AMT-2019-107: Retrieval of Temperature From a Multiple Channel Pure Rotational Raman-Scatter Lidar Using an Optimal Estimation Method (Gamage et al.)
Response to Referee 1 (**Christoph Ritter**)
04 July 2019

The Referee's comments are in blue, are responses are in black.

- You show a complete error analysis for the OEM technique which I found convincing. However to better judge these results it would be very interesting to have a similar error estimation for the traditional Raman technique. Especially in your case 1 fig4 it seems as if the Raman result is only plotted up to 12 km although in the manuscript a change of vertical resolution in this altitude is Mentioned page11. Can you comment on this?
We strongly agree that the community of users of the traditional temperature method would benefit from a detailed investigation of that technique in the spirit of the 3 papers by the group of NDACC lidar scientists who have done comprehensive studies of the traditional ozone and Rayleigh scatter temperature determinations, as well as quantifying the vertical resolution of the determinations [see the references at the end of this reply], and we would be glad to participate in that effort. It is, however, tangential to the purpose of this manuscript which is to show a new way to retrieve temperature, which offers some advantages (and disadvantages) relative to the traditional method. For instance in Jalali et al. 2018 and Farhani et al. 2019 the OEM uncertainty budgets were shown to compare well with previous studies for Rayleigh scatter temperature profiles and DIAL ozone profiles (including the NDACC work). These comparisons give us confidence in our uncertainty budgets for lidar retrievals using OEM.

As far as to our choice of plotting the traditional method up to 19km (Fig4: traditional temperatures goes up to 19km not 12km), the traditional temperature estimates are derived from the MeteoSwiss routine temperature analysis, which works as follows.

The vertical resolution is not constant; it starts at 30m and it increases to 400m.
  - The change in vertical resolution is based on the calculated uncertainty of the temperature profile at each height. The maximum height resolution allowed is 400m, until the temperature statistical uncertainty becomes smaller than a threshold value of 1K.
  - The calculated profile is cut off based again on the uncertainty. When the algorithm can't calculate the next range gate within the threshold value of 1K it stops the profile at the last range gate.

In Fig. 4 the traditional retrievals are shown up to ~19km. For that specific case (Case 1), the traditional temperature vertical resolution is 30m up to 12.5km, then changes to 400 m above this height. The temperatures are cutoff at the height where the uncertainty reaches 1K (19km).

Above information on the traditional method is given in Section 5 of the manuscript.

- Do you assume the same overlap for both channels? Why do you need the overlap? Do you really think to be able to retrieve the overlap with the required precision to obtain aerosol extinction information? In this case an error analysis would be required otherwise revise your wording. I think for this paper such an effort is not necessary – as the particle extinction is the same for the high and low channel, hence the temperature from the OEM should not depend on the extinction?

  Yes, we assume the same overlap for both channels based on the work of Dinoev et al. 2012. We need the overlap since in OEM we forward model the raw backscatter profile of each channel and hence, have to specify an overlap function. At a given altitude, it is not possible in our retrieval to determine both overlap and extinction. Therefore, our approach is to retrieve whatever quantity we know less well. Generally this is overlap below 6km and extinction above 6km, since above 6km full overlap can be safely assumed. In case of clouds with a ceiling below 6km, we retrieve overlap up to the ceiling and extinction above. Furthermore, the results for extinction and lidar ratio look reasonable compared to other studies. One benefit of OEM is the ability to estimate the effect of a model parameter on the retrieved quantity, so given we have made reasonable choices for the model parameter uncertainties their impact on the retrieved temperature is well characterized.

  Moreover, we trust the extinction retrieval and its uncertainty above 6km but not below and we changed the text in Section 4.3 of the manuscript as shown below to clarify this.

  "The effect of geometrical overlap and particle extinction on the signals are strongly coupled and hence retrieving both parameters simultaneously with the given data channels is not possible unless at least one of the effects is highly constrained. We assume that particle extinction is well known from the backscatter ratio outside clouds, and that overlap is well known above the height of full overlap, i.e. above 6 km (Dinoev et al., 2010).We use this knowledge to define a transition height, 6 km in clear skies or at the cloud base height, whatever is lower. Below this height overlap is retrieved, and above this height particle extinction is retrieved. The a priori overlap function is estimated from measurements in clear sky conditions. A 50% standard deviation is used for geometrical overlap below the transition height and a constant standard deviation of 10^{-3} is used above this height, constraining the geometrical overlap to the a priori values above the transition height. For particle extinction, a standard deviation of $10^{-6}km^{-1}$ is used below the transition height to constrain the retrieval, then a 50% standard deviation is used above this height, allowing the OEM to retrieve exclusively the particle extinction. The a priori covariance matrices for both particle extinction and geometrical overlap are determined using a tent function with a 100m correlation length."

