APPLYING A RANGE DEPENDENT MULTIPLE SCATTERING CORRECTION TO RETRIEVALS OF EXTINCTION USING LITE DATA

Ralph. E. Kuehn[1], **Mark. A. Vaughan**[1], **David Winker**[2]

[1]*SAIC, Mail Stop 435, NASA Langley Research Center, Hampton VA 23681, email: r.e.kuehn@larc.nasa.gov, m.a.vaughan@larc.nasa.gov*

[2]*NASA Langley Research Center Mail Stop 435, Hampton VA 23681, email: David.Winker@nasa.gov*

ABSTRACT

In this work we demonstrate the application of an extinction algorithm that incorporates a range dependent multiple scattering parameterization. The particulate-layer average lidar ratio can also be calculated when transmittance measurements of the layer are available. For elevated particulate layers that are not vertically adjacent to other layers, the attenuated molecular signal from above and below the layer can be used to measure its transmittance. For LITE orbit 83, over a region spanning part of the country of Western Sahara and the Atlantic Ocean (25.9N, 14.3W to 27.5N, 15.4W), 31 transmittance measurements were possible for an elevated aerosol layer. Using an multiple scattering parameter modelled for dust, the mean retrieved lidar ratio at 532 nm, was 33.7 sr. If no multiple scattering is assumed then mean retrieved lidar ratio was 23.9 sr. In comparison, results from AERONET data indicate that the lidar ratio for dust is 32 sr [1], and from high spectral resolution lidar are in the range from 42 to 55 sr [2].

1. INTRODUCTION

For space based lidar systems, such as the Lidar In Space Technology Experiment (LITE)[3], the multiple scattered contribution to the single scattered lidar return must be accounted for to accurately retrieve profiles of extinction from aerosol or cloud layers. The multiple scattering contribution is significant for cloud layers since half of the transmitted beam scatters in the diffraction peak and travels along with the main beam contributing to the lidar signal. For aerosol particles, where the width of the forward scattering peak is very broad, the multiple scattering contribution can also be significant. Because a space based lidar is far away from the scattering medium (260 km for LITE), and the footprint of the lidar receiver field-of-view is large, (≈ 900 m), there is is a high probability of multiply scattered photons returning to the receiver.

Here we demonstrate the application of an extinction retrieval algorithm for a space based lidar system that incorporates the use of a range dependent multiple scattering parameterization. The multiple scatter parameterization[4] utilizes a factor that modifies the optical depth term of the single scattered lidar equation. An iterative numerical method similar to that shown in [5] has been derived for the parameterized lidar equation such that the extinction profile can be retrieved in a top-down scheme, once a lidar ratio has been specified. When the transmittance of the layer is known then the algorithm can be further constrained to calculate the layer averaged lidar ratio. For lidar measurements at 532 nm, and where particulate layers are elevated such that they are not vertically adjacent to the ground or other layers, the attenuated molecular backscatter signal from above and below the layer can be used to measure the transmittance of the layer.

2. BACKGROUND

This section shows the single scattering lidar equation along with other notation definitions. The single scattering lidar equation is defined as:

$$P(r) = \frac{C_n}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\cdots \exp\left(-2\int \sigma_p(r) + \sigma_m(r) + \sigma_{O_3}(r)dr\right) \quad (1)$$

where $P(r)$ is the power incident on the receiver from range r, C_n is the lidar system constant, $\beta_p(r), \beta_m(r)$ are the aerosol and molecular scattering cross sections per unit volume from range r, respectively ($\mathrm{km}^{-1}\cdot\mathrm{sr}^{-1}$), and $\sigma_m(r), \sigma_p(r), \sigma_{O_3}(r)$ are the molecular,aerosol and ozone extinction cross section per unit volume at range r, (km^{-1}). Equation 1 can be rewritten so that the extinction due to molecular and aerosol components are separated, and so that the returned power is normalized by range and C_n to get the total attenuated backscatter:

$$\beta'(r) = P(r)\frac{r^2}{C_n} = \left[\beta_m(r) + \beta_p(r)\right] T^2_{air}(r) T^2(r) \quad (2)$$

Where $T^2_{air}(r) = T^2_m(r)T^2_{O_3}(r)$, $T^2_m(r)$ and $T^2_{O_3}(r)$ are the two-way transmittances of the column due to air and ozone molecules, respectively, and, $T^2(r)$ is the two-way transmittance of the column due to aerosols. The layer average lidar ratio is defined as,

$$S = \frac{\sigma_p(r)}{\beta_p(r)} \quad (3)$$

so that the aerosol transmittance can be written as,

$$T^2(r) = \exp\left(-2S\int \beta_p(r)dr\right) \tag{4}$$

Also, the attenuated scattering ratio is defined as a ratio between the total attenuated backscatter, equation 2, and the product $\beta_m(r)T^2_{air}(r)$ to get the attenuated scattering ratio:

$$\frac{(\beta_m(r)+\beta_p(r))}{\beta_m(r)}T^2(r) = RT^2(r) \tag{5}$$

Where T^2_{air} and $\beta_m(r)$ are determined from meteorological data.

