MULTI-WAVELENGTH ANALYSIS OF A LOFTED AEROSOL LAYER MEASURED BY LITE

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ABSTRACT

A newly developed optimization technique is used to derive lidar ratio at 1064 nm from a lofted aerosol layer measured during the Lidar In-space Technology Experiment (LITE). In addition to the lidar ratio, this optimization scheme simultaneously retrieves the particulate backscatter color ratio, $\chi = \beta_{1064} / \beta_{532}$. Lidar ratios for the layer were also retrieved at 355 nm and 532 nm using the long-established transmittance method. Combining the information obtained from all retrievals allows us to characterize the optical properties of the layer in terms of color ratios for both backscatter and extinction for all wavelength pairs.

1. INTRODUCTION

Accurate estimation of cloud and aerosol optical depths using backscatter lidar data requires knowledge of the relationship between the particulate backscatter and the corresponding extinction. This relationship is commonly parameterized using the lidar ratio (i.e., the extinction-to-backscatter ratio). When reliable measurements of the molecular backscatter intensity can be made at both the near and far boundaries of a layer, estimates of the lidar ratio can be derived directly from the profile of attenuated backscatter coefficients via use of an iterative procedure constrained by a measurement of the layer two-way transmittance (e.g., as in Young [1]). The ability to make the required clear air measurements is a function of signal-to-noise ratio (SNR) and layer optical depth, and further depends on the molecular scattering efficiency at the wavelength used to make the measurement. Because this scattering efficiency falls off as the wavelength increases, measurements of molecular scattering at 1064 nm require higher fidelity instrumentation than is the case at 355 nm or 532 nm. Thus far, the design constraints imposed on space-based lidars such as LITE [2] and the upcoming Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission [3] have precluded the use of the transmittance method for measurements made at 1064 nm.

Applying the transmittance method requires the assumption that the layer is homogeneous with respect to particle composition and size distribution, and is therefore characterized by a unique, range-invariant (but perhaps spectrally dependent) lidar ratio. Recent work by Vaughan [4] explicitly extends this assumption of layer homogeneity to include the backscatter color ratio, $\chi = \beta_{1064} / \beta_{532}$. Doing so facilitates the formulation of a new retrieval technique that simultaneously generates optimal estimates (in the least squares sense) of both χ and the 1064 nm lidar ratio, S_{1064}, from two wavelength elastic backscatter lidar measurements of transmissive clouds and/or lofted aerosol layers. In the current work we present a brief outline of this new algorithm in the context of measurements made using an Nd:YAG laser. In addition, we provide a comparison of some structural aspects of the scheme to those used in an earlier two-color lidar ratio retrieval method. The new algorithm is then demonstrated via application to a segment of LITE data.

2. ALGORITHM OVERVIEW

For layers suitable for analysis using the transmittance method, we can derive both the lidar ratio, S_{532}, and a range-resolved profile of particulate backscatter coefficients, $\beta_{p,532}(r)$, directly from the measured data [1,5]. Having done so, we then invoke the requisite assumptions regarding layer homogeneity, and assert that both the backscatter color ratio and the 1064 nm lidar ratio remain constant throughout the layer. These assumptions allow us to expresses the particulate backscatter and extinction coefficients at 1064 nm in terms these two (currently unknown) constants and of the retrieved (and hence known) values of $\beta_{p,532}(r)$, as follows:

$$\beta_{p,1064}(z) = \chi \cdot \beta_{p,532}(z) \quad (1)$$

$$\sigma_{p,1064}(r) = S_{p,1064} \cdot \chi \cdot \beta_{p,532}(r) \quad (2)$$

Denoting the integral of the 532 nm particulate back-scatter from feature top to range r as $\gamma_{p,532}(r)$, we can revise the lidar equation for the 1064 signal to obtain, as in the successive steps shown in equation (3), an expression that relates the measured values at 1064 nm to the retrieved values at 532 nm.

$$\mathrm{B}_{1064}(\mathrm{r}) = \frac{\mathrm{r}^2\,\mathrm{P}_{1064}(\mathrm{r})}{\mathrm{C}_{1064}\,\mathrm{T}_{\mathrm{m},1064}{}^2(\mathrm{r})} \tag{3}$$

$$= \left(\beta_{\mathrm{m},1064}(\mathrm{r}) + \beta_{\mathrm{p},1064}(\mathrm{r})\right) e^{-2 S_{\mathrm{p},1064} \int_0^{\mathrm{r}} \beta_{\mathrm{p},1064}(\mathrm{r}')\,d\mathrm{r}'}$$

$$= \left(\beta_{\mathrm{m},1064}(\mathrm{r}) + \chi\beta_{\mathrm{p},532}(\mathrm{r})\right) e^{-2\chi S_{\mathrm{p},1064}\,\gamma_{\mathrm{p},532}(\mathrm{r})}$$

