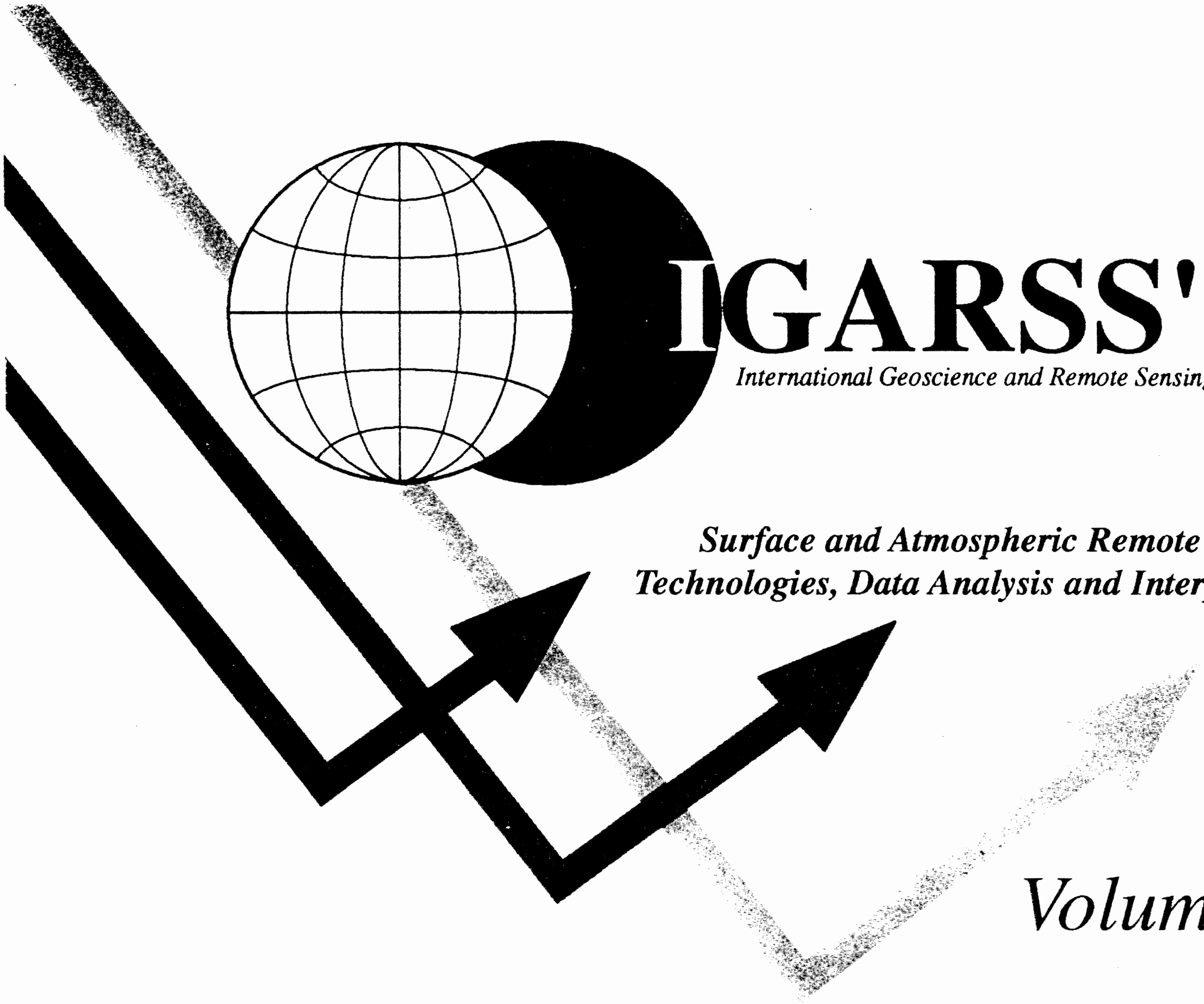

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LIDAR MEASUREMENTS OF WATER VAPOR CONCENTRATIONS IN THE TROPOSPHERE

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ABSTRACT

A multi-wavelength Raman lidar has been used to measure water vapor profiles in the troposphere under a wide range of geophysical conditions. The transportable LAMP lidar instrument has been used to make measurements at several locations, at our central Pennsylvania campus location, on shipboard between Arctic and Antarctic, and in a coastal environment at Point Mugu, CA. The Raman technique provides an accurate way to measure the concentration profile of water vapor by measuring the ratio of Raman vibrational (1st Stokes) signal of water vapor to that of nitrogen. The measurements have been made using the vibrational Raman backscatter intensity of the 660/607 ratio from 532 nm, the 407/387 ratio from 355 nm, and the 294/283 ratio from 266 nm. The Nd:YAG laser double (532 nm) and triple (355 nm) Raman backscatter signals have been found to be about equally useful in measuring the water vapor concentrations during night conditions. Having both sets of measurements allows additional examination of the results, particularly the small correction for aerosol differential extinction. The quadruple (266 nm) Raman scatter signals have been examined for daytime measurements where the troposphere is shielded from wavelengths below 300 nm (solar blind region) by the stratospheric ozone absorption. These measurements are complicated by the need to make corrections for the absorption of tropospheric ozone and other minor species. The Raman signals from molecular oxygen and nitrogen provide a suitable way to correct for the tropospheric species influences on the measurements. Measurements of the water vapor concentrations have been made over a wide range of atmospheric conditions and comparisons have been made with the current techniques used on meteorological balloons. From the studies which have been carried out, a convincing case can be made for the ability of lidar to accurately measure the water vapor concentrations from the surface to 8 km at night and from the surface to 2-3 km during daylight.

INTRODUCTION

During the past twenty years, researchers at several laboratories have demonstrated that lidar has special capabilities for remote sensing of many different properties of the atmosphere. One of the very useful scattering properties is the specie unique vibrational Raman process. The first Raman measurements of atmospheric properties with lidar were carried out by Leonard (1967) and Cooney (1968). Melfi, et al. (1969), Cooney (1970, 1971) and Strauch, et al. (1972) showed that it was possible to measure water vapor using the Raman lidar technique. A significant contribution was made by Inaba and Kobayasi (1972) in suggesting several species that could potentially be measured using vibrational Raman techniques. While the early tests showed that it was possible to measure the water vapor with limited range and accuracy, recent investigations have shown significant improvements. Particularly, the investigations of Vaughan, et al. (1988), Melfi, et al. (1989) and Whiteman, et al. (1991) have shown rather convincingly that the Raman technique has a high potential for making accurate water vapor measurements. A most useful review of the Raman and DIAL lidar techniques applied to the water vapor measurement has been given by Grant (1991). The measurements of water vapor during the daytime have been demonstrated by Renaut and Capitini (1988) using the solar blind region of the ultraviolet spectrum. Their work showed that the optimum wavelength for the measurement was near the fourth harmonic for the Nd:YAG laser. There the measurements of N_2 and H_2O are contaminated, at least to a small degree, by the absorption of ozone and SO_2 in the lower troposphere, however it appears that an adequate correction can be obtained from the use of the Raman signals of the N_2 and O_2.

