Response to the report of reviewer #1:

We appreciate the detailed comments and suggestions from the reviewer, which are very helpful in improving the clarity of this work. Please find our response as follows. We have made corresponding revisions in the manuscript also detailed below.

Interactive comment on "Inversion of multi-angular polarimetric measurements from the ACEPOL campaign: an application of improving aerosol property and hyperspectral ocean color retrievals" by Meng Gao et al.
Anonymous Referee #1 Received and published: 7 April 2020

The paper uses data collected from two airborne multi-angle polarimeters (MAPs) flying together on the ER-2 over a SeaPRISM site off the southern California coast to investigate whether multi-angle polarimetry will improve atmospheric correction of a hyperspectral instrument. The question is important because of the NASA PACE mission scheduled to launch in less than three years. The flagship PACE instrument is a hyperspectral radiometer, but it will be flying with two MAPs. Will those MAPs improve the radiometer's ability to retrieve ocean-leaving radiance by constraining aerosol properties? The study is presented well, is backed up with real validation and comes to a solid conclusion. There are a few points that I think should be considered before publication, but overall my take is that the revisions will be very minor.

Thanks for the interest in this work and the positive comments.

Comments:
1. Addressing the lack of UV in the study.
For me the biggest challenge for atmospheric correction in PACE is not the hyperspectral, but the UV. The atmosphere in the UV range is thick with Rayleigh and with aerosol scattering/absorption, making atmospheric correction even more uncertain than it is even in the deep blue (410 nm). Yet, the ocean community is excited by the UV measurements by OCI and intends to exploit that data, which they absolutely will not be able to do without a better plan for UV atmospheric correction.

I fully understand that addressing UV is outside the scope of this paper, but there are small things that can be done here to clarify the limitations of this paper and express the need for a future focus on the UV. The authors would be doing the community a great service.

Thank you for the comments. We agree that the UV coverage which will be provided by PACE is important for both atmosphere and ocean community, but unfortunately it cannot be explored in this study due to the limitation in the measurement data. We have made necessary revisions to emphasize the importance of atmospheric correct at UV, which are listed below in the responses to the specific comments.

P3 Line 1. SPEXone has true UV measurements.
P4 Line 27. SPEX airborne does not have UV measurements
P3 Lines 21-22. "SPEX Airborne collects hyperspectral radiometry, and thus can be used as a proxy for OCI in developing hyperspectral ocean color algorithms." With the

caveat that it is missing measurements in the true UV part of the range.

We added the following sentence to clarify the missing UV measurements in SPEX Airborne:

> "The spectral range from the SPEX Airborne measurements used in this study is from 470 to 750 nm. This does not cover the UV bands, which is nevertheless important and deems further research for the PACE mission (Frouin et al 2019, Chowdhary et al 2019)."

P20 Line 2. "The resulting hyperspectral water leaving reflectances agree well with the AERONET OC and MODIS OC products." But not below 470 nm. This has implications for the UV.

We revised the statement by specifying more details for both RSP Rrs and SPEX Rrs:

> "…
> The retrieval uncertainties on RSP Rrs is within 0.0004 sr^{-1}(same to SPEX Rrs), while the comparison of the two cases with the AERONET Rrs shows a difference less than 0.0003 sr^{-1} for RSP Rrs, and a maximum difference of 0.0004 sr^{-1} (Case 10/25) and 0.001 sr^{-1} (Case 10/23) for SPEX Rrs. The difference of SPEX Rrs for Case 10/23 is larger than the retrieval uncertainties which is likely due to the radiometric uncertainties from the sensors.
> "

2. Cases at very low aerosol loading
The two cases examined in the study are at very low AOD. There are a few places in the paper where the low aerosol loading introduces some concerns. P5 Line 11. "For AOD less than 0.2, uncertainties in the AERONET inversion properties…. (Dubovik et al., 2000)".
For what wavelength is AOD < 0.2?

