

Authors' answer to the interactive comments of anonymous referee #2 on "Building the COCCON: Long term stability and ensemble performance of the EM27/SUN Fourier transform spectrometer" by Frey et al., Atmos. Meas. Tech. Discuss., amt-2018-146

First of all, we would like to thank the anonymous referee #2 for the help in further improving the current presentment by a thorough assessment with regards of content and the careful technical proofreading resulting in the identification of several imprecisions and typos.

Referee: "Overall comments:

This paper analyzes multi-year analysis of EM27/SUN results compared to TCCON. The long-term performance and stability of the EM27/SUN systems is important to use EM27/SUN results for science analysis and satellite validation. The EM27/SUN systems have potential as lower cost stationary instruments, and for use in shorter term field campaigns since EM27/SUN are easier to move.

I agree with reviewer 1 that column averaging kernels should be shown and compared to TCCON and LR TCCON."

Authors: The averaging kernels of the EM27/SUN have already been presented and discussed in comparison to TCCON in the literature [Hedelius et al., 2016]. We have added this information explicitly in the revised version. Please note that the scope of this paper is the characterization of the instrumental performance of the spectrometers used for COCCON.

Referee: "The assessment of EM27/SUN results relies on comparisons to a specially processed, modified TCCON dataset, called LR TCCON. LR TCCON is reduced resolution TCCON, with a differently derived ILS, and processed with the PROFFIT software. However, LR TCCON has not itself been validated."

Authors: This is true, we are fully aware of this limitation. However, the TCCON LR and EM27/SUN data products have been generated by applying exactly the same processing scheme. The idea behind this approach is to use the TCCON LR dataset to quantify instrument-to-instrument biases and possible instrumental drifts. This approach offers a much higher sensitivity in this regard than a direct comparison with official TCCON products derived from high-res interferograms, because the sensitivities of the reference and device under test are perfectly matched. The fact, that the TCCON LR data product is unvalidated is not harmful in our context, as we are aiming at only a highly sensitive relative comparison (between comparable sensors, comparable in the sense that we expect identical trace gas results if the same atmospheric state is observed).

Referee: "Significant differences are seen between EM27/SUN and the full resolution TCCON (shown in Figures 4 and 6) for XCO₂ and XCH₄. These errors should be quantified in the paper. The errors are seasonally dependent and look to have peak-

to-peak seasonal errors of about 1 ppm for XCO₂ and 20 ppb for XCH₄, larger than the TCCON errors compared to aircraft validation (0.4 ppm for XCO₂ and 5 ppb for XCO₂ for GGG2014 (Wunch, 2015)). Comparisons of EM27/SUN results to LR TCCON are very good. However, LR TCCON has NOT been validated and comparisons of EM27/SUN versus LR TCCON is NOT validation of the EM27/SUN results and does NOT tie EM27/SUN to WMO.”

Authors: An exhaustive comparison with TCCON will be given in a paper under preparation by the FRM4GHG consortium. We agree that the tying to WMO suffers from a significantly larger uncertainty than the instrument-to-instrument calibration within COCCON. The instrument-to-instrument calibration should be based on the comparison with TCCON LR, only the tying to WMO needs to be done via the official TCCON data products.

Unfortunately, due to higher spectral resolution the TCCON observations have different sensitivity characteristics than COCCON. If the a-priori profile shape assumed by TCCON differs from the truth (its quality might depend on season, and on the current meteorological situation, as demonstrated in the paper for the situation of polar air intrusion), it will give rise to e.g., seasonal differences between TCCON and COCCON of the observed size. Proof of this is given in section 3.5, where a period of polar air intrusion is discussed and in an upcoming FRM4GHG paper.

Following the suggestion of the referee, we have added a short discussion concerning the level of uncertainty with respect to WMO tying of COCCON, which is significantly higher than the internal consistency. This discussion is based on the results provided in tables 3 and 4, which clearly indicate the higher scatter in the EM27/SUN versus TCCON residuals, suggesting a current calibration uncertainty of 0.15% for XCO₂ and 0.24% for XCH₄ with respect to TCCON.

Referee: *“In summary, if LR TCCON can be validated versus aircraft/AirCore with similar errors as the standard TCCON, then this paper will set useful limits on EM27/SUN errors. As the paper stands, validation that must be considered is versus the standard TCCON product, which is marginal for satellite validation and on the high side for other uses.”*

Authors: We do not agree to this statement. The choice of TCCON LR product is fully appropriate for demonstrating the level of internal consistency achievable by COCCON. The paper under consideration does not claim to solve the problem of tying the COCCON data to WMO, as the title says, it aims at demonstrating the long-term stability of the EM27/SUN spectrometer, and it investigates the ensemble performance. The construction of a TCCON LR data set is in our opinion the best possible approach for achieving this.

