CLOUD INFORMATION CONTENT ANALYSIS OF MULTI-ANGULAR MEASUREMENTS IN THE OXYGEN A-BAND : APPLICATION TO 3MI AND MSPI

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Dear AMT-D Editor,

The authors would like to thank the anonymous reviewer #2 for his/her comments and suggestions to improve the paper. Please find hereafter our point by point responses to comments and suggested corrections.

General comments:

This paper reports theoretical results of retrieving cloud top height and geometrical thickness from simulated multi-angular TOA radiances in the oxygen A-band. The authors carry out a sensitivity study of the A-band radiance ratio to cloud height and thickness. Using the Shannon information content analysis they compare the information content of two future multi-angular satellite instruments: 3MI and MSPI. They conclude that the retrieval of cloud height is possible with high accuracy in almost all cases investigated while the retrieval of cloud thickness is possible for optically thick clouds above a black surface only. The paper subject is appropriate to AMT. The paper contains significant original material that can be of interest for the developers of operational cloud algorithms for 3MI and MSPI. Earlier work is adequately recognized and credited. The abstract provides a sufficiently complete summary of the paper. The paper is well organized and clearly presented. I recommend the paper for publication after the authors address to the following comments.

Specific comments:

Introduction.

When the authors mention that the cloud cover vertical distribution has a significant impact on meteorological processes they may want to add the following reference that describes detection of multi-layer clouds using satellite passive instruments:
J. Joiner, A.P. Vasilkov, P.K. Bhartia, G. Wind, S. Platnick, and W.P. Menzel, Detection of multi-layer and vertically-extended clouds using A-Train sensors, Atmospheric Measurement Techniques, 3, 233247, 2010.

Thanks for this suggestion. We added it in the introduction along with other relevant references:

l.26: + For example, Jonhansson et al. (2015) show that cloud vertical structure has a strong impact on the summer monsoon over the Indian subcontinent. Furthermore, cloud vertical extent plays a crucial role in the radiative budget of the Earth (Ohring and Adler, 1978) and this effect is still poorly understood, especially for low clouds (L'Ecuyer et al., 2008).

Section 2.3.

*Only a single layer model of clouds is used in the radiative transfer simulation. It is know that two layer clouds can substantially differ in terms of absorption/scattering from the single layer clouds (*see e.g. Vasilkov et al., JGR,113, D15S19, 2008 for the Raman scattering case). *I strongly recommend to consider the two layer model of clouds in the future study.*

We fully agree with the reviewer's comment and in fact the question of vertical inhomogeneity is being studied already as part of a follow-up analysis. As raised by Dr. Loyola in another comment on this paper, the impact of vertically inhomogeneous cloud is indeed very relevant and multilayer situation can be treated as an extreme case of a vertically inhomogeneous clouds. The authors are currently investigating this question and such a comprehensive study is currently ongoing as part of the lead author's PhD work.

We added the following:

l. 75: + But our study remains limited to homogeneous single-layer clouds without aerosols.

We also added a clarification about the applicability of our results with respect to 3D effects and vertical cloud inhomogeneity, as follows:

In the section 2.3:

l. 179 : + and we only considered homogeneous single-layer clouds without aerosols.
For the sake of simplicity, our study is limited to the cases of homogeneous single-layer clouds without aerosols. Conclusions could be different in presence of cloud inhomogeneity and 3D effects, and with aerosols above the clouds, as they can have strong impacts on multi-angular measurements. [Loeb and Coakley, 1998; Buriez et al. 2001; Várnai and Marshak, 2007; Di Girolamo et al., 2010; Liang and Di Girolamo, 2013]. Furthermore, Heidinger and Stephens (2002) show that 3D structures modify the photon mean path-length and hence the O2 absorption in *reflected* A-Band radiances, but it remains unclear how 3D effects can modify its distribution when observed under multi-angle geometries. In contrast, there have been several theoretical, computational, and observational studies have addressed the effects of 3D cloud structure on *transmitted* A-Band radiances and derived path-length statistics; see Davis et al. (2009), Davis and Marshak (2010), and references therein.

And in the conclusion:

l. 528: + This study is restricted to homogeneous plane-parallel clouds, but cloud inhomogeneity and 3D effects are known to modify significantly the multi-angular measurement but also the photon path length. We have shown that the angular distribution of observed O2 A-band absorption carries information on cloud geometrical thickness. Though the absolute values of radiances are known to be directly impacted by 3D effects, it remains to be established to what extent this modifies the relative angular distribution of observed 02 A-band absorption as derived from two-band ratios. In this respect, future study will investigate cases of heterogeneous cloud covers in order to estimate the effects of cloud inhomogeneity on the information content evaluated here as well as the implications on the retrieval of both cloud top height and geometrical thickness.

