Lidar profiles of atmospheric structure properties

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ABSTRACT

Comparisons of the lidar derived profiles of the atmospheric structure properties, density and temperature, with the standard meteorological rocket profiles have been made. Seventeen flights of meteorological rockets, using both datasonde and passive falling sphere payloads, provide the first study to compare and evaluate the lidar measurements simultaneously with rocket measurements. The measurements were made at Poker Flat Research Range, Alaska during the period February through April 1986. The molecular backscatter lidar signal from a Nd:YAG laser has been used, in regions of the atmosphere where molecular scattering dominates, to determine profiles of the relative atmospheric density. By comparison with radiosonde balloon measurements in the region where the scattering is purely molecular, typically the 27 to 30 km altitude region, the density profile can be placed on an absolute scale. The temperature profiles have been determined directly from integration of the relative density profile, using the assumption of hydrostatic equilibrium. While the backscatter signals from the region of the atmosphere above 25 km are usually representative of the molecular density, the lidar was developed using a two-color approach to provide added discrimination against particle scatter. By using two wavelengths, 532 and 355 nm, we can discern the region where the molecular scattering results are expected to be valid. The results show the present capability of the lidar remote sensing technique for measurements of the structure properties of the atmosphere. The results point out the directions for the design of a lidar sounder that can be used as an operational sounder to replace the meteorological rocket and balloon techniques in the future.

INTRODUCTION

The idea of using the molecular scattering of light as an active remote sensing technique for determining the properties of the atmosphere was first explored with the searchlight experiments of Elterman[1]. The advent of the laser led many investigators to the use of the pulsed laser for range resolved measurements of the backscatter intensity from particles and molecules of the atmosphere. The early attempts have demonstrated that usable returns could be obtained, but the lack of stable laser performance and the complicated experimental equipment have delayed the routine use of laser remote sensing. Lidar applications for the measurement of meteorological properties have been a long term goal of several research thrusts. The potential for use of lidar to replace meteorological rocket probes would allow an expensive system which is based on expendable hardware to be replaced by a reliable and inexpensive remote sensing technique. The goal is to be able to use remote sensing profiles from lidar to fulfill most of the requirements for middle atmosphere structure data. The properties of the middle atmosphere, 10 to 100 km, have become extremely important because of the recent realization of the fragility of the middle atmosphere and its importance to the biosphere. The development of

0-8194-0601-5/91/$4.00

middle and upper atmosphere climatology, which is needed to improve models of the tropospheric weather, is dependent upon middle and upper atmosphere profiles of the structure parameters. The measurements have historically been accomplished with balloons and rockets, which are very expensive and are limited to snapshot investigations. The remote sensing techniques, particularly lidar, should allow us to greatly expand our understanding of the atmospheric dynamics and chemistry by use of high spatial and temporal resolution measurements.

The current investigation is one step toward the development, examination of the accuracy and limitations of the lidar measurement technique. The simultaneous comparison of rocket and lidar measurements provides the opportunity to examine the lidar measurements relative to our currently adopted measurement techniques, that is the measurements of datasondes and passive spheres. The region of the atmosphere above about 30 km, where we generally believe that molecular scattering provides the only significant contribution, should prove the easiest region for an operational sensor. The possibility to fulfill the goal of developing a meteorological lidar for the density, temperature and wind, as well as several atmospheric species, is near. Most of the atmospheric regions, at middle and low latitude (less than 60°), are expected to exhibit exclusively molecular scattering properties at altitudes above about 25 km. The only expected exception is the period following a large volcanic eruption which can inject significant scatters to altitudes near 35 km for a period of several months. At high latitude however, in the cold winter lower stratosphere, the aerosol scatters in polar stratospheric clouds, are known to form during the polar winter night. These add to the scattering of particulate layers that exist continuously in the 15 to 25 km region. Early measurements of these stratospheric scattering layers were obtained with balloon flights[2]. Also at high latitude, the summer polar mesosphere provides the conditions of vertical water transport and adiabatic cooling which result in formation of particles near 85 km, clouds known as noctilucent clouds[3].

Figure 1 shows the lidar instrument used to obtain these results. The set of measurements described here were obtained using GLINT transportable lidar[4,5] which was designed and prepared while the author was at the Air Force Geophysics Laboratory (now part of the Phillips Laboratory). During this particular measurement period, we located the instrument at the Poker Flat Research Range, Alaska (operated by the Geophysics Institute of the University of Alaska). This high latitude site allowed the opportunity to compare the lidar and meteorological rockets under a wide range of atmospheric conditions.