Dubovik 2000 is a very old reference. I looked through the materials on the AERONET web site including this document.
https://aeronet.gsfc.nasa.gov/new_web/Documents/U27_summary_final.pdf
It seems to imply a different set of uncertainties that are actually larger than what is stated here, especially for refractive indices and SSA. Size distribution products can tolerate lower aerosol loading, but anything to do with absorption just falls apart when there is insufficient signal.

Also the implication by this statement on P5 is that the same uncertainties hold for all AOD 0.2 and less. This means that AOD = 0.04 has the same uncertainties as AOD =0.20, and the AERONET document, and especially the graphs at the bottom do not support this.

Now I find it interesting that the authors do mention the challenge of retrieving microphysical properties when the aerosol loading is small. (P6 Line 15 and P16 Lines 6-8).

Then why imply minimal uncertainty for these very, very low loadings of the cases studied in this paper? I am sufficiently distressed about trying to make retrievals of intrinsic particle properties when the AOD at 550 nm is less than 0.04, that I question the results of these retrievals in Figure 5 and Table 3, and some of the overall conclusions.

Thank you for the comments on the AOD, also thank you for providing the AERONET uncertainty document. We agree that the statement on the AERONET aerosol uncertainties may not best describe the particular cases in our study. We revised our manuscript according to the reviewer's suggestions, which are listed below in the responses of specific comments.

Specific items that need to be addressed:

The statement on P5 should be updated.

It is challenging to provide an accurate theoretical assessment of the uncertainties for the particular cases in our studies, we removed the general statement, and instead we only use the uncertainties evaluated by the daily average of the AERONET product as an estimate. We also made it explicit that the inversion uncertainties increase with smaller AOD by citing the AERONET uncertainty document:

> "Note that the actual inversion uncertainties for the aerosol properties, such as the refractive index and single scattering albedo (SSA), may be larger than their daily averaged result for small AOD cases as reported by the AERONET Version 3 uncertainty analysis (Description of Aerosol Inversion Uncertainty for Level 2 Products). In general, AERONET retrievals of aerosol microphysical properties become less certain as AOD decreases."

In figure 5, the AERONET properties are plotted with their daily variation, but not their uncertainties. The uncertainties are larger than the range of the daily variation. This should be stated explicitly.

We specifically mentioned that the AERONET results are plotted with its daily variation as:

> "The results from AERONET product are plotted in green, and the vertical width indicates its daily variation."

The possible larger uncertainty from AERONET product are also added as in the response to the last comment.

P16 Line 4, check those AERONET uncertainties again. I think they are too small.
This is similar to the above statement in P5, we removed it.

P19 Line 16. The absolute values also agree better with the AERONET aerosol product. " This is not true for SSA. But… there are large uncertainties for SSA in AERONET because of the low AOD.

We revised it as follows:

> "The absolute values also agree better with the AERONET aerosol product except SSA probably due to the large uncertainty of SSA from both the MAP and AERONET inversions at low AOD."

3. Systematic biases between airborne SPEX and RSP
Beginning on P6 Line 28, the paper mentions "systematic differences", but never describes which is higher, SPEX or RSP. This becomes important in the conclusion. P17 Lines 15-18. Here systematic differences between RSP and SPEXairborne are mentioned again, but which one is higher? And it isn't stated which one is right. So when speaking of impact on aerosol retrievals, how would these instrumental differences cascade into the aerosol retrievals? What should be expected from these differences, and why or why not were these expectations met?

Thank you for the questions. The systematic differences the reviewer referred are the differences in radiometric calibration between the two instruments as reported by Smit et al 2019. The radiometric bias from both instruments could contribute to the systematic difference between these two instruments. We have revised the paragraph to indicate which sensor has larger reflectance as follows:

> "…Over the four RSP bands of 410, 470, 550, 670 nm, the random noise contribution to differences of reflectance are 2%, 2%, 2% and 4%. RSP reflectance is slightly larger than SPEX reflectance at 410 and 470 nm as indicated by their systematic differences of around 4% and 3% respectively, larger than the random differences; the systematic differences at the other two bands are relatively small with values of 0% and 1%."

