Dear Reviewer,

Thank you so much for taking care of our manuscript and we appreciate the opportunity to revise it with comprehensive comments. We highly appreciate the detailed valuable comments from the referees on our manuscript of "A Multi-Angle and Polarization-Based Retrieval Algorithm for Aerosol Layer Height of Smoke and Dust". The suggestions are quite helpful and we have incorporated them in the revised version of manuscript. And we hope that the reviewers and the editors will be satisfied with our responses to the 'comments' and the revisions for this manuscript. Please find our detailed responses below to all these comments/suggestions.

Yours sincerely,

Yong Xue

General Comments

This manuscript presents an aerosol layer height (ALH) retrieval algorithm based on PACE/HARP2 multi-angle polarimetric observations using an optimal estimation framework. The authors first investigate the information content of multi-angle polarization measurements for ALH retrieval using Degrees of Freedom for Signal (DFS) analysis and subsequently develop an ALH retrieval scheme based on HARP2 observations at 441 nm. The retrieval results are validated against EarthCARE/ATLID lidar observations and further compared with the TROPOMI ALH product.

Overall, the topic is scientifically important and timely. With the advent of next-generation multi-angle polarimetric satellite missions, such as PACE and 3MI, retrieving aerosol vertical structure from multi-angle polarization measurements has become an active and important research area in atmospheric remote sensing. The manuscript is generally well organized, and the results demonstrate that polarization measurements can effectively improve ALH retrieval capability. However, several aspects of the manuscript require further clarification and improvement, particularly regarding the algorithm description, uncertainty characterization, validation strategy, and discussion of the results. In particular, the retrieval framework strongly relies on externally provided AOD products and prescribed aerosol models, while the impacts of these assumptions on the retrieved ALH are not sufficiently discussed. Therefore, I recommend that the manuscript undergoes minor revision before it can be considered for publication.

Response:

We sincerely thank the reviewer for the careful reading and constructive comments. These suggestions are very helpful for improving the clarity and robustness of the manuscript. We have addressed all comments point-by-point as follows.

Major Comments / Suggestions for Improvement

1. Please clarify whether any quality control procedures or filtering criteria were applied to the ATLID lidar observations used for validation. Since ATLID retrieval quality may vary under different atmospheric conditions, it is important to describe how the ATLID

data were screened prior to the intercomparison analysis.

Response:

We thank the reviewer for this important comment. In the revised manuscript, we have added a detailed description of the quality control applied to ATLID observations. Specifically, to ensure the reliability of the ATLID validation dataset, quality control and target-type screening were applied to the EarthCARE Level-2 products. Observations were first filtered using the Quality Status flag (Q_{ALD}), retaining only data with Q_{ALD} values of 0, 1, and 2, corresponding to high-quality retrievals, valid data with increased layer complexity, and cases with minor inconsistencies in layer height relative to the A-TC product, respectively. In addition, aerosol type information from the A-TC product was used to further select relevant aerosol categories. Since this study focuses on absorbing aerosol layers, only Dust, Smoke, Dusty_smoke, and Dusty_aerosol_mix cases were retained. This procedure reduces the influence of non-target aerosol types and improves the robustness of the ALH validation.

2. The collocation strategy among HARP2, TROPOMI, and ATLID observations is not sufficiently described. The manuscript should clearly specify: the maximum spatial collocation distance; the temporal collocation window; the spatial averaging strategy; the quality control criteria applied to each dataset. These details are essential for reproducibility and for properly interpreting the validation results.

Response:

Many thanks for your suggestions. In the revised manuscript, we have explicitly added:

- Spatial collocation radius: 10 km
- Temporal window: within 1 hour
- Spatial averaging strategy: mean of pixels within radius

Quality control procedures were applied to both the TROPOMI and ATLID datasets following the recommended product quality flags. For HARP2, this study directly used standard Level 2 retrieval products, which have undergone the mission’s internal calibration and screening processes.

These details have now been added to Section 2 of the revised manuscript to improve reproducibility and clarity.

Revision:

Lines 920-922: During the collocation process, HARP2 and TROPOMI pixels are first spatially matched with the ATLID ground track, and the data are then aggregated within a 10 km × 10 km window to reduce the impact of spatial scale mismatches.

