Laser Remote Sensing of Water: Raman Lidar Development

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Introduction

We outline here our research program to develop an optimized critical design for a Raman lidar system for measuring daytime profiles of atmospheric water vapor. The Raman lidar technique is a leading candidate for providing the high-resolution, day-night profiling of water vapor that is critical to programs in global climate change research. Because of the crucial role that water vapor plays directly in the earth's radiation budget as an absorber, as well as its role in cloud formation and optical phenomenology, accurate, three-dimensional measurements of water-vapor concentration are an essential part of the experimental capability that we anticipate will be required for climate-change research.

Raman lidar is currently used to perform meteorologically important, sustained, reliable nighttime profiling of water vapor; typical configurations yield random uncertainties of less than ±10% out to ranges of 7 km in 2-minute integration periods with range resolution on the order of 100 m (Melfi and Whiteman 1985; Melfi et al. 1989; Whiteman et al., in press). Daytime measurements are much more difficult because of the difficulties inherent in detecting the weak Raman signal against solar backgrounds. Demonstrations to date have been limited to ranges on the order of 1 km (Petri et al. 1982; Renaut et al. 1980; Renaut and Capitini 1988).

This paper will describe our development of a solar-blind Raman lidar capable of extended-range daytime profiling of atmospheric water vapor. The first part of the paper will describe the principle of solar-blind operation and discuss the computer model being developed to guide optimization of the instrument configuration. The second part of the paper will focus on an overview of the laboratory research being performed to support the model and instrument development. Finally, we will describe our participation in SPECTRE (Spectral Radiance Experiment), a major field experiment held during the fall of 1991.

Solar-Blind Raman Lidar Principle and Modeling

Conventional lidar systems, which detect backscattered radiation at the same wavelength as the transmitted laser beam, provide no species selectivity. 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 (2331 cm^{-1} shift) is observed simultaneously with the water-vapor Raman signal (3652 cm^{-1} shift); proper ratioing of the signals directly yields the water-vapor mixing ratio. Detection of the unshifted backscatter, which is due to Rayleigh and Mie scattering, provides information about atmospheric density and aerosol loading at little additional cost.

The principle of the solar-blind Raman lidar is based on choosing an excitation wavelength sufficiently short that the wavelengths of all the detection channels occur in the solar-blind region of the spectrum ($\lambda<300$ nm). Tropospheric and stratospheric ozone (and other gases for the shorter wavelengths) absorb practically all of the incoming solar radiation in this region of the spectrum, providing a "black background" for detection of the weak Raman signals. The difficulty with such a choice of excitation wavelength, however, is that tropospheric ozone also absorbs the transmitted laser beam and the backscattered return signals, reducing the range to which signals can be detected even in the absence of any background. The result is that the optimum excitation wavelength must be short enough to result in only a small level of background radiation, but at the same time long enough to result in sufficient atmospheric penetration. An added difficulty at these wavelengths is the need to correct the ratio of the water-vapor and nitrogen measurements caused by differences in the ozone absorption cross-section at the two wavelengths. This correction can be determined by measuring the oxygen Raman signal (1556 cm^{-1} shift) in addition, and calculating the ozone concentration from the ratio of the nitrogen and oxygen signals (Renaut et al. 1982; Renaut and Capitini 1988).

We are developing a detailed instrument performance model to guide development of a lidar system that will provide an optimized balance among increased range, greater measurement precision, and decreased data acquisition time during daytime operation. This model uses realistic atmospheric profiles, measured background sky radiance, and experimentally determined values for the lidar system parameters. It also takes into account attenuation by sulfur dioxide, nitrogen dioxide, oxygen (in the weak Herzberg I band), Rayleigh scattering, and aerosols, in addition to ozone. While our preliminary estimate is that the optimum excitation wavelength is likely to be in the 260-264 nm range [in reasonable agreement with Petri et al. (1982), Renaut and Capitini (1988), and Grant (1991)] considerable additional work is required before a definitive result can be provided.

Laboratory Research Program

The most attractive laser sources for UV lidar systems are excimer lasers (KrF at 248 nm, XeCl at 308 nm, and XeF at 351 nm) or harmonics of Nd:YAG lasers (third harmonic at 355 nm and fourth harmonic at 266 nm). Because Nd:YAG systems currently cannot approach the average-power capabilities of excimer systems, we have concentrated on the latter. Unfortunately, it is already fairly clear that the optimum wavelength falls between 248 nm and 308 nm, and thus we are exploring the capabilities of a Raman-shifted KrF laser. Table 1 lists some likely candidates for Raman-shifting gases, their Raman shifts, and the resulting wavelengths of the lidar return signals. Hydrocarbons present potential difficulties because photolysis can lead to soot formation in the Raman-shifting cell, which in turn can lead to window damage. As a rule of thumb, photolytic effects increase with the "complexity" of the hydrocarbon. We have included methane and deuterated methane in the table, but even they are unlikely to be suitable for high-average-power applications.

