Title: Measurements of the Concentrations of Graphitic Carbon in Aerosol, Cloud, and Snow, and Inferences of Removal Efficiencies for Carbonaceous Aerosol Material by Snow

Administrative Data

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Other

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Models of Aerosol Backscatter, Extinction, and Absorption Profiles for Desert Aerosols Based on Aircraft Instrument and Ground-Based Lidar Measurements

by

E. M. Patterson and J. O. Oullet
School of Earth and Atmospheric Sciences
Georgia Institute of Technology

Final Report
for
Work Performed Under
Department of Commerce/NOAA PO 43RANR605269

March 1, 1991
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Measurements of atmospheric aerosols were made during the ALIVE II (Army LIDar Validation Experiment) project, held from July 10, 1989 through July 14, 1989. The measurements were taken by airborne instruments on NOAA's King Air aircraft and ground-based instruments. The airborne instruments included an Active Scattering Aerosol Spectrometer Probe, a Forward Scattering Spectrometer Probe, a Three-Wavelength Nephelometer, an Aethalometer, and a Condensation Nucleus Counter. The ground-based instruments included a Lidar, and an Aethalometer similar to that on the aircraft. Among the goals of this program was the assessment of the utility of lidar systems for the inference of aerosol attenuation and absorption and the determination of the relative importance of soot and soil particles in providing atmospheric absorption.

The direct measurements did not provide a complete data set, so, additional optical modeling was necessary to meet these goals. The purpose of this thesis was to analyze the data from the various instruments, to form models of aerosol optical properties, and to calculate absorption, extinction and backscatter as functions of wavelength and altitude. As part of the modeling effort, the relative contributions of small and large particles to the particle optical effects were assessed.
CHAPTER I

INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has conducted a series of field measurement programs, the ALIVE (Army Lidar Validation Experiment) series, to characterize atmospheric aerosols over the desert regions of south central New Mexico. The second in the series, ALIVE II, took place from July 10, 1989 to July 14, 1989. Among the goals of this program was the assessment of the utility of lidar systems for the inference of aerosol attenuation and absorption, and the determination of the relative importance of soot and soil particles in providing atmospheric absorption. Knowledge of absorption is important because of its effects on the global radiation balance and global climate change.

Data were collected with airborne and ground-based instrumentation. The aircraft data were collected during 8 flights of NOAA’s King Air aircraft, which included segments at constant altitude levels as well as vertical profile segments. Flight dates and times are shown in Table 1.1. Times and altitudes for the constant altitude segments are shown in Table 1.2. All flights originated from and returned to El Paso, Texas.
Table 1.1 Flight Times

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The King Air carried instruments to measure aerosol concentrations, size-number distributions and optical characteristics, as well as other atmospheric parameters. A list of aircraft instrumentation is shown in Table 1.3. Five of these instruments, the Active Scattering Aerosol Spectrometer Probe (ASASP), the Forward Scattering Spectrometer Probe (FSSP), the aethalometer, the nephelometer, and the condensation nuclei counter, are used for aerosol studies.

The ground-based instrumentation included a vertically pointing lidar system operated by personnel from Georgia Tech and an aethalometer similar to that on the aircraft. Table 1.4 lists the times that the lidar was operating. This instrument and the airborne instruments are described in further detail in a later section of this report.

The direct measurements did not provide enough information to determine the desired characteristics, so additional optical modeling was required. The measurements, modeling processes, and results will be described in this thesis.

Optical models were based on Mie calculations of optical quantities using size-number distributions and complex refractive indices. Complex refractive indices were not measured directly, but were estimated using the in-situ absorption data measured during ALIVE II, as well as previously measured refractive index data. The models were
Table 1.3  Instruments on King Air Aircraft

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Parameter Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerosol Instruments</strong></td>
<td></td>
</tr>
<tr>
<td>Aethalometer</td>
<td>Absorption due to Graphitic Carbon</td>
</tr>
<tr>
<td>3-Wavelength Nephelometer</td>
<td>Scattering Coefficients at 450, 550, and 700 nm</td>
</tr>
<tr>
<td>Active Scattering Aerosol Spectrometer Probe</td>
<td>Aerosol Particle Size Distribution</td>
</tr>
<tr>
<td>Forward Scattering Spectrometer Probe</td>
<td>Aerosol Particle Size Distribution</td>
</tr>
<tr>
<td>Condensation Nucleus Counter</td>
<td>Number of Condensation Nuclei</td>
</tr>
<tr>
<td><strong>Atmospheric Instruments</strong></td>
<td></td>
</tr>
<tr>
<td>Pitot Tube/Static Pressure Port</td>
<td>Dynamic/Static Pressure</td>
</tr>
<tr>
<td>Cooled Mirror Hygrometer</td>
<td>Dew Point Temperature</td>
</tr>
<tr>
<td>Rosemount Temperature Probe</td>
<td>Temperature</td>
</tr>
<tr>
<td>Static Pressure Port</td>
<td>Pressure</td>
</tr>
<tr>
<td>Loran-C</td>
<td>Latitude</td>
</tr>
<tr>
<td>Air Data Computer</td>
<td>Longitude</td>
</tr>
<tr>
<td><strong>Fast Response Temperature Probe</strong></td>
<td>True Air Speed</td>
</tr>
<tr>
<td>Magnetic Gyro</td>
<td>Wind Direction</td>
</tr>
<tr>
<td>Short-wave Sun Photometer</td>
<td>Wind Speed</td>
</tr>
<tr>
<td></td>
<td>Gilmer’s Temperature</td>
</tr>
<tr>
<td></td>
<td>Heading</td>
</tr>
<tr>
<td></td>
<td>Solar Intensity</td>
</tr>
<tr>
<td>Date</td>
<td>Time</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>July 10, 1989</td>
<td>3:28 - 7:14 PM</td>
</tr>
<tr>
<td>July 11, 1989</td>
<td>8:03 - 10:59 AM</td>
</tr>
<tr>
<td></td>
<td>2:43 - 4:59 PM</td>
</tr>
<tr>
<td></td>
<td>8:02 - 10:49 PM</td>
</tr>
<tr>
<td>July 12, 1989</td>
<td>7:24 - 10:02 AM</td>
</tr>
<tr>
<td></td>
<td>1:27 - 5:02 PM</td>
</tr>
<tr>
<td></td>
<td>7:13 - 10:53 PM</td>
</tr>
<tr>
<td>July 13, 1989</td>
<td>1:03 - 5:01 PM</td>
</tr>
<tr>
<td></td>
<td>7:02 - 10:57 PM</td>
</tr>
<tr>
<td>July 14, 1989</td>
<td>3:06 - 5:57 AM</td>
</tr>
</tbody>
</table>
verified by comparison with three-wavelength scattering measurements from the NOAA nephelometer. Calculations were made for absorption at wavelengths of 450, 530, 550, 700, and 1064 nm, for extinction at 450, 550, and 700 nm, and for backscatter at 355, 530, 1064, and 1500 nm. The values calculated for the models were then averaged by height to form height profiles of the optical properties. As a part of the modeling effort, the relative importance of different types of aerosol particles to aerosol optical properties was determined.

