

## Characterization of upper troposphere water vapor measurements during AFWEX using LASE

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## ABSTRACT

Water vapor profiles from NASA's Lidar Atmospheric Sensing Experiment (LASE) system acquired during the ARM/FIRE Water Vapor Experiment (AFWEX) are used to characterize upper troposphere (UT) water vapor measured by ground-based Raman lidars, radiosondes, and in situ aircraft sensors. Initial comparisons showed the average Vaisala radiosonde measurements to be 5-15% drier than the average LASE, Raman lidar, and DC-8 in situ diode laser hygrometer measurements. We show that corrections to the Raman lidar and Vaisala measurements significantly reduce these differences. Precipitable water vapor (PWV) derived from the LASE water vapor profiles agrees within 3% on average with PWV derived from the ARM ground-based microwave radiometer (MWR). The agreement among the LASE, Raman lidar, and MWR measurements demonstrates how the LASE measurements can be used to characterize both profile and column water vapor measurements and that ARM Raman lidar, when calibrated using the MWR PWV, can provide accurate UT water vapor measurements.

## 1. INTRODUCTION

Improving the parameterization of radiative processes in General Circulation Models (GCMs), which is a primary objective of the DOE ARM Program, requires an accurate specification of the atmospheric state. Water vapor measurements are especially important for this characterization because uncertainties in the water vapor field dominate the spectral effects in the atmospheric window region. Measurements obtained at the ARM Southern Great Plains (SGP) site have indicated that uncertainty in the routine water vapor measurements is the limiting factor in assessing the performance of the radiation models. The largest differences in water vapor profiles are found in the upper troposphere, where differences between operational Raman lidar and Vaisala radiosonde water vapor profiles often exceed 20%<sup>1</sup>.

ARM has conducted a series of experiments at the SGP site to characterize and ultimately improve the accuracy of water vapor measurements. The goal is to develop techniques to reduce uncertainties in upper troposphere (UT) water vapor measurements to less than 10%. As the latest in these series of experiments, the ARM-FIRE Water Vapor Experiment (AFWEX) was conducted at the SGP site during late November to early December 2000 to resolve differences in measurements of absolute water vapor amounts and to characterize the upper troposphere water vapor measurements acquired at the SGP site. During AFWEX, the NASA DC-8 aircraft was deployed and carried a suite of instruments to help characterize UT water vapor measurements. One such instrument was the Lidar Atmospheric Sensing Experiment (LASE) system, which provided absolutely calibrated water vapor profiles both above and below the aircraft. We discuss the LASE system, the LASE water vapor measurements acquired during AFWEX, and describe how these measurements have been used to assess and characterize the UT water vapor measurements acquired by several other sensors.

## 2. LASE SYSTEM

LASE is an airborne DIAL (Differential Absorption Lidar) system that was developed to measure water vapor, aerosols, and clouds throughout the troposphere. This system uses a double-pulsed Ti:sapphire laser, which is pumped by a frequency-doubled Nd:YAG laser, to transmit light in the 815-nm absorption band of water vapor. LASE operates by

locking to a strong water vapor line and electronically tuning to any spectral position on the absorption line to choose the suitable absorption cross-section for optimum measurements over a range of water vapor concentrations in the atmosphere. For AFWEX, LASE operated using strong and weak water vapor lines in both the nadir and zenith modes, thereby simultaneously acquiring data both above and below the aircraft. Typical horizontal and vertical resolutions for water vapor profiles between 0.2-12 km are 14 km (1 min) and 330 m, respectively, for nadir measurements, and 70 km (3 min) and 990 m, respectively, for zenith measurements. Previous comparisons of water vapor measurements with other sensors showed the LASE water vapor mixing ratio measurements to have an accuracy of better than 6% or 0.01 g/kg, whichever is larger, across the troposphere<sup>2</sup>.

### 3. LASE MEASUREMENTS DURING AFWEX

After the transit flight of the DC-8 to Tinker Air Force Base (AFB) on November 29, there were a total of six science flights of the DC-8 over the ARM SGP site between November 30 and December 10. LASE collected approximately 26 hours of data during these flights. The flight patterns typically consisted of a spiral ascent over the SGP site, followed by a series of level leg segments at several different altitudes in the upper troposphere, followed by a spiral down over the SGP site before the DC-8 returned to Tinker AFB. The spiral portions of each flight permitted the DC-8 in situ water vapor sensors to acquire a vertical profile over the SGP site. The level leg segments were performed at several altitudes between about 7.7 and 12.4 km above the SGP site. These segments, which were oriented both parallel and perpendicular to the wind at these altitudes, were approximately 10 minutes (140 km) in duration and were centered over the ARM SGP site.

