ATMOSPHERIC OPTICAL EXTINCTION MEASURED BY LIDAR

C. Russell Philbrick
Daniel B. Lysak, Jr
Applied Research Laboratory
Penn State University
PO Box 30
State College PA 16804, USA

SUMMARY

Two independent lidar techniques, one using Raman scatter in a monostatic configuration and one using the polarization ratio of the scattering phase function in a bistatic configuration have been developed to determine the optical properties in the lower atmosphere. The direct backscatter measured at the transmit wavelength of a monostatic lidar has been found to have limited utility in describing the important parameters because the measurement is a mixture of signals from molecular and particle scattering. A bistatic lidar technique has been used to demonstrate that useful information on number, size and distribution of particles is contained in measurements of the polarization ratio of the scattering phase function. An independent Raman lidar technique can be used to provide measurements of the molecular scattering profiles at several wavelengths through the lower atmosphere. The departures of the signal profile from the molecular density gradient then provide a direct measure of the optical extinction. The optical extinction profiles at visible and ultraviolet wavelengths are routinely measured today using Raman lidar.

INTRODUCTION

We have been able to demonstrate that it is possible to measure the optical extinction and describe changes in the particle number, size, and distribution width of the optical scattering components using a bistatic lidar in the lower atmosphere [1, 2, 3]. The measurements were made using signals from a bistatic lidar technique which measures the polarization ratio of the scattering phase function. Additionally, the profiles of molecular species measured by Raman lidar techniques directly provide a measurement of the optical extinction from the gradients in the profile [4,5,6]. The Raman return signals scattered of the N_2 and O_2 components in the atmosphere differ from the density scale height only by the extinction due to scattering losses along the transmitted and received paths. The factors which cause the extinction are particle scattering, molecular scattering and absorption. The scattering losses expected from molecular extinction are known directly from the density scale height and the molecular scattering cross sections of nitrogen and oxygen. The scattering losses from the particle component of the atmosphere can be separated by examining the gradient in the signal compared to the density gradient, thus providing extinction profiles of the particle scattering component of the lower atmosphere. The technique is able to provide the extinction profiles through clouds, as long as any signal remains to be detected. Many cases of cloud measurements have been obtained which have optical extinction coefficients up to the ranging up to 10 km^{-1}.

The profiles from the rotational Raman scattered signal at 530 nm (from the 532 nm transmitted beam of the 2nd harmonic of the Nd:YAG laser) provide a direct measure of the atmospheric aerosol extinction component at mid-visible wavelengths. The vibrational Raman 1st Stokes scatter signal from molecular nitrogen at 607 nm provides the simultaneous extinction at a second wavelength, which is sensitive to a slightly different size particle. The same measurement can be made from the rotational Raman scatter at other laser wavelengths from the 3rd or 4th harmonics of the laser transmitter (355 nm and 266 nm for the Nd:YAG laser). Example cases are used to describe the atmospheric optical properties using three wavelengths, 285, 530 and 607 nm.

OPTICAL EXTINCTION FROM BISTATIC LIDAR SCATTERING PHASE FUNCTION

Single ended remote sensing instruments, whether using lasers, radars, or microwaves, have difficulties determining absolute extinction from

Paper presented at the RTO SET Symposium on "E-O Propagation, Signature and System Performance Under Adverse Meteorological Conditions Considering Out-of-Area Operations", held at the Italian Air Force Academy, Naples, Italy, 16-19 March 1998, and published in RTO MP-1.

backscattered signals along a propagation path. This is due to the large variations in the ratio of the extinction (forward scattering) to the backward scattering components from different particle size distributions [7]. The bistatic linear array receiver was developed to provide useful information on the scattering phase function of the aerosols [1,2,3]. The bistatic remote receiver utilizes a linear photodiode array to image the radiation scattered from any high power CW or pulsed laser system. By observing the angular scattering variation along a horizontal path, where the distribution of scattering particles is relatively uniform, additional information that is obtained from the scattering angle phase function can. We have demonstrated a new technique to estimate particle density, size and distribution widths (of spherical scatters) by use of the unique information contained in the polarization ratio of the scattering phase function versus angle obtained from the ratio of signals parallel and perpendicular to the scattering plane.

