ATMOSPHERIC EXTINCTION FROM RAMAN LIDAR AND A BI-STATIC REMOTE RECEIVER

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Introduction

The scattering of optical radiation in the visible, ultraviolet and infrared regions of the spectrum has a major impact on commercial air traffic and on many military systems. It has become critically important, with modern systems, that the electro-optical environment be properly characterized. Lidar techniques show great promise for describing the electro-optical scattering environment. Most of the past applications of lidar have failed to provide satisfactory results because the techniques have generally focused on measurements of the backscattered radiation at the laser fundamental wavelength. We have been able to demonstrate that the rotational and vibrational Raman backscatter can be used to determine the extinction profile through optical scattering regions containing aerosols and cloud layers.

We have developed a secondary bi-static remote receiver designed to collect scattering angle and polarization information from a laser remote sensing system. This instrument collects an image of the radiation scattered from the first few kilometers of the atmospheric path to help determine atmospheric particle size distributions. By collecting data at different angles from the laser transmitter, additional information contained in the scattering angle phase function can be obtained. The Raman lidar extinction together with the backscatter phase function and polarization provide information on the particle size distribution that should allow extension of the extinction and transmission calculations to a wider range of wavelengths.

Background

It has been a considerable challenge to remotely measure the extinction and transmission through a cloudless region of the atmosphere. Lidar techniques show the best promise for describing the electro-optical environment. However, most of the past applications of lidar have failed to provide satisfactory results because the techniques used have generally focused on measurements of the backscattered radiation at the laser fundamental wavelength. The extinction is related to the backscattered energy by the equation $\beta(r)=C(r)\alpha(r)^k$, where $\beta(r)$ is the backscattered intensity, $\alpha(r)$ is the extinction and C(r) and k are frequently assumed constant. But C(r) is a function of range and k is different for each scatterer, so given the backscatter intensity $\beta(r)$, the extinction $\alpha(r)$ can not be reliably obtained. This presents a problem for techniques relying on the inversion of a single-ended lidar return to obtain range dependent atmospheric extinction coefficients. This technique will only be useful for regions of the atmosphere with uniform scatterers and small extinction coefficients, like those found in stratospheric aerosols [1,2].

A more reliable method using lidar to measure atmospheric extinction has been developed independently by M.R. Paulson [3] and G.J. Kunz [4]. This lidar inversion algorithm uses a double ended lidar technique where the relationship between the backscatter and extinction coefficients is eliminated by comparing the backscatter signal returned from a volume common to each lidar located at opposite ends of the propagation path. Figure 1 shows plots of extinction calculated from both single-ended [C(r) assumed constant] and double-ended lidar backscattered returns [5]. These data sets show very clearly how unreliable standard inversion techniques are at obtaining extinction from a single backscattered lidar return. However, if the values of C(r) are known as a function of range and allowed to vary, standard single-ended lidar returns could be inverted to reliably obtain extinction coefficients [5]. More information is needed about the scatterers so that C(r) can be calculated for each range bin. The ratio of the 532 nm to the 355 nm backscattered two-color lidar return is theoretically proportional to C(r). But this has yet to be used in an inversion algorithm to accurately and uniquely calculate extinction [6]. The double-ended lidar technique is a proven method for measuring the extinction along a path, but it is not a practical solution for instantaneous