Please explain why the relatively obsolete k-distribution technique is used instead of the exact line-by-line calculation and provide an estimate of errors involved with the use of the approximation.

As the reviewer is probably well aware, the correlated k-distribution (ckd) allows us to perform the calculations in a much more reasonable time compared to line-by-line calculations, with a gain in accuracy that does not appear necessary here since the exact spectral response functions (SRFs) of channels being considered are not known and the bandwidth of the absorbing channels are rather large. Therefore, although we agree that considering real instrument spectral response functions is really critical, we argue that for practical implementation and given the rather large spectral width of channels considered here the use of full line-by-line simulation is only required for computation of ckd coefficients. In all cases, for our sensitivity studies, since the exact SRFs are not know, such intensive line-by-line calculation were clearly not required and application of ckd is deemed sufficient for our purposes.

Section 3.

Please clarify the definition of the average band ratio and the angular standard deviation. How many data points are used in the calculation of those quantities?

The average band ratio is the mean value of the band ratios observed in each direction and the angular standard deviation is computed similarly as the standard deviation of the different angular measurements. The number of angular measurements is determined by the Angular Sampling configuration (referred to as AS1, AS2 and AS3 in Fig2). For 3MI, there are 14 angular measurements available in the AS1 configuration.

l. 265: for the AS1 (cf. Fig. 2) + for 3MI's 14 view angles […]

Section 4.1.

Please explain why the ratio noise is smaller than 1% (see Lines 341-342) provided the radiance noise is of the order of 2-3%.

Calibration of POLDER instrument is performed through in-flight vicarious calibration and so will be the 3MI. In addition to the absolute calibration of all channels that is performed using multiple techniques (Fougnie, 2016), the O2 A-Band channels for POLDER are calibrated vicariously using the apparent pressure derived from the ratio of the two O2 A-Band channels. Therefore the ratio of the two bands is directly calibrated statistically against observed surface pressure and it is considered that the ratio of the two channels (which is a relative value) is known with a better accuracy than their absolute individual counterparts. We have added a reference to Fougnie (2016) as well as a brief discussion to explain the lower uncertainty considered for the band ratio.

l. 334: " + The uncertainty used for the band ratio is smaller than the uncertainty for individual channels because the calibration of the two channels can be performed directly by relating their ratio to the apparent surface pressure, which is considered to provide higher accuracy than what can be achieved for absolute calibration of single channel measurements (Fougnie, 2016)."

Section 4.3-4.6.

The degree of freedom and a posteriori error are indeed linked. However, the retrieval error is more illustrative than the degree of freedom. That is why I would recommend to provide the retrieval error in Fig. 12-18. This would give a potential reader the quick understanding of how big error (in physical units) can be in the retrieved cloud height and thickness.

We chose to show the degrees of freedom instead of retrieval errors because, contrary to the retrieval errors, it sheds light on the feasibility of the retrieval (when DOF > 0.5). We provide an explanation on lines 372 through 379. We understand the value of providing the error in physical units and have added a new figure **(Fig. 12)** to help interested users convert the degree of freedom into physical uncertainty.

l. 378: + Figure 12 represents the relationship between the degrees of freedom and the a posteriori errors (in kilometers on CTOP and on CGT). As expected, the a posteriori errors decrease with the degree of freedom since the intake of information decreases the errors on the retrieved parameters.

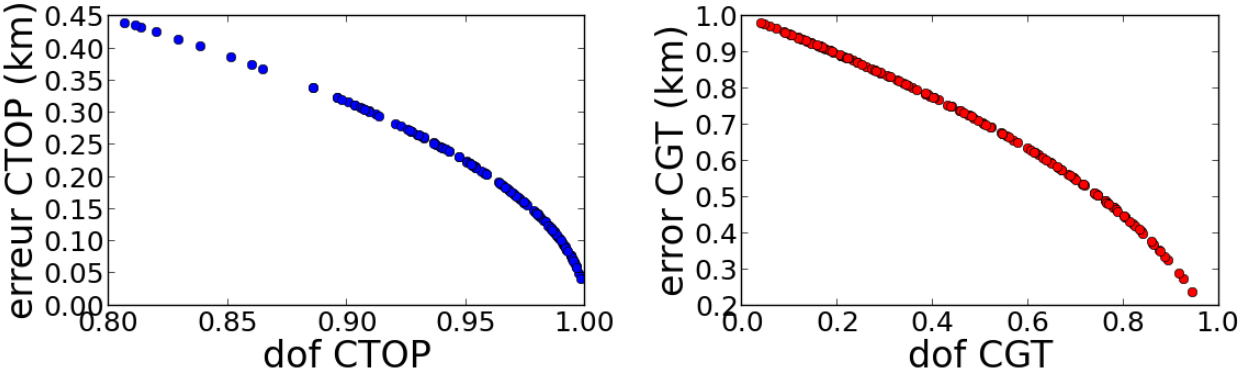


Figure 12. Relation between the DOFs and the a posteriori errors on CTOP (left) and on CGT (right).