Previous experiments with the bistatic lidar technique have used a scanning laser beam to attempt to reconstruct a scattering phase function from tropospheric aerosols [8,9,10]. The measurement technique presented in this paper does not attempt to reconstruct a scattering phase function of the particles. Instead, a ratio is obtained from the image of the scattering signal of two orthogonal polarization components as a function of angle, one in the scattering plane and one perpendicular to the scattering plane along a horizontal path, as shown in Figure 1. The use of a ratio cancels the effects of many measurement problems, including detector linearity and extinction differences due to different path lengths for each scattering angle. Figure 1 demonstrates the ability of the bistatic receiver to simultaneously image the backscattered radiation from an angle range of 155° to 180°, where the scattering function is most sensitive to the size of the particles. The assumption of a uniform horizontal path was verified with horizontal extinction profiles from the Raman lidar analysis during each data set [4,5]. The Penn State LAMP lidar [6] was alternately operated on a horizontal path and a vertical path. The LAMP lidar collected rotational Raman temperature profiles, vibrational Raman water vapor profiles, vibrational Raman nitrogen profiles, and aerosol/molecular scattering profiles at the fundamental laser wavelength of 532 nm, while the bistatic detector measured the angular scattering. The first tests of this measurement technique were conducted in September 1995, during the CASE I (Coastal Aerosol Scattering Experiment) at Wallops Island, Virginia. This location was chosen for its humid coastal/marine environment and for an unobstructed 3.28 km horizontal path over a salt marsh. One of the goals of this research was to determine how well Mie theory [11], with a lognormal distribution of scatterers would describe actual aerosol data, in a humid coastal/marine environment [12]. Analysis of the data was made using a 9 parameter optimization fit of the polarization ratio versus angle from a model of polarization ratio from Mie scattering theory with trimodal lognormal size groups defined by size, width and number density in each group. The molecular scattering component had to also be added to the aerosol distribution model to obtain a satisfactory set of aerosol fit parameters. A polarizer was used on the receiver to measure the cross polarization to estimate the amount of multiple scattering and nonsphericity of the particles in the scattering volume. Results, which can be represented by trimodal lognormal size distributions, were obtained from both clear and hazy/misty nights. Extinction calculated from the size distributions has been compared with extinction from the Raman lidar at two different wavelengths. On calm evenings with high humidity and decreasing temperature, the inversions also show increasing particle sizes consistent with radiation fog formation. The results show remarkable agreement with a tri-modal aerosol distribution when using a spherical scattering model (Mie theory).

The measurements were made on a horizontal path under low wind and stable conditions so that the particle distribution should have been uniform as a function of angle. The analysis for the experiments performed required the assumption that the particle size and density were stable for more than 15 seconds, the minimum time to obtain a data set, and uniform over a scale of about 500 meters, the path corresponding to the range of scattering angles used, 150 to 175°. The magnitude of the scattered signal was nearly constant over the range of angles because the increase in surface brightness due to compression of the image on the detector off-sets the $1/R^2$ decrease from the greater distance.

An example of the bistatic measurement technique is shown in Figure 2a, with the best fit of the model, and the corresponding trimodal distribution in Figure 2b. The time sequence of the changing

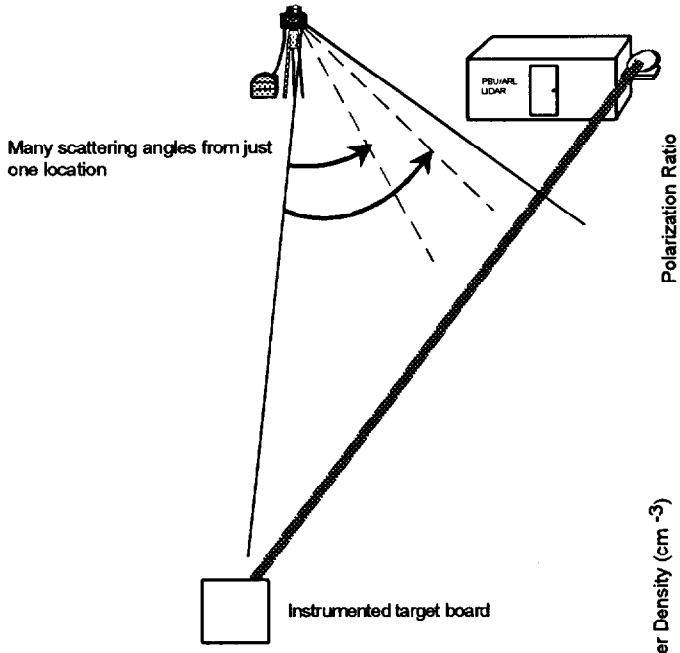

Figure 1. By operating in the horizontal mode, the bistatic lidar is able to collect radiation from many scattering angles, between 155° and 180°, from just one location.