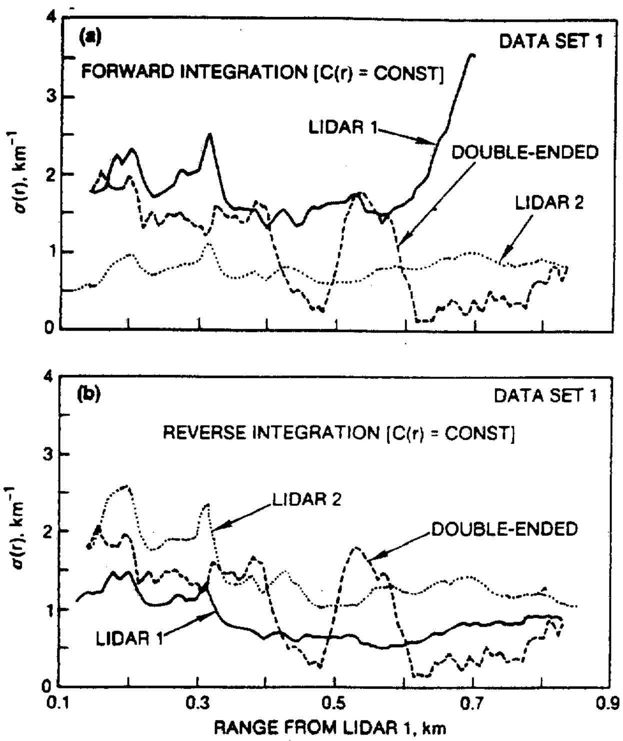

Figure 1. Comparison of extinction coefficients versus range calculated using forward and reverse integration on a single-ended lidar return and using the double-ended lidar technique. (from Richter and Hughes, 1991) [4]

measurements above altitudes of a few meters and for locations where instruments can not be located at each of the end points. The scattering properties are much too complicated for the simplistic single-ended backscattered inversion approach and much more information is needed to characterize the processes.

Raman lidar extinction

We have been able to demonstrate that the Raman molecular profile can be used to determine the extinction profile through optical scattering regions such as clouds. Figure 2 shows an example of a return from a Raman shifted signal through a cloud. The backscattered signal from the Raman shifted return contains only extinction information. As long as the amount of extinction is significant, like that through a cloud, an extinction coefficient can be calculated by using the Beer-Lambert law and looking at the change in signal strength through the cloud in the Raman channel. The signals from either the N_2 channel shifted from 532 nm to 607 nm or shifted from 355 nm to 387 nm can be used for this calculation. Our strongest signals come from the rotational Raman channels of 528 and 530 nm, both shifted from 532 nm to obtain temperature. These two channels are added together to reduce the temperature dependence before calculating an extinction coefficient. The Beer-Lambert law is used in the following form,

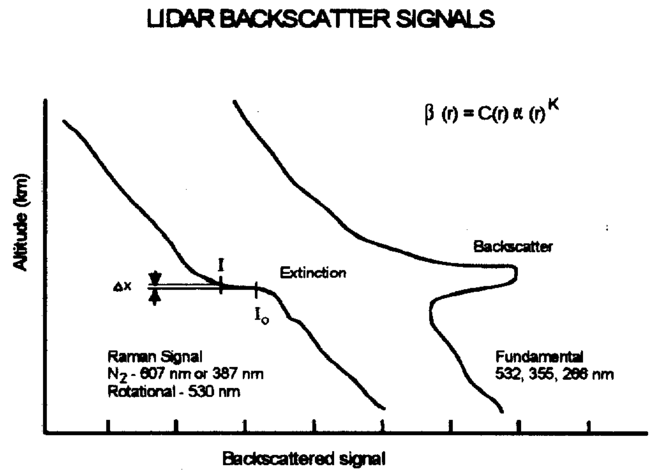

Figure 2. Example of how extinction can be calculated through clouds using the Raman shifted return.

$$\alpha = -\frac{\ln \frac{I}{I_o}}{2x} = \textit{Extinction coefficient}$$

Where x equals the range bin size in meters. Because the Raman lidar return is compared to the US Standard Atmosphere, only large amounts of extinction can be calculated. We first tie the lidar signal to the US Standard Atmosphere above 10 km, where we can expect molecules to be the dominant scatterers. The Raman lidar signal is then normalized by dividing it by the US Standard Atmosphere. This resultant signal is then used in the above Beer-Lambert equation to calculate the extinction coefficient point by point.

Figure 3 shows data obtained with the Penn State LAMP (Lidar Atmospheric Measurement Program) lidar at State College, Pa. on September 13, 1994 [7]. A large cloud with a peak just before 8 km can be seen in the Rayleigh/Mie 532 nm channel. At the same altitude the rotational Raman channel's signal decreases by about an order of magnitude. This amount of extinction is clearly large enough that any variation in the molecular atmosphere will have little effect on the total calculated extinction. Figure 4 shows a plot of the extinction coefficient versus altitude calculated from the Raman profile in Figure 3. This type of range resolved profile can be most valuable in

