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LATITUDINAL LIDAR MAPPING OF STRATOSPHERIC PARTICLE LAYERS

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ABSTRACT

Between October 1991 and January 1992, The LAMP lidar took part in the LADIMAS campaign. The instrument profiled density and temperature structure of the middle and lower atmosphere, along with water vapor profiles of the lower troposphere. Measurements were taken from 70°N to 65°S aboard the German research vessel, RV Polarstern. Strong backscattered signals due to aerosols from the eruption of the Pinatubo volcano in the Philippines were observed between 20 and 33 km. These layers were detected at all measurement locations from Andeness, Norway to Antarctica. A characterization of the aerosol layers is made possible by the two-color lidar technique at wavelengths of 355 and 532 nm, and latitudinal mapping from aboard the RV Polarstern.

INTRODUCTION

Aerosol particles are very important components of the atmosphere in interactions with solar and terrestrial radiation which influence the energy balance of the earth-atmosphere system. Small nuclei which are distributed in the atmosphere are also important contributors to the formation of clouds and fog. They also influence many heterogeneous atmospheric chemical processes. The eruption of the Pinatubo volcano in the Philippines (15.14°N, 120.35°E) on June 15, 1991, produced the largest impact on the stratosphere ever observed by modern airborne, spaceborne, and ground-based scientific instruments. The volcanic aerosols were ejected into the upper troposphere and the stratosphere to heights of 33 km. Due to their long residence time, the volcanic aerosols were transported around the globe in about three weeks [1], and by September 27 small amounts were observed as far north as Norway.

Significant amounts of stratospheric aerosols can cause a cooling of the earth's surface due to the scattering of solar radiation back into space. Likewise a warming of the stratosphere where the particles reside can occur due to absorption of upwelling infrared radiation [2]. Estimates, from the SAGE II experiment of NASA, place the aerosol mass produced by this eruption between 20 and 30 megatons, approximately twice the amount produced by El Chichon in 1982 [3]. NASA models also predict a surface temperature decrease, in 1992, of about three times the standard deviation of the annual global mean [2]. This temperature decrease is sufficient to reverse current global warming trends for the next couple of years. It is therefore very important to study and understand aerosol distribution and variation in the stratosphere to see how they contribute to the thermodynamic exchange processes of the atmosphere.

In this paper we discuss measurements of the Pinatubo aerosols made by the new LAMP (Laser Atmospheric Measurement Program) lidar developed at The Pennsylvania State University. We report measurements of backscattering intensity, scattering ratios of 532/355 nm radiation, layering structure, and latitudinal distribution measurements while the lidar was deployed on the RV Polarstern ice breaker as part of the LADIMAS (LAtitudinal DIstribution of Middle Atmospheric Structure) campaign between October 1991 and January 1992.

INSTRUMENTATION

The LAMP instrument was designed to operate as both a middle atmosphere sensor and a lower atmosphere meteorological sounder. To accomplish this task, The profiles of many atmospheric properties including nitrogen concentration, water vapor concentration, aerosols, density, and temperature must be monitored over a large altitude range simultaneously. The LAMP instrument was also built as a test bed for the development of more advanced meteorological sensors capable of automated operation. The LAMP lidar is a rugged self-contained transportable instrument capable of operating in almost any environment, as was demonstrated by its operation aboard the German ice breaker RV Polarstern in Antarctica during December 1991.

The instrument uses a pulsed Nd:YAG laser transmitting near-infrared radiation of 1064 nm, 1.5 joules per pulse at a pulse repetition frequency of 20 Hz. The fundamental output frequency is doubled and tripled by nonlinear crystals to produce outputs at wavelengths of 532 nm and 355 nm with energies of 600 mj and 250 mj respectively. Table I provides a summary of parameters for the LAMP lidar. The system design is an advanced development from two earlier lidars, the GLINT and GLEAM systems developed by Philbrick at the Air Force Geophysics Laboratory (currently Phillips Laboratory) [4,5].

Table I. Penn State lidar parameters.

