We’d like to thank the editor for handling our manuscript, as well as reviewer #3 for reading our manuscript and providing numerous, helpful comments. We have carefully read through all the comments and questions and revised the manuscript accordingly. Please find our point-to-point response to reviewer #3 below. Here, the reviewer’s general remarks are formatted to be left-aligned text in italic font, the specific questions/comments are shown in left-aligned text in bold and italic font, while our responses are indented and formatted in regular font.

Point-to-point Response to Anonymous Referee #3

Received and published: 16 September 2016

General

The paper addresses an important research question on the applicability / validity of 1D radiative transfer calculations for high spatial resolution cloud property retrievals. Thereto the authors adapt an existing retrieval scheme for large pixels from MODIS to small pixels from ASTER.
This paper fits well into AMT. The scale dependence of cloud property retrievals is very important question and the research is very relevant for interpretation of satellite cloud retrievals.
The paper is well-written, contains important results based on solid work, and will probably lead to future papers on the same topic. The number of figures is large, and could possibly be reduced. The paper can be accepted when the following comments are taken into account.

Main comments:

(1) The complication of atmospheric absorption in the wide VNIR band of ASTER (channel 3) is hardly discussed. Atmospheric correction has a much stronger effect for ASTER due to its broad VNIR band than for MODIS. In the broad VNIR channel of ASTER, the O2 A-band absorption and H2O band absorption play a large role. Please describe how you correct for these atmospheric absorption bands. The correction will depend on cloud height: the lower the cloud, the more correction is needed. Please show the sensitivity of the correction to cloud height. Please show the atmospheric absorption spectrum together with the spectral response function of the instrument bands in Figure 1.

> The reviewer is correct, in that the ASTER VNIR band includes the alpha band of atmospheric oxygen, as well as absorption features by atmospheric water vapor. This means that atmospheric correction (and uncertainties associated with atmospheric correction) will be more important for ASTER than for MODIS. Figure 1 of this reply shows the ratio of atmospherically corrected to uncorrected (measured at top-of-atmosphere, TOA) reflectance in the (a) VNIR and (b) SWIR bands as a function of cloud top height z_{top}. ASTER data is shown in black; MODIS data is shown in green.
>
> As expected, the ratio (both in the VNIR and SWIR) approaches unity for large z_{top}, whereas the atmospherically corrected reflectances increase (compared to TOA reflectances) with decreasing z_{top}.

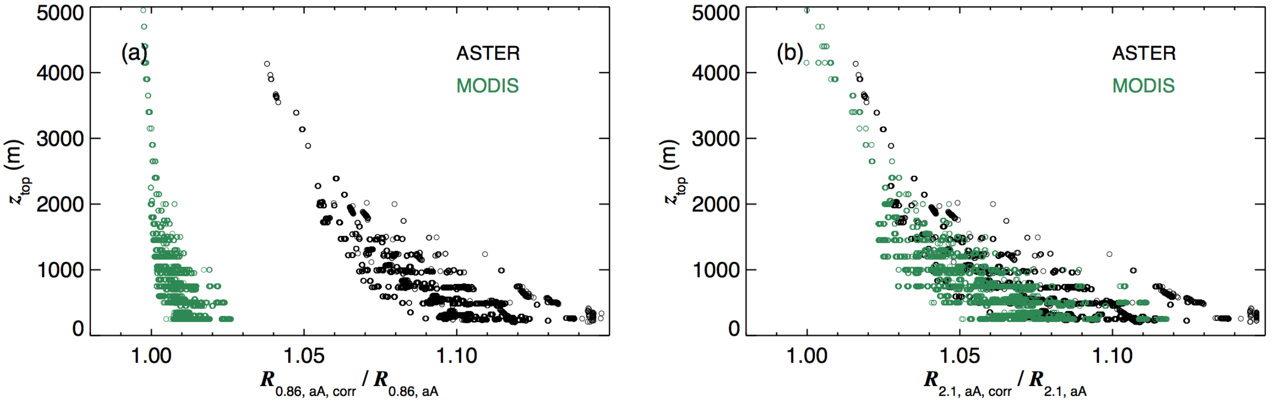

Fig. 1.: (a) Ratio R_{cor}/R_{toa} as a function of z_{top} for the VNIR band of both ASTER and MODIS. z_{top} has been assigned to the y-axis. (b) Same as (a) but for the ASTER and MODIS SWIR bands.