The background information for the ALIVE II project came from the National Oceanic and Atmospheric Administration (L. Gunter, NOAA\ERL\ARL\Aerosol Research Group; private communication). The time information for the Lidar system was provided by Dr. G. Grams at Georgia Tech. The data used for this investigation also came from those sources.
CHAPTER II
INSTRUMENT DISCUSSION

The aerosol data used in this investigation were collected from the six aerosol instruments listed in chapter I. The purpose of this chapter is to provide a brief introduction to these instruments. The aircraft instruments are described first, followed by a discussion of the lidar system.

**Active Scattering Aerosol Spectrometer Probe**

The Active Scattering Aerosol Spectrometer Probe (ASASP) and the Forward Scattering Spectrometer Probe (FSSP) are manufactured by Particle Measurement Systems (PMS), Inc. These probes and several others are commonly referred to as Knollenberg devices after their developer, R. G. Knollenberg (Pinnick and Auvermann, 1979). The ASASP used for the ALIVE II project was the ASASP-100-X (Gunter, private communication).

This probe, which is designed for aircraft use, measures the number of aerosol particles in fifteen size intervals (bins) between 0.12 and 3.12 microns in diameter. The bin intervals and particle sizes measured in each bin for this instrument are shown in Table 2.1.

The ASASP-100-X utilizes both parabolic and flat
Table 2.1  ASASP Calibration Data

0.12 - 3.12 microns

<table>
<thead>
<tr>
<th>Bin</th>
<th>Particle Size (microns)</th>
<th>Interval (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.120 - 0.145</td>
<td>0.025</td>
</tr>
<tr>
<td>2</td>
<td>0.145 - 0.195</td>
<td>0.050</td>
</tr>
<tr>
<td>3</td>
<td>0.195 - 0.270</td>
<td>0.075</td>
</tr>
<tr>
<td>4</td>
<td>0.270 - 0.370</td>
<td>0.100</td>
</tr>
<tr>
<td>5</td>
<td>0.370 - 0.495</td>
<td>0.125</td>
</tr>
<tr>
<td>6</td>
<td>0.495 - 0.645</td>
<td>0.150</td>
</tr>
<tr>
<td>7</td>
<td>0.645 - 0.820</td>
<td>0.175</td>
</tr>
<tr>
<td>8</td>
<td>0.820 - 1.020</td>
<td>0.200</td>
</tr>
<tr>
<td>9</td>
<td>1.020 - 1.245</td>
<td>0.225</td>
</tr>
<tr>
<td>10</td>
<td>1.245 - 1.495</td>
<td>0.250</td>
</tr>
<tr>
<td>11</td>
<td>1.495 - 1.770</td>
<td>0.275</td>
</tr>
<tr>
<td>12</td>
<td>1.770 - 2.070</td>
<td>0.300</td>
</tr>
<tr>
<td>13</td>
<td>2.070 - 2.395</td>
<td>0.325</td>
</tr>
<tr>
<td>14</td>
<td>2.395 - 2.745</td>
<td>0.350</td>
</tr>
<tr>
<td>15</td>
<td>2.745 - 3.120</td>
<td>0.375</td>
</tr>
</tbody>
</table>
mirrors to collect light that is scattered between 35 and 120 degrees from the laser beam’s forward direction. The laser used by this instrument is a hybrid He-Ne laser operating at a wavelength of 632.8 nm (PMS, 1980). Figure 2.1 (PMS, 1980, figure 1) presents a diagram of the optical system of the ASASP-100-X. Because of the intra-cavity configuration of the ASASP, it has a large energy density in the active cavity, leading to enhanced sensitivity to small particles.

In operation, the ASASP draws air that contains aerosols into the instrument, and passes it through a laser beam. The light that is scattered by the aerosols then passes through collecting optics to photodetectors. The light scattered by single particles is then fed into a 15 channel pulse height analyzer, which sorts the particles by scattering intensity, which is related to particle size by a calibration with particles of a known size. Particles that do not pass within the region of maximum laser intensity are electronically rejected (Pinnick and Auvermann, 1979) to increase sizing accuracy. The theory for this type of instrument is summarized in Schuster and Knollenberg (1972).

**Forward Scattering Spectrometer Probe**

The Forward Scattering Spectrometer Probe (FSSP), which is also designed for aircraft use, may be used to measure number densities and size distributions of aerosols between
Figure 2.1  Optical System of the ASASP-100-X
(from PMS, 1980)
2 and 100 microns in diameter. This size range makes it useful for measuring water droplets in clouds, as well as aerosols (Lock and Havenac, 1989a). In this experiment the measured sizes ranged from 2 to 32 microns. The bin intervals and particle sizes measured in each bin for this instrument are shown in Table 2.2.

The FSSP works in a manner similar to the ASASP, except it is not an intra-cavity device. Illumination is provided by a 5 mW He-Ne laser. Light that is scattered between 3 and 13 degrees from the forward direction of the beam by aerosols is collected (Pinnick and Auvermann, 1979).

The FSSP has a special circuit to avoid undersizing the aerosols that pass through it. Undersizing occurs when a particle passes too closely to the edge of the laser beam. The time required for particles to pass through the beam is measured electronically, and an average travel time is calculated. If a particle’s travel time through the beam is greater than the average, it is accepted. If the travel time is less than the average, it is rejected (Baumgardner, 1983).

