Laser Remote Sensing of Water Vapor: Raman Lidar Development

J.E.M. Goldsmith, M. Lapp, and S. E. Bisson
Sandia National Laboratories
Livermore, CA 94551

S. H. Melfi and D. N. Whiteman
NASA Goddard Space Flight Center
Greenbelt, MD 20771

R. A. Ferrare and K. D. Evans
Hughes STX
Lanham, MD 20706

Introduction

The goal of this research program is the development of a critical design for a Raman lidar system optimized to match Atmospheric Radiation Measurement (ARM) Program needs for profiling atmospheric water vapor at Cloud and Radiation Testbed (CART) sites. This work has emphasized the development of enhanced daytime capabilities using Raman lidar techniques, but the evolution of the ARM Program has led us to investigate other characteristics as well, in order to provide a range of options for implementing a Raman lidar system at CART sites.

Raman lidar systems detect selected species by monitoring the wavelength-shifted molecular return produced by Raman scattering from the chosen molecule or molecules. For water-vapor measurements, the nitrogen Raman signal is observed simultaneously with the water-vapor Raman signal; proper ratioing of the signals yields the water-vapor mixing ratio. Raman lidar is used currently to perform meteorologically important, sustained, reliable nighttime profiling of water vapor. Daytime measurements present added challenges because of the difficulties inherent in detecting Raman signals against solar backgrounds. One approach to overcome this problem is to operate in the solar blind region of the spectrum (wavelengths shorter than ~285 nm). This approach effectively reduces the solar background, but attenuation of the laser beam and the backscattered Raman radiation (primarily due to absorption by tropospheric ozone) greatly reduces the signal also. Alternatively, the background skylight reaching the detector can be reduced by using a narrow field-of-view receiver and narrowband spectral detection. We have pursued both of these approaches in our studies.

This abstract touches briefly on the main components of our research program, summarizing the results of these efforts, and provides references for more detailed information.

Nighttime Measurements

Two advanced lidar systems have been used to quantify the "real-world" capabilities of Raman lidar systems for profiling atmospheric water vapor in a variety of field campaigns. Two such campaigns are especially relevant to the ARM Program. Shortly after the second ARM Science Team Meeting in October 1991, the Raman lidar system developed at the NASA Goddard Space Flight Center participated in the FIRE/SPECTRE[a] Field Campaign at Coffeyville, Kansas, from November 12 until

(a) First ISCPP (International Satellite Cloud Climatology Project) Regional Experiment/Spectral Radiance Experiment.

December 7, 1991 (Melfi et al. 1992). The high-quality measurements produced by this system, and the reliability of its operation, provide a striking demonstration of its utility in this "mini-CART" environment.

Detailed evaluation of the performance of Raman lidar systems (or lidar systems in general) is complicated by the lack of an appropriate instrument that can provide accurate measurements for intercomparison purposes. Several studies have demonstrated the limitations of radiosondes for such evaluations. To provide a more rigorous test of Raman lidar capabilities, the system developed at Sandia National Laboratories was collocated with the Goddard system at the Goddard Space Flight Center in Greenbelt, Maryland; a number of intercomparisons were performed from October 26 through November 20, 1992. These intercomparisons, using lidar systems based upon different excitation wavelengths and two different formats of detection packages, resulted in water-vapor profiles of remarkable similarity. They provide a striking confirmation of the precision of Raman lidar systems for profiling atmospheric water vapor (Goldsmith et al. 1993a; Goldsmith et al. submitted).

Performance Modeling

We have developed a detailed Raman lidar instrument model to predict the daytime and nighttime performance capabilities of Raman lidar systems. The model simulates key characteristics of the lidar system, using realistic atmospheric profiles, modeled background sky radiance, and lidar system parameters based on current instrument capabilities. The model operates by tracking photons through the atmosphere and the instrument, incorporating atmospheric attenuation (due to Rayleigh and aerosol scattering and absorption by ozone and oxygen) at all of the wavelengths of the Raman lidar process.

We have used this model to guide our development of lidar systems based on both the solar-blind concept and the narrowband, narrow field-of-view concept for daytime optimization. The model, assumed lidar parameters, and representative results are presented in Goldsmith and Ferrare (1992) and Goldsmith et al. (1993b). Briefly, ranges of 3-4 km with 75-m range resolution and ~10-minute counting times are predicted for systems based on both concepts using large (but commercially available) laser systems and telescopes.

Laboratory Studies

Our model calculations indicate that the optimum excitation wavelength for the solar-blind concept is in the range 260-266 nm (Goldsmith and Ferrare 1992; Goldsmith et al. 1993b). Unfortunately, this wavelength range lies between the two wavelengths most readily obtained from high-average-power laser systems, namely 248 nm from KrF lasers and 308 nm from XeCl lasers. Although 266-nm radiation can be produced by frequency-quadrupling the output of Nd:YAG lasers, current (flashlamp-pump) technology limits the output power of these systems to substantially lower values.

Our laboratory research has therefore emphasized the development of the Raman-shifting technology necessary to wavelength-shift the output of KrF lasers into the 260- to 266-nm range. In particular, we have performed a comprehensive study of a KrF pumped, nitrogen Raman shifter with emphasis on optimizing the first Stokes conversion efficiency at 263 nm (Bisson et al., 1992; Bisson, submitted). First Stokes conversion efficiencies as high as 12% were achieved in nitrogen:helium mixtures. Further improvements were achieved by seeding the Raman cell with the backward first Stokes radiation. Experiments were also conducted with a frequency-doubled Nd:YAG laser as the pump source. These experiments showed that conversion efficiencies as high as 20% might be obtainable with a KrF laser if the beam quality were improved.

Daytime Capabilities

We have pursued two concepts for extending the daytime capabilities of Raman lidar. As described above, for the solar-blind approach, model calculations suggest an optimum excitation wavelength in the 260- to 266-nm range. To explore solar-blind operation concurrent with our wavelength-shifting studies, we performed measurements using the 248-nm output of a KrF excimer laser (Whiteman et al. 1993). Measurements to a range of 2.5-3.0 km were obtained using ozone profiles provided by electrochemical cell radiosondes (ozone profiles are needed to correct the experimentally observed water vapor and nitrogen signals for the different absorption coefficients at the two wavelengths). The range we are able to obtain and our ability to adequately derive ozone profiles directly from the lidar data both appear to be limited primarily by afterpulsing in our photomultipliers; we are currently investigating methods to avoid this difficulty.

We have also investigated the narrowband, narrow field-of-view approach using 308-nm XeCl laser excitation (Bisson and Goldsmith 1993). Preliminary measurements have demonstrated measurements to a range of ~3 km even under relatively dry conditions during mid-afternoon with a clear sky. Recent modifications to the detection system should enable a further reduction in the field-of-view, providing further enhancement in the daytime capabilities of the system.

Conclusions

We are currently acquiring an additional set of daytime measurements using the modified narrowband, narrow field-of-view system, and comparing our measurements (both daytime and nighttime) to our computer model. We have also started the final phase of the program, in which we integrate all of our results into a design plan that displays a range of options for implementing a Raman lidar system at CART sites. In these design options, we include the capabilities of Raman lidar systems for measuring other physical parameters, such as aerosol characteristics (Ferrare et al. 1992; Ferrare et al. 1993) and temperature (Ferrare et al. 1990, 1993; Evans et al. 1993). Finally, our designs will incorporate possibilities for measuring additional physical parameters such as cloud phase information from polarization studies, cloud structure from physical scans, and aerosol size information from multiple excitation wavelengths.

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