

#Response to the RC2

General comments

I find this paper is interesting to show the differences between the ALH products and appreciate the thoroughness of the comparisons. I am also happy to see the MERRA-2 vertical profiles, which is largely simulated by a CTM, is robust enough to be representative of the ALH. On the other hand, I do have several concerns listed below that should be clarified/addressed before the paper is accepted for publication.

1. Different ALH products should be put into a context of the physical/optical meaning. As indicated in the paper, different products have different definitions. To help the readers grasp what they actually retrieve, it would be very helpful to have a reference dataset to indicate the vertical locations of these ALH. I think the CALIOP data can be used as such reference, i.e., the altitude of various ALH can be plotted on the CALIOP vertical curtain to show if the products represent the aerosol top, or the peak height, or optically weighted height, or something else.

Author's response:

It is a good advice. But we have to stress that exploring what is the physical/optical meaning of each ALH products is not the main purpose of this work (we are aiming to find an ALH that follows our understanding of UVAI altitude dependence). Instead, we will add the comparison between various ALH product with CALIOP climatology in Appendix D.

Change of the manuscript:

Appendix D: validating satellite ALH with CALIOP measurements

We validate satellite ALH products used in this paper with CALIOP measurements. Fig. D1 presents the zonal average of each ALH product (blue and green lines) against corresponding CALIOP climatology (contour). For better understanding the physical mean of each ALH products, we also calculate the ALH from CALIOP extinction profiles using ALH definitions introduced in Section 2.

The ALH reported in OMAERUV (first column) generally presents lower values except for that at high latitudes and the mid latitude in the Southern Hemisphere. This is consistent with Fig. 5a, where OMAERUV ALH over remote ocean is significantly higher than source regions. The potential reasons, as we explained in Section 3.1, are aerosol type misclassifications, the unrealistic ALH assumptions when no climatology data available, and high sensitivity to outliers due to less observations, etc. Between 10-30°N where the dominant aerosols come from the world dust belt according to Fig. 5c, the OMAERUV ALH matches well with the 'effective' heights (H_{aer}^{β} , H_{aer}^{τ} and H_{aer}^{63}) derived from CALIOP climatology, which may own to the proper ALH determination for dust aerosols (Torres et al., 2013). However, the ALH is almost close to the surface at biomass burning regions in tropics (0-30°S). The reason could be that the ALH for smoke aerosols is determined to be less than 3 km if no climatology data is available (Torres et al., 2013).

The comparison between OMI O2-O2 ALH and CALIOP (second column) only covers 3 seasons as CALIOP data is only available from June 2006. The ALH retrieved by SSA = 0.90 (blue line) is slightly lower than that retrieved by SSA = 0.95 (green line), which agrees with conclusions in Chimot et al. (2017). The OMI O2-O2 ALHs are close to the top boundary of the aerosol layer (H_{aer}^{τ}) within 0-30°S. Combined with data distribution provided in Fig. 5d-f, the ALH well presents the smoke plumes over tropics and subtropics. It also captures the dust outbreaks during JJA. During DJF and SON, the ALHs are retrieved mainly for urban aerosol in East Asia, where aerosol extinction is strongest near surface. The magnitude of OMI O2-O2 ALH is between the effective height and the top boundary height. However, in high latitude in the Southern Hemisphere, the ALH is remarkably high. The reason is that the high sensitivity to the retrieval outliers due to the lack of retrievals (Fig. 5d, 5g).

The last two column shows the comparison between TROPOMI ALH and GOME-2 AAH with CALIOP profiles. Although the TROPOMI ALH and GOME-2 AAH are collected during the similar period, the latter has larger variations due to the wider spatial coverage over both continents and oceans (Fig. 5l, 5o). Similar to the OMAERUV ALH, the magnitude of both TROPOMI ALH and GOME-2 AAH match well with the 'effective' heights (H_{aer}^{β} , H_{aer}^{τ} and H_{aer}^{63}) derived from the CALIOP profiles at latitudes between 10 and 30°N. At these locations, both ALH products are mainly retrieved for dust outflows over ocean. Disagreements between these two satellite ALH products and CALIOP profiles appear at mid to high latitudes regions. At these regions, the satellite ALHs are only available for individual cases (with UVAI larger than certain values) that are not visible in CALIOP profiles due to

averaging effects. For example, the high values of TROPOMI ALH present the smoke plumes due to fire events at the South America in DJF, Australia in DJF and MAM and South Africa in SON, and the high values of GOME-2 AAH present the smoke plumes due to fire seasons in the North America from MAM to SON and Asia in MAM and JJA. The Australia fire presented in TROPOMI ALH but invisible in GOME-2 AAH is also due to the averaging effect, since the latter has wider coverage over ocean (AAH over remote ocean is generally lower compared with smoke plumes).