Much work has been done with the FSSP, and several studies have been done to verify the accuracy of these instruments (Pinnick and Auvermann, 1979; Pinnick and Rosen, 1979; Pinnick et al., 1981; Baumgardner, 1983). Studies have also been done to provide corrections to the values from these instruments (Lock and Hovenac, 1989a; Lock and
<table>
<thead>
<tr>
<th>Bin</th>
<th>Particle Size (microns)</th>
<th>Interval (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00- 4.00</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>4.00- 6.00</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>6.00- 8.00</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>8.00-10.00</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>10.00-12.00</td>
<td>2.0</td>
</tr>
<tr>
<td>6</td>
<td>12.00-14.00</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>14.00-16.00</td>
<td>2.0</td>
</tr>
<tr>
<td>8</td>
<td>16.00-18.00</td>
<td>2.0</td>
</tr>
<tr>
<td>9</td>
<td>18.00-20.00</td>
<td>2.0</td>
</tr>
<tr>
<td>10</td>
<td>20.00-22.00</td>
<td>2.0</td>
</tr>
<tr>
<td>11</td>
<td>22.00-24.00</td>
<td>2.0</td>
</tr>
<tr>
<td>12</td>
<td>24.00-26.00</td>
<td>2.0</td>
</tr>
<tr>
<td>13</td>
<td>26.00-28.00</td>
<td>2.0</td>
</tr>
<tr>
<td>14</td>
<td>28.00-30.00</td>
<td>2.0</td>
</tr>
<tr>
<td>15</td>
<td>30.00-32.00</td>
<td>2.0</td>
</tr>
</tbody>
</table>
The FSSP was externally mounted with no internal airflow. The ASASP requires air to be drawn through the instrument, possibly leading to the loss of large particles in the inlet. It should be noted that other instruments that require air to be drawn into them, such as the nephelometer and aethalometer, could also suffer from these losses. Since the FSSP is mounted externally, it should not suffer from these losses.

**Aethalometer**

The aethalometer was developed by the University of California at Berkeley’s Lawrence Berkeley Laboratory, Energy & Environment Division. The name for this instrument was taken from the Greek word αἰθαλόμετρον, which means to blacken with soot. The instrument is used to make real-time measurements of graphitic (black) carbon concentration which is determined by means of an absorption measurement (Hansen et al., 1982).

The Aethalometer measures changes in attenuation of a light beam due to collection of aerosol particles on a filter. Figure 2.2 (Hansen, et al., 1982, figure 1) presents a block diagram for the instrument. Air is drawn into the instrument and through a filter that is partially covered by a transparent mask. The uncovered part of the filter collects particles from the air. Light from a
Optical and Aerosol Collection Components:
A,B, Source Optics; C, Quartz Light Guide; D, Transparent Mask; E, Filter with Particles Collected on Portion Underneath Hole in Mask; F, Filter Support with Optical Fibers Set in; G, Flowmeter.
Electronic System Components:
1, Silicon Photodetectors; 2, Logarithmic Amplifiers; 3, Difference Amplifier Giving Output Proportional to ln(I/lo); 4, A/D Converter; 5, Storage and Subtraction; 6, Variable Time Base; 7, D/A Converter.

Figure 2.2 Block Diagram of Aethalometer
(from Hansen, et al., 1982)
stabilized incandescent lamp is directed by a quartz light guide to illuminate the filter uniformly (Hansen, et al., 1982). The instrument used in this experiment had a broadband light source centered at a wavelength between 700 and 800 nm (A. Hansen, private communication). The light is collected by two optical fibers, one located behind each of the two parts of the filter. It is then passed to silicon photodetectors where the beam intensity for each portion of the filter is determined. This information is then passed to a logarithmic ratiometer, which determines the attenuation caused by the particles on the filter. This information is then recorded in digital form, but can also be converted back to analog form. The relationship between the attenuation and the amount of graphitic carbon was determined by laboratory calibration; this calibration factor was then used to calculate the graphitic carbon concentration for the measured attenuation (Hansen, et al., 1982).

**Integrating Nephelometer**

The nephelometer used for this investigation is a three-wavelength integrating nephelometer that measures aerosol scattering at 450, 550, and 700 nm wavelengths. It integrates light that is scattered over the angles of 6-170 degrees. Air flows continuously through the instrument while it is in operation. The air is illuminated by a 150-
watt tungsten-halogen lamp. The scattered light is detected by three photomultiplier tubes. The three different wavelengths are determined by a color-splitter and three thin-film interference filters (Bodhaine, et al., 1989). Figure 2.3 (Bodhaine, et al., 1989, figure 1) is a diagram of the optical geometry of this instrument.

This instrument is designed for airborne operation. Pressure and temperature inside the scattering volume are measured continuously. This allows calculations of the internal air density to be made. From this, the Rayleigh scattering can be subtracted from the total scattering to get the scattering contribution from the aerosols. This instrument can also determine the Rayleigh scattering by measuring filtered air. It will store the values of Rayleigh scattering and update them as the temperature or pressure change. It can also be operated so that it switches back and forth between filtered and ambient air. These qualities make this nephelometer suitable for airborne use at several different pressure levels (L. Gunter, private communication).

This general type of nephelometer has been extensively used in visibility studies (Gordon and Johnson, 1985). A description of the problems associated with comparing visibility data from an integrating nephelometer to aerosol spectrometer probe data was presented by Loveland and
Figure 2.3 Optical Geometry of the NOAA Three-wavelength Nephelometer. (from Bodhaine, et al., 1989)
Lindberg (1988). The possible problems discussed in this article were the choice of complex refractive index, the limited acceptance angle of scattered light for the visibility meter used, the inability of the spectrometer probes to measure very small particles, and a problem with the improper transit time rejection circuitry in the probes, causing improper particle counts at low pulse repetition rates. Each of these problems varies in significance, depending on the conditions that the measurements are taken under.

**Condensation Nuclei Counter**

Condensation nuclei counters determine the number of particles of a given size range by optical methods. This instrument works by saturating an aerosol sample with water vapor, and then adiabatically expanding it to a lower pressure. This causes supersaturation, which in turn causes water droplet growth on the condensation nuclei. The water droplets are then measured by either light-transmission or light-scattering techniques (Liu and Pui, 1974). The condensation nuclei counter used in this experiment was the General Electric Condensation Nuclei Counter (L. Gunter, private communication). It measured particles ranging from approximately .01 to 1 micron in diameter (J. Boatman, private communication). In the remainder of this report the condensation nuclei counter is referred to as the cn counter.
**Aircraft Data Storage**

The data from the airborne instruments were collected by the onboard data collection system. During post flight processing, three types of files were generated. One type of file contained the ASASP data, one type contained the FSSP data, and the third type contained the remainder of the airborne data. There were two sets of these files for each flight. One set was averaged over ten second time periods and the other was averaged over one minute time periods. Since the ten second averaged files require much more computer time for reduction and would give only slightly better resolution, only the one minute averaged files were used.

**Lidar**

The term lidar is an acronym for light detection and ranging. Lidars work in a manner similar to radar, and are therefore also referred to as laser radars (Grams, 1970) or optical radar (Fiocco and Grams, 1964).

