Interactive comment on “The operational cloud retrieval algorithms from TROPOMI on board Sentinel-5 Precursor” by Diego G. Loyola et al.

Reply to Anonymous Referee #2

Referee comments are written in black font.
Author replies are written in red font.
Changes in the revised manuscript are written in blue font.

Review of the manuscript by Loyola et al.
The manuscript describes the OCRA cloud fraction and ROCINN cloud pressure algorithms and their modifications that were made to adapt the algorithms for TROPOMI. Most material of the manuscript has been published. However, the paper contains some original material that is mainly related to the modification of the ROCINN algorithm. This material may be of interest for the developers of cloud algorithms for satellite hyperspectral radiometers. Moreover, the OCRA and ROCINN cloud algorithms were selected for TROPOMI; that is why it is important to document the algorithms in the literature. The paper subject is appropriate to AMT. Earlier work is recognized and
credited. The abstract provides a sufficiently complete summary of the paper. The paper is well organized. I think that the paper needs significant revisions before recommending it for publication. The authors should address the following comments.

General comments

1. The authors state that the cloud pressure algorithm, ROCINN_CAL, provides better cloud-top retrievals than ROCINN_CRB. The TROPOMI cloud products are intended to use in trace-gas retrievals. It is not obvious that the cloud-top pressures can produce better trace-gas retrievals.
The authors refer to the reply to “Section 1, Introduction, p 2, l 8-12” from referee #1.

The Mixed Lambertian Equivalent Reflectivity (MLER) model compensates for photon transport within a cloud by placing the Lambertian surface somewhere in the middle of the cloud instead of at the top. As clouds are vertically inhomogeneous, the pressure of this surface does not necessarily correspond to the geometrical center of the cloud, but rather to the so-called optical centroid pressure (OCP). Cloud OCPs are the appropriate quantity for use in trace-gas retrievals from satellite instruments. Cloud-top pressures are not equivalent to OCPs and do not provide good estimates of solar photon path lengths through clouds that are needed for trace-gas retrievals from ultraviolet and visible wavelength solar backscatter measurements (Ziemke et al., 2009; Joiner et al., 2012). The authors should prove that the ROCINN_CAL cloud-top pressures do produce better trace-gas (e.g. O3 or NO2) retrievals. That is particularly important in the view that the TROPOMI NO2 algorithm makes use of OCPs from the MLER-based FRESCO+ cloud algorithm (van Geffen et al., TROPOMI ATBD of the total and tropospheric NO2 data products, URL: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-5p-tropomi/document-library, 2016).
J.R. Ziemke, J. Joiner, S. Chandra, P.K. Bhartia, A. Vasilkov, D.P. Haffner, K. Yang, M.R. Schoeberl, L. Froidevaux, and P.F. Levelt, Ozone mixing ratios inside tropical deep convective clouds from OMI satellite measurements, Atmos. Chem. Phys., 9, 573-583, 2009.
The authors emphasize that a full study of the impact on the accuracy of the trace gas retrieval is out of the scope of the present manuscript.
As already stated on page 15, lines 23-24, a forthcoming paper on the TROPOMI/S5P special issue will demonstrate that ozone total column accuracy is improved when using the CAL model. Furthermore, in section 2 of the paper we will add a summary and references to previous work

