Reply on Anonymous Referee #2 (AMT-2017-50)

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1 Introduction

The comments of the reviewer have been helpful to improve the manuscript. We are especially thankful for the plenty corrections of the text and punctation!

The detailed replies on the reviewers comments are given below.
The reviewers comments are given bold while our replies are written in regular roman letters. Citations from the revised manuscript are given as indented and italic text.

Detailed Replies

It carries the potential to be implemented for existing imagers (MODIS, VIIRS) which, for some reason, is not emphasized in the current version.

We agree that the proposed method could be implemented for MODIS or VIIRS. The reason why we did not highlighted this explicitly is that we think we would have to prove it when making this statement. In the revised version we carefully addressed the possibility to use the method for satellite imagers; once in the algorithm description and once in the conclusions.

> *Except for λ_1, all wavelengths that were chosen for the algorithm are covered by the satellite imagers MODIS and VIIRS. To apply the algorithm to global observations by these instruments, λ_1 can be exchanged by the 1240 nm wavelength band where cloud reflectivity is still most sensitive to $r_{\mathrm{eff,S}}$.*

> *Therefore, the proposed retrieval method has some potential to be implemented for existing spaceborne imagers such as MODIS or VIIRS. Due to the limited number of spectral bands, for these two instrument λ_2 would have to be exchanged by the 1240 nm wavelength band where cloud reflectivity is still most sensitive to $r_{\mathrm{eff,S}}$.*

1) The language, structure and grammar diminish the potential impact of the manuscript because it becomes hard to read as a result. In sections 4 and 5, it was obvious that it had not been fully proof-read, and it seemed premature to afford it a full review at this point in time. It is beyond the scope of a science review to highlight such issues, but a

few examples are listed below. It is in the interest of the authors to revise the language. In some sections (4 and 5 in particular), it could be shortened without losing its content.

We are sorry about the incorrect language and grammar. We revised the manuscript and tried to improve as much as possible. However, as we are no native speakers, we suggest to have a professional copy-editing by the journal. Languages changes in the text can be found in the highlighted manuscript version.

2) In general, the science seems sound. However, it is surprising that the retrieval characterization is done without invoking principles of general inverse theory. This is especially important because the retrieval grid is not orthogonal for the most part. This means that there is no 1:1 mapping from observations to retrieval parameters, as the authors clearly acknowledge. But why, then, is the error characterization and propagation done in a fairly "brute force" way as visualized in Figure 7? In the framework of optimal estimation, one could have arrived at a statistically defensible retrieval characterization on the basis of the a-posteriori co-variance while fully taking into account measurement and model uncertainties. That said, a less rigorous error analysis such as done here is acceptable for initial and exploratory studies, as long as it is categorized as such.

Yes, this is right! To fully understand the uncertainties of the retrieval other statistical methods would have been needed. However, the intention of our study was to illustrate the concept of such a tri-spectral retrieval that allows to combine cloud and snow optical properties. Therefore, we kept the uncertainty analysis simple, also because the retrieval was only applied to two selected cases of specific solar zenith angle and to the nadir viewing direction of the airborne measurements. A more detailed analysis should also take into account the different sensitivities for different viewing geometries. We therefore changed the manuscript at different locations in order to point out clearly, that the manuscript presents only a feasibility study to the method but not a fully developed and characterized retrieval algorithm. A detailed comprehensive uncertainty analysis is beyond the scope of this paper and can be part of studies where the method is applied to a more general data set.

> *In a feasibility study, spectral cloud reflectivity measurements collected by the Spectral Modular Airborne Radiation measurement sysTem (SMART) during the research campaign Vertical Distribution of Ice in Arctic Mixed-Phase Clouds (VERDI, April/May 2012) were used to test the retrieval procedure.*
>
> *In a feasibility study in Section 5, the algorithm that is limited to cases of liquid water clouds is applied to two specific cases,...*
>
> *The retrieval algorithm was tested in a feasibility study for airborne observations by SMART during VERDI in 2012.*
>
> *For this first application of the new tri-spectral retrieval algorithm, a rather simplistic analysis was applied. A more general understanding of the retrieval sensitivities and uncertainties can be achieved by optimal estimation techniques, which is beyond of the scope of this paper.*

*** It should be mentioned somewhere in the manuscript that this study is strictly valid only for snow-covered surfaces with sufficient geometric (and therefore optical) thickness of the snow. The reference to Malinka (2016) is a bit mis-**

leading because it sounds as though white ice could be still be represented as snow. This is in stark contrast to multiple publications by, e.g., Perovich for such cases. They show a distinct spectral dependence in the visible wavelength range, and albedos well below 1.