The Raman H_2O signal measured at 660, 407 or 294 nm ratio to the corresponding Raman N_2 signal at 607, 387 or 283 nm provides an accurate profile of the water vapor concentration. The N_2 fraction of the atmospheric profile is known, and the atmospheric profile can be obtained from the temperature profiles combined with a surface pressure value. The error caused by the extinction differences between the backscatter wavelengths is small (few percent) and can be corrected by using the multiple wavelengths.

While demonstrations by several researchers have shown the potential of lidar to measure many properties of the atmosphere, there have been few efforts to develop the lidar techniques sufficiently for them to be used for routine measurements. The research lidars generally require intensive interaction by highly specialized personnel to obtain useful measurements and thus the investigations have been generally limited to short and intensive measurement periods. The transition of the technical capability of lidar to operational applications in meteorological data collection, atmospheric physics investigations, studies of the environment, investigations of radiative transport and global climate analysis requires that instrumentation be developed and automated. One of our research goals is to make lidar a useful instrument for routine measurement applications within the next few years. Toward that goal, we have sought to perfect the techniques and to automate the operation and data retrieval from lidar. The multi-wavelength Raman lidar techniques have been chosen to provide the profiles of density, temperature, water vapor and optical extinction in the troposphere because they appear to have the best capability of meeting the measurement requirements. During the past two years, we have focused the LAMP lidar efforts on demonstration the capability of vibrational Raman techniques for water vapor measurements and on the use of rotational Raman for temperature measurements, in the presence of a background of aerosols and clouds.

The first major field experiment using the LAMP lidar was the LADIMAS (<u>LA</u>titudinal <u>DI</u>stribution of <u>M</u>iddle <u>A</u>tmosphere <u>S</u>tructure) campaign (Philbrick, et al. 1992, 1994). The results from the LADIMAS experiment have provided a unique data set to improve our understanding of atmosphere properties. The project included coordinated ship-board measurements between 70°N and 65°S, as well as measurements at the Andoya rocket range, to study the structure, dynamics and chemistry of the atmosphere. Results on dynamical processes, such as gravity waves, as well as, the formation of the layers

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of meteoric ion and neutral species, have been obtained using lidars, digisonde, microwave radiometer, and spectrometers. The cooperative study of the atmosphere was undertaken by researchers from several laboratories, including Penn State University, University Bonn, University Wuppertal, Lowell University, and others. Instruments were assembled aboard the German research vessel RV *Polarstern* while this vessel was sailing from the Arctic to the Antarctic between October 8, 1991 and January 2, 1992. During the voyage, the water vapor in the troposphere was measured by lidar (McKinley and Philbrick, 1993) and in the middle atmosphere by microwave radiometry (Croskey, et al., 1993).