Note that the vertical sensitivity offered by COCCON differs slightly from TCCON, but is not systematically poorer than TCCON (see Hedelius et al., 2016). Therefore, when a similar dataset of in-situ measurements will be exploited for COCCON, the tying to WMO is expected to be of similar quality as for TCCON. Work in this direction, also including AirCore observations, is under progress in the FRM4GHG project.

Referee: *“Specific comments*

Introduction:

The COCCON project should be introduced in the introduction, with the objectives of the COCCON, and who is participating in COCCON, the length of the project (for example)."

Authors: We added the following paragraph in the introduction:

"COCCON is intended to be a lasting framework for creating and maintaining a greenhouse gas observing network based on common instrumental standards and data analysis procedures. Currently, about 18 working groups operating EM27/SUN spectrometers are contributing. We expect that COCCON will become an important supplement of TCCON, as the logistic requirements are low and the spectrometers are simple to operate. It will increase the global density of column-averaged greenhouse gas observations and due to the fact that the spectrometers are portable will especially contribute to the quantification of local sources."

Referee: *"In the introduction, add in the importance of TCCON for OCO-2 and GOSAT validation, adding a sentence after line 23 something like: "TCCON stations are also the primary validation for OCO-2 (cite https://oco.jpl.nasa.gov/files/ocov2/OCOC22_SciValPlan_111005_ver1_0_revA_final_signed1.pdf) and validating the satellite observations at different locations is critical for the validation effort (Wunch et al., 2017)."*

Authors: Ok, done

Referee: *"A figure showing the TCCON (original and degraded resolution) and EM27 spectral range and radiance would be helpful for the reader, or a reference to a previous paper showing this."*

Authors: "We added a reference [Hedelius et al., 2016] in section 2.1. The figure contains a TCCON (original resolution) and EM27/SUN spectrum. We refrain from adding a figure in this paper because we think that the additional information from TCCON (degraded resolution) is marginal."

Referee: *"The spectral ranges and approximate resolution should be given in wavelength in addition to wavenumber. Some scientists are used to wavelength and the translation is not immediately obvious."*

Authors: "We included this information in section 2.1. For the sake of readability, in the other sections, only the wavenumber notation is given."

Referee: *"Section 2.2 The description of the HR125 low resolution data set should include the software used to analyze it. I infer it is PROFFIT, but should be stated."*

Authors: Ok, done

Referee: *"Page 5, line 15. Define ILS, modulation efficiency, phase error."*

Authors: The paper includes a reference to a paper where the procedure of instrumental line shape measurements is explained in detail [Frey et al., 2015].

Additionally we added a reference for a more general description of the used ILS model [Hase et al., 2012].

Referee: *"Page 5, line 22. How is the phase error calculated – describe or cite a reference. Why is phase error important? What does it affect?"*

Authors: We included an additional sentence in the manuscript with a reference to the original LINEFIT paper [Hase et al., 1999]. Figure 1 and 2 of this reference illustrates the effect of differing modulation efficiency amplitudes and phase errors on a spectral line.

Referee: *"The statement on line 7, page 7, "The remaining difference can be attributed to the different measurement heights of the HR125 (112 m) and EM27/SUN (133 m)." This needs to be further explained and quantified. Is it the total column? It would be useful to the reader to have a calculation accounting for the offset."*

Authors: In this section total columns are discussed. So here it is expected that the total columns differ for instruments at slightly different heights. For an estimate of the ratio the barometric height formula can be utilized. As for this study the main interest lies in the analysis of XCO₂ and XCH₄, where the height dependency is expected to largely cancel out, we chose not to dwell on the small differences observed in the total columns at different heights.

Referee: *"Table 2, it would be useful to show the effect on XCO₂, etc, which is the key result. The reader looks between columns and thinks it will probably cancel for XCO₂ but is not sure."*

Authors: We agree that this information is vital. We now include the information not only in the text, but also in the caption of the table. Including the information in the table would enlarge the table too far, and we feel it is important to keep the basic information of the total columns.

Referee: *"Page 8, line 11, "From this higher variability it can be concluded that the airmass dependency in the official TCCON O₂ retrieval is higher than for the PROFFIT retrieval, a finding also observed by Gisi et al. (2012)." This statement needs to be modified for clarity to "...higher than for the PROFFIT retrieval on reduced resolution TCCON measurements."*

Authors: We changed the wording accordingly.

Referee: *"Page 8, line 25. "There are no obvious steps between the EM27/SUN and the HR125 LR data sets so that it can be concluded that the EM27/SUN is stable." The offset versus time needs to be quantified as well. Step functions and slower drift are both important to quantify."*

Authors: We changed the wording accordingly: "There are no obvious steps and there is no significant drift between..."

