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Laser Scattering in Clouds

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Abstract

Experimental results on optical scattering in clouds have been obtained using lidar techniques. These techniques have been used to develop a theoretical interpretation of optical extinction in various cloud structures and in the stratospheric aerosol layer. Measurements have been made with the LAMP (Laser Atmospheric Measurement Program) lidar of Pennsylvania State University. The inverse lidar equation must be used to calculate the extinction coefficient in order to profile the atmospheric density. Two inversion methods have been used to calculate the extinction coefficient: (1) Klett's inversion method and (2) inversion of the lidar equation directly using the 607 nm N_2 Raman wavelength return. These methods have been compared using results obtained during several different atmospheric conditions.

Introduction

The LAMP lidar is a research instrument used to investigate properties of the lower and middle atmosphere. The LAMP lidar transmits at the 532 nm and 355 nm wavelengths. Table I provides a summary of the LAMP lidar. Profiles of the backscatter signal which result from molecular and particle scatter were collected by independent detectors for altitudes above and below 15 km at these wavelengths. Profiles were also obtained for the N_2 Raman (607 nm) and water vapor Raman (660 nm) wavelengths. On its first field trip, the LAMP lidar was operated aboard the German research vessel RV POLARSTERN as part of the LADIMAS (LAtitudinal DIstribution of Middle Atmospheric Structure) campaign. Measurements were obtained aboard the POLARSTERN from 70° N to 65° S between October 1991 and January 1992. The LADIMAS data was used to map the stratospheric aerosols, which were enhanced due to the eruption of the Pinatubo volcano in June of 1991 [1].

Since its return to PSU in March 1992, the LAMP lidar has been operated on a regular basis at State College, PA. The measurements have been conducted under a wide variety of cloud conditions, allowing characterization of the lidar system performance over a range of atmospheric situations. The three wavelengths, 532 nm, 355 nm, and the N_2 Raman-shifted 607 nm, are valuable for the characterization of clouds. The particle backscatter ratio (532 nm signal return/355 nm signal return), corrected for the molecular contribution, provides a measure of the changing size distribution of the particles in the atmosphere. Between 19 and 32 km, the particle backscatter ratio was found to be an almost constant value near 0.5 during the October - December 1991 measurements. The particle backscatter ratio of the two wavelengths vary widely with cirrus clouds and other tropospheric clouds, indicating that they contain a variety of particle density, size, and shape. While the size and density distributions of particles change rapidly in cloud layers, we find that useful information can be obtained with the inversion calculations [2,3]. This paper first provides a background of the lidar equation and the relevant scattering techniques. The two inversion methods are then described, followed by results.

Table I. LAMP System Parameters

TRANSMITTER	
Laser:	Continuum NY-82, Seeded Nd:YAG, 1064nm Fundamental Wavelength
Wavelengths:	532nm 355nm
Energy/Pulse:	600mj 250mj
Pulse Width:	7ns
Pulse Rate:	20 Hz
RECEIVER	
Telescope:	f/15 Cassegrain
Aperture diameter:	40.6 cm
Return Wavelengths:	355nm, 532nm (elastic return) 607nm (Nitrogen), 660nm (H_2O vapor) (Raman return)

Lidar Equation

The scattering form of the lidar equation is

$$P(r) = P_0 \frac{c\tau}{2} \frac{A}{r^2} \beta(r) \exp[\int_0^r (\alpha_t(r') + \alpha_r(r'))\, dr']$$

where,

$P(r)$ is the instantaneous received power at time t,
P_o is the transmitted power,
c is the velocity of light,
τ is the pulse duration,
A is the effective receiver area,
r is the range,
β is the volume backscattering coefficient,
α_t is the transmitted volume extinction coefficient,
α_r is the received volume extinction coefficient.

The signal from the lidar is analyzed to provide information on the magnitude of backscatter and attenuation experienced by the pulse as it propagates through the atmosphere. The range from which the signal is being received is provided by the time interval between the firing of the pulse and the reception of the signal [4]. The attenuation of the transmitted energy is due to atmospheric interactions. While some of the light is scattered back in the direction of the receiver, the rest is either scattered out of the field of view or absorbed, depending on the wavelength [5]. The relevant scattering processes for LAMP lidar are: Rayleigh, particle and Raman scattering.

