Responses for reviews of "The Orbiting Carbon Observatory (OCO-2): Spectrometer performance evaluation using pre-launch direct sun measurements"

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Reviewer comments in *black italic*, responses in red

Rev. #1:

The paper under review evaluates pre-launch performance of the grating spectrometers onboard the recently launched Orbiting Carbon Observatory (OCO-2). The study is based on spectra collected during an on-ground testing phase about 2 years before launch. Then, the OCO-2 instrument was fed with direct sunlight via a heliostat. The setup allows for comparison to similar measurements by a Fourier Transform Spectrometer (FTS) operated nearby within the Total Carbon Column Observing Network (TCCON). The study examines quality of the spectral fitting, random noise patterns, consistency of the spatial detector channels, instrument line shapes effects, linearity of the detector electronics. The manuscript further demonstrates the feasibility of detecting temporal concentration variability above Los Angeles well below the 1 ppm level with temporal resolution of seconds (when the instrument is operated in direct sun view).

The paper is timely and of great interest to readers of Atmospheric Measurement Techniques (AMT) who work on instrument development and characterization, OCO-2 retrieval algorithms, and OCO-2 data usage. The paper is well written; most analyses and conclusions appear robust and accurate. Therefore, I recommend publication in AMT after consideration of some comments below.

We thank the reviewer for his/her positive and constructive comments and will respond point-by-point to specific comments below:

Comments:

1. The manuscript attributes inter-footprint differences in XCO_2 (p.7650, l.12+) and variability for different exposure conditions (MATADOR test, p.7651, l.15+) to variable illumination of the spectrometer slit by the heliostat. Are the time dependent inter-band differences between XCO_2 retrieved from the wCO2 and sCO2 bands also due to this effect?

We misspoke about the variable illumination of the slit. In the up-looking experiment, the heliostat was not large enough to fill the entire pupil, which has a different effect than an inhomogeneous image scene and won't happen in orbit. The Matador test will even further change the pupil illumination and might have effects that are somewhat different than in orbit. A more detailed description in provided in Liebe, C. C., Pollock, R., Hannah, B., Bartman, R., Costin, R., Rud, M., "System for establishing best focus for theOrbiting Carbon Observatory instrument", Opt. Eng., Vol. 48, 073605 (2009); doi:10.1117/1.3180867, which we will refer to in the revised version to explain this effect. The time dependent bias between the bands may be related to this but at the current stage, there is no conclusive answer to that. ILS errors may also contribute to time-dependent XCO2 between footprints as the solar zenith angle changes.

While it appears true that heliostat effects are of no concern per se for OCO-2 performance in orbit, heterogeneity within the footprint of the nadir-viewing OCO-2 instrument could cause inhomogeneous illumination of the detector slit. Could you comment on the sensitivity of in-orbit performance on scene heterogeneity?

As mentioned above, the effect is somewhat different as the illumination of the pupil is inhomogeneous in the up-looking tests. However, scene inhomogeneity can indeed affect the spectra. For this purpose, OCO-2 records so called color-slices at 20 spectral positions per band, for which all spatial pixels are read out and not co-added as is done for the full spectra. For each of these 20 spectral positions, it provides 20 individual measurements in the spatial domain within each footprint, which can be used to quantify scene homogeneity. If we find that this has a strong impact on performance, we will be able to filter out these scenes.

