Response to Review Comments

“Retrieval of Lower-Order Moments of the Drop Size Distribution using CSU-CHILL X-band Polarimetric Radar: A Case Study”

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We thank the editor and reviewers for their time and constructive comments. In the text below, we quote the reviewer’s comments verbatim in bold and follow their comments with our responses in regular font and revised manuscript text in red. Additionally, we have numbered the reviewers’ comments for clarity and reference purposes.

Reviewer #1

R1.1a. This manuscript opens a chance to retrieve the lower-order moments with dual-pol radar measurement. The accuracy in retrieval is remarkable and there are some rooms for microphysical interpretation of retrieved moments/parameters. The review recommends to accept this manuscript with a minor revision. See the below comments.

R1.1b. We believe the measured Z is relatively accurate and the moment(s) close to measurements should be retrieved most accurately. However, the results show the accuracy in M6 is not better than others. This should be elaborated more.

R1.1c. The reviewer recommends further studies as separate papers to explore microphysical evolution of precipitation systems after applying this retrieval technique.

Response:
1.1a. We thank the reviewer for comments that will improve the paper.
1.1b. We address this comment regarding retrieval of M6 in our response to R1.15 and R1.16 below.
1.1c. As to future work, we do intend to use such retrievals for microphysical evolution studies. Thank you for this suggestion!

R1.2. More comments are below:
Line 6 :→ **0th moment of DSD, M0**

Response:
Thank you. We have fixed this in the revised manuscript.

R1.3. Line 19 $\sim$ 20: the radar-retrieved characteristic diameter with M0.. More specific.

Response:
We have replaced the concerned text in the revised manuscript as follows:
... the radar-retrieved mass-weighted mean diameter with M_0 ...

R1.4. Line 52 $\sim$ 63 : any moment Mk can be expressed as power laws of Mi, Mj, **and the k-th moment of** $h(x) \rightarrow$ **any moment Mk can be expressed as power laws of Mi, Mj in which the coefficient is and the k-th moment of** $h(x)$ **and the two exponents are pre-determined by I and j.**

Response:
Thank you for being precise. We have changed this accordingly in the revised manuscript.

R1.5. lines 91 $\sim$ 94 : Multi-step -minimize the parameterization errors???

Response:
We have modified this sentence as:
This multi-step procedure was found to minimize the parameterization errors (also referred as algorithm errors) in the estimation of M_3.

R1.6. Line 150: Schönhuber et al. (2008)$\rightarrow$ (**Schönhuber et al.** 2008)

Response:
Thank you. We have fixed this in the revised manuscript.

R1.7. Line 162 $\sim$ 169 : Please further describe ”drizzle mode’, ”shoulder” and ”precipitation mode”

Response:
The term “drizzle mode” was used by Abel and Boutle (2012) to describe a peak in $N(D)$ that occurs when $D < 0.5$ mm. Our use of “shoulder” and “precipitation” modes are not precise but used here merely to go with Fig. 1. We have added the following text in the revised manuscript:
...defined by a peak in $N(D)$ occurring when $D < 0.5$ mm (Abel and Boutle 2012). The “shoulder” is the diameter range where the $N(D)$ either remains steady or falls off more “slowly” (generally found under equilibrium conditions (McFarquhar, 2004)). The precipitation range is used here for larger-sized drops after the “shoulder”, if any. These ranges are used here only to illustrate Fig. 1.

References:

Abel, S. J. and Boutle, I. A.: An improved representation of the raindrop size distribution for single-moment microphysics schemes, Quarterly Journal of the Royal Meteorological Society, 138, 2151–2162, 2012.

McFarquhar, G. M.: A new representation of collision-induced breakup of raindrops and its implications for the shapes of raindrop size distributions, Journal of the Atmospheric Sciences, 61, 777–794, 2004.

R1.8. Fig 1: It is interesting to find two peaks at $D = 1.3$ mm and $\mathrm{D} = 2.2$ mm. Any comments in terms of the equilibrium DSD?

Response:

We are not confident in commenting on the peaks based on the MPS data, given that this figure shows only an example of one 3-minute spectra. We do mention that the $N(D)$ is "equilibrium-like" and provide following three references.

References:

Low, T. B. and List, R.: Collision, coalescence and breakup of raindrops. Part II: Parameterization of fragment size distributions, Journal ofthe Atmospheric Sciences, 39, 1607–1619, 1982.

McFarquhar, G. M.: A new representation of collision-induced breakup of raindrops and its implications for the shapes of raindrop size distributions, Journal of the Atmospheric Sciences, 61, 777–794, 2004.

Straub, W., Beheng, K. D., Seifert, A., Schlottke, J., and Weigand, B.: Numerical investigation of collision-induced breakup of raindrops.Part II: Parameterizations of coalescence efficiencies and fragment size distributions, Journal of the Atmospheric Sciences, 67, 576–588, 2010.

R1.9. Fig. 2: It is worthwhile to show the same image from the X-POL.

Response:

Thank you for this suggestion. However, the corresponding X-band PPI for Fig. 2 is (understandably) quite attenuated and would distract the reader from the thrust of this Section.

R1.10. Fig. 6: Any better way to show the pixel-to-pixel data? Currently, they are quite confusing.

Response:

Thank you for this question. This is an established method that has been used earlier in many publications to compare radar measurements with surface instruments (e.g. Thurai et al. 2012). We have explained this with clarity in lines 260-265.

References:

Thurai, M., Bringi, V. N., Carey, L. D., Gatlin, P., Schultz, E., and Petersen, W. A.: Estimating the accuracy of polarimetric radar-based retrievals of drop-size distribution parameters and rain rate: An application of error variance separation using radar-derived spatial correlations, Journal of Hydrometeorology, 13, 1066–1079, 2012.