### 4. AVERAGE WATER VAPOR COMPARISONS

Water vapor measurements acquired by three ground-based lidars (CART Raman (CARL), NASA GSFC Scanning Raman, MPI DIAL), three radiosonde sensors (Vaisala RS80-H, Sippican, Inc. (formerly VIZ Manufacturing Company) carbon hygistor, Snow White chilled mirror), and two DC-8 in situ sensors (NASA Langley diode laser hygrometer (DLH), cryogenic frost point hygrometer) were compared with the LASE profiles. Thirty minute average profiles from the two Raman lidars were compared with the UT water vapor measurements from LASE. MPI DIAL profiles were limited to altitudes below about 8 km. The number of individual comparisons with the various sensors varied from 75 (LASE and CARL) to 16 (LASE and chilled mirror sonde).

Average differences between the LASE water vapor profiles and the profiles measured by the ground based lidars and radiosondes were computed as a function of altitude. Figure 1 shows the average difference (%) between the LASE water vapor values and the corresponding values from the other sensors as a function of altitude; the boxes represent +/- 2 standard error of the average, and error bars represent +/- 1 standard deviation of the measurements. There was generally very good agreement among the ground-based Raman lidars, the MPI DIAL system, and LASE with average differences generally less than 10% for altitudes between 0-12 km. Both Raman lidars were calibrated such that the precipitable water vapor (PWV) derived by integrating their water vapor profiles matched the PWV measured by the ARM SGP ground based microwave radiometer (MWR). Additional comparisons with instruments on the SGP 60 m tower, radiosondes, GSFC Raman lidar, and MPI DIAL water vapor profiles revealed a slight altitude dependence of the CARL overlap correction. Modifying this overlap correction altered the CARL water vapor calibration slightly and reduced the CARL UT water vapor profiles by about 4%. Incorporating the temperature dependence of the Raman water vapor filter response also slightly reduced the CARL UT water vapor measurements. Together, these corrections reduced the CARL UT water vapor profiles by about 8%. A similar correction for the temperature dependence of the Raman water vapor filter also reduced the NASA GSFC Raman lidar UT water vapor measurements by about 3%.

The Vaisala radiosonde UT water vapor profiles were about 8-10% drier than the LASE profiles. The average difference between LASE and the Vaisala radiosonde increased with altitude suggesting that the sonde dry bias increases with altitude. This dry bias is similar to what has been reported in previous UT water vapor comparisons<sup>3</sup>. In an attempt to correct for this dry bias as well as to remove significant radiosonde batch-to-batch variability, ARM has computed another Vaisala radiosonde water vapor dataset by applying a single, altitude-independent scaling factor to the Vaisala water vapor profiles so that the sonde PWV matches the MWR PWV. Although this scaling generally moistens the lower troposphere and impacts the PWV, Figure 1 shows that this scaling does not significantly affect the Vaisala UT water vapor profiles. A correction scheme to account for a number of factors that affect the Vaisala humidity measurements is also under development. Portions of this correction scheme were applied to the AFWEX

