Response to Editor

According to the reviewers, substantial issues remain unresolved after the last major revision. The issues raised concern both the AEH retrieval scheme, the content of the analyses presented, as well as the quality of the presentation. Nevertheless, the reviewers do highlight the relevance of the topic for the AMT community. Therefore, I would like to encourage the authors to make another major revision to the manuscript addressing the issues identified.

Please see below my comments on the manuscript:

1. The AEH retrieval strategy needs to be presented more clearly. The retrieval of AEH is challenging since the information content of the measurement is limited while many other parameters (AOD, aerosol characteristics, scene parameters) influence the measurement. It needs to be clarified, which prior information is used for the retrieval, and where this prior information on these other parameters is taken from.

2. The presentation of the AEH retrieval scheme needs to be supported by sensitivity analyses. The scheme exploits the O2-O2 Slant Column Density (SCD) retrieved form the O2-O2 absorption signature near 470 nm. The sensitivities of the AEH to the O2-O2 SCD and to the other parameters that influence the measurement, need to be presented.

3. The expected AEH retrieval uncertainty needs to be quantified, in particular in view of the uncertainty in the available a-priori information on these other parameters that influence the measurement. I recommend trying to identify regimes in which the retrieval is expected to provide useful information and regimes in which this is not expected. Such regimes could be defined in terms of AOD, surface albedo, even layer height itself, etc.

Ans from 1-3) Thank you for the opportunity to answer questions. These comments are very important for our manuscript for better understanding of AEH retrieval. To supplement these points, we revised the overall algorithm explanation in Section 3 including the explanation of Figure 2. In addition, the Figs. 4~6 are included to explain the sensitivity analysis for the AEH retrieval uncertainty due to the aerosol and surface optical properties. Overall, Section 3 is revised to explain the detailed algorithm structure and theoretical performance of AEH retrieval.

4. The poor correlation with reference data from CALIOP and TROPOMI (Figures 6 and 8) raises questions on the performance of the AEH algorithm. This needs to be explained. Sub-setting of the data should be considered such that the comparisons are restricted to regimes in which both the AEH and the correlative observation data set are expected to be meaningful.

Ans) Thank you for the comment. For the better understanding, Figures 9 and 11 are revised in the revised manuscript to show the performance of AEH algorithm based on the case studies. Also, we revised all the figures of case study and intercomparison using CALIOP and TROPOMI in the revised manuscript.

Again, thank you for the kindly and detailed comments for our manuscript.

Response to Reviewer#1

Review of manuscript "Retrieval Algorithm for Aerosol Effective Height from the Geostationary Environment Monitoring Spectrometer (GEMS)", by Park et al., 2023.

The revised paper entitled introduces the GEMS aerosol effective height (AEH) product, presenting the initial results of aerosol vertical structure information. Is an interesting new product with a little heritage adding an important value in the community regarding the aerosol height retrieval from passive satellite sensors. The main object of the manuscript, is to demonstrate the performance of the GEMS operational aerosol retrieval algorithm and to evaluate the AEH product compared to reference products from satellites such as CALIPSO and TROPOMI. The objective of this paper is clear in general, which intends to show the performance of operational GEMS aerosol product under different situations. Although the authors have generally carried out a carefully validation analysis of GEMS AEH, more parts need additional explanation before the article is acceptable for publication. I suggest that the paper deserves to be published, but first the presentation quality, especially the English grammar and writing style needs to be improved significantly. I would suggest the authors to revise the English writing style throughout the text. The paper needs to be carefully proof read. There are quite a few places that I tried to guess what the authors were trying to say.

Ans) Thank you for the review and comments for improving the manuscript. We revised the manuscript based on reviewers' suggestions including bellowed comments. We considered the readability of manuscript. In addition, we added the results in validation and sensitivity analysis of AEH in the revised manuscript.

From my perspective I tried to highlight as more as possible major and technical suggestions/corrections, making the manuscript more readable and friendly. I would appreciate if the authors followed the comments below, as I believe they will help to the manuscript improvement:

- A careful validation of the satellite product is required in order to prevent the propagation of the resulted biases. Is there any recommended criterion flag that will allow the use of maximum data reliability by GEMS? Through the manuscript the only mentioned criterion applying on GEMS data is AOD (e.g. > 0.4). Do I understand correctly?