In summary, the OMAERUV ALH, TROPOMI ALH and GOME-2 AAH indicate the ‘effective’ height (the altitude where aerosol extinction is strongest) for dust dominant aerosols layers. Large discrepancy between these satellite ALHs and CALIOP profiles are found at mid and high latitudes. For OMAERUV ALH, the disagreement mainly due to the unreasonable ALH determination, while for the other two products, the mismatches also result from the difference in spatial coverages due to the retrieval algorithm limitation and averaging effects of CALIOP profiles. On the other hand, the OMI O2-O2 ALH varies along with CALIOP profiles and captures the aerosol layer top boundary height for smoke aerosols, although it is sensitive to outliers in high latitude regions.

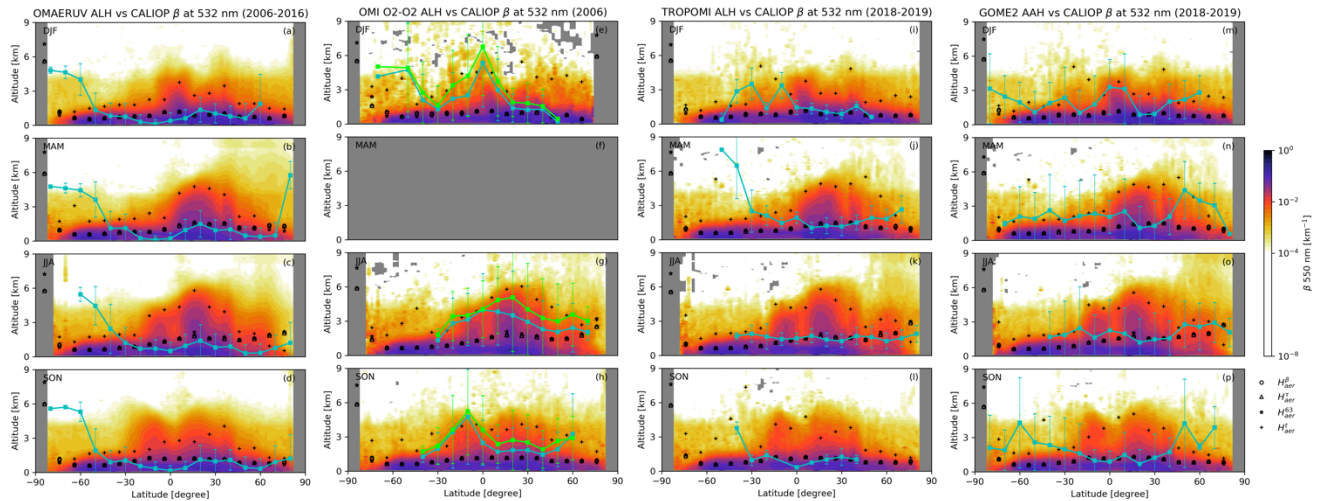


Figure. D1 The zonal average and the standard deviation of the satellite ALHs (blue lines) against the zonal average of the CALIOP extinction coefficients (contours) during the corresponding periods. Rows represent different seasons and columns represent different ALH products. For OMI O2-O2 ALH (second column), the ALHs retrieved SSA = 0.90 and 0.95 are indicated by blue and green line, respectively. The ALHs calculated for CALIOP profiles using different ALH definitions introduced in Section 2 are also indicated by different markers.

2. It has been emphasized several times in the paper that the purpose is “to find an ALH data set for interpreting aerosol absorption from UVAI”. I wonder how can that be achieved from a “robust” ALH? UVAI depends not only the ALH but also the amount of absorbing aerosol in the atmosphere. It will be helpful to add a few sentences how aerosol absorption (e.g., aerosol absorption optical depth) can be obtained from knowing the UVAI and ALH.

Author’s response:

The motivation of this paper is that, UVAI is a qualitative measure of aerosol absorption. It is a global data sets with long-term record since 1978, which is of potential to derive quantitative aerosol absorption, such as SSA or AAOD. In our previous studies (Sun et al., 2018, 2019), we have proved this possibility for individual cases. But to have a global aerosol absorption database, one of the major challenging is the lack of aerosol vertical distribution data. The aim of this paper that finds such an ALH data set for interpreting aerosol absorption from UVAI. This we used to put in the introduction part. Here we have made some changes to make it clearer.

