Response to the comments from the Referee #1: Optimal Estimation Method Retrievals of Stratospheric Ozone Profiles from a DIAL Lidar

Comment: P2 L12, 'spatial' resolution may be an incorrect word choice.
Response: We changed it to vertical, so the sentence reads:

DIAL (Differential Absorption Lidar) is a ground-based instrument which can measure ozone vertical distribution with high temporal and high vertical resolution, especially in the lower stratosphere.

Comment: P2 L14, likely some older references to O3 DIAL (e.g. Megie)
Response: We added Megie et al. (1985) to the list of references.
The sentence reads:
The traditional analysis of DIAL ozone measurements was presented by Megie et al. (1985), McDermid et al. (1990) and Godin-Beekmann et al. (2003).

Comment: P3 L5, 'relatively lower' absorption cross section as opposed to 'low'
Response: Done

Comment: P3L10, Overlap function O(z) is introduced without the definition. C = ... should be added.
Response: The O(z) term is added to Eq. 1.

Comment: P4, should add the aerosol component into eq. 2/6. It is fair to say that using ancillary data at OHP we have determined that aerosols were not a strong influence on these retrievals. But, it should still be included in the OD calculation.

Response: The aerosol term is embedded in the correction term. Note that the aerosol differential correction term includes a term linked to differential backscattering and differential extinction (as explained in Godin-Beekmann et al., 2003.).
Moreover, in page 3, line 15, we changed Rayleigh and Mie with molecular and particulate.
The sentence reads as:
$\alpha(\lambda,z)$ is the atmospheric extinction coefficient which includes both molecular and particulate scattering extinction coefficients

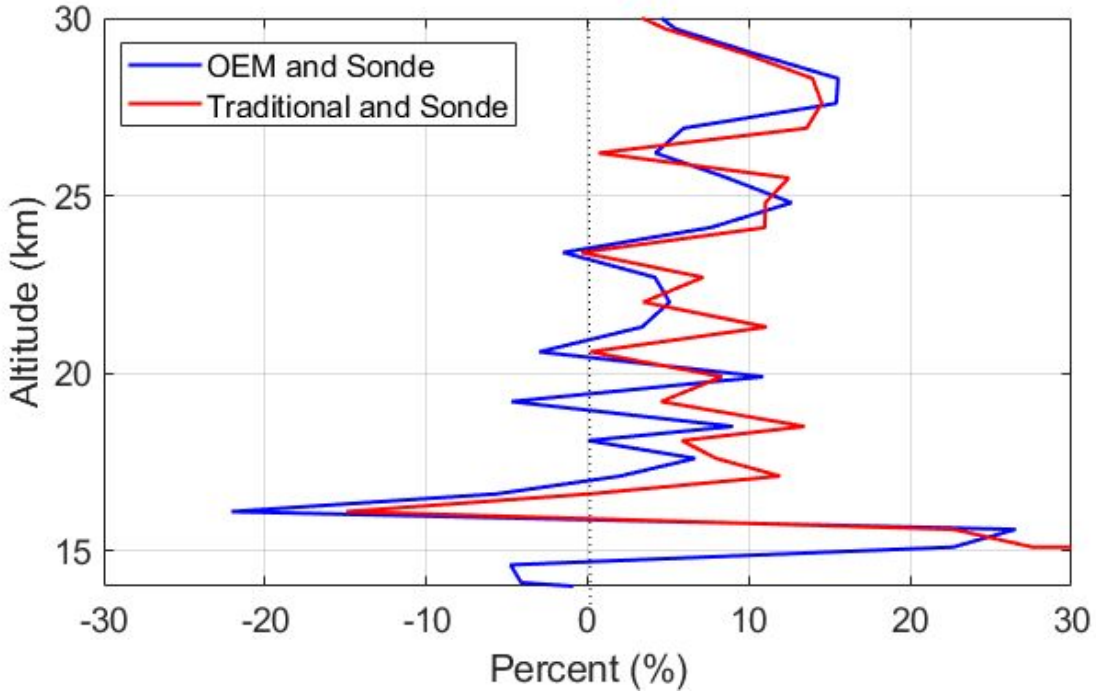
Comment: P7, L27, there will likely be fluorescence from the hydroxyl radical at 308 nm between 80-100 km. Has this impacted the background subtraction model?
Response: This is an important effect to consider, but the OHP system has never observed an influence from OH fluorescence at 308 nm.

