# Reply to Annmarie Eldering

We thank the referee for her time and effort in critically reading and reviewing our manuscript. Below we reproduce the questions/comments in bold and address them in plain text. Changes in the manuscript are marked in different colors. In response to the overall reviews, we have expanded the manuscript to include

- joint retrieval results in which we adopt the MAP-band concept (section 7), and
- discussion on the retrieved aerosol properties in Appendix B.

**General comments:**

**This is a very interesting paper that addresses a very important, relevant question. The authors use a simulation system to investigate the benefits of including multiple angles and polarization sensitivity for instrumentation aimed at characterizing XCO2. It is a well structure paper - clearly explains the experiment that was conducted and the outcome. There are a few areas where I'd like to see some additional information, as this work suggests a real transformation in our ability to retrieve XCO2 from space, so any critical assumptions should be articulated.**

Thank you for your positive remarks and careful reading.

**Specific comments:**

**[1] The performance shown in Figure 7 is astonishingly good. It would be a significant advancement if we can see this performance with remote sens- ing data. Therefore, it is critical that there is an understanding of how the simulation relates to actual data. Without experimental data that has the features described, this is hard to do, but I believe that a number of groups have performed simulation and then applied their algorithms to real data - for example RemoteC and ACOS applied to GOSAT and OCO-2? If earlier work informs us how do the simulations compare with the reality we can gain confidence that there are not significant error sources missing from the simulation system. The Wu et al paper on MSR makes a brief comparison between simulations and actual OCO-2 retrievals. I would recommend that the authors review the literature and see if there are more detailed discussions in Butz et al or O'Dell et al. to clarify the expected relationship between simulations of XCO2 retrievals and real life performance.**

Studies by Butz et al., Guerlet et al., and Wu et al. (complete references are available in the revised manuscript) indicate that retrieval performance using synthetic data predicts quite well the actual performance using real data from GOSAT or OCO2.

We added some text to address this in the last paragraph of section 7 (page 25 lines 547-549).

**[2] The separation of the spectrometer error out from the other errors is a good strategy. How did you decide on that allocation?**

From our experience with spectrometers and MAP, we consider equal proportions of the error for the two instruments to be reasonable estimates. This error partitioning may change over the course of the mission implementation.

**[3] You don't have any discussion of the errors that will come from weaknesses in the forward model - the gas spectroscopy has remained a source of error for the OCO-2 mission, and I fully expect this will remain. How can you also consider that error in your analysis or estimate the impact?**

Our analysis does not consider errors in the data product due to spectroscopic uncertainties. In this paper, we define payload and instrument specifications. Spectroscopy is certainly an issue but is of secondary relevance for the work here. We added some text to address this in the last paragraph of section 7 (page 25 lines 545-547).

**[4] The Frankenberg et al paper (2012) addresses multiple angle measurements and how they might help both aerosol and xco2 characterization. that paper should be cited in the introduction where a review of literature on the interference of aerosols and the value of multi-angle measurements is presented.**

Thank you for pointing this out. The paper is now cited in the third paragraph in the introduction (page 2 line 51, page 3 lines 61-64).

**[5] Is the the linear error analysis section with all the OE equations really needed? Citation of earlier papers (such as Hasekamp et al or Kulawik et al) should be sufficient. Alternatively, include the central equation in the paper and the rest in the appendix. Don't need to lay out that math in every paper that uses OE and applied linear error analysis.**

We understand your concern. However, the two-step approach in our linear error analysis includes a unique element, i.e. the aerosol contribution to XCO2 errors. Since this new aspect is an integral part of the analysis, we feel that it is important to keep the math in its entirety in the main text.

**[6] Is there enough difference in the aerosol variables of the simulation and those in the retrieval?? Some of the terms remain the same, and it isn't clear if that contributes to . I think it would be useful to have one table that has the simulation and retrieval info all in once place. I found myself repeatedly flipping back and forth so I could see how the retrieval set up differed from the simulation set up.**

The simulation and the spectrometer-only retrieval adopt different aerosol size distributions. The simulation and the joint retrieval use the same aerosol models (consistent retrieval). Fu & Hasekamp 2018 (the complete reference is available in the manuscript) indicated a limited impact when performing 2-mode aerosol retrievals on synthetic measurements with 5 aerosol modes. Based on this, we consider it appropriate to apply a consistent aerosol model for the purpose of this

paper. Inconsistent joint retrieval is a subject of further investigation and is currently being studied.
Having all retrievals and simulation in one table could potentially be confusing because they are discussed in separate sections. We will take care that Table 2 (joint retrieval state vector) and Table 3 (aerosol set-up in the simulation) are placed on the same page during the final layout editing.

**[7] I am very interested in the performance of the aerosols themselves. The authors just say this won't be addressed. If this is to be written up in a separate paper, say that. If not, some information about the performance should be included. This could even be an appendix - There is a lot of insight to be gained about the overall retrieval system if we see all of the parameters.**
We have now added a discussion about the retrieved aerosol properties in the appendix (Appendix B).

**[8] What is the variability of water vapor and temperature profile information? Where we they drawn from? Was there any analysis of correlation of errors with these variables?**
The water vapor and temperature profiles were drawn from the AFGL atmospheric profiles. This information has been added to the manuscript (page 11 lines 300-302).
We do not analyse the error correlation with water vapor and temperature, which is a typical aspect of spectrometer-only retrievals and has been discussed in the literature. Here we investigate the benefit of the MAP instrument and we focus on the aerosol-induced XCO2 errors. The analysis of the water vapour and temperature interference is therefore outside the scope of the paper.

**[9] Again, the results presented here are impressive - a significant advance for remote sensing of XCO2. The simulations are all conducted for land surfaces, as the driver for this work is the study of human emission of CO2. But, for the larger carbon cycle science community, such an advance would be important. Can the authors add a few comments about how this work could be extended for glint measurements or if they explored the performance over water bodies (perhaps at a range of distances from the glint spot)? Or perhaps this is planned work for a future manuscript?**
For CO2M, coverage over land surfaces will be given the priority so we do not explore water bodies in our analysis. For the glint geometry, the direct light dominates the light path distribution so we expect less atmospheric scattering. Glint-mode performance with the MAP instrument on board CO2M will be the topic of future research.
We have added glint-related remarks to the manuscript (section 7 page 25 lines 541-544).

**<u>Technical corrections</u>:**

**[10] line 33: spelling of Commission**

Corrected (now line 35).

**[11] line 73: verb and subject don't match. Also, sentence structure us awkward. Suggest rewording to this "Linear error analysis is part of our study, to derive the optimal instrument specification for each of the two MAP concepts with regard to wavelength range, number of viewing angles and the measurement uncertainties."**

Suggestion taken (lines 77-80).

**[12] line 77 and following - I don't think commas are needed. These sentence are correct if written this way: For the retrieval input we generate synthetic measurements that correspond to an ensemble of atmospheric and geophysical scenes over land. The MAP instrument for which the synthetic measurements are generated is tailored to the CO2M mission precision and accuracy requirements.**

Corrected (lines 83-87).

**[13] line 382 - refer to Equations A1, 2-4. What is A1? There is no appendix that I am aware of.**

There is a short Appendix A just after the box-plot figure. It is hopefully easier to find now that the appendix has been expanded to include aerosol analysis.