Characterization of Optical Extinction Profiles Using Raman Lidar Techniques

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1. Introduction

The presence of aerosol particles and cloud droplets in the atmosphere strongly affects the propagation of light through the atmosphere. These particles have an important impact on the Earth's climate and the operation of electro-optical sensors. A useful tool for measuring optical extinction due to aerosols is a Raman lidar. Raman lidars also have the capability to measure atmospheric temperature and humidity. The lidars we have at Penn State also have the capability to measure ozone in the lower troposphere. This profile can then be used to determine the extinction due to ozone absorption. The present lidar system provides extinction measurements at UV and visible wavelengths. The technique has been verified over a horizontal path with independent measurements of the particle size distribution and provides measurements with a high degree of temporal resolution.

The current lidar system employs Raman scatter from a ND:YAG laser beam from the 2^{nd}, 3^{rd}, and 4^{th} harmonics at 532, 355, and 266 nm to obtain the profiles of optical extinction. The measurements have been made using the molecular nitrogen profiles at 607, 387, and 285 nm, which are the first Stokes vibrational Raman shifts from the ND:YAG laser. The rotational Raman scatter at 530 nm has also been used to obtain optical extinction profiles. This paper will begin with a description of the two Raman lidars used to acquire the data to be presented. Next, the details of our analysis will be discussed. Then, the capabilities of the system will be illustrated with several examples of data taken during two field campaigns.

2. Background

The Raman lidar technique is a powerful way of measuring a variety of atmospheric properties. At Penn State we currently have two Raman lidars, LAMP and LAPS. The LAMP system began operation in 1991 and has been used to make a variety of atmospheric measurements[1]. In their current configuration, both LAMP and LAPS are capable of measuring water vapor, temperature, ozone, and extinction profiles in the troposphere. The LAPS lidar system is a second generation version of LAMP[2]. The LAPS system has a much greater return signal, due in part to a larger receiving telescope and a more powerful laser. In addition, the system was designed as an operational prototype with numerous automated systems. This makes its operation easier and somewhat more reliable and stable. Table 1 summarizes the specifications of the two systems.

Table 1. Specifications for the Penn State LAMP and LAPS lidar systems.

	LAMP	LAPS
Transmitter	Continuum NY-82 ND:YAG laser 20 Hz 400 mJ at 532 nm 80 mJ	Continuum 9040 ND:YAG laser 30 Hz 600 mJ at 532 nm 120 mJ at 266 nm
Receiver	0.41 m diameter telescope	0.6 m diameter telescope
Detector	7 PMT channels 528, 530 nm - Temperature 660, 607 nm - Visible Water Vapor 295, 284 nm - UV water Vapor 277, 284 nm - Ozone	7 PMT channels 528, 530 nm - Temperature 660, 607 nm - Visible Water Vapor 295, 284 nm - UV water Vapor 277, 284 nm - Ozone
Data System	100 MHz count rate 75 m range resolution	100 MHz count rate 75 m range resolution

For both of the systems, water vapor profiles are determined by taking the ratio of the vibrational Raman return from water vapor to the vibrational Raman return from molecular nitrogen. The water vapor measurements are made at both ultraviolet and visible wavelengths using the 295/284 and 660/607 ratios. The UV measurement is corrected for ozone absorption by measuring the O_2 vibrational Raman signal. The ratio of the molecular oxygen to the molecular nitrogen signal provides a Raman/DIAL measurement of the tropospheric ozone density[3]. The system uses the temperature dependence of rotational Raman scattering to obtain profiles of atmospheric temperature using the ratio of 530/528 signals[4]. These measurements provide useful background meteorological data for studying changes in optical extinction. The aerosol extinction coefficient is determined by observing departures from the expected gradient of the Raman lidar profiles. The analysis used for this method will be presented later.

The Raman lidar data can also be used to measure the optical extinction at 284, 387, 530, and 607 nm. The lidars measure the scattered light corresponding to the 1st Stokes vibrational Raman transition for molecular nitrogen to obtain a profile of atmospheric nitrogen. Any deviation in this profile from the gradient of the molecular atmosphere is due to aerosol extinction. Figure 1 shows a schematic representation of this. The figure shows the range corrected signals for a Raman shifted nitrogen channel and a corresponding elastic backscatter channel. The figure demonstrates when there is a large increase in the backscatter there is a deviation in the slope of the molecular nitrogen Raman signal. We are trying to measure the change in this slope, which is proportional to the exponential attenuation term in the Raman lidar equation. Figure 2 shows an example of the raw photon count profiles from LAPS on 9 October 1996 while it was aboard the U.S.N.S. Sumner. The profiles rapidly increase to a maximum as the laser fully enters the field of view of the telescope at approximately 1000 m [5]. Above this altitude the profile shows an altitude region where the slope of the profile is much greater than the expected gradient for the molecular atmosphere. This increased slope is caused by an increase in the optical extinction due to scattering particles.