Change of the manuscript:

From our perspective, quantitatively interpretation of aerosol absorption from the ultra-violet aerosol index (UVAI) satellite records requires information on the aerosol vertical distributions. No matter deriving SSA by forward radiative simulations of UVAI (Sun et al., 2018) or by statistically based machine learning methods (Sun et al., 2019), the aerosol vertical distribution is always one of the important factors to UVAI. So far, UVAI has a four-

decade global record, while a corresponding long-term global daily aerosol vertical distribution database is not yet available. (line 46-51)

3. It is not clear to me if the feature of altitude-AOD dependence on UVAI or the actual altitude is more important for interpreting aerosol absorption from UVAI? For example, the study finds three products, TROPOMI O2-A, GOME2, and MERRA-2 Ht are the robust products judging from their features of altitude and AOD variation with UVAI. However, the actual altitudes are far apart among the three: taking from Figure 2 and 5 in the southern hemispheric biomass burning season, the altitudes are 2-2.5 km, >10 km, and ~4 km for TROPOMI, GOME2 and MERRA-2 Ht over southern Africa (similar discrepancy in South America as well). How will you use these remarkably different ALH in retrieving the aerosol absorption?

Author's response:

As we discussed in section 1 Introduction, different measuring techniques, different retrieval algorithms, and different assumptions made in retrieval algorithms, different definitions of ALH, etc. make it difficult to directly compare different ALHs. Also as described in Torres et al. (2013), a direct comparison between above ALH data sets is not very meaningful as these definitions represent different aspects of the aerosol vertical distribution (section 4).

Alternatively, we focus on the UVAI dependence on ALH for two reasons: (1) this relationship is comparable among different data sets; (2) we are interested in the relationship rather than the absolute ALH values, as ALH itself is just a representation of aerosol profiles, rather than the actual location of aerosol layers. When we are using machine learning methods to derive aerosol absorption from UVAI, the UVAI-ALH relationship is more important than their absolute values, as input features are usually normalized (so the absolute values do not matter).

4. Using AERONET to “quality control” the ALH from OMAERUV over ocean: This is very unclear. The paper identified that OMAERUV ALH is extremely high (without approve) so additional quality control is necessary. However, 1) AERONET data is overwhelmingly over land and it has only a few sites on the islands, and 2) AERONET data does not have any ALH information to be used to “correct” OMAERUV ALH. In that regards, CALIOP would be more useful, but it is part of the climatology of ALH built in the OMAERUV already. Also, I found that dismissing the OMAERUV ALH data is unnecessary.

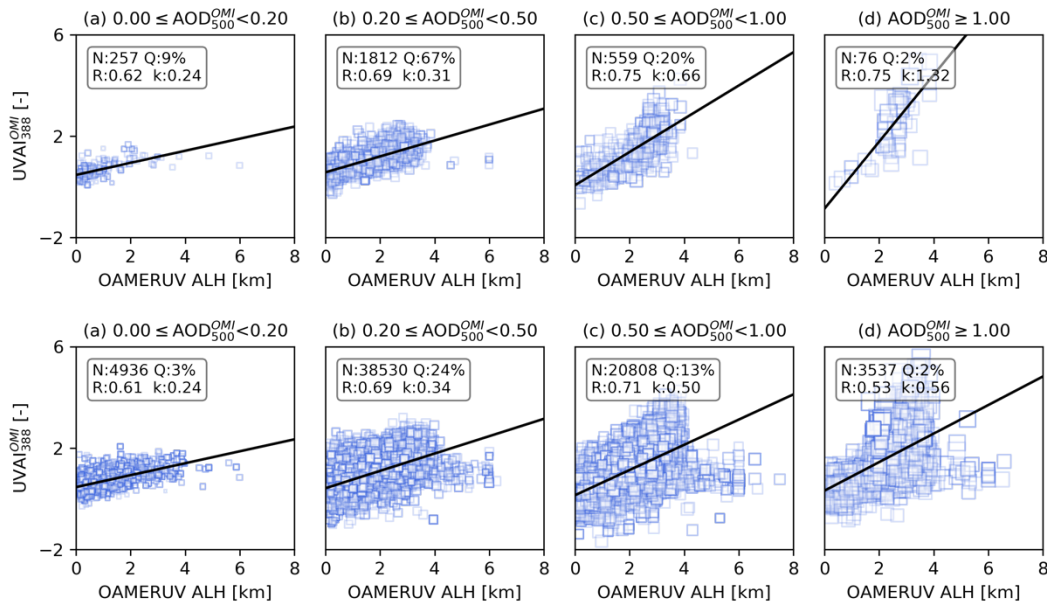
Author's response:

Note that the AERONET data screening is applied to both AOD and SSA of OMAERUV and MERRA-2, i.e. the AOD and SSA of OMAERUV and AOD and SSA of MERRA-2 should pass the criteria at the same time, then the pixel is accepted, otherwise, rejected. We apply this screening for two reasons:

(1) to improve the data quality. The OMAERUV ALH (SSA) is not a real retrieved parameter but a ‘by-product’ during the AOD retrieval. The AERONET does not contain information on aerosol vertical distribution, but by constraining the OMAERUV AOD as well as SSA quality using AERONET measurements, we expect a better quality of ALH, although it may not be always true. As shown in the following figures, the data after AERONET screening is indeed better than the raw data at least in terms of UVAI-ALH relationship. For the same reason, the AERONET quality screening is also applied to the MERRA-2. Although MERRA-2 AOD is partly assimilated from AERONET, the SSA is not;

(2) to directly compare the UVAI-ALH relationship of OMAERUV and MERRA-2. Using AERONET screening ensures that OMAERUV and MERRA-2 are reference to the same AERONET samples, thus they can compare to each other under the same condition. This method is not applicable to other data sets (OMI O2-O2, TROPOMI and GOME2) as the data availability is only near 1 year in this study, the number of collocated data (OMAERUV-OMI O2/O2/TROPOMI/GOME-2-AERONET) is not statistically representative.

We admit that the AERONET screened data suffers from the even coverage over land and oceans, but the AERONET is still the first choice for validating satellite retrieved aerosol properties. The correction of OMAERUV ALH using near-real time CALIOP is actually not necessary, as we want to evaluate the UVAI-ALH relationship of OMAERUV.



5. The slopes in some of the figures (e.g., Figure 7, 10) looks very strange – they don't go through the data points. Please confirm.

Author's response:

The slopes are correct, they seem not go through the data with higher UVAI, because the data distribution is skewed to lower UVAI. In other words, there are many samples with smaller UVAI at the bottom of the plot which bias the slope to smaller values. It would be clearer on a density plot, but to show the information on AOD, we still use the scattering plot.

Specific comments:

Page 1, line 32: I would delete "occasionally". Tropospheric aerosols are being transported across the tropopause over the Asian summer monsoon region regularly every summer.

Author's response:

Corresponding change has been done.

Change of the manuscript:

Although initially emitted in the lower part of the atmosphere, aerosol particles can be transported across the tropopause and stay in stratosphere for several months (Islam et al., 2017).

Page 2, line 51-52, lidar data: True, lidar data are limited in spatial or temporal coverages, but for this work the statistics is the most important, not event-by-event. I strongly encourage to use the lidar data such as CALIOP, since you already used them for MERRA-2 evaluation.

Author's response:

Lidar data like CALIOP is more suitable for case evaluations, as long as there exist co-located samples. The MERRA-2 aerosol vertical distribution validation in Appendix B is based on monthly climatology.

As you suggested, we have added a comparison of various ALH data sets using CALIOP profiles as the reference in Appendix D, see previous changes.

Page 2, line 65-66 to Page 3, line 67: The sentence is recursive: AAH has become an official product of the GOME-2: : that retrieves the AAH. Revise.

Author's response:

Corresponding change has been done.

Change of the manuscript:

Recently, the absorbing aerosol layer height (AAH) has been developed to be an official product of the GOME-2 instrument (Tilstra et al., 2019).

Page 3, line 82: How good is "good"? e.g., within x meters? within y%? To what extent the error is acceptable?

Author's response:

The validation is not based on ALH but extinction profiles. According to Buchard et al. (2017), they validate the seasonal MERRA-2 aerosol profiles with CALIOP for regions of interests. Compared with M2REPLAY (control run without AOD assimilation), the MERRA-2 profiles show similar structure as CALIOP, with maximum attenuated backscatter at about the same height. MERRA-2 tends to underestimate sea salt backscatter attenuation over ocean. This is mentioned in the corresponding MERRA-2 section (section 2.1).

Page 4, MERRA-2: Just keep that in mind that MERRA-2 aerosol vertical profile is NOT a reanalysis product. Only column AOD is.