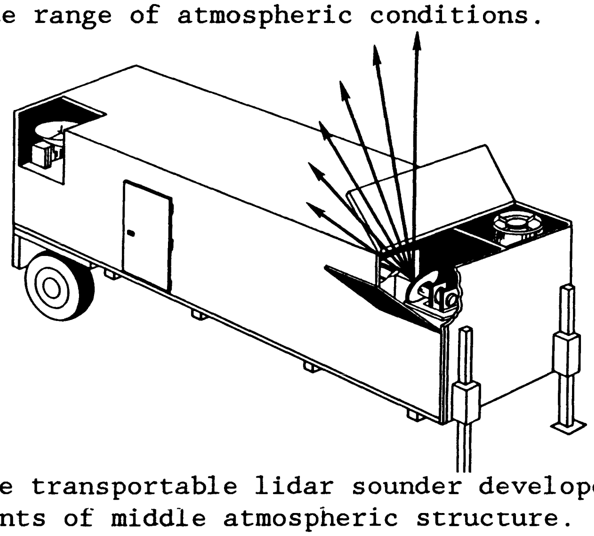


Fig 1. The transportable lidar sounder developed for field measurements of middle atmospheric structure.

The lidar transmitter, a Nd:YAG laser with a 1.2 joule output at the fundamental wavelength, produces pulses of approximately 8 ns at 10 Hz. In the normal operating configuration, the power output measured at 532 nm is about 500mj, when the tripling crystal is de-tuned. For a period of 15 minutes, at the beginning and the end of each night, the 355 nm output was maximized (near 170 mj), while backscatter data on the green and ultraviolet wavelengths were simultaneously obtained. Figure 2 shows the layout of the transmitter and receiver. The beam was expanded through a 5 power beam expander to provide a 0.14 mrad beam divergence. The energy output of each pulse was monitored and the average output was recorded with the data. The primary receiving telescope is a 32 cm Dall-Kirkham configuration which is co-aligned with the optical axis of the laser. A mechanical shutter, which cut the image of a Fabry lens, prevents the low altitude return from saturating the photon counting PMT's. The photomultiplier tubes were cooled to reduce the background noise. The results of the low altitude system are being presented here, however, we have also included in the instrument system a larger 62 cm telescope, a Raman detector and a narrow-band daytime detector. The daylight background detector uses a narrow band thermally stabilized filter followed by a piezoelectric tuned Fabry-Perot filter, to obtain a band pass of 0.03 nm. This allows us to measure the laser molecular backscatter of the atmosphere above the day sky background to altitudes near 60 km.

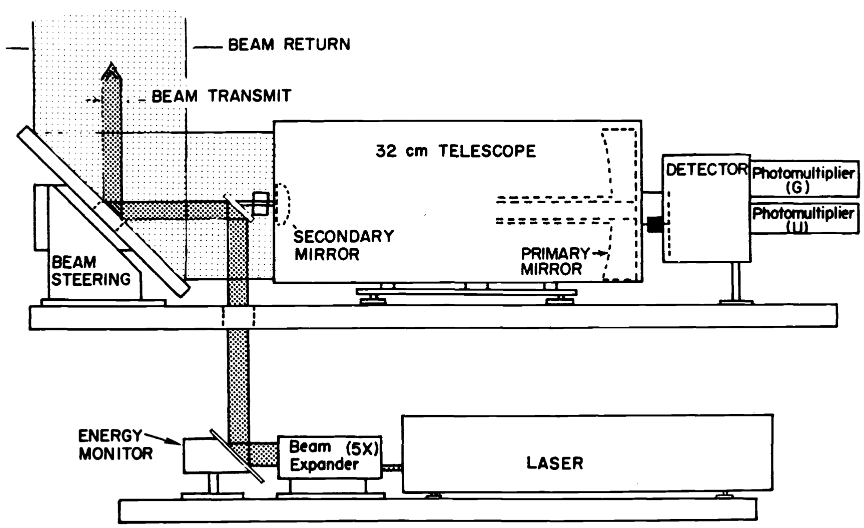


Fig 2. The optical diagram for the primary transmitter and receiver used in the GLINT lidar system.