The transmittance of an elevated layer can be computed by taking the ratio of RT^2 above and below the layer. In cases where the particulate scattering is assumed to be negligible above and below the layer, the scattering ratio, $R = 1$ in these regions. So, the transmittance of the layer is calculated by:

$$R(r_1)T^2(r_1)T^2_{layer} = R(r_2)T^2(r_2)$$
$$T^2_{layer} = \frac{T^2(r_2)}{T^2(r_1)} \tag{6}$$

3. MULTIPLE SCATTERING

The multiple scatter contribution from particulate layers results in a measured lidar signal that is greater than expected from any given range, effectively reducing the amount of observed attenuation if only single scattering was assumed. The multiple scatter contribution can be modelled to be an addition to the single scattered lidar return:

$$P_{TS}(r) = P_{SS}(r) + P_{MS}(r) \tag{7}$$

Where the subscripts TS, SS, and MS stand for *total scattering*, *single scattering*(see equation 1), and *multiple scattering*, respectively. The term $P_{MS}(r)$ depends on the lidar receiver field-of-view, particle phase function, and the extinction profile. [4] has shown that the extinction profile can be retrieved from equation 7 with the introduction a range dependent multiple scattering factor that modifies the layer optical depth term. The parameterized lidar equation for multiple scattering is:

$$\beta'(r) = [\beta_m(r)+\beta_p(r)]\,T^2_{air}(r)\cdots$$
$$\exp\left(-\eta(r)\int \sigma_p(r)dr\right) \tag{8}$$

Where $\eta(r)$ is the aerosol multiple scattering parameter defined as:

$$\eta(r) = 1 - \ln\left[\frac{P_{TS}(r)}{P_{SS}(r)}\right]/\tau(r) \tag{9}$$

and $\tau(r)$ is the optical depth from the top of the column to range r. Furthermore, [4] has shown that for a specific transmitter beam divergence and receiver FOV, profiles of $\eta(r)$ depend primarily on the scattering phase function, so that once a $\eta(r)$ profile has been modelled for a specific particulate type it can be applied to any lidar measurement where the same type of particulate is observed.

4. A NUMERICAL SOLUTION FOR THE EXTINCTION RETRIEVAL

Existing analytic solutions for $\sigma_p(r)$ can not be adapted to accommodate equation 8; however numerical solutions can be found if the following two assumptions are made: 1) The lidar ratios S_m, S are constant with respect to range so that $\sigma_m(r) = S_m\beta_m(r)$ and $\sigma_p(r) = S\beta_p(r)$; and 2) $\eta(r)$ is a known function of range and any molecular multiple scattering parameter is considered a constant $= 1$. Now, equation 8 can be written as follows:

$$\mathsf{B}(r) = \frac{\beta'(r)}{T^2_{air}(r)} = [\beta_m(r)+\beta_p(r)]\cdots$$
$$\exp\left(-2\eta(r)S\int_0^r \beta_p(r)dr\right) \tag{10}$$

So, at the near-range boundary of any layer, (i.e. feature top for a space-based lidar) equation 10 becomes:

$$\mathsf{B}_t = (\beta_{m,t}+\beta_{p,t})\,T^2_{t-1}\cdots$$
$$\exp\left[-S\eta_{p,t}\Delta r(\beta_{p,t}+\beta_{p,t-1})\right] \tag{11}$$

Where $\Delta r_k = r_k - r_{k-1}$, and $\mathsf{B}_t = \mathsf{B}(r_t)$. By definition, at the top level $\beta_{p,t-1} = 0$ and $T^2_{t-1} = 1$. For any given value of S there exists a transcendental equation with a single unknown, which can be solved numerically (e.g. by Newton's method) to obtain $\beta_{p,t}$. The solution at the next range increment is the same except the the range increments have been advanced by one. This methodology follows approximately that shown by [5], and in the most general form is:

$$\mathsf{B}_k = (\beta_{m,k}+\beta_{p,k})\,T^2_{k-1}\cdots$$
$$\exp\left[-S\eta_k\Delta r(\beta_{p,k}+\beta_{p,k-1})\right] \tag{12}$$

where,

$$T^2_{k-1} = \exp\left[-S\eta_k\sum_{j=top}^{k-1}\Delta r_j(\beta_{p,j-1}+\beta_{p,j})\right]$$