We are aware that snow and white ice albedo are different at visible wavelengths. But there are reasons why the retrieval approach is still applicable, with larger uncertainties, to white ice or a mixtures of sea ice, open leads or melt ponds. In this cases still more accurate cloud properties compared to methods assuming a fixed snow/sea ice albedo can be derived, because the tri-spectral retrieval considers the change of the spectral albedo at the three wavelengths.

1) Visible wavelengths where white ice albedo and snow albedo have different spectral signatures are not used in the proposed retrieval. At larger wavelengths, where mostly the absorption by ice and not the scattering processes are relevant, the spectral pattern of white ice albedo, which is not water saturated, i.e. dry white ice, is similar to a snow albedo. Therefore, also the snow albedo model used in our retrieval approach can be applied to approximate the albedo of white ice in these spectral ranges. But of course not in the visible part of the solar spectrum. More sophisticated albedo models such as by Malinka et al. (2016) have to be used to construct the full spectral albedo. But then either measurements at visible wavelengths have to be included or information on the effective optical thickness are needed. In the revised manuscript we corrected:

> *Additionally, at wavelengths larger than 1000* nm *the albedo of white sea ice that is not covered by snow and not water saturated, i.e. dry white ice, is lower than that of snow-covered sea ice and, therefore, can be characterized by larger effective snow grain sizes (Malinka et al., 2016).*

2) The retrieval does not provide a retrieval of the full spectral surface albedo. The aim is to retrieve a parameter, the effective snow grain size $r_{\mathrm{eff,S}}$, which determines the surface albedo in the applied snow albedo model. Of course, we can not reconstruct the albedo of sea ice in the full solar spectral range as the snow albedo model does not capture this. Using three wavelengths, only information at these wavelengths are available. Therefore, we can only say that a certain snow albedo model fits best to the measurements at these wavelengths. The snow albedo model used in the algorithm is based only on one parameter, the effective grain size. In this sense, the effective snow grain size is only a parameter defining the most likely surface albedo at the applied wavelengths. That's why we always name it "effective". Considering the "effective" character of $r_{\mathrm{eff,S}}$, also the albedo of white ice can be parameterized using $r_{\mathrm{eff,S}}$ (see 1).

3.) Other common satellite grain size retrievals that are only applied in clear sky condition, such as mentioned and presented in the study, do consider similar snow albedo models that are based only on the effective grain size $r_{\mathrm{eff,S}}$.

4.) However, to avoid larger uncertainties by white sea ice, the cases presented in the manuscript are carefully selected and are dominated by snow-covered sea ice. We highlighted this in the revised manuscript at different positions. E.g.:

> *..., observations have been selected where the surface conditions are close to the required pure snow surface.*

> *Photographs on a flight section in the same area below the clouds showed that the fast ice was partly free of snow, which may have caused the higher variability and the single peak of* $r_{\mathrm{eff,S}} = 300\,\mu\mathrm{m}$

However, the spectral signature of white sea ice and melt-pond-covered sea is close to the spectral albedo of pure snow for the wavelengths used in the retrieval. In that case, the retrieved $r_{\mathrm{eff,S}}$ is interpreted as an effective snow grain size representing an arbitrary surface albedo (white sea ice or melt ponds) with the same spectral characteristics above 1000 nm wavelength as a snow surface with $r_{\mathrm{eff,S}}$.

Furthermore, "white" ice is not explained. What other ice types are there that might be relevant for cloud remote sensing? A wider literature overview may be helpful.

Of course also other sea ice types are relevant for cloud remote sensing. Unfortunately, the proposed retrieval algorithm is not capable of considering these, e.g., blue ice, because of the different spectral albedo. Therefore, the algorithm is proposed for snow-covered surfaces. The only exceptions is the dry white ice, because it approximately can be treated similar to snow of large grains at wavelengths larger 1000 nm. We therefore, do not want to include the definition of other ice types because this might be misleading and give the impression that the retrieval might be also working for such surfaces. Which is not the case. For "white ice" a reference is given in the introduction.

*** p5, L5-11. The reflectance at 1600 nm and 2100 both depend on optical thickness and effective radius; it is simply wrong to decouple them. Figure 2 clearly shows the non-orthogonality of such a lookup table.**

We did not state that both parameters are decoupled. We explicitly state on Page 6, Lines 5-7 that "... the reflectivities at both wavelengths are coupled to both cloud parameters.". Our only idea why the reviewers made this comment is that the sentence Page 5, Lines 9-11 lead to the impression, that the parameters are only linked to one wavelength. This sentence was used to describe the general idea of an bi-spectral cloud retrieval, were the different dependencies are utilized to derive cloud optical thickness and effective radius. To avoid the misinterpretation of this sentence, we rephrased:

The retrieval uses the different dependencies of $\gamma_{1600\,\mathrm{nm}}$ (less-absorbing wavelength) and $\gamma_{2100\,\mathrm{nm}}$ (high-absorbing wavelength) on cloud optical thickness and cloud droplet effective radius and basically follows the method by **?**.

