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Atmospheric Measurement Techniques Discussions

Interactive comment on "The On-Orbit Performance of the Orbiting Carbon Observatory-2 (OCO-2) Instrument and its Radiometrically Calibrated Products" *by* David Crisp et al.

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We greatly appreciate the detailed review by Anonymous Referee #2. We have attempted to address all of the issues that they have raised. These changes are documented here and in the text. We hope these changes adequately address these concerns.

Referee # 2: general: - you should state what the absolute radiometric calibration goals were for OCO-2 and if those goals were met. You really only discuss relative calibrations and changes in the text. Details are likely in the Rosenberg paper, but a short paragraph would be valuable to set the stage for the reader.

A brief summary of the absolute radiometric calibration was added to section 5.1, stating: Prior to launch, the absolute radiometric calibration of the instrument was established from observation of an integrating sphere, with reference radiometers validated against National Institute of Standards and Technology (NIST). This system was required to meet a 5% absolute radiometric requirement, but yielded much smaller uncertainties (1.6%, 3.2%, and 2.9% in the ABO2, WCO2, and SCO2 channels, respectively; Rosenberg et al., 2016).

- you discuss briefly the ILS, perhaps expand that discussion and show a graph of the determined ILS for each channel since potential changes to the ILS are critical to "on-orbit performance of OCO-2".

The ILS was not discussed in detail here because it is the primary topic of the papers by Frankenberg et al. 2014 and Lee et al. (2016), which describe its pre-launch characterization and calibration. At this point, there is no evidence that the ILS has changed by a measureable amount, as noted in section 5.2. This conclusion is reinforced by a the paper by Sun et al. that has recently be submitted to this journal. It is not clear that we can add anything to the previous papers, without simply repeating their results verbatim.

specific: 1/21 "These" are particularly : : :. ; Remove "the"; spell "observatons" correctly Reworded as "This is a particularly challenging remote sensing observation because all but the largest ..."

2/13 changes "in" the line core done

15 the implication here is that there is a single spectrograph with 3 detectors in the focal plane, rather than 3 separate spectrographs. This is an important distinction due to scattered light considerations.

Reworded as: "To record these small changes in the reflected solar spectrum, OCO-2 carries and points a single instrument that incorporates 3 imaging grating spectrometer

channels ..."

18 sensitivity add "(s/n > 400)"

Added: "(continuum signal-to-noise ratio typically > 400)"

20 remove terminology "full-physics". Say "detailed" or some such word if you want to emphasize its technical ability. Full physics is not very meaningful – can never be full physics

Changed to "Coincident measurements from the three spectral channels are combined into "soundings" that are analyzed with a state-of-the-art retrieval algorithm"

25 in the ( ), aren't these reversed relative to line 24?? The detectors should be coldest?

Corrected. It now reads: ". . . cooled to their operating temperatures (near -6.4 °C and -152.4 ïĆřC, respectively)"

3/16 a "common" relay optics assembly Added.

/18 perhaps add the level of rejection by the narrow pass filter

It varies, but we added "(out-of-band transmission < 10-4 of peak transmission).

/21/22 the statement regarding the alignment of the 3 polarizers leaves open the possibility that the polarizer axes are not co-aligned since the spectrographs may have rotated polarization sensitivities. Please clarify.

This was modified to "light light polarized perpendicular to the long axis of the slits (e.g. in the direction of dispersion)"

/23 "a" spectrometer slit

Done.

/26 might want to mention level of thermal emission as a fraction of the continuum level

in each channel?

We do not discuss thermal emission in detail here because it is negligible in the ABO2 channel, and is reduced to near zero counts in the WCO2 channel. It produces a small offset in the SCO2 channel that is removed as part of the dark offset calibration, introducing negligible noise (< 15 counts, which is less than half of the detector read noise). We did add the following clarification to the description of the cold filter at the bottom of pg 3: "A second, narrowband filter, which is cooled to approximately -93 ïĆřC , has been installed just above each FPA to further reduce the out-of-band light at wavelengths > 2% away from the central wavelength of the channel. This filter also limits the impact of thermal emission from the optical bench, which would otherwise introduce a source of noise in the CO2 channels."

/28 mention that only 160 pixels spatially are illuminated so the caption to figure 2a is more easily understood – only part of the spatial direction of the FPA is utilized

Added statement "The slits illuminiate only the central ∼190 of the 1024 pixels on each FPA (Figure 2a)."

4/2 "returned as unilluminated reference pixels"

Added

/11 "to" the FPAs . . .

