# Review of AMT-2016-123 by Zinner et al.

This is another in a series of valuable and interesting papers from the community that demonstrate the utility of spectral information for retrieving properties of clouds from passive shortwave remote sensing. It focuses specifically on cirrus clouds based on ground-based spectral imaging. The challenge for this type of cloud is the small optical thickness combined with a high degree of spatial variability, as well as the unknown composition in terms of crystal shape and roughness. Transmittance measurements of liquid and ice clouds alike also suffer from the ambiguity of the relationship between optical thickness and downwelling radiance, where an increasing number of cloud particles initially increases the amount of diffuse radiation that is scattered out of the direct beam and towards the sensor. At larger optical thickness (generally above four), attenuation decreases the downwelling radiation below clouds. The resulting ambiguity of a low- and a high-optical thickness retrieval for one radiance observation was tackled through several avenues (thorough literature reviews are provided by *McBride et al.* (2011) and *Brückner et al.* (2014); this paper is a bit sparse in this regard; a reference list is given at the end of this review). The solution to the ambiguity problem was found by *LeBlanc et al.* (2015) by introducing the spectral slope around 550 nm, but neither this nor a similar paper by *Brückner et al.* (2014) were based on an imaging spectrometer as done in the current manuscript. Figure 6 and the accompanying text from *LeBlanc et al.* (2015) are included below for clarification as the genesis and physics are not very well described by the manuscript in its current form.
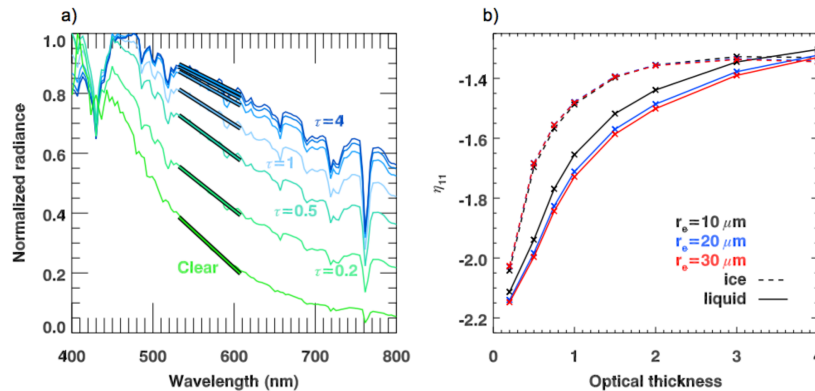
Figure 6. (a) Normalized transmitted radiance of liquid water clouds of varying optical thickness and effective radius of 20 μm and **(b)** the slope of normalized radiance for the wavelength range of 530–610 nm, η_{11}, as a function of τ for ice and liquid clouds, evaluated for three different effective radii. In **(a)**, the slope in the visible is identified by the highlighted region. The normalized radiance spectra and the η_{11} calculated from them were modeled with ancillary inputs based on 25 May 2012 for a solar zenith angle of 50°.

Quote from LeBlanc et al. (AMT, 2015): For clouds with $\tau < 4$, where radiance in the mid-visible is still increasing with τ, the normalized transmitted radiance spectra show an influence from molecular scattering. The spectra in Fig. 3a for $\tau = 0.2$ matches more closely the clear sky spectra, which is inversely proportional to the fourth power of the wavelength, than the normalized radiance spectra for $\tau = 100$, which is roughly proportional to the inverse of the wavelength. As τ is reduced, the magnitude of signal at wavelengths between 550 and 700 nm decreases and its slope becomes more negative until they match the spectrum of clear sky. The clear sky spectrum (green spectrum in Fig. 3a) is entirely dependent on scattering by molecules (Rayleigh scattering) and the solar zenith angle. The slope of the spectrum in the visible is proportional to τ until scattering by cloud particles dominates scattering by molecules. This transition occurs at lower τ for ice clouds (near 1) than liquid clouds (near 2), obscured by radiance

transmitted through optically thicker clouds in Fig. 3. After this transition, the slope of normalized radiance in the visible varies less and depends on τ, re, and ϕ, rather than on molecular scattering. Similar results are also observed by Brückner et al. (2014), where instead of a slope in the mid-visible, they used a ratio of transmittance at 450 and 680 nm.

The other noteworthy paper needed to put this manuscript into context is the one by *Schäfer et al.* (2013), which sought to capitalize on *imaging* (i.e., radiance measurements as a function of viewing angle) to derive optical thickness and habit information from transmitted radiance.