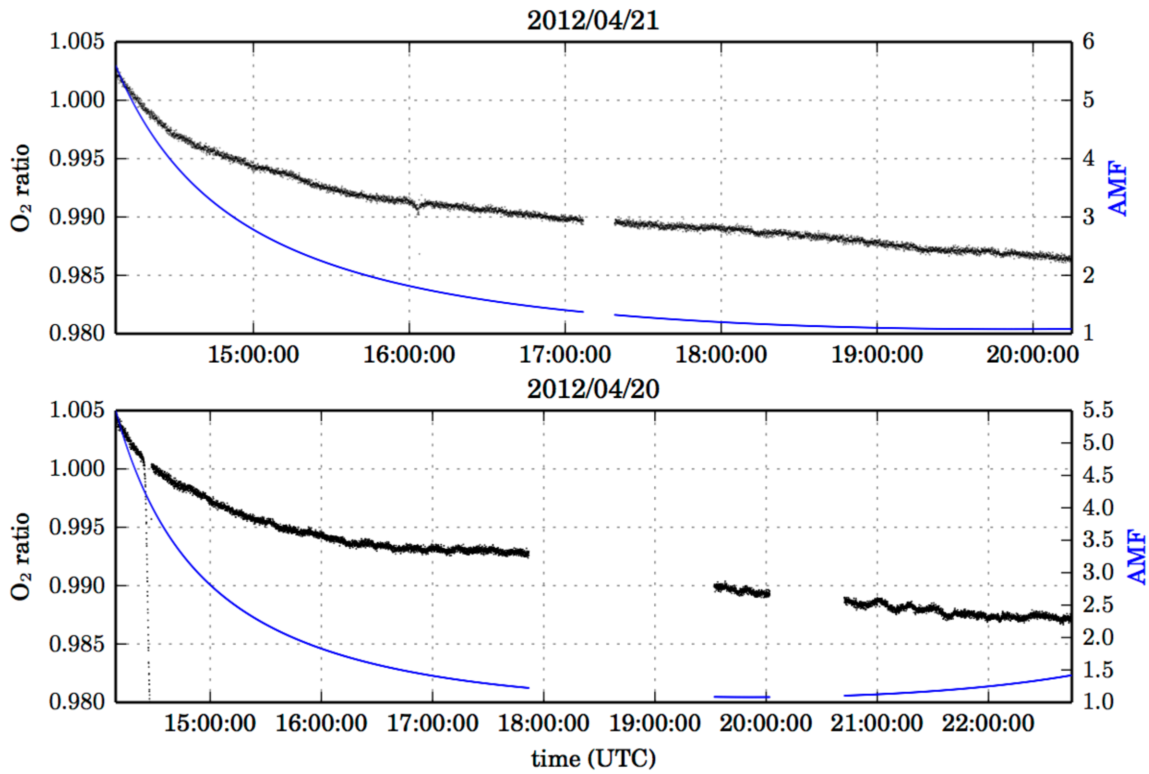
2. The MATADOR test is not very convincing with respect to its initial goal of quantifying (non-) linearity. If taken at face value, the 2-3 ppm differences for smaller signal levels in Figure 8 could be of concern, but then, the test seems inconclusive due to changes in the optical imaging. The latter might be of concern by itself (see comment above).

Would it be possible to strengthen the case? It might be helpful relating to lab-based non-linearity testing, showing ratios of spectra with strong and weak illumination, comparing weakly and strongly absorbing bands (which should be affected differently by non-linearity, in particular if non-linearity is most severe for low count rates)?

This is a very good point. We initially prepared ratio spectra figures already but omitted them so far as we already had a lot of figures. However, we also see the need for these and will include examples in the revised manuscript. It should be mentioned that this test was critical for the calibration of OCO-1, where the sphere set-up was not as good as for OCO-2 and led to large nonlinearities in the initial calibration, which were revealed by the matador tests (O'Dell et al., 2011). Because of the highly-improved integrating sphere set-up in OCO-2, the nonlinearities were almost non-existent, and the "ratio tests" merely validated this.

3. Figure 11 compares XCO_2 derived from the wCO2 and sCO2 bands to TCCON records. While TCCON XCO_2 is calculated from observed O_2 concentrations, XCO_2 from the OCO-2 instrument is calculated from external pressure records (if I under- stand correctly). Would it make things better or worse using O_2 concentrations from OCO-2's O_2A-band? How does the OCO-2 derived O_2 concentrations compare to TCCON and the external pressure data?

Initially, we only plotted the retrieved column densities, as we wanted a comparison of pure vertical columns as opposed to XCO_2, which (as you say) include a ratio by O2. However, CO2 units in ppm made it somewhat easier to judge the impact, so we ratio'ed all column with the same O2 values to keep the consistency. The O2 columns alone cannot be directly compared to TCCON as TCCON uses a different band and includes an airmass-factor correction. The figure below shows the ratio of retrieved O2 to the one derived from surface pressure. Within the AMF range of 2-5, the variability is about 0.5%.



