Author’s response to comments from reviewer 4

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We thank the reviewer for their thorough reading of our paper and for providing thoughtful comments. We have addressed each one below.

Reviewer’s General Comments

1. The manuscript discusses the retrieval of vertical droplet size profiles from multispectral solar reflectance observations with high radiometric accuracy using a constrained optimal estimation inversion technique applied to MODIS observations. The study leverages VOCALS-REx field campaign data to develop the forward model constraints, which improves retrievals from, in particular, the lower optical depth levels of moderately thick liquid phase clouds. The high radiometric accuracy and spectral sampling follows from the design specifications for the upcoming CLARREO Pathfinder (CPF) instrument to be flown on the ISS in the 2026-27 timeframe. The findings highlight the value of high radiometric accuracy compared with current state of the art satellite imagers, as well as the challenges in comparing retrievals against in situ measurements in heterogenous clouds due to the profound differences in sampling volume.

2. The study contributes to a better understanding of future cloud microphysical profile retrieval information content from solar reflectance observations and nicely expands on previous efforts. The manuscript is very well-written, successfully capturing the history of previous studies as well as appropriate details of the author’s work. I characterized one comment as major but all others are minor.

Major Comments

Fig. 4: This is a very important figure in terms of the study findings but I was confused.

1. I interpret the y-axis to be absolute reflectance, not relative reflectance like the accuracy specs for MODIS or CPF. If that’s correct, the choice of r_bottom and dr_bottom will

scale the y-axis value Jacobians without changing the MODIS or CPF lines. If that's the case, I don't know how to interpret the results (e.g., if dr_bottom is effectively zero, all bars will be zero on the y-axis). If not the case, please elaborate.

a. *Authors' Response:* The y-axis is absolute reflectance, and indeed the y-axis values would change for different values of r_{bot} and Δr_{bot}. The y-axis is the change in reflectance due to a small perturbation in the radius at cloud bottom. For the i^{th} iteration and the j^{th} spectral channel, we estimate the y-axis values using the following equation:

$$\Delta R(\boldsymbol{x}_i, \lambda_j) = R\big((r_i^{top}, r_i^{bot} + \Delta r_i^{bot}, \tau_{c_i}), \lambda_j\big) - R\big((r_i^{top}, r_i^{bot}, \tau_{c_i}), \lambda_j\big)$$

The measurement uncertainties shown in Figure 4 for MODIS and CPF are also displayed in absolute reflectance. We used the reported radiometric uncertainties for the MODIS and CPF instruments and multiplied these percentages with the original reflectance, $R\big((r_i^{top}, r_i^{bot}, \tau_{c_i}), \lambda_j\big)$, for each spectral channel. Therefore, these curves would also change for different values of r_{bot}.

With all that said, we acknowledge the reviewer's point. The figure may be more useful if shown in relative values. The measurement uncertainties for MODIS and CPF are typically reported as a percentage. Therefore, it may be more useful to readers to show the percent change in reflectance along the y-axis. This has the added benefit of normalizing the change in reflectance with the initial reflectance, which depends on the current value of the radius at cloud bottom.

The following provides more details on how Figure 4 was created. We sought to use a representative cloud example, defined as having the median droplet profile found in Figure 1, except with varying optical depth. Δr_{bot} is defined as $\Delta r_{bot} = 0.35\, r_{bot}$ (L253). As described in the paper, this value was chosen so that the Jacobian terms with respect to the radius at cloud bottom, $\frac{\Delta R_\lambda}{\Delta r_{bot}}$, would not be dwarfed by the measurement uncertainty. However, we had to strike a balance between estimating the Jacobian, defined as the rate of change of reflectance with respect to some infinitesimal change in r_{bot}, with the measurement uncertainty. We found if Δr_{bot} was too small, measurement uncertainty dominated. If Δr_{bot} was too large, we no longer accurately estimated the local slope. We determined $\Delta r_{bot} = 0.35\, r_{bot}$ through trial and error. The phrasing in our manuscript may be misleading because we cannot always guarantee our estimate of the Jacobian exceeds the measurement uncertainty, because reflectance depends on the state vector. We decided to use a single value that worked for a broad set of state vectors.

b. *Proposed changes to the manuscript:* We will add additional information to the description of Figure 4 that more thoroughly explains how the y-axis values and the measurement uncertainty, which are reported as absolute reflectance, are computed. We will also explain the sensitive nature of reflectance with the state vector.

2. While the text mentions the spectral dependence of the Jacobians, it's not clear which channel(s) are being used in the figure.

   a. *Authors' Response:* The channels used are listed by their center wavelengths along the x-axis of the plot. All seven channels used in the multi-spectral retrieval (Table 1) are shown. Note that they are not in sequential order according to channel number but rather increasing in the value of the center wavelength.

   b. *Proposed changes to the manuscript:* None.

