Authors' reply to Review of Ding et al, for AMT, 2016

Passive satellite measurements of backscattered solar radiance provide information as to the total loading of aerosols in the atmosphere. Recent research has suggested that the use of oxygen A and B bands (O2-A and O2-B) can help to derive vertical profiles of aerosol, and future satellite missions may have these capabilities. This paper attempts to quantify the information content provided by backscattered radiance and degree of linear polarization (DOLP) in the O2 A and B bands, for the problem of retrieving aerosol vertical profile. Quantitatively, DOLP in O2 A and B bands is found to be more sensitive to aerosol peak- height (H) and half-width (γ) than radiance itself, especially over the bright surfaces (with large visible reflectance). Assuming the surface and/or aerosol column (optical depth) is well constrained, the sensitivity increases with H. Further analysis demonstrates that more measurements in more bands helps to increase signal.

Major comments: I have very few, if no major comments. I think this paper is a very well written paper, and very informative. I was on a roll for identifying minor issues (comments below, e.g. run-on sentences), but ran out of steam by the end.

Reply. We thank the reviewer for thorough review and providing us encouragement and constructive comments for improving this manuscript.

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• There are a few plots I would like upgraded, but mostly it is plotting style rather than content. I would like to see the "baseline" of black surface (As = 0.0), even though as I work through the paper, I understand that complete absorption is like creating its own black surface. I think the colors (red, green, blue) are overused in the plots, as sometimes it represents different surface, and otherwise different altitudes/levels.

Reply. In figure 1 and figure 2, now As = 0.0 is plot as black line.

• Overall, I am very satisfied with the introduction, as well as the theoretical and discussions in Figures 1, 2 and 3. But then there is section 3.4, where discussion seems to "speed up". Each figure has decreasing amount of text associated with it. Figure 11, in particular, should include more discussion.

Reply. More discussions are now added, including "These results suggest that the information content in DOLP in O2 A and B band decreases with aerosol absorption. Hence, a combination of using both UV radiance and DOLP in O2 absorption band may enhance the information content for charactering profiles of absorbing aerosols".

• The summary is weak. The purpose of the study (to be ready for future satellite missions that have O2-A and B capabilities) is well defined in the introduction. So now that you have done this study, what next? How might you apply the retrieval to real data? Do you see any collaboration with data from other instruments? For example, what about OMI-type measurements in the UV that are sensitive to aerosol height and loading? Since the EPIC instrument has O2 bands, plus UV bands, and PACE should have both, plus DOLP, you really are on the cusp of something very special.

Reply. Thanks for such a good suggestion. The revision adds the following. "For future studies, real measurements of DOLP in O_2 A and B bands are needed to further evaluate their potential as well as their combination with DOLP in atmospheric window channels (such as proposed to the PACE) for retrieving aerosol profiles over land. Meanwhile, existing satellite sensor, NASA's Polychromatic Imaging Camera (EPIC), do measure radiance in both O_2 A and B band as well as in the atmospheric window channels in UV at the top of atmosphere from the Lagrangian point 1 (L1, 1,500,000 km from the Earth). A combined use of all these measurements may augment existing (OMI-based) UV-only technique to retrieve aerosol height information. With PACE and EPIC-type sensors in the coming decade, it is foreseeable that passive remote sensing of at least one piece of information for aerosol vertical profile can be conducted on the global and daily basis. But, challenges exist, especially when sensor's instantaneous field of view is large (~20 km for EPIC and OMI) and can often be contaminated by clouds. Since cloud often has much larger optical depth and particle size than aerosols, it is also necessary to study how cloud contamination may affect the results presented here, and whether or not DOLP in O_2 A and B band can add valuable information for cloud detection and for the existing cloud top height retrieval technique that uses the intensity in O_2 A band (Fisher et al., 1991).".

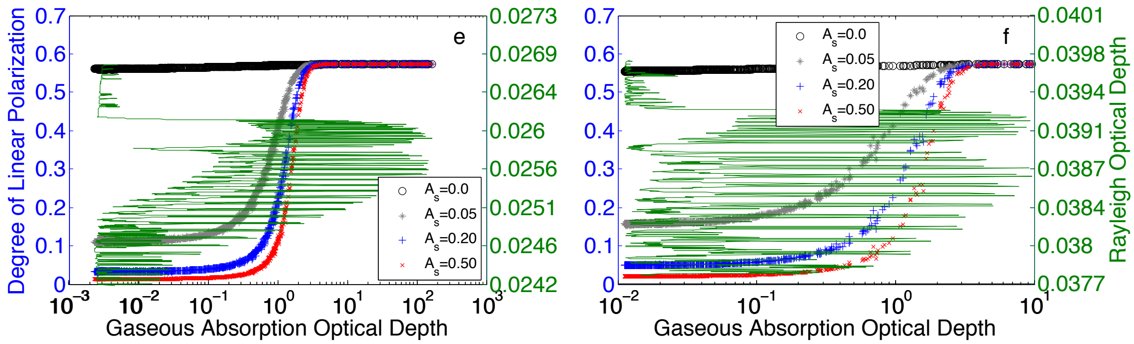
• For the final sentence, something stronger than "For future studies, real measurements of DOPL in O2 A and B bands are needed to further evaluate their potential as well as their combination with DOLP in atmospheric channels for retrieving aerosol profiles over land."