Scattering

Whenever a particle, be it an electron, atom, molecule, gas, liquid, or solid, is illuminated by an electromagnetic wave, the electric charges in the particle oscillate due to the electric field of the incident wave. The oscillations cause electric charges to radiate electromagnetic energy in all directions. This secondary radiation is the scattered radiation from the particle [8]. Scattering constitutes a directional redistribution of energy, which may lead to a significant reduction in beam intensity for large path lengths. The type of scattering is determined by the physical size of the scatterer [6]. Figure 1 shows the types of scattering utilized by LAMP.

In Rayleigh scattering, the bound electrons of an atom or molecule are displaced by the incident electric field. This incident harmonic field induces a dipole in the particle. The displacement of the bound electron is determined by the polarizability of the atom or molecule. The induced dipole and incident radiation oscillate at the same frequency, placing the molecule or atom in a higher energy level, and as a result, electromagnetic radiation is emitted. This "instantaneous" emission results in the dipole field distribution of the scattered light [4].

Mie theory is used to explain scattering by particles, aerosols, and small water droplets. Mie's scattering theory describes particle scattering by taking into account the size, shape, dielectric constant, and absorptivity of the particle. The attenuation due to particle scattering is much greater than that due to Rayleigh scattering because its cross section is generally so much larger. Mie theory uses the product, *ka*, to describe the scattering function of a particle, where *k* is the propagation constant and *a* is the particle radius. The product, *ka*, and the refractive index difference between the particle and air determine all of the scattering characteristics.

Raman scattering is an inelastic interaction of the optical beam involving excitation of the energy levels of a molecule and re-radiation at a different frequency [6] Raman scattering is a weak scattering occurring at a shifted wavelength associated with the vibrational and rotational energy states of the molecule. This radiation is in addition to the molecular scattering that occurs at the same wavelength as the irradiating wavelength. The frequency shift of the incident wavelength is related to the rotation-vibration energy states of the molecule and is characteristic of the particular molecular species in the scattering volume. Raman scattering can occur for any incident wavelength but its scattering function is approximately three orders of magnitude less than the peak of the molecular scattering functions [7].

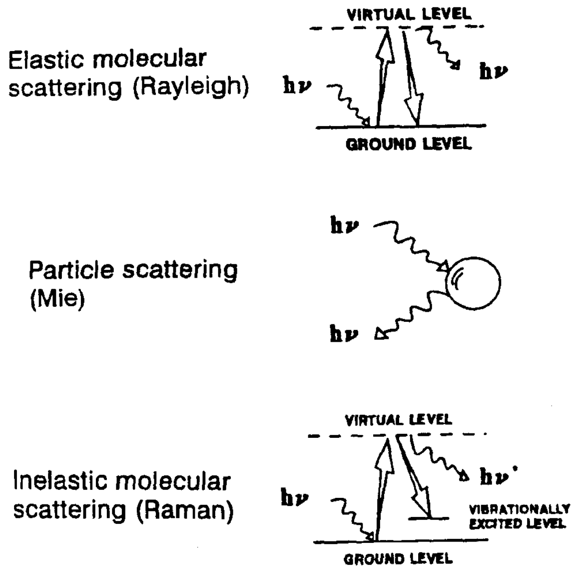

Figure 1. Scattering techniques used by LAMP.

Extinction

Extinction is the attenuation of an electromagnetic wave by scattering and absorption as it propagates through the atmosphere [8]. If multiple scattering is negligible, the intensity of a light beam is exponentially attenuated while traversing a distance R through the atmosphere according to,

$$I(R) = I_o \exp[-\alpha R],$$

where,

$I(R)$ is the intensity at range R,
I_o is the incident intensity,
α is the volume extinction coefficient.

Extinction can be observed in many normal instances; sunlight through a dust storm or a polluted layer of air, automobile headlights in fog, skin diver's light in murky water.

The volume extinction coefficient accounts for all the atmospheric interactions that extract energy from the laser beam such as scattering and absorption. The total volume extinction coefficient is the sum of three major components,

$$\alpha = \alpha_R + \alpha_P + \alpha_A\ ,$$

where

α_R is extinction due to molecular scattering,
α_P is the extinction due to particle scattering,
α_A is the extinction due to absorption by molecules or aerosols.

The volume extinction coefficient is proportional to the number of interacting particles in the volume of atmosphere. The strength of the interaction with each particle in the volume is described by a cross-sectional area that interferes with the beam. For a uniform particle distribution, $\alpha = \rho\sigma$, where ρ is the number density of particles (m^{-3}) and σ is the cross section of a single scatterer (m^2) [5].