Ans) We retrieved the AEH value under AOD>0.3 pixels. However, as shown in Section 3, the retrieval sensitivity is reliable at AOD>0.4 from the sensitivity test in Figures 4 and 5. For the long-term validation test, we additionally analyzed the AOD>0.4 and 0.8 cases to identify the AEH retrieval performance change due to the AOD change.

- What is the information about the GEMS AEH data product requirements? Are there official target uncertainty requirements?

Ans) Thank you for the comment. To clarify the AEH data performance, we deleted the target requirement in the revised manuscript.

- Please, provide some guidance about the quality flags for GEMS AEH. It is necessary for each operational satellite product used in the study analysis to be accompanied by the corresponding QA indicators. Provide relative information from the respective ATBD/PUM if available for the GEMS product.

Ans) Thank you for the comment. Now, GEMS AEH quality flags have been renewal. So, the ATBD for AEH is not adoptable to this manuscript as the reference. For this reason, we include the detailed

retrieval processes of AEH retrieval algorithm and input data selection in Section 3 in the revised manuscript.

- I don't see anywhere in the "Data selection and collocation" section a detailed discussion about the methodology used by the authors regarding satellite collocation matching. A thorough information about the GEMS and TROPOMI comparison process is missing. It's important to explain and include the process.

Ans) Thank you for the review and comments for improving the manuscript. We added the data selection of CALIOP, GEMS, and TROPOMI in section 2.4 in the revised manuscript. We included the detailed data selection as considering the spatial scale, temporal scale, and pixel selection conditions.

- The reader should have some knowledge about the CALIOP product limitations, used in the study. What quality flags have been applied on CALIOP extinction profiles regarding several aspects? (such as e.g. the presence of clouds, unreliable values etc). Explain and provide necessary References. Ans) Thank you for the comment. In section 2.3, we included the data selection of CALIOP product.

- Are you using the AOD product from CALIPSO in your comparisons against GEMS? Since it is mentioned in the text, please explain in detail.

Ans) We added the AOD product for data selection in lines 257-258 in the revised manuscript. For the data selection of intercomparison, we used the GEMS AOD data. In addition, we used the AOD from CALIPSO by vertically integrating the aerosol extinction coefficients at 532 nm. We added the sentences in lines 216-225 in the revised manuscript.

- How many CALIPSO orbits does the long-term analysis include in total? What are the selection criteria for the selection of the orbits?

- Please clarify the study area (domain of interest) for which this analysis is being carried out. Ans) We used the 3 or 4 orbits per day by spatially and temporally matching the pixels. In lines 228-229 and 237-239, we added the sentences for the field of interest of GEMS and orbit selections of LEO satellites in the revised manuscript.

- For statistical correctness, add STD values where mean bias values are shown through the manuscript.

Ans) We revised the statistical description in the revised manuscript.

- Looking at the Figures 6a & 9a, GEMS vs. CALIOP AEH differences are quite remarkable. Obviously, the mean bias is small/within a kilometer, but the scatterplots indicate no correlation. I suggest using RMSE statistical metric throughout the analysis part, to assess the performance of the algorithm.

Ans) For the performance of the GEMS AEH algorithm, we checked and changed the Figures 9a and 12a in the revised manuscript. Due to the duplicated selection of CALIOP, we also added the mean and standard deviation of CALIOP AEH and GEMS AEH.

- The authors also leave out what they plan to do to improve the product's performance in the future. It would be useful for the reader to have a final message/discussion about the future development plans. A few sentences may be added in the conclusions.

Ans) We revised the reviewer's comment in Section 6 in the revised manuscript.t

I encourage authors to spend time studying in detail relevant articles where CALIPSO data are used for validation procedures. I give some examples:

• Xu, X., Wang, J., Wang, Y., Zeng, J., Torres, O., Reid, J. S., Miller, S. D., Martins, J. V., and Remer, L. A.: Detecting layer height of smoke aerosols over vegetated land and water surfaces via oxygen absorption bands: hourly results from EPIC/DSCOVR in deep space, Atmos. Meas. Tech., 12, 3269–3288, https://doi.org/10.5194/amt-12-3269-2019, 2019.

