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Optical extinction from Raman lidar measurements

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ABSTRACT

Lidar can be an effective tool for measuring the optical extinction along atmospheric paths. The Penn State University LAMP lidar recently participated in a series of atmospheric measurements at NASA's Wallops Island test facility in September 1995. The LAMP lidar was operated with the beam pointed along horizontal and vertical paths. This paper discusses the determination of atmospheric extinction coefficients with Raman lidar measurements. Lidar measurements show the presence of aerosol layers in the atmosphere as a marked departure from the expected molecular profile for a Raman lidar signal. The horizontal extinction coefficient can be determined directly from the range corrected slope of a horizontal Raman profile. The vertical extinction coefficient can be determined by comparing the gradient of the Raman lidar profile with the gradient of the molecular atmosphere. The LAMP lidar has also been used with a bistatic receiver to measure the scattering phase function which can then be used to calculate the aerosol particle size distribution and the optical extinction coefficient. This paper will discuss the experimental method and present several representative examples from Raman lidar measurements. The extinction coefficients determined from the Raman lidar data will then be compared with the extinction coefficients determined from the bistatic receiver data.

Keywords: lidar, Raman lidar, optical extinction, troposphere, aerosols.

1. INTRODUCTION

The measurements described in this paper were taken with Penn State University's LAMP (Lidar Atmospheric Measurements Program) lidar. A summary of the LAMP system's characteristics is given in Table I. The system began operation in 1991 and has been used to make a variety of atmospheric measurements[1]. In its current configuration, the lidar is capable of measuring water vapor, temperature, ozone, and extinction profiles in the troposphere. 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 ultra violet 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 this signal to the molecular nitrogen signal provides a Raman/DIAL measurement of the tropospheric ozone density[2]. The system uses the temperature dependance of rotational Raman scattering to obtain profiles of atmospheric temperature using the ratio of 530/528 signals[3]. These measurements provide useful background meteorological data for studying the extinction effects. The aerosol extinction coefficient is determined by observing departures from the expected gradient of the Raman lidar profiles. The analysis of this method will be presented in a later section.

The LAMP lidar was used in September 1995 to measure the particle size distributions and extinction properties of coastal aerosols in the CASE I (Coastal Aerosol Scattering Experiment 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 [4]. 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 receiver. The bistatic receiver measures the scattering phase function from the aerosol particles. The particles are assumed to be described by the Mie theory for particle scattering and the data is inverted to determine the tri-modal lognormal particle size distribution. This distribution is then used to calculate the aerosol extinction coefficient [5]. The two measurement techniques can then be compared and have been shown to agree within the experimental error.

Table 1. Summary of LAMP lidar characteristics

Transmitter	Continuum NY-82 ND:YAG laser, 20 Hz 400 mj at 532 nm 80 mj at 266 nm
Receiver	0.41 m diameter telescope
Detector	7 PMT channels 528 and 530 nm -- Rotational Raman Temperature 660 and 607 nm -- Vibrational Raman Water Vapor 295 and 284 nm -- Daytime Water Vapor 277 and 284 nm -- Raman/DIAL Ozone
Data System	100 MHz count rate 75 m range resolution

2. OPTICAL EXTINCTION DETERMINED FROM RAMAN LIDAR

Several research groups have shown that it is possible to obtain profiles of the aerosol extinction coefficient from Raman lidar measurements[6,7]. The LAMP lidar uses the Raman technique to obtain profiles of water vapor and temperature. LAMP measures 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 an example of three simultaneous raw photon count profiles from the LAMP lidar on 19 September 1995 at NASA's Wallops Island test facility. The profiles rapidly increase to a maximum as the laser fully enters the unobscured field of view of the telescope at approximately 800 m. 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 aerosol particles.

