RESPONSE TO REVIEWER #2 (Reviewer's comments in italic)

Analyses of the polarimetric measurement of snow by the Research Scanning Polarimeter (RSP) instrument aboard NASA ER-2 aircraft are reported. Substantial revisions are necessary before the manuscript in its present form is accepted for publication. Below are some specific comments for the authors' consideration.

1) The quality of figures needs to be improved. In particular, the font size for the figure legend of Figure 1 is too small and essentially illegible.

Figure 1 was assembled with the intention of having it of full-page size in the final form of the paper. While we could not control the size in the Discussions phase due to the "slide" format of the draft, we'll work with the editorial office to make sure it will get printed in the right size.

2) For remote sensing applications, the asymmetry factor is not very useful. To simulate polarized radiative transfer in the earth-atmosphere coupled system involving snow surface, the complete scattering phase matrix is needed. For the revisions, the phase matrix associated with the retrieved asymmetry factor should be presented.

This is a very good suggestion. We have added the following figure showing the phase functions elements obtained by averaging, scene by scene, all retrieved minima:

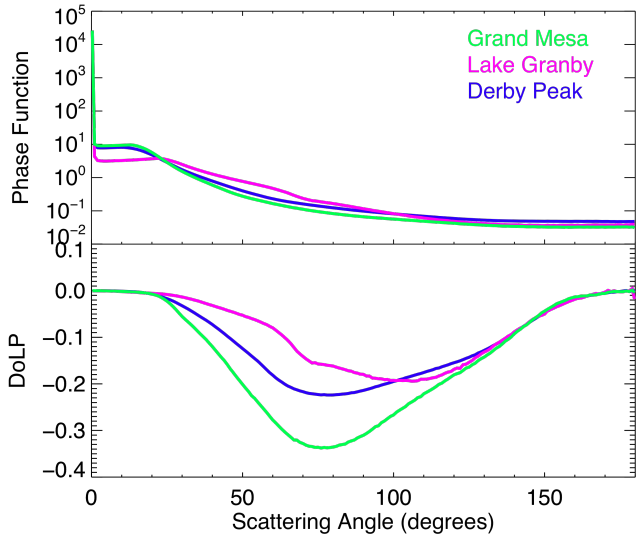

Figure 3. Phase function (*upper panel*) and degree of linear polarization (*lower panel*) resulting from the average over the optimal habits retrieved for each scene,. The color-coding is the same as in Fig. 2.

Also, we have added the following to the text:
"Figure 3 shows the phase function and the degree of linear polarization for each scene, obtained by averaging over all the phase matrices associated with the retrieved minima. The lack of halo peaks in the 20°-40° range of the phase function characteristic of pristine crystals, and the general smooth behavior (except from the strong forward peak) is consistent with the moderate-to-high roughness parameters determined in the analysis."

3) In terms of ice crystal habit model, the manuscript largely cites the work by a coauthor, Dr. van Diedenhoven, assuming hexagonal ice crystals. Over the years, Dr. Bryan Baum and colleagues have extensively considered the effects of various ice crystal habits. However, those studies are completely ignored in this manuscript. Overall, the selection of the references in this manuscript is largely biased.

The database by Yang et al., which is used by Dr. Bryan Baum, contains several different ice habits. However, it has been shown previously that complex habits that are made of hexagonal components (i.e. all habits in Yang's database excluding the droxtal) have phase matrices that closely resemble the phase matrices of the individual components (Iaquinta et al., 1995; Um and McFarquhar 2007; 2009; Fu 2007). For example an aggregate of plates has a phase matrix that is very similar to an individual plate that has the same aspect ratio as the plates in the aggregate. By far the most important properties of these complex crystals determining their scattering phase matrix are the aspect ratio of the components and the level of surface roughness.
In the database of Yang et al., the aspect ratios of (components of) crystals are based on very limited in situ measurements or educated guesses. It is clear from cloud particles observed in situ that particular habits feature a substantial variety of realizations (e.g., Um et al. 2015). The database of Yang et al. does not capture this variation and in our view is therefore too limited for useful implementation in a retrieval algorithm. As noted by Cole et al. (2014), the variation in POLDER measurements could not be captured by the simulations based on the database of Yang et al. The dependency of the assumed aspect ratios of crystal components with crystal size complicates matters further as results depend on the assumed crystal size, as found by Cole et al. (2013, 2014).
Räisänen et al. (TC, 2015) recently attempted to use the Yang et al. database to fit to a limited set of measured phase functions of blowing snow. They constructed a rather arbitrary mixture of habits to fit the data, but, encountering similar issues as described above, they concluded that this mixture "…most probably does not represent properly the actual distribution of snow grain shapes in blowing snow (or snow on ground)."
This rationale is the basis of our approach in which we use single columns and plates as radiative proxies of complex crystals consisting of hexagonal components. This simplification allows us to use a database that contains a virtually continuous