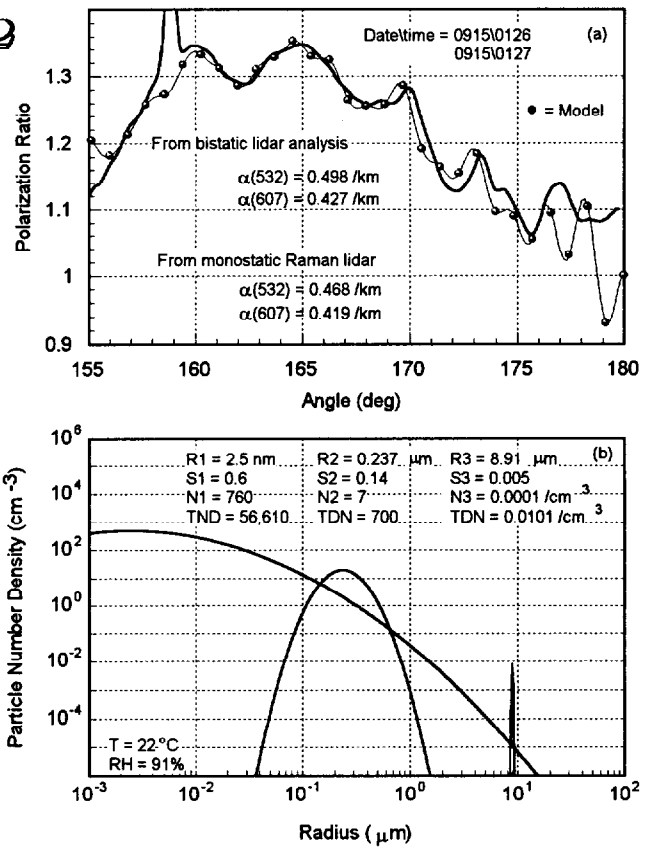

Figure 2. (a) An example of the bistatic lidar measurement technique, showing the best fit result from the ratio of the polarization scattering function versus angle from a Mie scattering theory model. The feature at 159° is due to a glint from an insect. The signal beyond 175° is ignored since these correspond to the last 2 km of the 3.2 km path. (b) The lognormal size distribution and density determined from the model fit to the data shown. The extinction values calculated from the particle distributions shown in (b) are listed in the panel (a) and compared with the simultaneously determined extinction from the Raman lidar analysis. The radiation fog mean radius grew from 6.46 μm to 8.91 μm in 2.5 hours (see Stevens dissertation [1] for several additional examples).

particle size was followed over a period of several hours during this evening while the temperature decreased and the extinction increased as a radiative fog formed. The second mode of the distribution was found to narrow in distribution width as it increased from a radius of 0.166 μm to 0.237 μm. At the same time the third mode increased from a radius of 6.46 μm to 8.91 μm. This data set is most striking because the model follows almost every contour in the data between 155° and 180° as seen in Figure 2a. Not only does the model fit the data almost perfectly as the mode radii increased, but the calculated extinction coefficients are also the same as those measured by the Raman lidar. The extinction values from the calculated size distribution and the extinction values calculated from the Raman lidar profile at wavelengths of 532 and 607 nm are shown in Figure 2a. Figure 2b shows the particle properties derived for the data in the upper panel.

OPTICAL EXTINCTION FROM RAMAN LIDAR

The molecular profiles from the Raman scatter signals provide direct measurements of the optical extinction. Figure 3 shows the visible and uv profiles measured when a thin cloud is present.

The signal from the fundamental transmitted wavelength at 532 nm exhibits a profile of combined molecular and particle scattering that is difficult to analyze for significant properties, except cloud height. However, analysis of the Raman signals can provide unique vertical profiles of the optical extinction.