Reply. See the reply as above.

Medium comments and questions

• What is the relative vertical distribution of molecular scattering versus molecular absorption (e.g. Fig 1e/f)? This would provide physical intuition to these figures.

Reply. We plot the figure as below. We didn't find that the variation of Rayleigh optical depth can explain the DOLP variation in O2 A and B band. This is now added in the discussion. "It should be noted that the O_2 absorption (often larger than 1) is much larger than the Rayleigh scattering optical depth (0.026 - 0.024 and 0.040 - 0.037 respectively) in O_2 A and B bands, and hence, the *spectral variation* of DOLP in these bands has visually no dependence on spectral variation of Rayleigh optical depth (figures now shown)." . While in both figures there is a generally slightly increase of Rayleigh optical depth as gas optical depth increases (and hence DOLP increases), this general trend is due to the absorption line structure of O2 A (and to some extent O2 B) which lead to the general increase of O2 A with wavelength and (so decrease with Rayleigh). But, the fluctuations of Rayleigh with DOLP increase suggest that Rayleigh change is not a factor in change DOLP.



• I wonder about the utility of trying to calculate DFS when you combine radiance and DOLP together? Right now they are separate, but a real retrieval might use both sets of information. On a side note, I wonder what happens if you already have AOD "perfectly" measured (or retrieved), how will that influence the DFS?

Reply. The radiance has much less sensitivity to aerosol profiles over bright surfaces, as shown in the paper. The O2 A band (760), the surface albedo is often very high, even for vegetated surfaces. Therefore, retrieval of AOD using wavelengths at bands close to O2 A would have larger uncertainty. Given that current remote sensing technique can already retrieve AOD with reasonably good accuracy, we have assumed that AOD can be known priori before aerosol height needs to be retrieved. In our analysis, we have considered the measurement uncertainty as the sum from AOD uncertainty, instrument uncertainty, and RTM modeling uncertainty due to other aerosol properties.

• I did not check the equations related to Jacobians, so I have no comments in that section. Someone with the requisite background should check these equations.

Reply. We have checked to make sure they're consistent with our past papers.

• Could this retrieval be performed above a cloud? (say a boundary layer cloud, where As→1.0)?

Reply. We will be conducting research on this topic. The expectation is that it will be difficult unless we know the cloud top height and cloud microphysical properties.

• There is a mention about "measurement error of 0.05" (line 199). What does that mean?

Reply. In our analysis, we have considered the measurement uncertainty as the sum from AOD uncertainty, instrument uncertainty, and RTM modeling uncertainty due to other aerosol properties. We now added this in the text.

• Related to measurement error, normally an instrument will have an expected accuracy for typical reflectance (e.g. 2% for something like MODIS) or polarization (expected 0.5% for APS). What are the tolerances that can be accepted here? Since the idea is to work in hyperspectral space, how accurate does the wavelength characterization need to be (for example, could instrument be wrong by 1 nm, or 0.1 nm?)

Reply. As discussed above, the measurement error here includes the errors from instrument error and radiative transfer modeling error (due to the uncertainty in AOD and aerosol optical properties). We also looked the results if the measurement errors are larger than 5%. We found that measurement error up to 8% won't affect the results significantly (e.g., DFS difference is less than 0.1 for cases where DFS is larger than 0.8, see the figures at the end of this document). Some hyperspectral measurements can have finer spectral resolution of 0.02-0.04 nm. We added some discussion in the text. Figure S2 and S3 are presented for analysis with different assumptions of measurement errors.

• I think the physics/intuition can be explained a little bit better. I provide some suggestions below.

Thanks.

Minor comments: Note line numbers - probably an AMT format issue, but the line numbers are only two digits. I do my best to guess the hundreds digit in my comments.

• All: Suggest writing as "O2-A" and "O2-B" bands, (without the "-" the A and B modifiers tend to dangle off by themselves in some sentences).