Lines 190-195: The local overpass times of PACE, SNPP, Sentinel-5P, and EarthCARE are approximately 13:00, 13:30, 13:30, and 14:00, respectively. Therefore, the temporal differences among HARP2 observations, TROPOMI ALH products, and ATLID Lidar measurements are generally within about one hour. This relatively short time interval facilitates effective intercomparison and validation between ALH retrievals derived from multi-angle polarimetric observations and those obtained from independent active and passive satellite measurements.

Lines 239-244: In addition, the TROPOMI ALH product provides a continuous Quality Assurance (QA) metric ranging from 0 to 1, where 0 indicates retrieval failure or unreliable results, and 1 indicates fully successful retrieval. To ensure data quality, only pixels with QA≥0.5 are retained for validation in this study, while those with QA<0.5 are considered unreliable and excluded. Furthermore, the ALH product has been cloud-screened using the VIIRS/SNPP Enterprise Cloud Mask (ECM), which further improves the reliability of the data.

Lines 268-278: To ensure the reliability of the ATLID validation dataset, quality control and target-type screening were applied to the EarthCARE Level-2 products. First, observations were filtered based on the Quality Status flag (Q_{ALD}) provided in the Quality Status dataset, retaining only samples with QALD values of 0, 1, and 2. Here, $Q_{ALD} = 0$ indicates high-quality observations; $Q_{ALD} = 1$ denotes valid data but with the number of aerosol layers exceeding a configurable threshold; and $Q_{ALD} = 2$ indicates that the retrieved layer height shows some inconsistency with the A-TC (Target Classification) product, although the data remain valid. In addition, aerosol types were further screened using the A-TC product. Since this study focuses on the vertical structure of absorbing aerosols, only observations classified as Dust, Smoke, Dusty_smoke, and Dusty_aerosol_mix were retained for subsequent statistical analysis. This procedure helps reduce the influence of non-target aerosol types on the ALH validation results.

3. The retrieval algorithm relies on externally supplied VIIRS AOD products. Since AOD is a key parameter governing atmospheric radiative transfer, uncertainties in AOD are expected to propagate into the retrieved ALH. It is suggested that the authors clarify: the sensitivity of ALH retrievals to AOD uncertainties; whether retrieval errors increase significantly under low-AOD conditions. A simple sensitivity analysis would greatly strengthen the robustness assessment of the proposed method.

Response:

We thank the reviewer for raising this important point. We have now added a sensitivity analysis to quantify the impact of AOD uncertainty on ALH retrieval. The results indicate that ALH retrieval is sensitive to AOD uncertainty, with larger biases under low-AOD conditions.

Revision:

Lines 635-669:

Table 4 Retrieval errors in ALH as a function of the δ_{AOD} for the 0.5 and 1.0 AOD conditions[a] (Unit: km).

Error Source	Uncertainty	Smoke (ALH=5 km)		Dust (ALH=5 km)	
		AOD=0.5	AOD=1.0	AOD=0.5	AOD=1.0
AOD (land)	+(0.03+20%)	−0.30	0.06	−0.41	0.17
	−(0.03+20%)	0.56	0.26	1.29	0.24
AOD (ocean)	+(0.03+5%)	−0.17	0.02	−0.17	0.07
	−(0.03+5%)	0.26	0.09	0.57	0.09

[a]The relative error of ALH in the table is $ALH_{ref} - ALH_{retrival}$, and here $ALH_{ref} = 5\ km$.

To evaluate the impact of AOD uncertainty on ALH retrieval, a sensitivity analysis was conducted within the LUT-based optimal estimation framework. In this experiment, all other input parameters, including viewing geometry, surface reflectance, and aerosol model parameters, were kept unchanged, and only the uncertainty in AOD was considered to examine its propagation into the retrieved ALH. This setup is intended to mimic the effect of AOD product uncertainties in practical satellite-based retrievals.

Specifically, two representative aerosol scenarios, i.e., smoke and dust, were selected, with an ALH of 5 km and AOD values of 0.5 and 1.0 used as baseline conditions. AOD uncertainty was introduced as $\pm(20\%\tau + 0.03)$ over land and $\pm(5\%\tau + 0.03)$ over ocean to represent the typical uncertainty levels of the VIIRS AOD product.

