

Reply to comments of Reviewer #1:

We would like to thank Reviewer 1 for their helpful comments. Our reply to each of Reviewer 1's comments and changes to the manuscript based on them follow.

Comment: page 2, line 26: 'Examples of publically available numerical methods capable ...'

I must comment here that not all of these methods are publicly available as usable codes, only as algorithms.

**Reply: This is true. 'publically available' was removed.**

Comment: page 2, line 34: You missed the database by Kuo et al. (2016). They use random orientation. There is also the database by Tyynela and Chandrasekar (2014), which also uses fixed orientation for ice crystals and it is also publicly available at [http://helios.fmi.fi/\\_tyynelaj/database.html](http://helios.fmi.fi/_tyynelaj/database.html), but the database itself has not been officially published.

K.-S. Kuo, W. S. Olson, B. T. Johnson, and R. Meneghini (2016), The Microwave Radiative Properties of Falling Snow Derived from Nonspherical Ice Particle Models. Part I: An Extensive Database of Simulated Pristine Crystals and Aggregate Particles, and Their Scattering Properties, *J. Appl. Meteor. Clim.* 55, 691-708, doi:10.1175/JAMC-D-15-0130.1

**Reply: Thank you. We have added these two papers to the revised manuscript on page 2 line 34.**

Comment: page 3, line 25: 'As such, we do not use this method ...'

It is unclear what method you are referring to here. Do you mean you are not using cubic lattice? Maybe it would be clearer if you mention that you are not using FFT and that you are using the 'sparse' mode in ADDA.

**Reply: We did not use the DDA method for ice aggregates because the ADDA manual suggests testing the 'sparse' mode before using it and we wanted to avoid any inadvertent errors in its application to aggregates. We will replace 'this method' with 'the DDA method'.**

Comment: page 6, line 14: You are using the dimensional relationship and sizes of needles, but you specify them as columns. These are two different crystal types (N1e vs N1a).

**Reply: Yes, we used N1a. However, we varied the thickness (maximum dimension of the basal face) by factors of 1 and 2, thus roughly covering the range of the N1e crystal types as well. In general, we collectively call these crystals 'columns' rather than 'needles' because they are representative of columnar crystals. We now explicitly state this on page 6 line 14 of the modified manuscript.**

Comment: page 7, line 9: 'In order to retain polarimetric information for each ...'

The motivation seems to be a bit backwards here. To me it seems like the reason for using fixed orientation is that, according to many studies (e.g., Cho et al. 1981, Thomas et al. 1990, Matrosov et al. 2005, Noel and Sassen 2005), some single ice crystal types tend to fall in preferential orientations and that is why we get more information using polarimetric observables.

Cho, H. R., J. V. Iribarne, and W. G. Richards, On the orientation of ice crystals in a cumulonimbus cloud, *J. Atmos. Sci.* 38, 1111-1114, doi:10.1175/1520-0469(1981)038<1111:OTOOIC>2.0.CO;2

Thomas, L., J. C. Cartwright, and D. P. Wareing (1990), Lidar observations of the horizontal orientation of ice crystals in cirrus clouds, *Tellus B*, 42, 211-216, doi:10.1034/j.1600-0889.1990.00001.x-i1

Matrosov, S. Y., A. J. Heymsfield, and Z. Wang (2005), Dual-frequency radar ratio of nonspherical atmospheric hydrometeors, *J. Geophys. Res.* 32, L13816, doi:10.1029/2005GL023210

Noel, V., and K. Sassen (2005), Study of planar ice crystal orientations in ice clouds from scanning polarization lidar observations, *J. Appl. Meteor.* 44, 653-664, doi:10.1175/JAM2223.1

Reply: We do not dispute the reviewer's comment (and the assumption in the papers cited) that some ice particles fall with a preferred orientation. Our database does contain the necessary information to simulate ice particle scattering in such situations. But we can imagine situations where particles deviate from their preferred free-falling orientation, for example, charged ice particles in an electric field, as has been reported in the literature (e.g., Caylor and Chandrasekar, 1996; Hubbert et al., 2014; Hubbert et al., 2010; List and Schemenauer, 1971). Our objective was to provide a comprehensive library to allow users to model any situation.

Caylor, I. and V. Chandrasekar, 1996: Time-varying ice crystal orientation in thunderstorms observed with multiparameter radar. *IEEE Trans. Geosci. Remote Sens.*, 34, 847–858.

Hubbert, J.C., S.M. Ellis, W.-Y. Chang, S. Rutledge, and M. Dixon, 2014: Modeling and Interpretation of S-Band Ice Crystal Depolarization Signatures from Data Obtained by Simultaneously Transmitting Horizontally and Vertically Polarized Fields. *J. Climate and Appl. Meteor.*, V53, pp. 1659 – 1677.