Corrected.

/19 might want to expand on the lack of need for a physical shutter. After readout, are the pixels reset to zero, or is there a potential memory effect due to residual charge

Modified: "For routine science operations, a 220 (spatial rows) by 1016 (spectral columns) pixel window on each FPA is continuously scanned using a "rolling readout" method for recording and resetting each pixel on the FPAs to their bias levels (Haring et al. 2004)."

/24 replace “for” with “during” since this mode is only used occasionally

Done.

5/7 add to the list of mrad and deg, the projected size on the ground in km

Done. “0.14 mrad (∼0.1 km at nadir),“

6/12 really the measurement is of the absolute radiometric response of the instrument with any changes in the solar diffuser embedded in that measurement, as you note on line 21

Added parenthetic reference to solar calibrator: “(and solar calibrator)”

9 the discussion at the top of pg 9 is confusing. 8/24 states dark offset of each pixel is sensitive to small (mK) changes in the temp of the FPA, whereas top of pg 9 states that the “dark offset is relatively insensitive to temperature”. L3 states that a few samples have much greater temperature sensitivity (Fig 6). Fig 6 graphs are fairly clear, but what are the well-behaved and temp-sensitive samples? Why are some samples more sensitive than others? This is confusing.

We clarified the statement on 8/24 to read “. This component of response must be updated frequently in orbit because the dark offset of a few pixels is sensitive to small (millikelvin, mK) changes in the temperature of the FPA.“ The discussion that follows now states ”For most spectral samples, this extrapolation has minimal impact because the dark offset is relatively insensitive to temperature, while a few samples have much greater temperature sensitivity (Figure 6).”

/21 relative “to” the OBA

Done.

11/5 is it possible to quantify “measurable amount” in km projected at the surface of the Earth?

Modified to “measurable amount (∼0.07 mrad, or 50 m at nadir)“

/6 please give the indicated “specification” for alignment in km projected at the surface of the Earth

Modified to: “was within specification (< 1ïĆř)“

/8 add in parentheses the half size of the OCO-2 footprint in km

Modified to quantify actual detection limits: “This effort yielded geolocation errors no larger than 0.25 mrad (0.2 km at nadir), which is much smaller than the specification (0.9 mrad per axis, 3ïĄş or ∼0.9 km worst case at nadir). ”

/30 which was – add space

Done.

/18 why are not gain corrections applied to individual pixels prior to incorporation? If because so small the weighting does not matter, state that.

To clarify this, we added the phrase “sample because the instrument controller was not fast enough to perform this calculation on board.”

12/26 does this mean that previously pixels labeled as bad were changed to be labeled as OK?

To clarify, we added the parenthetic comment: (Note, while bad samples can be recovered through further calibration, individual pixels labeled as “bad” are not subsequently relabeled as “good”).

15/6 “v”7

Done

16 you refer to figure 12 for the first time in L24, but before that refer to figs 13 and 14. Numbering of figs?

A reference to Figure 12 was omitted by accident in the first paragraph of this subsection. It has been included in the sentence: “The focal plane arrays are therefore slightly rotated, or “clocked,” with respect to the slit and grating (Figure 12).”

/24 might be interesting to give the angular rotation of each of the 3 channels – Figure 12 shows the angle to be nontrivial

The rotation angles are now included: “ . . . small (∼0.3ïĆř counter-clockwise, 0.2ïĆř clockwise, and 0.5ïĆř clockwise, for the ABO2, WCO2, and SCO2, respectively),”

17/21 do you mean screened “out”?

Yes. We made that change.

/32 “wavelength” dependent polarization ...

Changed.

20/26 the “science” aperture is mentioned. Not entirely clear what this means. Perhaps change the sentence to read “These measurements are made in the normal Earth observing mode without the solar or lamp diffusers in place and indicate ...”

We modified this to “These measurements, which are made in the normal Earth-observing mode, without the diffuser in place, indicate that only about one-fifth of the observed attenuation can be attributed to reductions in the throughput of the telescope and spectrometers.“

21/4 how is it independently concluded that the lamps are decreasing in output since what is observed is the combination of lamp/diffuser that is actually observed?