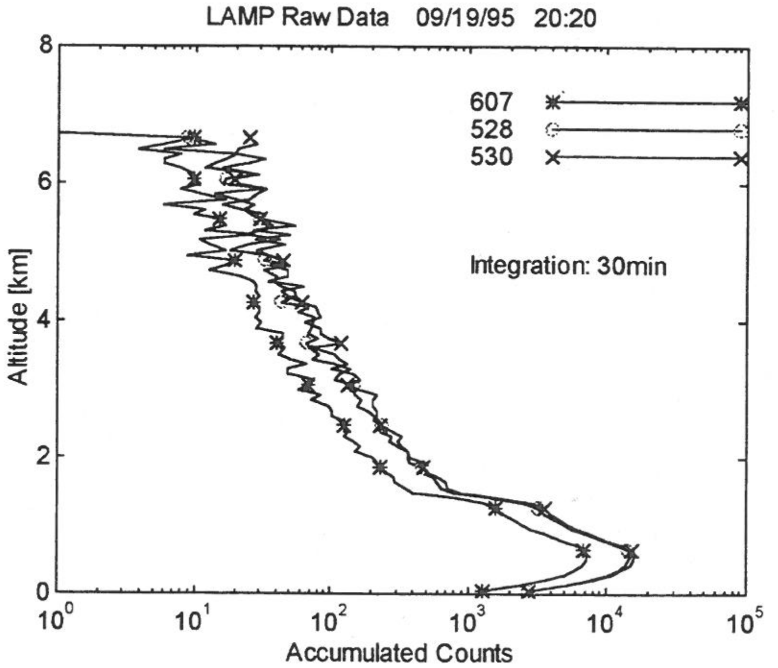

Figure 1. This figure shows a plot of the raw data of the LAMP lidar taken on 19 September 1995 at 20:20 EDT in Wallops Island, Virginia. The profiles show two regions of heavy aerosol extinction.

It is possible to derive a relation for the extinction coefficient from the Raman lidar equation. The Raman lidar equation is given as,

$$P_R(z) = k\frac{\xi(z)}{z^2}N_R(z)\frac{\partial\sigma}{\partial\Omega}\exp\left(-\int_0^z\left(\alpha_0^{mol}(z)+\alpha_R^{mol}(z)+\alpha_0^{aer}(z)+\alpha_R^{aer}(z)\right)dz\right) \quad , \tag{1}$$

where $P_R(z)$ is the received signal power at the Raman shifted wavelength, k is an instrumental constant, $\xi(z)$ is the telescope form factor, $N_R(z)$ is the molecular number, $\partial\sigma/\partial\Omega$ is the Raman backscattering cross section, α_0^{mol}, α_R^{mol} are the molecular extinction coefficients for the transmitted laser wavelength and Raman scattered wavelength, α_0^{aer}, α_R^{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,

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

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 signals. The received signal for the rotational Raman channels is also given by (1). In this case the transmitted wavelength and Raman wavelength aerosol extinction coefficients are assumed to be the same because they are only separated by a few nm. The 532 nm aerosol extinction coefficient is then determined with,

$$\alpha_{532}^{aer} = \frac{d}{dz}\left[\frac{1}{2}\ln\frac{N(z)}{(P_{528}(z)+P_{530}(z))z^2}\right] - 2\alpha_{532}^{mol}(z) \ . \tag{3}$$

The return signals from the 528 nm and 530 nm channels are added together in order to minimize the temperature sensitivity of the rotational Raman scattering cross section. This value 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.

3. EXPERIMENTAL RESULTS

In the CASE I experiment, atmospheric electro-optical properties were measured simultaneously with background meteorological conditions. This enables the study of growth and dissipation phases of clouds and aerosols. Aerosol extinction values determined from the Raman lidar data and the bistatic receiver were compared to verify the Raman lidar extinction technique. Figure 2 shows an example of the extinction coefficient determined using the Raman lidar technique with the lidar operating in the horizontal mode. The extinction coefficient is determined in the region between the range where the laser is completely in the field of view of the telescope and the hard target at the end of the 3.3 km path. Figure 3 shows a plot of a scattering phase function taken simultaneously with the bistatic receiver. The bistatic receiver 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 [8]. The aerosol extinction coefficient that corresponds to this distribution is then calculated. At 532 nm the extinction coefficient determined from the Raman signal was 0.26 km^{-1} compared to 0.28 km^{-1} from the size distribution. At 607 nm the values are 0.21 and 0.24 km^{-1}. The two extinction coefficients agree within the experimental error for both methods.