Hubbert, J.C., S. M. Ellis, M. Dixon, and G. Meymaris, 2010: Modeling, Error Analysis, and Evaluation of Dual-Polarization Variables Obtained from Simultaneous Horizontal and Vertical Polarization Transmit Radar. Part II: Experimental Data. *J. Atmos. and Ocean. Tech.*, V27, pp 1599 – 1607.

List, R. and R. Schemenauer, 1971: Free-Fall Behavior of Planar Snow Crystals, Conical Graupel and Small Hail. *J. Atmos. Sci.*, v28, pp. 110 - 115.

Comment: page 7, line 16: 'The right-handed xyz-coordinate system used to describe ... is one important coordinate system.'

The ending seems arbitrary. Why is it important?

Reply: Thank you for pointing out this awkward phrasing. We changed the sentence to read: "We used one right-handed xyz-coordinate system, called the particle coordinate system, to describe the orientations of the ice particles."

Comment: page 8, line 9: 'Unfortunately, the GMM and DDA methods have no efficient ...'

Actually for DDA, there is a way, as described by Mackowski (2002).

Mackowski D. W. (2002), Discrete dipole moment method for calculation of the T matrix for nonspherical particles, *J. Opt. Soc. Am. A* 19, 881-893

Reply: Thank you for pointing out this oversight on our part. Actually, the GMM method can also be used to calculate random-orientation averaged scattering properties (<http://diogenes.iwt.uni-bremen.de/vt/laser/codes/Yu-linXu/Yu-linXu-codes.htm>). This sentence was removed and the logic flow of the paper was not affected by doing so.

Comment: page 11, line 8: 'The residual spread about the best-fit line ... is explained by near field interactions within the crystals.'

This explanation seems like a non-explanation, since DDA includes the near-field interaction between dipoles. You can explain anything with near-field interactions. Besides, for Rayleigh-type scattering, the induced dipole moments should be the same inside the particles, so there is no ‘near-field effects’. If you want to provide an explanation, you should at least argue, how the effective density (mass for a given size) along the horizontal direction is different between the particle types, which will produce differences for Rayleigh-type scattering.

Reply: We added a reference to an earlier paper (Lu et al. 2013) where this is discussed in detail. In short, we can summarize the explanation as follows. For a column, the exciting electric fields of the dipoles are mainly weakened by its neighbors when the incident direction is parallel to the column. For a plate, when the incident direction and the polarization direction are both in the plane of the plate, the exciting electric fields of the dipoles are weakened by its neighbors along the incident direction but enhanced even more by its neighbors along the polarization direction. Therefore, plates have a higher backscattering cross section than columns with the same mass and density. That is, all “Rayleigh scatterers” of the same mass and density are not equal.

Since this idea was discussed in Lu et al. (2013), we prefer not to add the discussion to this paper.

Lu, Y., E. E. Clothiaux, K. Aydin, G. Botta, and J. Verlinde, 2013: Modeling variability in dendritic ice crystal backscattering cross sections at millimeter wavelengths using a modified Rayleigh–Gans theory. *J. Quant. Spectrosc. Radiat. Transf.*, 131, 95–104, doi:10.1016/j.jqsrt.2013.05.008.

Comment: page 11, line 13: ‘Finally, the spread in the backscattering cross sections of aggregates...’

You start this sentence by explaining the spread of the backscattering properties of aggregates, but you switch to explain all the types including single crystals and graupel.

Reply: ‘aggregates’ was replaced by ‘ice particles’.

Comment: page 11, line 27: You can also say that they are Rayleigh-scatterers in this orientation since the dipoles are all in phase.

Reply: We understand what is being said here but we would prefer to stay away from using one person’s name to describe different particles with different scattering properties. The use of the words “Rayleigh scatterer” to describe scattering properties of particles small compared to the wavelength has perhaps led to the idea that small spheres, prolate spheroids and oblate spheroids of the same mass and density scatter in the same way. Using one name to identify three different types of particles with different scattering properties can lead to confusion, confusion that we wish to avoid. In our view, applying a single name to one dimension of a particle complicates matters even further. We hope the reviewer can appreciate our perspective even if they do not agree with it. The following addition to the end of that sentence should serve the same purpose: “...because the thickness of each crystal is much smaller than the wavelength resulting in induced dipoles that are all in phase.”

Comment: page 11, line 30: You should add that, at oblique incidence for wavelength-scale particles, there are both constructive and destructive interference happening for the scattered waves.

Reply: Thank you for pointing out the logic gap. The sentence was added.

Comment: page 12, line 21: It would have been interesting to see the scattering properties plotted as a function of the incidence angle. You already stated earlier that your database is unique in this sense, so why not then show it?

Reply: The effects of the incident angle on scattering properties of particles small compared to the wavelength are discussed from page 11 line 27 to page 12 line 6 for Fig. 5 and from page 13 line 1 to line 7 for Fig. 6d. For particles with sizes comparable to the wavelength backscattering is in the resonance regime and becomes unpredictable. Therefore, a figure with the scattering properties as a function of incident direction does not provide intuitive results for all the particles, and we choose not to include such figures in the paper.