Authors' response to anonymous referee #2 comments on "Smithsonian Astrophysical Observatory Ozone Mapping and Profiler Suite (SAO OMPS) formaldehyde retrieval"

We will like to start by thanking the referee for the thoughtful and productive comments. We feel they have helped us to improve our paper. In the text that follows each one of the referee comments is going to be copied in black with our answers in blue. How we propose to change the manuscript is shown in purple.

Abstract, line 8: 'similar concept' is really a 'similar retrieval approach' is it not? Both OMI and OMPS are instruments using a similar concept. Both are grating spectrometers using 2D CCD detectors flying in low earth orbit satellites with similar overpass times. That is what we want to express with "two different instruments that share a similar concept". The retrieval approach we are using is similar to the one we did used for OMI. We propose to modify the text as follows: "We are now able to produce a consistent set of long term data from two different instruments that share a similar concept using a similar retrieval approach in both cases".

Abstract, line 21: Would be good to include which OMI datasets were used here. We will include this information. The abstract should read now as "We compare different OMI products (SAO OMI v3.0.2 and BIRA OMI v14) with our OMPS product…"

P 9211, line 21: Typo, 'trophosphere' We will correct the typo, the new text should read "troposphere"

P 9214, line 15: Regarding the radiance references I_0, are the radiances on a static wavelength grid? Or are individual radiances interpolated onto a common wavelength grid, before being averaged to produce I_0? How many spectra go into a single I_0 spectrum? How do retrievals change if a +/- 2 day window is used? For each cross track position radiances between 30°S and 30°N are co-added using a static wavelength grid. Once we have calculated the average spectrum for each cross track position it is wavelength calibrated using a high resolution solar spectrum. Typically about 130 spectra go in to the calculation of each cross track position radiance reference.

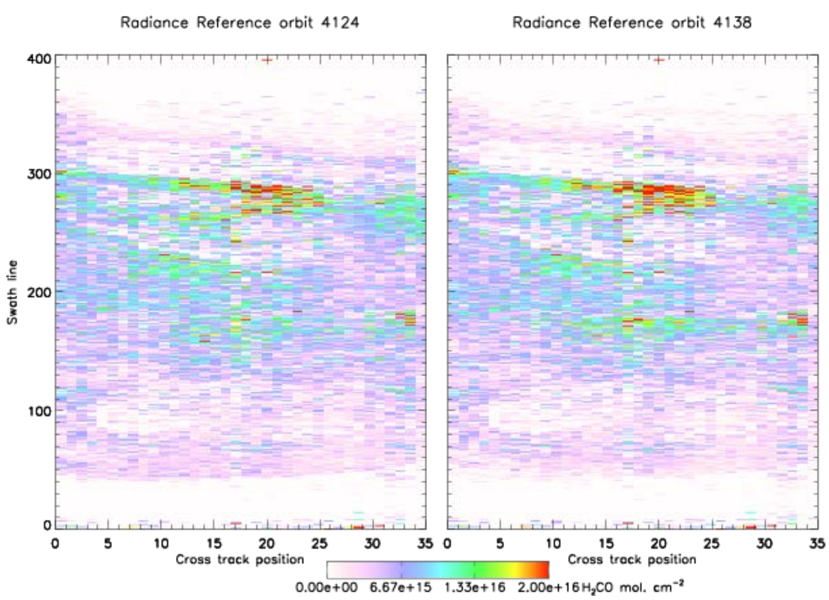

Figure 1. Retrievals for orbit 4129, August 14 2012. Left panel shows the results, reference sector corrected vertical columns, when using orbit 4124 over the Pacific (14 August) to calculate the radiance reference while right panel shows results using orbit 4138 (15 August).

Incrementing the temporal span for the selection of the radiance reference over the Pacific Ocean will not modify the selection of the orbit to be used as radiance reference. We are always using the closest (temporally speaking) radiance reference to the time of the target orbit which is usually within +/- 1 day. However we think it is interesting to illustrate the effect of using 2 different radiance reference orbits for a given target orbit. We have chosen a random orbit, 4129, and we have performed the retrieval using 2 different radiance references orbits: 4124 and 4138.