Here the subscripts m and p represent, respectively, the contributions from molecules and particulates, where particulates are assumed to represent either clouds or aerosols as required. Examining the range-dependent components of equation (3), we see that $\mathrm{B}_{1064}(\mathrm{r})$ is a known via measurement and $\beta_{\mathrm{m},1064}(\mathrm{r})$ is assumed to be known from either meteorological data or models. Because we have previously obtained a solution at 532 nm, $\beta_{\mathrm{p},532}(\mathrm{r})$ and $\gamma_{\mathrm{p},532}(\mathrm{r})$ are likewise known values. Thus the only unknown values in equation (3) are the range-invariant quantities χ and $S_{p,1064}$. Given a layer thickness that spans two or more range bins, the measurements of $\mathrm{B}_{1064}(\mathrm{r})$ can be seen as representing a system of equations in two unknowns: χ and $S_{p,1064}$. This system can be solved using the method of least squares; that is, we seek the minimum of a function $\mathrm{F}(\chi, S_{\mathrm{p},1064})$ where

$$\mathrm{F}(\chi, S_{\mathrm{p},1064}) = \frac{1}{2} \sum_{k=\text{layer top}}^{\text{layer base}} \left(f(r_k)\,g(r_k) - \mathrm{B}_{1064}(r_k)\right)^2 \tag{4}$$

with $\quad f(r_k) = \beta_{\mathrm{m},1064}(r_k) + \chi\,\beta_{\mathrm{p},1064}(r_k)$

and $\quad g(r_k) = \exp\left(-2\,\chi\,S_{\mathrm{p},1064}\,\gamma_{\mathrm{p},532}(r_k)\right).$

Estimates for χ and $S_{p,1064}$ can now be obtained by applying standard techniques for the numerical solution of nonlinear least squares problems (e.g., as in Dennis and Schnabel [6]).

Though the formulations are quite different, this new algorithm is nonetheless similar in spirit to one originally proposed by Sasano and Browell [7] and subsequently modified by Liu et al [8]. Using two-wavelength measurements, Sasano and Browell derive the lidar ratio at 1064 nm by minimizing a performance function defined by

$$\mathrm{J}(S_{1064}) = \sum_{i=i_1}^{i=i_2} \varphi(R_{532}, R_{1064}, A)^2$$
$$= \sum_{i=i_1}^{i=i_2} \left[\frac{\beta_{\mathrm{p},532}(r_i)}{\beta_{\mathrm{m},532}(r_i)} - A\frac{\beta_{\mathrm{p},1064}(r_i)}{\beta_{\mathrm{m},1064}(r_i)}\right]^2. \tag{5}$$

In this expression R_λ is the scattering ratio at wavelength λ ($R_\lambda = \beta_{p,\lambda} / \beta_{m,\lambda}$), and A is a constant of proportionality. For each value of S_{1064} that is tested, A is determined via the method of least squares so as to minimize $J(S_{1064})$. An extended discussion of the performance characteristics of $J(S_{1064})$ and the procedure for obtaining a minimum value can be found in [8]. We confine our remarks here to exploring the relationship between the physically meaningful quantity χ used in the current work, and the constant of proportionality, A, used in the Sassano and Browell method.

Because Rayleigh backscattering varies as the fourth power of the wavelength, the molecular backscatter coefficients $\beta_{m,532}(r)$ and $\beta_{m,1064}(r)$ are related by a constant factor of 16. The function $\varphi(R_{532}, R_{1064}, A)$ can therefore be rewritten as

$$\varphi = \frac{1}{\beta_{\mathrm{m},532}}\left(\beta_{\mathrm{p},532} - 16\,A\,\beta_{\mathrm{p},1064}\right). \tag{6}$$

Solving for A and taking the limit as $\varphi \to 0$ (i.e., as $J(S_{1064})$ goes to its theoretical minimum) shows that $\beta_{532} / \beta_{1064} = 16A = \chi^{-1}$. We suggest therefore that this new formulation results in three modest improvements over the previous algorithm: (1) as in [8], the problem is cast solely in terms of physically meaningful quantities; (2) additional information describing the scattering characteristics of the layer is extracted (i.e., χ); and (3) whereas the Sasano and Browell method requires repeated solutions of a least-squares problem for $J(S_{1064})$ – i.e., one solution for each discrete value for S_{1064} that is tested – and is only then followed by a table look-up to determine the final value of S_{1064}, the numerical solution for the method presented here can be immediately obtained by solving a single (albeit non-linear) least squares problem.