Comment: P12, L10 "The trade-off between the retrieval resolution and the retrieval uncertainty should be considered when comparing the methods." This is a subtle aspect of lidar analyses, is

it possible to quantify this somehow. "Using the same VR scheme in the traditional and OEM results in a xx % increase in our statistical uncertainty assessment".
Response: this is a good point, it is not clear in the current manuscript that we will go on to investigate this in detail. We propose changing the sentence to "... when comparing the methods and the reader is referred to the discussion below.

Comment: Fig 8 - OEM minus sonde appears to result in a negative value above 20 km. However, these curves are positive in this region. Is this actually Sonde minus OEM instead? Perhaps making the x-axis [-20,20] limits and a grid box would enhance this discussion as well. Also, at some point there is mention of Raman lower gain channels, are they also plotted on here? Is there differences there as well?
Response: Thanks for catching our mistake. Yes, it is (Sonde-OEM), we corrected this in our manuscript. And we changed the figure and add the following paragraph to explain the figure:

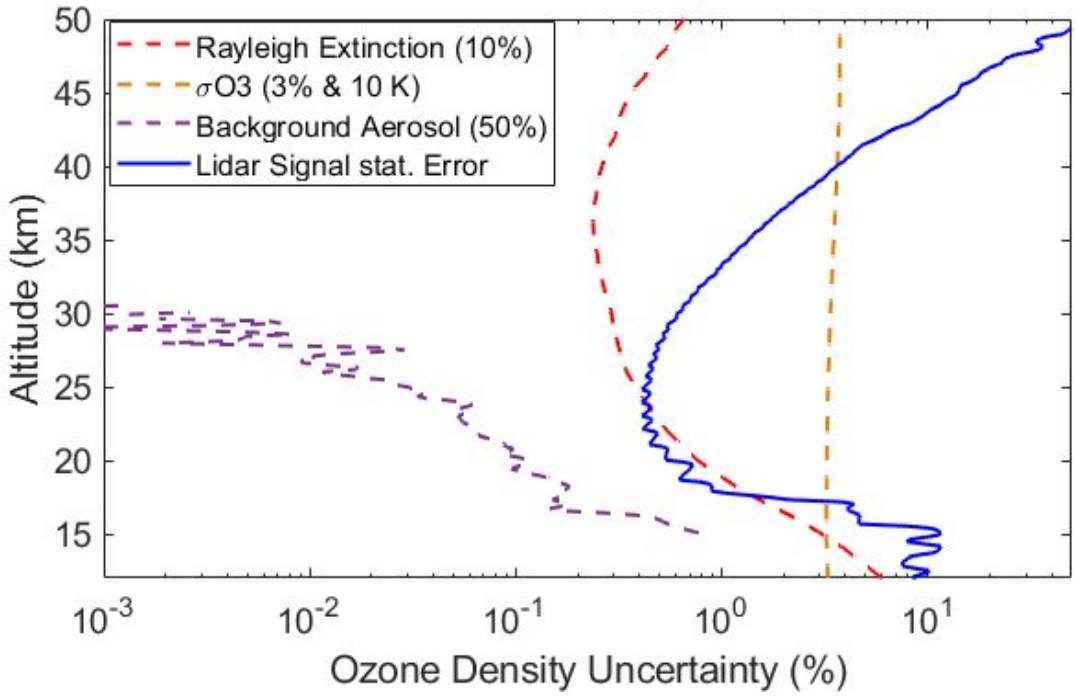
In order to account for the higher vertical resolution of the ozonesonde measurements, we use the OEM averaging kernels to ``degrade" (smooth) the sonde profile using:
\begin{equation}
x_{smoothed} = \mathbf{A} + (\mathbf{I}_{n}- \mathbf{A}) \mathbf{x_{a}}
\end{equation}
where $\mathbf{I}_{n}$ is the unity matrix, and $x_{smoothed}$ is the smoothed sonde profile. Fig. \ref{fig:comparison} (left panel) shows the percentage difference between the smoothed sonde and the OEM (in blue) as well as the percentage difference between the smoothed sonde and the traditional profile (in red).



