Water Vapor Raman Lidar for Measurements to the UT/LS: Performance, Validation, and Lessons Learned.

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ABSTRACT

Over the past several years we have developed a Raman lidar system for measurements of water vapor profiles throughout the troposphere and into the upper troposphere/lower stratosphere (UT/LS). Two validation campaigns have already been held, MOHAVE I and II, and a third is currently being planned. The first campaign revealed biases in the lidar profile at high altitudes and H_2O mixing ratios ≤10 ppm. The system was modified to correct these biases as demonstrated in the second campaign. Various methods of calibrating the lidar have been studied and the limitations of using radiosondes for this purpose have been revealed. An improved, hybrid calibration procedure using both radiosondes and a standard lamp has been developed and proved to be effective. This presentation will discuss some of the important lessons learned as we continue to try to improve the performance of this lidar system.

1. INTRODUCTION

Water vapor plays a fundamental role in the chemistry, dynamics, and radiation budget of the Earth atmosphere. Due to its very strong infrared absorption, it is the single most important greenhouse gas on a per molecule basis contributing more than 80% of the total effect. However, the distribution of water vapor, its climatology, and the short and long-term variability of its concentration in the upper troposphere and lower stratosphere (UT/LS) are not well enough known. Despite its abundance in the troposphere its exact effect on the climate system is also still not fully understood. To contribute to addressing these issues and to provide much needed satellite validation measurements, the Network for the Detection of Atmospheric Composition Change (NDACC) has included water vapor Raman lidar in its suite of high quality long-term monitoring instruments. A high capability Raman lidar was developed at the Jet Propulsion Laboratory Table Mountain Facility, CA (TMF) with the objective of measuring water vapor up to 15-20 km altitude. This new lidar instrument is an important complement to the existing lidars at TMF which have been measuring tropospheric ozone, stratospheric ozone, temperature and aerosols for over two decades now.

2. WATER VAPOR RAMAN LIDAR

The water vapor Raman lidar measurement principle is relatively simple and easy to implement [1,2]. Laser light is transmitted into the atmosphere and inelastically backscattered by the atmospheric molecules. The light Raman scattered by nitrogen and water vapor is received by a telescope, spectrally separated, and time-sampled (i.e., altitude-sampled). After various common lidar-specific signal corrections, the ratio of the signals received at the two wavelengths is a quantity directly proportional to water vapor mixing ratio. This quantity is then normalized, for example using the mixing ratio value measured independently by another instrument. The normalization process is usually referred to as the lidar "calibration".

In its original configuration, Fig. 1, the lidar utilized a high-energy per pulse (700 mJ) Nd:YAG laser operating at 355 nm at a repetition rate of 10 Hz, one 91 cm-diameter and three 7.5 cm-diameter telescopes, one optical fiber, and a set of dichroic beamsplitters and interference filters directing the light collected by the telescopes into eight selective Rayleigh (355 nm), nitrogen Raman (387 nm), and water vapor Raman (407 nm) channels. Each channel comprises a photomultiplier tube connected to a Licel multi-channel photon-counting scaler.