A laser is used to emit an intense pulse of light through the lidar’s output optics toward a target area. The pulse is then scattered by the target, and some of the light is returned to the lidar (Measures, 1984). The returned light is collected by a telescope and focused onto a photomultiplier detector. After this, the information from the detector is processed and recorded (Stull, 1988).
The lidar used for this experiment was built by the Georgia Tech Research Institute (GTRI) under a contract from the University of Washington. It uses a Nd:YAG laser that emits pulses of energy at the fundamental wavelength of 1.064 microns and the frequency doubled wavelength of 0.532 microns. The light that is backscattered is collected by a 14" Cassegrain telescope. The light is then collimated and directed to a dichroic mirror which is at an angle of 45 degrees to the beam. The 1.064 micron light is transmitted directly through the mirror, through a 0.8 nanometer narrow band interference filter, and is then focused onto a silicon avalanche photodiode. The 0.532 micron light is reflected through a 0.5 nanometer narrow band interference filter and onto the face of a 2" diameter photomultiplier tube (C. Wyman, private communication). The signal from these collectors are then passed through preamplifiers and logarithmic amplifiers and then digitized by 12-bit analog to digital converters. The information is then stored on an IBM PC/AT computer.

Information from the ground-based Lidar came in the form of photographs of color coded time profiles of backscatter values (Grams, 1990).
Chapter III

ANALYSIS OF AIRCRAFT DATA

Before models of aerosol optical properties could be formed, it was necessary to first analyze the data set. This required many calculations and the making of several assumptions. The purpose of this chapter is to detail the analysis of the data set. Unless otherwise mentioned, the plots in this chapter are from flight 1. These plots provide a good representation of all eight flights.

Division into Small and Large Particle Sizes

Logarithmic plots of the number of particles/cm$^3$/micron versus diameter provided by NOAA were studied. Figure 3.1 is a representative example of the NOAA plots from flight 3. From this and the other plots, it can be seen that the slope of the distribution changes at particle sizes near 1.0 microns in diameter, indicating different particle modes. Therefore, the data set was divided into small and large particles at 1.0 microns.

By looking at the bin size ranges of the aerosol spectrometer probes where the slope changed, it was decided to make the mode separation after ASASP bin number eight (1.020 microns). This means that ASASP bins one through eight were considered to be small particles, and ASASP bins
Figure 3.1 Number of Particles/cm³/micron vs. Diameter (From NOAA)
nine through fifteen and all fifteen FSSP bins were considered to be large particles.

There was however, a problem with overlap of particle size ranges between these two instruments. ASASP bins thirteen through fifteen measured particles from 2.070 microns to 3.120 microns in diameter. The first bin of the FSSP measured particles from 2.00 to 4.00 microns in diameter. In order to determine which instrument best represented this region of data, plots of the number of particles per cm$^3$ versus time were generated for the range in question. The plot for flight 1 is shown in figure 3.2. Since the ASASP suffers from the sampling problems discussed in chapter II, it may underestimate the number of larger particles. The data in these plots indicate that this is the case. For this reason, it was decided to omit ASASP bins thirteen through fifteen in this analysis.

**Source of Aerosols**

The age of aerosol samples can be determined from the number of condensation nuclei (CN) in the sample. This information is also useful for determining the origins of the sample. Large numbers of CN indicate new aerosols, and therefore a local source. Lower numbers of CN (approximately equal to the number measured by the ASASP) indicates well aged aerosols, and therefore a distant source.
Figure 3.2 Number of Particles/cm$^3$ vs. Time from ASASP bins 13 through 15 and FSSP bin 1, Flight 1.
The number of particles per cm$^3$ vs. time were plotted for the ASASP, FSSP and condensation nuclei counter. Figure 3.3 shows this information for flight 1. By looking at the information from the CN counter, it can be seen that the number of particles measured by this instrument is higher than the values from the other two instruments. Since the CN counter measures smaller particles than the other instruments, this result was expected. Part of this plot shows low numbers (on the order of $10^3$ particles per cm$^3$) of CN particles, indicating a well aged aerosol. The other part of this plot shows higher peaks (on the order of $10^4$ particles per cm$^3$) of CN particles, indicating a newer aerosol.

The newer aerosols should have a more local source than the well aged aerosols. Since the measurements were taken over desert regions, it would be expected that CN may be associated with soil particles. Since the peaks measured by the FSSP are correlated with the peaks detected by the CN Counter, this expectation is confirmed.

**Calculation of Particle Mass**

NOAA had calculated the mass of aerosol particles for the ASASP and the FSSP as part of the data set. However, since we made the division between small and large particles as described above, new values for particle mass had to be calculated from the aerosol spectrometer probe data. This
Figure 3.3  Number of Particles/cm$^3$ vs. Time from ASASP, FSSP, and CN Counter, Flight 1.
was done for each minute of the eight flights using the formula:

$$\text{Mass} = \Sigma N_i \times \frac{4}{3} \times r_i^3 \times \pi \times \rho$$

(3.1)

where \( \rho \) is the density of the particles. The density of the large particles was taken to be 2.5 grams/cm³ after Patterson and Gillette (1977). This differed from the value of 2.0 grams/cm³ used by NOAA. This number was chosen because it was a better match to the densities of some of the major constituents of soil aerosol particles (Weast, 1988). The mass of particles is expressed as the number of grams in a cubic meter (grams/m³).

**Mie Calculations**

The Mie calculations of absorption, scattering, and backscatter due to both large and small particles was calculated from the aerosol spectrometer probes for different complex indices of refraction using the formula:

$$\sigma = \Sigma N_i \times \pi \times r_i^2 \times Q$$

(3.2)

where \( \sigma \) is the coefficient of the property of interest (absorption, scattering, extinction, backscatter), \( N_i \) is the number of particles in a bin multiplied by the width of the bin, \( r_i \) is the average radius for the bin, and \( Q \) is an average value for the efficiency of the property for each bin, calculated using Mie theory programs developed by Grams.
Twenty values of the efficiencies were calculated in each bin, and were then averaged. This formula yields values expressed in units of m$^{-1}$.

All of the aerosol particles were assumed to be perfect spheres to allow for calculations with this formula. The real component of the complex index of refraction was chosen equal to 1.525 for both small and large particles, based on measurements of Grams, et al. (1974).

Formation of Optical Models

After the preliminary analysis of the aerosol data was performed, the optical models were developed. This required the determination of the imaginary component of the complex index of refraction for both large and small particles.

Large Particles

The method used to determine the imaginary component of the complex index of refraction for large particles required the calculation of the specific absorption of the large particles from the size distributions measured by the aerosol spectrometer probes and then a comparison to the specific absorption measured by ground based instruments. A discussion with A. Hansen provided the information that the average value of the specific absorption from ground based measurements for light centered between 700 and 800 nm was 0.007 m$^2$/g. After this discussion we decided to make our calculations at the representative wavelength of 700 nm.
The specific absorption is the amount of absorption per unit mass, and is therefore calculated by dividing the absorption due to the large particles by the mass of the large particles. Calculations were made with values of the imaginary component of the complex index of refraction equal to 0.0003, 0.0004, 0.0005, 0.0006, 0.0007, and 0.001 and then plotted against time.