The LAMP (Lidar Atmospheric Measurements Profiler) and LAPS (Lidar Atmospheric Profile Sensor) instruments use the molecular scattering properties of the species in the lower atmosphere to simultaneously measure profiles of ozone, water vapor, temperature, and optical extinction. The measurements can be made both daytime and nighttime because of the capability of the instrument to use the "solar blind" portion of the ultraviolet spectrum from the 4th harmonic of the Nd:YAG laser. The ozone profiles are obtained from a DIAL (Differential Absorption Lidar) analysis of the Raman shifted scatter of N_2 (285 nm) and O_2 (276 nm) which occur on the steep side portion of the Hartley absorption band of ozone. The water vapor profiles are obtained from the vibrational Raman scatter from the 2nd (532 nm) and 4th (266 nm) harmonics of the Nd:YAG laser. The temperature profiles are obtained from the rotational Raman profiles of the molecular nitrogen and oxygen components of the atmosphere.

The optical extinction profiles of the atmosphere are obtained from the gradients of the rotational Raman molecular profile and the N_2 vibrational Raman profiles measured at 530, 607 and 285 nm. The temporal resolution of the ozone and temperature profiles is about 30 minutes and the profiles of water vapor and optical extinction are obtained each minute. The wavelength dependent optical extinction can be used to describe changes in the particle size distribution as a function of altitude for the important small particles. These measurements can be interpreted to determine the air mass parameter and atmospheric optical depth.

Measurements of optical extinction are based upon gradients in the molecular profiles, using the N_2 vibrational Raman or a band of the rotational Raman lines. We have used the technique to measure the true optical extinction for clouds and aerosol layers. In order to calculate extinction due to aerosols from Raman lidar measurements, the following procedure is used:

1) Apply the range correction to the backscatter Raman shifted signal.
2) Correct for the attenuation due to molecular scattering on the way out at 532 nm and the Raman shifted wavelength on the way back to the lidar. The ground level molecular attenuation coefficients for 532 and 607 nm are known from the cross-sections for N_2 and O_2,

$$\alpha_{m532} = 0.013\ km^{-1} \qquad \alpha_{m607} = 0.007\ km^{-1}$$

3) The aerosol extinction coefficients at 530 nm and at 532 nm are assumed to be the same. Then using the 530 nm data, the altitude dependent extinction value for 532 nm can be calculated comparing the signal gradient with the atmospheric scale height using that part of the profile that is not affected by the telescope form factor (beyond about 1 km).

$$I(z) = I_0\, e^{-2\alpha_{532} z}$$

$$I(z) = I_0\, e^{-(\alpha_{532}+\alpha_{607}) z}$$

4) The extinction of the 607 nm is obtained by fitting the function,to the 607 nm profile. This algorithm can only determine the sum of the two extinction paths but with the extinction determined at 532 nm, the extinction for 607 nm can be directly calculated. Figure 3 (upper panel) shows an example of the aerosol extinction profile. The Raman lidar equation can be written to emphasize the extinction at the transmit wavelength and the Raman scattered return wavelength. The optical extinction due to scattering and absorption is separated into the outgoing transmit wavelength path and the return path at the Raman shifted wavelength in the equation,

$$P_R(z) = \frac{\xi(z)}{z^2} N(z) \frac{\partial\sigma}{\partial\Omega}\ exp\left(-\int^z (\alpha_{O,mol}+\alpha_{R,mol}+\alpha_{O,aer}+\alpha_{R,aer})dz\right)$$

O - outgoing - 532 or 266 nm *R* - return - 530 (rot), 607 (N_2), 285 (N_2) or 276 (O_2) nm