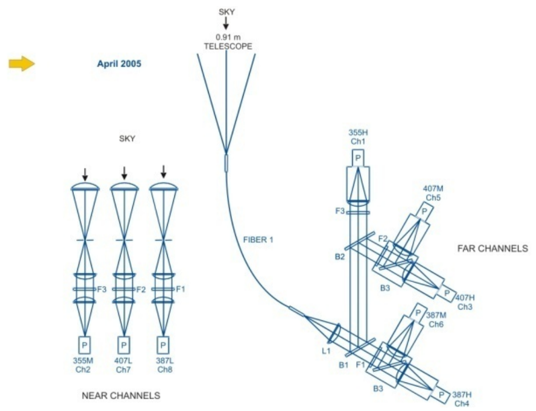

Figure 1. *Original configuration of the Raman lidar.*

Data are acquired typically during two hours at the beginning of the night and simultaneously with the two other operating lidars on site (tropospheric ozone lidar, and stratospheric ozone/aerosols/temperature lidar). The two-hour long measurements are sliced into 5-minute interval datasets, providing vertical profiles with high temporal resolution for altitude ranges with sufficient signal-to-noise ratios. The data are acquired with a vertical sampling of 75-m, then smoothed during signal processing, typically yielding vertical resolutions ranging from 150 m to 3 km, depending on altitude and integration time. Calibration is obtained using the mixing ratio value measured in the lower troposphere (~4 km altitude) by a meteorological radiosonde launched from the lidar site. For that purpose the JPL lidar team uses its own Vaisala RS92 radiosonde station. One RS92 radiosonde is launched from TMF on

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each lidar measurement night. The launch time is optimized to coincide with the first hour of the lidar measurement. Multiple launches may occur if the lidar measurements extend beyond the standard 2-hours. In a typical year, 150 to 200 2-hour-long lidar profiles are obtained, therefore requiring the launch of at least 150 to 200 radiosondes per year.

Figure 2 shows a summary of the water vapour profiles measured by lidar and by RS92 before October 2006 by the system in its original configuration.

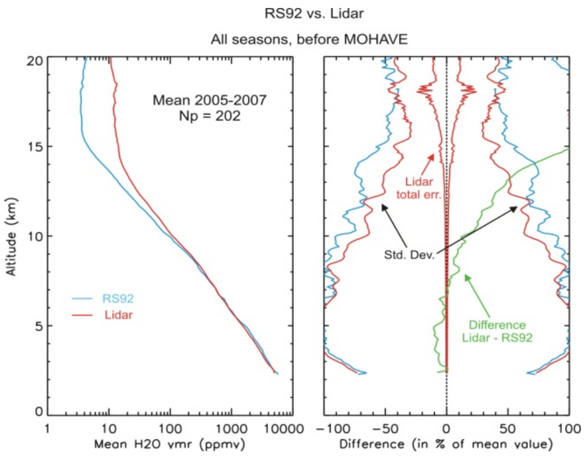

Figure 2. *Average (2005-2006) profiles from simultaneous lidar and RS92 measurements.*

Inspection of figure 2 shows excellent agreement between the lidar and the radiosonde up to about 9-10 km, and an increasing difference as we approach and cross the tropopause, the RS92 being too dry and/or the lidar being too wet. The excessive dryness of the RS92 in the upper troposphere has been known and well documented for many years [3,4]. However, the possible wet lidar bias in the UT/LS could not be confirmed until the lidar profiles were compared to accurate measurements in this region. These comparisons took place during the Measurements Of Humidity in the Atmosphere and Validation Experiments (MOHAVE) campaign held in October 2006 with the primary objective of validating the Raman water vapor lidar measurement in the UT/LS.

3. MOHAVE

Two mobile lidars from the Goddard Space Flight Center (GSFC: AT-Lidar, T. McGee [5]; and SRL, D. Whiteman [6] were deployed at TMF, and 50 RS92 radiosondes and 10 Cryogenic Frost-point Hygrometers (CFH) [7] were launched from TMF during the 15 nights of the campaign. The NRL water vapor microwave radiometer, one GPS from JPL (T. Manucci) and one GPS from GSFC (D. Whiteman) also participated. Each of the three collocated water vapor lidars acquired over 150 hours of measurements (2 to 10 hours per night). The JPL tropospheric ozone lidar was operated simultaneously with the water vapor lidars, and the JPL stratospheric ozone/temperature lidar was operated occasionally during the campaign. At least one balloon per night was launched, each payload including one or two RS92. Ten payloads also contained a CFH and an ozonesonde. The lidar data corresponding to the first hour after launch were systematically processed and compared with the balloon measurements. Figure 2 shows an average of four profiles acquired in similar conditions throughout the campaign.