A comparison of the specific absorption from the probes at times when the aircraft was at low altitudes to Hansen’s surface value was then made. Figure 3.4 is a plot of the specific absorption for imaginary complex index of refraction values of 0.0005, 0.0006, and 0.0007. The bold horizontal line marks the specific absorption value of 0.007 m²/g at the times that the aircraft was flying at low altitudes. This shows that the value of 0.0006 for the imaginary component of the complex index of refraction best matches Hansen’s value of 0.007 m²/g for the specific absorption at a wavelength of 700 nm. Since the large particles are composed almost entirely of desert soil aerosols, the complex index of refraction will be constant at a given wavelength.

Since the value of the imaginary component of the complex index of refraction at this wavelength agrees with Lindberg and Gillespie (1977), their values of the complex index of refraction at other wavelengths were used. Table 3.1 lists the imaginary indices of refraction for large soil-derived particles at other wavelengths.
Figure 3.4 Specific Absorption vs. Time, Flight 1.
Table 3.1  Values of the Imaginary Component of the Complex Index of Refraction for Large Particles

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Imaginary Component of the Complex Index of Refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>355 nm</td>
<td>0.01</td>
</tr>
<tr>
<td>450 nm</td>
<td>0.007</td>
</tr>
<tr>
<td>530 nm</td>
<td>0.004</td>
</tr>
<tr>
<td>550 nm</td>
<td>0.0035</td>
</tr>
<tr>
<td>700 nm</td>
<td>0.0006</td>
</tr>
<tr>
<td>1064 nm</td>
<td>0.0006</td>
</tr>
<tr>
<td>1500 nm</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
Small Particles

The small particles were assumed to be composed primarily of graphitic carbon with a secondary aerosol such as ammonium sulfate. In order to justify this assumption, averaged values of mass for small particles and carbon particles were plotted against time. This information is shown in figure 3.5. This plot shows that the mass of small particles followed a slightly different pattern than the mass of carbon particles from the aethalometer, and therefore, the composition of the small particles was variable. Internal mixing within the small particle mode causes the imaginary index of refraction to change as the percentage of primary and secondary aerosol changes. Therefore, the complex index of refraction was not constant for the small particles as it was for the large particles.

The method used to determine the imaginary component of the complex index of refraction for the small particles required a comparison of the absorption calculated from the aethalometer to the absorption calculated from the aerosol spectrometer probes.

The aethalometer data came in the form of hand integrated values of the concentration of carbon averaged over a time period. These values were compiled by J. Boatman at NOAA/ERL/ARL/Aerosol Research Section. The absorption due to the carbon was found by multiplying the concentration of carbon by the specific absorption
Figure 3.5  Average Mass of Small Particles and Average Mass of Carbon from Aethalometer, Flight 1.
calculated for this wavelength. A value for the specific absorption based on measurements by Szkarlat and Japar (1981) was found to be 6.1 m$^2$/g at 700 nm. The aethalometer values were based on surface values of the flow rate of air through the instrument. In order to compensate for the changes of altitude during data collection, the given values were multiplied by the ratio of the density from the Standard Atmosphere at the average height for each segment of aethalometer measurements to the density of air at sea level.

Figure 3.6 is the time profile comparing absorption due to large particles to that determined from the aethalometer. On average, the large particle absorption was much less than that measured by the aethalometer. This allowed us to model the absorption from the small particles by assuming that the absorption was due entirely to the small particles.

Absorption by small particles was calculated with values of the imaginary component of the complex index of refraction equal to 0.005, 0.0075, 0.01, 0.015, 0.02, and 0.05. Figure 3.7 is a time profile of absorption from the aethalometer and from the spectrometer probes with the imaginary component of the complex index of refraction equal to 0.01, 0.02, and 0.05. This shows that no one value matched for the whole data set. Models were formed by matching the calculated absorption from the aethalometer
Figure 3.6  700 nm Absorption vs. Time, Flight 1, Comparison of Aethalometer and Large Particles.
Figure 3.7  700 nm Absorption vs. Time, Flight 1, Comparison of Aethalometer and Small Particles with Different Complex Indices of Refraction.
with the absorption calculated from the spectrometer probes with different values of the complex index of refraction. Figure 3.8 shows the results of this modeling for flight 1. These models for all eight flights are presented in Appendix A. The complex indices of refraction for the small particles were assumed to be constant with wavelength.

**Verification of the Optical Models**

In order to verify that the optical models from the absorption intercomparison were correct, an intercomparison of the nephelometer scattering data and the modeled scattering was performed.

The scattering coefficients for the nephelometer were presented in units of $m^{-1}$ for wavelengths of 450, 550, and 700 nm in the data set. The scattering coefficients for the spectrometer probes were calculated using formula (3.2) with values of $Q_{\text{sc}}$, the scattering efficiency at the different wavelengths calculated from Mie theory using refractive indices determined for large and small particles.

Figures 3.9 through 3.11 are time profiles of the measured scattering coefficients from the nephelometer and the modeled scattering coefficients at 450, 550, and 700 nm, respectively. From these graphs, it can be seen that the measured scattering is lower than the modeled values. The difference is smaller at 450 nm, but increases to approximately a factor of 2 at 700 nm.
Figure 3.8 Modeled Small Particle Absorption at 700 nm, Flight 1.
Figure 3.9 Modeled and Measured Scattering vs. Time at 450 nm, Flight 1.
Figure 3.10  Modeled and Measured Scattering vs. Time at 550 nm, Flight 1.
Figure 3.11 Modeled and Measured Scattering vs. Time at 700 nm, Flight 1.
There are two factors that led to the differences. Since the nephelometer requires air to be drawn into the aircraft, while the FSSP does not, the nephelometer may underestimate the number of large particles due to sampling inefficiencies. In addition, the nephelometer measures light scattered over the range of 6-170 degrees from the forward direction. Since the large particles being measured are significantly larger than the wavelength of light being used, a significant portion of the scattered light will be concentrated in the forward 6 degrees of the beam that is not measured by the nephelometer. The relative importance of scattering by large particles increases as the wavelength of light increases. This means that the comparison of the nephelometer data with the models should show the best agreement at 450 nm. The figures presented show that this was the case. A plot of the ratio of modeled to measured scattering vs. the ratio of large to small particle mass is shown in figure 3.12. This plot demonstrates the effect of the large particles.