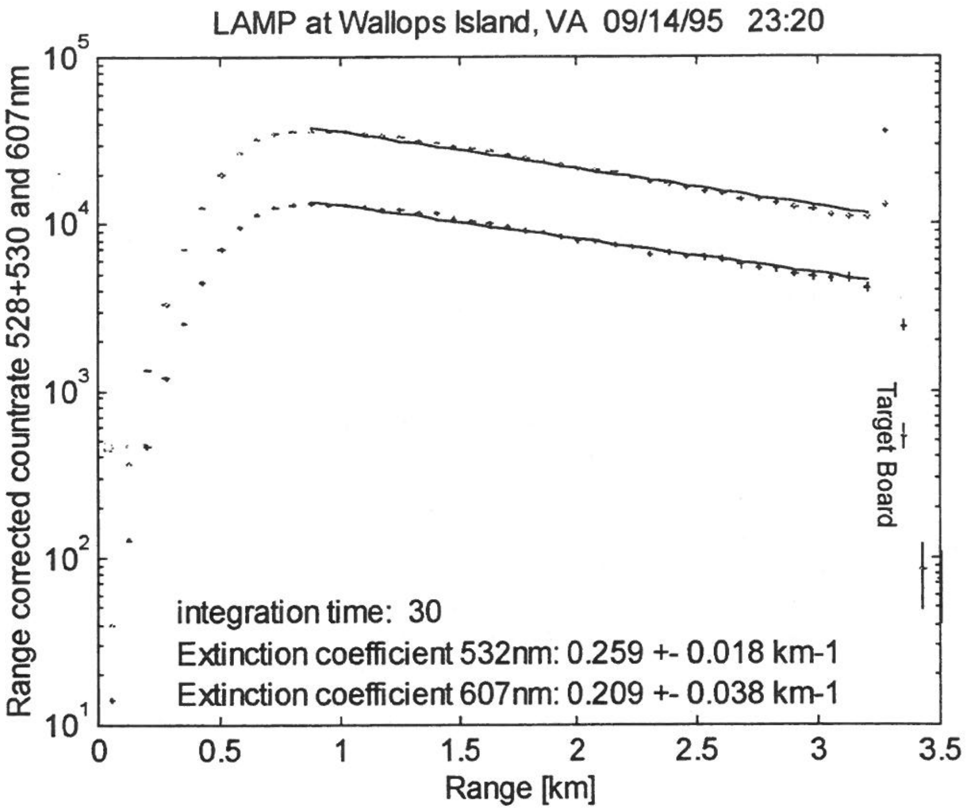

Figure 2. Optical extinction measured over a 3.3 km horizontal path on 14 September 1995 at 23:20 EDT in Wallops Island, Virginia. The measured signal is corrected for range dependance and molecular scattering. The slope of the profile, beyond the telescope form factor, provides a direct measure of the extinction coefficient.

The LAMP lidar also measured the aerosol extinction coefficient while operating in the vertical mode. An example of the extinction coefficient determined for the 532 nm and 607 nm wavelengths is shown in Figure 4. Both wavelengths show a large increase in the extinction coefficient at approximately 1 km. The profiles shown in Figures 5 and 6 result from an analysis of the raw data shown in Figure 1. Figure 5 shows in the extinction coefficient of a cloud at 1.4 km. An hour later the extinction coefficient, shown in Figure 6, had decreased by a factor of three.

4. CONCLUSIONS

In this paper the determination of the aerosol optical extinction coefficient from Raman lidar data has been described. The method can use the data from rotational and vibrational Raman scattering to obtain vertical or horizontal profiles of the extinction coefficient. Several examples from the CASE I experiment have been used to show the capability of the technique. The horizontal values determined with the Raman technique compared favorably with independent measurements using a bistatic lidar receiver. The vertical profiles showed that this technique can be successfully employed to measure extinction coefficients in the lower troposphere for light to moderate aerosol layers.