Klett Inversion Algorithm

The Klett inversion algorithm [9] presents a simple, analytical method of inverting the lidar equation in order to extract the extinction and backscatter coefficients from the return signal of a single-wavelength lidar system. Klett's inversion method is based on a new form of a well-known analytical solution which will be presented in detail. This algorithm makes use of a power-law relationship between the backscatter, β, and extinction, α, coefficients of the form,

$$\beta = C \times \alpha^k,$$

where C is a constant and k depends on the lidar wavelength and the various properties of the obscuring aerosol. Several observations and theoretical studies substantiate this relationship and have shown this relationship under a wide range of circumstances where particle scattering is dominant. The value k was found to be in the range $0.67 \le k \le 1.0$.

The technique involves using the lidar equation represented as,

$$P(r) = P_o \frac{c\tau}{2} \frac{A}{r^2} \beta(r) \exp[-2\int_0^r \alpha(r')\, dr'] ,$$

where P(r) is expressed as a logarithmic range-adjusted signal,

$$S(r) = \ln [r^2 P(r)].$$

Substituting S(r) and the power law relationship into the lidar equation and solving , the solution obtained is,

$$\alpha(r) = \frac{\exp[\frac{(S-S_o)}{k}]}{\frac{1}{\alpha_o} - \frac{2}{k}\int_0^r \exp[\frac{(S-S_o)}{k}]\, dr'} ,$$

where $\alpha_o = \alpha(r_o)$, however, this solution is highly unstable. Since the signal is usually attenuated with increasing range, α is determined as the ratio of two numbers, both of which become progressively smaller with increasing r. Also, the denominator, which must approach zero at nearly the same rate as the numerator, is the difference between two relatively large numbers. This unstable structure, combined with the fact that even the smallest error in the initial value α_o leads to very large errors makes this solution inaccurate at best. Fortunately, if this solution is represented in a slightly different manner, the results turn out to be quite accurate. If the reference range, r_m, is chosen at the far end of the signal rather than the near end,

$$\alpha(r) = \frac{\exp[\frac{(S-S_m)}{k}]}{\frac{1}{\alpha_m} + \frac{2}{k}\int_0^r \exp[\frac{(S-S_o)}{k}]\, dr'} ,$$

where $S_m = S(r_m)$ and $\alpha_m = \alpha(r_m)$. Now, as r decreases from r_m, α is expressed as the ratio of two numbers, each of which become progressively larger. In this manner, stability and accuracy of the "far end" solution are assured. The denominator now is in such a form that the dependence of the solution on α_m decreases with decreasing r. In fact, the solution form is relatively insensitive to errors in k and α_m values [9].

Raman Inversion Algorithm

The 607 nm nitrogen return provides a signal which is directly proportional to atmospheric density.

The Raman return is not affected by aerosol backscatter but is extincted in the presence of clouds and aerosols and to a small well known amount by the molecules. The 607 Raman signal can be used to extract extinction from the lidar equation given the number density. The number density, N(z), is obtained from rawinsonde data or from an appropriate model. The lidar equation for a Raman-return signal is,

$$P(r) = \frac{K}{r^2}\beta(r)\exp[\int_0^r (\alpha(\lambda_L, r') + \alpha(\lambda_R, r'))\,dr']$$

where,

K contains all range-independent parameters,
$\alpha(\lambda_L, r)$ is the extinction coefficient from the incident wavelength and,
$\alpha(\lambda_R, r)$ is the extinction coefficient from the Raman-shifted wavelength.

The lidar equation can be expressed as,

$$\int_0^r [\alpha(\lambda_L, r) + \alpha(\lambda_R, r)]\,dr = \ln(K) + \ln[\frac{\beta(z)}{z^2 P(z)}],$$

which has a corresponding differential equation,

$$\alpha(\lambda_L, z) + \alpha(\lambda_R, z) = \frac{d}{dz}[\ln\frac{\beta(z)}{z^2 P(z)}]$$

$$= \frac{d}{dz}\ln\beta(z) - \frac{d}{dz}S(z).$$

Upon substituting for $\beta(z)$ ($= N(z)\alpha$), the extinction coefficient from the aerosol component is,

$$\alpha_P(\lambda_L) = \frac{\frac{d}{dz}lnN(z) - \frac{d}{dz}S(z) - \alpha_R(\lambda_L)\,[1+(\frac{\lambda_L}{\lambda_R})^4]}{[1+(\frac{\lambda_I}{\lambda_R})^4]}.$$

The extinction coefficient from Rayleigh scattering is given by,

$$\alpha_R = N(z)\,x\frac{8\pi}{3}x5.45x10^{-32}x[\frac{550}{\lambda(nm)}]^4.$$

The total extinction coefficient is a sum of α_R and α_P at the Raman wavelength, 607 nm.