Referee: *"Page 9 line 7. The green line on Fig. 4 shows significant differences between TCCON and EM27, on the order of 1 ppm it looks like. This seasonal cycle*

amplitude difference should be quantified. The pink difference (comparison to LR TCCON to EM27) looks very good. As stated in the overall comments, if the difference of EM27/SUN vs. TCCON is larger than the reported TCCON error, then it is important to determine the cause of this difference. PROFFIT should be applied to the full resolution TCCON data, OR GFIT should be applied to the low resolution TCCON data to separate out the PROFFIT/GFIT differences vs. ILS/truncation differences to determine the source of the difference between full-resolution TCCON and LR TCCON. LR TCCON needs to be validated versus aircraft/AirCore before it can be used to validate EM27/SUN."

Authors: As we discussed before in this reply and have illustrated in the paper exemplary on the intrusion event seen in March 2016, the differences are mostly due to different sensitivities. In our context of demonstrating the level of long-term stability and ensemble consistency, it is just important to use a common choice for the EM27/SUN and TCCON LR analyses. A comparison of GFIT with PROFFIT for both high- and low-resolution spectra is well beyond the scope of this paper.

Referee: *"Similar comment for XCH4. In Fig. 6, differences for XCH4 between EM27 and full resolution TCCON look to have seasonal differences of about 20 ppb, which is higher than the TCCON estimated XCH4 error of 5 ppb."*

Authors: As explained before, this discrepancy simply reveals the smoothing errors inherent in both time series (TCCON and COCCON). The occurrence of larger differences during an episode of a polar air intrusion mentioned in the paper is clearly demonstrating the mechanism.

Only in simple situations – e.g. if one can assume that a certain excess signal is due to a nearby source generating enhanced values in the boundary layer, one can approximately correct for the differing sensitivity characteristics [Wunch et. al, 2011, Hedelius et al. , 2017], but in general, when differences in the seasonal cycle are observed, it is not possible to remove the smoothing error without knowledge of the real mixing ratio profile in the atmosphere.

Referee: *"Wording/formatting suggestions:*

Line 11, suggestion: change "as demanded by" to "as specified by""

Authors: Ok, done

Referee: *"Line 16, word suggestion: "Nonetheless" change to "However""*

Authors: Ok, done

Referee: *"Line 20: "However, recently OCO-2 data was used for estimating the source strength of power plants (Nassar et al., 2017)", would reword to emphasize coverage issues, "Recently OCO-2 data was used for estimating the source strength of power plants (Nassar et al., 2017). However, this can only be done for power plants that lie directly under the OCO-2 overpass locations.""*

Authors: We rephrased the sentences as suggested.

Referee: *"Make the dots bigger on the Fig 2-7 legends. It is very hard to tell which dot is blue and which is black in the legend."*

Authors: We will change the size of the dots in the legend.

Referee: *"Page 7 line 11, "Before, a sensitivity study is provided demonstrating the effect of changes in the ILS on the gas retrieval." I think change "Before" to "First"."*

Authors: Ok, done

Referee: *"I see reviewer 1 suggests deleting Fig. 10. However I think Fig. 10 is useful to show the size of the instrument. Perhaps make this figure small."*

Authors: As stated in the reply to reviewer 1, we will check that the size of the figure is appropriate in the final version of the paper.

References:

Hase, F., Blumenstock, T., and Paton-Walsh, C. (1999): Analysis of the instrumental line shape of high-resolution Fourier transform IR spectrometers with gas cell measurements and new retrieval software, Appl. Opt., 38, 3417–3422, <https://doi.org/10.1364/AO.38.003417>

Wunch, D., Wennberg, P. O., Osterman, G., Fisher, B., Naylor, B., Roehl, C. M., O'Dell, C., Mandrake, L., Viatte, C., Kiel, M., Griffith, D. W. T., Deutscher, N. M., Velasco, V. A., Notholt, J., Warneke, T., Petri, C., De Maziere, M., Sha, M. K., Sussmann, R., Rettinger, M., Pollard, D., Robinson, J., Morino, I., Uchino, O., Hase, F., Blumenstock, T., Feist, D. G., Arnold, S. G., Strong, K., Mendonca, J., Kivi, R., Heikkinen, P., Iraci, L., Podolske, J., Hillyard, P. W., Kawakami, S., Dubey, M. K., Parker, H. A., Sepulveda, E., Garcia, O. E., Te, Y., Jeseck, P., Gunson, M. R., Crisp, D., and Eldering, A. (2017): Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) XCO₂ measurements with TCCON, Atmospheric Measurement Techniques, 10, 2209–2238, <https://doi.org/10.5194/amt-10-2209-2017>