Since the differences between the values of scattering determined by these two instruments can be explained by differences in the collection efficiencies of the two instruments, and by the optical efficiency of the nephelometer, the modeled values of scattering appear to be substantially correct.
Figure 3.12  Ratio of Modeled to Measured Scattering at 550 nm vs. Ratio of Large to Small Particle Mass, Flight 1.
CHAPTER IV

Models of Aerosol Optical Properties

Time Profiles of Aerosol Optical Properties

Once the optical models of the aerosols were determined and verified, they could be used to calculate values of other optical properties at different wavelengths. Modeled time profiles of absorption, scattering, extinction and backscatter cross sections were formed showing the relative contributions of large and small particles to the total. Height profiles of these properties were also formed. The wavelengths chosen included those used by the nephelometer and by the lidar. Data for flight 1 were representative of the entire data set, and are presented here. Height profiles for all 8 flights are presented in Appendix B.

Absorption

Time Profiles of absorption were formed at wavelengths of 450, 530, 550, 700, and 1064 nm. The values of absorption were calculated from the spectrometer probes by using formula (3.2) with absorption efficiencies calculated for each wavelength of light. Profiles showing the relative contribution of small and large particles to the total are presented for flight 1 in figures 4.1 through 4.5.

By looking at these figures it can be seen that the large particles play an important part in absorption for
Figure 4.1 Modeled Time Profile of Absorption at 450 nm, Flight 1.
Figure 4.2 Modeled Time Profile of Absorption at 530 nm, Flight 1.
Absorption (per meter)

1.000E-04

1.000E-05

1.000E-06

1.000E-07

1.000E-08

0 20 40 60 80 100

Time (minutes after start)

Small    Large    Combined

Figure 4.3  Modeled Time Profile of Absorption at 550 nm, Flight 1.
Figure 4.4  Modeled Time Profile of Absorption at 700 nm, Flight 1.
Figure 4.5 Modeled Time Profile of Absorption at 1064 nm, Flight 1.
light at short wavelengths, while at longer wavelengths the small particles are more important. It is also interesting to notice that the amount of absorption decreases as wavelength increases. At 450 nm, the average value of total absorption is approximately $5.0 \times 10^{-6}$ m$^{-1}$, while at 1064 nm, the average value of total absorption is $8.0 \times 10^{-7}$ m$^{-1}$.

Scattering

Profiles of scattering were formed at wavelengths of 450, 550, and 700 nm. The scattering values were also calculated from the spectrometer probes using the formula (3.2) with scattering efficiencies calculated for each wavelength. Time profiles showing the relative importance of small and large particles to the total are presented in figures 4.6 through 4.8.

By looking at these profiles, it can be seen that the small particles contribute heavily to the scattering at short wavelengths, while large particles are more important at longer wavelengths. It can also be seen that the values of scattering are larger than the values of absorption. At 450 nm, the average value of total scattering is slightly less than $3.0 \times 10^{-5}$ m$^{-1}$. This is almost an order of magnitude higher than the absorption at the same wavelength. The total scattering also shows less variation with wavelength. At 700 nm, the average value of the total scattering was only reduced to approximately $2.0 \times 10^{-5}$ m$^{-1}$. 
Figure 4.6  Modeled Time Profile of Scattering at 450 nm, Flight 1.
Figure 4.7 Modeled Time Profile of Scattering at 550 nm, Flight 1.
Figure 4.8 Modeled Time Profile of Scattering at 700 nm, Flight 1.
Extinction

Extinction profiles were formed by adding the values of absorption and scattering. Since scattering was calculated at only 450, 550, and 700 nm wavelengths, extinction could be calculated at only these wavelengths. Extinction time profiles showing the relative contributions of large and small particles to the total are presented in figures 4.9 through 4.11.

By looking at these plots, it can be seen that the small particles are more important at short wavelengths, while large particles are more important at longer wavelengths. Since these values were calculated by adding the absorption and the scattering, and the scattering is approximately an order of magnitude larger than the absorption, this result was expected. However, since absorption depends more on small particles as wavelength decreases and large particles as wavelength increases, the effect of changing wavelength is not as great for extinction. Also, since these values were calculated by adding the other two, the extinction is greater than either the scattering or the absorption. At 450 nm, the average value of extinction is slightly greater than $3.0 \times 10^{-5}$ m$^{-1}$.

Backscatter

Time profiles of Backscatter were calculated at four wavelengths used by Lidar. These wavelengths were 355, 530,
Figure 4.9 Modeled Time Profile of Extinction at 450 nm, Flight 1.
Figure 4.10  Modeled Time Profile of Extinction at 550 nm, Flight 1.
Figure 4.11 Modeled Time Profile of Extinction at 700 nm, Flight 1.
1064, and 1500 nm. These values were also calculated with formula (3.2). The Mie programs used to calculate the backscatter efficiencies calculated radar cross sections instead of backscatter cross sections. This parameter differs from backscatter cross sections by a factor of 4. It is equal to the backscattering phase function as defined by Measures (1984) multiplied by the scattering cross section. Since the backscatter profiles will be verified by comparison to height profiles from the Lidar, time profiles are not presented.

Formation of Height Profiles

Once the time profiles of the aerosol optical properties were formed, they could be used to produce height profiles of these values. However, the height of observations were not recorded as part of the data set, and therefore had to be calculated.

Calculation of Height

Since air pressure was recorded in the data set, the height of the observations were calculated from the pressure using the hydrostatic equation:

$$\frac{dP}{dz} = -\rho g$$  \hspace{1cm} (4.1)

The equation of state was used to substitute for $\rho$, the density of the air.

$$\rho = \frac{P}{RT}$$  \hspace{1cm} (4.2)
This yielded the equation:

\[ \frac{dP}{dz} = -\frac{Pg}{RT} \]

or,

\[ \frac{dP}{P} = -\frac{gdz}{RT} \quad (4.3) \]

By assuming that \( g/rt \) was constant with height, equation (4.3) was integrated from sea level where \( z=0 \) and \( P=P_0 \) to an arbitrary height \( z \) where \( P=P \),

\[ \frac{dP}{P} = -\frac{g}{RT} \, dz \quad (4.4) \]

which then yields

\[ \ln\left(\frac{P}{P_0}\right) = -\frac{gz}{RT} \quad (4.5) \]

The scale height of an isothermal atmosphere is given by

\[ H = \frac{RT}{g} \quad (4.6) \]

Substitution of equation (4.6) into equation (4.5) and solving for \( z \), the height above mean sea level, gives

\[ z = H \ln\left(\frac{P_0}{P}\right) \quad (4.7) \]

The value of the scale height, \( H \), was chosen from the U.S. Standard Atmosphere, 1976. The altitude of the El Paso airport is listed as 3762 feet (1147 meters). Therefore, a scale height corresponding to a geometric height of 1150
meters was used. This gives a scale height of 8218.7 meters.