Since the manuscript emphasizes (p3, l16-19) that it combines spectral information with imaging for the solution of the ambiguity problem mentioned above, it should discuss *Brückner et al.* (2014), *LeBlanc et al.* (2015), and *Schäfer et al.* (2013) properly (*Brückner et al.* (2014) is currently not cited). At the very least, it should briefly describe how these three papers resolve the ambiguity. This would show that the current manuscript actually pursues the same method as introduced by *LeBlanc et al.* (2015) (not only by using the same spectral slope, but also by normalizing the radiance spectrum first) with the exception that the current manuscript uses *fewer* spectral parameters than the LeBlanc paper; on the other hand, the *imaging* capabilities that the *Schäfer et al.* (2013) manuscript relies on are not used to resolve the ambiguity; instead they serve to provide context measurements. For these reasons, the statement "We will present a combination of both, a solution for the transmittance ambiguity…" should be revised to reflect that the same or a similar approach as employed by the *LeBlanc et al.* (2015) and *Brückner et al.* (2014) papers was used here. Instead of making this clarification at this point, it may be more appropriate in Section 3.1 where the idea is introduced (either way, the proper credit to the origin of the idea should be given). In the same vein, the statement "a new method for the retrieval of ice cloud optical thickness … from transmitted radiance" in the summary is probably not quite correct, since the additional observable (spectral slope in the mid-visible) had been proposed earlier.

Notwithstanding the minor concern about the origin and genesis of the idea, the manuscript provides a valuable new perspective on the challenges that are encountered when retrieving cirrus cloud optical properties (as mentioned at the beginning of this review). The direct inter-comparison of ground-based retrievals with concurrent satellite observations (geostationary and polar-orbiting) seems especially valuable, revealing that there may be significant differences even from satellite to satellite retrieval that need to be resolved in the future. The main suspect for the discrepancies between the different algorithms are the insufficiently constrained scattering phase functions for cirrus clouds. Spectral imaging is probably the method of choice for resolving this problem in the future, and the manuscript is a nice step towards addressing it. The sequential comments below outline some doubts about the methodology on how the phase function (crystal shape) related biases are estimated, but those, as well as all the other suggested changes should be fairly easy to implement in the revised manuscript.

Sequential major comments:

P2, L27: King et al. (2004) is the wrong reference for the adaptation of the Nakajima/King algorithm to ice clouds. At this point, the MODIS retrievals were already fully operational. One of the Platnick references is probably more appropriate; the cited paper is for the retrievals over bright surfaces, an entirely different problem. A nice review of ice cloud retrievals (with emphasis on the problematic phase function) is provided by *Wang et al.* (2014).

P3, L16: Clarify (here or later) that *LeBlanc et al.* (2015) used the spectral slope of normalised mid-visible transmittance (or radiance), and that this is what the algorithm in this manuscript relies on as well (rather than using the *combination* of the spectral slope and imaging capabilities, as the subsequent sentence implies). See also the comments on pages 1 and 2 of this review. Also change this appropriately at later occurrences (for example in the summary); it should be stated that the idea for resolving the ambiguity problem was first introduced by the 2014 and 2015 papers.

P4, L24: 16 streams seem too few to properly resolve the features of the scattering phase function unless the cited intensity correction works properly for small and medium optical thickness values (single or low-order scattering) – this is of course especially true for scattering angles near the halo angles or other pronounced features. It would be highly recommended to show a plot of simulated downwelling radiance as a function of viewing angle such that the ability of the RT code to simulate the halo in the right place becomes credible. Too few streams in the solver may misplace the halo despite the application of the intensity correction. Perhaps such a plot could be added in an appendix?

Section 2.2.2, optical properties: Using all six habits from "HEY" may not be appropriate since some of the habits are highly unlikely to occur in the study region. The authors do mention that the errors due to crystal shape represent an upper bound for this reason, but even that may not be correct if a certain habit does not occur at all in the kind of cloud that is observed. This point, combined with the previous one (are the features of the phase functions are resolved by the intensity-corrected 16-stream radiances?) cast some doubt on the concluded magnitude of the bias due to unknown habit.

Section 2.2.3, surface albedo: MODIS surface albedo products are known to have problems in regions with pronounced topography. Given that, why was the sensitivity to surface albedo and its uncertainty not tested in similar ways as done for the other parameters (see table 1)? This seems even more important than testing the sensitivity to the presence of aerosols.

P6, Eqn (2) This parameter is equivalent to η_{11} from *LeBlanc et al.* (2015), except that they used radiance (not transmittance) to derive it, which is conceptually the same – see also previous comments.

P6,l24: "Consequently, it is *now* possible to…" See comments above (origin/genesis).