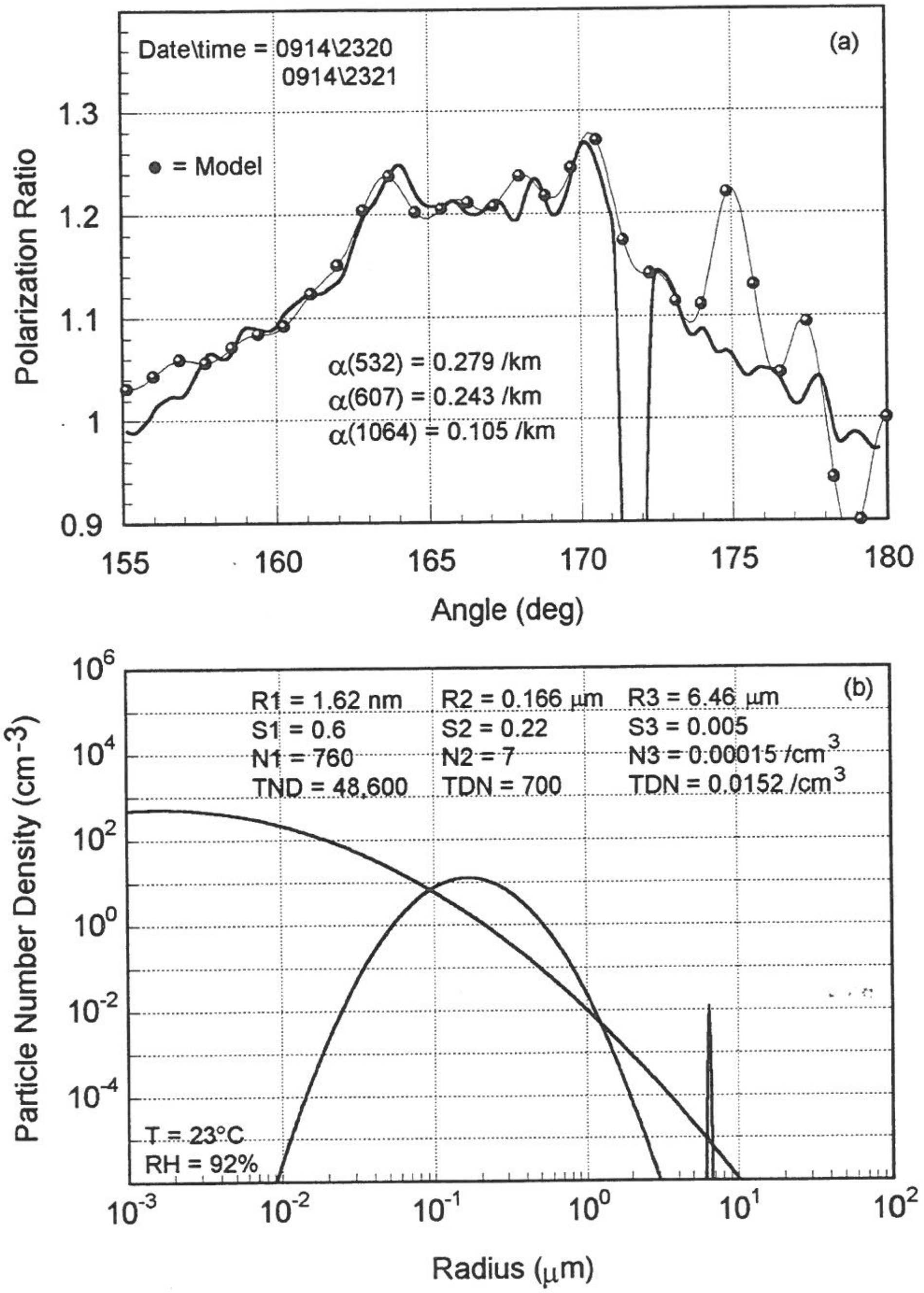

Figure 3. (a) The polarization ratio determined with the bistatic receiver on 14 September 1995 at 23:20 EDT in Wallops Island, Virginia. This shows a best fit of a spherical model, using the distribution in (b), with the data. Also shown are the calculated extinction coefficients.