Reply. here our denotation of O2 A and B bands follows the textbook by Goody and Yung, "Atmospheric Radiation, theoretical basis, section edition".

• Lines 29-32: Is a run-on sentence. Actually there are scattered run-on sentences throughout the manuscript. (e.g. line 93-98).

Reply. We have revised these long sentences into different shorter sentences.

• Line 32: Is IPCC, 2014 the right reference? Usually people do IPCC, 2013 for the science, and 2014 for the policy.

Reply. we now changed this reference to IPCC 2013.

• Line 42: Instead of "obtain the information", maybe "observe" (I could obtain the information from the model). I guess I could also propose a high-resolution network of ground/aircraft monitors, but probably would be super expensive!

Reply. We changed "obtain" to "measure".

• Lines 57-58. What is the O2-A band, anyway? Where is it (spectrum) and why is it called the O2-A band? (Same with O2-B band). Is it O2 absorption only, or is it also other constituents that absorb? (info later in paper, but could use a short description here).

Reply. We added this sentence to introduce O2 A and B. "O_2 A (760 – 775 nm) and O_2 B (687 – 695 nm) bands are the two absorption spectrum introduced by the change of oxygen electronic energy levels through vibrational-rotational transitions and molecular collision (Goody and Yung, 1989)"

• Line 99. Currently awkward. How about writing "Our study is different from past studies in two ways".

Reply. Changes made as suggested.

• Line 102-104. "potential of radiance in in O2 A..." is awkward. How about: "While Sanghavi et al. (2012) and Vasilkov et al. (2013) have demonstrated that measured radiance in O2 A and B can be used for retrieving aerosol profile over dark surfaces, ours is the first to test whether DOLP in these bands can add information."

Reply. Changes made as suggested.

• Lines 106-112- Another run-on (too many subjects in one sentence). And should be "Fourier".

Reply. We reword the text.

• Lines 150-162: Suggest to use bullets for readability?

Reply. Done.

• Lines 199: I don't understand what is a "measurement error of 0.05". Are there units? Is this in reflectance, or in DOLP?

Reply. The measurement error was defined as absolute error of 0.05 for DOLP, and relative error of 0.05 (or 5%) for intensity. Those are based on our past studies (Xu and Wang, JGR, 2015) and we now clarify them in the paper. Note, measurement error here also include RTM model error (from computation or numeric).

• Lines 205-ish (and Table 1). Normally, one reports the center radius and the variance to calculate the size distribution, drive a Mie code, and calculate the effective radius.

Reply. we now provide Rg and sigma_g in Table 1.

• Line 220 – What kind of aerosol has peak height of 16 km? Volcanic ash? While I am thinking about very high altitude aerosols, what about cirrus clouds? If they are present, what would happen to aerosol retrieval?

Reply. This is good question. Another reviewer also asked the same question. We add some discussions on this. As discussed in the introduction of the manuscript, several studies have already used radiance in O2 A band to retrieve cloud top height. We believe cloud contamination would have important impact on the DOLP in O2 A band, but DOLP may also help to help detect cloud and minimize the cloud contamination. We have not done any work in these regards yet. So, instead, we acknowledge this the revised text as the following: "Furthermore, since aerosol and cloud are often co-exist in real atmosphere in the instantaneous field view of a satellite sensor and cloud often has much larger optical depth, it is also necessary to study how cloud contamination may affect the results presented here, and whether or not DOLP in O_2 A and B band can add valuation information into the existing cloud top height retrieval technique that uses the intensity in O_2 A band (Fisher et al., 1991)"

• Line 230: (and Figure 1). Misspelling of wavelength. I am curious if information would be more clear, if plotted panels A/B on same vertical scale, and C/D on same vertical scale. Also, I wonder if "penetration altitude" is the best term for the variable plotted in panels C/D. I find the term misleading. Unfortunately, I have no suggestions for a better term. This is for nadir (solar zenith angle = 0) ?

Reply. Several textbooks use penetration depth to describe how deep solar radiation at different wavelength can penetrate into the water. However, since we often give the aerosol layer height value with respect to the the ground (e.g., altitude of zero), we end up to use "penetration altitude" here. We also give the definition of term in the figure caption. Yes, solar angle is 0 and this information is now added into the caption.