Equation (4.7) was evaluated for every minute of the eight flights. Figure 4.12 shows the heights calculated from this equation for flight 1. It is important to note that the calculated heights are meters above sea level. The altitude can be found by subtracting the height of the surface from these values. The calculated heights for all eight flights are presented in Appendix B.

This method does cause some error. The major cause of error with this method is the assumption of an isothermal atmosphere to determine the scale height. This gives very good agreement at low levels, but because of the decrease of temperature with height in the atmosphere, the heights of the higher levels are slightly overestimated. A better method would have been to use the measured temperatures to evaluate equation (4.6) for each minute of the flights. Future work could also use a Standard Atmosphere to derive the heights from pressure to height relationships.

Averaging of Height Profiles

Since heights were calculated for each minute of the flights, profiles could be formed by plotting the values directly against height. Figure 4.13 shows the results of plotting absorption against height. From this figure, it can be seen that there is more than one value of absorption at some heights. This makes the plots very confusing. In
Figure 4.12  Calculated Height vs. Time, Flight 1.
Figure 4.13  Absorption vs. Height at 700 nm, Flight 1.
order to avoid this confusion we averaged the profiles in height ranges.

The optical properties were averaged by height in increments of 100 meters over the heights where data was available. If there was no data present in a given 100 meter interval, no average was calculated for that interval. The averaged height profiles for the modeled optical properties are presented for flight 1 in the following sections.

Absorption, Scattering, and Extinction

Figures 4.14 through 4.16 present height profiles of absorption, scattering and extinction at wavelengths of 450, 550, and 700 nm for flight 1. These figures show the same dependence on particle size as the time profiles. However, information about the vertical distribution can be determined from these profiles. For example, at a height of approximately 1800 meters (altitude of approximately 800 meters) there is a sharp drop off in the modeled values. This is interpreted as indicating the top of the surface mixed layer (or PBL). There is also apparently an enhanced population of large particles at the higher altitudes of the aircraft measurements. The height profiles of absorption, scattering, and extinction for all eight flights are presented in Appendix C.

Backscatter

Figure 4.17 presents height profiles of backscatter,
Figure 4.14  Height Profiles of Absorption, Flight 1: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 4.15  Height Profiles of Scattering, Flight 1: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 4.16  Height Profiles of Extinction, Flight 1:
(a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 4.17  Height Profiles of Radar Cross Sections, Flight 1: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
modeled as radar cross sections, at wavelengths of 355, 530, 1064, and 1500 nm for flight 1. This graph shows that small particles are important only at 355 and 530 nm wavelengths, while at longer wavelengths the backscatter is caused almost entirely by the large particles. These models were compared to lidar data taken during this experiment. Figure 4.18 (Grams, 1990, figure L5) is a color coded time/height profile of the lidar data for a segment of flight 3. Figure 4.19 presents the modeled radar cross sections for this flight. Because of problems with the 1064 nm channel, only the 530 nm data could be compared.

Although both data types are presented as radar cross sections, the modeled profiles show only the aerosol contribution to backscatter, while the measured values show total backscatter (i.e. aerosol and air molecule contributions). In order to compare these two data sets, the molecular backscatter had to be added to the modeled values. It is also important to remember that the modeled values were calculated for height above mean sea level, while the lidar data were based on height above ground level. Therefore, approximately 1000 meters must be subtracted from the modeled heights to match the measured data.

The molecular backscatter was calculated for different heights by multiplying the radar cross section per molecule
Figure 4.18  Color-Coded Time/Height Profiles of Radar Cross Sections, Flight 3. (from Grams, 1990)
Figure 4.19  Height Profiles of Radar Cross Sections, Flight 3: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
for the atmospheric constituents at 530 nm \((7.25 \times 10^{-25} \text{ cm}^2)\) (Grams, 1966) by the number density of air molecules from the U.S. Standard Atmosphere, 1976 at that height. These values were then compared to the color-coded time profiles. Table 4.1 shows a partial list of the color codes used to interpret the data by Grams (1990).

Table 4.2 shows the results of the comparison of the two data sets for flight 3. The modeled and measured profiles show reasonable agreement, although the modeled values appear to be at the low end of the Lidar ranges. In order to make a more meaningful comparison, the Lidar would have to be analyzed with narrower intervals. The models do however, show some of the features shown by the Lidar. For example, at an altitude of approximately 2800 meters the Lidar shows a decrease in the amount of backscatter from a range of \(2 - 5 \times 10^{-5} \text{ m}^{-1}\) to a range of \(1 - 2 \times 10^{-5} \text{ m}^{-1}\). The models also show a decrease in backscatter at the corresponding height.

**Ratios of Backscatter to Absorption**

In order to determine the suitability of determining absorption from Lidar, a study of the relationship between backscatter and absorption was performed. Modeled values of backscatter were plotted against modeled values of absorption at 1064 and 530 nm. Figures 4.20 through 4.23 are representative examples of these plots. From these plots, there appears to be a correlation between backscatter
<table>
<thead>
<tr>
<th>Color</th>
<th>Intensity (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>Less than $1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Cyan</td>
<td>$1 \times 10^{-6}$ to $2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Light Blue</td>
<td>$2 \times 10^{-6}$ to $5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Blue</td>
<td>$5 \times 10^{-6}$ to $1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Green</td>
<td>$1 \times 10^{-5}$ to $2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Light Green</td>
<td>$2 \times 10^{-5}$ to $5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Yellow</td>
<td>$5 \times 10^{-5}$ to $1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Table 4.2 Comparison of Lidar Data

<table>
<thead>
<tr>
<th>Altitude Range (meters)</th>
<th>Modeled Backscatter ($x \times 10^{-5} \text{ m}^{-1}$)</th>
<th>Measured Backscatter ($x \times 10^{-5} \text{ m}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1000</td>
<td>2.1 - 2.7</td>
<td>2-5</td>
</tr>
<tr>
<td>1000-2000</td>
<td>1.7 - 2.0</td>
<td>2-5</td>
</tr>
<tr>
<td>2000-2800</td>
<td>1.5 - 1.8</td>
<td>2-5</td>
</tr>
<tr>
<td>2800-3000</td>
<td>1.4 - 1.5</td>
<td>1-2</td>
</tr>
</tbody>
</table>
Figure 4.20  Backscatter vs. Absorption at 1064 nm, Flight 1.
Figure 4.21  Backscatter vs. Absorption at 1064 nm, Flight 5.
Figure 4.22  Backscatter vs. Absorption at 530 nm, Flight 1.
Figure 4.23  Backscatter vs. Absorption at 530 nm, Flight 5.
and absorption. To get a better look at this relationship, the backscatter was plotted against absorption at the same wavelengths for all 8 flights. These plots are shown in figures 4.24 and 4.25. These figures show that there is some type of correlation for this set of flights. The data from this set of flights suggests that the lidar measurements may be sufficient to infer absorption on an empirical basis. The generality of this relation for other similar data sets cannot be assessed at this time, but should be investigated.
Figure 4.24  Backscatter vs. Absorption at 1064 nm, Flights 1-8.
Backscatter (per meter)

Figure 4.25  Backscatter vs. Absorption at 530 nm, Flights 1-8.
Measurements of desert atmospheric aerosols were taken by airborne and ground-based instruments during the ALIVE II field project. Some of the goals of this project were to assess the ability of different lidar systems to infer aerosol attenuation and absorption, and to determine the relative importance of soot and soil particles in causing atmospheric absorption. The measurements alone did not provide enough information to determine this information, so subsequent modeling of different optical properties was necessary.

