29D2

ATMOSPHERIC DIAL TEMPERATURE PROFILE MEASUREMENTS

C. Laurence Korb, Geary K. Schwemmer, Coorg Prasad[1],
Chi Y. Weng[2], Joseph Famiglietti and Cyrille N. Flamant[3]
Laboratory for Atmospheres
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

[1]Science and Engineering Services, Inc.
[2]Science Systems and Applications, Inc.
[3]University of Maryland, Permanent address: Service
d'Aeronomie, Universite Paris

Differential absorption lidar (DIAL) measurements of the atmospheric temperature profile have been made in the lower troposphere using the oxygen *A* band. A 1 K accuracy was obtained with a 300 m vertical resolution and a 90 s integration time. High vertical resolution temperature profile measurements with a resolution of a few hundred meters or better are needed to resolve significant structure in the atmosphere such as temperature inversions. Passive instruments which are used for temperature profile measurements from satellites are limited to a 5 to 8 km vertical resolution due to the width of the weighting functions. Lidar can provide the high vertical resolution needed.

A two-wavelength differential absorption lidar technique (Korb and Weng, 1979, 1982) is used for measuring the atmospheric temperature profile. A measurement of the absorption is made at the center of a high J line in the oxygen *A* band which originates from a quantum state with high ground state energy. The population of the state depends strongly on temperature through the Boltzmann distribution and can be used to obtain a highly sensitive temperature determination. The absorption is found experimentally by ratioing the signal for the appropriate oxygen line to a reference measurement at a nearby unabsorbed (off-line) frequency.

Our alexandrite lidar system (Schwemmer *et al.* 1987) includes two narrowband pulsed alexandrite lasers with associated diagnostic instrumentation, a 40 cm diameter telescope, photomultiplier detectors, low noise amplifiers, and a microcomputer controlled data acquisition system. The laser diagnostics include a wavemeter which measures and records the on-line laser spectrum pulse by pulse (Prasad *et al.*, 1988) with an optical resolution of 0.0038 cm^{-1} and a frequency precision of 1 part in 10^8.

The DIAL temperature measurement requires a laser with better than 0.01 cm^{-1} resolution and better than 0.002 cm^{-1} frequency stability. To achieve this we developed a frequency stabilized diode laser injection seeded alexandrite system (Schwemmer *et al.*, 1991). The on-line laser is injection seeded with the output of a low power, continuous wave, single mode diode laser which is frequency stabilized to the center of the absorption line used for temperature measurement. The diode is attached to a multi-stage thermo-electric cooler for broad wavelength temperature tuning, and housed in a vacuum chamber to prevent condensation from obscuring the beam or shorting the leads. We operate with a diode having a room temperature wavelength between 773 and 780 nm, and cool it to about -30°C to shift the wavelength to the 768.3 nm oxygen line. The diode laser current is dithered a small amount, causing the wavelength to oscillate. A non-resonant photoacoustic cell, housed inside a gas cell, is used to generate a feedback signal for controlling the laser current to actively stabilize the laser to the oxygen absorption line.

The atmospheric temperature profile measurements were made on 28 April 1992. The injection-seeded laser was tuned to the ^{P}P27 line of oxygen at 13010.81 cm^{-1} and the off-line laser set at a non-absorbing frequency near 13008 cm^{-1}. The on-line laser energy was 12 mJ per pulse and the off-line energy was set at 6 mJ. The lidar signal returns were measured with a 200 nsec range gate (30 m vertical sampling). The signals were averaged over 900 shots (90 s). In order to analyze the data, the fraction of the signal scattered from aerosols and molecules is determined. The off-line signal is first range squared corrected. We found a clean, nearly aerosol-free atmospheric return at 9.8 km altitude, just below the tropopause and used this region to determine the molecular backscatter at this altitude. The molecular return was then calculated as a function of altitude using the ratio of the atmospheric density at each altitude to that at 9.8 km. This could have been accomplished using a climatic estimate for the temperature profile and surface pressure from which the pressure profile and hence the density profile are determined. In our case, we used radiosonde data taken at the same time 54 km away. The backscatter ratio, one plus the ratio of the aerosol to molecular backscatter, was then determined as shown in Fig. 1 at a resolution of 30 m. The reference level near 9.8 km which corresponds to a minimum in the backscatter ratio is clearly evident.