Author's response:

Thank you for reminding, we have noticed that.

Page 4, line 128: Again, please avoid the subjective adjectives such as "good". Be more quantitative.

Author's response:

Same as previous response, the comparison is based on seasonal profiles rather than ALH.

Page 7, line 181-182: $366 \text{ days in } 2016 \times 100 \text{ profiles/day} = 36600 \text{ profiles}$. Where is 401800 coming from?

Author's response:

We use MERRA-2 data from **2006 to 2016**, in total 11 years. $11 * 365 * 100 \sim 400000 \text{ profiles}$.

Page 7, line 183: How did you change the vertical grid size in MERRA-2?

Author's response:

We change the grid size by resampling the given profile in different resolution. We add more description on this point.

Change of the manuscript:

For each profile, we modify the profile by changing its vertical grid size (i.e. resample in different vertical resolution)...

Page 7, line 187: I think the vertical grid is also denser near the tropopause in MERRA-2.

Author's response:

The denser grid at the lower part of the atmosphere is relative to the upper part of the atmosphere. The vertical resolution is decreasing along the increasing altitude.

Page 8, line 214-215, "Ht is better associated with AOD", and Figure 2: I wonder why anyone should expect ALH to be positively associated with AOD. The common knowledge is that the transported plumes are lifted higher (i.e., higher Ht) but AOD is lower than those near the source region. In that regards, Ht makes less sense. It would be informative if you could plot the profiles over the source regions as well as over the transported regions (e.g., North Pacific, North Atlantic) for comparison. Figure 4 only shows the vertical profiles over the source regions. Profiles over open ocean will be helpful.

Author's response:

Agree, not expectation that ALH is positivity associated with AOD. It is just that the H_t has this property because the H_t capture a certain threshold of extinction coefficient, where extinction above this threshold makes little contribution to the total AOD (the threshold varies with different profiles, i.e. inconstant). Corresponding change has been done.

But the lifted plume is not necessarily to have lower AOD than that aerosol layers near ground.

The Antarctica in Fig.4 is actually a non-source region (clean region). Fig.3 zonal average plot also contains profiles of source and non-source regions.

Change of the manuscript:

By contrast, the spatial-temporal variation of H_{aer}^t is associated with AOD. One can easily recognize the seasonal aerosol sources from the spatial and temporal variation of H_{aer}^t , e.g. the biomass burning regions in the central Africa during winter, the Sahara dust and its outflows over the Northern Atlantic during summer, etc. It is because that the H_{aer}^t captures the height above which the extinction coefficients make little contribution to the total AOD.

Page 9, line 271: “extreme” high ALH in Figure 5a over oceans: it should be “extremely”.

How high is extremely high? Over ocean the ALH from OMAERUV is about

4 km. How does it compare with independent data?

Author’s response:

The extremely high is respect to OMAERUV ALH at source regions. The OMAERUV ALH over (remote) ocean is around 4 km, while that over source regions is only around 2-3 km, which is not consistent with our knowledge. The direct comparison with independent data is not very meaningful as the ALH is differently defined. However, compared with GOME-2 AAH that ALH over open oceans is generally lower than that over source regions (OMI O2-O2 ALH and TROPOMI O2-A band ALH do not have many measurements over open ocean), the OMAERUV ALH over ocean seems extremely high.

We have made this statement clearer.

Change of the manuscript:

The extremely high ALH over open oceans relative to that over source regions (Fig.5a) may be caused by many factors.

Page 9, line 273: How is the over-ocean ALH determined in OMAERUV? Is most of them from CALIOP or CTM, or assumed according to aerosol type (thus may have high bias if UVAI is high-biased)? Besides, Fig 5b shows much lower UVAI over ocean than over land; how does the lower UVAI produce higher ALH over ocean?

Author’s response:

The OMAEUV ALH determination starts with aerosol type classification, no matter there are CALIOP or CTM climatology available. Thus, the error in UVAI may lead to errors in ALH. But please be noted that it is not only the UVAI, but also the CO index (COI, calculated from ARIS) and the scene type is also used to determine the aerosol types.

Change of the manuscript:

The extremely high ALH over open oceans relative to that over source regions (Fig.5a) may be caused by many factors. For instance, the row anomalies and sun-glint pixels that cannot be detect by the quality flag may lead to errors in UVAI, and also errors in other support information for aerosol classification (carbon monoxide index and scene types) which further affects ALH determinations; the unrealistic a-priori assumptions of ALH when no climatological entry exists; or the high sensitivity to outliers as the number of observations is small over remote oceans, etc.