Table 4 summarizes the median ALH retrieval errors (unit: km) induced by AOD uncertainty under baseline AOD values of 0.5 and 1.0, calculated across all viewing geometry nodes in the LUT. The results indicate that AOD uncertainty has a significant impact on ALH retrieval, exhibiting clear nonlinear and asymmetric characteristics. For the smoke scenario, when AOD = 0.5, positive uncertainty propagation leads to an ALH error of −0.30 km, while negative uncertainty propagation increases the error to 0.56 km. When AOD increases to 1.0, the corresponding error range decreases to −0.06 km to 0.26 km. A similar behavior is observed in the dust scenario, where the ALH error under low-AOD conditions (0.5) is significantly larger, reaching up to 1.29 km under negative uncertainty propagation, while it decreases to 0.09–0.24 km when AOD = 1.0. Moreover, the dust scenario exhibits higher sensitivity to AOD uncertainty. Specifically, under AOD = 0.5 with negative AOD uncertainty, the ALH error reaches 1.29 km, which is substantially larger than that in the smoke scenario (0.56 km), indicating a stronger dependence of dust aerosol retrieval on AOD a priori information. This is consistent with the findings of Lee et al (2015).

In addition, a comparison between different surface conditions shows that the ALH error induced by AOD uncertainty is generally smaller over ocean than over land. For example, at AOD = 0.5, the ALH error ranges from −0.17 km to 0.26 km over ocean, compared to −0.41 km to 0.56 km over land.

Overall, the results indicate that the impact of AOD uncertainty on ALH retrieval is most pronounced under low-AOD conditions, and exhibits clear variations across aerosol types and uncertainty settings. This highlights that AOD, as a key a priori input parameter, can significantly affect the stability of ALH retrieval through radiative transfer processes.

4. The authors selected the 441 nm channel for ALH retrieval. Although shorter wavelengths generally exhibit stronger sensitivity to aerosol vertical distribution due to enhanced molecular scattering, it remains unclear why 441 nm was ultimately chosen instead of other available HARP2 wavelengths. It would be beneficial if the authors could provide quantitative evidence supporting this choice, for instance by conducting ALH sensitivity analyses at different wavelengths, comparing DFS across channels, and examining Jacobians with respect to ALH. These analyses would strengthen the justification for selecting the 441 nm channel.

Response:

We thank the reviewer for this valuable comment. In Section 3.3 of the revised manuscript, a quantitative comparison of the ALH degrees of freedom for signal (DFS) at different HARP2 wavelengths has been conducted. As shown in Fig. 1, the information content of ALH retrievals decreases with increasing wavelength, following the order 441 nm > 549 nm > 669 nm > 873 nm. Under identical conditions, the 441 nm band provides the highest DFS. Therefore, the 441 nm channel is selected for the ALH retrieval.

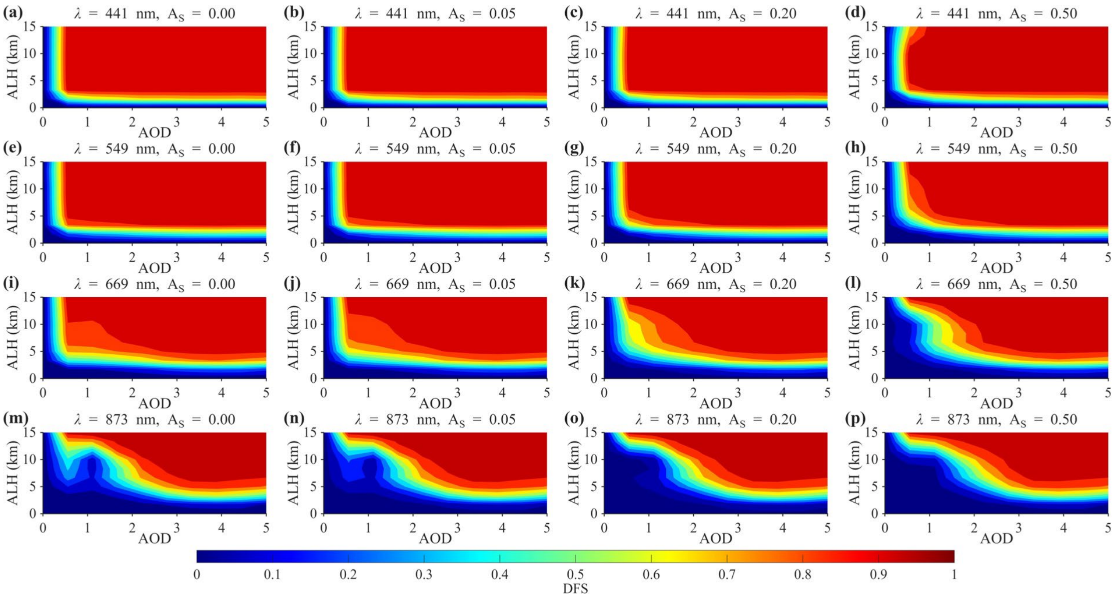

Fig. 1. Characteristics of ALH-AOD-DFS distributions derived from radiance under different

