Dear Ralph,

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 and notes 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

A great deal of work has gone into this paper, and I think it is certainly appropriate for publication. I made a few notes, included here, based on our practical as well as our theoretical experience with the MISR multi-angle, radiance-only retrieval algorithm mentioned in the paper, in case they are of use.

Response:

We sincerely thank you for the positive evaluation of our manuscript and for recognizing the effort invested in this work. We are also very grateful for the insightful notes based on your practical and theoretical experience with the MISR multi-angle radiance-only retrieval algorithm. These comments and notes are highly valuable and have helped us further improve the clarity and robustness of the manuscript. We have carefully considered all the suggestions and incorporated the relevant revisions into the revised version.

• The main reference for the MISR MINX algorithm is:

Nelson, D.L., M.J. Garay, R.A. Kahn, and B.A. Dunst, 2013. Stereoscopic Height and Wind Retrievals for Aerosol Plumes with the MISR INteractive eXplorer (MINX). Remote Sens. 5, 4593-4628, doi:10.3390/rs5094593.

This paper contains important points relevant to the current study that are not included in the earlier references cited in the discussion paper.

Response:

We thank the reviewer for pointing out this important reference. We have carefully reviewed the paper by Nelson et al. (2013). Accordingly, we have added this reference and incorporated the relevant discussion in the revised manuscript.

• The vertical resolution of MINX retrievals is between 250 and 500 m, due to the pixel resolution of the MISR imagery and to the geometric nature retrieval algorithm, which does not depend on radiometric calibration uncertainty, AOD uncertainty, or retrieved or assumed particle microphysical properties (relevant to Lines 95-100 in the discussion paper). What is required is su9icient AOD to produce contrast features in the multi-angle imagery of the layer – the rest is geometry. (MISR particle properties are retrieve separate, radiometric retrieval algorithms that do depend on calibration, etc.)

Note that a constraint on AOD magnitude applies to all techniques, including those that apply polarization information. The specific AOD requirements vary among the techniques, and depend on the wavelengths used, viewing and solar geometry, the actual aerosol size distribution and light-absorption properties, and in some cases, surface properties, as you know. (For lidar, aerosol concentration as a function of elevation matters for the backscatter signal.) Note that a wind correction is included in the MINX algorithm, to account for any proper motion of the layer over the time it takes for MISR to acquire images at multiple angles.

Response:

We sincerely thank the reviewer for this valuable clarification regarding the physical basis and performance characteristics of the MISR MINX algorithm. The statements in Lines 95–100 of the original manuscript were not sufficiently rigorous, and we have therefore removed this part in the revised manuscript. In addition, we have revised the discussion of the MISR MINX algorithm to provide a clearer description of its characteristics and advantages.

Revision:

Lines 79-88:

Multi-angle stereo parallax methods estimate aerosol plume height by retrieving the geometric displacement of aerosol features observed from different viewing angles, achieving high vertical resolution (~250–500 m). The retrieved plume height is primarily constrained by geometric information and is therefore independent of radiometric calibration uncertainty, AOD retrieval uncertainty, and aerosol microphysical assumptions. The algorithm also incorporates wind correction to account for plume displacement during the multi-angle acquisition period. The MISR INteractive eXplorer (MINX) software system, developed by the NASA Jet Propulsion Laboratory (JPL) team based on MISR multi-angle observations, has been successfully applied to the height retrieval of wildfire smoke plumes, volcanic ash, and dust aerosols.(Diner et al., 2008; Nelson et al., 2013, 2008).

• MINX keys on the layer of maximum spatial contrast in the multi-angle images. As such, the results tend to skew lower than the highest elevations reported by the CALIPSO lidar, but higher than the infrared spectral methods that typically sample deeper into and even below the aerosol layer (e.g., IEEE Geosci. Remt. Sens. Lett. 2020, doi:10.1109/LGRS.2019.2936332); the UV height retrievals (e.g., TropOMI) can be higher or lower relative to other techniques, depending on several factors, as you know. A point made in several papers (e.g., J. Volcanology and Geothermal Research 2017, doi: /10.1016/j.jvolgeores.2017.03.010, Figure 2 and associated text) is that these techniques ***can yield different layer-height results and still all be correct***, as they are sensitive to different aspects of the aerosol layer.

Response:

We sincerely thank the reviewer for this insightful comment regarding the interpretation of ALH differences among different retrieval techniques. Differences among these retrieval products do not necessarily indicate retrieval errors, as each technique provides information related to different aspects of aerosol vertical structure. We have added additional discussion in the revised manuscript to emphasize that ALH comparisons should consider the underlying retrieval principles and physical definitions of each method.

• On theoretical ground, one would expect the addition of polarization to the multi-angle data in the new algorithm to increase sensitivity to single-scattering (relative to multiple-scattering) and to smaller particles, other factors being equal. So, looking at Figs. 2-6, I'm wondering in a bit more detail than discussed in the current manuscript how results using this algorithm when polarization is included differ from those for the same algorithm and layers when only the multi-angle data are used. Understandably, the biggest differences tend to appear when the surface albedo is 0.5, especially when the AOD is just 0.3 (and I think you are assuming fine-mode particles).

One thing I could not find is the view-angle range for HARP-2. The 80˚ VZA is quite steep; for MISR the VZA range is nadir to ±70.5˚, and from our sensitivity studies, the range of VZAs sampled is one of the leading factors in determining layer-height sensitivity, more important for geometric height-retrieval applications than the number of view angles, once at least 4 or 5 well-spaced view angles are available. (This also shows up in your Fig. 7.) At the steepest view angles, however, atmospheric refraction, surface texture and shadowing, and other factors become increasing issues. In our experience, another factor of practical relevance is pixel resolution, which sets a limit on height resolution for geometric retrievals. For HARP-2, the pixel-resolution is 2.5 km at nadir and varies with view angle (you use the 3.5 km pixel product), vs. 275 m at nadir in all channels and at all angles in the red band for MISR; full resolution is used in the MINX retrieval for this reason.