We calculated the sensitivity S of this correction as follows:

$$S = \frac{d(R_{cor}/R_{TOA})}{dz_{top}} \cdot \frac{z_{top}}{R_{cor}/R_{TOA}} = \frac{d\ln(R_{cor}/R_{TOA})}{d\ln(z_{top})},$$

where R_{cor} indicates the atmospherically corrected and R_{toa} is the uncorrected (measured at TOA) reflectance. This definition of sensitivity follows the relative sensitivity (susceptibility) definition used in e.g., Feingold et al. (2003), Werner et al. (2014) and others.

For the SWIR band both ASTER and MODIS are characterized by very similar sensitivities of -0.025 and -0.024. The negative sign indicates the decrease of the ratio R_{cor}/R_{toa} with increasing z_{top} . For the VNIR band, conversely, S is about four times higher for ASTER than for MODIS, with values of -0.021 and -0.006, respectively.

However, the applied atmospheric correction scheme uses the exact same ancillary data sets and algorithms as the operational MODIS C6 retrieval. Details of this algorithm are documented in Section 3.2.2 of the manuscript and the referenced literature. This means that the same well tested and successfully applied atmospheric correction scheme is used for both ASTER and MODIS in our comparison. While it is true that uncertainties associated with this scheme will induce larger uncertainties in the ASTER VNIR band (compared to MODIS), the very good comparison of ASTER and MODIS reflectances (see Figure 13) and subsequently retrieved cloud optical thicknesses (see Figure 14) give us confidence that the atmospheric correction scheme works reliably.

Based on the reviewer's suggestions, we made the following changes to the revised manuscript:

(i) We added atmospheric transmittance lines, based on atmospheric profiles for the U.S. 1976 Standard Atmosphere and simulations with the moderate resolution atmospheric transmission (MODTRAN) version 4.2r1. These curves show the absorption features of the O_2-Alpha band and atmospheric water vapor.

A brief description of these features is added to Section 2.3:
"The center position and width of the ASTER VNIR band implies that measurements are affected by important absorption features of atmospheric oxygen (O_2-A band around 0.760μm) and water vapor (mainly between 0.810-0.840μm). These features become apparent in the atmospheric transmittance spectrum T_{atm} (grey), which was derived by simulations with the moderate resolution atmospheric transmission (MODTRAN) code version 4.2r1 (Berk et al., 1998), assuming profiles for atmospheric gases following the U.S. 1976 Standard Atmosphere. The atmospheric correction scheme, which accounts for these absorption features, as well as the associated uncertainty is described in Section 3.2 and 5.4."

(ii) We added the sensitivity discussion in the "Uncertainty Contribution" section (5.4):
"Because the ASTER VNIR band covers absorption features of atmospheric oxygen (O_2–A band) and water vapor, it is more sensitive to the atmospheric correction scheme than the respective MODIS VNIR band. The sensitivity has been derived by means of a susceptibility analysis, similar to the method described in Werner et al. (2014). The susceptibility *S* is defined as the relative change of the ratio of uncorrected to corrected reflectance (^R0.86,aA/R0.86,aA) with a change in cloud top height z_{top}, which for the collocated ASTER VNIR data can be written as:

$$S = \frac{\mathrm{d}(R_{\mathrm{cor}} / R_{\mathrm{TOA}})}{\mathrm{d}z_{\mathrm{top}}} \cdot \frac{z_{\mathrm{top}}}{R_{\mathrm{cor}} / R_{\mathrm{TOA}}} = \frac{\mathrm{dln}(R_{\mathrm{cor}} / R_{\mathrm{TOA}})}{\mathrm{dln}(z_{\mathrm{top}})} \quad . (5)$$

Deriving *S* for all 48 MBL cloud scenes yields similar values of −0.025 and −0.024 for the ASTER and MODIS SWIR bands, respectively, indicating a similar sensitivity towards the atmospheric correction for both instruments. Conversely, *S* in the VNIR bands is −0.021 (ASTER) and −0.006 (MODIS), indicating that measurements in the ASTER VNIR band

