Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2019-100-AC4, 2019

Atmospheric Measurement Techniques Discussions

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AMTD

Interactive comment

Interactive comment on "The importance of particle size distribution shape for triple-frequency radar retrievals of the morphology of snow" *by* Shannon L. Mason et al.

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Received and published: 5 August 2019

In a previous response the quoted changes were displayed incorrectly.

We thank the reviewers for their constructive feedback on the manuscript. A recurring suggestion was that we apply the retrieval to more data than the 25-minute case study from 21 February 2014 originally used. We agree that this is desirable, reiterating that while the colocated remotely-sensed and in situ measurements of snow from BAECC 2014 are extremely valuable and of a high quality, the number of cases are limited. A related comment was that we should more clearly acknowledge the limited measurement period to which our retrieval was applied. In addressing both of these

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suggestions, we have both included an additional case study and de-emphasised the retrieval of the PSD shape parameter in discussing the results.

During the snow experiment intensive observation period of BAECC there were three cases in which all three radars were zenith-pointing during a snow event, and where the snowfall at the surface was not affected by melting (the cases shown in Kneifel et al. 2015). The snowfall at the surface during one of these cases (7 February 2014) was insufficient for the in situ snow retrieval of von Lerber et al. (2015). We have therefore expanded our study to include 60 minutes of snowfall from the 16 February 2014 case. This case also includes riming, but is notable for the presence of secondary ice production due to rime splintering (the Hallett-Mossop process). These secondary needles rapidly aggregate, such that the radar measurements in this case are dominated by large aggregate snowflakes with a very open structure, while the in situ measurements include a mixture of graupel, large aggregates, and needles.

In applying our retrieval to this case, it was evident from PIP measurements that the PSD shape was nearly constant, but that significant changes in the triple-frequency radar signature could be attributed to the presence of large aggregates of needles, consistent with the findings of Leinonen and Moisseev (2015). We have therefore expanded the scope of the study to include the effects of variations in the internal structure of aggregates, which are represented within the SSRGA. We hope the reviewers agree that expanding the study to address both the PSD shape parameter and the internal structure of aggregates strengthens this effort to better understand and interpret the parameters affecting triple-frequency radar measurements.

To summarise, we have made the following changes:

- The title is now, “The importance of particle size distribution and internal structure for triple-frequency radar retrievals of the morphology of snow”
- We added a coauthor, Leonie von Terzi at the University of Cologne.

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- We expanded our discussion of the coefficients of the SSRGA, especially those relating to the internal structure of aggregate particles, in Sections 2.1 and 3. L. von Terzi's contribution to the study was to perform simulations of aggregation of various monomers and their SSRGA coefficients; we use this to identify aggregates of needles as having triple-frequency radar signatures with especially low values of DWR_{35-95} compared to aggregates of other monomers.
- Section 5 now uses the 16 February case study to explore triple-frequency radar measurements and retrievals from a case featuring rime splintering. This is a very distinct situation from the first case study, and combined the two cases cover the wide range of triple-frequency radar measurements from during BAECC 2014.
- The discussion and conclusions (Section 6) have been substantially re-written to be more concise, while addressing the expanded scope of the paper.

Reviewer #1

Specific comments

This may be personal preference, but throughout the paper "PSD shape" is used to refer to the parameter μ–while I understand in the normalized distribution space μ does modify the actual shape (width) of the distribution, when talking about μ I think it may be clearer to refer to this as the "PSD shape factor" or "PSD shape parameter", as done on P4 L9.

We agree that this is most consistent and clear, and now refer everywhere to "PSD shape parameter".

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P2 L30-L32: Are triple-frequency measurements always at precisely 95 GHz, 35GHz, and a third frequency below 15 GHz? Or is that just what is used in this study? I would consider modifying this sentence to say something like "Typically,..." or "In this study,...".

Good point. In the literature on triple-frequency signatures of snow this configuration of radars is typical. However, it's true that the lowest frequency radar have been any of C, X or Ku-bands radars. The sentence now reads:

> The triple-frequency radar 'signature' consists of radar measurements at three frequencies spanning the millimeter wavelength range, the two dual-wavelength ratios (DWRs) of which reveal information about non-Rayleigh scattering from larger snowflakes. Typically radars at 95, 35 and a third frequency between 3 and 15 GHz are used (e.g. Kneifel et al. 2015; Leinonen and Szyrmer, 2015; Barrett et al., 2019).

P3 L13-L14: This sentence needs some clarification, as numerous studies have already been described that employ triple-frequency radar retrievals. Can the exact novel aspect of this study's triple-frequency radar retrieval be stated more clearly here?

Indeed, the novelty is that both the triple-frequency radar reflectivity factors and mean Doppler velocity measurements are assimilated in order to estimate different aspects of the particle morphology. This sentence now reads,

> To our knowledge a retrieval assimilating both triple-frequency radar reflectivity factors and mean Doppler velocity to estimate the properties of snow has not yet been described. This approach should have the advantages of constraining particle density with Doppler velocity (as in Mason et al.