• Xu, X., J. Wang, Y. Wang, J. Zeng, O. Torres, Y. Yang, A. Marshak, J. Reid, and S. Miller (2017), Passive remote sensing of altitude and optical depth ofdust plumes using the oxygen A and B bands: First results from EPIC/DSCOVR at Lagrange-1 point, Geophys. Res. Lett., 44, 7544–7554, doi:10.1002/2017GL073939

• Chen, X., Wang, J., Xu, X., Zhou, M., Zhang, H., Garcia, L. C., Colarco, P. R., Janz,

S. J., Yorks, J., McGill, M., Reid, J. S., de Graaf, M., and Kondragunta, S.: First retrieval of absorbing aerosol height over dark target using TROPOMI oxygen B band: Algorithm development and application for surface particulate matter estimates, Remote Sens. Env., 265, 112674, 2021

• Nanda, S., de Graaf, M., Veefkind, J. P., Sneep, M., ter Linden, M., Sun, J., and Levelt, P. F.: A first comparison of TROPOMI aerosol layer height (ALH) to CALIOP data, Atmos. Meas. Tech., 13, 3043–3059, https://doi.org/10.5194/amt-13-3043- 2020, 2020.

Ans) Thank you for your comment. Based on the reviewer's suggestion, We revised the manuscript in Section 2.3 and 2.4 in the revised manuscript.

Technical/minor suggestions:

L. 53-54: "In addition, aerosol vertical information is also important information for the application." What application do you mean? Please rephrase. Ans) We revised it.

L. 59: Please Correct: "... that measure in UV-visible.." Ans) We revised it.

L.128-129: Keep only the CALIOP acronym. I t has been introduced previously in the text. Ans) We revised it.

L. 129-130: Suggest rephrasing to: "Finally, in section 6, the summary and main conclusions are presented."

Ans) We revised it.

L. 163-165: Can you elaborate further this statement?

Ans) We revised the sentence in lines 162-164 in the revised manuscript as: "For this reason, L2SFC was used as reference data for the surface products for the air mass factor estimation to all trace gas retrieval algorithms."

L. 195-199: This paragraph is not so clear to me, and it is needed a rephrasing and a better explanation.

Ans) We revised the sentence in lines 193-199 in the revised manuscript as:

"However, the TROPOMI ALH product has strong dependence of the surface albedo, especial to the bright surfaces (Sanders et al., 2015). From Michailidis et al. (2023), a mean bias of -0.51 ± 0.77 and -2.27 ± 1.17 km is estimated over ocean and land, respectively. In this study, we use version 02.04.00 of

the TROPOMI offline level 2 AER_LH product (European Space Agency, 2021) with the spatial resolution is $3.5 \text{ km} \times 5.5 \text{ km}$ at nadir viewing geometry."

L. 224-225: Suggest rephrasing to: "To ensure that the number of retrieved observation pixels is remain statistically significant, we relax the spatial limits for collocation matching." Ans) We revised it.

L. 238-241:" To consider the cloud contamination...". In addition to using QA=1 on the TROPOMI data, do you also apply additional flags as you mention for the cloud screening?
L. 316: "Although the fitting quality was good overall..." What do you mean good? Please, quantify.
L.372: Please explain what "yellow" dust means. Clarify within the text.
Ans) We deleted 'Yellow' in the revised manuscript.

L.467-470: Sentence repetition (see L.437-441). Rephrase.L.480: "the AI value for UV" to "UVAI".Ans) We revised it.

Line 556. "Comparing these results to Figure 8...". There is no Figure 8b. Maybe you mean Figure 10b.

Ans) We checked and revised all of figure numbers in the revised manuscript.

L. 556-557: "However, the standard deviation of the two surface types indicated a significant difference. Over the ocean surface, the histogram is very narrow.". Provide quantitative information.

L. 562: Rephrase to: ".. with low positive UVAI values..." Ans) We revised it.

L. 564-567: I cannot fully understand these sentences. Please rephrase in as simple terms as possible.L. 568: "...as shown in Figure 10b." Maybe you mean Figure 12b.Ans) We checked and revised all of figure numbers in the revised manuscript.

L. 570-571: "Similar to Figure 8c..". Figure 8c does not exist. Please correct. Ans) We checked and revised all of figure numbers in the revised manuscript.

L. 572-573: "In addition, the difference in the definition of ALH from TROPOMI and AEH from GEMS impacted the comparison." Generic statement. I'm not sure if can be used here. Ans) We deleted this sentence in the revised manuscript.