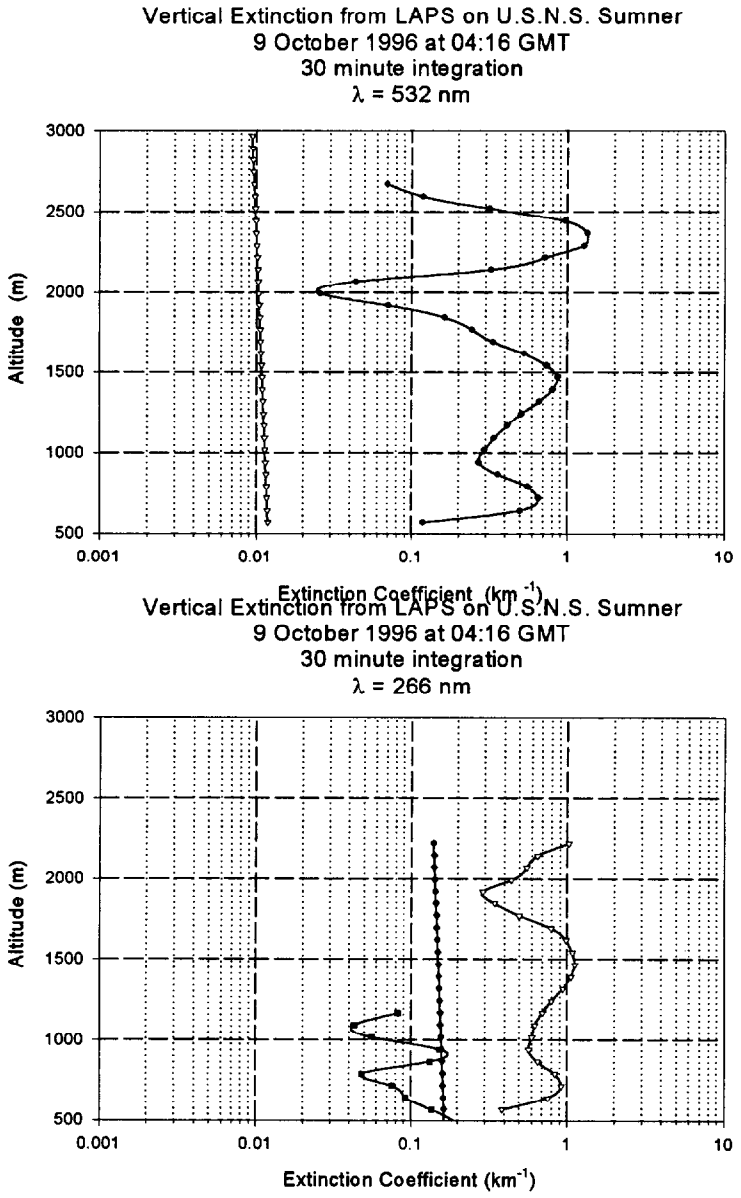

Figure 3. The optical extinction measured at visible and ultraviolet wavelengths from the LAPS Raman lidar on 9 October 1996. The extinction from molecular and aerosol scattering components are shown and the ozone absorption at 285 nm is based on the DIAL analysis of the Raman signals for N_2 and O_2.

The relationship can be rewritten to solve for the optical extinction at the Raman shifted return wavelength. The first calculation is applied to the case when the extinction at the rotational Raman signal at 530 nm is measured. That wavelength is so close to the 532 nm transmit wavelength that no difference due to wavelength dependence of the scattering cross section exists. By first calculating the extinction at 532 nm from the 530 nm path and substituting this extinction as the aerosol extinction of the outgoing pulse, it is possible to then calculate the optical extinction at 607 nm. This approach provides the 607 nm optical extinction from the N_2 Raman without assuming any wavelength dependence.

The results in Figure 3 show the measured extinction profiles at visible (530 nm) and ultraviolet (285 nm) wavelengths which are ascribed to the scattering by the molecular and the aerosol components of the atmosphere are shown. In addition, the extinction at 285 nm due

to the measured tropospheric ozone profile is shown. It is interesting to note the general similarity between the visible and ultraviolet aerosol extinction values. The wavelength dependence of the aerosol extinction is seen to be relatively small in this case, but there are significant differences in the aerosol profiles. The molecular extinction profiles were calculated from the model profile of density. The molecular scattering cross-section between the visible and ultraviolet differ by the factor of ~12 ($1/\lambda^4$). The total extinction at the ultraviolet wavelength is generally much greater than at the visible wavelength. However, as the aerosol extinction increases, it can make the total extinction at both wavelengths comparable, in clouds the visible extinction can be even larger.

The instrument provides a unique opportunity to simultaneously measure the variations in the ozone profile, while at the same time determining the atmospheric dynamics from variations in the water vapor profiles. These results, together with the temperature profiles and particle scattering optical extinction at several wavelengths will provide valuable input for investigations of the physical and chemical processes in the lower atmosphere, also for development of models of atmospheric pollution events.