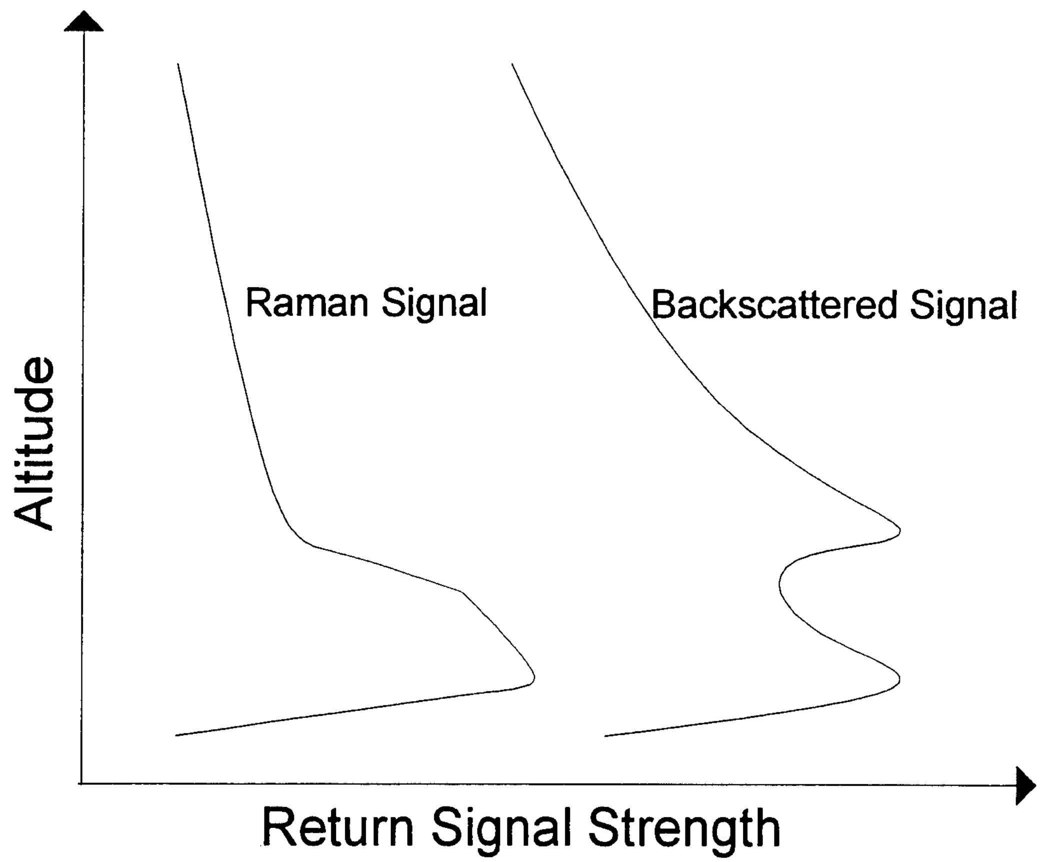

Figure 1. This figure depicts the change in the slope of the Raman signal as the lidar hits an intense scattering layer.

