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 #1 for his/her comments and suggestions to improve the paper. Please find hereafter our point by point responses to comments and suggested corrections.

Major comments:

1) *My first major concern is how cloud inhomogeneity and 3-D effects would influence the presented retrieval method. The retrieval method presented in Figure 6 utilizes the difference between the observations from viewing angles. An implicit underlying assumption is that the difference is due to the variations of CTOP and CGS. However, this is a valid assumption only for plane-parallel clouds. In reality, many other factors, in particular cloud inhomogeneity and 3-D effects, could also cause the cloud reflectance differences between different viewing angles. In fact, there are already a couple of studies on this issue. For example, [Liang and Di Girolamo, 2013] argued that the cloud reflectances from different MISR viewing angles would be consistent if clouds were plane-parallel. However, after analyzing global MISR observations, they found that in most regions of the globe, there are significant inconsistency of directional cloud reflectance between different MISR viewing angles. This indicates that most clouds can not be considered as plane-parallel, especially when clouds are broken and when the sun is low. There are also a number of other studies on this issue [e.g., Loeb and Coakley, 1998; Várnai and Marshak, 2007; Di Girolamo et al., 2010]. Based on these studies, I think cloud inhomogeneity and 3-D effects could have strong impacts on the retrieval algorithm described in this study. Unfortunately, I found no discussion on this important issue.*
The bowtie effect is another important issue to consider. Note that the pixel size could change significantly from nadir to oblique viewing direction.
Here are my suggestions. First, it needs to be pointed out clearly in the paper that the current method is based on plane-parallel cloud assumption. Second, the above studies should be mentioned in the text to remind the readers that multi-angular cloud observations could be strongly influenced by cloud inhomogeneity and 3-D effects, and therefore current algorithm is only applicable to homogeneous clouds. Finally, it should be clarified how to determine cloud homogeneity using the standalone 3MI or MSPI observations and what is the appropriate cloud homogeneity such that the current method can be applied. It would be even better if some sensitivity study can be performed using 3-D radiative transfer model.

The authors fully appreciate the concerns of the reviewer concerning the potential impact of 3D effects and agree that this point was not recognized and discussed enough in the paper. We are well aware that 3D effects and cloud heterogeneity can have a strong impact on multi-angular measurement and also on the photon path length in the cloud and hence on absorption. However, the question of cloud 3D effects strongly depends on the spatial scale and on the wavelength at which clouds are being observed. How the multiangular signal in O2 A-band is affected by 3D effects remains largely an open question. So far, we also remind that, for practical remote sensing applications, the assumption of plane-parallel clouds remains widely in use, especially for operational processing.

Regarding the “bowtie” effect, we would like to point out that this problem is only specific to certain type of scanning instrument with constant IFOV and does not impact all instruments in the same way. For instance the POLDER design used an aspherical lens combined with a telecentric optic to maintain a nearly constant pixel size on a flat Earth and therefore nadir and oblique view do not exhibit such strong differences as those observed using MISR or MODIS-type instruments. However, the reviewer's point is well taken and we will introduce in the paper a brief discussion that, similarly to 3D effects, caution is due with respect to potentially varying resolution of multi-angle measurements.

Another aspect to keep in mind is that we are not directly analyzing total radiance angular distribution but rather the angular variation of the ratio of two bands. It is an interesting question to evaluate whether the use of band ratio can mitigate partly the angular signature of 3D effects. Indeed, it was shown that for the retrieval of absorption of aerosols above clouds, the use of the ratio of total radiances limits the 3D effects (Peers et al. 2015).

Regardless, we agree with reviewer that those points deserved to be better identified and discussed. We now insist more in the paper on the fact that our conclusions are valid for near-homogeneous clouds and may not apply for cases of strongly heterogeneous and fractional cloudiness.

We added in the introduction:

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

And 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.

2) It is mentioned a few times in the paper that "Previous studies have not formally considered the impact of measurements and forward model errors on the retrievals." Well, this is not true. For example, more than 15 years ago, [Heidinger and Stephens, 2000] already did a comprehensive analysis of the information content of the O2-A band for cloud observation, in which not only measurements and forward model errors, but many other factors are considered.

