A HIGH CAPABILITY RAMAN LIDAR FOR UPPER TROPOSPHERIC AND LOWER STRATOSPHERIC WATER VAPOR MEASUREMENTS

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ABSTRACT

A new Water Vapor Raman lidar is being built at the Table Mountain Facility (TMF) of the Jet Propulsion Laboratory (JPL) in California (34.4N, 117.7W). The new system is designed to reach accuracies better than 5% anywhere up to 12 km altitude, and with the capability to measure water vapor mixing ratios as low as 1 ppm near the tropopause and in the lower stratosphere. The principal components of the proposed lidar, a high-energy Nd:YAG laser and a large telescope, are already available at TMF. The lidar receiver system, and data acquisition hardware and software are currently being implemented. The initial system in a non-optimized configuration already showed promising results, as water vapor lidar returns were clearly detected up to 20 km altitude. The initial configuration, and preliminary results are discussed in this short paper. The optimized configuration of the system, and the first calibrated water vapor profiles obtained from this optimized system will be shown at the conference.

1. INTRODUCTION

Water vapor in the troposphere and lower stratosphere plays a major role in the radiative budget of the Earth. It also plays a key role in several aspects of Upper Troposphere-Lower Stratosphere chemistry. Despite its abundance in the troposphere, and because its role in stratosphere-troposphere exchange is arguably unknown, its exact effect on the climate system is not well understood and many questions remain unresolved at this time.

The water vapor molecule strongly absorbs infrared radiation and consequently water vapor constitutes a primary greenhouse gas. Studies have reported [1], that a global increase in lower stratospheric H2O mixing ratio, similar to that observed locally since 1981 [2], would contribute to a surface warming reaching 40% of that responsible from CO2 increases over the same period. The resulting lower stratospheric cooling would be of same order of magnitude as that caused by changes in ozone concentrations. This sensitivity of the Earth's radiative balance to water vapor variations requires high accuracy water vapor measurements (typically 3-10%) if one wants to fully understand and properly quantify and predict future water vapor-related radiative and chemical processes that impact climate change. A large concern in this respect is that many instruments currently cannot achieve such measurement accuracy without thorough calibration and validation. The recent SPARC Assessment of Upper tropospheric and Stratospheric Water Vapor (SPARC, 2000) pointed out many discrepancies in the water vapor profiles measured by different techniques. The extreme dryness of the stratosphere (first observed by [3]) dramatically contrasts with the troposphere and makes accurate water vapor measurements difficult if not impossible. Also, the very high variability, on short time and small horizontal and vertical scales, makes detection and quantification of water vapor extremely sensitive to sampling. Finally, the spatial distribution of lower stratospheric water vapor has often been found to be inconsistent with past theories of cross tropopause exchange and is still subject to debate.

The development of a new water vapor Raman lidar for tropospheric and lower stratospheric profiling contributes to both aspects of tropospheric and lower stratospheric water vapor assessment discussed above. This new system will complement two other lidars that are already operating at the JPL-Table Mountain Facility (TMF), California. The current expectations of this new lidar are the production of 120-m vertical resolution water vapor profiles, with a total error less than 5% in the free troposphere up to 12 km, and the detection of mixing ratios as low as 1 ppm at 15 km and above; the maximum estimated range being 20 km. Using our existing transportable lidar facility the system could potentially later be moved to any other site if necessary.

DESCRIPTION OF THE LIDAR SYSTEM

The water vapor Raman lidar measurement is noise limited and therefore the single pulse energy of the laser transmitter becomes more important than the average power [4]. We have available a high energy Nd:YAG laser which is capable of producing approximately 900 mJ per pulse at 355 nm and 10 Hz repetition rate. Also available is a large aperture, 91 cm
diameter (36''), Newtonian telescope. The basic lidar setup will follow that which we have used successfully in the tropospheric ozone system in use at TMF [5].

The transmitted laser beam is first expanded by a factor of 8 using low-loss off-axis beam expander [6]. This reduces the laser divergence to <200 μrad and allows a smaller field-of-view in the receiving optics and a corresponding reduction in the sky background intensity. The larger beam expander mirror is also used to steer the laser and align it with the telescopes. Small telescopes (lenses) are used to collect the near range lidar returns with one telescope for each received wavelength. The large telescope collects the far range signals with all received wavelengths merged. Fiber optics are used to couple the telescopes to the chopper and receiver system.

![Figure 1. Schematic diagram of the optical receiver.](image)

By separating the near and far range signals into different fibers they can be independently shuttered by the chopper thus allowing turn on times at different altitudes [5]. This eliminates the need for any electronic gating of the detectors. After the chopper, the near range signals is collimated, filtered and then refocused onto the photocathode of a miniature photomultiplier tube (Hamamatsu) as shown in figure 1. The component wavelengths in the far range signals are separated by a series of dichroic beamsplitters and interference filters. In figure 1, the first beamsplitter (B1) reflects the UV wavelengths desired and transmits everything else thus eliminating visible light from the detection chain. The second splitter (B2) transmits the nitrogen Raman signal at 387 nm and reflects the water vapor signal at 407 nm and the elastic scattering at 355 nm. The final beamsplitter (B3) reflects the 407 nm signal and transmits the 355 nm signal. This sequence of beamsplitters was established through consultation with the proposed manufacturer (Barr Associates) to optimize both the efficiency and spectral discrimination of the arrangement. Interference filters (F1, F2, F3) are used to further isolate the required wavelengths.

The signals from the photomultipliers is input to a photon counting multichannel scaler (MCS) system (Licel). This system provides amplification and discrimination of the single photon pulses with a bandwidth of >250 MHz and a maximum temporal resolution of 50 ns (equivalent to 7.5 m).

