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Interactive comment

Interactive comment on "Improved rain-rate and drop-size retrievals from airborne and spaceborne Doppler radar" *by* Shannon L. Mason et al.

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We thank the reviewers for their constructive comments, and hope that our responses have helped to improve the paper.

A common thread across the reviews was a request for more justification of the retrieval of a height-invariant Nw, and for evaluation of the retrievals through the vertical profile. In response we have added Figs. 5, 9 & 12 evaluating the averaged vertical profile of retrieved and forward-modelled variables in key precipitation regimes: moderate stratiform rain (case 1), light stratiform rain with strong evaporation (case 2), and moderate warm rain (case 3).

In evaluating the instances where the constant-Nw representation was not able to re-

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produce the profile of 9.6 GHz radar observations, we thought it worthwhile to add a demonstration of the retrieval in which Nw is represented as a linear gradient (Section 6). We show that introducing another degree of freedom allows us to resolve some of the variations in the DSD through the profile as expected for collision-coalescence, and that these changes lead to an improved ability to forward-model the independent 9.6 GHz radar measurements. This is possible with the high vertical resolution of the airborne radar observations, and therefore worth demonstrating, but we do not necessarily anticipate retrieving a vertical profile of Nw from EarthCARE, which will have coarser 500m vertical resolution.

Major comments

1. I wonder how the absorption by liquid water clouds is handled. Liquid phase clouds below the melting layer will contribute to the total PIA. Their contribution can be substantial especially for lighter rainfall. Neglecting cloud absorption will result in overestimation of PIA due to rain. Cloud base heights can be significantly lower than the melting layer.

Radar attenuation by liquid cloud water is estimated within the forward model as for liquid rain water; however the detection of liquid clouds below the melting layer is difficult from above, where lidar tends to be extinguished and radar is dominated by the larger drops. We can be confident that the rain will dominate the radar attenuation, but it's true that this will be an upper estimate of the attenuation attributed to rain, and could include some fraction due to unseen clouds.

Changes:

This uncertainty has been made more explicit in Section 2.2 Target Classification; the relevant paragraph now includes an additional statement:

> As a result of the uncertain presence of liquid clouds within rainy profiles, the path-integrated attenuation of the radar that is attributed to rain may be partially due to undiagnosed liquid cloud.

2. Assuming that Nw is constant with height does not account for drop collision-coalescence, evaporation and breakup processes. It is a rather heavy assumption and it needs more justification.

Retrieving constant Nw for each profile is an improvement over assuming Nw is constant everywhere; however, we agree that the representation of Nw is not expected to be borne out physically in many cases. Therefore the constant Nw may be best interpreted as a profile-averaged Nw; but this warrants further discussion in the text.

There may indeed be sufficient information in some cases to retrieve more complex representations of the profile of Nw, may better fit our understanding of microphysical processes, and we agree this was important to discuss in more detail.

Changes:

To better justify the decision to retrieve constant Nw, we have added the following discussion in Section 2.3.3 defining the rain state variables:

> Additional state variables increase the degrees of freedom of the retrieval, and require more information from observational variables to constrain the

> retrieval. Therefore we retrieve a single value of Nw for each profile, with the physical interpretation of representing Nw as constant with height, or as the vertically-averaged value. The representation of Nw as constant with height is not expected to be borne out in cases where evaporation or collision-coalescence processes modify the drop number concentration through the vertical profile.

To explore the possibility of retrieving more detailed profiles of Nw, we have added Section 6, in which we retrieve Nw as a linear gradient for the warm rain case. The vertical profile of moderate warm rain is evaluated against the 9.6-GHz radar variables, and we show that by allowing the additional degree of freedom for a linear gradient of Nw we can better represent the mean Doppler velocity toward the surface, improving the fit to independent radar measurements, as well as (qualitatively) resolving the drop growth, and decreasing drop concentration, toward the surface we would expect from collision-coalescence processes in this context.

In the discussion and conclusions, we have added a paragraph to discuss the representation of Nw, summarising the findings of Section 6.

Other comments

1. Do you account for changes in raindrop terminal velocities with altitude as air density changes?

Terminal velocity is corrected for air density through the profile, however this had been unclear in the methods section ("... corrected for air density").

Changes:

The description of mean Doppler velocity now says "...scaled to account for air density changes with altitude."

2. From the text I understood that gaseous attenuation is calculated from model profiles of temperature and humidity. In stratiform rain, however, relative humidity is often 90-95% and if model profiles suggest lower humidity (e.g., the model does not forecast rain in a particular pixel) the water vapor absorption contribution in PIA can be underestimated.