In fact, I think most of the information content studies would consider the measurements and forward model errors. I'd suggest not to over-emphasize on this rather trivial point.

We agree that our initial phrasing was inadequate as we were trying to target the information content of multi-angle measurements. We have removed this comment :

l. 68: - Most of the studies have been limited to monolayer optically thick clouds over ocean. In addition, except for the study of Scheussler et al. (2014), most previous studies have not formally considered the impact of measurements and forward model errors on the retrievals.

And rephrased as follows:

l. 60: - a recent information content analysis (Shuessler et al., 2014)
+ Previous information content analyses (Heidinger et al., 2000; Shuessler et al., 2014) have have explored the information content of high resolution spectral measurements in the A-Band (Heidinger et al., 2000) and were applied to different sensors such as GOME and GOME-2 (Shuessler et al., 2014). Our present study focuses on the O2 A-band information content arising from multi-angle observations.

3) I'm also,disappointed by the lack of explanation of the physics underlying the retrieval algorithm. For example, it is understood that the mean O-2 band ratio is chosen as one dimension of the look-up-table in Figure 6. But what is the reason of using standard deviation? Why not to use the difference between two directions, such as nadir and oblique viewing direction to obtain largest contrast? Why is standard deviation sensitive to CTOP and/or CGS? Some discussions are needed there.

Section 3 of the paper is dedicated to the physical explanation concerning the sensitivity of the O2 A-band to cloud top and geometrical thickness. The figure 4 and 5 shows the A-band ratio as a function of the air mass, which is directly linked with the angular geometry. The value of the mean O2-band ratio represent the shift of the curves in function of CTOP and CGT and the standard deviation is a way to summarize the multi-angular measurements of 3MI. We chose this quantity as a simple metric for illustration purposes only and in reference to a previous study by Ferlay et al. (2010) that shows that the statistical relationship between the angular standard deviation of the O2 pressure and the cloud geometrical thickness is almost linear. Our goal is not to use this metric for retrieval itself because it indeed depends on the geometrical sampling and many other factors. Rather we want to illustrate how the angular variation of the O2 A-band ratio provides, in some situations, information that is orthogonal to the average photon path-length. Figure 6 is therefore used simply as an illustration to link the statistical information used by Ferlay et al. (2010) with the more comprehensive information content of the next part. The terminology "look-up table" is misleading, so we removed it and now talk about "isolines of CTOP and CGT in <R> and σr domain."

We changed this terminology in the title of Figure 6 and in line 428.

In order to be clearer, we added the following sentences.

l. 266 : + The average value of O2 A-band ratio is directly linked to the mean photon path-length which to a first order is determined by the cloud top altitude, hence the shift of the curves in Figure 4 and 5 for the different CTOP values. In order to summarize the angular measurements variations, following Ferlay et al. (2010), who shows that the standard deviation of the oxygen pressure is linearly linked with the geometrical thickness, we use the standard deviation of the O2 A-band ratio. Note that this metric does not retain all the information contained in the angular variation of the signal, but provides a useful qualitative link to previous studies by Ferlay et al. (2010). Physically, as will be discussed later on, the angular variation of the signal is linked to varying photon penetration within the cloud which depends on cloud extinction (or CGT as we consider COT as fixed and the cloud as homogeneous), air mass factor and details of the cloud particle phase function (through primarily their asymmetry factor). To first order, the larger photon penetration will result in a larger dependence on air mass factor, hence a larger standard deviation of angular measurements.

l.270: ... less dependent on . + Indeed, as explained before, CTOP variations imply change of molecular absorption above the cloud, which acts principally on the A-Band ratio average (Fig. 4).

l.271: ... formula only. + The modification of CGT for constant optical thickness produces a change of extinction inside the cloud and of the penetration depth, which causes a stronger angular dependence as the photon path length in the cloud depend on the view direction (Fig. 5).

