Response to Reviewer 1, egusphere-2026-507: "Estimation of wet radome and rain induced attenuation in cloud radar observations"

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Thank you to the editor and the two reviewers for the constructive feedback offered. In the following, reviewers' comments are given in italics with the authors' responses in normal text. Updated or new text is copied here where appropriate in **bold**. The full set of differences in the manuscript are attached in the tracked-changes document.

Reviewer 1

Recommended revisions:

3 Methods

3.1 Difference in heights of radar and disdrometer sampling volumes

3.1.a) *Lines 136-137: “The increase between the first and third gates is in the order of 1 dB. This feature is consistently present in most if not all radar reflectivity profiles.”*
For the two study cases considered or for all rain data of HYDRA-W?

Thanks, this is a point worth clarifying. This feature is present in all radar reflectivity profiles. The sentence has been amended to address this: **”This feature appears consistently in most, if not all, radar reflectivity profiles obtained from HYDRA-W measurements in the entire observational dataset.”**

3.1.b) *Lines 144-145: “It should be noted that the correction factor decreases with altitude and can be neglected for the range gate three and higher.”*
That depends on how large is the pointing error?

We agree that the magnitude of the effect depends on the size of the pointing error. In the revised manuscript, we clarified this by explicitly illustrating the impact of a small but realistic misalignment of 0.05°. This value was chosen to represent a small residual pointing offset in a system where the radar software already applies parallax correction based on the nominal antenna geometry. As such, large pointing deviations are not expected, and the example demonstrates that even small offsets can noticeably influence the correction. We have revised this part of the manuscript accordingly to improve clarity.

”It is assumed that there are no antenna pointing errors, **as the software should already compensate for parallax effects under nominal alignment. However, even a small residual pointing offset can affect this correction. For example, a misalignment of 0.05°, representing a small but plausible residual pointing error,** increases the correction factor to 4 dB for the lowest gate and 2 dB for the third gate. **Although the software accounts for parallax, the correction remains sensitive to small pointing errors. For range gates at and above the third gate, the correction is comparatively small, whereas the lowest gates are more sensitive. Consequently, minor pointing errors could contribute to the anomalous reflectivity behaviour observed in the lowest three gates.”**

3.1.c) *Lines 182-185: Which pointing error can explain the 1 dB increase of the reflectivity from range gate 1 to range gate 3? For this pointing error, what will be the error for the range gate 3?*

We thank the reviewer for this comment and realize that the original text may have caused confusion regarding the 1 dB value. The 1 dB refers to the difference at the third range gate between the uncorrected reflectivity and the reflectivity after applying the parallax correction, rather than the difference between range gates. For clarity, the difference in reflectivity between the first and third range gates is approximately 1.6 dB without correction and increases to about 2 dB when assuming a pointing offset of 0.07°. Based on our calculations, such a pointing offset would increase the parallax correction at the third range gate from about 1.3 dB to approximately 2.3 dB, corresponding to an increase of about 1 dB. Even for this slightly larger misalignment, the associated uncertainty at the third range gate remains on the order of 1 dB. We have clarified this point in the revised manuscript.

"A more plausible explanation is a small antenna pointing misalignment, which increases the parallax error correction. This effect is strongest at short ranges, where beam overlap is incomplete, and decreases with increasing height as the overlap improves. To quantify the sensitivity, a slightly larger pointing offset of about 0.07 °would increase the correction at the third range gate (153 m) from approximately 1.3 dB to about 2.3 dB, corresponding to a 1 dB increase in reflectivity. Even in this case, the resulting uncertainty at the third range gate remains on the order of 1 dB. Therefore, in this study, radar measurements from the third range gate are used."

3.2 Computation of DSD parameters and radar variables

3.2.a) *Line 208 (typo): ....and θ is the elevation angle in radians...*

Thanks, done.

3.3 Forward model of disdrometer measurements

3.3.a) *Lines 3-4: "For simplicity sake, we will assume that DSDs follow a Gamma functional form and therefore can be described using three parameters, as presented in the previous section."*
To strengthen this statement, the authors may cite the following article: "A critical evaluation of the adequacy of the gamma model for representing raindrop size distributions" by C. Gatidis et al. (2020), which shows that most of the DSDs at 30 s time resolution are not far away from the gamma model, unless a rain transitional period is considered.