• Page 235: I am not following this logic: "Hence, the spectral contrast of reflected sunlight in terms of their intensity and polarization contains information of atmospheric scattering (including aerosol scattering) at different altitudes of the atmosphere (Figure 1 e- f)." The figures are as a function of absorption optical depth, so we need some sort of information about the scattering profile, (maybe it could be plotted on the same graph as a black dotted line?) And then this might help answer my next comment as well

Reply. This sentence is not exactly referring to Figure 1 e-f, and so we revised it as. "Hence, for a given atmospheric profile with well characterized vertical profile of O_2 absorption, the spectral contrast of reflected sunlight in terms of their intensity and polarization in these bands contains information of atmospheric scattering (including aerosol scattering) at different altitudes of the atmosphere.". Then, after this sentence, the following paragraph starts with: "To quantitatively illustrate the sensitivity of backscattered intensity and polarization with respect to the vertical profile of scattering, we first conduct the UNL-VRTM calculation for aerosol-free conditions.".

Figure 1 e-f is for aerosol-free atmosphere only. In both O_2 A and B bands, the variation of Rayleigh optical depth and aerosol optical depth change are small, and such variations are considered in all RTM calculations and information content analysis. As we provided in our reply earlier, the variation of Rayleigh optical depth doesn't contribute to the large variation of DOLP; it is the relative position of aerosol and Rayleigh scattering with respect to the large variation of DOLP.

• Lines 240-ish (and Figs 1-e/f) reads: "Figures 1 e–f the DOLP at the top of an aerosol-free atmosphere over various surface types (with reflectance from 0.05, 0.2 to 0.5) as a function of molecular absorption optical depth. It should be noted that the O2 absorption is much larger than the Rayleigh scattering optical depth in both bands." Molecular absorption refers to O2 only. Molecular scattering (Rayleigh) refers to other gases as well. What are typical values for scattering optical depth in these bands (how much larger is absorption than scattering?).

Reply. We change the text to "O_2 absorption depth". And also add information about Rayleigh optical depth. "It should be noted that the O_2 absorption (often larger than 1) is much larger than the Rayleigh scattering optical depth (0.026 - 0.024 and 0.040 - 0.037 respectively) in O_2 A and B bands".

• Lines 245-258: I think the explanation mostly makes sense here. In a molecular scattering atmosphere above a black surface, the DOLP can attain its maximum value (For completeness, I would like to see a curve with As = 0.00 – analogous to an ocean scene?) As soon as one adds a surface target, the polarization signal gets muted. Hence, DOLP gets reduced. But I am having trouble understanding why as you add absorption to the path, why DOLP is increased? I guess what is happening is that the super thick absorption acts like a black surface?

Reply. Yes. Your understanding is consistent with our calculations. We also added As = 0.0 in Figure 1 e-f. some discussion is now added. "In summary, when surface is black and/or O_2 absorption in the lower part of the atmosphere is large enough to completely preventing the light reach the surface, the backscattered DOLP is from the Rayleigh scattering only and is always close to 57%. For black surface only, there is a slight (~1%) increase of DOLP as O_2 optical depth increases (from nearly zero to 10); this small increase of DOLP is due to a slight decrease of Rayleigh optical depth (as the light penetrate altitude increases) and single decrease of single scattering albedo (as for same upper atmospheric layer, O_2 absorption increases). Because atmospheric aerosols can affect scattering optical depth at various altitudes, it is expected that aerosols will change DOLP and the spectral variation of DOLP should have information on vertical distribution of aerosol scattering."

• Lines 265-269 and Figures 2a-b: I am satisfied with the figures and explanations, except for the colors. In Fig 2a, Red, green, and blue curves are different Hpeak values, whereas in 2b, 2c, the same colors represent different As values. Suggest different colors, or at least different line styles for each set of figure panels.

Reply. Good points. We have changed both line color and line style.

• Figure 3: I would suggest making a Figure 3.5, which has the same panels, but for a continuum wavelength.

Reply. We plot the similar figure for the continuum band and add this Figure as the supplementary Figure S1. It can be seen that DOPL is not sensitive to the Hpeak and Gamma for surface albedo = 0.2 or 0.5. Some discussions are now added in the text.

• Line 318: Why not perform a test for only radiance in the O2-B band? And then a part (e) would be radiances + DOLP in both bands. To make more readable, maybe could be written as bullets.

Reply. As discussed in the introduction, several past studies already looked at the radiances in O2 A band over the ocean surfaces. Over the bright surfaces, O2 A radiance contains very little information, and so does O2 B band. Since the focus here is the aerosol height and DOLP, we didn't combine the both in the analysis. Some near-future research is now planned along these lines and is discussed at the end of the manuscript.

• Line 325 (and Fig 4): What do you mean by number of channels? I understand this is hyperspectral, but what are the channel widths? This information is stated more clearly later in the paper, but it could be useful here.

Reply. We now add this information. "we calculate the DFSs for aerosol peak height *H* at each individual wavelength (or channel at 0.01 nm spectral resolution across O_2 A and B bands)"