METEOROLOGICAL ROCKET MEASUREMENTS

The two meteorological rocket payload techniques, which have been accepted and are most frequently used for the measurements above 20 km, are the datasonde and passive sphere. Each of these payloads (see Figure 3) are launched on a small rockets, usually the Super-Loki rocket, to apogee altitudes near 80 km, for the datasonde, and 95 km, for the passive sphere. A summary of the techniques and a brief description of the measurement capabilities have been prepared by Schmidlin[6]

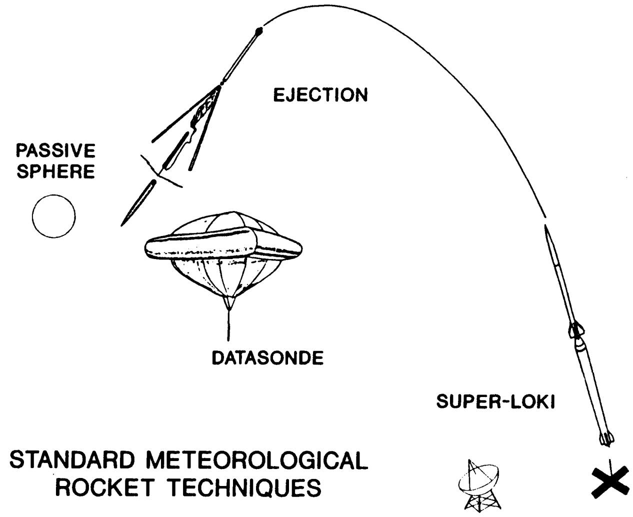


Figure 3. The primary meteorological rocket systems are the datasonde and passive sphere.

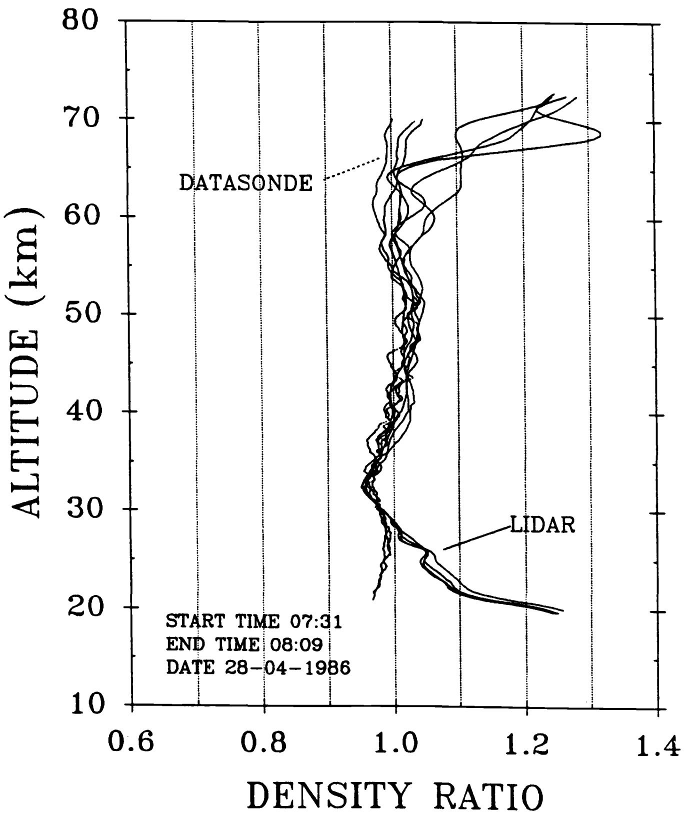
The datasonde consists of an instrument package of a miniature bead thermistor together with a telemetry transmitter which, after ejection near apogee, drifts downward on a 1.3 meter starute parachute. The horizontal drift measured by radar provides a measure of wind velocity. The transmitted temperature measurements are useful between 20 and 70 km, however those measurements are subject to significant corrections above 50 km due to the reduced thermal coupling with the atmosphere. The corrections of the bead thermistor values due to lead conduction, payload radiation, solar direct and scattered radiation, and related effects become significant. At altitudes above 50 km, the time response of the sensor does not permit the measurement resolution to follow the wave features which could be present. The density and pressure profiles are obtained by tying to the density and pressure measurements, in an overlap region between 20 and 25 km, to the upper end of data from a balloon sonde. The overlap region provides a starting value, at the low altitude end, which is used to generate the profile from integration of the hydrostatic equation.