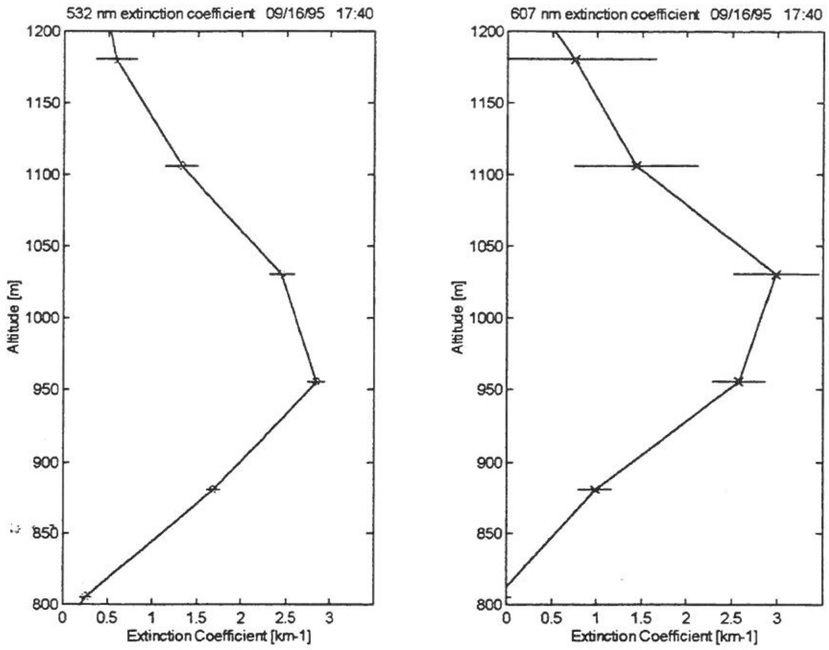

Figure 4. Vertical profiles of the aerosol extinction coefficient for 532 nm and 607nm determined from Raman lidar measurements using the LAMP lidar on 16 September 1995 at 17:40 EDT in Wallops Island, Virginia.

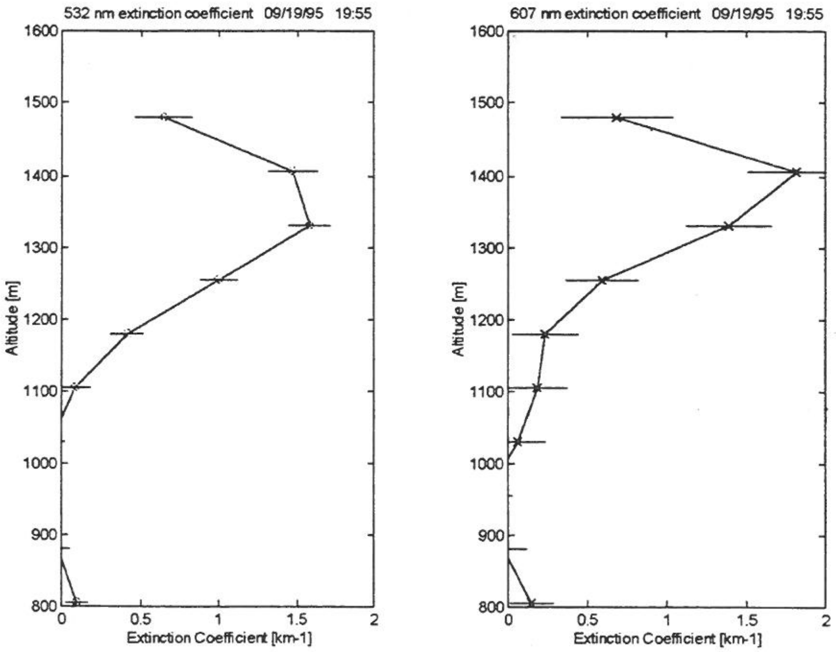

Figure 5. Vertical profiles of the aerosol extinction coefficient for 532 nm and 607nm determined from Raman lidar measurements using the LAMP lidar on 19 September 1995 at 19:55 EDT in Wallops Island, Virginia.

