

Response to referee #1's comments

The author would like to thank Anonymous referee #1 for the constructive and helpful suggestions on this manuscript.

We replied to 1 general comment and 8 specific comments.

General Comment

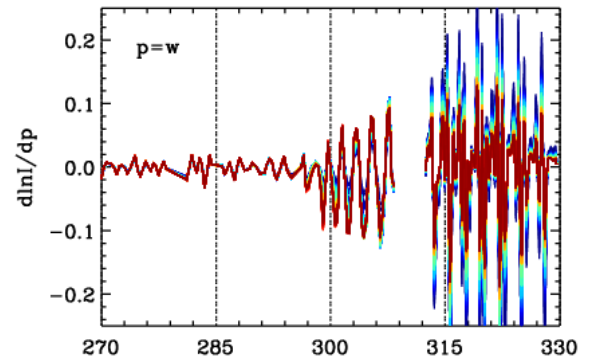
C1. The paper applies a linearization of the ISRF for the retrieval of ozone profiles from OMI measurements. The linearization approach was introduced by Beirle et al., 2017 (BE17 hereafter), which is referenced appropriately. However, the authors should generally specify more clearly which steps are adopted from BE17, and what are original/new ideas/methods/results of their study. The adaptation of the ISRF parameterization for radiances seems to be new and interesting. However, there are some complications which have to be investigated in detail and discussed thoroughly. I recommend publication in AMT after these major revisions have been made.

R1. According to this comment, we have specified what this paper adopted from BE17 and what we advanced in implementing the slit function linearization in Section 2.2, as following “ In Beirle et al. (2017) a slit function linearization was implemented only to fit solar irradiances from GOME-2. We implement the slit function linearization to fit radiances in the SAO ozone profile algorithm (Liu et al. 2010), (Liu et al. 2010). ~ In DOAS analysis, the pseudo absorber is defined as $\frac{\partial S}{\partial p} \otimes \sigma_h$ (σ_h is a high-resolution absorption cross section), which could be calculated at a computationally low-cost. In our optimal estimation based ozone profile retrievals, it is conceptually defined as $\frac{\partial S}{\partial p} \otimes I_h$ (I_h is a high-resolution simulated radiance), which is computationally very expensive because of on-line radiative calculation for a ~ 60 nm wide fit window on the spatial pixel-to-pixel basis. We now introduce how to implement the slit function linearization to derive the derivatives of the OMI radiances with respect to slit function changes in two different radiative transfer approaches used in the SAO ozone profile algorithm, i.e., the effective cross section approach in Liu et al (2010) and the updated high-resolution convolution approach described in Kim et al. (2013), respectively.”

Specific Comments

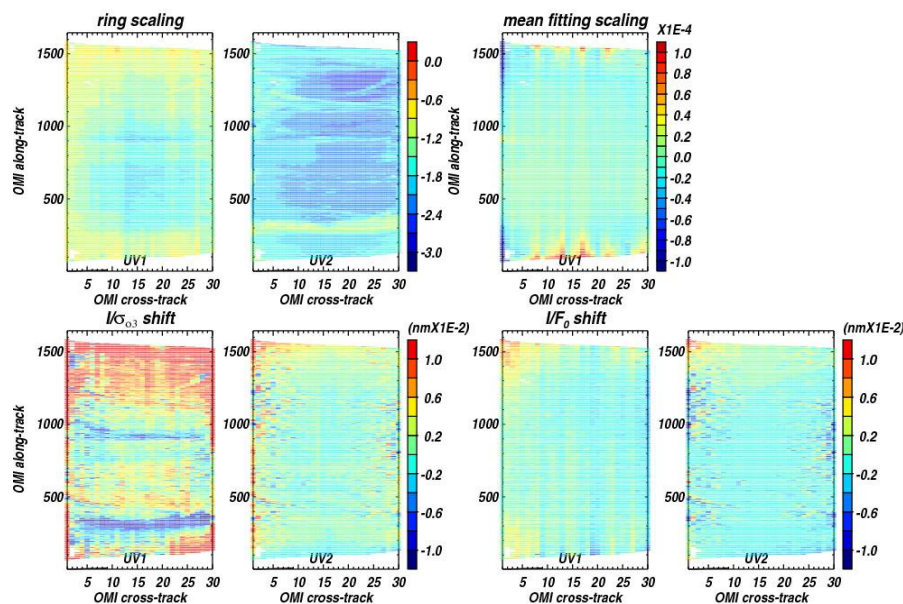
C1. Irradiance vs. radiance. BE17 presented the ISRF parameterization for a fit of a measured irradiance to a high-resolution solar atlas. In the current study, the authors apply the parameterization to radiances. This implies that the PAs depend on the Ozone column, and the spectral structures are different for each satellite pixel! This is not clearly stated in the manuscript and should be quantified (i.e. compare the PAs for high/medium/low ozone). Other absorbers have the same effect, i.e. the spectral patterns of the PAs depend e.g. on the strength of the Ring effect (thus on clouds!). This has to be discussed.