The passive sphere is a 1 meter metalized mylar balloon which inflates at apogee and falls through the atmosphere. It is tracked, as it falls, by a precision radar which records the position and velocity. The horizontal wind components are obtained from the horizontal velocity measurements. The vertical acceleration is determined and used to measure the atmospheric drag force. The atmospheric density is determined directly from the drag acceleration using the wind-tunnel measurements of drag coefficient, assuming that the vertical wind component is zero.

ATMOSPHERIC DENSITY AND TEMPERATURE STRUCTURE

The use of the molecular backscatter signal for measurements of atmospheric structure in the clear atmosphere has been demonstrated by several research groups and has been used for intensive investigations of the middle atmosphere by us and by the French CNRS investigators[7], who have produced a sustained record of measurements during the past few years. At mid-latitude, the measurements may be directly usable above 25-30 km. We have been concerned about clearly defining the region where the particle backscatter may contaminate the results, this was the basis for our decision to use the two-color approach[8]. The results have shown that by measuring at the 532 and 355 nm wavelengths, the region with aerosol backscatter can be clearly defined, thus providing more confidence in the results.

Figure 4 shows the results of a set of four rocket measurements and corresponding lidar profiles obtained on 28 April 1986. The general agreement and consistency of the measurements during the 4 hour period when they were made is considered good. The differences are primarily due to aerosols at low altitudes (below 27 km), the smoothing of the wave structure at the higher altitudes is due to the poor resolution of the datasonde, and the small scale differences which are due to the atmospheric granularity in the turbulent cells observed with high resolution sensors. The measured lidar signal is proportional to the molecular density. The density profile is obtained by tying to the rawinsonde balloon results near 27 km in the region of pure molecular scattering, which is chosen by examination of the two-color lidar results. The temperature is determined by integrating the signal which is proportional to the density[9].



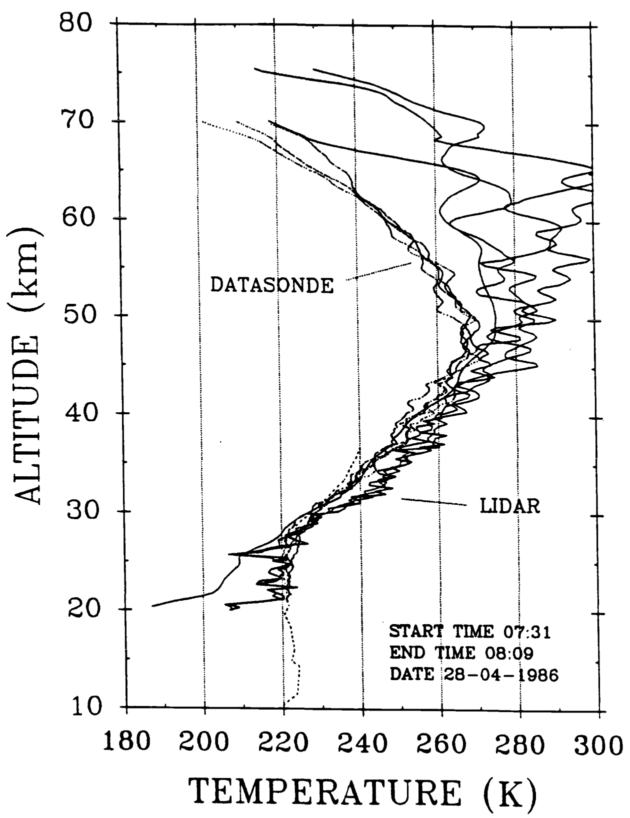


Fig 4. The four datasonde rocket flights and the corresponding lidar results are shown for the density ratio to the USSA76 model and for the temperature.

The results obtained in March 1986, which are shown in Figure 5 also show good agreement between the measured profiles from the lidar and those obtained with the rocket payloads. The rocket flights of two passive spheres and the corresponding lidar results are shown. The amplitude of the middle atmosphere wave structure is larger in the winter, for example compare Figure 5 (8/9 March) with Figure 4 (28 April). The difference in the mean profiles above 60 km indicates to presence of additional scatters, possibly the optical scattering associated with formation of polar mesospheric clouds.