5. CONSTRAINED SOLUTION

As shown by equations 5, and 6 the transmittance of an elevated layer can be calculated from the attenuated scattering ratio:

$$\frac{[\beta_m(r)+\beta_a(r)]}{\beta_m(r)}T^2(r) + \frac{P_{MS}(r)}{T^2_{air}(r)\beta_m(r)}$$
$$= RT^2(r) + \frac{P_{MS}(r)}{T^2_{air}(r)\beta_m(r)} \tag{13}$$

So, the measured transmittance of the layer is represented by:

$$T_{meas}^2(r_1 : r_2) = \left[T^2(r_2) + \frac{P_{MS}(r_2)}{T_{air}^2(r_2)\beta_m(r_2)}\right] / T^2(r_1) \quad (14)$$

Where $R(r_1) = 1$, and $P_{MS}(r_1) = 0$. Note that the bracketed term in equation 14 is the calculated value $R(r_2)T^2(r_2)$, and is shown to illustrate that when multiple scattering contribution is significant, then measured transmission through the layer will be reduced. Nevertheless, T_{meas} can still be used to determine a value of S for the layer. An iterative bisection algorithm (see algorithm 1), is used, assuming that there exists a value of S and a profile of β_p, that satisfy the equation:

$$T_{meas}^2(r_1 : r_2) = \exp\left(-2S\eta(r_2)\int_{r_1}^{r_2} \beta_r(r)dr\right) \quad (15)$$

After the optimal value of S has been determined, the true transmittance of the layer is calculated by:

$$T_{true}^2(r_1 : r_2) = \exp\left(-2S\int_{r_1}^{r_2} \beta_a(r)dr\right) \quad (16)$$

Furthermore, if the lidar ratio is computed using a constant $\eta = 1$, meaning that the backscatter signal is assumed to contain only singly scattered photons. Then the retrieved lidar ratio is equivalent to $S^* = \bar{\eta}S$, where $\bar{\eta} = \langle\eta(r)\rangle$.

6. RESULTS AND DISCUSSION

The data segment used for this analysis is part of LITE orbit 83, and is a 232 kmswath extending from the eastern Atlantic Ocean over the country of Western Sahara. The LITE 532 nm backscatter data, (see figure 1), was averaged to a 75 m vertical and 7.5 km horizontal resolution to increase the SNR in the profiles of attenuated scattering ratio that were used to measure the aerosol layer transmittances. To further reduce errors in the calculation of T_{meas}^2, the data was averaged in the clear air region from 7 to 10 km to calculate the factor, $R(top)T(top)^2$, for the entire segment, rather than for each profile individually. Also, $R(r)T(r)^2$ was averaged between the bottom of the elevated aerosol layer and the top of the planetary boundary layer clouds and aerosols. The layer transmittances were then calculated for each of the 31 segments in the analysis region, and optimal lidar ratios were determined using algorithm 1. A comparison of the retrieved transmittance and extinction profiles using a range dependent $\eta(r)$ and constant $\eta = 1$ are shown for one segment, (at 26.7172N, 14.8299W) in figure 2, the corresponding retrieved lidar ratios are 31 and 22, respectively. The retrieved lidar ratios, and layer transmittances for the entire analysis region are shown in figure 3. The mean of the retrieved lidar ratios is 33.7, using range dependent $\eta(r)$, and is 23.9 using $\eta = 1$. Also, the average of the layer transmittances, are 0.77 and 0.85, respectively. The error in T_{meas}^2 due to signal noise is approximately 5%, and the error in S^* is estimated to be less than 20% [6]. The errors in T_{true}^2 and S due to signal noise are expected to be the same as T_{meas}^2 and S^*, the total error my be larger than that however. If the aerosol model used to calculate $\eta(r)$ is different than the aerosol measured than there could be bias errors. The magnitude of such errors has not yet been studied. Lidar ratios retrieved for desert dust derived from AERONET[1] data is 32 sr [1], and from high spectral resolution lidar measurements are in the range from 42-55 sr[2], which is an indication that our retrieval using a range dependent multiple scattering parameter is a better representation of the real aerosol layer lidar ratio.

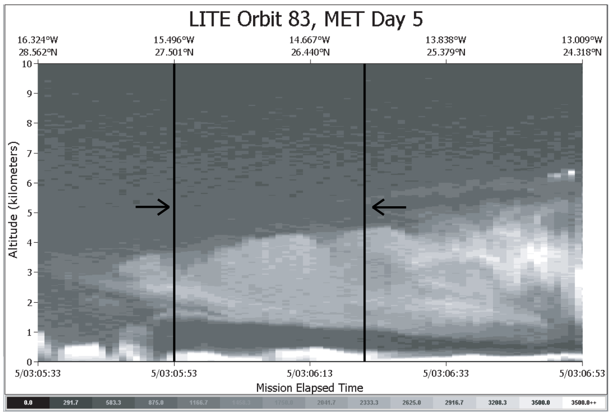

Figure 1. 532 nm attenuated backscatter data from LITE orbit 83. The region shown between the two vertical black lines is the section of the elevated aerosol dust layer used for the retrieval of layer transmittances and lidar ratios.