spectral bands and surface reflectance conditions. Rows correspond to wavelengths of 441 nm, 549 nm, 669 nm, and 873 nm, respectively, while columns represent different surface reflectance conditions ($A_s = 0.00, 0.05, 0.20, 0.50$). Colors indicate the DFS values of ALH, ranging from 0 to 1.

5. Only six case studies are used for validation in this manuscript. Although these cases appear to be representative, the sample size is relatively limited. Please clarify: the criteria used to select these six cases; whether only favorable observational conditions were considered. In addition, the authors should discuss the extent to which these selected cases are representative of global aerosol conditions.

Response:

We thank the reviewer for pointing out the need to clarify the case selection process. The six cases in this study were not selected based on favorable retrieval results, but were chosen according to several objective criteria. First, these cases correspond to well-documented and widely studied aerosol events, including major biomass burning and dust transport episodes. Second, data availability and quality were a primary constraint; only cases with simultaneous high-quality observations from both HARP2 and TROPOMI on the same day were considered to ensure meaningful intercomparison among sensors. Third, we prioritized scenes with strong aerosol loading (e.g., high AOD and clearly identifiable aerosol plumes) to ensure sufficient signal strength for multi-angle polarimetric retrievals. Fourth, cases with minimal cloud contamination were selected to reduce uncertainties introduced by cloud–aerosol mixing. Finally, spatial continuity and coherence of aerosol plumes were also considered to ensure consistent comparisons across different satellite products.

Revision:

Lines 681-690: The selection of these cases was based on multiple objective criteria rather than retrieval performance. First, all selected events correspond to well-documented and widely studied biomass burning and dust transport episodes. Second, only cases with simultaneous high-quality observations from HARP2 and TROPOMI on the same day were retained to ensure reliable cross-sensor comparison. Third, strong aerosol loading conditions, characterized by elevated AOD and clearly identifiable aerosol plumes in true-color imagery, were prioritized to guarantee sufficient signal strength for multi-angle polarimetric retrieval. Fourth, scenes with minimal cloud contamination were selected to reduce uncertainties associated with cloud–aerosol mixing. Finally, spatially coherent and continuous aerosol plumes within the study region were required to ensure consistency among different satellite retrieval products.

6. The forward simulations in this study assume a single aerosol layer. However, multilayer aerosol structures are frequently observed in real atmospheric conditions, especially during biomass burning and dust transport events, where elevated aerosol layers often coexist with boundary-layer aerosols. It is recommended that the authors clarify: what physical quantity is actually retrieved under multilayer aerosol conditions; whether the retrieved ALH is more representative of an extinction-weighted height, centroid height, or dominant aerosol layer height; the potential biases introduced by multilayer aerosol structures. Furthermore, this limitation should be explicitly discussed in the Conclusions or Discussion section.

Response:

We thank the reviewer for this insightful comment regarding the assumption of a single-layer aerosol structure. In response to this comment, we have revised the manuscript to explicitly clarify the physical meaning of the retrieved ALH under multilayer aerosol conditions. Specifically, we now state that, due to the single-layer assumption in the forward model, the retrieved ALH should be interpreted as an extinction-weighted height of the aerosol layers, rather than the height of individual aerosol layers. In addition, we explicitly state in the Conclusions section that the current method has limitations in resolving vertically separated aerosol layers. We also outline possible future directions to address this issue, including the integration of multi-angle stereoscopic information, enhanced polarimetric constraints, and the use of active lidar-derived a priori vertical structure information to improve the capability for characterizing multilayer aerosol structures.