The transmission due to the oxygen absorption is found as the ratio of the on-line to off-line signal. The differential absorption over various layers is calculated from the transmission for layer thicknesses of 300 m. The backscatter ratio is utilized since different scattering processes affect the absorption on the return path from the atmosphere. The analysis also included a technique for correcting for laser spectral impurity which was found to be 6%. For the outgoing path, the spectral width of the atmospheric absorption is much broader than the width of the spectrally narrow laser. In the case of aerosol scattering, the absorption on the return path is essentially the same as that on the outgoing path since the signal is elastically scattered with no change in the shape of the incident spectrum. In the case of molecular (Rayleigh) scattering, the signal is broadened in the scattering process due to the Doppler effect since the molecules are moving with an ensemble of velocities along the line of sight of the laser beam. Thus, each spectral component of the incoming signal is scattered into a Gaussian spectrum with a width of $2b_d$ where b_d is the Doppler width. The resultant spectrum after scattering is the sum of these Gaussian spectra with a width of $2b_d$ for each incoming spectral component. This spectrum is then only partially absorbed on the return path through the atmosphere since it is spectrally broader than the absorption line. In addition, approximately 3% of the molecular scattered signal is Raman scattered. This signal is treated as being absorbed due to resonant absorption only along the outgoing laser path. The laser spectral impurity was treated as follows: The observed transmission is treated as having two components, one a narrowband spectrally pure component which is absorbed by the atmosphere, and a second spectrally impure component which is not absorbed. The laser spectral impurity is found by matching the observed to the calculated transmission at a relatively high altitude, 6.5 km, where the transmission is small, known, and far above the temperature measurement region. As a result, the correction could be made in two iterations in a manner which is relatively independent of the temperature measurement. Non-homogeneous scattering had a significant effect on the measured temperatures, and corrections for this were made.

The differential absorption for each of the measured layers is calculated using the backscatter ratio to determine the fraction of the signal scattered by aerosol and molecular processes. The temperature profile is then calculated by finding the temperature for each layer such that the calculated differential absorption agrees with that which is measured. A single point calibration procedure using radiosonde data is used to calibrate the molecular absorption line parameters to the measured data.

The resulting temperature profile is shown in Fig. 2 for a vertical resolution of 300 m (on 150 m spacing) and a 900 shot average. The radiosonde profile taken at Dulles airport, 54 km away, is also shown for comparison. The average deviation of the lidar and radiosonde data is 0.9 K. The inversion feature just below 2 km altitude matches the shear aerosol layer which is clearly shown in the backscatter ratio. Other measurements have also been recently reported (Theopold and Bosenberg, 1993) for a smaller altitude range.

REFERENCES

Korb, C. L. and C. Y. Weng, 1979: A two-wavelength lidar technique for the measurement of atmospheric temperature profiles. Proc., 9th Int. Laser Radar Conf., Munich, *Amer. Meteor. Soc.*, 185-186.

Korb, C. L. and C. Y. Weng, 1982: A theoretical study of a two-wavelength lidar technique for the measurement of atmospheric temperature profiles, *J. Appl. Meteor.*, **21**, 1346-1355.

Prasad, C. R., C. L. Korb, and G. K. Schwemmer, 1988: Laser wavemeter measurement in presence of speckle. 14th International Laser Radar Conf., Abs., Innichen-San Candido, Italy, *Amer. Meteor. Soc.*, 253-256.

Schwemmer, G. K., M. Dombrowski, C. L. Korb, J. Milrod, H. Walden, and R. H. Kagann, 1987: A lidar system for measuring atmospheric pressure and temperature profiles, *Rev. Sci. Instrum.*, **58**, 2226-2237.

Schwemmer, Geary K., H. S. Lee, Coorg Prasad, 1991: Narrowband alexandrite laser injection seeded with frequency dithered diode laser, Earth and Atmospheric Remote Sensing, Robert J. Curran, James A. Smith, Ken Watson, Eds., Proc. SPIE 1492, 52-62.

Theopold, F. A. and J. Bosenberg, 1993: Differential absorption lidar measurements of atmospheric temperature profiles: Theory and experiment, J. Atmospheric and Oceanic Technology, **10**, 165-179.