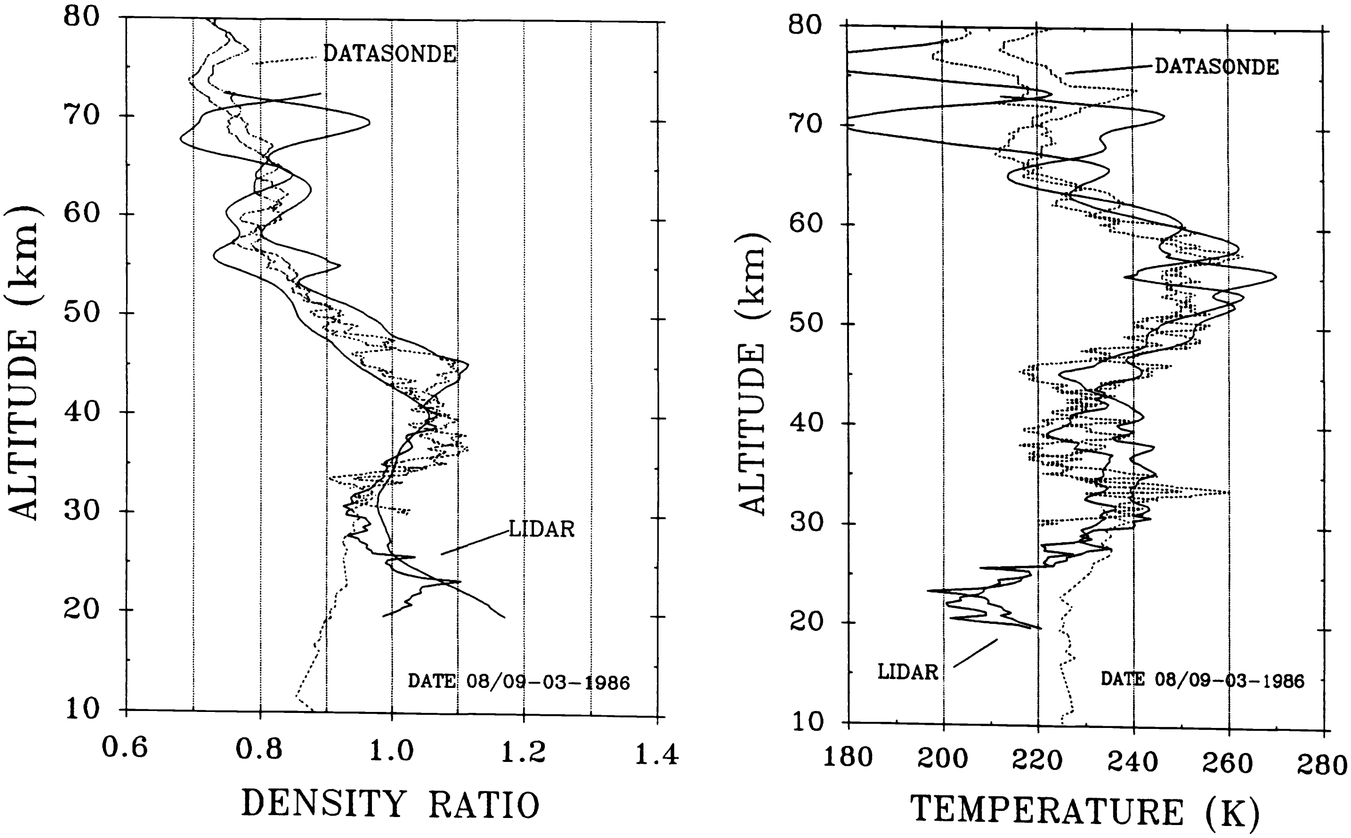


Fig. 5. The density and temperature results obtained on 8 and 9 March 1986 at the same time by rocket instrument and lidar.

Most of the results exhibit good agreement, but when evaluating the performance several extreme cases must be considered. The results in Figure 6 show a case with rather large differences between the passive sphere rocket data and the lidar results. This case is during a period of very high horizontal wind speed, 120 m/s at 65 km and greater than 60 m/s between 35 and 55 km. Under these conditions, it would be expected that a large vertical winds could also be present. Vertical wind components up to 6 m/s have been found to be associated with gravity waves in the middle atmosphere[3]. The vertical wind of a few meters per second can affect small changes in the apparent density. A large horizontal wind shear velocity can also change the effective Mach number and associated drag coefficient. The point that the difference is probably due to atmospheric dynamics effects on the sphere can be seen by comparison with the datasonde results.