> are significantly more sensitive to the atmospheric correction scheme than the respective MODIS measurements. This also implies that sampled reflectances in the ASTER VNIR band are more susceptible to uncertainties in the atmospheric correction scheme. However, the research–level retrieval algorithm presented in this manuscript employs the same ancillary data sets, as well as the extensively documented and tested atmospheric correction algorithm implemented in the operational MODIS C6 code. The good agreement between ^R0.86,aA and ^R0.86,M, shown in Figure 13(e)–(f), can be attributed to the reliability of this scheme.”

(2) Can you already give conclusions on 3D effects seen in cloud retrievals from ASTER?

Because the scope of this paper is to prove the documentation of the retrieval algorithm and the feasibility of cloud property retrievals with ASTER, the data shown in this manuscript do not provide the means to discuss impacts of 3D radiative effects. In fact, we aggregated the high-resolution ASTER observations within the MODIS resolution, thus intentionally reducing the native ASTER resolution to the same 1km. The only high-resolution retrieval results are shown exemplary in Figures 7-8, providing (naturally) much more detail than the MODIS retrievals.

However, based on this study and the documented retrieval algorithm, we are currently working on a study on the scale dependence of the plane-parallel bias, using high-resolution ASTER data. We are also working on a manuscript that uses the theoretical framework presented in Zhang et al. (2016) to correct for the plane-parallel bias based on subpixel reflectance variability. A third study concentrates on partially cloudy pixels and i) whether MODIS can reliably discriminate between overcast and PCL pixels, ii) some MODIS retrievals are biased because of a false overcast classification and iii) whether high-resolution retrievals over overcast and PCL pixels (the cloudy part) differ and how this changes with scale.

This first manuscript, which details the ASTER retrieval algorithm and proves the feasibility and reliability of the ASTER results, provides the technical basis for these future studies.

Minor and textual comments:

Abstract:

l. 8, l. 10, etc.: symbols with subscripts lead to too heavy notation. Please shorten where possible.

> The subscripts are necessary to distinguish between the LUT, MODIS, ASTER and aggregated ASTER variables without introducing new variable notations for each quantity. We carefully considered shortening all subscripts throughout the manuscript. While we decided to keep the wavelength designation (i.e., "0.65", "0.86", "2.1"), we shortened the subscript "AaM" (ASTER aggregated in MODIS) into "aA" and "LUT" into "L" (similar to "A" for ASTER and "M" for MODIS).

\gamma is a strange symbol for reflectance. Please use R or \rho.

> We used \gamma to follow the notation on page 159 in Wendisch and Yang (2012). However, since it is technically not the BRDF we are discussing and since in satellite remote sensing capital R is more widely used, we agree that \gamma is not the best symbol choice. We changed it throughout the manuscript.

l. 13: There are too many details in the abstract.

> We shortened and simplified the abstract by leaving out information about the subpixel cloud cover, scene statistics and the variable names for the atmospherically corrected reflectances.

l. 20 ff: So is 1D retrieval good enough at these small scales? This is an important finding. Are there biases due to 3D RT for fully cloud covered pixels ? The effect of broken clouds on biases in reff is well known for 1D RT clouds. (E.g. Wolters et al., JGR, vol. 115, D10214, doi:10.1029/2009JD012205, 2010).

> As mentioned in our reply to "Main comment #2", the statistical comparison presented in this manuscript is performed with co-located ASTER observations, which are derived from an aggregation of the high-resolution data within the MODIS geometry. This is done because we want to document the ASTER retrieval algorithm and prove the feasibility of a cloud property retrieval from ASTER observations. The only high-resolution retrieval results in the manuscript are shown exemplary in Figures 7-8. The only conclusions that can be drawn at this point, qualitatively, are i) that there is a good agreement in the patterns and absolute values of τ and r_{eff} and that there is (naturally) a lot more detail in the high-resolution retrievals. We point these facts out in Sections 4.2 and 6.

Section 1: At the end of the introduction, please briefly outline the setup of the paper.