3. (3) The y-axis for the Jacobians should be labeled delta reflectance, delta reflectance/drbottom, or something similar unless I'm mistaken about (1).

   c. *Authors' Response:* Yes, we agree.

   d. *Proposed changes to the manuscript:* The y-axis label will be updated to reflect the changes from comment (1).

Minor Comments

1. L34: "effective droplet radius" or "effective droplet absorption" is proportional to 1-ssa? While it's true that $kr_e \sim 1 - ssa$ for an absorbing wavelength, it's an ill-defined definition for r_e when $ssa = unity$ (i.e., reduces to $r_e = 0/0$).

   a. *Authors' Response:* We thank the reviewer for pointing out this mistake. Our intention was to highlight the relationship between the effective radius and the fractional absorption of incident light due to multiple scattering within warm clouds. We will correct this sentence.

b. *Proposed changes to the manuscript:* We changed this sentence to say the following: "The fraction of incident light absorbed by optically thick warm clouds is proportional to the effective droplet radius over the solar spectrum."

2. L49, 60: While Twomey and Cocks (1982) provides a nice overview of the retrieval theory, a more focused retrieval study was done in the follow-up Twomey and Cocks (1989, Beitr. Phys. Atmosph.), which used 5 spectral channels simultaneously in the retrieval (not bispectral) and presented the solution space in terms of residual contour plots similar to your Figs. 7, 8. I'm not suggesting you include the following relevant historic τ, r_e retrievals references but just for awareness: Other airborne retrievals (Foot (1988), Rawlins and Foot (1990)); AVHRR (Arking and Childs, 1985), Platnick and Twomey (1994).

    a. *Authors' Response:* We thank the reviewer for suggesting the study by Twomey and Cocks (1989) as an early example of a multispectral retrieval of effective radius and optical depth. While the paper was hard to track down, it has proved insightful. We will review all suggested papers for potential incorporation into the historical section of our manuscript.

    b. *Proposed changes to the manuscript:* The introduction has been updated to include several of the suggested papers, all of which were early examples of airborne retrievals of cloud microphysics.

3. L60: suggest adding the qualifier "nearly independent from one another for optically thicker clouds …"

    a. *Authors' Response:* We agree.

    b. *Proposed changes to the manuscript:* The suggested qualifier has been added.

4. L64: "… radius, cloud optical depth, and various surface spectral reflectance assumptions."

    a. *Authors' Response:* We appreciate the suggestion.

b. *Proposed changes to the manuscript:* We included the above phrase about surface spectral reflectance in our sentence that mentions the free parameters varied to produce look-up tables for the MODIS Collection 6 cloud products algorithm.

5. L123, Sect. 4.2: As a simulation, it doesn't make a difference for present purposes, but I'm curious why the simulations were done for EMIT spectra instead of CPF, which is mentioned prominently as the motivation for the study (including the abstract). Was it in anticipation of doing EMIT retrievals as a follow-on? It would be useful to explain the rationale.

   a. *Authors' Response:* Multiple reviewers asked a similar question, so we reached out to the instrument team that developed HySICS (the HyperSpectral Imager for Climate Science), the spectral instrument on board CPF, and asked if we could obtain the spectral response functions so that we could simulate CPF-sampled TOA reflectance.

   b. *Proposed changes to the manuscript:* We were given access to the HySICS spectral response functions and have altered the analysis in section 4.2 such that the TOA reflectance spectra used to generate the contour plots in Figures 7 and 8 now simulate the HySICS spectral channels.

6. L184: What effective variance (ν_e) is used? The alpha "width parameter" is mentioned on L294 but would be helpful to put it in terms of ν_e. Are the same value(s) used for all 100 layers?

   a. *Authors' Response:* The relationship between the alpha parameter and the effective variance is defined by Emde et al. (2016): $\alpha = \frac{1}{\nu_{eff}} - 3$. We will include this definition in the paper and report the alpha values in the more familiar effective variance form. All 100 layers use the same effective variance. This parameter could vary with the vertical dimension in future iterations of our forward model.

   b. *Proposed changes to the manuscript:* The manuscript will be updated to include the relationship between the alpha width parameter and the effective variance. We will also report the effective variance used and make clear that this is constant for all 100 layers of the discretized cloud.