Minor comments:

> *4) The current title is too large and can be revised to be more specific, something like "Investigate the possibility of simultaneous retrieval of CTOP and CGS from multi- angular O2-A band observations"*

Proposal of new title:

Information content of multi-angle measurements in O2 A-Band for cloud top and geometrical thickness retrieval: Application to 3MI and MSPI

> *5) The Abstract is different from Introduction. It should focus on key results not the motivations.*

We rewrote the abstract to focus more on results rather than motivation:

Information content analyses on cloud top altitude (CTOP) and geometrical thickness (CGT) from multi-angular A-Band measurements in the case of mono-layer homogeneous clouds are conducted. In the framework of future multi-angular radiometers development, we compared the potential performances of the 3MI (Multi-angle, Multi-channel and Multi-Polarization Imager) instrument developed by EUMETSAT, which is an extension of POLDER/PARASOL instrument, and MSPI (Multi-angle Spectro-Polarimetric Imager) developed by NASA's Jet Propulsion Laboratory. Quantitative information content estimates were realized for thin, moderately opaque and opaque clouds for different surface albedo and viewing geometry configurations. Analysis show that retrieval of CTOP is possible with a high accuracy in most of the cases investigated. Retrieval of CGT is also possible for optically thick clouds above a black surface, at least when CGT > 1-2 km and for thin clouds for CGT > 2-3 km. However, for intermediate optical thicknesses (COT ~ 4), we show that the retrieval of CGT is not possible simultaneously with CTOP. 3MI and MSPI comparison shows a higher information content for MSPI's measurements traceable to a thinner filter inside the oxygen A-band yielding higher signal-to-noise ratio for absorption estimatation. Cases of cloud scenes above bright surfaces are more complex but it is shown that the retrieval of CTOP remains possible in almost all situations while the information content on CGT appears to be insufficient in many cases and particularly for COT < 4 and CGT < 2-3km.

> *6) "In particular, the cloud cover vertical distribution has a significant impact on a large number of meteorological and climatic processes." What are meteorological and climatic processes? And references.*

We added in introduction:

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).

7) In simulation assumptions part, it should be mentioned whether and how in-cloud O2 absorption is treated in the simulation, and whether it is important.

The O2 absorption is of course treated inside the cloud in the same way as outside the cloud and the adding-doubling code accounts for the coupling between absorption and scattering within the cloud.

We added a few words line 180: "The O2 absorption is accounted for in and outside the cloud including an interpolation of the O2 concentration when cloud base or cloud top altitude are between atmospheric levels."

8) What is the definition of O2-band ratio? Equation should be given.

We have included a formal expression for the ratios:

l.122: + Those pairs of measurements are usually used in the form of ratios between the absorbing band in the A-Band and a non-absorbing band with approximatively the same scattering properties. We will employ then the "thin/broad" band A-Band ratio (eq. 1) for the 763 nm + 765 nm configuration and "in/out" A-band ratio (eq. 2) for the 763 nm + 754 nm configuration.

l.141: + Similarly to 3MI, we used the following in/out A-band ratio for MSPI.

9) Are aerosols, either below or above clouds, considered at all in this study? Why are they not important

We do not include aerosols for this information content study as they are expected to have a limited impact in most situations. First their optical thickness in the 750-770 nm spectral range will usually be small. Secondly, aerosol layers will in most cases be located below clouds except for some specific regions, as discussed by Waquet et al. (2013) and Peers et al. (2015). Clearly, accounting for aerosols might be necessary for cases of thick aerosols layers above clouds but this question is currently out of the scope for our present study.

We added in the conclusion:

l. 519: + This study show the possibility of retrieving cloud top and cloud geometrical thickness. However, in order to develop an operational algorithm, precautions should be taken in case of heterogeneous cloud or when aerosols lay above clouds as both will modify the photon path length and hence the absorption of the radiation.

10) Why are the a priori values of CTOP and CGT chosen at 5km ? 5Km seems rather small for CTOP,no ? References should be given here. It should be mentionned whether and how the *results are sensitive to the choice of a apriori values.*

We chose 5km for CTOP and CGT a priori standard deviation (not mean) because we studied separately liquid and ice clouds, which give us another piece of prior information.

We added:

l.339: ... for both CGT and CTOP + for both liquid and ice clouds.
l.341: … retrievals are performed. + Those a priori (co)variance values do not have a strong impact on the information content as they are chosen very large compared to the a posteriori variances ($S\mathbf{x}$).

NB. We also add the references below in the introduction:

l. 55: Davis et al. (2009) , + Asano et al., (1995), Kuji and Nakajima (2002)

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