We thank the reviewer for pointing out this relevant reference. We agree that it strengthens the justification for assuming a Gamma functional form for the DSD. We have therefore added a sentence citing C. Gatidis et al. (2020) and added two sentences summarizing their findings to support this assumption.

"For simplicity sake, we will assume that DSDs follow a Gamma functional form and therefore can be described using three parameters, as presented in the previous section. **This assumption is supported by Gatidis et al. 2020, who evaluated the adequacy of the Gamma model for fitting DSDs. Their results show that, at a temporal resolution of 60 s, a substantial fraction of observed DSDs can be well represented by a Gamma distribution, although deviations may occur, particularly during transitional rainfall periods."**

3.3.b) *Lines 229-230: "Given a number of observed droplets, i.e. by sampling the Poisson distribution, a simulated distribution of droplets can be obtained by sampling the Gamma probability density function defined by the intrinsic DSD parameters."*
Rewrite to make this content more understandable/clear for the reader. Rather than a long sentence, more sentences (shorter) could lead to clarify this content

We thank the reviewer for this helpful suggestion. We agree that the original formulation was too condensed and have therefore rewritten this part of the manuscript using shorter sentences to improve clarity and readability.

"Given the number of observed droplets, a simulated DSD is derived by sampling from a Gamma probability density function defined by the intrinsic DSD parameters."

3.3.c) *Lines 242-244: Compared to Fig. 1, what is the rationale for choosing a uniform distribution for* $\log_{10}(N_w)$*? What is the rationale for choosing a normal distribution for D0 and* μ*? What are the mean and standard deviation of the selected distributions?*

We thank the reviewer for this useful comment. We agree that the rationale for the selected distributions and their parameters was not sufficiently explained in the original manuscript. We have revised this section to clearly justify the choice of a skewed normal distribution for D0 and μ, and a uniform distribution for $\log_{10}(N_w)$, based on the observed shapes in Fig. 1. In addition, we now explicitly state the mean, standard deviation, and skewness of the fitted distributions to improve transparency and reproducibility.

"A **skewed normal** distribution is fitted to the parameters D_0 and μ, **as this best represents the shapes of the curves in Fig. 1. For D_0, the fitted distribution has a mean of 0.65 mm, a standard deviation of 0.5 mm, and a skewness of 4, with values ranging from 0 to about 4 mm. For mu, the mean, standard deviation, and skewness are -1, 14 and 10 respectively, with values ranging from -2 to about 60. In contrast**, for $log_{10}(N_w)$, a uniform distribution is fitted in between the range 2 to 5 $log_{10}(mm^{-1}m^{-3})$. **This choice is motivated by the need to sample the full observed range of droplet number concentrations, which spans approximately three orders of magnitude. Using a uniform distribution ensures that both low and high values are equally represented, whereas a normal distribution would under-sample the tails."**

3.3.d) *Line 244: "For $log_{10}(N_w)$, a uniform distribution is fitted in between the range 2 to 5 $mm^{-1}m^{-3}$." Correct the unit.*

Thanks, unit is corrected.

3.4 Inverse problem: from observations to an ensemble of intrinsic DSDs

3.4.a) *Fig. 2 caption (typo): "Schematic illustrating the steps taken in the forward (a) and inverse (b) models".*

Thanks, done.

3.4.b) *Eq. 9: Mention what the variable x is: ... where x is ...*

Thanks, the meaning of variable x is now added to the text. **"where x denotes the number of observed droplets."**

3.4.c) *Lines 287-288: "This procedure is repeated for every observed DSD, and a single intrinsic DSD can be linked to multiple observations."*
I could follow the idea of the methodology (Lines 283-287), but from this sentence, I don't understand how the observed DSD can be linked to a single intrinsic DSD. Which single intrinsic DSD will be selected? Here I miss a stepwise methodology (implementation), which makes this part of the research not reproducible. Explain like in the forward model with a stepwise approach: step 1, step 2, ... or an extra schematic or a small annex.