Response:

We thank the reviewer for this insightful comment. In the revised manuscript, we have expanded the discussion associated with Figs. 2–6 to clarify the physical mechanisms underlying the observed increase in DFS when polarization is included. Specifically, we explain that polarization measurements are primarily sensitive to single-scattering processes and are less affected by surface reflection compared to radiance measurements. As a result, polarization provides additional independent constraints on aerosol scattering geometry and vertical distribution. We further clarify that the DFS enhancement is most significant under conditions of high surface albedo and low aerosol optical depth, where radiance-only observations are strongly influenced by surface reflection and thus exhibit reduced sensitivity to aerosol vertical structure.

Regarding viewing angles, we have added information about the HARP2 instrument's viewing angles to the revised manuscript. Specifically, at the 441 nm wavelength used in this study, HARP2 provides 10 discrete viewing directions with nominal viewing angles ranging from approximately −55.9° to 53.8°. Here, the VZA range from 0° to 80° used in the DFS analysis was intended as a theoretical sensitivity experiment to investigate how the information content of ALH retrieval changes with observation geometry. In the actual ALH retrieval experiments, the observation geometry is fully determined by the HARP2 Level-1 product. Specifically, the pixel-level sensor zenith angle and relative azimuth angle provided by the geolocation data are directly used in the radiative transfer simulations and retrieval process. Therefore, the retrieval results are based on the actual HARP2 viewing geometry rather than the idealized VZA range used in the sensitivity analysis.

Regarding the pixel resolution, it directly limits the achievable vertical accuracy of geometric-based retrieval approaches. We previously considered applying the stereoscopic height approach used by MISR to HARP2 observations for ALH retrieval. However, due to the relatively coarse spatial resolution of HARP2 (approximately 3.5 km), the height retrieval uncertainty from a purely geometric approach was found to be relatively large. Therefore, in this study, we adopted a radiative transfer model-based approach to retrieve ALH, in which the multi-angle observations provide additional radiometric constraints and enhance the sensitivity to aerosol vertical distribution.

Revision:

Lines 500-548:

Under the same retrieval framework and identical aerosol layer conditions, the difference in information content between multi-angle observations and multi-angle polarimetric observations primarily arises from their different sensitivities to various scattering components involved in the radiative transfer process. Multi-angle radiance measurements primarily characterize the integrated radiative response of the coupled atmosphere–surface system, where the observed signal generally consists of contributions from surface reflection, aerosol single scattering, and multiple scattering processes. Under conditions of low AOD or high surface albedo, the surface-reflected component can become a dominant contributor to the measured radiance, while multiple scattering can obscure the signatures associated with single-scattering processes. Consequently, when only multi-angle radiance observations are used, the impact of ALH on the observed signal is mainly manifested through indirect modulation of radiative path length and scattering geometry. The resulting ALH sensitivity is relatively weak and can be strongly coupled with other parameters, such as AOD and surface reflectance, leading to a more ill-posed inverse problem (Dubovik et al., 2011).

In contrast, incorporating polarization information extends the measurement vector from radiance-only observations to a combined set of radiance and polarization states, thereby fundamentally altering the sensitivity structure of the observations to aerosol scattering processes. A key feature of polarized radiance is its enhanced sensitivity to single-scattering processes, whereas multiple scattering tends to reduce polarization through depolarization effects. Meanwhile, surface reflection generally contributes much less to polarized signals than to total radiance, particularly for rough or approximately isotropic surfaces. Therefore, polarization measurements can substantially reduce the influence of surface background and multiple-scattering contributions, providing a more direct constraint on aerosol scattering geometry and particle microphysical properties.

Under these conditions, the impact of ALH on polarization signals is primarily associated with changes in the scattering-angle distribution and the corresponding photon path geometry of single-scattering processes, resulting in enhanced physical sensitivity to aerosol vertical distribution. In addition, polarization measurements are more sensitive to the scattering characteristics of small-sized aerosol particles, such as fine-mode smoke aerosols, because particle-scale scattering processes produce stronger polarization responses. This further improves the detectability of variations in aerosol vertical structure. Within the optimal estimation framework, the inclusion of polarization information effectively expands the dimension of the observation vector, transforming the Jacobian matrix from one based solely on radiance sensitivity into a combined sensitivity matrix containing both radiance and polarization information. Since radiance and polarization observations exhibit different response patterns to aerosol and surface parameters, particularly with respect to the sensitivity relationships among ALH, AOD, and surface reflectance, the combined Jacobian matrix becomes less correlated, leading to improved parameter separability and increased DFS (Mishchenko et al., 2007). This enhancement is particularly pronounced under conditions where parameter coupling is strongest, such as high surface albedo (0.5) and low AOD (0.3). Under these conditions, radiance measurements are strongly influenced by surface contributions, whereas polarization measurements retain stronger sensitivity to atmospheric scattering, resulting in enhanced complementarity between the two observation types.

Overall, the incorporation of polarization information into multi-angle observations is not simply an increase in the number of measurements, but rather the introduction of an additional independent information dimension that is more sensitive to single-scattering processes and less sensitive by surface reflection. By reducing the coupling among aerosol and surface parameters, polarization observations improve the physical constraint on ALH retrieval. Consequently, the overall sensitivity to ALH is enhanced, while the dependence of retrieval performance on specific viewing geometries and surface conditions is reduced, enabling more robust ALH retrievals over a broader range of surface types and observation geometries.