The second major field investigation was a set of three measurement periods using the LAMP lidar at NAWC Point Mugu, CA, during the period July-November 1993 (Blood, et al., 1994). This location provided the opportunity to measure the properties of the marine coastal environment at a time of concentrated atmospheric measurements associated with a program called VOCAR (Variability of Coastal Atmospheric Refractivity). In addition, the instrument has been used for extensive testing at Penn State University while not involved in these field experiments.

LAMP INSTRUMENT DESCRIPTION

The LAMP (Lidar Atmospheric Measurements Program) lidar profiler was placed in service at Penn State University during the summer of 1991. The LAMP lidar uses two wavelengths in the upward propagating beam and up to eight detectors in the receiver. The instrument is arranged in a coaxial configuration, which permits useful measurements in the near field, as well as in the far field. Two detector systems have been prepared for the instrument, one for high altitude measurements and one which is specialized on the low altitude region. The high altitude detector system is used to obtain data between 1 km and 80 km. It uses a mechanical shutter to block the high intensity, low altitude signal, from the two high altitude detectors until the beam has reached an altitude of 18 km. The low altitude detector has the capability of measuring two N_2 and two H_2O vibrational Raman channels simultaneously and measuring two wavelengths of the rotational Raman spectrum for temperature determination. The instrument was originally designed to directly attach the high altitude detector by an optical transfer relay, however, the current use of an optical fiber permits the use of either detector. The Nd:YAG laser has an output of 1.5 j at 20 Hz at the 1064 nm fundamental output. The beam is passed through a doubling crystal and a mixing crystal to produce the 532 and 355 nm, or 266 nm, beams which are used for the lidar measurements. The primary receiver is a 42 cm diameter Cassegrainian telescope. The low altitude backscatter signals of the visible and ultraviolet beams can be detected as analog signals and digitized at 10 MSps to provide 15 meter resolution from the surface to 25 km or as photon counted signals with 75 m altitude resolution. The high altitude signals, obtained by photon counting techniques, are accumulated into 500 nanosecond range bins to provide 75 meter resolution, from 20 to 80 km. The detector also contains low altitude photon counting channels which measure the first Stokes vibrational Raman signals of the N_2 and the H_2O Raman signals. The transmitter, receiver, detector, and data system combination have been integrated into a standard shipping container, which serves as a field laboratory. The LADIMAS measurements have allowed the preparation of a map of the Pinatubo volcano aerosol distribution and an investigation of the latitudinal variation in the density and temperature structure of the middle atmosphere. Studies of the distribution of tropospheric water vapor and tropospheric aerosols, and an investigation of the optical scattering properties of the atmosphere have also been carried out using the results.

MEASUREMENTS

Figure 1 shows an example of the raw lidar signal, corrected for $1/R^2$ dependance, which are typical of the signals measured on several of the data channels. The figure show the signal from boundary layer aerosols, tropospheric clouds, high cirrus clouds and stratospheric aerosol layers. In the figure, the profiles of the low and high altitude channels have been overlapped to provide continuous profiles. The back-scatter and extinction associated with the stratospheric aerosols, clouds and the boundary layer can be readily observed in the profiles at these two wavelengths. Notice that the scattering ratio of the 532 nm compared to the 355 nm changes significantly with the changing size and other characteristics of the particle scatterers. When the stratospheric aerosol scattering intensities are compared to those for the tropospheric clouds, the change in extinction and back-scatter cross-section with particle size is obvious.

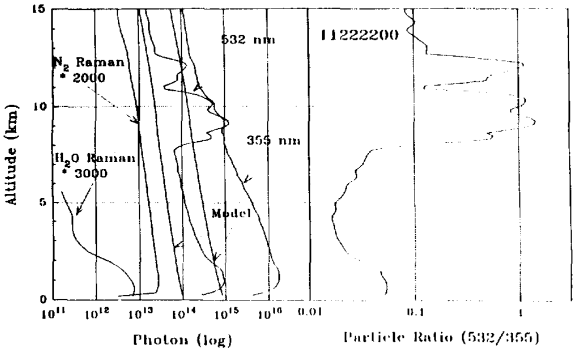

Figure 1. Examples of the continuous profiles of the data are shown. The slope change below 1 km is due to telescope focus and geometrical factors. This example is from 22 November 1991 when the instrument was near the equator on its transit from Arctic to Antarctic.