Algorithm 1 $T^2(Sa)$ indicates the transmittance that has been calculated for the layer after the extinction algorithm (as in section 4) has been run using a an aerosol lidar ratio with a value $S = Sa$. Also, $conv = |T^2(Sm) - T_{meas}^2|$.

Determine $T^2(Sa)$, and $T^2(Sb)$ such that $T^2(Sa) < T_{meas}^2 < T^2(Sb)$.
for $n = 0, 1, 2, \cdots$, until $conv \leq 1 \cdot 10^{-10}$ **do**
  Set $Sm = (Sa + Sb)/2$
  if $T^2(Sm) \leq T_{meas}^2$ **then**
    Set $Sa_{n+1} = Sa_n, Sb_{n+1} = Sm$
  else
    Set $Sa_{n+1} = Sm, Sb_{n+1} = Sb$
  end if
end for

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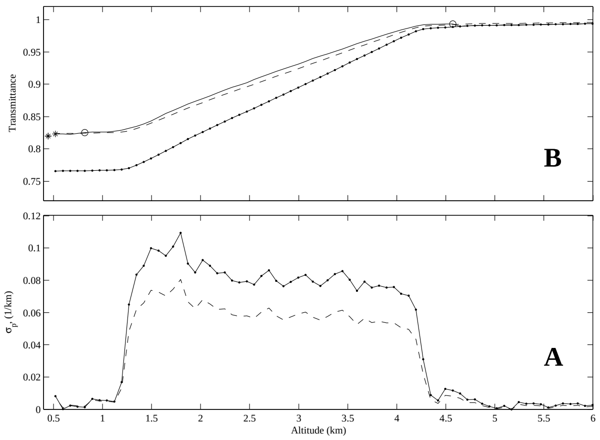

Figure 2. **A**: Comparison of an extinction profile retrieved from one segment of LITE orbit 83, at 26.7172N:14.8299W, using a range dependent multiple scattering parameter, $\eta(r)$, (solid line), and with a constant $\eta = 1$ (dashed line). **B**: Comparison of transmittance profiles from the same two extinction retrievals as in **A**. The transmittance profiles calculated using equation 15 with $S = 31$, (Solid line), and using $S = 22$ with $\eta = 1$, (Dashed line). Also plotted is the true transmittance profile, (Solid dotted line), as calculated by equation 16. The circles(stars) mark the 1st(2nd) layer base and top height found by a layer finding algorithm.

7. CONCLUSION

We have shown that a range dependent multiple scattering parameterization can be incorporated into a numerical extinction retrieval algorithm. The results from the application of this retrieval algorithm have shown that lidar ratios obtained from an elevated aerosol dust layer are more consistent with lidar ratios published by other investigators. In addition, the retrieved layer transmittances and extinction profiles will also better represent the real extinction of the layer. Our goal for future work is to provide a more rigorous calculation of the errors in the calculation of both the layer transmittances and lidar ratios. In addition, we will continue to provide the analysis for the several other cases in the LITE data set where elevated aerosol layers have been observed.

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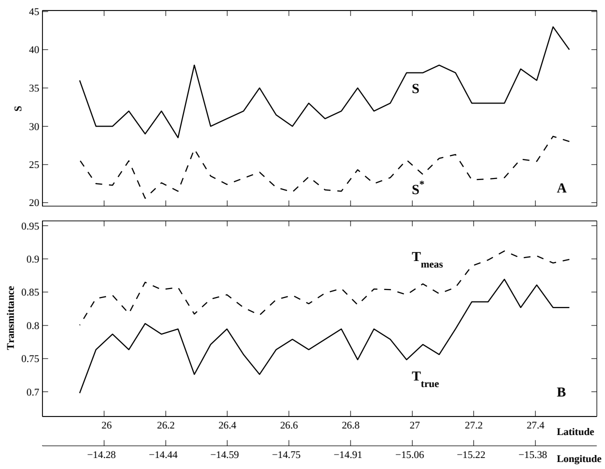

Figure 3. Layer transmittances, and Lidar Ratios for 31 segments of LITE orbit 83, using a range dependent multiple scattering factor, $\eta(r)$, (solid lines) and using a constant parameter $\eta = 1$, (dashed lines).

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