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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 reproduce 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.

General comments:

1. Page 11, line 5: Since you don't have independent measurements to validate your algorithm, you have elected to use Z9.6 and V9.6 as an indirect validation, which is OK but is certainly a limitation in the paper. It would be great to make the most out of it. So I wonder why you have decided not to show the whole vertical distribution (and maybe difference plots). That would characterize the errors in a more exhaustive way. A major improvement to the paper would be to demonstrate that with the limited validation you have, you can show that the vertical distribution is captured.

Our instinct was to limit the propagation of figures by comparing multiple retrievals on a single axes: hence the comparison of ZPIA, Zv and ZvPIA retrievals at a selected level above sea level; however, we agree that this didn't allow for sufficient evaluation of the vertical distribution.

Plots of the full vertical curtain plots for each retrieval (ZPIA, Zv, ZvPIA) tend to look quite similar, while the difference plots highlight errors at the tops and the bottoms of

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Discussion paper

the profile and in both cases, we felt these would significantly increase the number of figures and be relatively difficult to interpret.

We have therefore included averaged vertical profiles of observed and forward-modelled radar measurements and retrieved R, D0 and Nw over selected rain regimes for each case. The new Fig. 5 shows the moderate rain profiles of Case 1, Fig. 9 is for all of Case 2, and Fig. 12 shows the moderate warm rain profiles from Case 3. The new Fig. 5 replaces a previous figure showing a selected vertical profile, but illustrates much the same major points.

As discussed in responses to general comment 2 and specific comment 8, this evaluation in the vertical profile allows for some additional insights into how the DSD is resolved with height, and the limits of the constant-Nw assumption.

2. Discussion on case study 2, Fig. 8: No comment on the vertical distribution of D0 for that difficult case? In evaporation conditions is it realistic to see D0 decreasing at lower altitudes? The fact that Nw is held constant should be an issue here, as one might expect Nw to strongly diminish lower in height, and maybe Do increase due to removal of the smaller drops evaporating? That is one illustration of my general comment 1. You need to show the vertical distribution, not a selected height, because it does not tell the full story.

We now make a more detailed evaluation of the vertical profile for all cases. For Case 2 (Fig. 9) the forward-modelled mean Doppler velocity at both 94-GHz and 9.6-GHz are underestimated, but close to observations throughout the vertical profile, however the 9.6-GHz radar reflectivity is significantly underestimated in the lowest part of the profile, where evaporation is significant. This suggests D0 is well-constrained by the Doppler, and that the assumption of constant-Nw is leading to errors in the forward-modelled 9.6-GHz radar reflectivity.

In response to this and other questions about the assumption of constant-Nw, we have added Section 6, exploring the possibility of retrieving some additional information about the vertical structure: a retrieval of a linear profile of Nw is demonstrated for the warm rain case, in which we would expect collision–coalescence to lead to a decrease in drop number concentration toward the surface, combined with the increase in drop size.

For Case 2, if Nw is free to be represented by any linear profile (attached), we can improve the fit between forward-modelled 9.6-GHz radar reflectivity, with the retrieved Nw decreasing toward the surface and D0 increasing somewhat as the smallest drops evaporate, as you have suggested. This comes at the cost of an overestimate of 9.6-GHz mean Doppler velocity; this may indicate that the assumption of a constant shape factor mu=5 does not hold as the DSD becomes more monodisperse.

3. Page 17, lines 23-24: You say that in this study you have used measurements to investigate the prospects for improved global rain rate retrievals from spaceborne Doppler radar. However in order to study that more completely you could have chosen to simulate from these aircraft observations what EarthCARE would actually measure, and whether you would be able to get similar results between degraded spaceborne measurements and higher-resolution higher-quality airborne measurements. I feel this piece of work is missing to really make that claim. In that respect I would remove mention of "spaceborne" in the title of the paper, not to give the impression that you are actually improving satellite rain rates with this technique, as I don't think you showed that.

This is fair enough; the title has been changed.

Specific comments:

1. Page 1, line 11: separate "between" and "light".

Done

2. Page 3, line 10, "...unattenuated wavelength...". This is incorrect, there is still large attenuation at X-band. This needs to be rephrased and errors associated with potential X-band attenuation assessed.

That's true. Attenuation in the X-band is included in the radar forward-model.

Changes:

The line in question now reads "...at a less attenuated wavelength...", and further details has been added in Section 2.4 to make it clear that both W- and X-band radar attenuation are accounted for in the forward-model.

3. Page 3, line 15, "dual-radar" : do you mean dual-frequency radar?

Yes I did; fixed.

4. Section 2.3.4 title : What about 94 GHz attenuation due to graupel or hail ? Something needs to be said about that in this paper.

We have focused on stratiform precipitation here, where Doppler is expected to be most useful.

We expect that for EarthCARE a pre-check will flag convective precipitation, where graupel and hail are expected, and in which the radar is quickly attenuated.

Changes:

Title changed to "Stratiform precipitation melting layer"

We note that "Melting of graupel and hail, usually associated with convective precipitation, are not considered in this melting layer model."

5. Page 8, line 5 : "assume multiple scattering effects are negligible...". You should probably explain why you think that is reasonable (very small beamwidth). A comment is also needed to explain that this would need to be done in a spaceborne application.