showing that cloud model is more appropriated than a Lambertian model for (a) the retrieval of aerosol properties from UV measurements (Torres, O., H. Jethva, and P. K. Bhartia, Retrieval of aerosol optical depth above clouds from OMI observations: Sensitivity analysis and case studies, J. Atmos. Sci., 69(3), 1037–1053, doi:10.1175/JAS-D-11-0130.1, 2011) and (b) the estimation of the surface UV irradiance (Krotkov, N. A., Bhartia, P. K., Herman, J. R., Ahmad, Z., and Fioletov, V.: Satellite estimation of spectral surface UV irradiance 2: Effect of horizontally homogeneous clouds and snow, J. Geophys. Res., 106, 11 743–11 759, 2001), moreover, this more realistic cloud model will be used for the surface UV products from TROPOMI (Lindfors, A. V., Kujanpää, J., Kalakoski, N., Heikkilä, A., Lakkala, K., Mielonen, T., Sneep, M., Krotkov, N. A., Arola, A., and Tamminen, J.: The TROPOMI surface UV algorithm, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2017-210, in review, 2017).
Finally please note that the same team that developed the MLER model published a paper showing that a plan-parallel cloud model is superior to a LER and MLER model for trace gas retrievals: "Although one of these models (MLER) can be adjusted to agree reasonably well with the TOMS data, the adjustments are somewhat arbitrary and may not be suitable for interpreting satellite data if one desires high accuracy." (Ahmad, Z., P. K. Bhartia, and N. Krotkov (2004), Spectral properties of backscattered UV radiation in cloudy atmospheres, J. Geophys. Res., 109, D01201, doi:10.1029/2003JD003395).
See also the comment and reply to "Section 1, Introduction, p 2, l 8-12" from referee #1.
Section 2 of the revised manuscript will be extended as described.

2. The OCRA algorithm has been described in detail in Loyola et al. (2007) and Lutz et al. (2016). In those papers, the authors used the normalized RGB (red-green-blue) representation of colors. In this manuscript the authors propose the Green-Blue color system for TROPOMI. This switching to the GB system should be explained because the red channel (675-775 nm) is available in TROPOMI. The authors should also compare cloud fraction retrievals from RGB and GB using e.g. GOME-2 data.
The switching from RGB to GB is mainly twofold: First, the TROPOMI UV/VIS and NIR footprints will have a spatial mis-alignment. Hence, the GB and R colors will not see the same ground pixel. And second, OMI which is needed to provide the cloud-free reflectance background maps, does not have channels in the red, which could be used to define a color R.
We shown with OMI data that the OCRA color space approach also works with two colors instead of three colors. Since a mis-alignment correction poses as an additional error source, it was decided to use the GB two color approach instead.
A comparison of OCRA cloud fraction retrievals for GOME-2 test data using RGB and GB only will be carried out and the results will be presented in the revised manuscript.

3. The use of the Mie scattering model of clouds is new in the ROCINN algorithm. That is why it is important to show that the selection of a single water cloud model, i.e. a single phase scattering function, is representative. Clouds can be multilayer and vertically-extended. This significantly affects photon path lengths and thus oxygen absorption in the cloud. The authors should show that their selection of a vertically uniform cloud model with a single geometrical thickness of 1 km is sufficiently representative. The authors should provide an estimate of possible cloud pressure errors associated with the selection of the cloud model.
The parameterization of single layer liquid water cloud is representative especially for low clouds (mean geometrical thickness approximately 1 km). In the oxygen A-band window, most of scattered radiation originates mainly from the cloud top because only a small portion of light penetrates into the cloud. Therefore, the selection of CGT of 1 km should be sufficient. In a previous study by Schuessler et al. (2014) the CTH retrieval was proven to be insensitive to the cloud geometrical thickness uncertainties. See also the author reply to the comment "p6, l22" of referee #1.

The authors will summarize the results from the sensitivity study quoted above in the revised manuscript. In order to tackle the uncertainties in the presence of multi-layer clouds, the authors will show the impact of double-layer clouds on the retrievals.

4. The authors should add a couple of paragraphs describing how their radiometric cloud fraction is used in the DOAS trace-gas algorithms. It is important to highlight the differences between the use of the radiometric cloud fraction and effective cloud fraction that comes from the MLER model.
The OCRA cloud fraction is being used in the operational DOAS trace-gas retrievals since GOME/ERS-2, a detail description on how OCRA cloud fraction is used in trace gas retrievals can be found in (Van Roozendael et al., 2006), (Valks et al., 2011) (Loyola et al., 2011). Furthermore, the usage of OCRA and ROCINN for the TROPOMI SO2 retrieval is described in (Theys et al., 2017).
This will be stated in the revised manuscript.