Section 4.3.

It is quite desirable to provide an explanation of the finding that the information content for low and high optical depths is larger than for intermediate values of cloud optical depth.

For COT = 4, an intermediate optical depth, almost no radiation crosses the cloud completely, as it would for COT = 1, but the signal is neither saturated by multiple scattering as is the case for COT=40. Consequently, the A-band ratio varies with both COT and CGT in almost the same way at every angle leading to no variation of the standard deviation.

We added:

l. 280: At this intermediate optical depth, almost no radiation crosses the cloud completely, as it would for COT = 1, but the signal is neither saturated by multiple scattering as is the case for COT=40. Consequently, the A-band ratio varies with both COT and CGT in almost the same way at every angle leading to no variation of the standard deviation.

l. 429: … both CGT and CTOP is not feasible + for intermediate COT because they are both sensitive to the mean A-Band ratio.

Section 4.4.

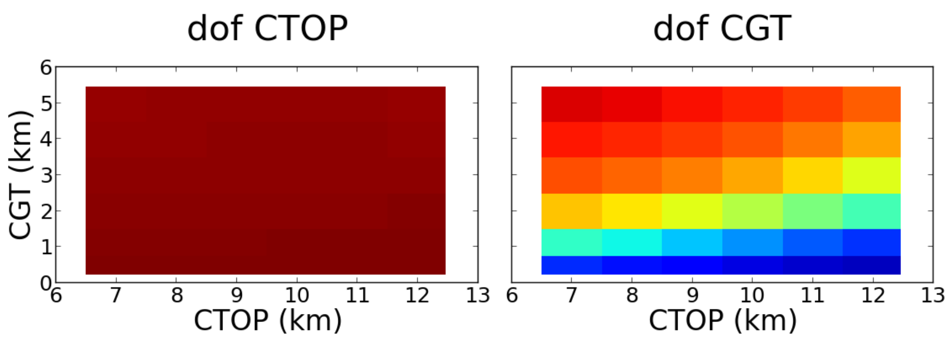
The use of the Henyey-Greenstein phase function is not logical because (1) it does not represent either liquid droplet or ice clouds, (2) all previous simulations were already carried out with a more realistic Mie phase function. Intuitively, variations of a scattering phase function can affect the A-band radiance ratio at least for low optical depths of cloud.

Lower values of the asymmetry factor lead to a higher photonpath, i.e. to more absorption, than higher values of the asymmetry factor. Fig. 14 shows results for cloud optical depth of 16 only. The authors should do the information content analysis for lower optical depths of cloud. The statement that « results can be extended to ice clouds» is too ambitious. You have to support the statement by doing simulations with an ice phase function.

We agree that the Henyey-Greenstein phase function is not realistic to represent either liquid or ice clouds. However the purpose of this section was not to study the information content for ice clouds, but rather to understand whether the information content analysis we made is dependent or not on the asymmetry factor and consequently of the type of particles. Here, the HG phase function simply provides a practical way to vary significantly the assumed asymmetry factor. The analysis leads to the conclusion that, at least for COT > 4, significant variation of the asymmetry factor do not reduce the information content. Of course this does not mean that *g* has no impact on the O2 A-band measurements.

To further respond to the reviewer's concern about realistic ice cloud phase function, we provide results of the same study for an exemple of ice clouds (figure behind). We used the IHM phase function (Inhomogenous Hexagonal Model, Labonnote et al., 2001) and computed the DOFs for different CTOP and CGT similarly to what was done for liquid clouds but for higher cloud tops. Those results are consistent with those already included in the paper for the liquid cloud cases. We don't think it is necessary to add yet another figure to the paper but we could if the reviewers and editor consider it to be desirable.

New caption:



Partial DOFs on CTOP (left) and CGT (right) for ice clouds with COT = 16 and IHM phase function (IHM model).

We rephrased our last sentence:

l. 448: Although the Henyey-Greenstein phase function provides a practical way to vary the asymmetry factor, one may question whether it can realistically represent ice clouds in our problem of interest. Similar results (not shown) are obtained when one uses realistic ice cloud phase function (IHM - Inhomogeneous Hexagonal Model, Labonnote et al., 2001) and for higher cloud top altitudes. Therefore the results of the information content presented in this paper can be confidently extended to different types of clouds such as, for example, ice clouds (at least for high optical thicknesses).

Section 4.6.