3.4.d) *Lines 288-290: "Because the forward model includes statistical uncertainties, DSD truncation and filtering, this link allows estimation of statistical uncertainties and possible biases of computed DSD parameters and radar variables."*
How are the statistical uncertainties, bias of computed DSD parameters and radar variables estimated? Related to this: how are the black boxes in Fig. 4 estimated? Develop this part (stepwise approach or schematic or annex). Like in 3.4.c) the concept is clear but that is not the case for the implementation. Explain to make this work reproducible.

Combined response on comments 3.4.c and d.
We thank the reviewer for these insightful comments. We agree that, while the concept of the inverse approach was described, the implementation was not sufficiently detailed to ensure full reproducibility. In the revised manuscript, we have clarified this part by providing a more explicit step-by-step description of the inverse procedure. In particular, we now clearly describe how intrinsic DSD ensembles are selected based on their consistency with the observed DSD, and how these ensembles are subsequently used to estimate uncertainties and biases in DSD parameters and radar variables.

We emphasize that no single intrinsic DSD is selected. Instead, each observation is associated with an ensemble of intrinsic DSDs whose simulated medians fall within the uncertainty ellipsoid of the observed DSD. The statistical properties of this ensemble (e.g., median, spread) are then used to quantify uncertainties and biases.

Furthermore, we have expanded the explanation of how the quantities shown in Fig. 4 (black boxes) are derived from these ensembles and added clarifications in both the text to improve transparency and reproducibility. We have rewritten this part of the manuscript as follows:

"Because the forward model includes statistical uncertainties, DSD truncation, and filtering, **the inverse problem can be used to estimate the statistical uncertainties and possible biases of the resulting DSD parameters and radar variables. The inverse problem is formulated in three steps:**

Step 1 **For the observed DSD, with its associated number of recorded raindrops, an expected uncertainty is defined using the standard deviations given by Eqs. (9). These standard deviations define the semi-axes of a three-dimensional ellipsoid, centered on the observed DSD parameters, in the (D_0, μ, N_w) space.**

Step 2 **The medians of all simulated DSD ensembles are checked against this ellipsoid. Since each median corresponds to one intrinsic DSD, the medians that fall within the ellipsoid identify the intrinsic DSDs consistent with the observation, yielding an ensemble of intrinsic DSDs associated with the observed DSD.**

Step 3 **The statistical properties (e.g. median and spread) and possible biases of the computed DSD parameters and radar variables are estimated from this ensemble of intrinsic DSDs.**

This procedure is applied independently to each observed DSD. As a result, a single intrinsic DSD can be linked to multiple observations. A schematic representation of this methodology is provided in Fig. 2b.

Figure 4 presents an example of an observed DSD, red line, fitted DSD using DSD moments, green line, and estimated DSD using median values of ensembles of intrinsic DSD parameters, blue line. **The boxplots and histograms represent the distribution of intrinsic DSD parameters in this ensemble and define the associated uncertainties. It should be noted that the green and blue** curves fit the observations well, the main differences appear in the small diameter range, $D < 0.5$ mm."

3.4.e) *Line 302: "As was shown in (4b-c) the ensembles of reflectivity and rain rates can also be estimated." Following on 3.4.d) How are the ensembles of reflectivity and rain rates be estimated? What is the meaning of the number of simulations in Fig. 4 (b)-(f)?*

We thank the reviewer for this helpful comment. We recognize that the original description of how the reflectivity and rain-rate ensembles are derived, as well as the interpretation of the number of simulations shown in Fig. 4, could be clearer. In response, we have revised this paragraph to better explain how these ensembles are generated from the intrinsic DSDs using the forward model, and to clarify that the number of simulations reflects the size of the intrinsic ensemble consistent with the observation. These changes aim to improve clarity and reproducibility.

"As shown in Fig.4b–c, **ensembles of intrinsic reflectivity and rain rate can also be obtained. Reflectivity and rain rate are computed individually for each DSD in the intrinsic ensemble using PyTMatrix (Leinonen, 2014). The resulting distributions are then used to quantify the associated uncertainties (e.g. spread). The number of simulations shown in Fig. 4 correspond to the number of intrinsic DSDs in the ensemble that satisfy the selection criteria described stepwise above, i.e. those consistent with the observed DSD within its uncertainty bounds. This number provides an indication of whether the ensemble is sufficiently large to yield robust uncertainty estimates."**

3.4.f) *Lines 305-306: "Because the uncertainties associated with the ensemble of rain rate are correlated, the standard deviation of the accumulated precipitation cannot be directly added over time."*
I suppose you mean: the variances of the accumulated precipitation cannot be added...