Figure 2 shows an example profile measured with the LAMP lidar of the water vapor concentration compared with a rawinsonde balloon. The time variation of the water vapor has been observed to change rapidly during a front passage. Figure 3 shows and example of the measurement of the marine atmosphere at Point Mugu, CA, on 29

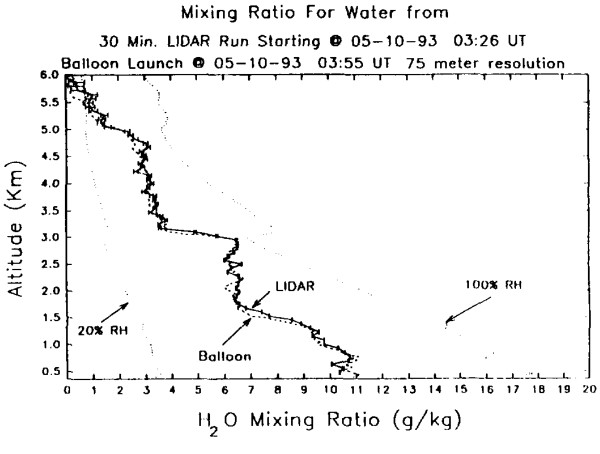

Figure 2. Example of the water vapor concentration obtained from the Raman lidar signals, with one sigma error shown, compared with a rawinsonde balloon profile. The measurement was made on 10 May 1993 at PSU.

August 1993. The lidar determined water vapor profile from the 660/607 ratio is shown with one sigma signal errors for a 30 minute integration at 0533 UT. A profile from a standard meteorological balloon released an hour earlier is shown for comparison. The first range bin at 45 meters shows a large departure from the balloon value, reasons for the often questionable result in the first data bin is under investigation. Figure 4 shows results at the time of the Santa Ana dry wind across southern California on 28 October 1993 and the following two days which show a gradual return to the moist boundary layer conditions.

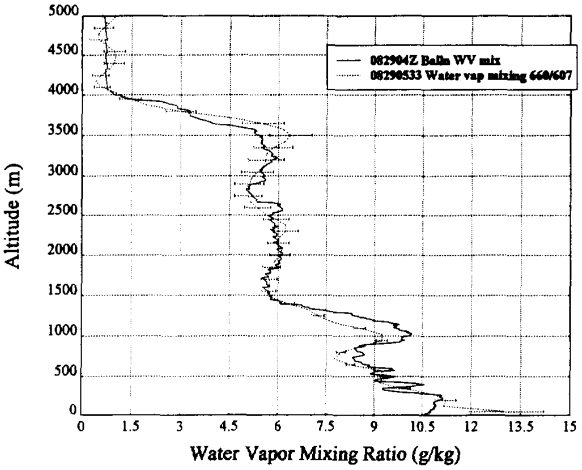

Figure 3. Lidar and balloon profiles of the water vapor are compared on 29 August 1993 at Point Mugu, CA.

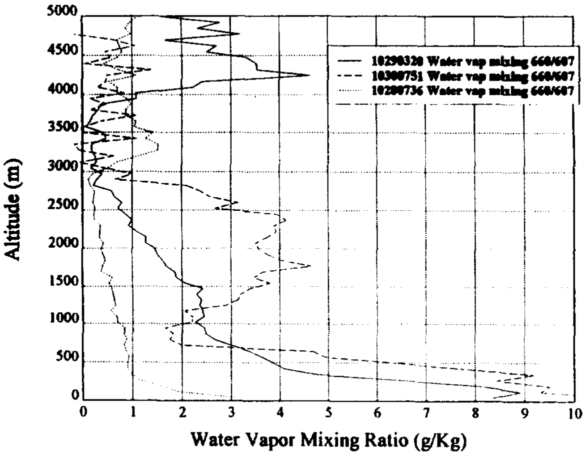

Figure 4. The profiles measured by the lidar when a Santa Ana condition occurred on 28 October and the recovery toward more normal conditions during the two following days.

The results gathered here have provided a data base from which a critical analysis of the technique can be made. The work in progress extends the measurements into daylight hours with improvements in detector filters and by making tropospheric measurements in the solar blind portion of the spectrum. The chance to obtain the concentrated set of measurements on the RV *Polarstern* over such a wide range of latitude was a special opportunity. The work in progress on those results will produce several additional papers during the coming year. Improved measurements of the properties of the atmosphere are required for meteorological forecasting, operational test support and for studies of the global environment. The long term goal of these efforts is to develop a lidar instrument which can provide routine measurements of the atmospheric properties.

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