Data Results

A comparison between the two inversion methods shows a good correlation of the results. Figures 2 and 3 provide extinction calculated from the Klett method for the 532 nm return and extinction calculated from the 607 nm Raman inversion along with the signal backscatter profiles for the 532 nm and the 607 nm returns. In the signal profile, the increased backscatter in the 532 nm return corresponds to the decrease in the 607 nm return due to extinction. There is fairly good agreement between the extinction coefficient data from the two wavelengths.

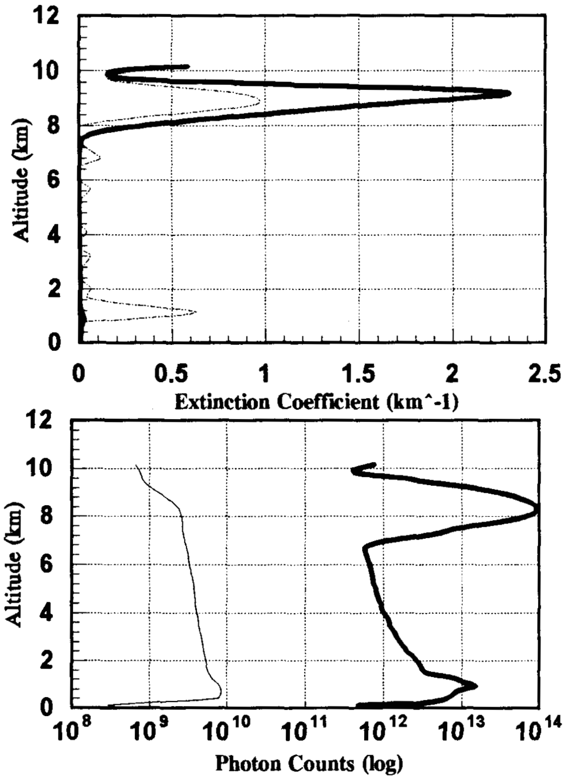

Figure 2. Extinction coefficients and backscatter signal return for the 532 nm and 607 nm wavelengths, October 23, 1993.

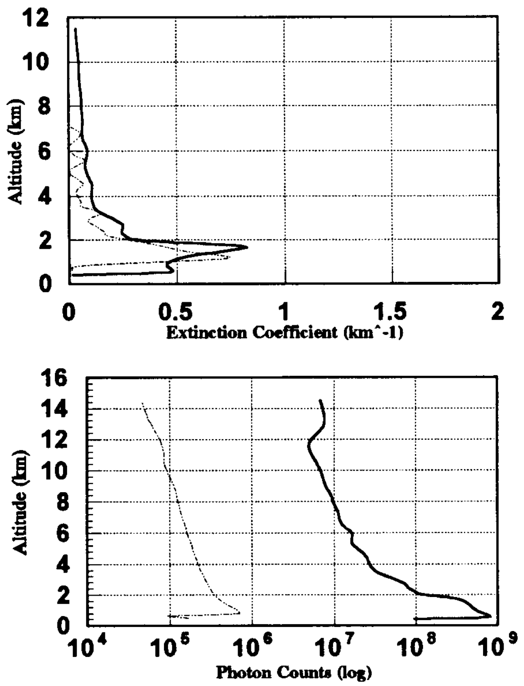

Figure 3. Extinction coefficients and backscatter signals for 532 nm and 355 nm, October 14, 1993.

Conclusion

This paper presents two inversion techniques to determine profiles of the extinction coefficients from a single wavelength in the troposphere. These methods were used to compute extinction through various cloud layers and aerosol distributions. The results have shown reasonably good agreement between the two techniques.

Acknowledgements

The authors would like to acknowledge ARL, NSF CEDAR Program, SPAWAR PMW-165 Navy Environmental Systems Program Office, and PSU College of Engineering Alfred Wegener Institute for Polar and Marine Research. Thanks are also due to Dan Lysak, Yi-Chung Rau, Tim Stevens, Paul Haris, Dave Machuga for their contribution and support.

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