For the current retrieval, the Raman channels are not used. We plan in the future to include them. Our forward model is based on using the Rayleigh channels. However, we use the product of the ‘’off-line’’ Raman channel counts and z^2 to generate a quantity proportional to the air density. The percentage difference between the retrieved air density and the above quantity is plotted in Fig. 11 (which became Fig 12 of the edited version).

Comment: Figure 10, are there uncertainty associated with resolving times (dead times) as well? What about a final summed standard uncertainty on this plot? These uncertainty values of ~10% near 35 km seem to be quite a bit larger than most traditional stratospheric DIAL measurements for an entire night. Is this evidence to modify the vertical resolution? This would be improved if you had the traditional uncertainty budget in a companion plot to show the differences.

Response: Table 2 in the manuscript addresses the first comment about the deadtime.
We also added the traditional uncertainty budget figure, in the right panel of Fig.10 (Fig. 11 of the edited version). The traditional uncertainty budget is also shown below:



We have added the following paragraph to the manuscript on page 16:

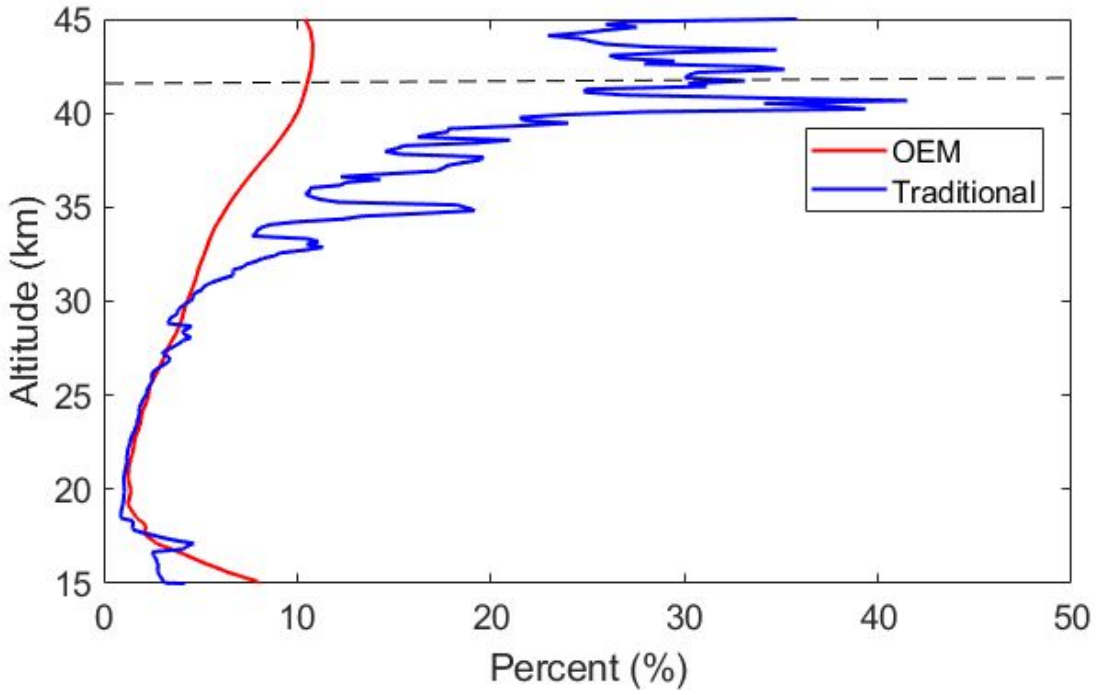
The calculated OEM uncertainty can be compared with the traditional uncertainty budget. Fig. \ref{fig:uncertainty} (right panel) shows the uncertainty of the traditional ozone profile. The Rayleigh-scatter cross section uncertainty has a maximum value of 8\% at the bottom of the profile, while above 20\,km it becomes less than 1\%. This result is consistent with the uncertainty calculated by our OEM retrieval.