We included a brief outline at the end of Section 1:
"The manuscript is structured as follows: an overview of ASTER and MODIS, as well as difference between important spectral bands of the two instruments, is given in Section 2. The applied cloud masking scheme and the ASTER–specific cloud property retrieval algorithm are presented in Section 3. Subsequently, a comparison of the retrieval products between the operational MODIS C6 and collocated ASTER results is shown in Section 5, followed by summary in Section 6."

l.101: in this spectral range oxygen and H2O absorption might be a problem

The reviewer is correct, in that there are absorption features in the ASTER VNIR band, mainly caused by the alpha band of atmospheric oxygen, as well as atmospheric water vapor.

We detailed all the changes in the revised manuscript in our response to "Main comment #1".

l. 118-120: These solar spectrum references are pretty old. Why not use a modern composite synthetic solar spectrum, like Gueymard (Solar Energy, 2004)?

Indeed, the solar spectra used here are older than the Gueymard spectra. However, these are the solar irradiance values used in the current version of the MODIS retrieval algorithm. To avoid any bias in the comparison between ASTER and MODIS results, we chose to derive reflectances using the same input solar irradiance values. However, these values can be easily replaced by newer spectra in future applications, where a comparison with MODIS is not the focus of the study.

l. 142: Please remove the brackets. This occurs at many places in paper.

We changed it throughout the paper.

l. 312: This correction will depend on cloud top height.

The reviewer is correct, in that the atmospheric correction is dependent on the cloud top height retrieval. The applied MODIS C6 retrieval algorithms use cloud top height as an input for atmospheric correction. As mentioned in the summary, retrieved cloud top heights from MODIS and collocated ASTER retrievals agree well, with mean values of 823m (ASTER) and 670m (MODIS).

We included information about the sensitivity of the ASTER VNIR and SWIR signal to the atmospheric correction scheme in Section 5.4 and also added this small passage to the introduction of the atmospheric correction in Section 3.2.2:

"Atmospheric correction, <u>which is a function of cloud top height</u>, is performed by…"

l. 386: what is the reason of this difference?

We decided to rewrite this section of the paper for a couple of reasons. The most important one is that Figure 5 and the respective discussion did not sufficiently explain the impact of the different SRFs on the retrieval. In the originally submitted manuscript version we only showed a specific case (with a low solar zenith angle).

The revised version includes the following changes:

(i) For two solar and viewing geometries complete ASTER and MODIS LUTs are presented, illustrating that the ASTER SWIR band is always brighter than the respective MODIS band. In contrast, the specific geometry determines, whether the ASTER VNIR band is slightly brighter or darker.

(ii) We include details about the underlying physical explanations for the band differences between the two instruments. Specifically we state at the beginning of the Section:
"The discussion in Section 2.3 showed that there are differences between the VNIR and SWIR SRFs of ASTER and MODIS, which requires the calculation of ASTER-specific LUTs where the spectral scattering properties (i.e., extinction coefficient, single-scattering albedo and scattering phase function) are integrated over the ASTER SRFs."

and:

"The shift towards a larger center wavelength for the ASTER SWIR band yields an increase in scattering efficiency and single-scattering albedo. As a result the ASTER SWIR bands appears significantly brighter than the respective MODIS band …"

Regarding the reviewer's question: In the region of the two VNIR bands there is an increase in extinction efficiency Q_e and a slight decrease in single-scattering albedo ω with increasing wavelength. Regarding the scattering efficiency, both tendencies basically offset each other. This is the reason for the good agreement between both sensors in the VNIR band (and subsequently $f_{0.86,\mathrm{L}} \approx 1$), as well as the visibly white appearance of clouds.

The change in wavelength also affects the scattering phase function and this impact is different from scene to scene.
The impact of the SRFs on the scattering properties is clearer for the SWIR band. As mentioned in the revised manuscript, both Q_e and ω increase with wavelength in the spectral region covered by both SWIR SRFs, leading to the brighter appearance of the ASTER SWIR band.

l. 396-398: what is the physical reason that the ASTER observation is brighter?