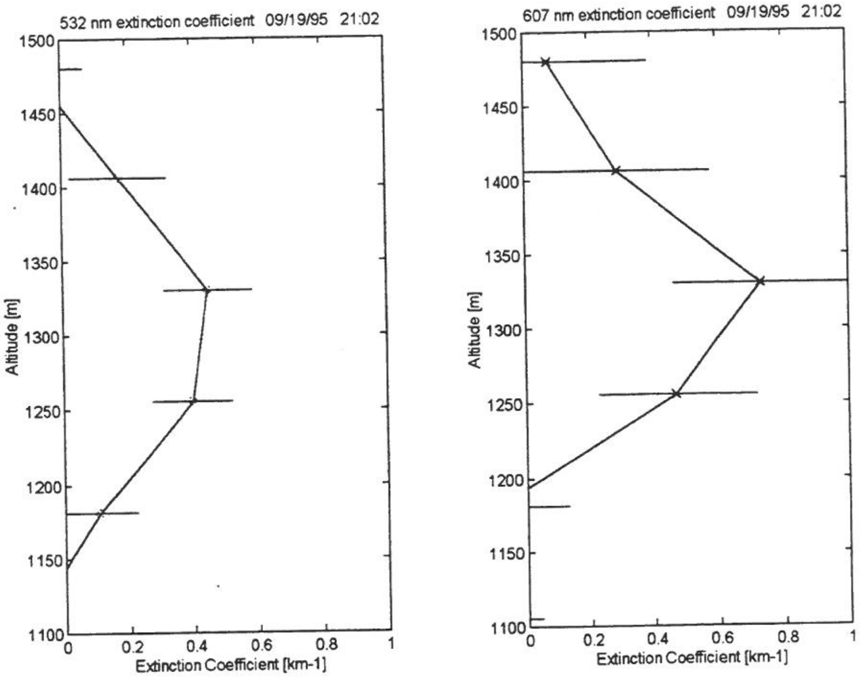

Figure 6. Vertical profiles of the aerosol extinction coefficient for 532 nm and 607nm determined from Raman lidar measurements using the LAMP lidar on 19 September 1995 at 21:02 EDT in Wallops Island, Virginia.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. C. R. Philbrick, "Raman Lidar Measurements of Atmospheric Properties," Atmospheric Propagation and Remote Sensing III, SPIE Vol. 2222, pp. 922-931, 1994.

2. F. Balsiger and C. R. Philbrick, "Comparison of lidar water vapor measurements using Raman scatter at 266 nm and 532 nm," SPIE Atmospheric Sensing & Forecasting, these proceedings, 1996.

3. P. A. T. Haris, "Pure Rotational Raman Lidar for Temperature Measurements in the Lower Troposphere," PhD Dissertation, Department of Electrical Engineering, Penn State University, 1995.

4. R. Harris, F. Balsiger, C. R. Philbrick, "Comparison of lidar water vapor measurements using Raman scatter at 266 nm and 532 nm," Proc. 1996 International Geoscience and Remote Sensing Symposium, Vol. III, pp. 1826-1829, 1996.

5. T. D. Stevens and C. R. Philbrick, "Particle Size Distributions and Extinction Determined By a Unique Bistatic Lidar Technique," Proc. 1996 International Geoscience and Remote Sensing Symposium, Vol. II, pp. 1253-1256, 1996.

6. A. Ansmann, U. Wandinger, M. Riebesell, C. Weitkamp, and W. Michaelis, "Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar," Applied Optics, Vol. 31, No. 33 pp. 7113-7131, 1992.

7. C.R. Philbrick, M. D. O'Brien, D. B. Lysak, T. D. Stevens, and F. Balsiger, "Remote Sensing by Active and Passive Optical Techniques," Proc. of NATO/AGARD Meeting on Remote Sensing, Toulouse France, 22-25 April 1996.

8. T. D. Stevens, "Bistatic Lidar Measurements of Lower Tropospheric Aerosols," PhD Dissertation, Department of Electrical Engineering, Penn State University, 1996.