R1.11. Lines $281 \sim 283$: Any explanation why ZDR is so different at ~ 2045 UTC?

Response:

The discrepancy is quite small ~ 0.5 dB and occurs during the heaviest rain rates. While Fig. 5 shows that most of the attenuation occurs beyond the instrumented site, there is some attenuation prior to that which could have caused the discrepancy. In our experience the direct comparison between radar-measured Z_{DR} (made aloft) and that computed from disdrometer DSDs (using forward model assumptions) is generally considered as "good" if the $\Delta Z_{DR} < 0.5$ dB.

R1.12. Lines $320 \sim 321$: The authors need to elaborate this.

Response:

We have replaced 320-322 by the following text in the revised manuscript:

As a result, the analytical equation (42; *L04*) where M_k is derivable exactly in terms of $[i, j;\ \mu, c;\ k]$ cannot be used. Instead eq. (43) of *L04*, reproduced in (1) below, is employed. The radar estimates of the moments (M_k, $k = 0, 7$) are obtained from the retrieved M_3 and M_6 and by numerical integration of the following function:

R1.13. Line 338 : D′M → D′m

Response:

Thank you. We have fixed this in the revised manuscript.

R1.14. Lines $347 \sim 349$: multi-step procedure: how does this minimize the overall errors? Please add more explanation.

Response:

By overall errors, we assume that the reviewer is referring to the sum of parameterization errors and measurement fluctuation errors? In lines 347-349, we only consider the parameterization errors and the steps are very clearly described (see Fig. 7). We do not claim that we have minimized the parameterization errors by our method. In fact, we placed the caveat "... This multi-step procedure was devised to minimize the parameterization (or, algorithm) errors but we note it is by no means the only way to achieve this."

The Appendix has a clear explanation of the step-by-step procedure to estimate the total error variance for all the moments M_0-M_7.

R1.15. Lines 407 $\sim$ 409 : It is not intuitive. M6 is the closet moment that we can measure with the radar but the estimation accuracy is worse than other moments. Why? Further detail explanation is required.

Response:
We respond to this comment together with R1.16 below.

R1.16. Lines 412 $\sim$ 520: Same as the above comment. M3(least IQR) and M5 (unbiased) is the most accurate. It is understandable for M3. Why does the M5 have the least bias, not M6?

Response:
In theory, the M_3 and M_6 being the reference moments should have the lowest errors. While the reviewer is correct to state that M_6 is the closest moment to reflectivity, it is actually true only for Rayleigh scattering. We are using X-band radar where the larger-sized drops fall in the resonant regime and there were plenty of those during the passage of the 55 dBZ over the disdrometers. If one looks closely at Fig. 7a it can be noted that it is a piece-wise linear fit of M_6 vs Z (for $Z < 37$ dBZ and > 37 dBZ). The slope of M_6 is smaller for $Z > 37$ dBZ relative to $Z < 37$ dBZ. This is due to resonant scattering. It follows that Z_H goes between M_5 and M_6 at X-band. This is a possible reason why M_5 is superior at X-band relative to M_6 in terms of relative bias as well as Pearson correlation coefficient.
We have added in line 429:
It might be unexpected that the retrieval of M_6 being one of the reference moments is less accurate than M_5. One possible reason is that, at X-band, the larger drops are resonant-sized and the Z_H does not vary as M_6 but rather closer to M_5 depending on the drop sizes. Fig. 7a, in fact, shows that the fit for M_6 has a smaller slope for $Z_H > 37$ dBZ because of resonant scattering.

R1.17. Fig. 11 and 12: What is the red line around 500?

Response:
Thank you for this question. The orange lines in Figs. 11 and 12 indicate the *inner fence*

beyond which data samples are considered *extreme outliers*. We have added following explanation of the box plot in Section 4.2 of the revised manuscript:
The extremities of the blue boxes are called *hinges* which span the IQR or the first (lower hinge) and the third (upper hinge) quartiles. The orange line within the blue boxes indicates the median. The outliers (orange circles) lie beyond the first and third quartiles by at least 1.5 times the IQR. In particular, the 1.5 and 3 times the IQR limit above (below) the upper (lower) hinges of the boxes are called upper (lower) *inner fence* and *outer fence*, respectively. A point beyond an inner fence on either side is considered a *mild outlier* while a point beyond an outer fence is an *extreme outlier*. The largest value below the upper inner fence and the smallest value above the lower inner fence are indicated by shorter grey horizontal lines called *whiskers*, within which lie extreme values that are not considered outliers. If there are no points beyond a whisker, corresponding inner and outer fences are not plotted. Similarly, if there are no samples between the inner and outer fences, only inner fence is shown on the plot. Otherwise, the inner fence is generally omitted and only the outer fence is depicted. For example, Fig. 8e shows only outer fence lines on top and bottom. While plotting multiple box plots on the same figure, only a common fence line that is closest and outside of all boxes is shown.

We have added following in the caption of Fig. 8e:
The orange horizontal lines on top and bottom indicate the upper and lower outer fences, respectively.

Similarly, we have added the following in the captions of Figs. 11 and 12:
The orange horizontal line on top indicates the upper inner fence.

R1.18. Lines $452 \sim 454$: Z was around $30 \sim 35$ dBZ in this later period. What will be the main reason of the dominant break-up process in such a moderate intensity?

Response:
The reviewer is correct in that the "time track" is not same as vertical profile. So, we have deleted the sentence on breakup process.