As can be seen in the figure 1, the spatial patterns of the retrieval are similar when using either orbit 4124 or orbit 4138 to calculate the radiance reference. The scattering plot shown in figure 2 helps to have a better idea of the differences in both retrievals. The correlation between both data sets is 0.989 with a linear slope of 0.97 and y intercept of -1.07^{14}. There is a mean negative bias of 1.26^{14} molecules cm^{-2} for the retrieval done using orbit 4138 as radiance reference versus the one that used orbit 4124 as radiance reference.

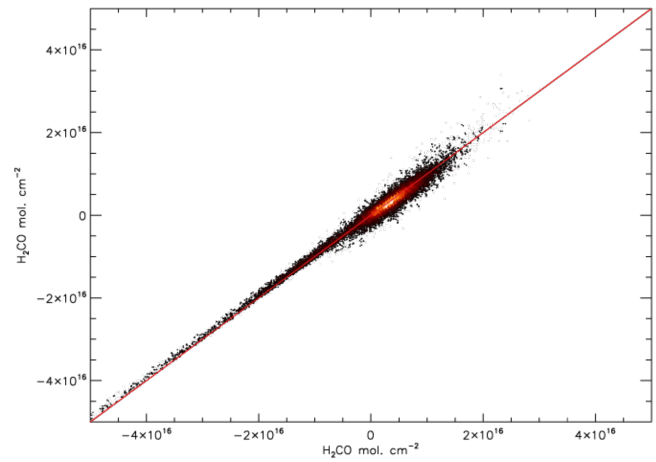

Figure 2. Cross correlation plot between reference sector corrected vertical columns for the retrievals performed for orbit 4129. X axis are results using orbit 4124 to calculate the radiance reference and y axis results obtained using orbit 4138 to perform such calculation.

P 9215, Line 19: there are no 'a_x' in equation 1. There are 'a_n' and 'a_m'. Please be explicit in what you mean here. What we mean by α_x is any of the alphas shown in equation 1 and by X_x any of the Xs shown in equation 1. We suggest to modify the text as follows: "In Eq. (1) alphas represent the fitting parameters while *Xs* are the undersampling correction, the cross sections or the different order of the polynomials".

P 9217, line 18: Why is the TOMS reflectance used? I struggle to understand this point, given the similar viewing characteristics of OMI and OMPS, why not use the OMI reflectances by Kleipool et al. (2008). Please discuss further. While we agree that the OMI reflectances developed by Kleipool et al. (2008) can be used we decided to use the TOMS climatology to be consistent with the climatology used by the cloud products algorithm as described in Vasilkov et al. (2014). We will modify the text to make it clear. "Information about the pixel surface reflectance is obtained from the Total Ozone Mapping Instrument (TOMS) climatology (C. Ahn, personal communication, 2015). This surface reflectance climatology is the same one that is used by Vasilkov et al. (2014) to retrieve cloud information (ϑ *and* c_p). Given the small…"

P 9218: How many observations go into the correction at any given latitude bin? I was not clear but it appeared that the corrections were done on a monthly basis, and then applied to each observation (i.e. daily)? I get the approach but it could be explained a little better. While GEOS-Chem data is a monthly climatology the radiance reference orbit changes each day. The reference sector correction takes in to account, for its first step, 2 data sets with different temporal resolutions. The key idea we are trying to transmit here is that for each different radiance reference the reference sector correction normalization will be different. It is important however to keep in mind that we are normalizing them to monthly data. The number of observations that go into the correction change with latitude. For the central bins (50^oS to 50^oN), where there is always Sun light and solar zenith angles are below 70^o, the number of observations are about 30 per latitude bin. These numbers start to decrease as we get closer to the poles, especially in the winter months. However we will like to highlight that for latitudes where there is no retrievals flag as successful over the Pacific Ocean it is expected to have a similar distribution of successful retrievals for the rest of the globe. We suggest the following addition to the text to further clarify the idea that the correction is different for each calculated radiance reference. Page 9218, line 9: "…ΔSCDs and the model SCDs. This correction is different for each radiance reference, so it changes daily, and is applied only to orbits retrieved with that particular radiance reference. We then assume that…"

