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Authors: Kuai et al.  
MS Title: Characterization of Aura Tropospheric Emissions Spectrometer  
Carbonyl Sulfide Retrievals

Dear Editor:

We would like to thank the referees for their time and invaluable comments.

Please see the supplement for our reply to the reviewers. Note that the referees' comments are in black and our responses are in [blue](#).

Please contact us if there are further questions.

Best regards,  
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Lead author  
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Anonymous Referee #1

Comments:

- The typical degrees-of-freedom for signal (DOF) of the OCS retrieval from TES are found 0.67. While being methodological valid, this seems a very low number of DOF in the view of science applications. Given that the a priori covariance matrix is anyway chosen in an ad-hoc way, why is it not chosen such that one gets at least DOF  $\geq 1$ ? Figure 6 indicates that there is non-vanishing contributions from noise and smoothing error to the total error. Allowing for more freedom in the retrieval would increase the noise error but decrease the smoothing error such that the total error might not change too much.

We choose the a priori constraint to balance the trade off between larger DOF for the TES retrievals and natural variability based on the ground-base and aircraft observations. The ground-base observations show that the OCS concentrations are about  $500 \pm 50$  ppt, which is about 10% variability. We tested the retrievals using different covariance matrices. These covariance matrices allow the OCS retrievals to vary by 10%, 20%, and 40% about the OCS a priori. We choose 20% because the retrieved OCS variability spans the variability observed by the in situ

measurements. We do not want to relax the constraint further because in that case the retrieved estimates will vary in an unrealistic range even though the DOFs of the retrievals increase.

With the qualify flag of  $\text{DOF} > 0.5$ , the current averaged DOF is about 0.67. Since we are not concerned about the vertical information and the profiles are averaged vertically, it is not necessary to have DOFs more than one.

- Figure 3: Why is the structure of the CO<sub>2</sub> and OCS a priori covariances so different? Are the secondary diagonal elements for OCS larger than the variances on the diagonal? Is the vertical grid different for H<sub>2</sub>O and CO<sub>2</sub>, OCS? Please clarify and reason why.

The structures of the a priori covariance matrices are different because each gas has different seasonal variability and vertical distributions.

For the CO<sub>2</sub> covariance matrix, the diagonal values come from the variability of aircraft measurements. The off-diagonal correlations come from model MOZART-3 correlations. CO<sub>2</sub> varies more in the boundary layer and less in the free troposphere than OCS.

As discussed earlier, we scaled the diagonal values of the OCS covariance to be a constant value in free troposphere with a variability of about 20% but decreasing in the stratosphere.

The reviewer is correct about the OCS off-diagonals; this is not a typical covariance. We scaled the off diagonal values inconsistently with the diagonal values. However, this improper OCS covariance matrix does not significantly affect our retrievals, because we show that the calculated errors of the OCS retrievals are consistent with actual errors. This first version of the OCS retrievals is likely to go through additional improvements, including changes to the *a priori* covariance. The plots for covariance matrices will be removed to prevent confusing the reader.

- Is the vertical grid different for H<sub>2</sub>O and CO<sub>2</sub>, OCS? Please clarify and reason why.

We use different retrieval levels for each trace gas based on the vertical variability of the trace gas. These retrieval levels can always be mapped to a common vertical grid in the forward model as discussed in Worden et al. (2004).

- For comparison to the airborne data, the TES OCS retrievals are averaged over several years (for the same month of the year). This results in sometimes smaller error bars than those of the comparison data set (figure 8 and 9). So, reducing the averaging periods would not hurt too much in terms of TES error bars. How does the comparison change when you restrict the TES averaging to single years or other subsets of the 2006-to-2010 period? Is

there inter-annual variability detectable? Does selecting smaller geographic bins impact the conclusions?

For the current version, the TES OCS data are not capable to detect the inter-annual variability yet. Selecting smaller geographic bins or averages for single-year data will enlarge the error bars.

This paper is focused on the algorithm description and validation. Comparisons of data at smaller scales will be performed in a future analysis.

- Conclusions on TES successfully catching the OCS seasonal cycle are based on comparisons at a single ground-based station (Mauna Loa) that provides local in-situ concentrations instead of vertical profiles or (partial) column estimates. OCS seasonal cycle amplitude will certainly depend on altitude. Did you investigate whether data exist from other validation sources such as ground-based solar-viewing FTS (e.g. NDACC) or ACE-FTS data that could help making the comparisons more robust.

We have not investigated other data sets for validating the TES OCS retrieval because there are very few data sets that are representative of both ocean and the free-troposphere.

The ACE-FTS is most representative of the upper troposphere and lower stratosphere and total column measurements of OCS will have significant contribution from the stratosphere. Therefore, comparisons between the TES OCS data and the ACE or total column will be problematic.