From the comparison of the Rrs with AERONET Rrs, it seems the radiometric calibration of RSP is more accurate at 410 and 470 nm (as in the revised statement in the response of comment 1). But it is not our intention to claim which measurement is more accurate than the other based on only two case studies. Moreover, in terms of aerosol retrievals, we are trying to mitigate the issues by relying more on the RSP DoLP measurements which has smaller systematic difference between instrument and also high sensor accuracy.

P17 Lines 21-23. Once again we are presented with differences, but are never told which instrument produces the higher result.

Similar to the response to the previous comment, we have added specifically which instrument produces higher results:

> "As discussed in Section 2, reflectance measured by RSP is larger than SPEX Airborne measurement by a systematic difference of 4% and 3% at 410 and 470 nm respectively."

Meanwhile in the same paragraph, we showed how much impact on the Rrs could come from the systematic difference on the bands of 410 and 470nm, and why we excluded the wavelength less than 470nm in Rrs comparisons. We added more discussions here:

> "The reflectances measured by RSP at 410 and 470 nm are 0.15 and 0.09, respectively. Based on the definition of Rrs, the 4% and 3% systematic difference in the reflectance will transfer into a large Rrs biases around 0.002 and 0.0009 sr^{-1}. Therefore the Rrs from both RSP and SPEX at wavelengths less than 470nm are not compared…"

4. Theoretical retrieval uncertainty and validation against measurements
The authors to their credit address uncertainty from both the theoretical perspective and then also by comparing with ground-based measurements with well-defined uncertainty. The act of validation validates the magnitudes of the retrieved properties.
In addition the act of validation validates the theoretical estimate of the uncertainties. The authors should explain explicitly in the paper when the theoretical polarimeter uncertainty is validated by the ground-based measurements and when it is not. I never believe the calculations of theoretical uncertainty until validation. On P17 Lines 11-12, "These reduced uncertainties in the aerosol micro-physical properties can help to determine aerosol type and its composition.." The authors here are discussing the theoretical reduced uncertainties. Have these reduced uncertainties been explicitly validated?

Thank you for the comments on validations. To make our discussion more accurate, we revised the corresponding statement by referring to explicitly "retrieval accuracy", and "retrieval uncertainties", and added the limitation in validation data and the requirement of future validation campaigns:

> "Meanwhile, we have shown polarization information can help to improve retrieval accuracy in the retrieval of aerosol optical depth, fine mode refractive index and SSA as shown in Fig. 5. Besides the theoretical retrieval accuracy analysis, validations with direct measurements are important to account for unknown uncertainties. The AOD results from polarimetric retrievals can be validated with ground-based measurement such as AERONET and lidar measurements such as HSRL, however, it is challenging to validate complex aerosol refractive index, SSA, and size distribution for the entire atmospheric column due to the lack of direct measurements. Such validation requires well-planned airborne field campaigns, concepts for which are under development (PACE validation plan 2020)"

The concern I have is that the authors believe their theoretical calculations of uncertainty too much. P16 Lines 3-5. "Note that AERONET aerosol product uncertainties are approximately 0.01 for AOD, 0.05 for refractive index, and 0.05-0.07 for SSA as mentioned in Section 2, which are comparable with the results for 7rho_t but larger than the ones from 7rho_t +5rho_t . " The implication is that RSP is more accurate than AERONET. There might be argument that RSP SSA retrievals are more accurate than AERONET inversion, but there is no way the RSP retrievals of AOD are going to be better than the AERONET direct sun measurements.

The point is that theoretical uncertainty calculations can only calculate the uncertainty that is known and when a retrieval is made in the real world, then the uncertainty that cannot be quantified theoretically, enters the picture and the actual accuracy of the retrieval is less good than the theoretical calculation.