Models of optical properties, based on Mie theory, were formed from the size-number distributions provided by the aerosol spectrometer probes by varying the complex indices of refraction. The properties modeled included absorption, scattering, extinction, and backscatter. The models were verified by comparison with measurements from other instruments. Both time and height profiles of these properties were modeled. These models allowed for the determination of the desired information.

The relative importance of large and small particles was determined for the different optical properties. Absorption
was caused primarily by large particles at short wavelengths, and primarily by small particles at longer wavelengths. Scattering and backscatter were caused primarily by small particles at short wavelengths and by large particles at longer wavelengths. Extinction was calculated by adding the values of absorption and scattering, so it showed the characteristics response of both properties to changing wavelengths. Since the values of scattering were usually much higher than values of absorption, the profiles of extinction tended to be similar to the profiles of scattering. However, the dependence on absorption reduced the effects of changing the wavelength.

The dependence of absorption coefficients on large or small particles may be interpreted to determine the relative importance of soot and soil particles. Since soot is associated with small particles, it is important at 700 and 1064 nm. The larger soil particles are more important at wavelengths of 530 nm and shorter.

The models of backscatter showed that short wavelengths were best for measuring small particles, and longer wavelengths were best for larger particles. A comparison of the modeled values of backscatter to values measured during this field project showed that the lidar and models showed reasonable agreement in determination of backscatter intensity changes and heights of features.

Plots of the ratio of backscatter to absorption were
generated to determine the relationship between backscatter and absorption. These plots showed a correlation that may allow for determination of absorption from backscatter by empirical methods. The extent and generality of this correlation was not investigated, but may prove to be an area for future work.
BIBLIOGRAPHY


Grams, G. W., 1990: "Analysis of Lidar Data Obtained at White Sands, July 1989, Final Report to Cloud and Aerosol Group, Atmospheric Sciences Department, University of Washington Under Contract Number 288507, Subcontract for NOAA Contract Number 50RANR900128, GTRI, Atlanta, GA.


APPENDIX A

Modeled Small Particle Absorption
Figure A.1  Modeled Small Particle Absorption at 700 nm, Flight 1.
Figure A.2  Modeled Small Particle Absorption at 700 nm, Flight 2.
Figure A.3  Modeled Small Particle Absorption at 700 nm, Flight 3.
Figure A.4  Modeled Small Particle Absorption at 700 nm, Flight 4.
Figure A.5  Modeled Small Particle Absorption at 700 nm, Flight 5.
Figure A.6  Modeled Small Particle Absorption at 700 nm, Flight 6.
Figure A.7  Modeled Small Particle Absorption at 700 nm, Flight 7.
Figure A.8  Modeled Small Particle Absorption at 700 nm, Flight 8.
APPENDIX B

Height Profiles of Absorption, Scattering, and Extinction
Figure B.1 Modeled Height Profiles of Absorption, Flight 1: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.2  Modeled Height Profiles of Scattering, Flight 1: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.3 Modeled Height Profiles of Extinction, Flight 1: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.4 Modeled Height Profiles of Absorption, Flight 2: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 8.5 Modeled Height Profiles of Scattering, Flight 2: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 8.6 Modeled Height Profiles of Extinction, Flight 2: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.7 Modeled Height Profiles of Absorption, Flight 3: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 5.8 Modeled Height Profiles of Scattering, Flight 3: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.9  Modeled Height Profiles of Extinction, Flight 3: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.10 Modeled Height Profiles of Absorption, Flight 4: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 3.11 Modeled Height Profiles of Scattering, Flight 4: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.12  Modeled Height Profiles of Extinction, Flight 4: (a) 450 nm, (b) 550 nm, (c) 700-nm.
Figure B.13 Modeled Height Profiles of Absorption, Flight 5: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.14 Modeled Height Profiles of Scattering, Flight 5: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.15  Modeled Height Profiles of Extinction, Flight 5: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.16  Modeled Height Profiles of Absorption, Flight 6: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.17 Modeled Height Profiles of Scattering, Flight 6: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.18 Modeled Height Profiles of Extinction, Flight 6: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure 8.19 Modeled Height Profiles of Absorption, Flight 7: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.20  Modeled Height Profiles of Scattering, Flight 7: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.21 Modeled Height Profiles of Extinction, Flight 7: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.22  Modeled Height Profiles of Absorption, Flight 8: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.23 Modeled Height Profiles of Scattering, Flight 8: (a) 450 nm, (b) 550 nm, (c) 700 nm.
Figure B.24 Modeled Height Profiles of Extinction, Flight 8: (a) 450 nm, (b) 550 nm, (c) 700 nm.
APPENDIX C

Calculated Height vs. Time
Figure C.1  Calculated Height vs. Time, Flight 1.
Figure C.2  Calculated Height vs. Time, Flight 2.
Figure C.3  Calculated Height vs. Time, Flight 3.
Figure C.4  Calculated Height vs. Time, Flight 4.
Figure C.5  Calculated Height vs. Time, Flight 5.
Figure C.6  Calculated Height vs. Time, Flight 6.
Figure C.7 Calculated Height vs. Time, Flight 7.
Figure C.8  Calculated Height vs. Time, Flight 8.
APPENDIX D

Height Profiles of Radar Cross Sections
Figure D.1  Height Profiles of Radar Cross Sections, Flight 1:  (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.2  Height Profiles of Radar Cross Sections,
Flight 2:  (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.3  Height Profiles of Radar Cross Sections, Flight 3: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.4  Height Profiles of Radar Cross Sections, Flight 4: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.5 Height Profiles of Radar Cross Sections, Flight 5: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.6  Height Profiles of Radar Cross Sections, Flight 6: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.7  Height Profiles of Radar Cross Sections, Flight 7: (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.
Figure D.8  Height Profiles of Radar Cross Sections, Flight 8:  (a) 355 nm, (b) 530 nm, (c) 1064 nm, (d) 1500 nm.