I doubt the statement «the retrieval of CTP over bright surfaces is feasible regardless of the COT and albedo» at least for low optical depths of cloud. Please provide physical considerations to support this *uncommon statement.*

We added in section 4.6 :

l. 493: Cloud top altitude can be determined here because, depending on the optical thickness, a significant part of the radiation is reflected near the cloud top and is more or less absorbed depending on its altitude. While this part of the cloud reflected radiation is sufficient to impact the total signal, information only on cloud top altitude can be retrieved even above a bright surface. However, this finding should be mitigated by the fact that we assume that the cloud optical thickness is known within 10% accuracy which might be difficult to achieve over very bright surfaces.

Technical notes:

Line 13. Ice cloud properties are not considered in the paper.

In practice we did consider ice clouds though we did not initially mentioned the IHM analysis as we thought the HG example was more relevant to illustrate the impact of unknown phase function/microphysics. We agree however that ice clouds might be a very different problem than liquid clouds once we start considering non vertically homogeneous clouds, which was not done here. We clarified the purpose of the HG analysis previously, and have added a comment on the ice cloud analysis now in the paper.

Line 71. Typo ‘hte’

Corrected

Fig. 3 caption. Typo ‘prented’

Corrected

Line 248-249. Please reword to clarify.

Corrected

Line 265. Remove ‘be’

Corrected

Line 501. Correct ‘account for'

Corrected

References:

Di Girolamo, L., L. Liang, and S. Platnick (2010) : *A global view of one-dimensional solar radiative transfer through oceanic water clouds, Geophys Res Lett, 37(18), L18809.*

Fougnie, B. (2016) : *Improvement of the PARASOL Radiometric In-Flight Calibration Based on Synergy Between Various Methods Using Natural Targets, IEEE Transactions on Geoscience and Remote Sensing (submitted).*

Heidinger, A. K., and G. L. Stephens (2000) : *Molecular Line Absorption in a Scattering Atmosphere. Part II: Application to Remote Sensing in the O2 A band, J. Atmos. Sci., 57(10), 1615–1634, doi:10.1175/1520-0469(2000)057<1615:MLAIAS>2.0.CO;2.*

Liang, L., and L. Di Girolamo (2013) : *A global analysis on the view-angle dependence of plane-parallel oceanic liquid water cloud optical thickness using data synergy from MISR and MODIS, J. Geophys. Res., 118(5), 2389–2403, doi:10.1029/2012JD018201.*

Loeb, N. G., and J. A. Coakley (1998) : *Inference of Marine Stratus Cloud Optical Depths from Satellite Measurements: Does 1D Theory Apply?, J. Climate, 11(2), 215–233, doi:10.1175/1520-0442(1998)011<0215:IOMSCO>2.0.CO;2.*

Stephens, G.L., and A. Heidinger (2000) : *Line absorption in a scattering atmosphere. I: Theory. J. Atmos. Sci., 57, 1599-1614.*

Várnai, T., and A. Marshak (2007) : *View angle dependence of cloud optical thicknesses retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS), J. Geophys. Res., 112(D6), D06203, doi:10.1029/2005JD006912.*

L'Ecuyer, T.S., N.B. Wood, T. Haladay, G.L. Stephens, P.W. Stackhouse Junior (2008) : *Impact of clouds in atmospheric heating based on the R04 Cloudsat fluxes and heating rates data set. Journal of Geophysical Research: Atmospheres, 113(D8), DOI: 10.1029/2008JD009951.*

Johansson, E., A. Devasthole, T.S. L'Ecuyer, A.M. Eckman, M. Tjernström (2015) : *The vertical structure of cloud radiative heating over the Indian subcontinent during summer mousson. Atmospheric Chemistry and Physics 15(20): 11557-11570.*

Ohring, G., S. Adler (1978) : *Some experiments with zonally averaged climate model, Journal of the Atmospheric Sciences, 35(2), 186-205.*

Waquet, F., Cornet, C., Deuzé, J.-L., Dubovik, O., Ducos, F., Goloub, P., Herman, M., Lapyonok, T., Labonnote, L. C., Riedi, J., Tanré, D., Thieuleux, F., and Vanbauce, C. (2013) : *Retrieval of aerosol microphysical and optical properties above liquid clouds from POLDER/PARASOL polarization measurements, Atmos. Meas. Tech., 6, 991-1016, doi:10.5194/amt-6-991-2013.*

Peers, F., Waquet, F., Cornet, C., Dubuisson, P., Ducos, F., Goloub, P., Szczap, F., Tanré, D., and Thieuleux, F. (2015) : *Absorption of aerosols above clouds from POLDER/PARASOL measurements and estimation of their direct radiative effect, Atmos. Chem. Phys., 15, 4179-4196, doi:10.5194/acp-15-4179-2015.*

A. B. Davis and A. Marshak, *Radiation Transport in the Cloudy Atmosphere: A 3D Perspective on Observations and Climate Impacts, Rep. Prog. Phys., vol. 73, 026801 (70pp), doi:10.1088/0034-4885/73/2/026801 (2010)*