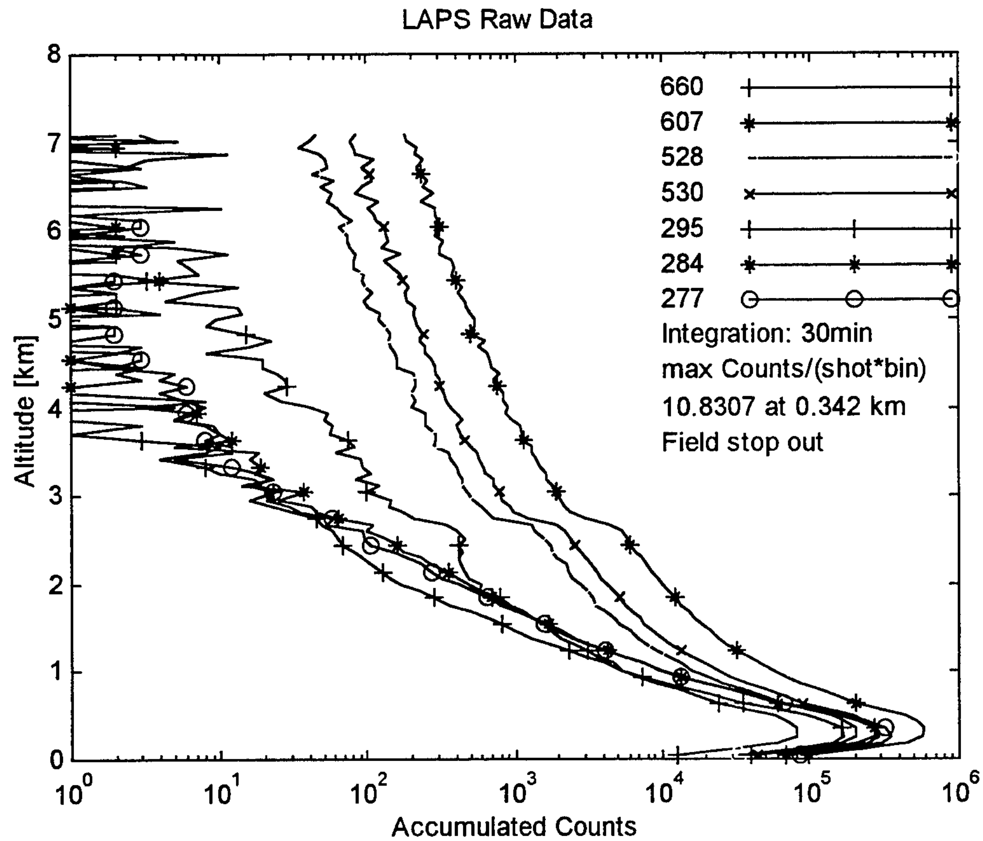

Figure 2. This figure shows a plot of the raw data from LAPS taken on 9 October 1996 at 03:16 GMT aboard the U.S.N.S. Sumner. The profiles show a region of heavy aerosol extinction.

3. Analytical Equations

It is possible to derive a relation for the extinction coefficient from the Raman lidar equation [6,7,8,9]. The Raman lidar equation is given as,

$$P(z) = \frac{\xi(z)}{z^2} N(z) \frac{\partial\sigma}{\partial\Omega} \exp\left(- \int_0^z \left(\alpha_0^{mol}(z) + \alpha_R^{mol}(z) + \alpha_0^{aer}(z) + \alpha_R^{aer}(z) \right) dz \right) , \qquad (1)$$

where P(z) is the received signal power at the Raman shifted wavelength, k is an instrumental constant, ξ(z) is the telescope form factor, N(z) is the molecular number density, $\partial\sigma/\partial\Omega$ is the Raman backscattering cross section, α_0^{mol} and $\alpha_{\mathrm{R}}^{\mathrm{mol}}$ are the molecular extinction coefficients for the transmitted and Raman scattered wavelengths, α_0^{aer} and $\alpha_{\mathrm{R}}^{\mathrm{aer}}$ are the aerosol extinction coefficients for the transmitted wavelength and Raman scattered wavelengths, and z is the range. The aerosol extinction coefficient can be determined from (1) and is given by,

$$\alpha_R^{aer} = \frac{d}{dz}\left[\ln\frac{N_R(z)}{P_R(z)\cdot z^2}\right] - \alpha_0^{mol}(z) - \alpha_R^{mol}(z) - \alpha_0^{aer}(z)\ . \qquad (2)$$

Only data above the altitude where the laser is completely in the field of view of the telescope is used in this analysis. The molecular number density and extinction coefficients are determined from a standard atmosphere and the known molecular scattering cross section. The aerosol extinction coefficient for the transmitted wavelength of 532 nm is determined from the rotational Raman signal. The received signal for the rotational Raman channels is also given by (1), and in this case the extinction coefficients of the transmitted and backscattered Raman wavelengths are assumed to be the same because they are only separated by 2 nm. The 532 nm aerosol extinction coefficient is then determined with,

$$\alpha_{532}^{aer} = \frac{d}{dz}\left[\frac{1}{2}\ln\frac{N(z)}{P_{530}(z)\cdot z^2}\right] - \alpha_{532}^{mol}(z)\ . \qquad (3)$$

This value of α_{532}^{aer} is then used as the value of α_0^{aer} in (2) so that α_R^{aer} can be calculated. This procedure assumes that the optical depth is not too great and that multiple scattering can be neglected.