Revision:

Lines 1088-1098: However, it should be noted that the current algorithm is based on a single-layer aerosol assumption. Under multilayer aerosol conditions, the retrieved ALH should be interpreted as an extinction-weighted height of the combined aerosol column, rather than the height of individual aerosol layers. As a result, the method cannot explicitly resolve vertically separated aerosol layers. Future work could address this limitation by incorporating multi-angle stereo parallax information, polarimetric constraints, and a priori vertical structure information from active lidar observations, in order to improve the capability for distinguishing multiple aerosol layers. In addition, further improvements in retrieval robustness and physical consistency may be achieved by refining aerosol optical models, optimizing surface reflectance parameterizations, and integrating multi-source satellite observations within a joint retrieval framework.

7. Additional literature must elaborate on the issue of: (i) aerosol particle size spectra collected at 2.5-min time resolution with a Scanning Mobility Particle Sizer at various height levels. See, for example: https://doi.org/10.1016/j.atmosenv.2012.05.015; (ii) the fact that the aerosol vertical distribution plays a crucial role in shaping the ozone vertical profile and strongly influences the biologically effective radiation that reaches the Earth's surface. See for example: Journal of Geophysical Research: Atmospheres 106.D14 (2001): 14843-14854.

Response:

We appreciate this suggestion. The two recommended references have now been added and discussed in the revised manuscript. They help to further support the importance of aerosol vertical distribution in controlling particle size evolution and radiative impacts on atmospheric chemistry and surface radiation.

Minor Comments / Typographical / Formatting

1. Page 2, line 64: "CALIOP provide" should be "CALIOP provides".

Response:

Corrected as suggested.

2. Suggest clearly and consistently define ALH throughout the manuscript. Different studies may define ALH as extinction-weighted height, aerosol centroid height, or aerosol layer top height. In addition, it should be clearly stated whether all ALH values reported in this study are referenced to mean sea level or to the local surface.

Response:

We thank the reviewer for this valuable suggestion. In the revised manuscript, we have clearly defined ALH. For passive sensors in this study, the retrieved ALH is derived under the assumption of a quasi-Gaussian aerosol vertical distribution and represents the centroid height. For lidar observations, the ALH corresponds to the extinction-weighted height. These two definitions are physically consistent in representing the effective vertical location of the aerosol layer. In addition, we have clarified that all ALH values in this study are referenced to mean sea level.

Revision:

Lines 357-361: The aerosol vertical distribution is assumed to follow a Gaussian-like profile (Spurr and Christi, 2014), defined as:

$$\tau(z) = K\frac{\exp(-\sigma|z - z_{peak}|)}{[1 + \exp(-\sigma|z - z_{peak}|)]^2} \tag{9}$$

where K is related to the column aerosol loading; z_{peak} represents the height of the AOD peak, i.e., the ALH; and σ_t denotes the aerosol layer thickness, which is set to 1.76 km.

Lines 908-919: To further quantitatively evaluate the accuracy of ALH retrieved from HARP2 multi-angle polarimetric observations, this study performs point-by-point collocation comparisons with ATLID lidar measurements. ATLID provides aerosol vertical profiles with high vertical resolution and is therefore widely regarded as a reliable reference for validating passive remote sensing retrievals. For quantitative comparison, the ATLID-based aerosol layer height (ALH_{ATLID}) is derived from the Level-2 355 nm extinction coefficient profiles following the method of Koffi et al. (2012), using an extinction-weighted height definition:

$$ALH_{ATLID} = \frac{\sum_{i=1}^{n} \beta_{ext,i} Z_i}{\sum_{i=1}^{n} \beta_{ext,i}} \tag{13}$$

Where $\beta_{ext,i}$ represents the aerosol extinction coefficient (km^{-1}) at altitude Z_i for the i-th vertical layer. The derived ALH_{ATLID} corresponds to the altitude where aerosol extinction is most significant, and its physical meaning is consistent with the quasi-Gaussian vertical distribution assumption adopted in this study (Chen et al., 2021a).

Lines 698-700: All ALH values used in this study—including the TROPOMI ALH product, ATLID-derived ALH calculated using extinction-weighted profiles, and HARP2-retrieved ALH—are defined relative to mean sea level.

3. Suggest carefully check all equations and ensure that every symbol and variable is explicitly defined when first introduced.

Response:

Thank you for your suggestion. We carefully reviewed all equations and ensured that all variables and symbols are now defined upon first appearance in the revised manuscript.