Response to the Editor

Dear Editor,

We would like to express our gratitude to the reviewers for dedicating time to a third review and for providing valuable comments. The comments and suggestions from both Reviewers have been carefully addressed in the revised version of the manuscript. We once more acknowledge the concerns raised by both Reviewers regarding the Rayleigh scattering assumption which is underlying our retrieval. We aimed to provide concise replies to their statements, by basically summarizing what we argued in previous revision rounds and by implementing more text about our motivation and possible future enhancements into the manuscript.

Consequently, we would like to submit the revised manuscript and the diff-version of the revised manuscript together with our responses to all the comments provided by the two reviewers. In our replies, all references to modified lines are given with respect to the final markup/diff-version of the manuscript (with differences).

Response to Reviewer #1:

R1-C1: I am not satisfied with the response regarding the applicability of Rayleigh scattering at Ka band. I do see that you have discussed the characteristics of different scattering models in 2.3, but what I am questioning is the applicability of Rayleigh scattering at Ka band. The four points after "We decided to assume the Rayleigh scattering …" may be used to explain the spheroidal approximation when you are using S/C-band radars, and we know that the Rayleigh scattering is a good approximation at such bands. The critical point is the applicability of Rayleigh scattering at Ka band, but the authors did not discuss this. I hope the authors take this comment seriously, since the current draft left me the impression that we do not need to care about the non-Rayleigh scattering of ice at Ka band. If it is true, you should elaborate it. Otherwise, it is misleading to readers!

R1-A1: We apologize for giving Reviewer #1 the impression that we didn't consider his/her comment. It is right, that Rayleigh scattering is well applicable to C/S band (e.g, Dufournet et al., 2011; Melnikov and Straka, 2013) but recent studies suggest that there is only a modest influence of non-Rayleigh scattering on polarimetric variables (Matrosov, 2021). Matrosov (2021) notes that the possible reason for the smaller influence of non-Rayleigh scattering on polarimetric variables is that they are differential (rather than absolute) quantities representing differences/ratios of radar parameters at two orthogonal polarizations. Indeed, non-Rayleigh scattering seems to have a moderate impact using the VDPS method, as we discussed in R1-A2 of the previous revision cycle. We added the acknowledgement of cm-wavelength radars to Section 2.3 lines 159-172: "*It is well known that the Rayleigh approximation is not always applicable to simulate scattering from individual and large ice particles at wavelengths shorter than C-band, which holds especially for absolute values such as reflectivity factor (Lu et al., 2016). At shorter wavelengths, the direct dipole approximation (DDA, Draine et al., 1994) can be used to simulate scattering of individual ice particles having a complex shape. Meanwhile, extensive databases exist (Lu et al., 2016) and found, e.g., special attention already for the application of multi-wavelength radar studies (Von Terzi et al., 2022). However, these simulations and associated studies are often limited to a number of predefined shapes and therefore do not necessarily represent the realistic distribution of ice particles observed by a radar (Leinonen et al., 2018). Simulations for a single particle also do not reflect the volumetric scattering effects of a large population of hydrometeors. In general, ice particles in a scattering volume have arbitrary shapes and the contribution of individual particles to the backscattering radar observables and especially polarimetric quantities is averaged out (Matrosov, 2021; Von Terzi et al., 2022). We decided to assume the Rayleigh scattering and the spheroidal particle approximation (Matrosov et al., 1991, Ryzhkov et al., 2001, Bringi et al., 2001) because (1) such a model explains general polarimetric scattering effects* *with just a few parameters (axis ratio, permittivity and canting angle), (2) the model parameters are well constrained by the observations, (3) the volumetric scattering is taken into account, and (4) the model allows a computationally effective derivation of the polarizability ratio.”*

R2-C2: In the conclusion section, I do not appreciate the added discussion on the “shortcomings of the Rayleigh approximation”. You did not discuss the shortcoming of using Rayleigh approximation, please elaborate the SHORTCOMINGS!

R1-A2: As requested, we extended the discussion of shortcomings in Section 2.3 (lines 159-172), See R1-A1), and in the Conclusions Section. We propose to add in the Conclusions Section Lines 513-523: *“Finally, in our study, we are assuming Rayleigh scattering and describe the particle shapes according to the aspect ratio and the permittivity. In reality, ice crystal shapes are more complex and need a more sophisticated scattering method to accurately capture scattering of particles with axis lengths exceeding the range of the Rayleigh scattering regime. This holds definitely true for absolute quantities such as reflectivity at wavelengths shorter than C-band (Lu et al., 2016, Von Terzi et al., 2022). However, a recent study of Matrosov (2021), demonstrates that the influence of non-Rayleigh scattering is weak for polarimetric variables such as LDR. As a likely reason for this behaviour, Matrosov (2021) hypothesizes that polarimetric variables are differential (rather than absolute) quantities representing differences/ratios of radar parameters at two orthogonal polarizations.”*

R1-C3: Regarding the definition of isometric particles, the authors say that “non-spherical particles with low density (low refractive index) also appear to be isometric”. The logic is awkward. Aggregates with low AR are expected to have polarizability ratio of ~1 due to low density, but they are not isometric.