3.4.g) *Lines 306-307: "Therefore, the propagation of uncertainty is calculated by* $\sigma^2 = a \sum^x a^T$*, where a is a row vector and* $\sum^x$*, is the variance-covariance matrix (Mardia et al., 1979)."*
How are the uncertainties related to the accumulated rain obtained? Explain the provided equation, $\sigma^2 = a \sum^x a^T$*. What does contain the row vector a ? What is x? Which variance-covariance matrix is considered?*

Combined response on comments 3.4.c and d.
We appreciate this comment, which highlighted that the description of the uncertainty propagation was too brief. We have revised this section to clarify the formulation and interpretation of the quadratic form, including the definition of the vector a, the precipitation time series x, and the construction of the variance–covariance matrix. In addition, we now explicitly explain how the uncertainties in accumulated precipitation are obtained by accounting for temporal correlations between timesteps.

"The propagation of uncertainty is therefore computed using the quadratic form

$$\sigma^2 = \mathbf{a} \sum^{\mathbf{x}} \mathbf{a}^{\mathrm{T}}, \tag{1}$$

where x represents the precipitation rate time series, a is a row vector defining the linear accumulation operator and $\sum^{\mathbf{x}}$ is the variance–covariance matrix of x (Mardia et al., 1979). For the case of accumulated precipitation over t timesteps, a consists of ones, representing the summation of precipitation rates over time. In this study, the diagonal elements of $\sum^{\mathbf{x}}$ are estimated from the ensemble-based variance at each timestep, while the off-diagonal elements represent temporal covariances. Because the ensemble data are generated independently at each timestep, they do not contain information on temporal dependence. Therefore, the off-diagonal elements are constructed using a lag-dependent autocorrelation function derived from the precipitation time series.

For accumulated precipitation, the quadratic form can be written equivalently as

$$\sigma_t^2 = \sum_{i=1}^{t} \sigma_i^2 + 2 \sum_{i<j} \rho(|i-j|)\, \sigma_i\, \sigma_j, \tag{2}$$

where σ_t is the variance of the accumulated precipitation over t time steps, σ_i and σ_j are the standard deviations of rain rate at time steps i and j, and $\rho(|i-j|)$ is the autocorrelation coefficient between these timesteps, accounting for temporal dependence in rainfall. This formulation separates the contributions from individual variances and the covariance terms arising from temporal dependence."

3.4.h) *Line 309 (typo):"... is computed from the disdrometer observations."*

Thanks, done.

4 Results

4.1 Radome attenuation

> *Lines 335-336: "This is illustrated for an event with minimal radome attenuation and one with a degraded radome resulting in strong radome attenuation."*
> *When was the radome changed in 2023? How do the authors assess the degradation of the radome? That is an important question for the ACTRIS network. The event 28-29 July 2023 (radome attenuation case) shows a heavy precipitation event (53 $mmhr^{-1}$), while the event 26 May 2022 (minimal radome attenuation case) presents largest rainfall rates less than 2.5 $mmhr^{-1}$. Therefore, radome attenuation could result from heavy rainfall rates, while having the radome not necessarily damaged? Can the authors comment on this?*

We appreciate this important comment. To provide additional context for the comparison, we now state that the radome in May 2022 had been replaced one day prior to the event, whereas during the July 2023 case it had been in operation for approximately one year. In addition, the discussion has been revised to make clear that the increased attenuation observed during the July 2023 event is not attributed solely to radome degradation. The very high rainfall intensities at the onset of the event likely contributed substantially to the attenuation. The revised text therefore emphasizes that the observed differences reflect a combined effect of rainfall intensity and radome condition.