PENN STATE LAMP LIDAR PARAMETERS			
Power aperture product = 1.55			
TRANSMITTER			
Type: Continuum NY-82, Seeded Nd:YAG			
	Fundamental	Doubled	Tripled
Wavelength	1064 nm	532 nm	355 nm
Pulse energy	1.5 J	600 mJ	250 mJ
Bandwidth		80 MHz	
Pulse length		6 ns	
Pulse rate		20 Hz	
RECEIVER			
Type: f/15, Cassegrain telescope			
Focal length	609 cm		
Primary diameter	40.6 cm		
Secondary diameter	10.2 cm		

OBSERVATIONS

The aerosols from the Pinatubo eruption plume were first detected by the LAMP lidar in Andenes, Norway (69° 17' N, 16° 01' E) on September 27, 1991 [6]. Figure 1 shows an example of how the backscatter intensity was calculated for the night of October 3, 1991. The backscattered return from the laser pulses represents the total scattering, both molecular and aerosol. The backscatter ratio, R, is defined by,

$$R(\lambda,z) = [\beta_a(\lambda,z)+\beta_m(\lambda,z)]/\beta_m(\lambda,z), \qquad (1)$$

where β_a and β_m are the volume backscatter cross sections for aerosols and molecules, respectively. A straight line approximating the molecular backscatter, β_m, of the atmosphere is fit to the results between 40 and 50 km, assuming this is a region of molecular scatter. Then it is tied to the lowest relative signal between the Pinatubo cloud and the tropopause. This is a relatively accurate approximation of the molecular atmosphere because the Pinatubo aerosols appear to be confined above 15 km during our measurement periods. Figure 2 displays a plot of the stratospheric aerosol backscatter intensity for the visible and ultraviolet wavelengths as function of altitude and latitude. The plot contains the results from 24 nights which provided a minimum of half hour averages for both the 355 and 532 nm wavelengths. Figure 2 shows backscatter ratio results from twenty four nights covering 70°N to 62°S as a function of altitude. A peak backscattering ratio of 19 was observed from the 532 nm wavelength near the equator at about 25 km. Likewise the 355 nm channel observed a peak backscatter ratio of 7.5. The time dependence of the measurement should be noted. When data was collected in Norway the Pinatubo cloud had not fully distributed itself latitudinally. There is a three month time differential between the measurements in Norway and the measurements in Antarctica. The largest optical thickness and largest backscatter ratio were observed near the equator, as expected. The most optically thick portions of the Pinatubo aerosols covered latitudes from 24°S to 30°N, and altitudes from 20 to 30 km. The aerosol cloud also settles to lower altitudes as it spreads north and south following the stratification contours established by the tropopause. The highest altitudes of enhanced aerosol scatter, above 30 km, are observed near the equator. As the cloud spreads southward it rises to about 33 km at 14°S and then the upper detectable altitude settles to 26 km at 62°S. The cloud's peak altitude steadily descends to 25 km as it spreads northward.

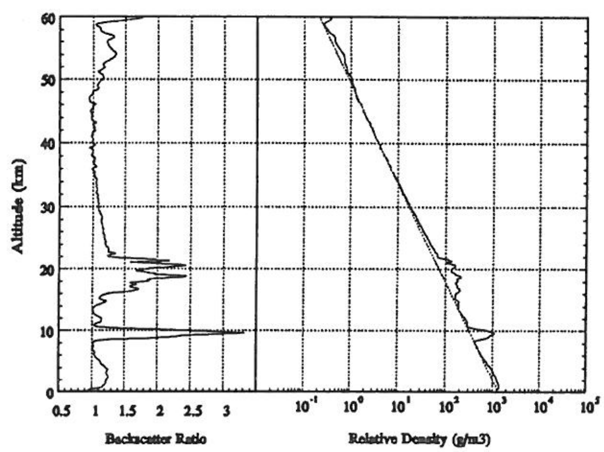

Figure 1. Backscatter ratio of the stratospheric particle layer collected with the LAMP lidar during the LADIMAS campaign of October 3, 1991.

Figure 3 shows a plot of a two-color lidar return from the ground to 40 km on the night of November 22, 1991 during the LADIMAS campaign. These profiles represent a 30 minute average with a 150 m height resolution. The profiles of the U.S Standard Atmosphere have been corrected for transmission loss using LOWTRAN 7. The profiles are then tied to this modified standard atmosphere above the Pinatubo aerosols where molecular scattering dominates. Since the molecular backscattering cross section is proportional to $1/\lambda^4$, the cross section for 355 nm is about 5 times the 532 nm backscattering cross section ($532^4/355^4 = 5.04$). The model return for 355 nm has been shifted by this same amount from the model return for 532 nm. The Pinatubo dust layer can be clearly seen on both wavelengths in the lower stratosphere between 20 and 30 km. However, between 8 and 10 km, a cirrus cloud dominates the 532 nm return, but has a much smaller signature in the 355 nm backscattered signal. This is because the molecular backscatter for the 355 nm signal is much stronger than that of the 532 nm signal, and the particle backscatter does not dominate the molecular backscatter for the 355 nm wavelength. We can then assume that the cirrus cloud consists of large particles because the scattering for both wavelengths have about the same magnitude. The particle backscatter ratio is now defined to add some understanding to the wavelength dependence of particle scattering.