Our initial laboratory explorations are focused on exploring the performance of a high-average-power system using nitrogen as the Raman-shifting gas and looking into such considerations as forward vs. backward scattering efficiencies and beam characteristics, optimization of a given Stokes order, and single-cell vs. oscillator-amplifier configurations. Other laboratory explorations will focus on concerns related to atmospheric absorption and fluorescence characteristics that are identified during the course of our program.

SPECTRE Participation

A new version of the Raman lidar system developed at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center will participate in SPECTRE, to be held in Coffeyville, Kansas, from November 13 -

Table 1. Wavelength Options for Raman-Shifted Laser Excitation

Raman Shifter		Wavelengths of Lidar Return Signals (nm)			
Gas	Shift (cm^{-1})	Rayleigh	Oxygen	Nitrogen	Water
(none)	0	248	258	263	273
CO_2	1388	257	268	273	283
O_2	1556	258	269	274	285
CD_4	2108	262	273	279	289
CO	2143	262	273	279	290
N_2	2331	263	274	280	291
CH_4	2917	267	279	285	296
D_2	2986	268	279	286	297
H_2	4155	276	289	296	308

December 7, 1991. SPECTRE is a major, multiple-instrument field experiment held simultaneously with Phase II of the FIRE program (First ISCCP Regional Experiment; ISCCP is the International Satellite Cloud Climatology Program). SPECTRE's main objective is accurate measurement of infrared radiance with simultaneous profiling of radiatively important atmospheric characteristics for testing of radiative models. The Raman lidar system will provide profiles of atmospheric water vapor, using unshifted KrF 248-nm radiation for daytime measurements and XeF 351-nm radiation for nighttime measurements. The configuration of this system is shown in Figure 1. Separate detection systems will be used for daytime and nighttime operation. Within each system, dichroic beamsplitters and interference filters will provide independent detection of the four wavelengths of interest; for each wavelength, increased dynamic range will be provided by dividing each signal into two channels, as shown for the water-vapor channel (but also built into the Rayleigh, nitrogen, and oxygen channels). Although daytime operation at 248 nm is not likely to yield optimized performance, the measurements obtained using this system will provide valuable insight for our continuing development of a daytime-optimized Raman lidar system.

Summary

Information from all three phases of our program (lidar modeling, laboratory research programs, and field-test experience from our participation at SPECTRE) will be meshed together in the design and testing of the next-generation Raman lidar system. We anticipate that this system will be similar in configuration to that shown in Figure 1, but with a (possibly narrowband) oscillator-amplifier KrF laser system followed by a Raman-shifting system. Other options also being explored include a narrowband, narrow field-of-view system operated at somewhat longer wavelengths, possibly combined with "partially" solar-blind operation. Following field tests of the optimized system, we will provide a conceptual design of a Raman lidar system suitable for implementation at Cloud and Radiation Testbed (CART) sites.

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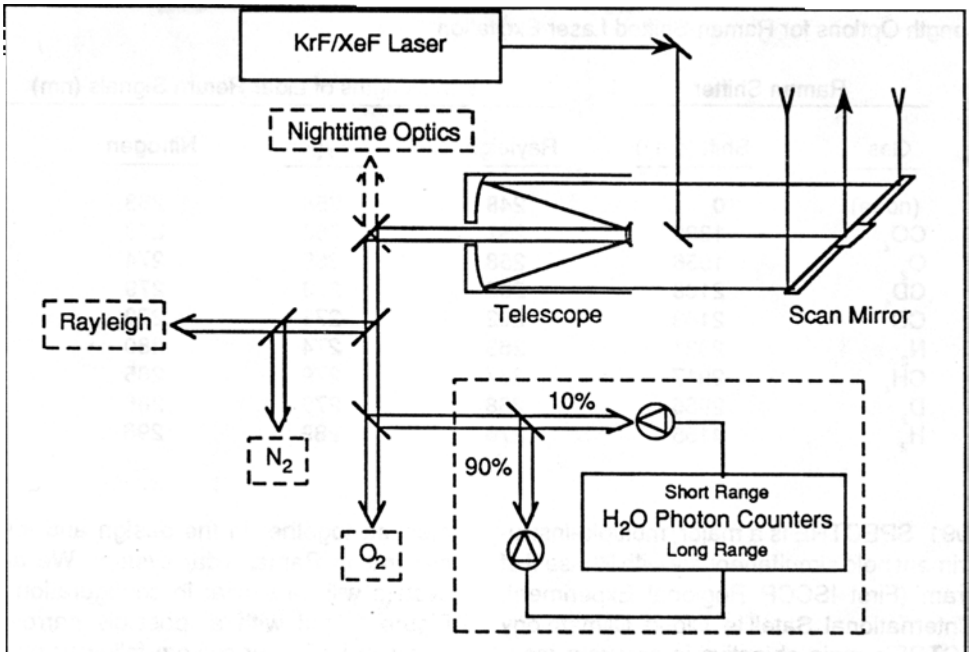

Figure 1. Raman Lidar System to be used at SPECTRE

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