- In some parts, I had the impression that the paper was written in a hurry. I strongly recommend revising the paper with a view on language issues. Examples:

\* Title, introduction: “tropospheric emissionS spectrometer” < -?- > “tropospheric emission spectrometer”

Thank you. The title has been corrected and the native English speakers who are co-authors will review the language.

\* p6978, l17: “b and ba represent the true state and the a priori of the state” This is wrong, b and ba are forward model parameters that are not part of the state vectors x and xa.

Agree. ‘**b** and **b<sub>a</sub>**’ are those parameters which are not retrieved but also affect the model radiance. The sentence is revised to:

‘**b** and **b<sub>a</sub>** represent the true state and a priori for those forward model parameters which are not retrieved but also affect the model radiance.’

\* p6978, l20: While the (unimportant) Jacobian matrix  $K_b$  with respect to the forward model parameters is explicitly defined, the (important) Jacobian matrix  $K$  with respect to the state variables is not defined.  $K$  in equation (3) is not  $K_b$ .

We have added one sentence after equation (3):

' $\mathbf{K} = \frac{\partial Y}{\partial x}$  is the Jacobian matrix for the retrieved state vectors.'

\* p6979, equation (4): There is no link of equation (4) to the preceding text.

We have moved equation (4) after the following statement:

' $A$  is the averaging kernel matrix, which describes the sensitivity of the retrieved state vector to the true state.'

\* p6986, l36: "Figure 9 shows the correlation of TES monthly OCS corresponding all HIPPO estimates convolved with the TES operator. TES OCS shows fairly well correlation ( $R=0.66$ ) with these bias corrected in situ data, which were applied with the TES operator during different months of the year. The bias has been removed using the TES operator . . ." -> How often did you apply the TES operator?

Each retrieval for a single sounding has an individual averaging kernel matrix. The TES operator is applied to each validation observation (generated from the HIPPO or MLO data) for each TES averaging kernel matrix.

\* p6980, l27: alia -> alias

Corrected.

\* p6983, equation (5): The TES a priori state  $x_a$  is already in logarithmic units. The new greek variable is probably meant to be the (non-logarithmic) concentration profile corresponding to  $x_a$  but it is not defined as such. Further, all the Greek variables are supposed to be vectors (vertical profiles) and thus, should be bold face (likewise equation (6)).

We corrected all the Greek variables to be bold face and revised the statement at Line18 to:

'By applying the TES averaging kernel,  $\mathbf{A}$ , and a priori **concentration profile**,  $\chi_a$ , to the in situ observed **concentration profile** ( $\chi_{std}^{OCS}$ ) in logarithm, we can perform the comparison between the TES tropospheric OCS and vertically convolved observations ( $\chi_{std\_AK}^{OCS}$ ) that accounts for the a priori regularization together with the sensitivity and vertical resolution of the TES retrievals.'

\* p6984, l21 to p6985, l9: Please clarify the text here. I cannot follow the various averaging procedures. If I understand correctly, a single data point for each latitudinal bin is compared in the end. Why not including the vertical averaging

procedure in equations (5) and (6) by introducing a tropospheric column operator in order to make the text clearer here?

Correct. There is only one single point for each latitude bin for the comparison between TES and the in situ data.

Note that we are not using a column operator but an averaging operator because the column operator has more weighting in the boundary layer and the TES OCS data have little sensitivity in the boundary layer.

We average the profile from 900 to 200 hPa. To make this averaging more explicit, we have adding a mapping operator ( $\mathbf{M}$ ) to Equation 6.

$$\mathbf{M} \cdot \ln(\chi_{corrected}^{OCS}) = \mathbf{M} \cdot \ln(\chi_{std\_AK}^{OCS}) + \mathbf{M} \cdot \mathbf{A}(\delta_{bias}) \quad (6)$$

\* table 1, “TES sample number”: I guess the sample number is given as a range because sample number varies for the latitudinal bins. This should be mentioned somewhere in the caption.

We added one sentence at the end of Table 1’s caption:

“The sample values listed here are the ranges of the numbers for TES retrievals in the grid boxes at difference latitude bins.”

\* Figure 5: “the one tenth of” – > “one tenth of the”

Corrected.

\* Figure 6: “compare” – > “compared”.

Corrected.

\* Figure 10: The caption should cover an explanation of what is shown.

We changed the caption for Figure 10 to:

**Fig. 10.** Taylor diagram of TES OCS as compared to in situ data. The radius of the diagram is in units of the standard deviation of the observations of the in situ data and the angle indicates the correlation to the in situ data. Perfect agreement with in situ observations is always located at one standard deviation and correlation of 1 (purple dot). The distance to the purple dot indicates the error. Individual comparison between TES and in situ data as in Fig. 8 are plotted in red dots and the comparisons of TES to all HIPPOs are in green dots.’