In the traditional analysis, for an isothermal atmosphere, the ozone absorption cross section uncertainty at 308\,nm is 3\%. The ozone absorption cross section uncertainty in our OEM retrieval is similar to \cite{LeblancThierry2016Part2}, whose Monte Carlo simulations allowed temperature to vary with height. In the traditional analysis, the background aerosol uncertainty is also calculated, which impacts the ozone profile by less than 1\% in the lower stratosphere. Aerosols are currently being added to the OEM forward model as a model parameter.
The statistical uncertainty of the traditional analysis at higher altitudes (above 25\,km) is smaller comparing to the OEM, which as explained earlier is the result of having a larger vertical resolution. However as shown in Fig.~\ref{fig:VR} (the black dotted lines), the OEM retrievals also have smaller statistical uncertainties if the vertical resolution increases. As discussed previously (Fig.~\ref{fig:VR-comparison}), for the traditional analysis using a similar vertical resolution to our OEM, the statistical uncertainty of the traditional method will be larger than for the OEM retrievals in the upper stratosphere, due to the regularization term in the OEM.

And, we added the following on page 5 explaining how we calculate the uncertainty budget:

The statistical uncertainty of the retrieved quantities and the model parameter uncertainties are calculated as follows:
\begin{equation}
\label{uncertainty_equ}
\begin{split}
\mathbf{S_{m}} = &\mathbf{G_{y}}\mathbf{S_{y}}\mathbf{G_{y}^{T}}\\
\mathbf{S_{f}} =
&\mathbf{G_{y}}\mathbf{K_{b}}\mathbf{S_{b}}\mathbf{G_{y}^{T}}\mathbf{K_{b}^{T}}\\
\end{split}
\end{equation}
where $\mathbf S_{m}$, $\mathbf S_{f}$, $\mathbf S_{b}$ are the covariances of the retrieval noise, the forward model parameter error, and the error covariance of the model parameters. The gain matrix, $\mathbf{G_{y}} = \frac{d\widehat {\mathbf{x}}}{d\mathbf{y}}$, gives the sensitivity of the retrieval to the measurements, while $\mathbf{K_{b}} = \frac{d {\mathbf{F}}}{d\mathbf{b}}$ is the Jacobian of the forward model with respect to $\mathbf{b}$.

Comment: Fig 12, it would be useful to have this figure with the different retrieval techniques using the same vertical resolution. It's not a straight forward to say one is picking out features and the other isn't if the VR is a factor of 3 different. Are the ozonesondes also being passed through the same low-pass filter for these comparisons?
Response: We propose adding a figure comparing the statistical uncertainty of the traditional ozone profile calculated with the same vertical resolution as the OEM (Fig. 7 of the edited version and below):



Also on page 13:
The traditional ozone profile can be calculated at a similar vertical resolution to our OEM retrieval. The statistical uncertainty of the traditional analysis, using the same vertical resolution as our OEM, is shown in Fig.~\ref{fig:VR-comparison_2}. Below 30\,km both methods provide the same uncertainties, however, above this altitude the OEM uncertainty is smaller. The OEM's smaller statistical uncertainty at higher altitudes increases more slowly than for the traditional method due to the contribution of the \textit{a priori} profile, which adds additional information. However, in the OEM retrieval an increased contribution from the regularization term of the solution means the response function becomes less than 1. Below 30\,km the \textit{a priori} profile has a small contribution in the final retrieval (as the response function is ~ 1), but between 30\,km to 40\,km the \textit{a priori} profile has a greater contribution. Above 40\,km the response function decreases rapidly (Fig.~\ref{fig:AK}).

Are the ozonesondes also being passed through the same low-pass filter for these comparisons?
Response: As mentioned in an earlier comment, we changed all the comparison figures to make sure that the ozone sondes have the vertical resolution equivalent to the retrievals.

Comment: Fig 13a Traditional DIAL background subtractions can be challenging to compare to 'truth'. Were there any other data sets (e.g. the NASA O3 Lidar), that would help bring closure to this discrepancy? Is this -10% bias in the top (<35km) could be attributed to improper background subtraction?

Response: The background subtraction is not an issue at 35 km. For the NASA O3 lidar, the figure below representing both profiles on that day does not show a lower value at 35 km by the NASA lidar.
We would need to evaluate all OHP profiles by OEM method in order to evaluate biases between them. In fact the profiles of July 20 does not show the same discrepancy.