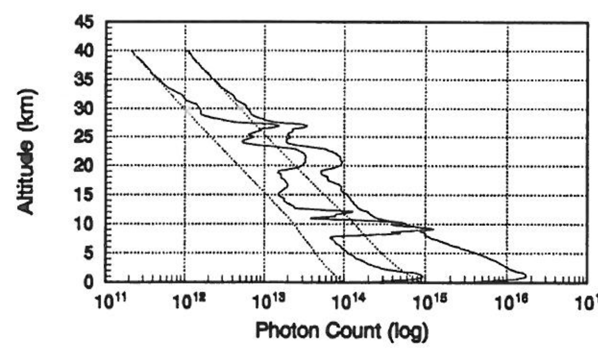

Figure 3. Lidar profiles for 355 and 532 nm wavelengths collected from the RV Polarstern on November 22, 1991.

The aerosol volume backscattering cross section, β_a, can be expressed for both the 355 nm and 532 nm wavelengths by using the lidar backscatter ratio from Equation 1. We can now define the particle backscattering ratio (PBR) as the ratio of the aerosol backscattering cross section at 532 nm to the aerosol backscattering cross section at 355 nm.

$$\textit{Particle Backscattering Ratio} = \frac{\beta_{a532}}{\beta_{a355}} = \frac{(R_{532}-1)\beta_{m532}}{(R_{355}-1)\beta_{m355}} \qquad (2)$$

The ratio of the aerosol backscattering cross sections for two wavelengths defines a relation that provides information on the particle size and distribution. Figure 4 shows the PBR for the lidar profiles in Figure 3. The PBR through the stratospheric aerosol layer between 19 and 32 km is almost constant at 0.5, while the PBR through the cirrus cloud between 9 and 10 km is clearly not constant. We can assume that the Pinatubo cloud consists of a uniform distribution of particles that remains constant through the region from 19 to 32 km. However, the cirrus cloud must contain a variety of particle shapes, sizes, and concentrations.

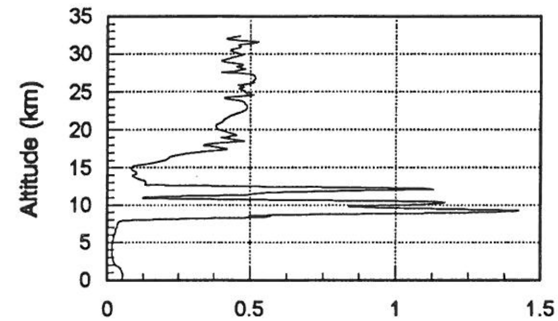

Figure 4. Particle backscattering ratio (PBR) showing the constant value of 0.5 through the Pinatubo aerosols.

Figure 5 is another example of the two-color lidar return tied to the U.S Standard Atmosphere as described above. These profiles were collected on March 29, 1992, about nine months after the eruption of the Pinatubo volcano, at The Pennsylvania State University (41°N). The plot to the right of the lidar profiles shows two distinct particle backscatter ratios between 18 and 32 km, indicating two regions of different particle size distributions. The region (17 to 22 km) with a PBR of 0.5 corresponds to a larger particle size than does the region (22 to 32 km) with a PBR of 0.25. From these lidar observations, we can conclude that after nine months the larger particles are settling to lower altitudes and separating from the smaller particles.

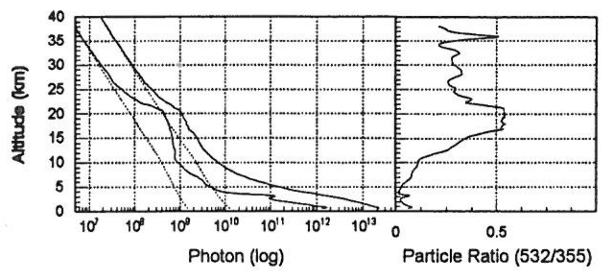

Figure 5. Lidar profiles collected at Penn State on March 29, 1992. The particle backscatter ratio is 0.5 but that layer has settled about 5km.