P 9219: Shouldn't eqn. 7 use the covariance matrix of HCHO, is this the cross-section? If so, shouldn't be the covariance matrix of all cross-sections fitted. Please clarify. As mentioned in text Eqn. 7 is using the covariance matrix, particularly the diagonal terms of the HCHO component of it. This covariance matrix$(K_x^T K_x)^{-1}$, where K_x is the forward model Jacobian. Eq. 7 has however a typo, missing a square. After including the explicit expression for the covariance matrix it should read as it should read like this:

$$\epsilon^2_{\Delta SCD_{random}} = RMS^2\left(\frac{m}{m-n}\right)\left(\boldsymbol{C}_j\boldsymbol{C}_j\right)$$

P 9220: Is the AMF error analysis conducted by implementing systematic changes in each input (e.g. 0.1 change cloud fraction) or are the individual sensitivities (or partial derivatives) calculated. It is not clear, and that latter approach is the more accurate for quantifying errors. Using a 10% error for GEOS-Chem profiles is also very optimistic. HCHO profile uncertainty is much greater over tropical latitudes (see Hewson et al., AMF, 2015). It is likely AMF errors are on average of order 50% - if we are really being honest. The AMF error analysis is conducted by implementing systematic changes in each input, we are modifying the text to explicitly mention how the sensitivity analysis was carried on.

Hewson et al. (2015) use GEOS-Chem HCHO uncertainties in tropical areas of 25% following the conclusions reported in Barkley et al. (2011). Few paragraphs below Hewson says "… where model HCHO can be simulated reasonably well (e.g. over the US; Millet et al., 2006), it is likely that AMF uncertainty from the profile shape will be less. To account for this, a further calculation in which the HCHO profile was scaled in a similar manner by 10% was also conducted. The resulting median AMF error from the profile shape decreased to about 30-40%". Since we are presenting a global product it will be a good approach to mention both possibilities in the discussion about AMF errors. We propose to change the text as follows to accommodate these 2 new ideas.

Page 9220 lines 3 to 6:

"To estimate the error associated with AMF calculations we have performed a sensitivity analysis by perturbing one at the time the input parameters of AMF calculations. The parameters considered are cloud parameters, surface reflectance, terrain height and GEOS-Chem climatological profiles as well as the wavelength dependency of *w(s)* with in the fitting window. The amplitude of each perturbation is reflecting the uncertainties reported in the literature for each one of the parameters. A shortcoming of this method is that it assumes that errors due to different parameters are not correlated."

Page 9220 lines 19 to 24:

"To finish the sensitivity analysis of the AMF calculation we tested the impact of the a priori profiles of H_2CO. Since it is the shape of the profile what affects the AMF calculation we have applied the reported uncertainty only to layers showing the highest VMRs, defined as those that contribute to the 90% percentile. GEOS-Chem biases with respect to in situ measurements vary around the globe. For example over the US, GEOS-Chem simulations have biases of around 10% (Millet et al., 2006) which translate in AMFs uncertainties up to 16%. Over tropical regions Barkley et al. (2011) reported biases of up to 25% which translate in 40% AMFs uncertainties.

Considering the contributions from all these factors we estimate ε_{AMF} to be between 38%, for an optimistic case with small GEOS-Chem profile uncertainty and cloud parameters being the most significant source of uncertainty, to 50% when surface reflectance and GEOS-Chem profile uncertainties are at their maximum becoming significant sources of AMF uncertainty that contribute as much as the uncertainty in the cloud parameters."

P 9221: How do the OMI and OMPS comparisons change for other cloud radiance fractions

We have carried on comparisons for SAO products using cloud radiance fractions of 0.1, 0.4, and 0.9. Table 1 summarizes the results of the experiment. The differences between OMI products and the OMPS 0.4 product are quite consistent for each region. Always the difference of OMI 0.9 with respect to OMPS 0.4 is the smallest. These result is not surprising if we consider the pixel size difference between OMPS and OMI, more OMPS pixels are affected by the presence of clouds, but accepting higher cloud fractions mitigates the difference. Another feature we will like to highlight is the small difference between OMPS 0.4 and OMPS 0.9 measurements. The high discrepancies between OMPS 0.1 and OMPS 0.4 for Southeastern US, Europe and East China are driven by winter months. Figure 3 shows the time series for all the regions and all the gridding schemes. We propose t0 extend the discussion in section 4 by including the following lines in the manuscript text:

Table 1. Comparison of SAO OMI and OMPS retrievals for different gridded products considering only pixels with cloud radiative fractions below 0.1, 0.4, and 0.9. The values shown here are relative vertical column differences of each product with respect to the OMPS SAO product computed considering only pixels with cloud radiative fraction below 0.4. These values have been computed considering averages for the whole period of study (August 2012-August 2013).