DISTINGUISHING BETWEEN MOLECULAR AND PARTICLE SCATTERING

The difference in scattering cross-section for particle and the molecular components can provide a powerful technique to identify and separate the particle scatter from the molecular component. A second way to distinguish the particle component is to examine both the fundamental and the 1st Stokes vibrational Raman scatter signal of nitrogen. The Raman signal provides a direct measure of the specific molecule, assuming that the extinction is not greatly different between the fundamental wavelength and the scattered wavelength, that is, the weak wavelength dependence or a known dependence of the particle scattering must be assumed.

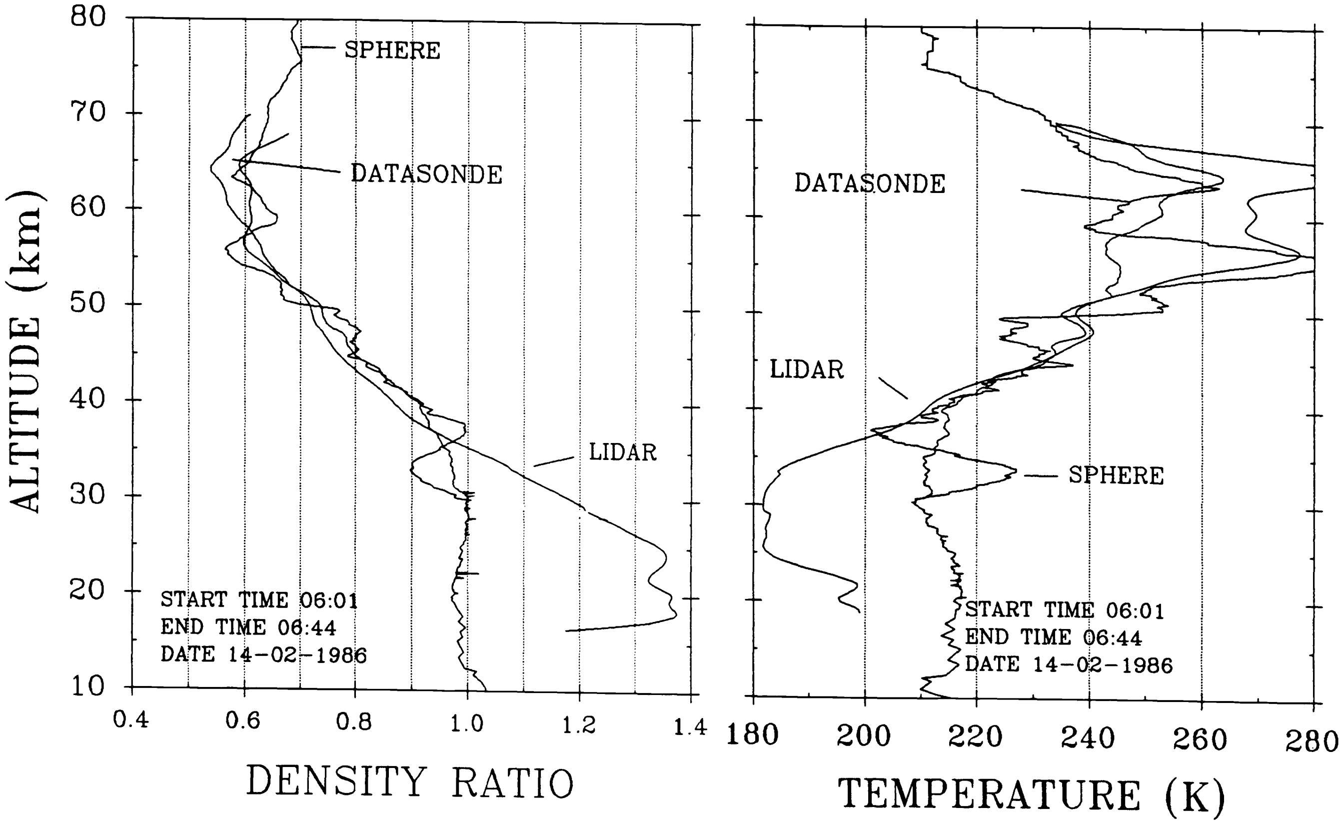


Fig. 6. The data obtained on 14 February 1986 exhibits significant departures between the lidar and rocket data. Two major difference are observed in this data set, the large wave response associated with the strong wind field during during this period and the additional optical scattering between 25 and 35 km.