R1. - Yes, PAs vary with each satellite pixel. We plotted PAs with respect to slit width for 138 different satellite pixels (S1). The amplitude of PAs increases with latitude/solar zenith angle, but the spectral structures do not change because it arises from errors due to the convolution process of high-resolution absorption cross sections dominated by ozone. This discussion has been included in the revised manuscript, “The amplitude of $\frac{dlnI}{dp}$ varies with different satellite pixels (e.g., ozone profile shape, geometry, and cloud/surface property), but the spectral peak positions do not change because they arise from the errors due to the convolution process of high-resolution absorption cross-sections dominated by ozone.” at line 211.



S1. $dlnI/dw$ for 138 pixels at cross-track = 15, $0 < lat < 80$, $sza < 80$, and cloud fraction < 0.1 . The difference colors represent from lower latitudes at red color to higher latitudes at blue color.

- As this review pointed out, other elements of the state vector also have some correlation with cloud fraction, surface albedo, cross track position (e.g. UV1 radiance/ozone cross section shift, UV2 ring scaling parameter, UV1 radiance/irradiance shift). However, it is complex to figure out how these state vectors are interacting with PA coefficients because of weak correlation ($< +/- 0.3$ for UV1 variables and $< +/- 0.1$ for UV2 variables) between their jacobians. The PAs are not directly dependent on the strength of the Ring effect in the current implementation, because Ring effect is not fully coupled with the VLIDORT, but calculated using a first-order single scattering model and then scaled with a polynomial to be fitted.



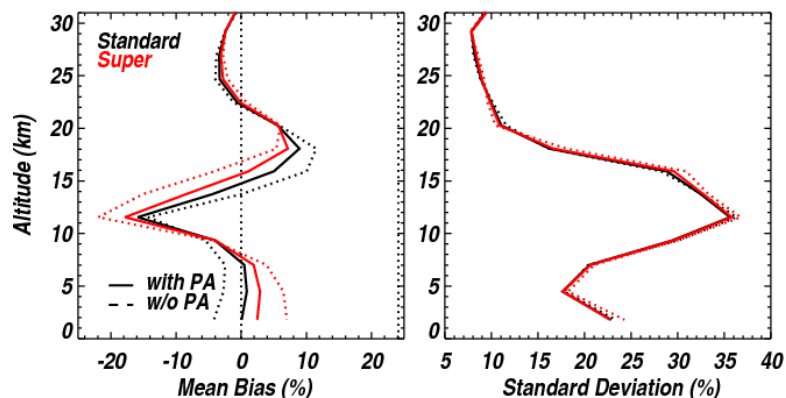
S2. Same as Fig. 4, but for other state vectors.

C2. The abstract contains some statements which are not supported by the presented data:

- a) Abstract, first sentence: "reduces the spectral fit residuals caused by the slit function errors". Please add a figure of the spectral analysis with and without PAs in order to substantiate this statement.
- b) End of abstract: "Comparisons with ozonesondes demonstrate substantial improvements with the use of PAs". In fig. 10, I see almost no difference, and particularly no "substantial improvements", no matter which function is used nor whether PAs are included or not. Obviously, there are systematic differences remaining compared to Ozone sondes which are not related to the ISRF parameterization.

R2-a. Figs 7 and 8 support the benefit of including a pseudo absorber to improve the fit accuracy. Figure 7 compares the root mean square (RMS) of relative difference (%) between measured and calculated radiances over the UV1 and UV2 ranges, respectively. Including the PAs makes little difference in the UV1 fitting residuals for most of individual pixels (1-5 %), but significantly reduces residuals in the UV2 range (10-25%). In Figure 8, the spectral fit residuals are compared with and without PAs, indicating that including PAs eliminates/reduces some spikes of fitting residuals as well as improves the consistency of the fitting accuracy between using standard and super Gaussians at wavelengths above 300 nm. But as the reduction in the fitting residuals compared to the overall magnitude of the residuals is small, I modify "reduces the spectral fit residuals caused by" to "accounts for"

R2-b. "Substantial" is replaced with "noticeable". It typically reduces the mean biases with relative to ozonesonde and significantly reduces the standard deviations at high latitudes in the case of super Gaussian. It also makes the mean biases consistent at different latitudes and between the use of standard Gaussian or super Gaussian. In Fig. 10, we think that the benefit of applying ISRF on comparison is not negligible. This figure is re-plotted below in the unit of % and added in the revised manuscript, showing that ~ 5 % of mean biases is eliminated by PA in the lower troposphere. Furthermore, including PAs clearly makes the retrievals consistent between standard and super Gaussians from up to 10% to within 2%.