P7,l10: Why does the LUT only include three different relative azimuth angles? Can this be justified by the geometric arrangement and a special sun-viewing geometry? The relevant angle for near-single scattering remote sensing (i.e., up to about 1 optical thickness) should be the scattering angle, not the viewing zenith + azimuth angle, correct? This may only be a minor point – however, typical LUTs usually feature more than the azimuth angles used in this study, so the question is why this study can get by with so few. A plot that shows the dependence of the radiance on viewing azimuth angle for a small optical thickness would help giving some credence to the approach. Combined with an earlier suggestion: The approach can only be regarded as sound if the halo (or another feature) can be simulated in the right place (in the 2D image) and resolved both in viewing zenith and azimuth angle.

P8,Eqn 3: It is unclear why the three terms (T550, T1600, SVIS) are each given equal weight in determining dT. After all, the measurement uncertainties propagate into each of these in different ways, and the individual terms should be weighed by their (different) uncertainty, rather than applying a global weight for the different LUT points as proposed in Eqn 5 later on.

P8/P9: Related to the comment above: How is the uncertainty in COD and REFF derived from the uncertainty in the measurements (the radiances)? dT cannot be regarded as a metric for the uncertainty because it is a merely technical quantity which would change for a different LUT gridding. Also, trading standard deviation for uncertainty as done on p12,l20-21 does not help. How do we know for certain that the error does not exceed the standard deviation? Particularly for small crystal size (on the order of 10-20 micron) and the optical thickness range shown, the effective radius may be highly uncertain because of the issues described by *McBride et al.* (2011). An error propagation analysis from the radiances to the retrieval parameters should be performed, not in terms of the LUT gridding, but in terms of the underlying physics. This is probably the most work-intensive revision that is suggested in this review.

P10,L9: See earlier comment concerning the azimuth vs. scattering angle. Azimuth does not seem to be the appropriate parameter to consider for singe-scattering conditions.

P10,l22-23: Would it help to limit to such habits that can realistically occur for the type of cloud under consideration? What about the distinction between habit and surface roughness (which seems to have a larger role than the habit when it comes to smooth versus "featured" phase functions)? Is it possible to say something about the roughness using the imaging capabilities of the instrument (in the vein of the Schäfer paper)?

P12,l20-21: See earlier comment: The standard deviation cannot replace a physics-based error analysis. Also: The impact of surface albedo uncertainty should be part of the retrieval error, unless it is deemed to be negligible.

P14,l16 & l18-20: Please consider earlier comments regarding the origin of the "*new third parameter*" for the removal of the ambiguity.

P16,l1-5: I commend the authors on tackling the arduous task to reduce the retrieval uncertainty due to crystal shape using spectral imaging!

Sequential minor comments (language/typos):
P1,l1: "for retrieval of" → "for *the* retrieval of" ?
P1,l7: delete "unknown" ?
P1,l7: typo with "." and "," at end of line
P1,l10: "be caused" → "arise" ? (sounds awkward otherwise)
P1,l11: "For optical…" Sentence does not make sense, perhaps because of the first "are"?
P4,l19: "We have used" → "We used" ?
P6,l27: "needed" → "required" (sounds a bit less awkward)
P10,l8: "on illumination" → "on other illumination" ?
P11,l16: duplication of "presented"

References:

Brückner, M., B. Pospichal, A. Macke, and M. Wendisch (2014), A new multispectral cloud retrieval method for ship-based solar transmissivity measurements, J. Geophys. Res. Atmos., 119, 11,338–11,354, doi:10.1002/2014JD021775.

LeBlanc, S. E., Pilewskie, P., Schmidt, K. S., and Coddington, O.: A spectral method for discriminating thermodynamic phase and retrieving cloud optical thickness and effective radius using transmitted solar radiance spectra, Atmos. Meas. Tech., 8, 1361-1383, doi:10.5194/amt-8-1361-2015, 2015.

McBride, P. J., K. S. Schmidt, P. Pilewskie, A. S. Kittelman, and D. E. Wolfe (2011), A spectral method for retrieving cloud optical thickness and effec- tive radius from surface-based transmittance measurements, Atmos. Chem. Phys., 11(14), 7235–7252, doi:10.5194/acp-11-7235-2011.

Schäfer, M., Bierwirth, E., Ehrlich, A., Heyner, F., and Wendisch, M.: Retrieval of cirrus optical thickness and assessment of ice crystal shape from ground-based imaging spectrometry, Atmos. Meas. Tech., 6, 1855-1868, doi:10.5194/amt-6-1855-2013, 2013.

Wang, C., P. Yang, A. Dessler, B. A. Baum, and Y.-X. Hu, 2014: Estimation of the cirrus cloud scattering phase function from satellite observations *J. Quant. Spectrosc. Radiat. Transfer, 138, 36-49*.