Response to Review Comments

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

V. Bringi, K. V. Mishra, M. Thurai, P. C. Kennedy, and T. H. Raupach

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 #2

R2.1. This manuscript presents a very interesting new technique with promising results for improving the DSD retrieval from microwave remote sensing measurements. I find no fatal flaws in this study, but do have some minor comments, which are listed below.

Response:
We thank the reviewer for a positive evaluation of our manuscript and helpful comments to improve the paper.

R2.2a. Biggest, minor concern: There is a notion that attenuation at low rainfall intensity is not significant enough to allow retrieval of lower order moments with acceptable uncertainty (i.e., measurement error is too large due to relatively lower signals).
R2.2b. The DSDs presented in Fig 8c are an example of this.
R2.2c. Also, early in the case study ($<$ 2030 UTC) when the precipitation is relatively light, the M3 and M6 retrievals are not in very good agreement with that observed.
R2.2d. The authors do allude to KDP being too noisy, which is well known at low rainfall intensities, but Ah is also derived from filtered psi-dp measurements. So it is not clear how Ah should be any better than KDP.

Response:
2.2a. The reviewer is correct that attenuation during light rainfall is not significant. However, in order to apply the ZPHI method, it is the the product of attenuation and the path that needs to be significant. For instance, long range of an S-band radar could compensate for low attenuation in a product. In fact, this is the motivation for ongoing considerations to adopt the direct use of A_h to retrieve rain rate at S-band in the

WSR-88D network (*Ryzhkov and Zrnić* 2019). At a shorter X-band range of 40 km, a $\Delta\phi_{dp}$ of 5° is sufficient to apply ZPHI method (see chapter 10.4, *Ryzhkov and Zrnić* 2019).

2.2b. We refer the reviewer to the Appendix, wherein Eq. (A9) provides details of the measurement errors in A_h. In Fig. 8c, which is based on scattering simulations using measured DSDs, the increase in scatter at low D_m is not because of "measurement error". Rather, it is due to DSD variability.

2.2c. We assume that the reviewer is referring to our Fig. 9, especially panel (c). This is traced back to Fig. 6a, where the DSD-based simulated Z_H is about 5 dB lower than that measured by radar for time period 20:00-20:30 UTC. In the revised manuscript, we explain this in Section 3.3. as follows:
Note that in Fig. 6a, the DSD-based simulated Z_H is about 5 dB lower than that measured by radar for time period 20:00-20:30 UTC. The measured Z_H was 18-25 dBZ, implying very low rain rates ($\sim$ 0.5 mmh^{-1}) and low number density of drops sampled by the disdrometers. In addition, it follows from the RHI taken at 20:27 UTC in Fig. 3 that the cells are moderately slanted from NNW aloft, where generating cells might have formed at 5 km AGL to SSE at surface. Given the unsteady conditions in this complex of echoes, it is not surprising that the disdrometer-based Z_H calculation is biased low by around 5 dB relative to low radar Z_H values of 18-25 dBZ. These problems are mitigated when heavier rain rates traverse the site about 15 mins later.

2.2d. The reviewer raised an important concern. Note that, in the computation of A_h (see Eq. (7.150), p. 505, *Bringi and Chandrasekar* 2001, itself based on *Testud et al.* 2000), the Ψ_{dp} is used only as a final value constraint, i.e., its value at the end of the beam (relative to the initial system offset value). As shown in Fig. 5, the beam ends at 40 km. Moreover, it follows from Eq. (7.150) that the resolution of A_h is same as that of Z_H and it has the same practical advantages as that of differential phase measurements, e.g. immunity to absolute system calibration offsets in Z_H and partial beam blockage, among others (see chapter 5, *Ryzhkov and Zrnić* 2019).

On the other hand, K_{dp} involves the derivative of Ψ_{dp} or the slope which needs to be calculated over a finite range interval. This leads to loss of resolution relative to the resolution of A_h and Z_H. In particular, the smoothing of K_{dp} is readily observed in high reflectivity compact cells with loss of resolution.

Note that some caveats do remain while using eq (7.150). First, the exponent of a A_h-Z_H power law is fixed based on scattering simulations. Second, the coefficient α in the relation $A_h = \alpha K_{dp}$ is either estimated as per the procedure in chapter 10, section 4, *Ryzhkov and Zrnić* (2019), assumed fixed to its most probable value based on scattering simulations or estimated using the method given in eq (7.153), pp 506, *Bringi and Chandrasekar* (2001).