L. 573-574: "Dust" types of aerosols are mainly transported in the free troposphere with gaussian-like shapes...". What do you mean? Rephrase.

Ans) We revised the sentence in lines 616-618 in the revised manuscript.

""Dust" type of aerosol is mainly transported in the free troposphere with gaussian-like vertical distribution, and the associated plume thickness is highly variable."

L. 578-579: Rephrase to: "Transport patterns and vertical distribution shape depending on aerosol types, can affect the accuracy of aerosol height retrievals." Ans) We revised it.

L. 595: "...very narrow." Add statistical details and rephrase the sentence accordingly.

Ans) We deleted the sentences due to change the intercomparison figures as updating the version of TROPOMI.

L. 596-597: "Although ... distribution" Rephrase to: "Even though there are 6.5 times more data for land compared to the ocean surface, the land surface still demonstrates a relatively broad histogram distribution".

Ans) We deleted the sentences due to change the intercomparison figures as updating the version of TROPOMI.

L. **598-600**: Rephrase to: "This inconsistency arises due to the non-Lambertian effect, which introduces bias in surface reflectance and also influences the variability in surface reflectance associated with observation geometry". Provide a Reference.

Ans) We deleted the sentences due to change the intercomparison figures as updating the version of TROPOMI.

L. 425: Rephrase to: "Figures 6b and 6c illustrate the comparison results between GEMS AEH and TROPOMI ALH, for the period of March 28 ~ 30, 2021 over land and ocean surface, respectively." Ans) We revised it.

L. 451-456: It is not clear which data are used exactly. Can you provide a ... Ans) We deleted and re-write the sentences in the revised manuscript.

L. 500: "L2AERAOD include significant uncertainty". Quantify "significant". Ans) We included the supplement sentence in lines 542-544 in the revised manuscript.

L. 509: "Causes significant variability in AEH". Quantify "significant". Ans) We deleted 'significant' and change to 'causes AEH variability' in the revised manuscript.

L. 514-518: I think that it is missing here a comparison with other relevant studies.

Ans) Thank you for your comment. This paragraph is aerosol type dependency for AEH retrieval. We revised the paragraph in lines 552-559 in the revised manuscript.

L. 533: "the smallest" to "the lowest" Ans) We revised it.

L. 551: I suggest to remove the "[(AEH from GEMS) – (ALH from TROPOMI)]" from the text. It's large and confuse the reader.

Ans) We revised to 'difference between GEMS AEH and TROPOMI ALH' in the revised manuscript.

L. 553: "The mean value of (AEH from GEMS)..." to "The mean difference value between GEMS AEH and TROPOMI ALH...." Ans) We revised it.

L. 656: Rephrase "..with.." to "..against.." Ans) We revised it.

L. 650-651: "... with variation of around 1.4 km based on the standard deviation for AOD > 0.4" to "...with a standard deviation of 1.4 km under the scenario of AOD>0.4" Ans) We revised it.

L. 672-674: "By changing the transport patterns, the AEH can be identified the vertical distribution of aerosols by difference of AEH and ALH". I cannot understand what the meaning is of this sentence.L. 741-742. The document cannot be accessed. Provide an updated document.

Ans) We revised it.

L. 873-876: Reference link does not exist. Please update the Appropriate ATBD version. Ans) We revised it.

Figure 4: I suggest adding a label for each sub-figure (e.g. (a), (b) ...). It's easier for the reader. Also, a suggestion to change the caption to: «Hourly GEMS AEH product for the dust case on March 29, 2021 over East Asia, from 00:45 to 06:45UTC»

Figure 5: Are these TROPOMI Map figures, correspond to QA=1.0 for ALH? Please add the full label in the colorbar: "Altitude [km] or Aerosol Height [km]".

Figure 6. what does the red and blue dotted line represent? Please clarify in the caption. Keep the same colors in same inclinations as the above CALIPSO scatterplot. Also add the statistical metrics presented in the plots e.g. "Annotated are number of scatter points (N), correlation coefficient (R), mean difference and the percentage of data points within the error envelop (EE). "

Figure 7: See comment on Figure 4.

Figure 8: See comment on Figure 5.

Figure 9: See comment on Figure 5.