5. The authors show a comparison of the OCRA radiometric cloud fraction with the MODIS geometrical cloud fraction. It is unclear why the authors do not carry out a similar comparison of the ROCINN_CAL cloud-top pressure with the MODIS cloud-top pressure. This comparison should be done and quantitative results of the comparison should be provided.
OMI does not provide information on the oxygen A-band, which is why a ROCINN_CAL cloud-top pressure for OMI cannot be retrieved.

Specific comments:
Abstract. Some numbers characterizing the error budgets are strongly recommended in the abstract.
The error budgets for synthetic simulations and for GOME-2 measurements are given in section 4.7 and 6 respectively. Providing this information in the abstract will be misleading as the reader will be expecting the error budget for S5P but this can be assessed only when the S5P data become available.

Introduction. Please add the following reference and discuss how your approach differs from that by Diedenhoven et al. (2007). Diedenhoven et al., Retrieval of cloud parameters from satellite-based reflectance measurements in the ultraviolet and the oxygen A-band, JGR, 112, D15208, doi:10.1029/2006JD008155, 2007.
The authors will add the suggested reference. The authors acknowledge that the two approaches are similar in the sense that the three parameters CF, CTH and COT are retrieved and that both information from the UV and NIR are exploited. However, the authors emphasize that the two approaches are different in the following aspects: OCRA/ROCINN does not retrieve all three parameters simultaneously. It is a two step process, where OCRA first determines the CF from the UV/VIS region and then this CF is used as an a-priori input to ROCINN, which retrieves CTH and COT in the NIR.
Update the manuscript according to the points mentioned above.

P.4, L.13. “the minimum Lambertian equivalent” should be “the mixed Lambertian equivalent”
Indeed, it should say mixed instead of minimum.
The manuscript will be updated accordingly.

P.4, L.17. “in the range 330-390 nm” is incorrect; OMAERUV makes use of just two wavelengths 354 and 388 nm.
This is correct.
The manuscript will be updated accordingly.
P.5, L.27. Is it correct that the scaling and offset factors are determined using daily satellite measurements, not monthly?

The scaling and offset factors are based on histograms of the differences between measured reflectances and corresponding cloud free reflectances. The cloud free reflectances are based on *monthly* background maps derived as outlined in section 3.2. The histograms of the differences (rho – rho_CF), which are used to derive alpha and beta, are generated for *daily* global measurements, representing all possible cloud conditions. Several daily global histograms covering all seasons were generated in order to investigate the temporal evolution of these factors. Since no significant seasonal dependence was found, only one set of alphas and betas per color was fixed.
A short clarification will be added to the manuscript.

P.6, L.5. "a simplified sun-glint correction". Do you mean "sun-glint flagging"? Please provide information about the performance of the cloud algorithms over the sun glint area. For instance, this information can include the cross-track dependence of daily averaged OMI cloud fraction and cloud pressure for such areas.
The authors clarify that this is a flagging and not a correction. Please refer to answer in referee #1 comment on Section 3.3.1.
A short clarification will be added to the manuscript.

P.8, L.21-22. Your statement about small effect of the cloud phase (water or ice) should be proven by radiative transfer simulations. Please provide comparisons of computed TOA radiances for water and ice clouds and corresponding cloud pressure errors. Section 4.4. Please provide information about a number of computational nodes over surface reflectance, surface altitude, solar and viewing angles.
Mie theory is not sufficient to describe the scattering from ice crystals. Please see also the reply to comment "p8, l21-22" from referee #1.
The authors will reformulate the statement about the effect of the cloud phase.

Section 4.4. Please provide information about a number of computational nodes over surface reflectance, surface altitude, solar and viewing angles.
The node point generation, RTM simulation, and neural-network training has been done using the smart sampling and incremental function learning technique (Loyola et al., 2016). The input space (surface properties, cloud properties and geometry) in not sampled using a regular grid, but instead a technique which optimizes the distribution of multi-dimensional points within the (input) state space. The total number of computational nodes was of the order of some hundred thousands. The surface height and albedo were restricted between 0 to 4 km and 0 to 1, respectively. The CTH and COT were computed in the range 2-15 km and 2-50, respectively. The following geometry was covered: RAA in [0, 180°], SZA in [0, 90°] and VZA in [0, 75°].
The node point generation is described in p.9, l.5-13. The total number of computational nodes will be added to the text.