**MEASURING CAPABILITIES AND PRELIMINARY RESULTS**

The Raman lidar technique for water vapor measurements uses the relative intensity of vibrational Raman scattering from the water vapor and nitrogen molecules [7]. After various corrections, the ratio of the signal backscattered from nitrogen to that backscattered from water vapor is directly proportional to the water vapor mixing ratio. Using adequate calibration, it is then converted into mixing ratio. A number of water vapor Raman lidars have been deployed around the world [8; 9; 10] and the two following central issues were quickly identified: (1) limited sensitivity to very low mixing ratios in the upper troposphere, and (2) necessity for instrument calibration with a better than 5% accuracy in the troposphere.

Simulation of synthetic raw lidar signals, together with the experience acquired during the past 15 years of lidar operation at TMF and Mauna Loa Observatory (MLO), Hawaii, have helped us to model the lidar performance that would meet the requirements necessary to address (1) and (2).

In figure 2, we show the actual lidar signals acquired during a 2-hour measurement from the initial non-optimized system, together with synthetic lidar signals simulated based on actual signals obtained from our operating ozone lidars, and based on the expected performance of the new water vapor lidar in its optimized configuration. In the cases shown, the actual measurements were obtained on September 30th, 2002. The magnitude of the simulated signals is representative of the high-energy per pulse of the available Nd:YAG laser (800 mJ), energy that is about 10 times higher than that of the three Nd:YAG lasers currently operational at TMF and MLO. As part of the validation requirements of NDSC, simulations of synthetic lidar signals have been successfully used at JPL in the past to test and improve many ozone and temperature lidar algorithms [Leblanc et al, 1998b]. We have used the same approach for water vapor. Several sets of synthetic signals (such as those shown on figure 2) were produced and then analyzed as if they were obtained from real measurements. The “synthetic
retrieved" water vapor profiles were compared to the "synthetic original" profiles used for the simulation of the "synthetic signals" in order to estimate the uncertainties and errors caused by the limitations of the instrument performance and method. The simulated dry and wet layers were easily captured by the retrieved profile, even at altitudes as high as 15 km which simulates the very low mixing ratios near and above the tropopause. During a first implementation phase that took place during summer 2003, actual water vapor profiles were measured using a non-optimized system configuration. A typical water vapor profile obtained at the time is plotted on figure 3, together with the simultaneous ozone and temperature profiles obtained by the two co-located JPL lidars. Though the analysis remains preliminary, water vapor could be retrieved up to 20 km with degraded vertical resolution, and sufficient time integration. It is anticipated that a similar cut-off altitude will be reached when the system configuration is optimized, but with a higher vertical resolution and/or time resolution. It is therefore reasonable to expect, depending on the overall instrument performance and on the sky background intensity, the actual water vapor profiles to be cut-off between 14 and 20 km with a 1 km resolution at the top, and a 1-hour integration time.

Validation campaigns imposed by the NDSC protocols are performed on a regular basis [e.g., 12; 13], usually whenever a mobile platform is made available for simultaneous co-located measurements. As we expect our new system to be included in NDSC, and taking into account the quality requirements of the water vapor measurements mentioned earlier, we are planning on extensive validation by the way of several inter-comparison campaigns conducted during which water vapor will be simultaneously measured using different techniques. The core of the planned validation, in the short term, will consist of the systematic use of improved Humicap-H sensors on RS90 Vaisala radiosondes. This choice is imposed by the need for comparison of numerous profiles at relatively low cost. The best quality of the radiosonde humidity profiles in the lower troposphere will also permit us to confirm the correctness, consistency, and durability of our calibration procedure, a central aspect of our proposed lidar validation plan.

Figure 3. Preliminary water vapor profile (normalized to climatology) obtained with a non-optimized system configuration.
EOS-AURA VALIDATION, AND LONG-TERM MEASUREMENT GOALS

After proper validation of our water vapor measurements, the validation of several instruments onboard AURA is the primary midterm goal. The simultaneous and co-located lidar measurements of water vapor, tropospheric and stratospheric ozone, temperature, and aerosols at TMF will constitute a rare opportunity for multi-parameter correlative measurements and validation of the MLS, OMI, HIRDLS and TES instruments. AURA is scheduled for launch early in mid-2004.

Our water vapor Raman lidar will be fully operational by mid-2004. As is the case for the stratospheric and tropospheric ozone, temperature and aerosols measurements at TMF and MLO, our new water vapor measurements obtained 4-5 times a week will be put into the NDSC long-term archive database. Additional measurements will be performed whenever useful for upcoming validations, and field campaigns like INTEX-NA (Intercontinental Chemical Transport Experiment – North America) in summer 2004 and spring 2006. The JPL lidar group currently has a transportable trailer available, and the proposed lidar could later be deployed to a different location. In particular emerging science requirements may dictate the proposed system to be moved to a tropical site for measurements through the Tropical Tropopause Layer, or to a high-latitude site for upper tropospheric measurements. These two hydrological regions of the troposphere are not yet well understood.

CONCLUSION

A new Raman lidar with the capability of measuring water vapor mixing ratios as low as 1-ppmv near the tropopause is being developed at the JPL-Table Mountain Facility, California. This system has already produced a few promising profiles in a non-optimized configuration, and is expected to be fully operational by mid-2004. At this time, it will significantly contribute to the validation of AURA’s satellite water vapor measurements, and complement the validation of temperature and ozone simultaneously measured at Table Mountain.

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REFERENCES