Author reply to referee 1 AMT-2016-123

Dear Reviewer,

thank you for your support and for your suggestions for improving our manuscript.

In general, all reviewers suggest to strengthen the literature review, especially to improve the discussion of earlier publications on imaging ice cloud remote sensing (Schaefer et al. 2013) and the introduction of the visible spectral slope solution for the transmissivity ambiguity (Brueckner el al. 2014 and Le Blanc et al 2015). This is an obvious weakness of our manuscript. The reason for this negligence on our side is partly due to the fact that our manuscript has had a long history already. In our group the spectral slope approach originally goes back to a Master‘s thesis of co-author Petra Hausmann from 2012. We obviously noticed that “our approach“ was published meanwhile in proper journals by others. Even though this is no excuse for gaps in our literature review, it might explain why we do not want to state any direct “use“ or “application“ of ideas introduced by the aforementioned authors. In our revision we do both, we try to strengthen our literature discussion, and at the same time we would like to include the Hausmann Master‘s thesis from 2012 as a reference. Although it is no peer-reviewed publication it is an official university thesis in English language available online.

Point by point reply to all major comments (all minor were considered as suggested apart from the ones mentioned below):

Major comments

1. **Literature review:** One main issue of the manuscript is the insufficient literature review and comparison to recently published studies. This concerns in particular the handling of the ambiguity between transmitted solar spectral radiance and cloud optical thickness as well as to comparisons of the results of the sensitivity study to literature values.

    a. **Ambiguity:** In the current manuscript, a third dimension is applied to the classical two-wavelength cloud retrieval by Nakajima and King (1990) to avoid the ambiguity between transmitted solar spectral radiance and cloud optical thickness. This third dimension is given by a slope-fit/ratio in the visible wavelength range between 485 and 560 nm. Recently, Brückner et al. (2014) published a similar method using ratios in the visible wavelength range for the third dimension. The method presented by Brückner et al. (2014) definitely should be considered and discussed in the current manuscript.

=> The section in the introduction now reads:

Recently Brückner et al. (2014) as well as LeBlanc et al. (2015) presented similar solutions for unambiguous retrievals of optical thickness and effective radius for pointing system without providing imagery. Both suggest the use of spectral slopes in the visible to separate between the two optical thickness regimes. We will present a combination of both, a solution for the transmittance ambiguity using a similar spectral slope (following ideas of Hausmann, 2012) and results for imaging measurements which provide context information on the distribution of optical thickness and effective radius over a large area.

b. **Sensitivity study:** The present manuscript provides a detailed and impressive sensitive study on possible retrieval uncertainties. However, the results should be compared to the results of the sensitivity study given by Schäfer et al. (2013). For a cirrus retrieval adapted to the measurements with a ground-based imaging spectrometer in the visible wavelength range, Schäfer et al. (2013) investigated the retrieval uncertainties of cloud optical thickness retrievals, e. g. including surface albedo and cirrus crystal shape.

We also mention Brückner and LeBlanc at the end of section 3 “Retrieval...“ where we presented our version of the idea and in the section 5 “Summary and Discussion“.
=> We included a comparison to the Schäfer et al results into the discussion section:

Schäfer et al. (2013) also assessed the sensitivity of their ground-based cirrus optical thickness retrieval to variation of certain parameters. The values can not be directly compared to our results, as they only refer to a small number of specific situations regarding observation geometry and cirrus situation and not a large range of combinations as in our sensitivity test. For variation of crystal habit and for small optical thickness up to 1 they showed large relative differences up to 80% with average absolute differences at 0.1. Though such cases are contained in the sensitivity test shown here, average impact over many different situations is smaller. Schäfer et al. (2013) also present large uncertainties for an albedo variation. This is caused by their choice of a test albedo which is extremely different from the measurement situation, while here it was assumed that the general albedo situation can be characterized well and remaining uncertainty has only small impact.

2. **2nd test case:** From my point of view, the discussion of the second test case from 2 October 2012 should be removed from the manuscript. The first case is already sufficient to demonstrate the ability of the introduced cirrus retrieval to give proper results. The manuscript will not benefit from the second case. Of course, it would be nice to have two satellite products to compare, but due to the contamination by low clouds, a comparison will not be significant. Furthermore, the data seem to be overexposed at multiple parts of the image, which may be the reason that no cloud retrieval could be adapted at those parts.

=> We think the second test case should stay in the manuscript.

(1) There is no overexposure in the data. For figure part (a) the color scale was cut at 0.5. We corrected that.

(2) We do not only want to show a single perfect example, but also show an example where the quality is not so good for good reasons (“quality“ was renamed “significance“ following a comment from another reviewer).

(3) This second example is also interesting because it demonstrates the possible advantages of a ground-based method. Looking upward, clouds below the mountain top do not directly affect the retrieval, except that they increase the albedo (in contrast to the satellite retrievals which obviously are affected). Very likely our results are the best possibility to provide a “ground truth“ for cirrus satellite retrievals in such situations. The possible implications of albedo changes by the underlying cloud patches around the sensor

position are also discussed in an additional “spectral albedo“ test case in the sensitivity tests and mentioned for this example. We discuss that in the end of this section:

An interesting aspect of this complex example is the demonstration of the potential of a ground-based method to provide accurate cloud properties compared to satellite methods, especially for thin cirrus. The same quantities are retrieved by both methods, utilising similar wavelength bands, but the ground-based method benefits from its much higher spatial resolution which allows to separate different parts (or layers) of the observed cloudiness. In the ground-based data there might still be an impact of increased albedo (low level cumulus below the instrument). The low levels of significance of our results at larger sensor zenith angles might be a sign of it (see Fig. 12d). Nonetheless the ground-based method is less affected by this problem and generally most likely much better at retrieving thin ice cloud properties than the satellite methods.

Minor and technical comments

1. **Acronyms**: Acronyms are often used several times before they were introduced the first time. Examples are LMU, specMACS, ACRIDICON, MODIS, SEVIRI, CloudSat, CALIPSO. I don’t know if I got them all. Please check all acronyms throughout the manuscript and introduce their full names whenever they are used for the first time.

2. **Indices and units:** Indices and units are sometimes written in italic letters and sometimes in non-italic letters. Throughout the manuscript this happens also for one and the same index or unit. For reasons of consistency you should write all indices and units in non-italic letters.

=>Acronyms: I tried to introduce all acronyms twice, in the abstract and in the main text as required by AMT guidelines. Unfortunately that leads to unreadable sentences in the abstract. I will leave a comment on that to the Copernicus type setting and ask them to find an acceptable solution.

=> Indices and units: Following the AMT guidelines equations and mathematical symbols should be in italic letters. I think this is also true for equation parts in the text. Units should not and I checked these.

11. **Fig. 8, 9, 12:** Please increase font size

=> I increased font size of Fig 8. For Figure 9 and 12 I would prefer a larger image size which also will depend on the later layout.

Reference:

- Hausmann, P.: Ground-based remote sensing of optically thin ice clouds, 89 pages, Master’s thesis, Ludwig-Maximilians-Universität, Munich, http://www.meteo.physik.uni-muenchen.de/DokuWiki/lib/exe/fetch.php?media=intern:abschlussarbeiten:2012:ma2012_hausmann_petra.pdf, 2012.