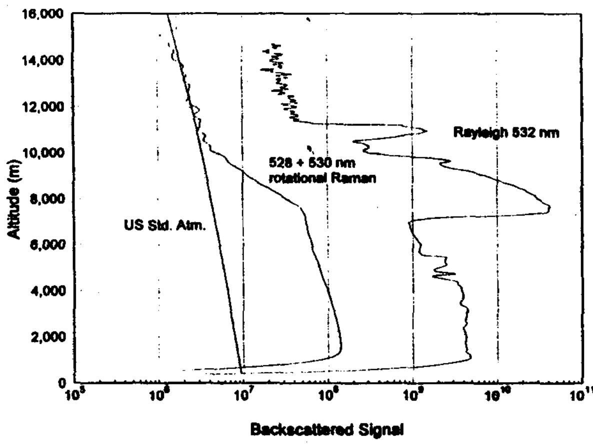

Figure 3. Data collected with the Penn State LAMP lidar on September 9, 1994 at State College, PA. The cloud at 8 km is seen as a strong peak in the 532 nm single, and as strong extinction in the rotational Raman channels.

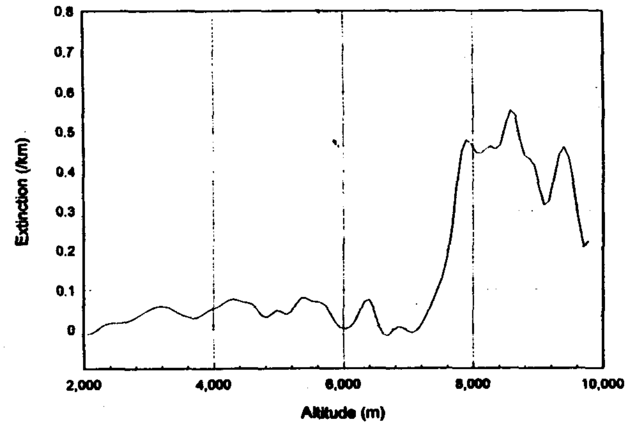

Figure 4. Extinction coefficient calculated directly from the rotational Raman data in Figure 3. A simple point-to-point calculation using the Beer-Lambert will give reasonably accurate results for large extinction values, like those in clouds.

describing cloud layers and their effect on the propagation of electro-magnetic fields at visible wavelengths. However, if we are to determine the optical properties over a wide range of wavelengths, and through a "clear" atmosphere a different method must be used.

Bi-static lidar extinction

A bi-static receiver can be used to collect angle and polarization scattering by imaging the radiation scattered from the first few kilometers of the atmospheric path. This will help to determine the atmospheric particle size distributions. It is our belief that important information needed to describe the scatterers is contained in the phase function and polarization of the backscattered lidar signal. Ultimately the knowledge gained from this type of measurement would allow atmospheric transmission and extinction to be calculated over a range of wavelengths from lidar measurements and meteorological conditions alone.

Figure 5 shows the geometry for the two modes of operation for the lidar and bi-static receiver. Data is collected by positioning the receiver at least 10 meters away from the laser source and imaging the laser beam onto the CCD array. Horizontal measurements will be collected when the aerosol distribution is uniform and the wind is calm. This will provide a range of angles as a function of pixel number. The receiver will them be moved either further from or closer to the lidar to image the same atmospheric volume, but now at a different angle. This will be done repeatedly to collect results at several angles over a range of a few degrees. A plot of the phase distribution versus intensity can thus be constructed. Two measurements will be taken at each position, one for each polarization. Figure 6 shows a plot of scattering phase function and percent polarization versus scattering angle for two indices of refraction and three effective size parameters ($x_m = 2\pi a/\lambda$). 'a' is the parameter of the size distribution given by,