Understanding of the atmospheric optical properties is critical for use and interpretation of many operational sensor systems. We have developed and used lidar instruments to provide measurements of the optical extinction at several wavelengths, to determine the spatial scales of particle scatters, and to determine particle properties from their scattering phase function. These investigations are conducted to provide a physical basis for describing optical propagation conditions for future tatical decision aids and for support of testing of advanced optical sensor systems.

SUMMARY

Two independent approaches to measurement of the optical properties of the atmosphere have been successfully demonstrated and compared. One depends upon the determination of the aerosol description from the polarization ratio of the scattering phase function and provides the extinction at any wavelength calculated from the number density, size and distribution width of the scattering particles, assuming the Mie scattering theory can be used to describe the particles. The second depends upon the fact that extinction produces a gradient in the Raman scatter profile of the principal molecular constituents. The Raman technique provides a reliable approach to obtain profiles of the molecular species which can be analyzed to directly determine the extinction at a wavelength. The "solar blind" spectral region has been found useful in measuring the daytime profiles of optical extinction and ozone absorption. Aerosol extinction measurements can be obtained at several wavelengths from the Raman molecular profiles. Simultaneous measurements of optical extinction at several wavelengths provides information on the variations in particle size, which can be particularly interesting around a cloud to determine whether it is in a growth phase or is dissipating.

ACKNOWLEDGMENTS

The developments leading to the capability for measuring the optical extinction have been advanced through the efforts of several graduate students, particularly the work of T. D. Stevens and M. D. O'Brien. This work has been supported by the Navy through the program directed by J. Richter, SSD-SD. Our appreciation goes to Geary Schwemmer and NASA Goddard colleagues for the cooperative measurement program at Wallops Island VA.

REFERENCES

[1] Stevens, T. D., "Bistatic Lidar Measurements of Lower Tropospheric Aerosols," PhD Thesis for Penn State University, Department of Electrical Engineering, May 1996.
[2] Stevens, T. D. and C. R. Philbrick, "Particle Size Distributions and Extinction Determined By a Unique Bistatic Lidar Technique," in Proceeding of IGARSS96 Conference on Remote Sensing for a Sustainable Future, Vol II pp 1253-1256, 1996.
[3] Stevens, T. D. and C.R. Philbrick, "Atmospheric extinction from Raman lidar and a bistatic remote receiver," in Proc. Conf. IEEE topical Symp. CO-MEAS, 170, 1995.
[4] O'Brien, M. D., T. D. Stevens and C. R. Philbrick, "Optical Extinction from Raman Lidar

Measurements," in Optical Instruments for Weather Forecasting, SPIE Proceedings 2832, 45-52, 1996.
[5] Philbrick, C. R. "Raman lidar measurements of atmospheric properties," in Proc. of Atm. Prop. and Remote Sensing III, SPIE 2222, p.922, 1994.
[6] Philbrick, C. R., D. B. Lysak, T. D. Stevens, P. A. T. Haris and Y.-C. Rau. "Atmospheric measurements using the LAMP lidar during the LADIMAS campaign," in Proc. of the 11th ESA Symp. ESA-SP-355, p.223, 1994.
[7] Hughes, H. G. and M. R. Paulson, "Double-ended lidar technique for aerosol studies," Appl. Opt. 27, 2273, 1988.
[8] Reagan, J. A. and B. M. Herman, "Bistatic lidar investigations of atmospheric aerosols," in Proc. Conf. Radar Meteorol., 14th, p.275, 1970.
[9] Devara, P. C. S. and P. Ernest Raj, "A bistatic lidar for aerosol studies," IETE Tech. Rev. Vol. 4, p.412, 1987.
[10] Parameswaran, K., K. D. Rose, and B. V. Krishna Murthy, "Aerosol characteristics from bistatic lidar observations," J. Geophys. Res. Vol. 89, No. D22, p.2541, 1984.
[11] Bohren, C. F. and D. R. Huffman, Absorption and Scattering of Light by Small Particles, Wiley-Interscience, New York, 1983.
[12] Gathman, S. G., and Jensen , D. R., "Maptip (Marine aerosol properties and thermal imager performance): Aerosol Characteristics in a Coastal Region", Naval Command, Control and Ocean Surveillance Center, San Diego, CA. RDT and E Div., NTIS ID No.: AD-A300 25 Aug 1995.