7. L188, 193: Eq. 5 is an approximation, though a reasonably good one, for the retrieved re since an exact weighting function is confounded by multiple scattering. I.e., suggest "represents the approximate retrieved …"

    a. *Authors' Response:* Yes, we agree.

    b. *Proposed changes to the manuscript:* This sentence has been updated to the following: "The wavelength-dependent column-weighted retrieved effective radius is approximated by:"

8. L91: A nice summary of the previous work. Platnick (2000) also did an information content study for MODIS-like imager, including the effect of calibration uncertainty, to help understand the number of independent parameters that can be retrieved for vertical profile inversions. Hard to make apple-to-apple comparisons but do your results seem somewhat consistent? Similar question with respect Fig. 8 accuracy sensitivity.

    a. *Authors' Response:* We thank the reviewer for bringing up this question. The information content study in Platnick (2000) highlights several key points relevant to our work that should be discussed in our manuscript. The number of independent pieces of information that can be retrieved to determine a droplet profile is, at most, equal to the number of spectral channels used. In the analysis by Platnick (2000), the three retrievals of effective radius using near-infrared wavelengths of 1.6 μm, 2.1 μm and 3.7 μm were found to provide only two pieces of information. The reason is that the difference between the retrieved $r_{1.6\mu m}$ and $r_{2.1\mu m}$ is less than the retrieval uncertainties for each.

       We expect the retrieval uncertainty to be the same or less than that assumed by Platnick (2000) because of the increased number of spectral channels. Therefore, our results appear in line with those of Platnick (2000) because we are only retrieving two pieces of information, the effective radius at cloud top and bottom, which was deemed possible with just three wavelengths by Platnick (2000). However, we have not explicitly computed the minimum eigenvalue of the scaled covariance matrix.

    b. *Proposed changes to the manuscript:* We will expand the Discussions and Conclusions section to include a discussion of our results and their consistency with those of Platnick (2000). In addition, the historical background within the introduction has been expanded to include the information content results from Platnick (2000).

9. Fig. 1: Please try to add some contrast to the line plot colors as some are hard to distinguish (esp. for color blind readers).

    a. *Authors' Response:* We will do so.

    b. *Proposed changes to the manuscript:* The colors of the different curves in Figure 1 have been updated to increase contrast and readability for color-blind readers.

10. L253, 254: Good idea.

    a. *Authors' Response:* Thanks!

11. L295: The MODIS retrieval wouldn't correspond exactly to the upper boundary re according to Fig. 1. Likely a small difference but worth a comment.

    a. *Authors' Response:* We agree with this clarification. The retrieval of effective radius is representative of droplet size below but near the cloud top. We will clarify this in the manuscript.

    b. *Proposed changes to the manuscript:* The manuscript will be updated to include the following clarification: "The retrieved effective radius does not represent the droplet size at cloud top. As the weighting functions in Figure 1 demonstrate, the retrieval represents the droplet size near but likely below cloud top. Nevertheless, we found this was an effective value to use for the a priori at cloud top."

12. L361/Sect. 4.1: For further context on the confounding effects that uncertainties in situ probes have on retrieval validation, including sampling issues associated with vertical and horizontal heterogeneity, I suggest looking at the recent Meyer et al. ORACLES study (amt.copernicus.org/articles/18/981/2025/). The paper discusses airborne spectral retrievals compared against two in situ cloud probes (CAS, PDI) having different measurement approaches in addition to some retrieval forward model errors. Retrieval evaluation with airborne probes continues to be an inherently challenging problem for the community. Nice discussion here and in Sect. 4.1.

    a. *Authors' Response:* We thank the reviewer for sharing this paper. The nuanced discussion on comparing remote retrievals with in-situ observations focused on different aspects than our own discussion, and we will include it in our manuscript. Consistent with other findings, Meyer et al. (2025) found remote retrievals of cloud effective radius to be larger, on average, than the coincident in-situ derived effective radii. This study attempted to reduce the differences between remote retrievals and in situ measurements by adjusting the complex index of refraction for liquid water and the effective variance of the droplet distribution within the forward radiative transfer model. This paper also has a great overview on the difficult nature of comparing remote retrievals and in-situ measurements and we will incorporate these results into our discussion in section 4.1.

b. *Proposed changes to the manuscript:* Section 4.1 will be updated to include the results of Meyer et al. (2025).

13. L377: Not sure that the cloud-top re retrievals "validate" use of the 2.1 μm MODIS bispectral retreival as a prior as much as demonstrates consistency with its use as a prior. I.e., much of the upper cloud re information content is coming from the 2.1 μm channel, regardless of which algorithm is used.

    a. *Authors' Response:* We agree with the reviewer's point. We included the 2.1μm MODIS bispectral retrieval of effective radius in Figure 3 to demonstrate that this value was consistently found to be near the in-situ derived values at cloud top. This result shows it is a suitable choice for the a priori at cloud top. This is not 'validation' in the technical sense, and we will adjust our phrasing accordingly.

    b. *Proposed changes to the manuscript:* Line 377 will be updated to the following: "The bi-spectral retrieval of effective radius was within range of the cloud top in situ measurement for each case, demonstrating consistency with its use as the a priori value for the radius at cloud top."

