Response to the Referee #2 comments on Optimal Estimation Method Retrievals of Stratospheric Ozone Profiles from a DIAL Lidar

Comment: Abstract: "first principle". We usually say "first principles".
Response: fixed!

Comment: Page 1, lines 20-24 & page 2, lines 1-4: This description of the ozone hole seems irrelevant to the paper.
Response: We agree with you and have re-written this paragraph as follows.

Stratospheric ozone plays a critical role, allowing life to thrive on Earth by absorbing the ultraviolet (UV) radiation emitted by the Sun. Moreover, the temperature structure in the stratosphere is determined by the absorption of UV radiation by ozone, which is followed by the exothermic recombination of $\mathrm {O}_2$ and $\mathrm {O}$. Thus, ozone is the main driver in defining the atmosphere's temperature structure \citep{andrews1987middle}.
After observing a significant global depletion of stratospheric ozone \citep{farman1985large, WMO11,WMO14}, the Montreal protocol was established as an international treaty to control and to halt the release of ozone depleting substances (ODSs). As a result, the abundance of anthropogenic ODSs in the troposphere has been decreased from its peak in 1994 by approximately 10\% \citep{WMO14}. Recently, the first signs of stratospheric ozone recovery over Antarctica was observed \citep{solomon2016emergence}. However, for non-polar regions since 2000, no significant positive trend has been detected \citep{WMO14}.

Page 2, line 12: "The technique also offers the advantage of making self-calibrated measurements." Perhaps a word or two of clarification would be helpful here. Other differential absorption spectrometers need calibration.
Response: We are adding the following to the paragraph.
DIAL (Differential Absorption Lidar) measures vertical distribution of ozone density with high temporal and vertical resolution. In the DIAL technique, two laser beams at different wavelengths are simultaneously transmitted to the atmosphere. The spectral range for the laser beams is chosen in the UV range where one of the wavelengths is highly absorbed by ozone, and is called the ``on-line'' wavelength. The other wavelength has a relatively lower absorption by ozone and is called the ``off-line'' wavelength.

As the ozone cross sections are well known, the differential lidar technique allows absolute number density to be determined from the combination of the on and off line measurements, without the need for external calibration.

Comment: Page 3, line 10: The overlap function is defined but does not appear in the equation.
Response: Thanks for catching this. We added it to Eq.1.

Comment: Page3, lines 19-21: Quoting the absolute value of the absorption cross section of NO2 tells the reader nothing unless the cross section of ozone is also given.
Response: the original sentence was not correct.
The original was:

> The differential absorption cross section of $\mathrm {NO}_2$ in the specified spectrum is on the order of 3×10^{-19} $\mathrm{cm} ^{2}$, thus considering the effect of $\mathrm {NO}_2$ in the ozone retrievals is not essential.

We changed it to:

> At mid-latitudes, the uncertainty of ozone number density due to absorption by $\mathrm {NO}_2$ reaches a maximum of 0.4\% between 25 and 30\,km altitude. Thus, the effect of $\mathrm {NO}_2$ on the ozone retrievals is not significant, and the third term of Eq.\ref{Optdepth} is small (Brasseur et al., 1999; Godin-Beekmann et al., 2003).

Comment: Page 3, lines 23 & 26: Is "paralyzable" a real word?
Response: Yes. A photomultiplier counting system is called paralyzable when it fails to record an event (i.e measure photocounts) when the time interval between receiving two events is shorter than a given interval time, known as the deadtime l (\gamma). The Donovan at all reference cited in the paper is well know, and describes this effect in detail.

Page 7, line 12: "The standard deviation to the 2 sigma level for this climatology is 50% below 25 km and 10%..." From the context I think you mean the standard deviation (i.e. 1-sigma), but this sounds like a confidence interval. In Table 1 some of the other parameters are described as standard deviations.

Response: It is common in OEM to give variability of parameters as either 1 standard deviation (sigma; that is 67% of the variability is within this range) or 2 standard deviation (95% included). We will reword the sentence as:

The variability of the climatology we use is 50\% at the 2 sigma level, encompassing 95\% of the variability, and 10\% above 20\,km altitude.

Comment: Page 7, lines 19, 30 (and elsewhere): "uncertainty" is not defined. Do you mean one standard deviation (1-sigma)?