S3. Comparison of relative differences (%) between OMI and ozonesonde as a function of altitude, with different slit function assumption and implementation.

C3. How do the derived ISRFs look like, and how do they compare to the prelaunch measurements performed for OMI?

R3. The comparisons between pre-flight ISRF measurements and the derived ISRFs from solar irradiances are detailed in Sun et al. (2017). In Sun et al. (2017) and this study, the ISRFs are parameterized as a super Gaussian or standard Gaussian from solar irradiance measurements, which are used to convolve high-resolution cross-section spectra into OMI spectral resolution for radiative transfer calculation. In this study, we furthermore focused on implementing the slit function linearization to account for the spectral structures caused by the ISRF difference between radiance and irradiance. A fitting parameter is included as a state vector to adjust the amplitude of this spectral structure with each different pixel. This parameter is named by “pseudo absorber coefficient”, which physically represents not directly ISRFs, but the deviation of ISRFs in radiances from those in solar measurements. ISRFs deviates temporally and spatially and thereby it is complex to represent the ISRFs in radiances.

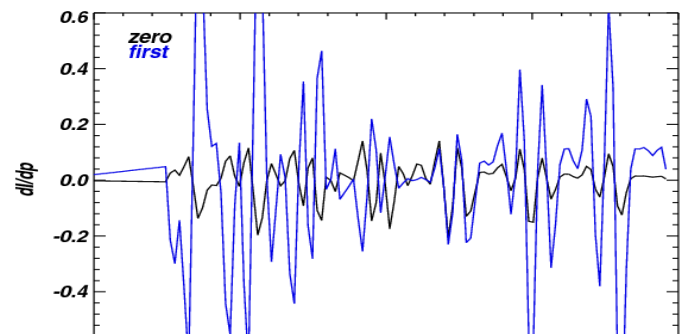
C4. Fig. 5: What is the meaning of the sum of PAs? Each PA has to be scaled by the respective Delta p. Thus the spectral patterns must not just be added!?

R4. The sum of PAs indicates the total spectral structures caused by the slit function errors. Yes, the PAs cannot be just added together; they will be scaled by the PA coefficients before added together. To avoid the confusion, we have declared it as “the sum of PAs multiplied by corresponding PA coefficients”.

- (Caption in Fig.5) Figure 5. (a.1) Pseudo absorber spectra multiplied by corresponding zero order coefficients, $\frac{\partial \ln I}{\partial p} \times \Delta p_0$ and (a.2) the sum of them for (left) super Gaussian and (right) standard Gaussian function parameterizations, respectively.
- (Line 250) In the UV1 range, the sum of PAs multiplied by corresponding coefficients, regardless of which Gaussian is assumed as slit function, is very similar because the spectral structure caused by the slit width change is dominant

C5. Fig. 5: The 1st order spectra look wrong. According to Eq. 9, they are 0 in the center of the wavelength window and increase towards the edges (compare Fig. 10 in BE17). The presented spectra look the other way round.

R5. The presented spectra for the zero and first order polynomial coefficients are defined as $\frac{\partial \ln I}{\partial p} \times \Delta p_0$ and $\frac{\partial \ln I}{\partial p} \times \Delta p_1 (\lambda - \bar{\lambda})$. The spectral features by multiplying $(\lambda - \bar{\lambda})$ in PAs are not clearly distinguished in the presented spectra due to the scaling by Δp . It is clearly shown if Δp is taken out as shown in S4.



S4. Comparison of PAs for zero and first order polynomial fit.

C6. Fig. 9: Specify the time range of the presented data.

R6. The time range of the resented data has been specified in the corresponding caption and moreover this figure has been changed to Table 1, according to the reviewer 2's comment.

C7. Fig. 10: The unit on the x axis must be DU per km or per vertical layer. Please specify.

R7. The ozone in the unit of DU represent the vertically integrated column for the given altitude range (i.e., DU at each vertical layer) and hence the unit on the x axis should be DU.

C8. Fig. 10: Abbreviation "MB" is not defined.

R8. In the revised manuscript, "MB" and "SD" have been spelled out to Mean Bias and Standard Deviation in the x axis title.