	Pacific Ocean	Southeastern US	Amazon basin	Europe	Southeastern Asia	Tropical Africa	Southern Africa	East China
OMI 0.1	0.43	-38.05	-36.58	-16.27	-23.08	-24.83	-23.34	-39.20
OMI 0.4	2.57	-32.51	-30.36	-16.64	-18.25	-20.76	-21.21	-29.66
OMI 0.9	3.68	-24.31	-29.01	-12.62	-17.59	-19.05	-20.13	-25.18
OMPS 0.1	1.78	-49.28	-7.01	-34.38	-4.60	-9.14	-22.82	-31.14
OMPS 0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OMPS 0.9	0.39	4.74	1.83	1.64	5.48	-2.07	-11.31	4.47

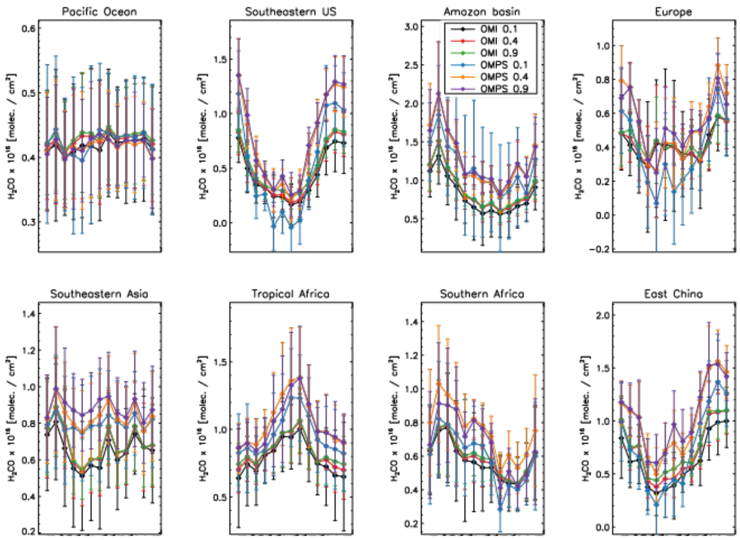

Figure 3. Monthly means time series for SAO OMI and OMPS retrievals using different radiative cloud fraction thresholds.

Page 9221, line 8: We have explored the impact of using other radiance cloud fraction to filter pixels with results from the OMPS and OMI SAO retrievals. The results for different cloud fractions are consistent between them with the exception of winter months in Southeastern US and Europe. This situation is most likely due to the reduced total columns for those months, the viewing conditions with higher SZAs, and the reduced planetary boundary layer. One question that remains to be answered for future studies combining both OMI and OMPS products is which radiative cloud fraction threshold should be used to each product to best combine them.

P 9222: What is the difference between SAO and BIRA OMI? Whilst the temporal variations are similarly observed, there are quite large biases in magnitude. This is quite disturbing, for data users this can result in large differences in results depending on their application. Whilst it is evident that OMPS can retrieve HCHO, I still need to be convinced on the actual application of both datasets within a single science study (but this is early days). Also, there should be mentioned somewhere of the consistent GOME, SCIA, OMI data sets retrieved by the BIRA group (this is not really mentioned in the paper).

A paper recently published in ACPD by Zhu et al. (2016) explores these questions for a particular region, Southeastern US, and time of the year, summer. The differences between BIRA and SAO OMI products are several. From the fitting window, to the direct fit of radiances (without low pass filter of radiance), to order and number of closure polynomials, pre fitting or not of BrO and O_3, to CTM models employed for the reference sector correction. We are going to include the following lines in the text to include a citation to this new paper and to mention the set of consistent BIRA retrievals.