Please see out response to the earlier question ("***l. 386: what is the reason of this difference?***")

l. 704-705: Absorption by O2 and H2O in the VNIR band does not only affect above- cloud correction, but also the cloud reflectance itself due to multiple scattering and absorption inside the clouds.

The reviewer is correct. However, these effects are accounted for in the forward model used to generate the LUTs. As mentioned in the manuscript, after the above-cloud atmospheric correction a Rayleigh scattering correction is applied. Both steps are identical to the operational MODIS C6 retrieval.

Figure 2: what kind of scene is this ? what about cloudiness ? please also give the gray scale image of the scene.

This scene is from the RICO campaign (Rauber et al., 2007). It is comprised of a multitude of small, individual trade wind cumuli. Overall, the scene cloud cover is 4%. We added the following information to the manuscript:
"This scene is characterized by a multitude of individual cumuli with small horizontal extent and a low scene cloud cover of $C_A = 0.04$."

The gray scale image naturally looks very similar to Figure 2(a), i.e., the VNIR reflectances. This similarity, and the fact that Figure 2 already contains 6 subfigures (which would get smaller if we added the gray scale image), means that we decided against including the gray scale image in the revised manuscript. However, we included it in this response:

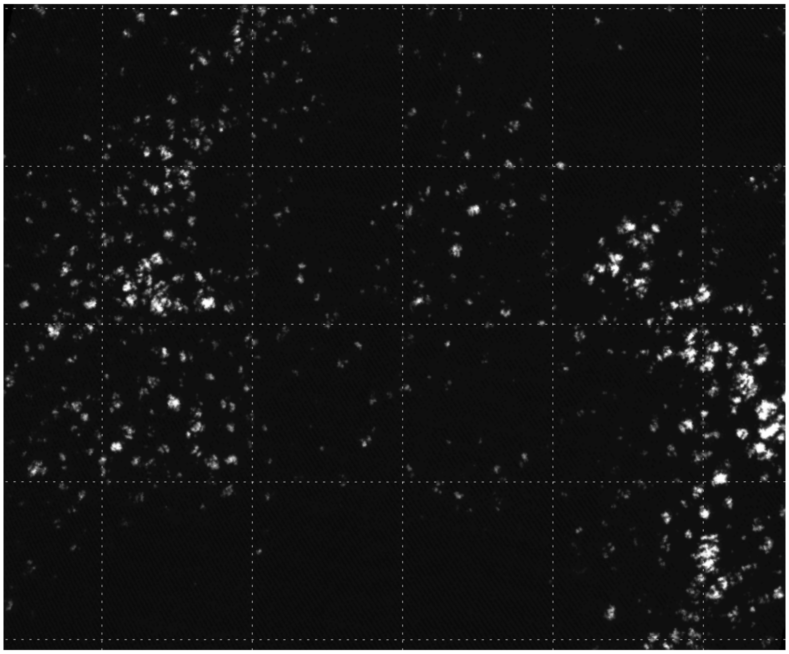

Fig. 2.: Single-band grayscale image of band 3N reflectances sampled by ASTER on 12/02/2004 in the tropical western Atlantic. More information on this and similar cases is provided in Zhao and Di Girolamo (2006) and Zhao and Di Girolamo (2007).

Figure 5: Caption: is the solar azimuth also the viewing – solar azimuth difference, which is the relevant quantity? What is the scale factor?

Please see out response to the earlier question ("***l. 386: what is the reason of this difference?***"). We now include model simulations for two different geometries. The relative azimuth angles are now stated for the two cases, both in text and in the Figure caption.

We referred to the variables $f_{0.86,\,L}$ and $f_{2.1,\,L}$ as scale factors because they resembled the theoretical, scene-dependent scale factor between ASTER and MODIS reflectances in the respective spectral bands. However, we simplified the description and now refer to the variables $f_{0.86,\,L}$ and $f_{2.1,\,L}$ simply as reflectance ratios.

Figure 6: how large is this scene?

ASTER scenes cover an area of 60x60 km. We mention this fact in Line 103.

Figure 7: please refer to the previous figure.

The captions of Figure 7 and 8 now both include the following sentence: "The corresponding single-band grayscale images of ASTER band 3N and MODIS band 2 reflectances are shown in Figure 6(a)-(d)."

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