Response: We use uncertainty as a shorthand for "uncertainty of our knowledge of X", and perhaps one could argue variability is a better word to use, but we would like to leave it as uncertainty.

Page 7, line 23 (and elsewhere): "correlation length" is not defined

Response: We added the following sentence to the paragraph (third paragraph in section 3):

In the case of ozone and air density there is a vertical correlation between the elements of retrieval states. This corresponds to the off-diagonal elements of the \textit{a priori} covariance matrix. The correlation length gives the vertical correlation between the retrieval elements. It can be difficult to quantify the correlation length depending on the quantity. We have used a correlation length (\l$_{s}$) of 1000 \,m for ozone at altitudes below 18\,km and the correlation length of 1400\,m at higher altitudes. The air density has a correlation length of 1400\,m for all regions, which is about ⅛ of a scale height and consistent with vertical resolution of density measurements used for Rayleigh-scatter temperature lidar. It is beyond the range of this study, but feasible, that an extend ozonesonde record from a location could be used to better assess the correlation length for ozone density. The effect of using no correlation length would be to make the retrieval overly sensitive to measurement noise; using a very long correlation length would act to smooth the retrieval beyond the resolution of the retrieval grid. Neither extreme is the case here.

Comment: Page 9, lines 1-2: An "uncertainty" of 19K for radiosondes sounds absurdly large. Uncertainties (1-sigma) for radiosondes are usually quoted in the range of 1K or less. I'm not familiar with MSIS uncertainties but 35K sounds pretty large. I can guess the temperature outside more accurately by simply looking at the calendar.

Response: As discussed previously, in this use of uncertain in OEM it is meant to be uncertainty due to variability. In the paper, the uncertainty of temperature in sonde is written wrongly and is only about 1 K, we have corrected this in the paper. In the stratosphere and above Sica and Haefele (2015) showed a reasonable variability for

temperature is that given in the MSIS temperature model. Hedin et al. (1991) gives an uncertainty (as a RMS uncertainty) of 35 K over season and solar cycle. Hence, we adopt this uncertainty in the upper stratosphere and above.

HEDIN, A. E. (1991), Extension of the Msis Thermosphere Model Into the Middle and Lower Atmosphere, Journal of Geophysical Research-Atmospheres, 96(A2), 1159-1172.

Comment: I think you mean "Retrieval a priori values"
Response: Yes. It is corrected now.

Comment:Page 10, lines 31-32: This description conflicts with that in the figure caption
Response:
Original: The **red line** shows that the averaging kernel for ozone density equals 1 up to 42.7\,km, thus below this altitude the retrieval is independent of the \textit{a priori} profile.

We have changed the sentence to the following:
The **dashed line** shows that the area of the averaging kernel for ozone density equals 1 up to 42.7\,km. Below this altitude the retrieval is independent of the \textit{a priori} profile.

Comment: Page 13, lines 20-24: Why is the lidar biased low in Figure 7? It seems to miss quite a bit of ozone.
Response: The low bias is seen for the traditional ozone profile (the blue line), at lower altitudes in the traditional method. This bias is like due to saturation of the photomultiplier tube, despite including an empirical deadtime correction. For most nights the empirical correction is sufficient. Our OEM method retrieves the deadtime on a profile by profile basis for each digital detector channel.

Comment: Page 13, line 25: Figure 8, not 7.
Response: Thanks for catching this. It is fixed now.

Comment: Captions, Figures 5 & 6: "...the maximum height at which the retrieval is independent from the a priori." is ambiguous (see Page 10, lines 31-32).
Response: We changed all captions related to the dashed line to:

The horizontal dashed line is a height below which the OEM retrievals is more than 80% due to the measurements.

Comment: Caption, Figure 7: "...horizontal dashed line shows the cut-off below which the effect of the a priori ozone profile is small less than 10%." We now have a third definition of this dashed line!
Response: We fixed it.

Comment: Figure 8 appears to be reversed (or the caption is wrong), as it shows the lidar higher than the sonde.
Response: Yes, it is (Sonde-OEM), we corrected this in our revised manuscript.

Comment: Page 16, line 5: "The ozone retrieval extends from 12 km to 70.2 km." How much of the upper part is a useful measurement?
Response: The ozone retrieval is useful to about 42.7 \km. We changed the sentence to:

The acceptable range of ozone retrieval extends from 12\,km to 43\,km...