3. APPLICATION TO LITE DATA

The utility of the algorithm is demonstrated using LITE data. Figure 1 shows a segment of LITE orbit 23 acquired during a nighttime pass over the central plains of the United States on 11 September 1994. In the northern portions of this orbit segment, the surface-attached aerosol layer (SAL) is seen to extend upward to 4-km. The lack of "clear air" below renders the lofted aerosol within this region unsuitable for application of the transmittance method. However, the southern half of the segment appears to be aerosol-free in the region between ~2.5-km and the base of the lofted layer at ~5.0-km.

During this portion of orbit 23, LITE was configured to make cloud measurements. As a consequence, the amplifier gains in the receiver were set low, so as to eliminate the possibility of saturation by strong returns from dense cirrus layers and/or stratus decks. Generating acceptable signal-to-noise ratios in the clear region beneath the lofted aerosol required extensive averaging of this low gain data, and therefore the analysis that follows is applied to a single averaged profile comprised of data that extends over an 80-km horizontal path, from 36.953º N, 97.094º W to 36.414º N, 96.527º W. The horizontally averaged profiles of attenuated backscatter coefficients are shown for all three wavelengths in Figure 2. The smooth curve in each panel denotes the molecular attenuated backscatter profile that was used in the analysis routines. Prior to conducting the optical analyses, the data for all three channels was further averaged to a 60-m vertical resolution.

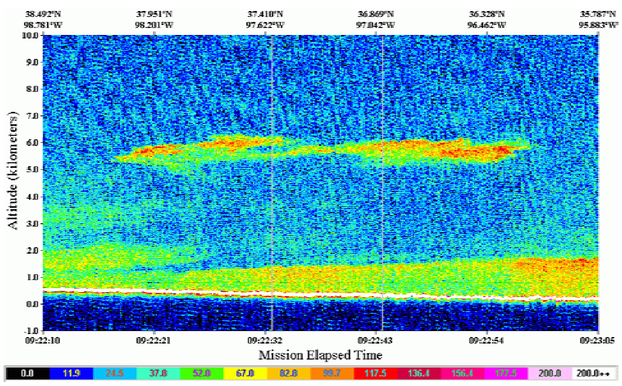

Figure 1: LITE aerosol measurements over north central Oklahoma; raw backscatter data at 532 nm, arbitrary units

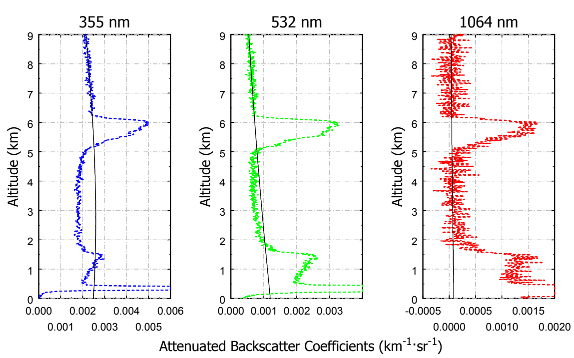

Figure 2: Averaged profiles of attenuated backscatter coefficients at 355 nm (left), 532 nm (center), and 1064 nm (right). The smooth curve in each panel represents the molecular backscatter profile appropriate to each wavelength.

To determine the two-way transmittances of the layer at 355 nm and 532 nm we first identified the 1-km region beneath layer base where the product of the slopes of the attenuated scattering ratios with respect to altitude was closest to zero; i.e., we minimize the product, computed over identical ranges of Z, of dR'_{355}/dZ and dR'_{532}/dZ. This metric has proven effective in identifying those regions of the return where the measured values most closely resemble the expected values computed from the molecular models. The minimum was located between 3.93-km and 2.97-km. The measured two-way transmittances within the region were 0.69 ± 0.02 at 355 nm and 0.76 ± 0.03 at 532 nm. The corresponding lidar ratios calculated using the transmittance method are 43.03 ± 0.65 at 355 nm and 58.78 ± 2.39 at 532 nm.

As demonstrated by Figure 2, even after a substantial amount of averaging, measuring the two-way transmittance at 1064 nm is not a viable option. This situation is endemic in space-borne lidar measurements at 1064 nm, and is in fact what necessitates the development of two-wavelength retrievals such as the optimization scheme presented here. Solving the over-determined system of equations generated by equation (4) yields a lidar ratio at 1064 nm of 52.20 ± 18.11 and a backscatter color ratio of 0.53 ± 0.01. The uncertainty estimates reported for S_{1064} and χ are obtained as in [4] using equation 12 and the biomass burning model. Solving the lidar equation using S_{1064} yields a two-way transmittance at 1064 nm of 0.88. The optical depth of this layer is thus 0.18 at 355 nm, 0.14 at 532 nm, and 0.07 at 1064 nm.