To summarize, A_h is "better" than K_{dp} in pure rain with compact convective cores of high Z_H for the purposes of retrieving W in a multi-step procedure as described in our paper.

In the revised manuscript, we clarify this in Section 3.2 as follows:
Note that using A_h for retrieval of W is restricted to precipitation comprising pure rain. In contrast, using K_{dp} (as in RBb) in pure rain entails spatial (range) smoothing which, in compact convective rain cells, "distorts" the spatial representation of the rain rate profile depicted by Z_H. In our multi-step retrieval procedure, it is reasonable to not mix different smoothing scales for the radar observables.

References:
Bringi, V. N. and Chandrasekar, V.: Polarimetric Doppler weather radar: Principles and applications, Cambridge University Press, 2001.
Ryzhkov, A. V. and Zrnić, D. S.: Radar polarimetry for weather observations, Springer, 2019.
Testud, J., Le Bouar, E., Obligis, E., and Ali-Mehenni, M.: The rain profiling algorithm applied to polarimetric weather radar, Journal of Atmospheric and Oceanic Technology, 17, 332–356, 2000.

R2.3. Other, less minor comments:
Line 128 ... reference to Huntsville site in this context is irrelevant. Suggest re-wording this sentence to better clarify that the same disdrometer and wind shield configuration was used in both Greeley and Huntsville, but this case study is focused on an event captured in Greeley when there was coincident X-band radar data collected.

Response:
Thank you for this suggestion. We have revised the text as follows.
Our retrieval algorithms (see Section 4) of the reference moments M_3 and M_6 were based on scattering simulations from the combined DSD data from two sites, namely Greeley, Colorado (GXY) and Huntsville, Alabama (HSV). The same disdrometer and wind shield configuration were deployed at both locations. However, the case study in this paper concerns the event of 23 May 2015 captured in Greeley, which also has a coincident CHILL X-band radar.

R2.4. Fig 1a and references in the text would benefit from plotting exponential and gamma DSD to show comparison with G-G, especially since the text mentions exponential in lines 168 – 169.

Response:
Thank you for this suggestion. We have added exponential and standard gamma fits in

Fig. 1c (reproduced below) in the revised manuscript.