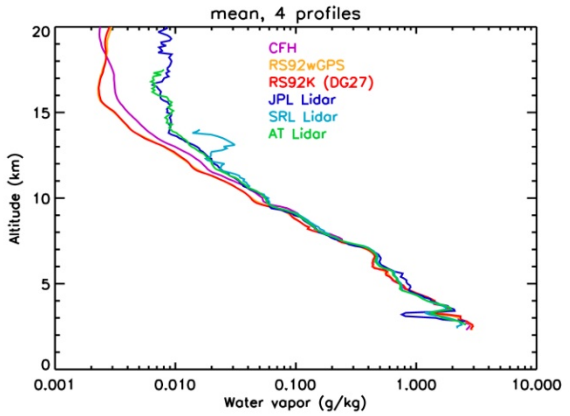

Figure 3. *Mean of 4 profiles measured simultaneously by the lidars, CFH, and RS92.*

If the CFH is taken as the reference profile, we again find a systematic dry bias in the upper troposphere for the RS92, and a wet bias for all three lidars, even though the lidars show excellent agreement with each other.

After investigating the possible sources of the lidar wet bias and running additional test experiments, signal contamination by fluorescence in the lidar receivers was identified which led all three lidar teams to modify their instrument configuration. For the JPL lidar, a 355 nm blocking filter was temporarily installed in front of the fiber optic. The instrument acquired 3 profiles simultaneously with a CFH in this configuration. The difference between the CFH and lidar profiles during these three flights was compared to that before the modification. The results are plotted on figure 4. As anticipated, the wet bias completely disappeared after the modification.

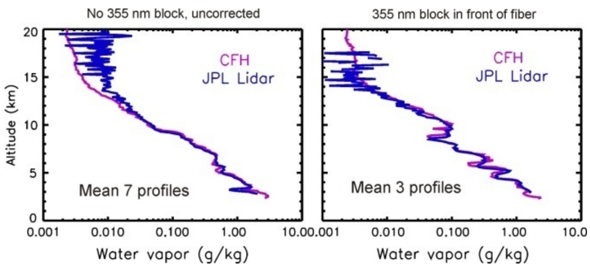

Figure 4. *Comparison of lidar profiles with CFH before (left) and after (right) blocking 355 nm.*

4. MOHAVE II

After MOHAVE, the front-end of the lidar receiver was re-configured to permanently suppress the fluorescence identified in the fiber optic during the campaign. The new configuration in July 2007 redirected the strong 355 nm Rayleigh signal out of the main optical path leaving fluorescence-free signals at 387 nm and 407 nm in the fiber optic [8]. The new and much stronger spectral selectivity resulted in an overall loss of signal of a factor of two, causing a decrease of 3 km (typically from 17 km to 14 km for 1-hour integration) of the uppermost altitude of the instrument.

Both mobile lidar teams that participated in MOHAVE came back to TMF for MOHAVE-II after having modified their instruments. MOHAVE-II was implemented following operational principles similar to that of MOHAVE [8]. Figure 5 shows the average of 10 profiles measured simultaneously by all participating instruments and techniques during the campaign. Though the (unsmoothed) lidar profiles appear noisier partly due to the signal decrease mentioned above, no wet bias appears anymore between the JPL lidar (pink curve) and the CFH (green). A dry bias is still present on the uncorrected RS92 profile (red). The CFH measurement remains the best quality among all instruments but its cost per profile is much higher (~$3000 per CFH launch) than that of the lidar and clearly prohibitive for long-term, routine monitoring.