We clarified this as follows: “Comparisons of results obtained using the primary calibration lamp, which is used on all nominal polar calibration orbits (Lamp 1) to that of the other two lamps, which are used less frequently (Lamps 2 and 3) indicate that the output of this calibration lamp has also decreased somewhat in the ABO2 channel.“

/24 might want to note that the data products go back to October 2014 and not give the impression it is only from June 2015

We made the time range more explicit: “Starting in June of 2015, the OCO-2 team began reprocessing the entire OCO-2 data record, extending back to September 6, 2014, using the V7/7r algorithm and delivering this product to the GES-DISC for distribution to the science community.“

22/10 might want to include a few words on bias correction

This is a very long topic that could substantially increase the length of the paper. It is also covered well by Eldering et al. (2016) and in a far more detailed paper that is currently under preparation (Odell et al.). Here, we directed the reader to Eldering et al. by adding the statement: “The impact of these uncertainties on the L2 products are being evaluated using comparisons with observations from the TCCON network and other standards. Using these comparisons, a bias correction has been developed and delivered to the comunity in the V7 “Lite Files” (Eldering et al. 2016).“

27 in Figure 2 caption, please give the spatial resolution of a super pixel

We added the sentence: “Each footprint has a cross-track dimension of < 1.3 km and a down-track dimension of ∼2.3 km at nadir”

27 in Figure 2 you might want to note that columns are horizontal in this figure and rows are vertical.

This is initially confusing while trying to digest this complicated figure since it is opposite of what one normally considers a column and a row. We modified the figure to avoid this potential source of confusion.

30/ you might want to put horizontal lines on Fig 5 to show minimum required s/n for each channel for a single sounding

The minimum continuum SNR needed for a single sounding is difficult to quantify ex-

actly, but something around 200 usually yields XCO2 estimates with single sounding random errors near 1 ppm. We have added this note the caption: “A continuum SNR exceeding 200 is typically needed to yield single sounding random errors near 1 ppm.”

31/ L4,7 – the definition of “training range” is unclear here and on 9/2

We modified the wording as follows: “. If the FPA or OBA temperatures move outside the range of values used in these fits”

32/ grating tilts not grading tilts?? Shifts not sifs. No label on RH ordinate (C?) – looks cut off in pdf version?

The typos were corrected and the plot size was reduced to avoid truncating the RH axes labels.

33/ why are the bad pixels concentrated on the RHS?

The short answer is “we don’t know.” As noted in the text, these are very old FPAs. Bad pixels often cluster in discrete areas of hybridized devices, possibly reflecting manufacturing issues or stresses encountered during storage or use. To address this question, we added sentence to the caption of Figure 9: “A larger number of bad samples are marked on the right hand side of the WCO2 and SCO2 FPAs because more bad pixels have appeared on that side of these FPAs.”

34/ Fig 9 – last sentence, “right hand edge” as assume you mean the * that are just flat with L1b column?

No. The ILS was difficult to quantify the ILS accurately for 20-50 columns near both edges of the FPAs. The quality of the calibration on the LHS is compromised by optical aberrations, while the quality of the ILS calibration near the RHS is compromised only by limitations our ability to fully sample both sides of the ILS for those pixels. The ILS calibration is described further in Lee et al. 2016.

37/ Fig 12 – might be nice to list the angular tilt of each band

We have included this in the text and in the figure caption by adding the sentence “The O2 lines are tilted counter-clockwise by 0.3ïĆř, while the CO2 lines in the WCO2 and SCO2 channels are tilted clockwise by $\sim$0.2ïĆř and 0.5ïĆř, respectively.”

39/ Fig 14 (b) – might want to comment on why columns around 179 wavenumbers are not chosen in a flat continuum region??

We added a sentence to the caption stating “Other color slices in strongly absorbing regions (i.e. those near columns 200 and 600) were intended for cloud screening applications. “

40/ tell the reader why the SCO2 channel is not properly corrected (cloud?) – not explained in text 17/20

We attempted to clarify this by adding the sentence: “The cause for the poor fit in the SCO2 channel is unknown, but may be related to the lack of true continuum in the SCO2 channel.”

42/ Fig 17 – add to the caption 18/23 - Note that SNR values near 200 are needed to yield XCO2 estimates with single sounding random errors less than 1 ppm.

We added the statement “This is adequate to yield XCO2 estimates with single-sounding random errors near 1.0 ppm.

43/ Fig 18 L2 – all data are referenced “to” the . . . the figure is labeled “solar, lunar, and lamp 2 mean : : :..”, but in the symbol label on the lower LHS, there is no symbol for lunar data, nor is lunar mentioned in the caption; it is discussed in the text

The typo in the caption was corrected. The title was also corrected, since the lunar data were removed from this plot for simplicity.

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