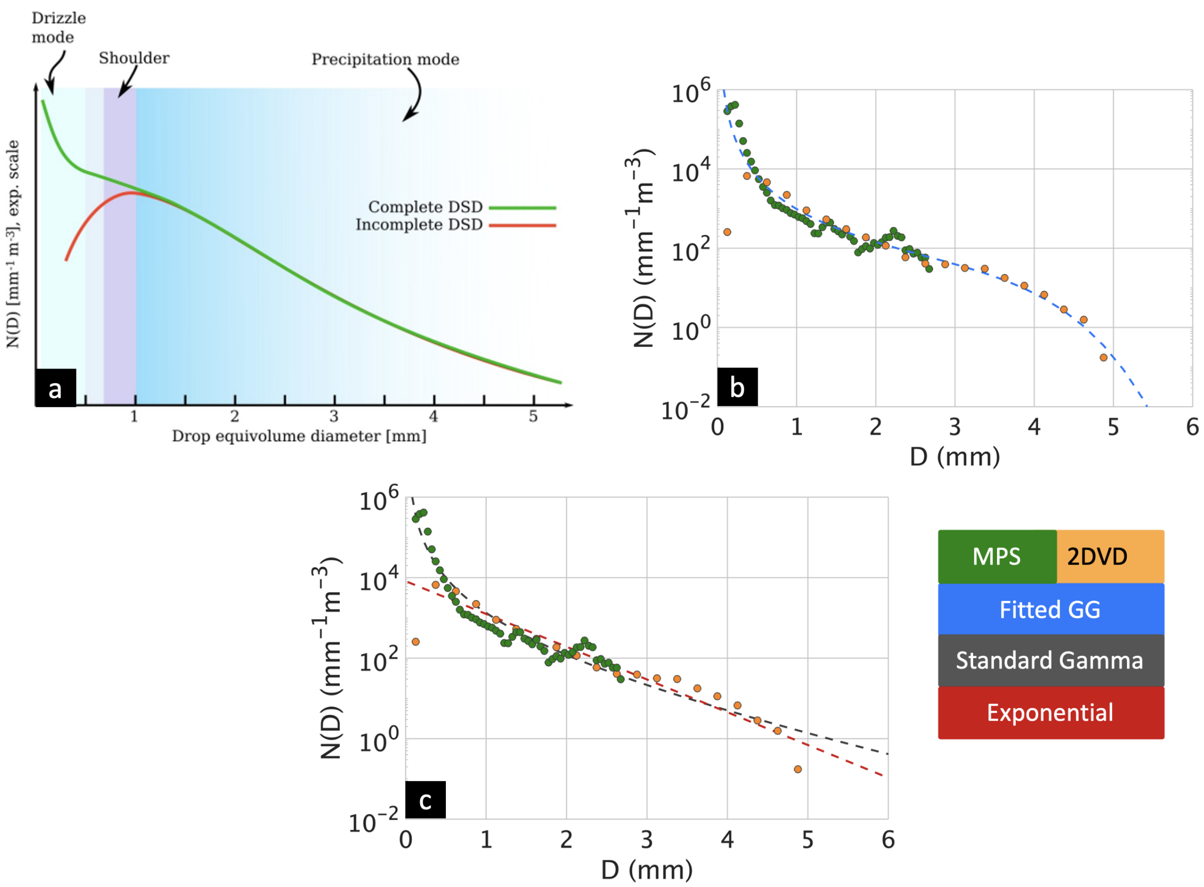

Figure 1: (a) Conceptual illustration of the complete DSD comprising the drizzle mode, the "shoulder" region and the precipitation mode. The incomplete DSD is due to drop truncation by instruments that cannot measure the concentration of small drops. (b) An example of measured 3-min averaged DSD ($R \approx 60$ mm h^{-1}) using collocated optical array probe with a 2DVD showing the separate measurements (note the high resolution of the MPS and the drop truncation of the 2DVD). The composite or compete spectrum is obtained by using the MPS for $D \leq 0.75$ mm and 2DVD for $D > 0.75$ mm. The dashed blue line is the G-G fit (with parameters $\mu = -0.3$, $c = 6$; see Eq. (1) for details) to the complete spectrum. Data from 23 May 2015 case study at 20:45 UTC. (c) Same data points as panel (b) but with the standard gamma (black) and exponential (red) fits.

We have also added the following line at the end of Section 2 of the revised manuscript: These features cannot be captured by either standard gamma or exponential fits, as shown in panel (c).

R2.5. Lines 201-203: "... good time resolution enabled validation..." could use some more theoretical elaboration or a citation that has results on the decorrelation of convective rain.

Response:
While a theoretical value of decorrelation time in a convective event is not precisely known, 90 s sampling time is "empirically" sufficient. In prior works such as *Thurai et al.* (2012), where a stratiform event with embedded convection was studied, the radar beam was stationary and pointed toward the disdrometer site at a range of about 13 km. The dwell time was set such that the radar data were available every 4 s over the disdrometer site. The autocorrelation of radar estimated D_0 from Z_{DR} was computed using the 4 s samples and the $1/e$-decorrelation time of 200 s was in close agreement with the same from the 2DVD DSDs. For strong convection, the decorrelation time would be much shorter. Therefore, the current 90 s sampling by the radar in our case is certainly much better than the 5 min sampling by the WSR-88D radar scans, even if one considers that it may not have been sufficiently within the decorrelation time for convective events.

We have added following text in Section 3.3 of the revised manuscript:
For an estimate of the decorrelation time of radar-retrieved D_0, we refer to *Thurai et al.* (2012) which studied stratiform rain with embedded weak convection using 4 s samples; the $1/e$-folding time was around 200 s, where e is the Napier's constant. For a highly convective case of our present case study, the decorrelation time would be substantially smaller but probably similar to our radar sampling of 90 s.

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.

R2.6. Lines 211-212: RHI first mentioned on line 211 and not defined until line 212.

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

R2.7. Fig 3. The X- and S-band RHI scans are offset by 1-min. Aren't they obtained at the same time?