Figure 11: Modify the caption ".... (Black dots and error bars denote the mean and standard deviation of AEH difference, while the grey-box indicates the number of points)"

Figure 12: Histograms of differences between ALH from TROPOMI and GEMS AEH from. The labels in incorrect, showing the GEMS-CALIPSO. Please correct. Suggest to remove the "[(AEH from GEMS) – (ALH from TROPOMI)]"

Figure 13: See comment on Figure 12.

Figure 14: See comment on Figure 11.

Ans) We checked and revised all of figures in the revised manuscript.

Response to Reviewer#2

I applaud the authors for making many revisions to the manuscript. I still have many concerns but will only list a few here.

Ans) Thank you for the review and comments for improving the manuscript. We revised the manuscript based on reviewers' suggestions including bellowed comments. We considered the readability of manuscript, and also added the sensitivity analysis and validations during the revision process.

(1) Thank you for showing the look-up-table information. Though the three panels show the LUTs for different aerosol types, I do not see any sensitivity; if any, it is really a poor sensitivity.

Ans) For only viewing for Figure 3 in the original manuscript, the aerosol height sensitivity is shown to be weak. For the supplement of sensitivity study in Section 3, we added the Figures 4~6 in the revised manuscript for relative difference of sensitivity between AEH and uncertainties from aerosol and surface input parameters (aerosol optical depth, surface reflectance, and aerosol types). Also, we added the paragraphs in lines 357-395 in the revised manuscript to explain the sensitivity of AEH.

(2) Abstract says "The AEH difference depends on aerosol optical properties and surface albedo. Compared to the aerosol layer height obtained from the tropospheric monitoring instrument (TROPOMI), differences of 1.50 ± 1.08 km, 1.59 ± 1.22 km, and 1.71 ± 1.24 km were obtained for pixels with single scattering albedo (SSA) < 0.90, 0.90 < SSA < 0.95, and SSA > 0.95, respectively, with significant dependence on aerosol type." Again, given the uncertainties, are 1.5 km, 1.59 km, and 1.71 km that different and statistically significant?

Ans) Thank you for your comment. Original sentences could potentially cause confusion. For this reason, we deleted the statistical significance in the revised manuscript and changed the sentence in lines 34-37 in the revised manuscript.

"Compared to the aerosol layer height obtained from the tropospheric monitoring instrument (TROPOMI), differences of 1.50 ± 1.08 km, 1.59 ± 1.22 km, and 1.71 ± 1.24 km were obtained for pixels with single scattering albedo (SSA) < 0.90, 0.90 < SSA < 0.95, and SSA > 0.95, respectively."

(3) Scatter plots comparing GEMS and CALIOP show no skill, whatsoever, for the retrievals but r values are still very high. Histograms of GEMS - CALIOP show a broad spread (~2 km to 4 km bias) but the shape is gaussian and hence close to zero mean bias. This does not give me any confidence in the retrievals. The precision is not good based on those figures.

Ans) Thank you for your comment. Although the intercomparison test between GEMS and CALIOP has broad spread distribution. However, this structure is also similar to the TROPOMI ALH intercomparison results as shown in Nanda et al. (2020). Although GEMS-CALIOP histogram show a broad spread profile, we included the detailed analysis as focusing on the uncertainties of aerosol optical properties (AOD, SSA, and aerosol types), DOAS fitting uncertainty, and aerosol indices, etc. (4) Word "significant" is used in many places with no context.

Ans) Thank you for your comment. Most of the parts, we deleted the "significant" in the revised manuscript.

(5) Despite other reviewers asking for potential way of improving the algorithm, no mention of it

except to say combine this technique with Oxygen A/B bands

Ans) Thank you for your comment. In Section 6, we added and revised the further study of the aerosol height algorithm development.

(6) etc.

In conclusion, I find that the authors have missed an opportunity to write a good paper. GEMS has been flying for three years now. No excuse for not showing at least one full year of data analysis to get good sampling of AEH retrievals for different aerosol types, and most important of all show what sorts of diurnal variations can be picked up and what issues exist with solar/satellite geometries. I am tempted to say "reject" but the authors have put in a good faith effort to revise. So please have someone rewrite to fix all editorial mistakes prior to publishing if that is the decision the journal makes.

Ans) Again, thank you for your detailed comments. We tried to improve the manuscript to explain the detailed error source of AEH retrieval, AEH validation based on the case study and half-year analysis. Although the AEH retrieval algorithm still remains the several improvement points, this algorithm result can contribute expanding the GEMS data application for environmental studies.