SUMMARY

By comparing the backscattering ratio, R(z), with the profiles from two wavelengths and the particle backscattering ratio (PBR), we can begin to discriminate molecular backscatter from particle backscatter. A comparison of particle size distribution between different layers and different nights can also be made. However, using only two wavelengths, actual particle diameters cannot be determined. This is due to the fact that the scattering region may consist of a variety of particle size distributions, which may or may not be spherical. An effective particle size and distribution could be calculated using the two different wavelengths if there were only one type of particle present and the size distribution function is assumed. However, the particle backscattering ratio profile does allow us to separate the particles into different groups based on their particle ratio values. During the LADIMAS campaign the stratospheric aerosols from the Pinatubo volcano eruption had a consistent PBR of 0.5. This tells us that we were observing the same particles with the same distribution between the latitudes of 70°N to 65°S. The LADIMAS campaign provided a unique opportunity for a lidar to observe the latitudinal distribution of the Pinatubo aerosol layers. The stratospheric aerosols are now being monitored from our measurement site at The Pennsylvania State University.

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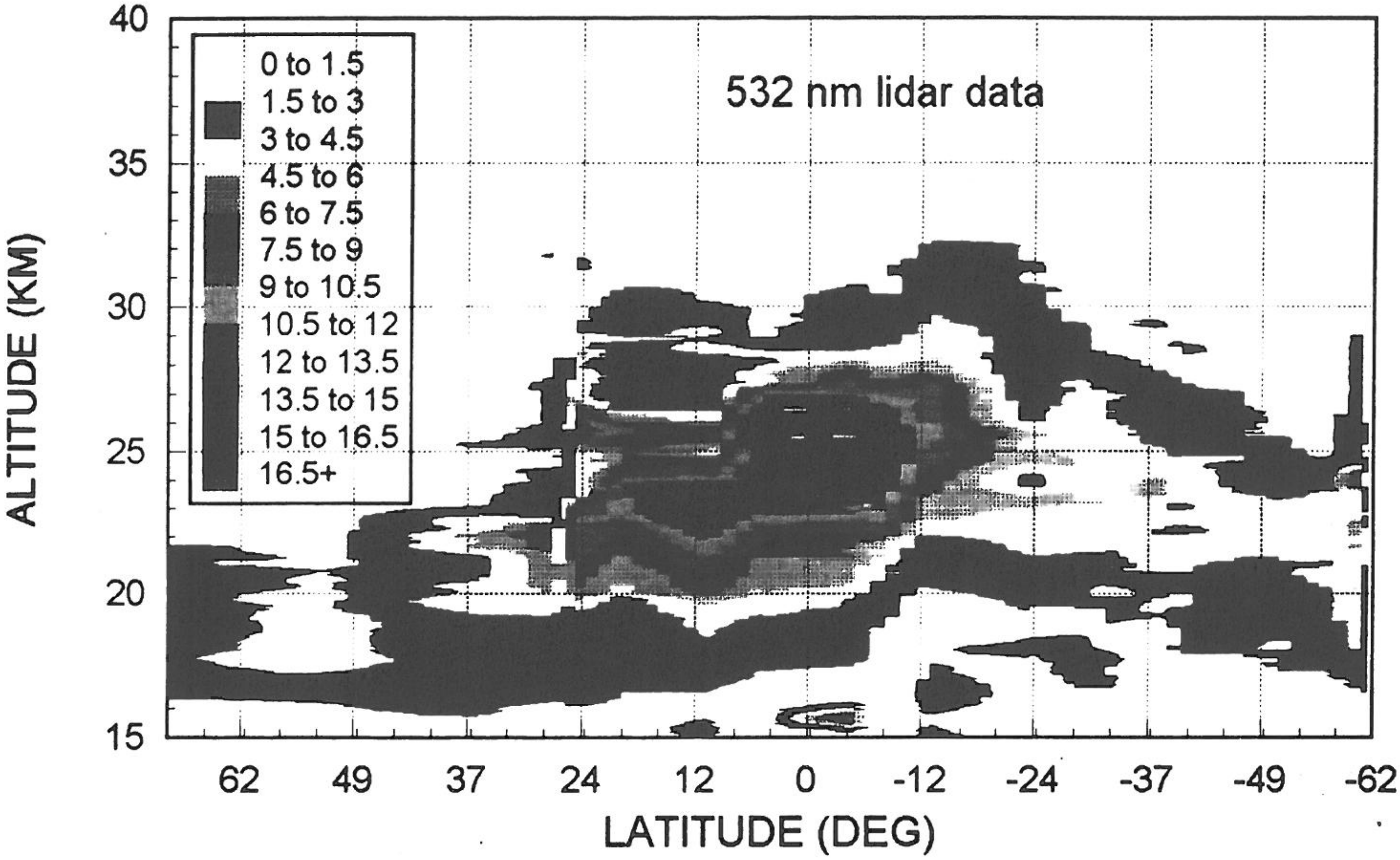
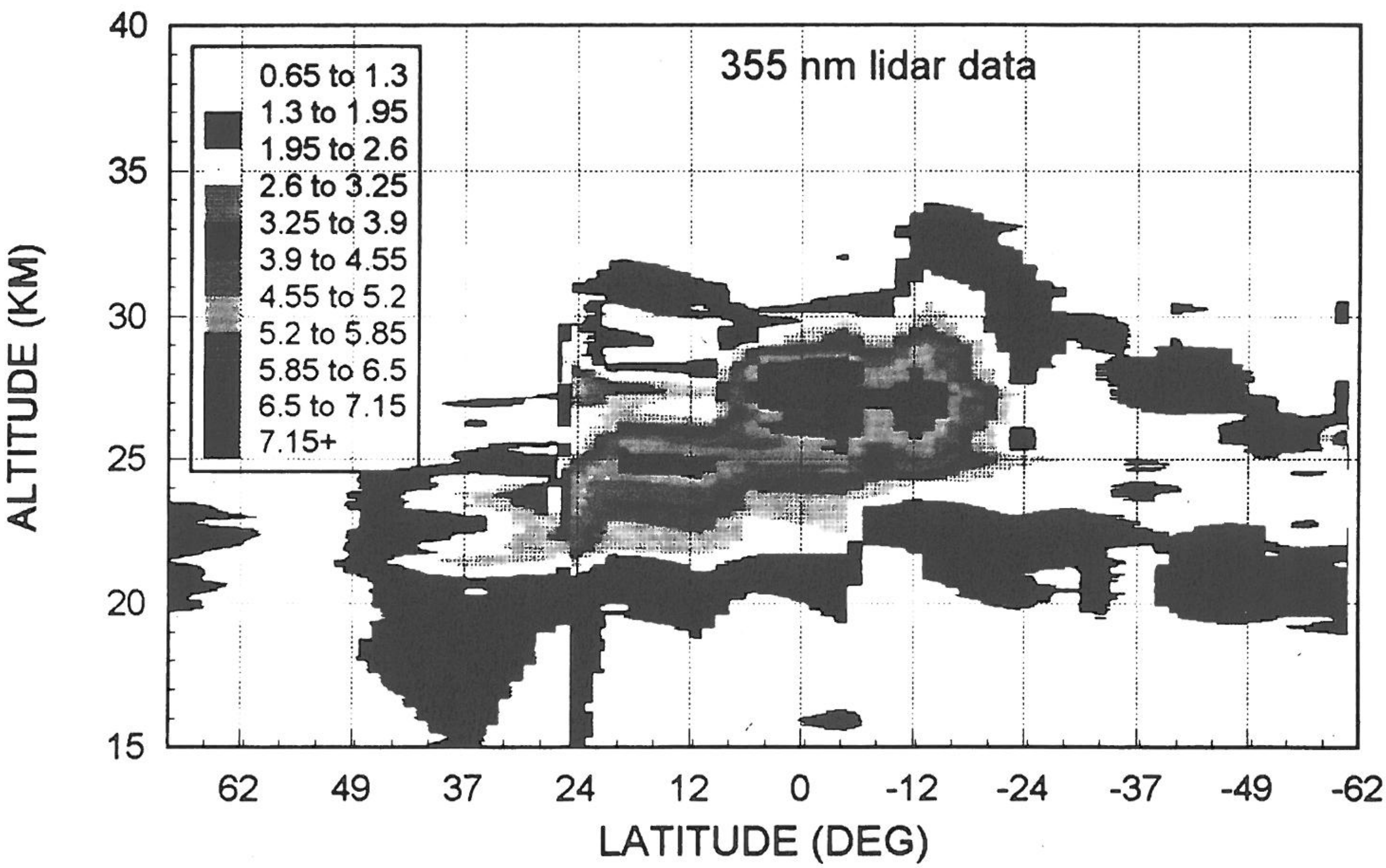

532 nm lidar data
0 to 1.5
1.5 to 3
3 to 4.5
4.5 to 6
6 to 7.5
7.5 to 9
9 to 10.5
10.5 to 12
12 to 13.5
13.5 to 15
15 to 16.5
16.5+
ALTITUDE (KM)
40
35
30
25
20
15
62
49
37
24
12
0
-12
-24
-37
-49
-62
LATITUDE (DEG)


355 nm lidar data
0.65 to 1.3
1.3 to 1.95
1.95 to 2.6
2.6 to 3.25
3.25 to 3.9
3.9 to 4.55
4.55 to 5.2
5.2 to 5.85
5.85 to 6.5
6.5 to 7.15
7.15+
ALTITUDE (KM)
40
35
30
25
20
15
62
49
37
24
12
0
-12
-24
-37
-49
-62
LATITUDE (DEG)