R1-A3: We did not intend to say that particles with low refractive index are isometric. What we mean is that certain particles may exhibit characteristics that make them appear isometric when observed with a radar, although they are not by geometric definition. Reason is that besides the geometric axis ratio, also the permittivity plays a role in the determination of the polarizability ratio. In the case of particles with a low refractive index (i.e., low permittivity), their reduced response to radar waves may lead to scattering characteristics that resemble those of isometric particles. We added Lines 178-180: “In *the case of particles with a low refractive index (i.e., low permittivity), their reduced response to radar waves may lead to scattering characteristics that resemble those of isometric particles*”

Response to Reviewer #2:

I like to thank the authors again for addressing my comments and concerns. I support the publication of the current article and don't want to delay it for another round of reviews and discussion. However, I am honestly a bit disappointed that I could not find answers to two of my main open questions regarding this undoubtedly promising and useful technique:

R2-C1: I cannot really agree with the author's in their argumentation related to the scattering properties: Of course, the radar always measures an average of the single scattering properties of all particles present in a certain radar volume. But how can you be sure the spheroidal Rayleigh approximation is indeed a good approximation for it? I also don't see why a comparison of the spheroidal method with simple solid-ice hexagonal ice plates or columns would be such a problem. Yes, the experiment would not be sufficient to answer whether the spheroidal approximation is accurate for the volume scattering properties, but it would shed light on the question how good the method is for specific situations (distinct shape). If this experiment reveals that the two methods agree well for specific shapes and configurations (orientation etc.), the assumption that the spheroidal method is indeed a good approximation for the volume scattering properties would be strongly affirmed.

R2-A1: Given the concerns raised by both reviewers, we acknowledge that the response of polarimetric parameters to non-Rayleigh scattering is a pressing topic. Unfortunately, this topic is out of the scope of the current study. The intention of our study was to bring the original STSR approach of Myagkov et al. (2016) to the broader community of SLDR radar application. For our study we base our assumption on the applicability of the VDPS method to non-Rayleigh targets on findings from other recent studies, such as the one of Matrosov (2021). As we discussed in R1-A2 of the previous revision cycle, non-Rayleigh scattering seems indeed to have only a moderate impact using the VDPS method. Please also note that we provide further responses to a similar question which was already raised by Reviewer 1 in R1-C1 and R1-C2. We thus kindly refer to our response R1-A1 and R1-A2. We added Lines 524-525 : *"If these are applied to realistic hydrometeor populations, a model-based validation of the hypothesis of Matrosov (2021) shall be feasible.".*

R2-C2: As the question regarding scattering assumptions are still open, a comparison with in-situ observations would be in my view even more important. Certainly, also in-situ methods have their uncertainties, but it would provide the possibility for a direct comparison of retrieved and real particle shape properties. At the moment we can neither be sure about the accuracy of the scattering properties nor about the uncertainty due to other assumptions, such as "same particles are present in the main spectra peak".

R2-A2: Yes, thank you for this remark. It is planned to compare the VDPS method with in situ observations in a currently ongoing campaign in Switzerland to validate the method. Results from this campaign will be available only by 03/2024.

Technical corrections :

R2-C3: L. 178: Add Figure before "2a"

R2-A3: We added Line 180: "Figures"

References:

Dufournet, Y. and Russchenberg, H. W. J.: Towards the improvement of cloud microphysical retrievals using simultaneous Doppler and polarimetric radar measurements, Atmos. Meas. Tech., 4, 2163–2178, https://doi.org/10.5194/amt-4-2163-2011, 2011.

Matrosov, S. Y.: Polarimetric Radar Variables in Snowfall at Ka- and W-Band Frequency Bands: A Comparative Analysis, Journal of Atmospheric and Oceanic Technology, 38, 91 – 101, https://doi.org/https://doi.org/10.1175/JTECH-D-20-0138.1, 2021.

Melnikov, V. and Straka, J. M.: Axis ratios and flutter angles of cloud ice particles: retrievals from radar data, J. Atmos. Ocean. Tech., 30, 1691–1703, doi:10.1175/JTECH-D-12-00212.1, 2013.