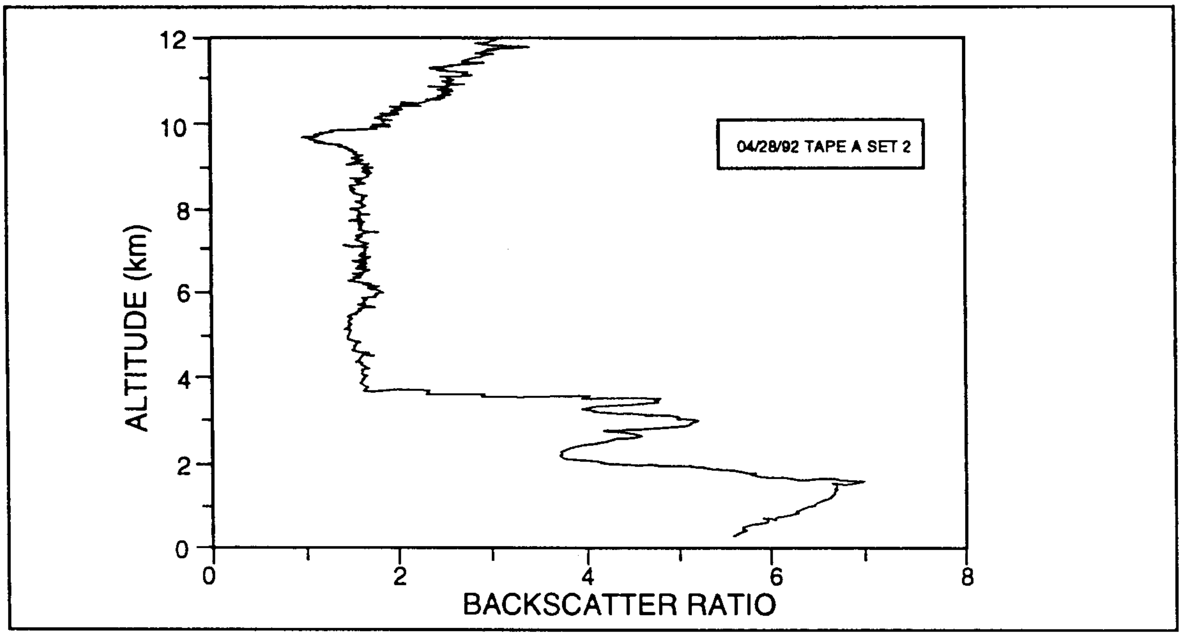

Figure 1. Backscatter ratio, (Mie + Rayleigh)/Rayleigh scattering, as calculated from the off-line signal for 30 m vertical resolution.

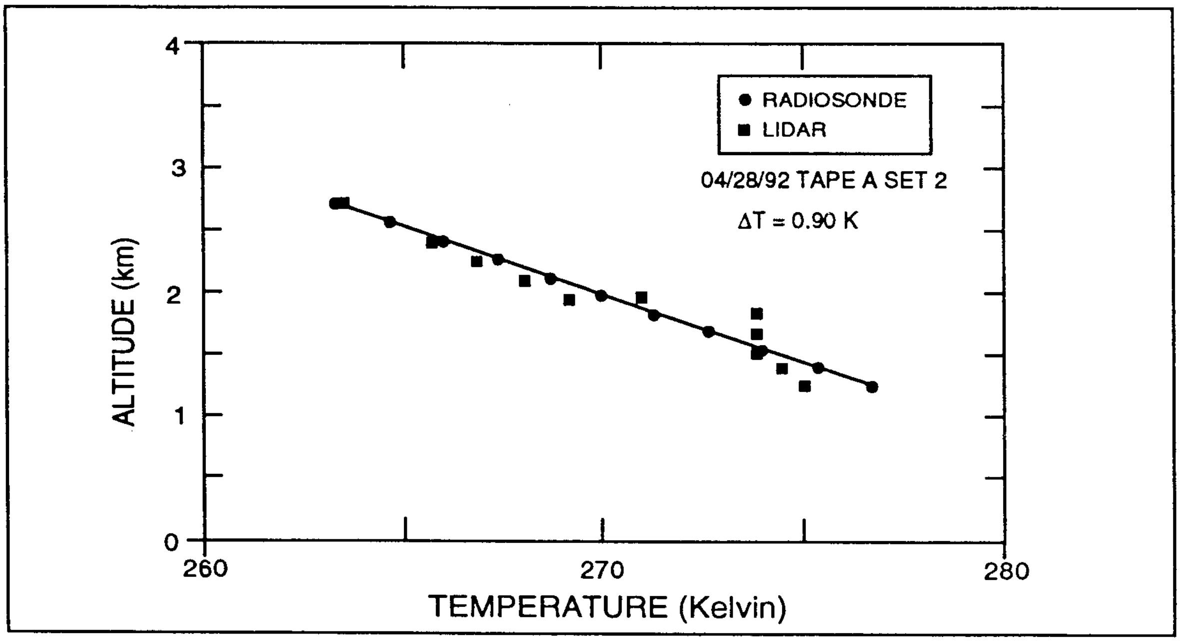

Figure 2. Lidar temperature profile measured at Goddard Space Flight Center with the upward looking lidar with a 300 m vertical resolution. Radiosonde measurements of temperature made at nearby Dulles Airport are shown for comparison.