range of aspect ratios and distortion/roughness values. This approach is subsequently rigorously tested. In van Diedenhoven et al. (2012), we calculated simulated measurements based on the database of Yang et al. and applied our retrieval approach to assess the results. All habits in the database (to that date) were included, i.e., droxtals, columns, plates, bullet rosettes, aggregates of columns, hollow columns, hollow bullet rosettes and aggregates of plates, all with three different roughness levels applied to them. A total of 270 combinations of habit, roughness and size distributions are included in the sample. Furthermore the mixtures of these habits created by Baum et al. were used to calculate additional simulated measurements. Asymmetry parameters were found to be retrieved to within 0.04 with a mean bias of 0.004 and standard deviation of 0.018.

In the manuscript, the relative paragraphs and the references have been thoroughly revisited and now are presented as:

"It should be noted that for the specific task of remote sensing of aerosols over snow, a model capable of accurately reproducing the contribution of the surface to the total signal should be considered successful regardless of its capability to mimic the true shape of the crystals. Räisänen et al. (2015) recently attempted to fit measured phase functions of blowing snow by using phase functions of several complex habits provided by Yang et al. (2013) in addition to phase functions of other habits. However, the selection of habits in their study remained limited and to fit the data a rather arbitrary mixture of droxtals, aggregates of plates and Koch fractals was needed, leading them to conclude that this mixture "most probably does not represent properly the actual distribution of snow grain shapes in blowing snow (or snow on ground)". Our approach is based on the recognition that hexagonal plates and columns can be effectively used as radiative proxies for more complex crystal habits (Fu, 2007; Um and McFarquhar, 2007, 2009; Baran, 2009; van Diedenhoven et al., 2012; Ottaviani et al., 2012a). As demonstrated by van Diedenhoven et al. (2012), matching measured polarized reflectances with a look-up table of values simulated by adjusting the aspect ratios and roughness parameters of simple hexagonal particles yields an estimate of the asymmetry parameter of more complex ice crystals within the top of the snowpack. Our database, initially created to be of use for the retrieval of ice clouds properties, contains 765 different combinations of aspect ratios and roughness parameters and was computationally assembled by running Monte Carlo simulations based on geometric optics (Macke et al., 1996), the performance of which was evaluated by van Diedenhoven et al. (2012). The retrieved aspect ratios are interpreted as the mean of the aspect ratios of the components of the complex crystals.''

4) Section 3 "Methodology" needs to be improved. To be more specific, the description of the technical approach used in this study is not clear although the Ottaviani et al. (2012) is cited. A brief summary of the method developed in the previous study will help the reader to better understand this paper.

We agree with the reviewer that the concerning paragraphs can be made less terse. For this reason, we have rewritten them as:
"The method employed for the atmospheric correction procedure is explained in detail in O12, to which the reader can refer if interested in the rigorous mathematical formalism. To provide a brief summary, the signal measured by the instrument is a non-linear function of the surface reflectance due to the interaction of the radiation reflected by the surface with the atmosphere above. For this reason, a linear regression cannot be applied to infer the model parameters. Nevertheless, a cost function with the departure of the model from the measurements can still be computed and minimized, provided the availability of the derivatives (Jacobians) of the radiative transfer model with respect to the descriptive parameters. The Jacobians, generated without extra-computational cost from the linearization of the Doubling-Adding radiative transfer code in use at GISS [deHaan, 1987], are used in an iterative scheme based on an inversion and optimization procedure of the Gaussian-Newton kind [Rodgers, 2000] to search for a minimum of the cost function. The result is the decoupling of the surface and the atmospheric contributions of the total signal measured at instrument altitude, i.e., an automated atmospheric correction. Within this scheme, […]"

5) In the conclusions, the term " a novel analysis" is used. Is the novel method significantly different from the method developed by Roger (2000)? At several places, the word "novel" is used, which should be justified.