*** Figure 3a/b are nice visuals of the main direction of this paper; perhaps this could be emphasized more.**

To emphasize the major results shown in these plots, we added in the abstract the following conclusions:

he impact of uncertainties of $r_{\mathrm{eff,S}}$ is largest for small snow grain sizes. While the uncertainties of retrieved τ are independent of the cloud optical thickness and solar zenith angle, the bias of retrieved $r_{\mathrm{eff,C}}$ increases for optically thin clouds and high Sun.

*** p8: The "standard deviation" and the "PCA" method are insufficiently explain. What is the data set that these methods operate on? Also, the PCA components don't necessarily have to map to a physical parameter as the manuscript seems to suggest.**

The data set used for these calculations was given in the first sentence of the section. In the revised manuscript, we more clearly described the use of the mean standard deviations to subsets of the simulations by adding the following sentences in the manuscript.

> *E.g., for each cloud, a standard deviation of all simulations with different $r_{\mathrm{eff,S}}$ was calculated. $\sigma_{r_{\mathrm{eff,S}}}$ is then derived by averaging these standard deviations for all different clouds.*
>
> *Similarly, the use of sub samples of the full cloud and snow parameter range investigated here might change the derived values.*

For the PCA it was already stated that we "... applied to the full set of simulations". It is true, that the weightings of the PCA do not necessarily have to map a single physical parameter. But obviously for the set of simulations presented in the manuscript this is the case. To avoid the impression, that this separation is given by theory, we changed the following sentence to:

> *Corresponding to the cloud and snow parameters changed in the simulations, the spectral weights Γ_1, Γ_2, and Γ_3 of the first three principle components are found to be associated with τ (Γ_1), $r_{\mathrm{eff,C}}$ (Γ_2), and $r_{\mathrm{eff,S}}$ (Γ_3).*

*** p10, L10: Using 860 nm as a reference wavelength for the first ratio is probably a bad idea unless the paper specifically limits itself to snow (rather than including ice). This is because (as stated above, and described by Perovich) ice has a distinct spectral shape and albedo magnitude at wavelengths below 1000 nm.**

Yes, for the current version we would like to limit the retrieval to snow covered surfaces and not extend it to other sea ice types. We first would like to illustrate the main idea that information of the surface albedo is still imprinted in spectral radiance measurements above clouds. Therefore, we prefer using measurements at 860 nm because at this wavelength the differences in snow and sea ice albedo is low. Of course, this similarity is completely gone once the sea ice starts melting or its surface gets water saturated. However, dry white ice with some scattering layer on top (of typically granular crystals) is comparable to the snow with not too fine grains. The publication by Malinka et al. (2016) states this exact point.

Also snow impurities do affect the spectral albedo less at 860 nm compared to shorter wavelengths. It is possible, that our approach can be extended to shorter wavelengths in order to detect a drop in the surface albedo at visible wavelengths related to different ice types. But therefore, we would need to use a more detailed snow/sea ice albedo model which is beyond the scope of this study.

*** p10, Table 1: This table is reminiscent of a covariance matrix. Why were these relationships not exploited in the framework of optimal estimation? What is the inverse theory foundation of this work?**

For us, the main intention of this study is to present the feasibility of retrieving cloud and snow properties simultaneously by making use of the spectral information that is provided by spectral measurements of cloud reflectivity. Therefore, we did not set the focus of our attention on the inverse theory but applied rather simple methods; spectral standard deviation and principle component analysis to identify sensitive spectral regions; propagation of normally distributed uncertainties through the retrieval to derive retrieved parameters with uncertainty estimate. As the sensitivities seems sound and the retrieval algorithm already provides reasonable results, we did not put more effort in improving the inverse method at this stage. Therefore, we now pointed out more clearly that the study should be seen as a feasibility study. Later, more detailed analysis of sensitivities and uncertainties may follow. For changes in the manuscript see answer to comment number 2).

Grammar/English:

Thanks a lot for identifying all these mistakes. We are sorry, that these were not found by ourself and collecting all increased your work. We corrected all and tried our best to eliminate other incorrect grammar and typos.