This is a very good point. We revised our manuscript as in the response to previous comments with acknowledgement of the limitation of the theoretical uncertainty and the necessary for more direct validation, which is repeated as follows:

> "Meanwhile, we have shown polarization information can help to improve retrieval accuracy in the retrieval of aerosol optical depth, fine mode refractive index and SSA as shown in Fig. 5. Besides the theoretical retrieval accuracy analysis, validations with direct measurements are important to account for unknown uncertainties. The AOD results from polarimetric retrievals can be validated with ground-based measurement such as AERONET and lidar measurements such as HSRL, however, it is challenging to validate complex aerosol refractive index, SSA, and size distribution for the entire atmospheric column due to the lack of direct measurements. Such validation requires well-planned airborne field campaigns, concepts for which are under development (PACE validation plan 2020)"

5. The results question the ability of PACE to produce Rrs at short wavelengths
P20 Line 2. "The resulting hyperspectral water leaving reflectances agree well with the AERONET OC and MODIS OC products." Well, not towards the blue, near 470 nm. Hasn't this always been the problem? Ocean biology products need water leaving radiance at the short wavelengths, and they are going to want the UV also. Here the authors show that towards the blue, the hyperspectral retrieved water leaving radiance deviates from AERONET and MODIS products by a lot. At 470 nm for the 10/23 case, the SPEX airborne retrieved remote sensing reflectance is half of what AERONET-OC measured. This does not bode well for the ability to use the blue and UV from the PACE hyperspectral Ocean Color Instrument in any reliable, consistent fashion. The authors examine two cases. In one out of the two cases the atmospheric correction fails at shorter wavelengths for the hyperspectral retrieval. This needs to be stated explicitly when describing Figure 6, but also explicitly in the Conclusions.

Thank you for the comments. In the response to comment 1 (repeat below), we revised statement on the comparison of RSP, SPEX and AERONET Rrs in the conclusion:

> "…
> The retrieval uncertainties on RSP Rrs is within 0.0004 sr^{-1} (same to SPEX Rrs), while the comparison of the two cases with the AERONET Rrs shows a difference less than 0.0003 sr^{-1} for RSP Rrs, and a maximum difference of 0.0004 sr^{-1} (Case 10/25) and 0.001 sr^{-1} (Case 10/23) for SPEX Rrs. The difference of SPEX Rrs for Case 10/23 is larger than

the retrieval uncertainties, which is likely due to the radiometric uncertainties from the sensors.
"

Meanwhile, MAP radiometric measurements are expected to have higher agreement with PACE OCI through cross-calibration, as discussed in section 5(second paragraph):

"…On-orbit MAP cross-calibration with OCI will be possible – for example, measurements at the $\pm 20^o$ viewing angle of SPEXone are expected to be cross-calibrated with OCI, transfering the high radiometric accuracy from OCI to SPEXone (Werdell et al 2019)"

The following discussion are added in the conclusion to clarify the implication to PACE OCI:

"Although the hyperspectral atmospheric correction for wavelength less than 470nm cannot be demonstrated by the SPEX airborne data, the PACE OCI will provide high quality hyperspectral measurement from 340 to 890nm and a few SWIR bands, and the demonstration of the atmospheric correction including UV spectral range will require future studies. "

More detailed comparison of the Rrs spectrum has been provided in the discussion of Figure 6

"… The RSP Rrs at 470 and 550nm are 0.0026 and 0.0020 respectively for Case 10/23, and 0.0025 and 0.0021 respectively for Case 10/25 as shown in Table 3. For AERONET Rrs, the values at 442, 490 and 550nm are 0.0027, 0.0028, 0.0017 sr^{-1} for Case 10/23, and 0.0028, 0.0029, 0.0017 sr^{-1} for Case 10/25. Using the interpolated value of AERONET Rrs at RSP bands, the difference between RSP and AERONET Rrs are within 0.0003 sr^{-1}."
More discussions on the comparison of SPEX and AERONET Rrs are in the revised file and diff file.

6. Smaller items, but some are still substantial
Abstract Line 4. "aerosols properties" should be "aerosol properties"

Done

P6 Line 19. "water leaving reflectance". Is the same as Remote Sensing reflectance mentioned on Line 16? The terms seemed to be used interchangeably, and I'm not sure that is correct.