Yes, the relative humidity profile from the model is not updated in the presence of rain. In practice for the cases studied here, we have confirmed that the relative humidity in the model data already exceeds 90% for most of the rainy part of the vertical profile.

However the situation seems likely to occur at times, so the water vapour contribution to gaseous attenuation could be set in the algorithm to be the larger of the re-analysis and 90%.

3. The statement that the gradient method requires an assumption of constant rain rate with height is misleading. In fact it requires an assumption that non-attenuated reflectivity changes are small compared to changes due to attenuation. This method provides an average rain rate in the height interval which is used to calculate the gradient.

Thank you for this clarification.

Changes:

The text now reads:

> Both approaches are implemented simultaneously, so that whereas the gradient method of Matrosov et al. (2007) is applied only at moderate to heavy rain rates wherein it can be assumed that the gradient of apparent radar reflectivity is dominated by attenuation, within the CAPTIVATE variational scheme the gradient of R and k can be estimated simultaneously from the profile of radar reflectivity and PIA.

4. When using 9.6 GHz data, do you account for rain attenuation at this frequency? Estimates show that attenuation at X-band at 10 mm/h at nadir pointing and in a 4 km thick layer could be around 1.3 dB. In addition to that the melting layer attenuation will add a contribution, which cannot be neglected.

The attenuation of the 9.6 GHz radar due to both rain and the melting layer are included in the forward model.

Changes:

In Section 2.3.4 on the melting layer, the corresponding value of k for X-band radar from Matrosov (2008) are now given.

In Section 2.3.5 on the radar forward model, we now mention both frequencies explicitly.

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5. How well are radar beams at X and W bands matched? The DDV measurements are very sensitive to beam mismatches.

The X- and W-band radars aboard ER-2 have been previously used for DDV measurements (e.g. Tian et al. 2007) from CRYSTAL-FACE, and by averaging to 5-second (1 km) along-track we expect that the matching between the two radar sampling volumes is strongly correlated despite differences in beam widths.

In terms of pointing error, visually there is no appearance of significant features being poorly correlated, and we do not correct for any known differences in radar pointing.

6. I believe the reference to Matrosov et al. (2008) in JAS in line 10 on page 7 for eq. (6) is wrong, it should be the reference to Matrosov (2008) IEEE TGARS, 1039-1047, doi: 10.1109/TGRS.2008.915757 This equation provides two-way attenuation. Your assumption of Xm=1 km actually corresponds to the melting layer thickness of 0.5 km, which accidentally is about right as melting layers often have thicknesses of around 0.5 km. Please correct the reference and the Xm definition.

Thank you for catching this: this was indeed the paper we intended.

Changes:

We have corrected the reference.

The definition of Xm is updated.

7. Figure 3. It appears that PIA is saturated at values lower than 60 dB, but the text says it is 65 dB.

Fixed.

8. Did you estimate what is the uncertainty of using the Mie theory instead of calculations for oblate raindrops?

The T-matrix method is also implemented in CAPTIVATE, so we calculated the effect of including oblate drops at larger diameters. Using Thurai et al. (2007) and Zhang et al. (2001) for the axial ratios of raindrops, the error in total backscatter due to assuming spherical drops is around 5% for a DSD with D0 of 1.5mm, which is roughly the largest D0 retrieved in this study; and much less for smaller median drop diameters. Errors in extinction are less than 2%.

Changes:

These uncertainties are now noted in Section 2.3.5 when radar reflectivity and extinction are described.

9. Figure 4 shows PIA-based retrievals also for the period when the W-band signal was completely extinguished (between 16:02 and 16:03 UTC), so PIA was not available. How it is possible?

When the radar is fully attenuated and the surface backscatter signal is indistinguishable from the noise, the PIA signal saturates, but is still available. This effect is accounted for in the forward-model, so that while the saturated PIA no longer provides an accurate estimate of the total attenuation in the profile, the information that the radar is extinguished still provides some information for the retrieval.

Editorial comments

1. Since you use natural logarithms in (4), (5), (9) and Table 1, you should change "log" to "ln".

Fixed

2. Page 8 line 24 and Table 2: 3 dBZ -> 3 dB (relative units).

Fixed.

3. Table 2. You do not measure Z as it is given in (7), but rather you measure attenuated Z.

True. The apparent reflectivity Za is now introduced in this section, and used in Table 2.

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