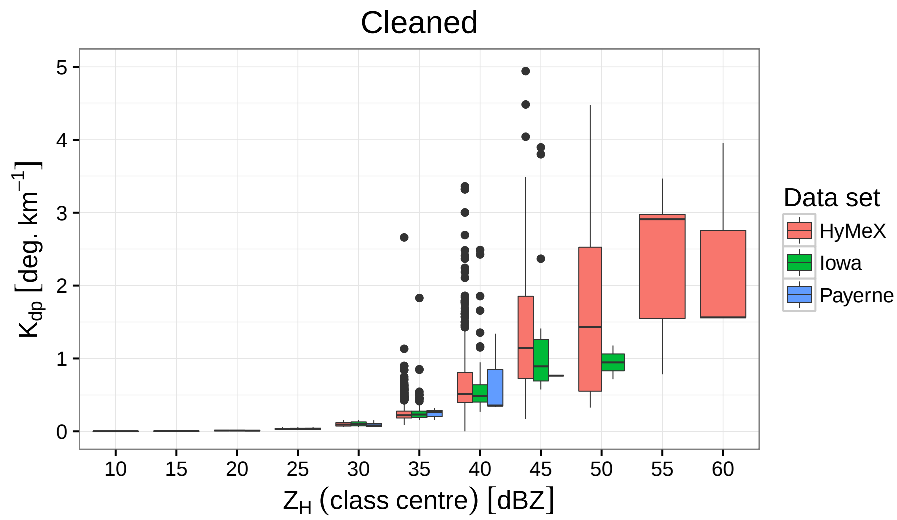

Fig. 6. Horizontal reflectivity to specific differential phase relationship in cleaned data.