> 2018), while using triple-frequency radar signatures to constrain some additional parameter affecting the microphysical properties or size distribution of precipitating ice particles.

P4 L16-17: This sentence is a bit confusing. Given the description of the assumptions on how each particle is treated (e.g., as a homogenous spheroid) when calculating the radar backscatter cross-sections, it might be clearer to state something along the lines of, "Approximations of the microphysical structure are used to calculate the radar backscatter cross-section", or, "The microphysical structure is represented through an approximation when calculating the radar backscatter cross-section".

We agree. The sentence now reads,

> The morphology of ice particles is represented by parameters controlling their microphysical structure, density, and shape. Approximations to the microphysical structure of ice particles are used to calculate the radar backscatter cross-section (σ) of each particle.

Figure 2: There should be boxes around the legends, particularly in panel (b) to differentiate it from actual data points. It should also be clarified that the y-axis units in(a) are in linear units (or convert them to log units) since it was previously stated DWR would be expressed in dB. Finally, the y-axis labels have no context – what is f? For(a), either explain in the caption or just convert it to dB, since DWR has already been explained in the text, and for (b) perhaps just state "Volume-Weighted Concentration".

We have modified the titles and y-axis labels of both subplots to make the quantities clearer, and have added an equation to define the dual-backscatter ratio (DBR) consistent with Kneifel et al. 2016, and which is now shown in dB. Boxes have been also added to the legends in plot (b).

P9 L29: "... The many narrow features of the backscatter cross-section ratio spectra are smoothed out" should have "when integrated across the PSD" added to it.

This is indeed clearer. We've made the change.

P14 L1-L4: I was initially confused with how this differed from the analysis presented in Figure 1, but gathered later that the PSD shape factor and density factor used were informed by the observed precipitation. I suggest making that fact more explicit and putting it earlier in the section.

Thank you, this was helpful feedback. To better highlight the important information in each figure, we no longer overlay the triple-frequency signatures with triple-frequency radar measurements in the first figure. This makes it easier in this figure to interpret how the triple-frequency radar signatures for different particle types change with the physical parameters, and leaves the comparison with measurements to the case studies (Figs. 7 & 12).

P14 L10: It looks to me like the frontal snow regime has DWR10-35 exceeding 10dB?

Thank you, we've made this change.

P16 L24: The sentence "the state vector is linearly interpolating between the retrieved state vectors at the retrieved value of PSD shape..." is unclear to me. Once the optimal μ value is found, which state vectors is the "retrieved" state vector interpolated between? Also, should "found by" be before "linearly interpolating"?

This sentence was not only unclear, but incorrect: we simply take the retrieved state vector from the retrieval that minimises the errors in DWR. This is now explained in the text.

> We carry out a pseudo-retrieval by running multiple $Z_{10,35,95}\,V_{35}$ retrievals in which the PSD shape parameter takes integer values from $\mu = -2$ to $\mu = 10$. The retrieved value is that which minimises the error in forward-modelled DWR_{35-95} and DWR_{10-35} between 400 and 600 m above ground level (Fig. 10a & b). The forward-modelled DWRs for a range of PSD shape parameters span up to 4 dB, with the range depending on the median volume diameter. To reduce noise in the pseudo-retrieval the minimisation is carried out at a smoothed temporal resolution of 15 s.

Technical Corrections:

Thank you for your thorough reading. We have gratefully made all of the suggested changes.

P1 L1: "cloud" should be "clouds"

P2 L26; P12 L8; P12 L20: "remote-sensed" should be "remotely-sensed"

P2 L26-L28: This sentence should be modified to be, "... in-situ measurements of snow events (Kneifel et al., 2015), but more detail of how the parameters... remains to be explored."

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P2 L31-L32: No hyphens are needed between the frequency and unit as they are not acting as compound descriptors in this context. 95 should also have a 'GHz' after it, and I'd add a comma after "35 GHz".

P3 L10-13: These sentences should be reworked avoid three separate clauses strung together with semicolons. Consider making the third clause its own sentence.

P4 L16: "in" should be "as".

P6 L6: "95-GHz" should be "95 GHz".

P6 L20: "assumptions to" should be "assumptions of".

P7 L8: "(Kneifel et al., 2015)" should be "Kneifel et al. (2015)".

P7 L25: I believe this semicolon should be a comma.

P9 L14-L15: I would be consistent and just refer to "the ratios between radar backscatter cross-sections at 10-35-GHz and 35-95-GHz" as the DWR10-35 and DWR35-95 as already done in the text. This applies to the legend and caption of Figure 2 as well.

P16 L27: "The retrieved timeseries of PSD..." should be "The retrieved time-series of PSD shape..."

P16 L29: "...the retrieved PSD noisy..." should be "... the retrieved PSD shape [factor] is noisy..."

P17 L24: "mixed-phase cloud" should be "mixed-phase clouds".

P17 L25: Should "distribution" be "relation"?

P18 L5: A space is needed after "surface".

P19 L1: "case comprised compact graupel..." should be "case was comprised of compact graupel..."

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2019-100, 2019.