At UV wavelengths a rotational Raman signal is not available so only the vibrational Raman signals are used. The extinction due to ozone absorption is determined with the ozone profile measured by the lidar. The difference between the extinction coefficients between the transmitted and received wavelengths is accounted for with a power law relationship, which assumes the same wavelength dependence for scattering as was found between 532 and 607 nm. The resulting equation is given as,

$$\alpha_{284}^{aer} = \frac{\frac{d}{dz}\left[\ln\frac{N(z)}{P_{284}(z)\cdot z^2}\right] - \left(\alpha_{266}^{mol} + \alpha_{284}^{mol}\right) - (\sigma_{266}^{O_3} + \sigma_{284}^{O_3})\cdot N_{O_3}(z)}{1+\left(\frac{284}{266}\right)^k}\ , \qquad (4)$$

where $\sigma_{266}^{O_3}$ and $\sigma_{284}^{O_3}$ are the ozone absorption cross sections for the transmitted and Raman scattered wavelengths, $N_{O_3}(z)$ is the ozone density profile, and k is determined by the wavelength dependence of particle scattering.

4. Results

Over the past years our research group has gathered data with the two lidar systems under a variety of conditions and locations. The LAMP lidar was used in September 1995 to measure the particle size distributions and extinction properties of coastal aerosols in the Coastal Aerosol Scattering Experiment I (CASE I) campaign conducted at NASA's Wallops Island test facility. The lidar was operated in vertical and horizontal modes. In the vertical operating mode, the lidar measured water vapor, temperature, and ozone profiles simultaneously with other lidar and balloon sensors[10]. In the horizontal operating mode, the aerosol extinction coefficient was determined from the Raman lidar profiles and from particle size measurements made with a bistatic lidar. The bistatic lidar consists of a camera that focuses an image of the horizontal laser beam onto a linear photodiode array. This allows for the measurement of the scattering intensity from the aerosol particles at a number of angles. Data from the ratio of the cross polarization scattering phase function is inverted to determine the particle size distribution[11]. The aerosol extinction coefficient that corresponds to this distribution is then calculated. A comparison of the extinction values determined with the two techniques is given in Table 2. The two extinction coefficients agree within the experimental error for the methods.

Table 2. Comparison of aerosol extinction coefficients measured with a Raman lidar and a bistatic lidar.

Wavelength	Extinction from Raman Lidar	Extinction from Bistatic Lidar
532 nm	0.259 (km^{-1})	0.279 (km^{-1})
607 nm	0.209 (km^{-1})	0.243 (km^{-1})

During the Fall of 1996 LAPS was deployed aboard the USNS Sumner for its first field tests. The system performed quite well and provided several hundred hours of data. One example of an extinction profile from this data is shown in Figure 3. This profile of optical extinction for 532 nm was obtained on 9 October 1996. The profile shows a several layers of strong extinction. At the same time we determined the extinction coefficient at 284 nm, which is shown in Figure 4. With the LAPS lidar system we have the capability to make measurements of the extinction coefficient with high time resolution. An example of this capability is shown in Figure 5.

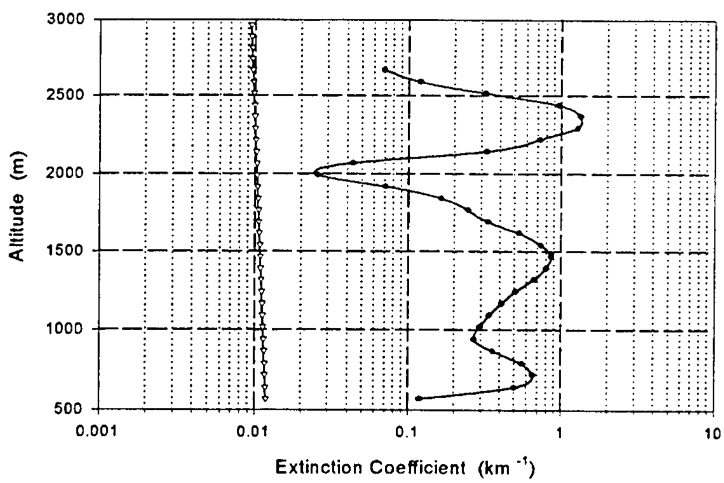

Figure 3. This Figure shows the optical extinction for 532 nm measured vertically with LAPS on 9 October 1996 at 04:16 GMT. The data was acquired with a 30 minute integration. The molecular extinction profile is shown for reference.