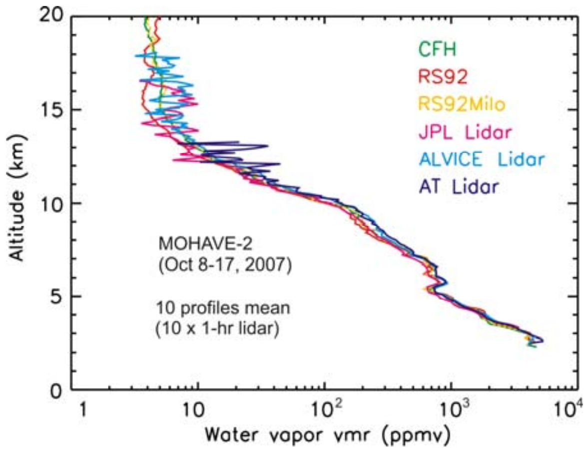

Figure 5. *Average water vapour profiles measured during MOHAVE II.*

5. CALIBRATION

The Raman lidar technique is relatively simple but the measured quantity is not directly water vapor mixing ratio but a quantity only proportional to it. Normalization to the actual mixing ratio, also known as "calibration", is therefore required and can be obtained using various methods [2,9]. The most commonly used technique consists of normalizing the lidar profile to an externally measured value, obtained for example from a nearby meteorological radiosounding such as discussed above. With this method, the overall accuracy of the calibrated lidar measurement is not only dependent on that of the lidar measurement but also on that of the radiosonde measurement. Given the very high spatial and temporal variability of atmospheric water vapor, the accuracy of this method is further affected by the non-simultaneity and non-collocation of the lidar and radiosonde measurements. We will discuss some of the limitations of typical calibration methods.

Issues with using a single radiosonde to calibrate the lidar arise from the different samplings i.e., the radiosonde is co-located with the lidar only near the ground, then drifts away from the lidar site, and provides instantaneous measurements along its flight path. The lidar on the other hand, remains at a fixed location and provides a vertical profile above the site representative of measurements averaged over a finite duration, two hours in the present case.

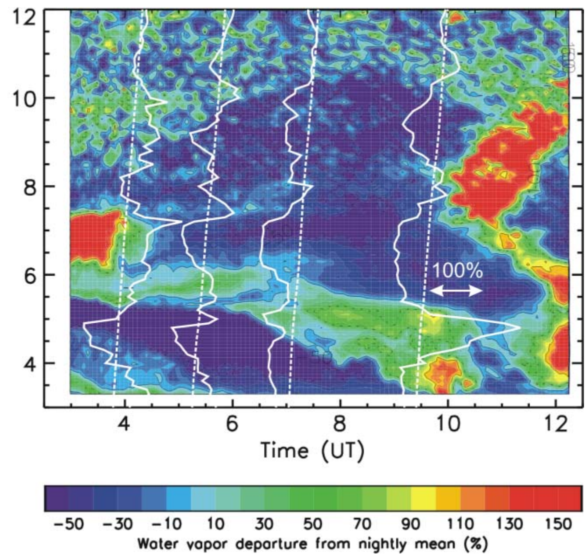

Figure 6. *Time-altitude plot of the water vapour mixing ratio deviation from the nightly mean (see text).*

Figure 6 shows an example of a 2D time-altitude color contour plot of the percentage deviation from the nightly mean water vapor mixing ratio sampled by lidar every 5-minutes. The white solid curves plotted over the color contours show the same departure from average but measured by each of four radiosondes launched on that night. The dotted white lines represent the zero-departure reference line for each radiosonde following the time-altitude path of the balloon. Given the well-known high variability of water vapor on short timescales (in the present case >150% within two hours after 0900 UT), one can easily question the accuracy of the normalization from a nearly - but not perfectly - simultaneous and co-located radiosonde measurement.

To overcome some of these calibration issues we have developed a hybrid procedure that uses both radiosonde measurements and a calibrated lamp. The lamp is permanently mounted above the telescope's primary mirror and directly illuminates the mirror surface. The calibration experiments consist of acquiring lidar signals coming exclusively from illumination by the lamp. The laser beam is shut down, the hatch by which the laser beam usually exits the room is shut, the room is completely dark, and the lamp is turned on. The lamp-only signals are acquired the same way as the lidar acquires actual atmospheric data, data acquisition taking place immediately before and after the lidar experiment. The ratio of the signals collected in the water vapor and nitrogen channels now represents the ratio of the overall (optical and quantum) efficiency of each channel convolved with the spectral irradiance of the lamp at each wavelength. It is not our intent that this measured ratio should provide an absolute calibration constant of the lidar. It is probable that the optical arrangement of the lamp does not provide uniform illumination of all of the receiver components. This is not an issue so long as the arrangement does not change. All that is required is that the ratio of the lamp's spectral output at 387 nm and 407 nm remains constant. Small changes in the absolute lamp irradiance should not be a problem. Assuming a constant lamp power output ratio over time, the variation over time of the channel ratios is equal to the variation over time of the lidar receiver's absolute calibration constant. Any change in the lidar calibration constant is readily revealed.

