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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.

Line 1: remove second ‘of’

Done.

Page 1, line 18: also A. Behrangi, 2012

Added.

Page 1, line 19: Lebsock et al., 2013 is a better reference than Lebsock et al., 2011

Added.

Page 1, Line 20: Stephens et al. only references intensity. Cite Abel and Boutle, 2012 for the DSD.

Added.

Page 2: line 5. I would mention the GPM DPR before bringing up cloudsat. It has increased sensitivity (12 dbz) vs PR (17 dbz).

This brief timeline of spaceborne cloud and precipitation radars was intended to introduce the capabilities of CloudSat's 94-GHz radar for sensing the vertical profile of light rain, including evaporation and drizzle, in contrast to precipitation radars; for brevity, and because CloudSat followed TRMM historically, we prefer not to introduce GPM here.

Page 2: Lines 14-16. CloudSat actually does not use the SRT (as in the Meneghini 1983 definition) method in its operation products. Instead a look-up-table of normalized surface cross section as a function of wind speed and SST from ECMWF analysis. But Lebsock et al. (2011) do use the SRT for cloud/precipitation water path estimates from CloudSat. The SRT can provide a superior estimate when the length scale of precipitation is short. In the next release of cloudsat precipitation products (release 05) cloudsat will use a hybrid method combining the LUT and SRT techniques each used where appropriate.

Thanks for making this distinction; we have clarified that that the surface cross-section can be estimated both from the SRT and from the surface wind speed and temperature.

The statement now reads:

> The path-integrated attenuation (PIA) can be estimated from the the ocean surface backscatter relative to either nearby clear-sky profiles (Meneghini 1983), or calculated from sea surface wind speed and temperature (Haynes 2009). Estimates of PIA are used in the rain retrieval algorithms of both TRMM (Iguchi 2000, Meneghini 2000) and CloudSat (L'Ecuyer 2002, Haynes 2009, Lebsock 2011) over the ocean...

Page 2, line 30: although these approaches have been challenged in practice due to the spectral dependence of the non-uniform-beam-filling and multiple scattering affecting the two frequencies.

That is interesting; however, notwithstanding these challenges, GPM rain retrievals are intended to use dual-frequency radar to retrieve two parameters of the DSD, and a more detailed discussion here is not required to justify the Doppler approach. With some minor changes, this sentence now reads:

> The recent global precipitation measurement mission (GPM; Hou et al. 2014), with the first dual-frequency radar in space, in intended to exploit differences in non-Rayleigh scattering at 35-GHz and 14-GHz to better constrain the rain DSD over land and ocean (Rose et al. 2006).

Page 3: Lines 27/28: should be Lebsock et al., 2011

Updated.

Equation 1: What is the structure of Jc? What is the structure of B? This is where all the magic happens. Also it's really hard to justify a prior in this retrieval. Why do you feel that you need one? And how do you justify it? The prior variance had better be large. Rodgers was doing sounding where you might actually have a moderately reasonable prior constraint. This approach shouldn't A prior of 0.1 mm/hr is going to make it hard to retrieve 10 mm/hr.

Thank you. We have added more detail and references to describe the terms in Equation 1.

As for a prior R, we do apply it with a large prior variance, so that its influence is small

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for a well-constrained retrieval. However, as we are demonstrating under-constrained ZPIA and Zv retrievals, the choice of prior does have some influence on the results; this sensitivity to the prior and the double-minimum problem is demonstrated in Section 3.

Changes:

To describe Jc and B in more detail, we now write:

> . . .and B is the error covariance matrix of xa in which the diagonal elements are the error variances of x; and Jc(x) provides the capability to apply flatness and smoothness constraints to reduce the effect of observational noise on the state vector (Twomey 1977). Additionally, profiles of retrieved variables can be represented smoothly as a set of cubic spline basis functions (Hogan 2007, and in Section 2.3.3).

To better explain the use of a prior R, we have added the following:

> For all retrievals a prior R of 0.1 mm/h is used. While a prior R is not strictly necessary, it is applied in combination with a large prior uncertainty such that the retrieved R should be relatively insensitive to the prior unless the retrieval is poorly constrained by observations. We note that this value for the prior variance implies that before the measurements are taken we assume there is a 44

Page 6, Line 28. I think the assumption is a necessary one but I think that the justification has less to do with rain rate and more to do rain type. For broad areas of stratiform precipitation I would suppose the invariance is most appropriate but that for any type of convection (light or heavy rain) I'm not so sure.

This distinction is important, and we had over-stated this assumption here; in practice, R is always represented as the basis functions of a cubic spline to allow for vertical variability.

This statement now reads:

> While in moderate stratiform rain R is often close to invariant with height (e.g. Matrosov 2007), processes such as evaporation in the lower atmosphere, and collision–coalescence in warm clouds, will lead to significant variation with height in many contexts. R is therefore represented as the coefficients of a cubic spline basis function with n elements (Hogan 2007); this has the effect of ensuring the vertical profile of R is smoothly varying and continuous with height, and also reducing the number of terms in the state vector.