14. Fig. 3a and 3c have the same MODIS retrieval values (blue dashed lines). One must be incorrect.

    a. *Authors' Response:* Thanks for catching this!

    b. *Proposed changes to the manuscript:* Figure 3a has been corrected.

15. L409: I think this often gets lost on those who use gradient searches as part of inversion algorithms, especially in higher dimensional spaces. So, good to make this point, as obvious as it may seem. Is there an example solution contour plot associated with Fig. 3 that you could show to illustrate this point (i.e., similar to Figs. 7, 8)?

    a. *Authors' Response:* We thank the review for the suggestion. Figures 7 and 8 show the ℓ^2-norm of the difference between the forward modeled reflectances and the measurements in two-dimensional space. In actuality, this 'residual space' occupies three dimensions, with a residual associated with each point in the r_{top} r_{bot}, τ_c space. There is a region within this residual space that meets our convergence requirements (the area within the isopleths of 1 in Figures 7 and 8 of our manuscript). We found the gradient to be large outside the convergence region, but once inside, the gradient was quite small. Even if we allow the iterations to continue within the isopleth of one, the slopes are so small that the algorithm quickly converges at one of the local minima.

    b. *Proposed changes to the manuscript:* We will add a figure highlighting how steep the solution space is outside the convergence region and how shallow it is within the convergence region.

16. L440: suggest "… approximately 1 km2". The effective pixel shape in the across track direction suffers from the finite integration time and so has a ~2 km triangular wide spatial weighting function for most MODIS channels though a bit less so for "1 km" channels aggregated from the native 250 m (bands 1, 2) and 500 m (bands 3-7) detector arrays. That said, L462 is correct that the across track sampling is 1 km.

    a. *Authors' Response:* Thank you for this clarification!

    b. *Proposed changes to the manuscript:* The adverb "approximately" was incorporated as suggested.

17. L446: Interesting number. Thanks for making the calculation.

18. Fig. 5 caption, L454, 455, and later text/captions.: Constant altitude flight lines aren't usually considered a "profile" in airborne sampling vernacular (at least in the cloud and aerosol community). Also, elsewhere in the manuscript profiles is used, without qualification, to describer vertical sizes only so it will be a source of confusion. Try "horizontal legs" or just "legs". I realize that constant altitude across three different

clouds during the campaign may end up sampling different depths relative to cloud top and so have some vertical profile information (e.g., the yellow curve in Fig. 5).

a. *Authors' Response:* We agree with this point and want to ensure readers have a clear distinction between vertically and horizontally sampled in-situ measurements.

b. *Proposed changes to the manuscript:* The manuscript will be updated so that the term 'profile' is used only when referring to vertical in-situ measurements or a retrieved vertical profile of droplet size. The term 'horizontal leg' is used exclusively for in-situ measurements within clouds at a near-constant altitude.

19. L458: "… and 6 μm (yellow)"

a. *Authors' Response:* Thanks for catching this!

b. *Proposed changes to the manuscript:* The manuscript has been updated so that the units are before the parenthetical descriptor.

20. Figs. 7, 8: Nice demonstration of more channels v. better accuracy, with the latter being the only way to dramatically reduce the delta radius solution space uncertainty. That's an important result. (1) Initially, I didn't notice that the y-axis had both positive and negative values. Would be helpful to add a horizontal line to the zero value so readers can quickly appreciate that a large region of the space is outside the constraint. Or add a slight shading to the negative regions. (2) Add a point on the plots to indicate the modeled cloud optical depth and delta effective radius that was used in the simulation (didn't see it mentioned in the text, nor the cloud top effective radius).

a. *Authors' Response:* We agree that both suggestions provide useful information to readers. As the reviewer correctly noticed, the left panel of Figure 7 shows that some of the state vectors within the isopleth of one (the convergence region) have values where $r_{top} - r_{bot} < 0$, which is outside the constraint we defined.

b. *Proposed changes to the manuscript:* We will update Figures 7 and 8 to include a shading that highlights the negative regions. We will also add points to indicate the modeled cloud optical depth and $r_{top} - r_{bot}$ values used in our simulation.

21. Data Availability: If MODIS L2 cloud data was used, please also mention that these files were obtained from LAADS. I strongly suggest providing a doi for both the L1B and L2 files, which should be available on the LAADS product information pages.

    a. *Authors' Response:* We agree.

    b. *Proposed changes to the manuscript:* The Data Availability section will be updated to include DOI's for the L1B, L2 and the MODIS geolocation files. We will cite LAADS as the source of all MODIS data used in our analysis.

References

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