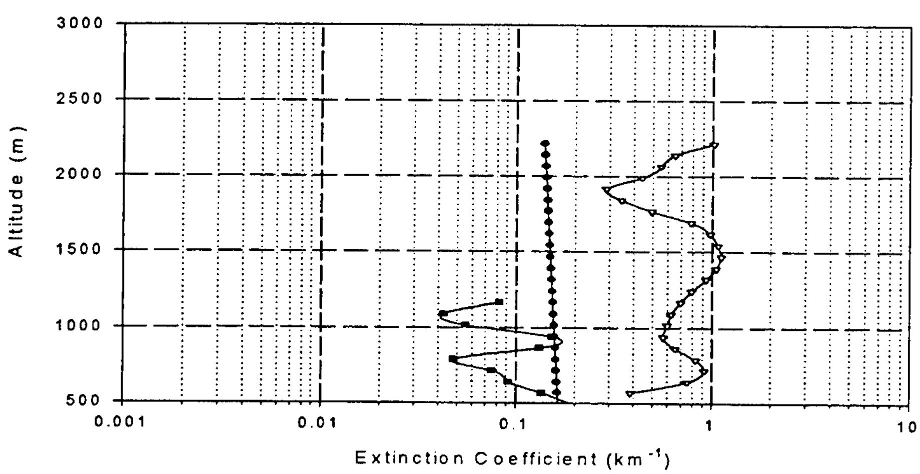

Figure 4. This Figure shows the optical extinction at 284 nm measured vertically with LAPS on 9 October 1996 at 04:16 GMT. The data was acquired with a 30 minute integration. The profiles left to right are ozone extinction, molecular extinction, and aerosol extinction.

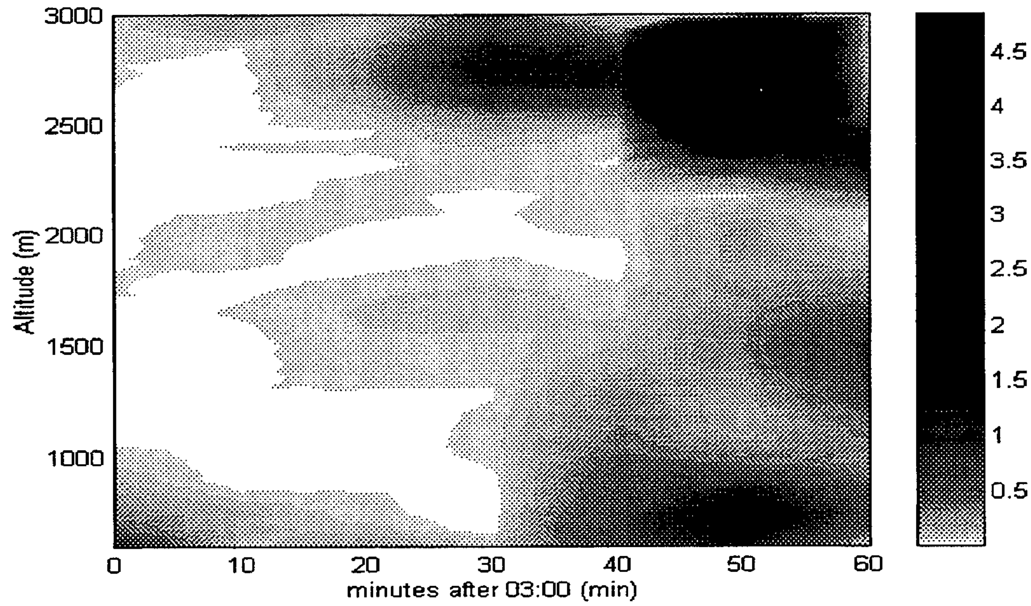

Figure 5. This Figure shows a time series of the 532 nm extinction coefficient starting at 03:00 EDT on 9 October 1996 from LAPS aboard the U.S.N.S. Sumner. The intensity scale is in km^{-1} .

4. CONCLUSIONS

The measurements presented in this paper have demonstrated the utility of the Raman lidar technique in measuring optical extinction. These measurements have been independently verified with the bistatic lidar measurements. The vertical profiles showed that this technique can be successfully employed to measure extinction coefficients in the lower troposphere for aerosols. In addition we have shown that the time resolved measurements of extinction provide a powerful way of studying aerosols in the atmosphere.

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