Page 10, line 275-276, using AERONET data: I already stated that in my general comments.

Author’s response:

Please see the previous comment. The AERONET is still necessary to ensure the quality of OMAERUV ALH.

Page 10, line 300+, and Figure 5: Fig 5d and 5g shows "extremely" high values of ALH with a good fraction of points above 10 km! Also, it seems that OMI O2O2 (5d-f) and TROPOMI O2A (5g-i) are almost identical? This is a bit puzzling given the differences in retrieving methods, pixel resolution, and spatial coverage (e.g., row anomaly of OMI).

General comment for Section 3: It would be helpful to indicate the nature of these different ALH products from satellite retrievals, for example, it is more representative of top of the aerosol layer, or median, or optical centroid, or effective (give definition), etc.

Author's response:

The extremely high values in Fig.5d and g maybe due to the algorithmic errors.

The Fig.5d-i are OMI O2-O2 ALH (row 2-3). Fig.5d-f is OMI O2-O2 ALH retrieval by assuming SSA is 0.9 and Fig.5g-i is OMI O2-O2 ALH retrieval by assuming SSA is 0.95 in the NN-algorithm. Thus, they are almost identical. Please refer to section 3.2 for more details.

The comparison between each ALH products and CALIOP profiles is provided in Appendix D, see previous response.

Change of the manuscript:

Page 12, line 366: What is CMT – typo?

Author's response:

It is a typo. Corresponding change has been done.

Change of the manuscript:

...as CTMs do not have corresponding UVAI fields...

Page 14, line 418: “: : are less variable” – I would say “: : have little variation”.

Author's response:

Corresponding change has been done.

Change of the manuscript:

Although the UVAI varies from 0 to 5, the effective heights have little variation in the highest AOD regime.

Page 15, line 428-429: Why are the AOD thresholds different for different ALH products?

Author's response:

Because different ALH data is retrieved / analyzed by different AOD data. OMAERUV ALH uses AOD at 500 nm from the same product. OMI O2-O2 ALH is retrieved based on MODIS data. TROPOMI ALH and GOME-2 AAH product does not have corresponding AOD retrieved, thus we use the co-located MODIS AOD to analyze.

Page 15, paragraph starting at line 30: The AERONET quality screen is only applied to the OMAERUV data over the ocean, right?

Author's response:

I think you are mentioning continent?

The comment on the AERONET data screening is mentioned in the response to the general comment.

Page 15, line 434-435: This needs to be quantified - if you use the original OMAERUV data without AERONET screening, how much difference does it make?

Author's response:

If no AERONET screening, the UVAI dependence on ALH becomes weaker. The AERONET screening has two roles, as explained in the beginning of this document.

Page 15, line 449 and 457: the products and websites are not consistent, e.g., product is MYD08_D3 but the website is MOD08_M3 in line 449.

Author's response:

Thank you for the correction. Corresponding change has been done.

Change of the manuscript:

The data access doi has changed into: http://dx.doi.org/10.5067/MODIS/MYD08_D3.006 and http://dx.doi.org/10.5067/MODIS/MOD08_D3.006

Page 16, line 479: I don't understand the argument that $R > 0.6$ for OMAERUV is unrealistic. The ALH in OMAERUV is mainly from CALIOP climatology, or a CTM; the UVAI is only used for selecting aerosol type. And it is not clear how much help the screening with AERONET data helps for a better correlation; if this is the reason to not

exclude the OMAERUV data, then just don't apply the screening.

Author's response:

The OMAERUV ALH is partly depended on UVAI. According to Torres et al. (2013), OMAERUV ALH is designed to retrieve accurate aerosol properties of absorbing aerosols in the UV channel (Torres et al., 2013). In the OMAERUV algorithm, the UVAI (together with COI) is used to determine the aerosol types. The OMAERUV ALH determination is based on the given aerosol types and other conditions (UVAI, viewing angles). For strong absorbing aerosols, the ALH is determined to be higher. For weak-absorbing or scattering aerosols, the ALH is artificially determined at lower altitude. For example, if the aerosol type is determined as sulfate, the ALH is 0 km by default. If the aerosol type is black carbon with UVAI smaller than 0.5, the ALH is 1.5 km. Thus, the UVAI dependence on ALH may be too 'optimistic' than the reality.

Please refer to the previous responses on AERONET data screen.