Page 7, Line 10: This value of k is not consistent with your retrieved rain rate DSD in that bin though is it? I'm not that concerned about this but if I'm correct you should make a note of it.

Matrosov (2008) assumed a Marshall–Palmer distribution in the rain below the melting layer, so there is indeed a mismatch in the DSD assumptions in the rain and in the melting layer,

This is now explicit in the text:

> The estimated attenuation through the melting layer is based on a Marshall–Palmer DSD for the rain below the melting layer (Matrosov 2008), and is not modified to match the retrieved DSD in the profile.

Page 8, Line 5: add citation for the models that use for attenuation. There are many.

Citation to Liebe (1985) added.

Page 8, Line 15: I'm really skeptical of this Matrosov approach. It really depends strongly on steady state rainfall. How often does this happen? In practice in CloudSat data I see that the stuff that really fully attenuates the radar is the convection, where I just wouldn't trust this assumption.

In response to comments from reviewer 1 we have clarified that the necessary assumption for this approach is not that the rain rate is constant, but only that attenuation dominates any observed gradient in apparent radar reflectivity. Subsequently the estimated R from this method is related to the average over the gates in question.

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Table 2: a little discussion about where these numbers come from is required. 0.3 dB would be a very good estimate of PIA. From the SRT method the instrument noise alone is probably close to this value. Is the 3 dBZ including the uncertainty in your DSD– Z relationship? Another thing to consider is whether this 3 dBZ uncertainty should be constant with height. In reality uncertainty should grow with depth into the column (e.g. Lebsock and L'Ecuyer, 2011) because any errors you make in your forward modeled attenuation in the range volumes up high is compounded as you descend into the rain column. This becomes an issue when the PIA is order 20 dB like the cases you explore later in the paper.

In practice the results of the ZvPIA retrieval are fairly insensitive to the uncertainties, with the exception of the under-constrained Zv and ZPIA retrievals. The uncertainty in these variables should include both measurement and forward-model error, so in response to several reviewer comments we now use more physically reasonable values: 3 dB for radar reflectivity,

1.0 m/s for mean Doppler velocity,

0.5 dB for PIA

Changes:

All figures have been re-run with the updated uncertainties. The changes are small, especially for the ZvPIA retrievals that are well-constrained by observations. Table 2 is updated, and the values of the uncertainties updated in the text.

The following discussion has been added:

> 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.

Fig 5a and elsewhere: I can't understand why the Zv retrieval is not matching the radar reflectivity. Doesn't Zv mean that both radar reflectivity and mean Doppler are used to constrain the solution. It looks like only Doppler is used in these plots.

The Zv retrieval does make use of both radar reflectivity and mean Doppler velocity, but is under-constrained, and therefore prone to bimodal errors as illustrated in Section 3.

In this case the Zv retrieval starts from the prior R of 0.1 mm/h, and stays in a low-R state. While D0 is constrained by the Doppler, without PIA R is under-estimated, and therefore—without including attenuation in the forward-model—the retrieval has difficulty resolving the gradient of Z. Conversely, starting from a higher prior R improves the performance of the Zv retrieval in this case, but would lead to high-R retrievals in the light rain profiles.

This sensitivity to the prior is not evident for the ZvPIA retrievals, which are well constrained.

onclusions: The idea that mean Doppler will help with light rainfall retrievals over land is good but I worry that you often won’t know whether you are looking at light rainfall or heavier rainfall that appears light because it is attenuated. This process will need to be automated in a retrieval algorithm and it doesn’t seem straightforward. Also, the signal in the Doppler is not all that large relative to the uncertainties that are expected.

It’s true that this will be a challenge, but we think the results shown here are promising. The synthetic profile in Section 3, and the moderate rain profiles with PIA 20 dB in Case 1 showed that the Zv retrieval can sometimes be used to distinguish weakly and strongly attenuated profiles based on the profiles of Z and v; however, it’s true that this will not always be sufficient in practice.

It may be necessary to estimate PIA over land (even with large measurement error) to help identify strong attenuation, or to assume Nw in the retrieval, so that t. A simple test for weakly attenuated profiles might be to identify profiles in which the maximum reflectivity is less than some threshold.

Changes:

A “further work” statement is added in the third-to-last paragraph on the contribution of Doppler to the retrieval, while the more optimistic statement about retrievals over land in the final paragraph has been removed.

Conclusions: Won’t Doppler be affected by Multiple scattering for EarthCARE? I haven’t done any calculations of this but I wonder how this might complicate things.

Multiple scattering is indeed expected to affect the Doppler for EarthCARE (Battaglia and Tanelli, 2011). We have added the following:

Changes:

The brief mention of multiple scattering in Section 2.4 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 2005), and the effects on Doppler radar measurements are expected to include both enhanced spectral broadening and modified mean Doppler velocity (Battaglia 2011); however, with the narrower beam of the airborne radar used in this study we can assume multiple scattering effects are negligible (Battaglia 2007).

In the conclusion we now reiterate the challenges of applying these methods to EarthCARE, including multiple scattering and measurement error.

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