Thanks for potting this out. We revised the "water leaving reflectance" as "water leaving signals". The definition of the water leaving reflectance is provided in Eq(2), and its connection with Rrs is in Eq(1).

Figure 6 caption. What do the error bars signify?

We revised the caption as follows:

> "The error bars for the RSP retrieved results with cost functions of 7ρt and 7ρt+ 5Pt indicate one sigma retrieval uncertainties. SPEX Airborne atmospheric correction use the same RSP retrieved aerosol models and therefore shares the same retrieval uncertainties (not indicated in plot). The error bar for the AERONET OC Rrs indicates its daily variation."

P8 Line 8. "uncertainties" is misspelled.
Corrected.

P9 Line 9. Does the rho_Sensor need a 'w' subscript?
Yes, thank you for spotting this. Corrected.

P9 Lines 13-15. That statement, "_Sensor w represents the water leaving signals originating from scattering in the ocean, and can be derived from the atmospheric correction process by subtracting the reflectance contribution of atmosphere and ocean surface from the measurement at the aircraft (Gao et al., 2019)." This statement warrants an explicit equation so that the reader does not need to look up the reference. Maybe repeat from the Mobley reference also.

Thanks for the suggestion. We added a formula for it:

"The water leaving reflectance ρ_w^{Sensor} represents the signals originating from scattering in the ocean and reached the sensor, and can be derived from the atmospheric correction process as
$\rho_{\mathrm{w}}^{Sensor} = \rho_{\mathrm{t}} - \rho_{\mathrm{t,atms+sfc}}^{Sensor}$
where $\rho_{\mathrm{t,atms+sfc}}^{Sensor}$ is the reflectance contribution of atmosphere and ocean surface at the aircraft (Mobley et al 2016, Gao et al 2019)"

P9 Lines 26-27. "The total amounts of water vapor and oxygen are computed from minimizing the difference between measurement and simulated SPEX Airborne measurement over all the bands. " This statement could be expanded upon to provide greater clarity.

Thank you for the suggestion. We revised the statement as follows:

> "We then simulated the reflectance spectra under SPEX geometries with the retrieved aerosol properties and various amounts of oxygen and water vapor. The simulated spectra are compared with SPEX Airborne measurement, and the best amounts of water vapor and oxygen are chosen to minimize the difference between the measurements and simulations. During this process the aerosol properties and ozone density are kept unchanged. "

P9 Line 32. "Each parameter was varied within a boundary as specified in Gao et al. (2018)." Could we have the details repeated here? The authors draw heavily upon references to their previous publications, which is fine, but these details need to be repeated here to make this paper complete in its own right.

We revised the sentence to provide the range of the key parameters:

> "Each parameter was varied within a boundary as specified in Gao et al. (2018 and 2019), where the wind speed is less than 10 m/s, the Chlorophyll a concentration is less than 30 mg/m^3, the aerosol refractive index varies effectively between 1.3 to 1.6 in its real part and between 0 to 0.03 in its imaginary part, and random mixing fractions of the five aerosol volume densities constrained by a maximum total AOD of 0.3."

P10 Lines 5-6. "viewing angles on the glint side, and the negative viewing zenith angles refer to the sun side." Isn't the glint and the sun on the same side? Glint is forward scattering. This confusion continues throughout. The paper needs this clarified.

We revised the Figure 1 captain by pointing out that the asterisk symbol indicate the antisolar point, we then revised the above statement as :

> "…the negative viewing zenith angles refer to the antisolar point in Figure 1b. … the reflectance and DoLP are simulated and compared with the measurements as shown in Fig. 2 and Fig. 3, where the viewing zenith angles are the same as defined in Figure 1(b) with the positive sign referring to the glint side ($\phi < 90^o$ or $\phi > 270^o$), and the negative sign referring to the other hemisphere containing the antisolar point."