Two-color Lidar

Figure 7 shows the profiles of the density ratio signal at 532 and 355 nm for one case. The fact that the molecular scattering cross-section at 355 nm is five times larger than at 532 nm, while the particle scattering wavelength dependence is relatively flat, means that the relative signal due to aerosols can be discriminated and removed. The ratio of the relative green to uv profiles shows clearly where the molecular scatter profile is affected by the particle scattering.

Raman Lidar

The results shown in the 14 February 1986 measurements can be explained if the additional signal is due to small particles, that is, particles which meet the Rayleigh scattering requirement for particles smaller than the wavelength. The additional scattering between 25 and 35 km does not show the discrimination between the two-color measurements, which would be expected for larger size particles. For now, we propose that the signal is due to small particles which may have been released in significent quantity to be observed from the decomposing stratospheric clouds, which may released at the end of the polar night. A much larger number of the small particles is required because of their smaller scattering cross-section. Using a Raman N_2 lidar channel, we expect to clarify this point in future investigations.

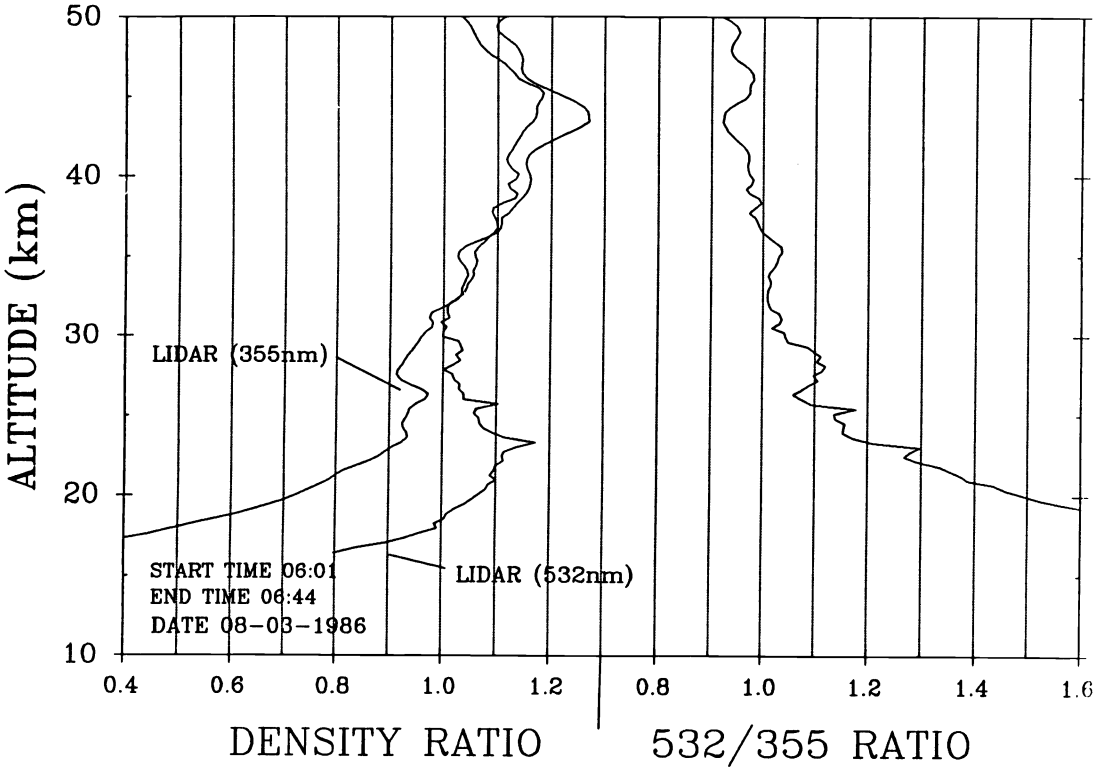


Fig. 7. The simultaneous measurement of the UV (355 nm) and the visible (532 nm) backscatter clearly shows the aerosol signal because of the relative difference in backscatter cross-section at the two wavelengths.

ACKNOWLEDGEMENTS

The author would like to acknowledge the long term collaboration of many colleagues, and particularly those who contributed and helped in various ways with the GLINT instrument development and the data collection, particularly, Dwight Sipler, Frank Schmidlin, Kris Bhavnani, Gil Davidson and Warren Moskowitz. The effort of the NASA launch, telemetry and radar crews and the PFRR personnel are gratefully recognized. Also, I want to recognize the enthusiasm and help of my graduate students in recent efforts, particularly their effort in development of the new LAMP lidar at PSU.

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