Technical comments:

p.7642, l.18: pppm -> ppm, Done, thanks

p.7642, l.22: Define "TVAC" e.g. in line 10., renamed to "the tests" and introduced TVAC in the intro.

p.7645, l.19: can't -> cannot, done

p.7649, l.11: ". . . to spectra collected within a short time period . . .". Please try to reword, sentence appears very complicated. Re-reading it, it truly was complicated. We removed the "to spectra collected within a short time period" part as it complicated the sentence without adding crucial information.

p.7649, l.24: it -> its, done

. *p.7651, l.21: remove "being" ,* done

. *p.7652, l.19: “in the other plots”. What other plots?* Removed the statement

p.7655, l.1: total column -> total column fit, done

Rev. #2:

Manuscript "The Orbiting Carbon Observatory (OCO-2): spectrometer performance evaluation using pre-launch direct sun measurements" from Frankenberg et al., submitted for publication in Atmos. Meas. Tech., covers an interesting topic appropriate for this journal. The manuscript is very well written, contains a number of relevant well prepared figures and contains interesting new material. I have not identified any major issues related to this manuscript. I recommend publication after the minor issues listed below have been addressed by the authors.

We thank the reviewer for his/her positive and constructive comments and will respond point-by-point to specific comments below:

Abstract: line 10: Add "(TVAC)" after "thermal vacuum tests" as this acronym is used at the end of the abstract.

Removed TVAC here and simply said "tests" as TVAC is explained in the introduction.

Abstract: line 18: typo "ppm"., corrected.

Abstract: last sentence: "A few remaining inconsistencies observed during TVAC may be attributable to the specific instrument setup on the ground and will be re-evaluated with in-orbit data, when the instrument is expected to be in a much more stable environment." I find it hard to believe that the in-orbit situation is a "much more stable" one than the one on ground. On page 7650 line 17 heliostat alignment changes are mentioned but if I understand correctly, this is not the main reason for this statement (if it is, then I would agree with the statement in the abstract). Instead it is argued by the authors that this is due to instable instrument thermal control and/or illumination conditions as mentioned on page 7653 top. Is it really clear that this will be better in orbit (definitely it will be more difficult to detect)? Please provide more evidence for this in the main text or consider removing ", when the instrument is expected to be in a much more stable environment" in the abstract.

This comment is very valid and similar to one by rev. #1. We misspoke about the variable illumination of the slit. In the up-looking experiment, the heliostat was not large enough to fill the entire pupil, which has a different effect than an inhomogeneous image scene and won't happen in orbit. The Matador test will even further change the pupil illumination and might have effects that are somewhat different than in orbit. A more detailed description in provided in Liebe, C. C., Pollock, R., Hannah, B., Bartman, R., Costin, R., Rud, M., "System for establishing best focus for the Orbiting Carbon Observatory instrument", Opt. Eng., Vol. 48, 073605 (2009); doi:10.1117/1.3180867, which we will refer to in the revised version to explain this effect. We do think that this is the most crucial difference between the heliostat setup and how OCO-2 will perform in orbit. Unfortunately, it also means that we won't be able to disentangle all effects seen in the heliostat experiments. The fact that the Matador test had varying impacts for different experiments at the same illumination level, however, speaks for the impact of pupil illumination. To strengthen that case, we will also include ratio spectra in the revised manuscript.

Please explain the meaning of all acronyms when they are used for the first time, e.g., page 7643: line 4 PDT, line 18 JPL, etc.

1 Introduction:

Page 7643, 1st paragraph: Harmonize the writing of "XCO2". See the different ways how this is currently written in line 6 and line 10, for example. done

Page 7643: Line 20: I recommend to replace "direct sun retrievals" by "retrievals using direct sun observations" and to replace "retrieval of reflected sun-light" by "retrieval using reflected sun-light". Good point, we changed it (was confusing the way it was written)

2 OCO-2 instrument overview:

First Figure 2 is referred to and discussed (page 7644, line 23) followed by Figure 1 (page 7645, line 14). Please consider to change the order of these two figures.

Changed the figure order.

Page 7645, line 19: "can't" -> "cannot"? done

3.4 The Matador test:

Page 7652, line 11: "spectrometer slits": OCO-2 has only 1 slit, or?

OCO-2 has a slit per spectral band, so slits was correct

4 Observing the Los Angeles urban dome . . .:

Page 7653, line 26: "onto the NOAA standard in situ CO2 networks" -> "onto the NOAA standard CO2 scale as used for the CO2 networks"?

done

Figure 1 caption: "0.01 nm" -> "0.1" nm?Figure 2 caption: "spectra dimension" -> "spectral dimension".Figure 10 caption: Harmonize use / not use of capital letters: Orbit, Nadir, glint/Glint. done