Table 3 caption. "parenthesis" should be parentheses. Plural.
Corrected

P15 Lines 10-12. "The coarse mode SSAs are of 0.7 – 0.8 for both days and both cost function options. Moreover, including polarization in the retrievals, the uncertainties for refractive index, SSA and AOD become 0.02 – 0.03 for refractive index, 0.02 – 0.04 for SSA, and 0.004 for AOD, which are reduced nearly by one half." Because these two sentence run one after the other, the second sentence appears to refer to the coarse mode, but the numbers seem to represent the conditions of the fine mode.

Thank you for the comments. The sentences are revised as follows:

> "For the fine mode, when including polarization in the retrievals, the uncertainties become 0.02 – 0.03 for refractive index, 0.02 – 0.04 for SSA, and 0.004 for AOD, with most values reduced by more than one half. The uncertainties for most coarse mode properties remain with similar magnitudes."

P16 Line 13. "in situ measurements". The MODIS retrievals are certainly not in situ measurements, and it is debatable whether we should be calling the AERONET

SeaPRISM measurements "in situ". Possibly for SeaPRISM.

Thanks for the suggestion. We revised the sentence as:

> "The results are compared with the MODIS OC products and the SeaPRISM measurements from AERONET OC in Fig.6"

P17 Lines 5-6. "The difference of the MODIS and SPEX Rrs at wavelengths smaller than 500 nm may be related to the measurement uncertainties where the effects are larger for the same percentage uncertainties due to the larger total measurement values." I did not understand this sentence at all.

We revised the sentences as follows:

> "The larger difference of RSP, SPEX and MODIS Rrs at wavelengths smaller than 500 nm may be related to the measurement uncertainties where the reflectance are larger at shorter wavelengths. "

P18 Line 7. VIS is never previously defined. Just write out "visible"
Done.

P18 Line 10-11. "Meanwhile, we have shown polarization information can help to improve accuracy in the retrieval of aerosol optical depth, fine mode refractive index and SSA as shown in Fig. 5." I actually see the opposite in Figure 5 for SSA, at least the retrieval without polarization gets closer to AERONET retrievals, but really how can we believe any of it when AOD is less than 0.04?

Here we intended to discuss the retrieval uncertainties, and we revised the sentences as follows:

> "Meanwhile, we have shown polarization information can help to reduce retrieval uncertainties in the retrieval of aerosol optical depth, fine mode refractive index and SSA as shown in Table. 3, but the retrieval accuracies are limited by the low AOD."

We also revised the statement in the conclusion to mention the disagreement with AERONET SSA:

> "The absolute values also agree better with the AERONET aerosol product except SSA probably due to the large uncertainty of SSA from both the MAP and AERONET inversions at low AOD".

P18 Lines 21-23. Do the authors really believe this? I find it very far-fetched that they are trying to assign type to an aerosol with AOD less than 0.04. Really? The Russell study was using a data base where the entries all had significant loading. Whatever they found would have no relationship to the cases of the present study, because the present study is way outside of the Russell study's dynamic range. This speculation should just be removed from the paper.

Thanks, we removed the discussion on aerosol typing.

Figure 7 is never referenced in the text.
Figure 7 is referred in page 19.

P19 Line 16. "The absolute values also agree better with the AERONET aerosol product." Not true for SSA.

The sentence is revised as follows (as mentioned previously):

> "The absolute values also agree better with the AERONET aerosol product except SSA probably due to the large uncertainty of SSA from both the MAP and AERONET inversions at low AOD".

P19-20 Lines 20-2. "In order to apply the retrieved aerosol properties from the MAP measurements to hyperspectral atmospheric correction, the principal components of the aerosol refractive index spectra are interpolated into the bands specified for SPEX airborne. The retrieval parameters from MAP measurements can be used directly with the hyperspectral measurements without interpolation." The two sentences are contradictory. The first states that the refractive index spectra have to be interpolated into hyperspectral. The second states that no interpolations is necessary.

Thank you for the comments. The interpolation is referred to the principal components of the refractive index spectra, each principal component is a spectrum. We removed the second sentence since the principal component coefficients cannot be interpolated.