Response:
Thank you for pointing this out. Although the archive files are written by separate data systems running on different computers for S- and X-band systems, a 1-minute difference noted by the reviewer should not exist. A closer examination of sweep times reveals the S- and X-band RHI files started at 20:26:45 and 20:26:46 UTC, respectively; this one-second difference is typical. We have updated the time for each scan to 20:27 UTC in the revised

manuscript.

R2.8. Line 243: the term "meteo" is not widely known ... is this referring to meteorological? Perhaps hydrometeor would be more appropriate since that is what is largely contributing to the backscatter at X-band.

Response:
Thank you for this suggestion. We have replaced "meteo" by hydrometeor in the revised manuscript.

R2.9. Line 267: "... Shifted by 60 sec as is common practice..." a few citations are warranted here.

Response:
Thank you for this suggestion. We refer the reviewer to May et al, (1999), which states "Obviously, there are important sampling issues inherent in the radar–gauge comparisons. The gauge data represent a time average at a particular location. For this study, the R comparisons are based on R derived from gauge data averaged over 5 min. These averages have been calculated centered within 1-min of the radar scan time and with delays of 2, 3, and 4-min to produce a correction for the time taken for the precipitation to reach the ground from the three radar elevations. These delays are incorporated in all the statistics and plots except where explicitly stated otherwise."

Accordingly, we have added following text in Section 3.3 of the revised manuscript:
The radar time series were shifted by 60 s as is common to match the peak in Z_h (e.g., *May et al.* 1999). A more general analysis of the error characterization of radar-gauge comparison is given in *Anagnostou et al.* (1999). However, such an analysis is not needed herein because of the narrow antenna beam and short range to the instrumented site.

References:
Anagnostou, E. N., Krajewski, W. F., and Smith, J.: Uncertainty Quantification of Mean-Areal Radar-Rainfall Estimates, Journal of Atmospheric and Oceanic Technology, 16, 206-215, 1999.
May, P. T., Keenan, T. D., Zrnić, D. S., Carey, L. D., and Rutledge, S. A.: Polarimetric radar measurements of tropical rain at a 5-cm wavelength, Journal of Applied Meteorology, 38, 750-765, 1999.

R2.10. Fig 6a ... early during the event ($<$ 2030UTC) the reflectivity simulated from the DSDs is 3-6 dB lower than that measured by CHILL and yet there is no mention of this rather large discrepancy. This should be mentioned

in lines 280-285 and a possible explanation provided.

Response:
This comment is similar to R2.2c. We refer the reviewer to our response to R2.2c.

R2.11. Lines 313-318....concerning the optimized values of mu and c...how do the distributions of mu and c for the climatological database in this study compare to those reported by Raupach et al. (2019), which used different case studies? In other words, we need more evidence showing the variability of the shape parameter c.

Response:
Thank you for raising this interesting question. For the retrieval technique presented in this paper, we are concerned with finding the best values of c and μ and, therefore, do not use their distributions. Rather, we fit a generalised gamma distribution on the median values of $h(x)$ per normalised size bin. In Raupach et al. (2019), different methods for fitting such "overall" values of c and μ were tested. The method we use is the one that produced the best overall performance in that previous study. A comparison with Table 3 of Raupach et al. (2019) shows that our c and μ fall within the 75^{th} percentile and median of 1-min c and μ values in the dataset used in Raupach et al. (2019), respectively. This similarity provides confidence that our c and μ values are reasonable. The validation of the technique from the previous study shows that the resulting c and μ values are representative of the "overall" shape of $h(x)$.

We have added the following text in Section 4.1 of the revised manuscript:
The optimised values of c and μ fall within the range of values fitted to one-minute DSDs reported by *Raupach et al.* (2019).

References:
Raupach, T. H., Thurai, M., Bringi, V. N., and Berne, A.: Reconstructing the drizzle mode of the raindrop size distribution using double-moment normalization, Journal of Applied Meteorology and Climatology, 58, 145-164, 2019.

R2.12. Fig 13: This is a great way to represent this data and a good tool to use for better understanding the microphysical processes at work. However, I have a minor suggestion... The color scale is not very discrete. So the plots would benefit from annotations of numbering the points sequentially to better match the reference to certain features described in the text.

Response:
Thank you for this suggestion. We did consider adding annotations to the plot. But the

number of points in each plot are too many and too close to provide a “clean” figure. However, the accompanying text in the manuscript explains the number of points and the sequence.