$$n(r) = constant\ r^{(1-3b)/b}\ e^{-r/ab}$$

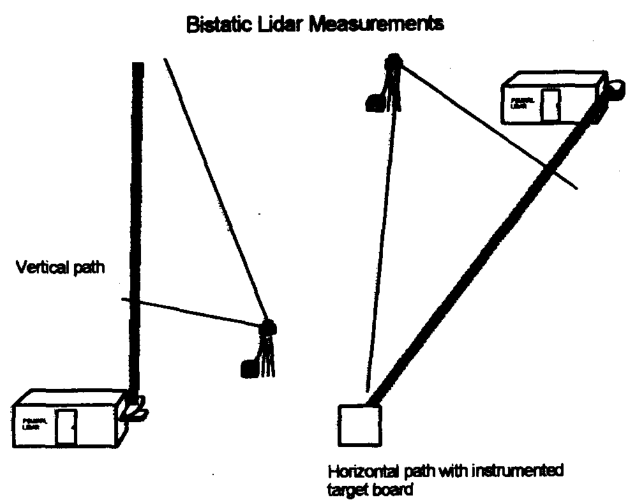

Figure 5. The lidar and bi-static receiver will be operated both vertically and horizontally. By operating a receiver with a linear array off-axis from the laser beam, phase information can be collected about the scatterers.

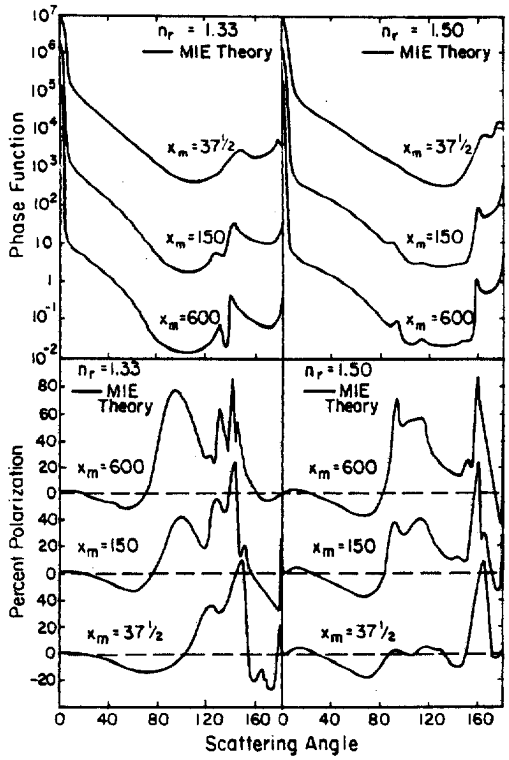

Figure 6. The scattering phase function and degree of polarization calculated from Lorentz-Mie theory as function of scattering angle (from Hansen and Travis, 1974) [8].

where n(r) is the number of particles per unit volume with a size that falls in the radius range r to r+dr, and the parameter b defines the variance of the distribution. Figure 7 shows the effect of increasing the variance of the distribution (parameter b). A larger variance in the size distribution smooths the extinction efficiency and the fine ripple structure from the interference disappears. Figures 6 and 7 show the basis for the motivation of a bi-static imaging device with a lidar. The goal is to generate curves like those in Figure 6 based on experimental data. Figure 7 shows what should be expected from a lidar return with two different wavelengths. If the particles are monodispersed (b=0), very different extinctions could be expected due to the large peaks and valleys, but this is probably rarely the case. A wider distribution is more likely and would scatter different wavelengths in a less complicated manner. Measuring the variance of the distribution (parameter b) and plotting curves like Figure 7 will be essential to determine the relationship between the extinction at multiple wavelengths and the particle size distribution. Calculations for a range of particle size distributions will be carried out as a basis for understanding the measured results.

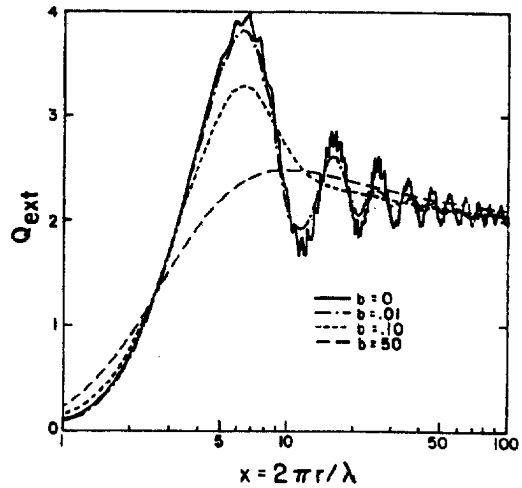

Figure 7. The extinction efficiency plotted as a function of the effective size parameter for the values of effective variance b. (from Hansen and Travis, 1974) [8].

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