In response to this and comments from other reviewers, in this section we now describe the assumption of negligible multiple scattering for the airborne data, as well as the expected effects of MS on satellite Doppler radar.

Changes:

This section now reads:

> Multiple scattering effects on radar and lidar backscatter can be estimated within CAPTIVATE using Hogan (2008). Radar reflectivity enhancement due to multiple scattering is especially relevant to spaceborne radar measurements at millimeter wavelengths (Battaglia et al 2005), and the effects on Doppler radar measurements are expected to include both enhanced spectral broadening and modified mean Doppler velocity (Battaglia et al 2011); however, with the narrower beam of the airborne radar used in this study we can assume multiple scattering effects are negligible (Battaglia et al. 2007).

6. Page 8, line 24: “as 3 dBZ, and as 0.5ms−1 for mean Doppler ...”. This seems large for reflectivity and too small for Doppler velocity. Vertical air motions can be 1-2 ms-1 in the lower troposphere easily in the clouds you are interested in ... That brings up a question you need to address (sorry...): how sensitive to this value are the results?

The ZvPIA retrievals are relatively insensitive to these uncertainties, however the Zv and ZPIA retrievals, being under-constrained, are significantly more sensitive to the choice of values.

In response to this and other comments we have reproduced the retrievals using more relaxed values that better fit with the expected combined measurement and forward-model errors: 3 dB for Z, 1.0 m/s for mean Doppler velocity, and 0.5 dB for PIA.

The following discussion has been added to this section:

> We have found that the weighting of errors between radar reflectivity and PIA is quite important for the retrieved rain rate, and that if only instrument errors are included the retrieval is not sufficiently constrained by PIA. This is believed to be because attenuation affects all forward-modelled radar reflectivity measurements in the same way, leading to them having strong error correlations. Error correlations are not accounted for in the R matrix, since they are profile-dependent and difficult to estimate, which can lead to the radar reflectivity measurements being over-weighted in the retrieval. To overcome this, we take the common approach (e.g. Weston et al. 2014) of inflating the reflectivity errors (and in our case somewhat reducing the errors in PIA) to better balance the information coming from the reflectivity profile and from PIA.

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7. Page 8, line 27, " .. by liquid water...". What about melting ice, graupel, hail ?

This was intended to focus specifically on the interpretation of profiles of apparent radar reflectivity in rain; however, it is true that we had not sufficiently addressed the attenuation due to other hydrometeors, and this is now discussed in more detail in Section 2.3.4 on the melting layer (in response to comment 4).

8. Page 14, line 31-32: What about at lower height? I would expect that if the Nw assumption is not satisfied lower down in the evaporating area, then D0 should have more errors and then Z(9.6 GHz) would be less good. It would actually be more interesting to show the whole vertical distribution instead of extracting one height for all these plots to demonstrate if the Nw assumption does create discrepancies on the vertical distribution of Z9.6. Hence my general comments 1 and 2.

Indeed, the errors in 9.6-GHz reflectivity are largest toward the bottom of the profile where evaporation is most significant. Figures 5, 9 and 12 showing the averaged vertical profile for each case have been added, allowing evaluation of the retrieval against the radar variables at all heights.

In light of this and other questions about the retrieval of constant-Nw, we have added a brief section (Section 6) to the paper, to investigate the retrieval of more a linear gradient of Nw, which improve the fit to 9.6-GHz observations.

9. Section 4.3.1, title: I think you could go to 12:46 for your comparisons? Why did you stop at 12:45 ?

This was a pretty arbitrary division based on cloud-top height; however, we agree 12:46 seems like a more suitable cutoff based on radar reflectivity and PIA. The time peri-

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ods have been changed in the title and discussion, and the period 12:41–12:46 is the subject of the added Section 6 on the retrieved profile of Nw.

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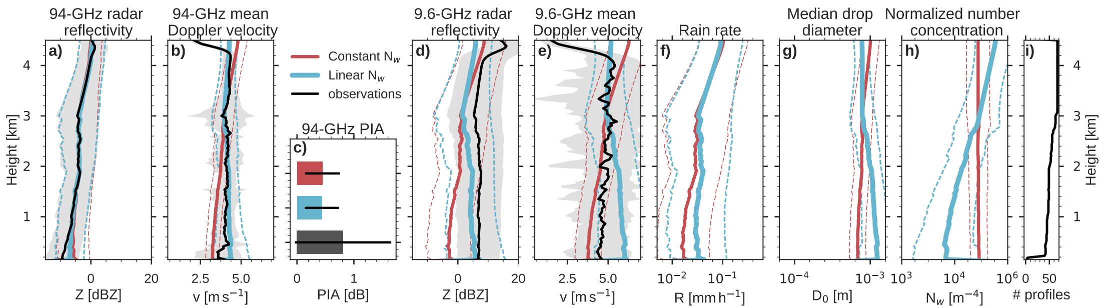

Fig. 1. Comparison of linear-Nw and constant-Nw retrievals over the evaporating cold rain regime (Case 2); a similar figure for Case 3 is now included in Section 6 of the manuscript.