The novel character of this study was explained at line 5, page 3063:
"With the exception of O12, the visible and SWIR behavior of the polarized reflectance of snow has not been previously published".
We assume the reviewer refers to the classic textbook by Rodgers (2000) on inverse methods for remote sensing applications. However, no specific (real) data are used in this book, and snow surfaces are not addressed.

6) Please define the "roughness parameter" used in Figure 2 in a quantitative manner (e.g., by using an equation). Because the ray-tracing code developed by Macke et al. (1996) is used, the effect of surface roughness is approximately simulated by randomly titling a particle facet for every incident ray impinging on the facet. This is a statistical approach. The "roughness parameter" for uniformly tilting the facet and that for tilting the facet based on Gaussian distribution are different. Thus, without a clear definition of the "roughness parameter", this quantity has little practical value for downstream applications. Furthermore, when the facet is substantially tilted, the shadowing effect and the effect associated with rays' re-entries into the particle are not considered. Thus, a large "roughness parameter" is unphysical and meaningless.

We agree and regret that the definition of the roughness parameter was left out the first version of the paper. Also, the reviewer is correct that roughness values of up to 1 are unphysical. For this reason the roughness parameter was limited to 0.7 as

described by van Diedenhoven et al. 2012. The following was added to the revised version of the manuscript:
"The microscale surface roughness is statistically accounted for by tilting, for each interaction with a ray, the normal to the crystal surface by an angle randomly selected in the $\delta \cdot [0^\circ, 90^\circ]$ interval, where δ is referred to as the roughness parameter. In our case, δ is limited to 0.7 (i.e., a maximum tilt angle for the facet of 63°) because for higher values the probability of unphysical scattering events strongly increases, resulting in progressively larger loss of accuracy of the GO calculations of a given number of rays. Neshyba et al. (2013) have shown that various other definitions and parameterizations of crystal surface roughness lead to similar results. Yang et al. (2008) found that such approaches are efficient, yet accurate treatments of microscale roughness. Furthermore, the effects of microscale surface roughness and macroscale crystal distortion were shown to be largely equivalent by Liu et al. (2014)."

7) Page 3060, "Fresnel kernel…for vegetated surfaces…": But the indices of air and ice are used (the line below Eq. 3). Furthermore, Fresnel formula is for the reflection and refraction at the interface of two continuous media. However, snow is a densely packed medium. Here (Eq. 3), the application of Fresnel formula needs to be justified. Wonder how much error will be produced if the effective medium theory (e.g., the Maxwell-Garnett mixing rule) is used. Furthermore, polarization state is not considered in Eq. (3). It is confusing how to apply Eq. (3) to the polarized radiative transfer code (De Haan et al. 1987) that fully considers the polarization state of radiation field.

This approach is a standard for polarization instruments like POLDER or RSP (note that gravel-like soils or vegetation canopies are not continuous media either). We have inserted a reference to Waquet et al. ,2009, that specifically addresses the formalism for RSP aerosol retrievals over land.
Regarding Eq. 3, the expression does consider properly the polarization field since Fp is the fractional polarized reflectance, i.e., the fraction of the total incident intensity that gets polarized upon reflection. Exhaustive explanations of the use of this equation can be found in Ottaviani et al. 2012 and references therein:
"Specular reflection is also the basic mechanism governing the reflection properties of most land surfaces, a fact that has been attributed to the smooth wax coating the leaves and to the mineral facets of bare soils [28]. In a reflection event, the Fresnel formulae predict that the component of light perpendicular to the plane of reflection always exhibits higher reflectivity than does the parallel component, in a variable amount that depends on the angle of incidence. For this reason, a specular reflector always polarizes light in a direction perpendicular to the plane of reflection, with the extreme case of 100% of polarization introduced at Brewster angle."
We also modified the line after Eq. 3 with:
"where <u>in our case</u> n1 and n2 are the indices of refraction of pure air and ice".

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