P.9, L.11-12. Please provide typical errors of replacing exact radiative transfer simulations by neural network calculations for different sun-view geometries.
The mean average relative error over the O2 A-band spectral window for all scene geometries is below one percent.
This information will be included to the revised manuscript.

P.10, L.2-3. "the surface albedo climatology"; please provide a reference
The MERIS black-sky albedo climatology at 760 nm is used:
Popp, C., Wang, P., Brunner, D., Stammes, P., Zhou, Y., and Grzegorski, M., MERIS albedo climatology for FRESCO+ O2 A-band cloud retrieval, Atmos. Meas. Tech., 4, 463-483, 2011.
The above reference Popp et al., (2011) will be added to the manuscript.

P.10, L.4. "only very small changes are allowed" is a qualitative statement. Please provide quantitative information.
The very small changes here refer to the differences between the retrieved value of cloud fraction (and surface albedo) and their corresponding a priori value. The regularization parameter for cloud fraction and surface albedo is very high and thus, these parameters are always well within 1% difference from the a priori values.
This information will be added to the revised manuscript.

Section 4.6. describes well known theoretical estimates of the DFS and retrieval errors. Why the numerical estimates are not used in the text? I would remove this section and retain just a reference.
The authors prefer to keep the section.
At the end of Section 6.2.1., typical values for DFS and SIC will be added for the given GOME-2 test day (1st July 2012).

Section 5. Most statements in this section are qualitative like "can be accurately retrieved" (L.18), "quite sensitive to", "less significant are ROCINN errors" (L.20). The section titled "Error characterization" should provide quantitative information.
The authors agree to provide more quantitative information.
The section on error characterization will be updated in the revised manuscript.

P.11, L.19. Do you really mean "cloud geometrical fraction", not radiometric?
Correct.
The word geometrical will be removed.

P.12, L.4. Why the NIR stray light effects "will be assessed when the instrument provides measurements from space"? You say that "stray light issues were identified in the NIR band". The stray light contribution can be important for most absorption lines of the oxygen A-band. The authors should assess the stray light effects on the retrieved cloud properties. It seems to be straightforward to simulate stray light and investigate the impact on cloud pressure retrievals.
The authors agree to include the assessment of the stray light effect on retrievals.
The results of this assessment will be included in the updated version of the manuscript.

P.13, L.21-22. "This OMI cloud fraction is based on the filling-in of solar Fraunhofer lines caused by Raman scattering" is incorrect. The OMCLDRR cloud fraction is derived at 354 nm where the Raman scattering contribution is minimal.
Thank you for pointing this out. As stated in e.g. Joiner et al. (2012), the determination of the *cloud optical centroid pressure* "...makes use of the filling-in of Solar Fraunhofer lines by rotational-Raman scattering (RRS)…between 345 and 355nm...", whereas for the *effective cloud fraction* "a wavelength not significantly affected by RRS (354.1 nm)" is used.
In the revised manuscript, the sentence "This OMI cloud fraction is based on the filling-in of solar Fraunhofer lines caused by Raman scattering" will be replaced by "This OMI cloud fraction is derived at 354 nm where the contribution of Raman scattering is minimal".

P.13, L.27. Please explain why "the UV sensors are not sensitive to optically thick clouds". What physics do you mean in this statement?
This is a typo. It should say "thin" instead of "thick".
It will be corrected.

P.14, L.2-3. Please explain the meaning of "OCRA and OMAERUV report cloud fraction values more representative of the radiometric cloud fraction measured by the instrument". The instrument measures TOA radiances.
The referee is correct.

The authors will rephrase it as: “...representative of the radiometric cloud fraction based on the TOA radiances measured by the instrument”.

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2017-128, 2017.