The backscatter color ratios for the remaining wave-length pairs are computed as the ratio of the layer integrated backscatters (e.g., $\chi_{532/355} = \gamma_{P,532}/\gamma_{P,355}$). The extinction color ratios, defined as $\alpha = \sigma_{\lambda_{longer}}/\sigma_{\lambda_{shorter}}$, are obtained from previously computed parameters using the relationship $\alpha = \chi\left(S_{shorter}/S_{longer}\right)$. Backscatter and extinction color ratios are presented for all wave-length pairs in Table 1.

Table 1: Aerosol color ratios for backscatter (χ) and extinction (α)

Wavelength Ratio	χ	α
1064/532	0.53	0.59
532/355	0.56	0.38
1064/355	0.29	0.23

4. DISCUSSION

While the two-color algorithm described here is most reliable when coupled with a solution at 532 nm obtained using the transmittance technique, it is not in principal limited to the analysis of transmissive layers. The two-color optimization scheme can actually be used on any occasion when (a) the lidar ratio at 532 nm is well known, and (b) an acceptable solution for $\beta_{p,532}(r)$ can be retrieved from within a layer. This method therefore has possible applications to the analysis of space-based measurements of aerosols in the planetary boundary layer in those cases where the lidar ratio at 532 can be assumed to be well known from auxiliary measurements or based on geographic and/or seasonal considerations.

We note too that the two-color algorithm presented in this work does not specifically account for the effects of multiple scattering. However, if we use the multiple scattering parameterization suggested in [1], and further define $S^*_\lambda = \overline{\eta}\, S_\lambda$, then both the transmittance method and the two-color algorithm can be applied without modification to existing computer codes. The concomitant proviso is that the retrieved quantity is actually S* rather than the desired quantity S. However, there now exists a modified version of the transmittance method which can accommodate a multiple scattering factor that is a function of range (i.e., $\eta(r)$, as in [9]). Implementation details for this revised transmittance method are given in [10]. Though as yet untested, adaptation of the two-color algorithm to the range-dependent multiple scattering model should be straightforward, requiring little more than the replacement of $g(r_k)$ in equation (4) with a modified version, $g_\eta(r_k)$, such that

$$g_\eta\left(r_k\right) = \exp\left(-2\,\chi\, S_{p,1064}\; \eta_{1064}\left(r_k\right)\gamma_{p,532}\left(r_k\right)\right).$$

REFERENCES

1. Young, S. A., Analysis of lidar backscatter profiles in optically thin clouds, *Applied Optics*, Vol. 34, pp. 7019-7031, 1995.
2. Winker, D. M., Couch, R. H., and McCormick, M. P., An overview of LITE: NASA's Lidar In-space Technology Experiment, *Proc. IEEE*, Vol. 84, 164-180, 1996.
3. Winker, D. M., Pelon, J., and McCormick, M. P., The CALIPSO mission: Spaceborne lidar for observation of aerosols and clouds, *Proc. SPIE*, Vol. 4893, 1-11, 2002.
4. Vaughan, M., An Algorithm for Retrieving Lidar Ratios at 1064 nm from Space-based Lidar Backscatter Data, in *Laser Radar Technology for Remote Sensing,* Christian Werner, Ed., *Proc. SPIE*, Vol. 5240, 104-115, 2004.
5. McGill, M. J., Hlavka, D. L., Hart, W. D., Welton, E. J., and Campbell, J. R., Airborne lidar measurements of aerosol optical properties during SAFARI-2000, *Journal of Geophysical Research*, Vol. 108, 2003.
6. Dennis, J. E. and Schnabel, R. B., *Numerical Methods for Unconstrained Optimization and Nonlinear Equations*, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, 1996.
7. Sasano, Y. and Browell, E. V., Light scattering characteristics of various aerosol types derived from multiple wavelength lidar observations, *Applied Optics*, Vol. 28, 1670-1679, 1989.
8. Liu, Z., Voelger, P., and Sugimoto, N., Simulations of the observation of clouds and aerosols with the Experimental Lidar in Space Equipment system, *Applied Optics*, Vol. 39, 3120-3137, 2000.
9. Winker D. M., Accounting for Multiple Scattering in *Retrievals from Space Lidar, in 12th International Workshop on Lidar Multiple Scattering Experiments*, Christian Werner, Ulrich G. Oppel, Tom Rother; Eds, *Proc. SPIE*, Vol. 5059, 128-139, 2003.
10. Kuehn, R. E., Winker, D. M., and Vaughan, M., Applying a Range Dependent Multiple Scattering Correction to Retrievals of Extinction Using LITE Data, in *Proceedings of the 22nd International Laser Radar Conference*, ESA SP-561 (current proceedings, in press), 2004.