Page, 9222, line 14: “It is clear that to obtain a better idea of the accuracy of the different retrievals independent validation studies like the one recently published by Zhu et al. (2016) are needed. In this paper H_2CO satellite products produced by different groups using different instruments are compared with in situ measurements. The products included in this comparison are BIRA OMI, GOME2A and GOME2B, SAO OMI and OMPS, and NASA Goddard OMPS. SAO OMPS retrievals are found to be bias 39% low over the Southeaster US between 5 August and 25 September 2013”.

The lack of variability in the BIRA OMI data, does this point to an overcorrection in their dataset which smooths the retrievals too much, or alternatively, the SAO reference correction introducing variability. I think more room for discussion on this point. Figure 6 is quite interesting, especially over the Pacific Ocean, here all three retrievals should be very similar but they are not. To me there is a lot ‘hidden’ possible effects and potential consequences in the reference correction approach, but it is what it is, and is unfortunately needed.

Figure 6, over the Pacific Ocean has changed since we corrected and error with BIRA version used (v13 vs v14). The figure will be updated with this new one. We agree with the reviewer. The reference correction approach makes assumptions that can a significant impact in the retrievals. This is one of the reasons to provide scattering weights and the uncorrected columns in our L2 files. The users can decide to use their own reference sector correction and calculate their own AMFs, specific for their region and time to try to mitigate the errors introduced by the assumptions and simplifications we introduce in order to produce a global product.

Include vcds from individual OMI vs OMPS swaths to get a visual comparison of different footprints.

Figure 4 shows an Africa over pass for September 2012. The width of the swath is similar for both instruments. We are going to insert this sentences in the text:

Page 9221, line 18: "… difference in the spatial pixel size. Figure 5 shows an almost coincident OMPS and OMI Africa overpass to better illustrate the differences in the pixel size. OMI has a nadir pixel of 24 x 13 km …. The apparent reduction of noise in OMPS retrievals in comparison with the OMI retrievals shown

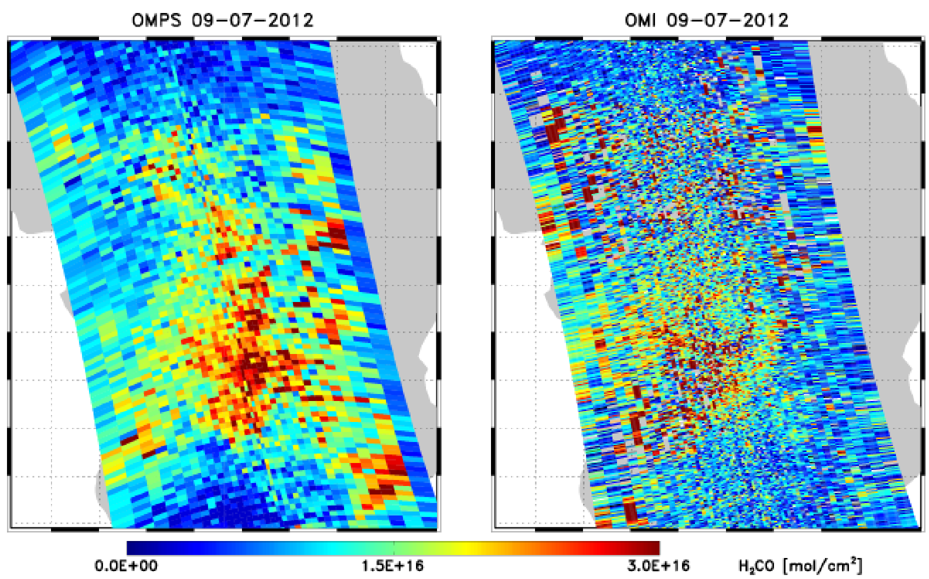

Figure 4. September 9, 2012 Africa over pass H2CO retrieval for OMPS (left panel) and OMI (right panel) illustrating the difference in pixel size between both instruments. Since 2008 OMI orbits are affected by the row anomaly. We have not filtered out OMI pixels affected by it.

in Figure 5 is a direct consequence of OMPS lower spatial resolution and its associated increase of SNR."