Response to Anonymous Referee #2

We thank Referee #2 for their thoughtful comments and questions.

Revisions to the text are necessary to address comments from both referees and the Editor's comments and we have prepared a revised manuscript.

Below we will respond to the comments and questions of Referee #2.

Comment #1:

Line 26-28: please add 'at Lamont' at the end of the sentence

Response:

We believe that the high sensitivity of the profile retrieval to temperature errors is not specific to the Lamont site, but to the retrieval algorithm, so we left the sentence as is.

Comment #2:

Line 61: "non-linear least-squares spectral fitting algorithm" is GFIT also based on the OEM? If yes, please mention it in the text. If not, please add some discussion about the retrieval method in the paper.

Response:

Yes GFIT is based on the optimal estimation method, specifically GFIT implements the "$(n+m)\times n$" problem described in Rodgers, 2000 "Numerical Efficiency. Which formulation for the linear algebra? The n-form". The text (Line 66-67) was updated from:

~~"Scaling retrievals do not require inter-level constraints on a priori concentration uncertainties. In GFIT, the a priori VSF value of the main target gas in a spectral window is 1 with an uncertainty of 106, and~~ XCO_2 can be retrieved with a 2-σ precision and accuracy of 0.8 ppm"

To:

"Technically, GFIT handles the scaling retrieval by weakly constraining the fitted VSF factor. The approach is equivalent to performing an optimal estimation of the VSF, assigning a value of unity to the a-priori VSF and a value of 10^6 as its expected range of variability. XCO_2 can be retrieved with a 2-σ precision and accuracy of 0.8 ppm"

Comment #3:

Line 62: "A forward model . . . a priori knowledge of atmospheric conditions", please also add instrumental conditions and the observation geometry.

Response:

The text was updated to:

"A forward model computes an atmospheric transmittance spectrum for a given observation geometry using a priori knowledge of atmospheric conditions and assuming a perfectly aligned instrument."

Comment #4:

Line 66: “Scaling retrievals do not require inter-level constraints on a priori concentration uncertainties. ”. A scaling retrieval is actually equal to a very strong inter-level constraint. Please re-write this sentence.

Response:

The scaling retrieval is indeed equivalent to a profile retrieval with very strong interlayer constraints, but this constraint is not adjustable in a scaling retrieval. The text was updated as suggested in the Editor’s comment and as shown in the response to Comment #2.

Comment #5:

Line 67. “an uncertainty of 10ˆ6 ”. Please check why the uncertainty is so large?

Response:

The a priori uncertainty is so large to allow unbiased retrievals in situations where we have no a priori knowledge of the gas amount. There is no advantage of imposing a tighter constraint because a scaling retrieval is much better conditioned than the profile retrieval and the a priori total column does not need to be close to the true column for a successful retrieval. However, the profile shape is implicitly infinitely constrained and cannot change from the a priori profile shape.

Comment #6:

Line 101. Does the wavenumber scales not included in GGG2014? If not, please mention it in the text.

Response:

The text was updated to:

“(2) a solar- gas stretch fitted to account for Doppler-driven differences between solar and telluric wavenumber scales, in GGG2014 only the stretch in the telluric wavenumber scale was fitted”

Comment #7:

Line 107: change “original TCCON spectral windows ” to “original TCCON retrieval windows”

Response:

The text was updated as suggested.

Comment #8:

Line 148:” We see no advantage to fitting non- contiguous windows in parallel, rather than in series, and then averaging the results. ”. How do you average the results? Do you apply the weighting function based on the SNR of each window?

Response:

The text was updated to:

“We see no advantage to fitting non-contiguous windows simultaneously, rather than separately, and then combining the results. In TCCON post-processing the total columns retrieved from different retrieval windows (CO_2 from the TCCON1 and TCCON2 windows, for example) are averaged after removing window-dependent multiplicative biases, using retrieval errors as weights.”

A different method was tested to combine the profile retrieval results but was not shown and still requires more work. But the principle is to obtain the combined profile x_r from the profiles retrieved in N windows as:

$$x_r = S_r\left(\left[\sum_{i=1}^{N} \hat{S}_i^{-1}\hat{x}_i\right] - (N-1)S_a^{-1}x_a\right)$$

$$S_r = \left(\sum_{i=1}^{N} S_a^{-1} + K_i^T S_{y,i}^{-1} K_i\right) - (N-1)S_a^{-1}$$

$$A_r = \left(S_a^{-1} + \sum_{i=1}^{N} K_i^T S_{y,i} K_i\right)^{-1} \sum_{i=1}^{N} K_i^T S_{y,i}^{-1} K_i$$

where $(N-1)$ contributions of the a priori are subtracted to obtain expressions equivalent to a joint-band retrieval. These combined profiles tend to be strongly weighted towards the profile retrieved from the Strong window and can amplify deviations from the truth caused by systematic errors. The removal of window-dependent biases as done for total columns in the TCCON post-processing was not straightforwardly applicable to retrieved profiles and will be the subject of future work.

Comment #9:

Line 312-314:As the GFIT2 does not allow retrieve 2 profiles simultaneously, have you ever tried to retrieve the H_2O profile first, and use the retrieved H_2O profile as the a priori profile to do the CO_2 retrieval?

Response:

No, we did not try this. This would be interesting to investigate after the implementation of a temperature retrieval.

Comment #10:

Line 444: What is the physical reason for the ‘zero-level offset’ error?

Response:

Zero-level offsets can be caused by detector non-linearity or aliased out-of-band spectral signal.

Comment #11:

Line 445: What do you mean by “higher altitudes ”? please note the vertical range specifically

Response:

>10 km was meant.

Following the Editor's comment, additional sensitivity tests were added as an Appendix with perturbations to the instrument field of view (which affects the ILS width), and to ZLO. And the text of Line 443-446 was changed to:

"Although the effect of typical perturbations in the instrument field of view, zero-level offset, and spectroscopic parameters is relatively small compared to the effect of temperature errors, the cumulative effect of these errors could explain the deviations from the truth in Fig. 9(a) and 10(a)."

Comment #12:

Line 545. Section 3.2.4, I expect the authors to present a table here summarizing all the uncertainties for the CO_2 profile at Lamont, together with the typical vertical variation of CO_2.

Response:

The profiles of uncertainty like Figure D8 should be more informative than a table for the uncertainty on retrieved profiles. Figure D8 shows profiles of noise, smoothing, interference, and retrieval errors which are representative of all the CO_2 profiles at Lamont. The last sentence of section 3.2.2 was updated to draw more attention to and summarize this analysis:

"Additional analysis of the vertical sensitivity of the retrieval is presented in Appendix D, as well as a decomposition of the retrieval error into the interference, measurement noise, and smoothing errors as shown in Fig. D8. The interference error is the smallest (<0.5%) contribution but does not include the effect of temperature errors. The measurement noise error decreases from ~1% at the surface to ~0.2% at pressures less than 0.6 atm (> 5 km), and the smoothing error dominates and decreases roughly from ~3% at the surface to 1% at the top of the atmosphere."

And the text in section 3.2.4 was updated to:

"Even when the errors due to the a priori meteorology are minimized, deviations from the truth due to instrument misalignment, radiative transfer, sun-tracker pointing, or uncertainties in line parameters are larger than the steepest vertical CO2 gradients (~5 ppm/km) observed in the ensemble of aircraft profiles from NOAA's ObsPack."

Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore, 2000.