Figure 1, shows the full uncertainty budgets of the overlap and particle extinction retrievals for the Case 3: Nighttime with cirrus cloud given in the manuscript. Overlap uncertainties are shown up to 6km and the particle extinction uncertainties are shown above 6 km.

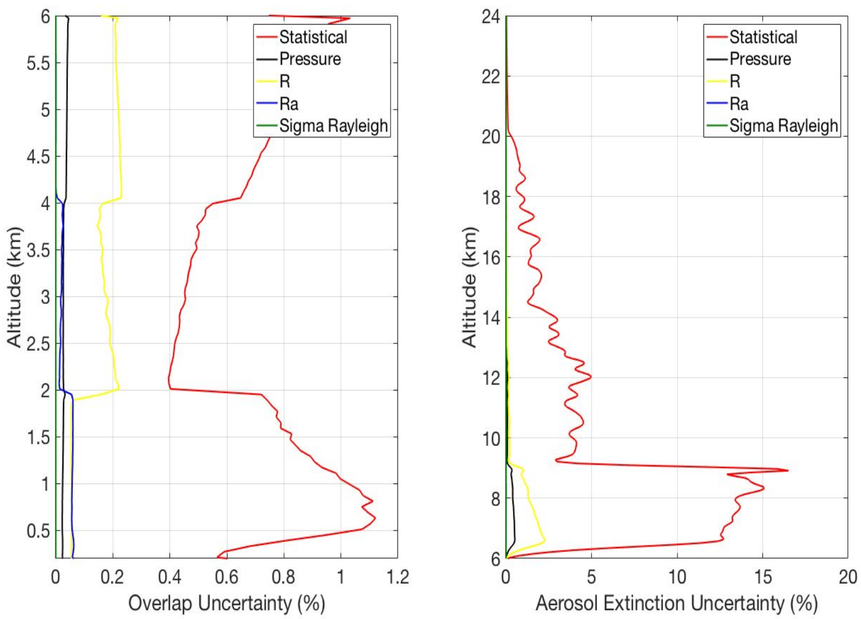

Figure 1: Left Panel: Full uncertainty budget of the overlap retrievals from the nighttime RALMO measurements on 05 July 2011 with a cirrus cloud present at 6km height. Uncertainty due to Rayleigh cross section, pressure, and coupling constants are in the orders of 10^{-4}, 10^{-1},and 10^{-1} respectively. Right Panel: Full uncertainty budget of the particle extinction. Uncertainty due to Rayleigh cross section 10^{-3} and due to analog coupling constant is 10^{-2}. Uncertainty due to pressure and digital coupling constants are about 1% and 2% respectively.

- Page 11 and Fig . 5 your error analysis is nice and one of the strong selling points of this paper. However, in the current form I cannot reproduce the values . A bit more information is required, how the values were obtained.

Forward model uncertainties are calculated based on the theory presented in the Rodgers textbook Section 3.2.2. We have also added the following equations that we used to compute the errors into the revised manuscript.

The uncertainty budget is determined from the measurement and model parameter covariance matrices (Rodgers, 2000). The total covariance S_{total} is:
$S_{total} = S_m + S_F$
where S_m is the retrieval covariance due to measurement noise and S_F is the retrieval covariance due to the forward model parameter uncertainty. The retrieval covariance due to measurement noise S_m is
$S_m = GS_yG^T$
where G is the gain matrix that indicates the sensitivity of the retrieval to the measurements. The retrieval covariance due to the forward model parameters S_F is
$S_F = GK_bS_bK^T{}_bG^T$
where K_b and S_b are the forward model parameter Jacobian and covariance matrices respectively. The model parameter Jacobians K_b, can be estimated analytically or numerically for each model parameter. To construct S_b we require the uncertainties of the model parameters. We recommend Rodger's textbook (Rodgers, 2000) for more details of the OEM.

Furthermore, in our work presented in the manuscript we have used the uncertainties used in the Table 2 in the manuscript to construct construct S_b .

- Page 1 quote Mahagammulla Gamage : I think in the introduction it is not necessary to quote a paper which is still under preparation. You may choose another quote here :
  agree will remove this.