However, the calibration ratio from the lamp experiments itself need calibration. This is done through campaigns such as MOHAVE during which the lamp partial calibration is "transferred" into absolute calibration using external measurements such as radiosondes or any other external measurements having the required accuracy. This new method has the double advantage of routinely identifying any fine variations in the lidar receiver transmission ratio (partial calibration), and optimizing the determination of the absolute calibration (optimization on both a theoretical and a logistical point of view). Furthermore it is not constrained by additional theoretical and/or technical difficulties mentioned by Sherlock [9] such as the convolution of the Raman cross-sections by the filters bandwidth, the accurate determination of the absolute transmission and efficiencies of the lidar receiver, the accurate knowledge of illumination geometry, or the accurate knowledge of atmospheric transmission. The hybrid method therefore seems suitable for the long-term monitoring of atmospheric water vapor.

6. RECENT CHANGES AND MOHAVE 2009

As mentioned above, installation of the additional optics to divert the 355 nm returns into a separate fiber reduced the overall signal levels. To try and recover the signal level and potentially increase it, it was decided to eliminate the fibers completely and to reposition the receiver at the telescope Newtonian focus.

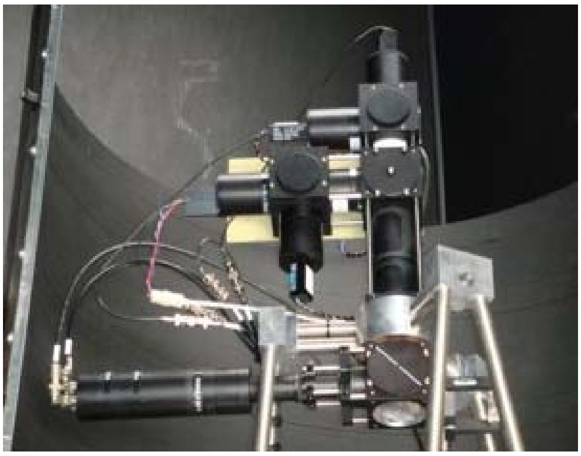

Figure 7. *Photograph of the repositioned receiver system. 355 nm is extracted first. The calibration lamp is also visible to the left of the first splitter.*

With so many changes to the TMF water vapour Raman lidar, and also to the GSFC systems, it was decided that another MOHAVE type campaign was necessary. This campaign will be held at TMF during October 2009 (simultaneous with this conference).

In addition to intercomparison and validation of various instruments, including AIRS and Aura satellite instruments, MOHAVE 2009 will attempt to:

- Identify and quantify UT Humidity (UTH) changes associated with transport processes in the vicinity of the Sub-Tropical Jet
- Estimate the capability of the Raman lidar in detecting such UTH changes
- Provide continuous water vapor profiles from the ground to the mesosphere by combining the measurements of the various participating instruments and techniques

Participating instruments and intuitions will include:

- 3 water vapor Raman lidars (JPL & GSFC)
- 15 CFH launches (JPL & GSFC)
- 3 Frost-point Hygrometer (FPH) launches (NOAA)
- 50 RS92 launches (JPL)
- 2 improved microwave radiometers (NRL & Univ. Bern)
- 2 ground-based GPS receivers (GSFC & JPL)
- 1 FTIR (JPL tentative)
- High resolution PV forecasts and analysis (JPL & CNRS/France)

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