Added these sentences in the first paragraph of section 4.1: **"The minimal attenuation case corresponds to 26 May 2022, when the radome had been replaced one day prior to the event and can therefore be considered to be in near-optimal condition. In contrast, the second event (28–29 July 2023) shows pronounced attenuation and occurred when the radome had been in operation for approximately one year."**

Furthermore, we added a discussion about the radome degradation: **"The assessment of radome condition in this study is based on both maintenance history and observed attenuation behaviour. The radome was newly installed prior to the May 2022 event, whereas in July 2023 it had been in use for approximately one year. In practice, the radome is replaced approximately every six months, with periodic checks for signs of wear, such as surface degradation or damage, each time we visit the site. The methodology presented here provides a complementary, quantitative means of monitoring radome performance and may support condition-based replacement strategies in operational settings.**

It is important to note that increased attenuation during the July 2023 event cannot be attributed solely to the radome condition. High rainfall intensities can lead to rapid wetting of the radome and thus enhanced attenuation. Under normal operation, the radome is expected to dry during periods of low or no rainfall due to the blower. However, during this event, elevated attenuation persists even after rainfall intensity decreases substantially (around 1600 UTC), indicating prolonged wetting of the radome. This suggests that both rainfall intensity and radome condition contributed to the observed attenuation."

> *Lines 356-358: "It should be noted that during the second event, there is also a notable difference in observations of precipitation accumulation. The weighing gauge measures about 47 mm of total precipitation accumulation during the event and disdrometer derived accumulation is only 42 mm.*

> *This difference exceeds expected uncertainty of disdrometer observations."*
> *Do the authors have some ideas on the possible reasons of this difference?*

This is an important point. A closer examination of the July 2023 event (Fig. 6c) indicates that discrepancies between disdrometer- and gauge-derived accumulation become more pronounced at rainfall intensities above approximately 3 $mmhr^{-1}$. In contrast, during the May 2022 event, when rainfall remains below this threshold, the differences largely stay within the expected uncertainty range. This pattern can be attributed to sampling limitations of the disdrometer, particularly its reduced sensitivity to larger drops at higher rainfall intensities. While the correction approach effectively compensates for truncation effects in the small-drop regime, it is less responsive to biases associated with larger drop sizes. This point has been clarified in the revised manuscript to better explain the observed discrepancy.

"It should be noted that during the second event, there is also a notable difference in observations of precipitation accumulation. The weighing gauge measures about 47 mm of total precipitation accumulation during the event and disdrometer derived accumulation is only 42 mm. **A closer inspection of the event (Fig. 6c) indicates that the discrepancy increase during periods with rainfall rates exceeding approximately 3 $mmhr^{-1}$. In contrast, during the May 2022 event (Fig. 5c), where rainfall intensities remain below this threshold, the differences are generally within the expected uncertainty range. This behaviour is likely associated with sampling limitations of the disdrometer, particularly the under representation of larger droplets at higher rainfall rates. While the applied correction method accounts for truncation effects in the small-drop regime, it is less sensitive to biases related to larger drop sizes, which may contribute to the observed difference in accumulated precipitation.**

4.2 Specific attenuation

> *Lines 396-398: "A second, less restrictive criterion is to compare projected and observed reflectivity values just below the melting layer. If the difference is less than 1 dB, than the attenuation correction can be applied."*
> *What is the rationale of this criterion? Explain*

This point is well taken. The underlying idea of this criterion is that the reflectivity should vary smoothly with height. Therefore, if attenuation along the path can be approximated by a nearly constant slope, the projected reflectivity profile and the observed reflectivity just below the melting layer should remain close. A small difference (within about 1 dB) thus indicates that the projection is consistent with the observed profile and that the attenuation correction is likely valid. This reasoning has now been clarified in the manuscript.

A second, less restrictive criterion is to compare projected and observed reflectivity values just below the melting layer. If the difference is less than 1 dB, **which is taken as a representative uncertainty in the radar reflectivity factor, the attenuation correction is considered applicable. The reason behind this criterion is that, in the case of approximately constant attenuation along the propagation path, the reflectivity profile should decrease smoothly with height. Consequently, the projected reflectivity and the observed reflectivity just below the melting layer should not differ significantly. A small discrepancy therefore indicates consistency between the projected and observed profiles.**