- Page 3 : and elsewhere is d sigma /d Omega really the ATTENUATED cross section? I am not sure, as you have Gamma^2 as extinction term in your eq. 1 ?
  Yes. this term is attenuated cross section. We define attenuated differential cross section term as the convolution of the instrument function with each line in the spectrum. This is shown in EQ 2, where attenuated cross section contains the terms $\tau^+(J_i)$ and $\tau^-(J_i)$ that are the transmission of the receiver at the wavelength of each RR line. However, this term is not a standard one and it is easy to see why it could be confused with attenuation due to atmospheric transmission. The atmospheric transmission is defined in EQ 1 in the usual manner.

- Page 10..fig. 1 : is the units of your analog signal MHz.how did you convert it? :

The RALMO analog raw data are sampled by Licel counters, and then converted to counts (ADC) . However, it does not change the unit of the analog signal. Thus, we have made a mistake in the analog signal units in Figures 1, 7,12 and 18. Units for the analog signals are now corrected to the units of mV.

However, in the OEM it doesn't matter what unit we use for signal as long as the forward model generated signal and the real measurements are in the same unit. Another advantage of OEM is that multiple detector channels, both analog and digital with differing vertical resolutions and units can be easily used. Thus, these changes have no effect on the results in the manuscript.

- Page19:a lidar ratio of 5sr is already quite small. Can you estimate an error for the lidar ratio?
  We can estimate a statistical uncertainty using standard error propagation. The lidar ratio is not directly retrieved in our OEM. Our estimate of LR is based on the retrieved particle extinction and ASR profiles calculated from elastic and PRR lidar measurements. Even though it is small mathematically it is possible to estimate an error and that is what we have done. We will add a phrase to the manuscript explaining how the uncertainty of lidar ratio was calculated. We have also updated Figure 17 in the manuscript, indicating the estimated LR errors.

- Page20: line9: I don't understand the "temperature range"– I thought the OEM only depends on K and K_a?
  The calibration coefficients of the calibration function used in the traditional temperature retrievals needs to be estimated over a wide range of possible temperatures. However, our OEM calibration constants (coupling constants) can be estimated over a narrow range of temperatures, or even one single point, without introducing extrapolation errors in the retrieval. The OEM depends on the two coupling constants R and R_a and estimation of those require temperatures, but does not require the assumption of a functional form relating these constants to temperature (refer to Eq.10 and 11 in the manuscript); the requirement of a functional form depending on multiple parameters rather than a constant is why the traditional method must use a wide range of temperatures.

- Page21:line11:what do you mean be"uncorrected "PRR measurements? :
  This was meant to be raw PRR measurements, that is a Level 0 product not corrected for saturation or background. We will change this word from "uncorrected" to "raw".

Thank you for noticing the following typos. We will fix these mistakes in the revised paper

- Page 4 : explain x_a in eq. 7. : x_a is the a priori.
- Page 5 : minus sign in eq. 8 is missing : Fixed.
- Page 9 : 2 times “from” in line 14 : Fixed
- Page 11 : line 13 : reduced : Fixed
- Page13: line 4: agrees line 4:deviates: Fixed
- Page20:line8:“by”missing…that by the OEM method[a] : Fixed

References :

1.Thierry Leblanc, Robert J. Sica, Joanna A. E. Van Gijsel, Sophie Godin-Beekmann, Alexander Haefele, et al.. Proposed standardized definitions for vertical resolution and uncertainty in the NDACC lidar ozone and temperature algorithms – Part 2: Ozone DIAL uncertainty budget. Atmospheric Measurement Techniques, European Geosciences Union, 2016, 9 (8), pp.4051-4078. 10.5194/amt-9- 4051-2016 . insu-01306627v2

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3. Dinoev, T., Simeonov, V., Arshinov, Y., Bobrovnikov, S., Ristori, P., Calpini, B., Parlange, M. and van den Bergh, H., 2013. Raman Lidar for Meteorological Observations, RALMO-Part 1: Instrument description. *Atmospheric Measurement Techniques*, *6*(ARTICLE), pp.1329-1346.

4. Jalali, A., Sica, R. J., and Haefele, A.: Improvements to a long-term Rayleigh-scatter lidar temperature climatology by using an optimal estimation method, Atmos. Meas. Tech., 11, 6043-6058, https://doi.org/10.5194/amt-11-6043-2018, 2018.

5. Farhani, G., Sica, R. J., Godin-Beekmann, S., and Haefele, A.: Optimal estimation method retrievals of stratospheric ozone profiles from a DIAL, Atmos. Meas. Tech., 12, 2097-2111, https://doi.org/10.5194/amt-12-2097-2019, 2019.