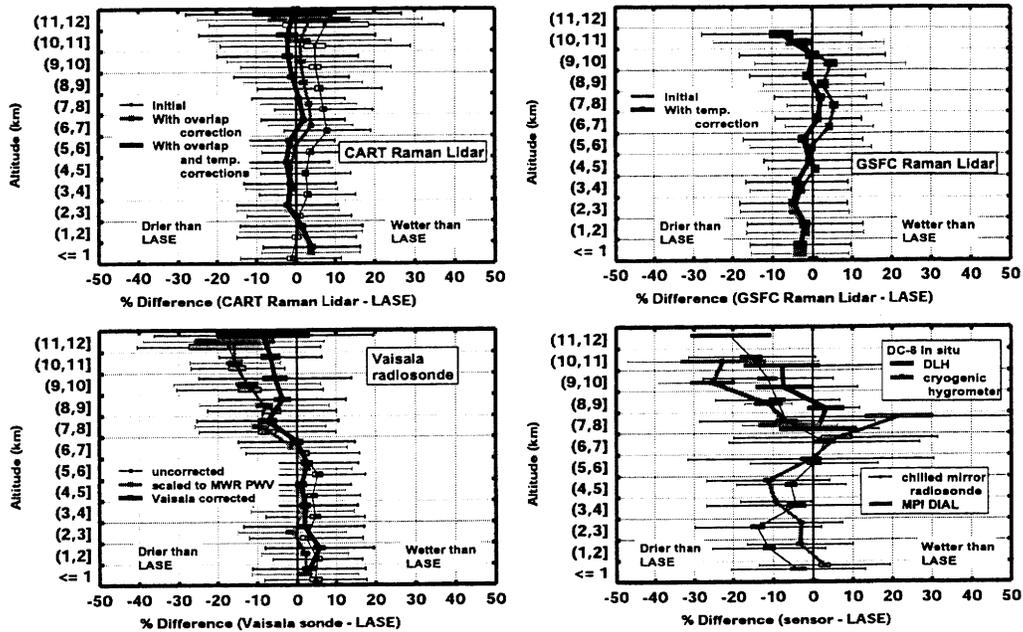


Figure 1. Average differences (%) in water vapor measurements between various AFWEX sensors and LASE. Boxes represent  $\pm 2$  st. error of the average and error bars represent standard deviations of the measurements.

data to account for the error in the basic RS80H calibration model, and to improve the representation of the temperature dependence of the RS80H calibration. (The AFWEX sondes were new and so no correction was applied to account for possible sensor contamination by outgassing of the plastic packaging material.) Figure 1 shows that this correction does increase the Vaisala UT water vapor profiles and bring them into closer agreement with the LASE and Raman lidar measurements. The corrections to the CARL and Vaisala radiosonde UT water vapor measurements bring them into closer average agreement (within  $\sim 5\%$ ) and within the 10% goal in mean differences in UT water vapor. The UT water vapor profiles measured by the carbon hygistor radiosonde sensor exhibited large variabilities and poor agreement with the other measurements and are consequently not shown. The chilled mirror UT water vapor measurements were generally drier than the LASE UT water vapor measurements, but were still within about 10% on average.

Comparisons of the LASE and DC-8 in situ UT water vapor measurements are also shown in Figure 1. The in situ water vapor measurements acquired during level leg flights were averaged together and compared with the LASE nadir (zenith) water vapor measurements acquired when the DC-8 flew at a higher (lower) altitude either just before or after the in situ measurements. Approximately 5-14 level leg comparisons were acquired at each 1 km altitude bin for a total of about 80 comparisons for each in situ sensor. The LASE and DLH water vapor measurements agreed within about 3% on average; however, the cryogenic frost point hygrometer values were about 14-17% less than the corresponding LASE and DLH measurements. This larger difference is most likely due to response characteristics dictated by physical properties (or restraints) of the chilled-mirror instrument and measurement technique. Previous comparisons between diode laser and cryogenic frost point hygrometers have also shown the tendency of cryogenic frost point hygrometers to measure smaller water vapor amounts than diode laser hygrometers<sup>4,5</sup>.

Figure 2 shows an overall comparison of UT water vapor measurements relative to the corresponding LASE measurements. Average differences between each sensor's measurements and the LASE measurements for altitudes between 7 km and the tropopause and for water vapor mixing ratio values below 0.2 g/kg are shown. Simultaneous temperature and ozone measurements indicated that tropopause altitudes varied between 10.5 and 13 km during these flights. The excellent agreement among the Raman lidars, which were calibrated using the MWR PWV, and LASE measurements indicates that the LASE absolute water vapor calibration agrees well with the MWR absolute water vapor calibration. This was verified by comparing PWV derived from the LASE water vapor profiles with the MWR PWV. When deriving PWV from the LASE profiles, two different methods were used to estimate the small ( $\sim 10\%$ ) contribution to the PWV for altitudes between the surface and the lowest LASE water vapor measurement about 250 m above the surface. The first method interpolated through this region using the LASE water vapor profile above 250 m and the tower water vapor measurements at 25 and 60 m. The second method used an average of the LASE water vapor measurements between 250 and 400 m above the surface as an estimate of the average water vapor below 250 m. The

average PWV computed from the LASE profiles using these methods agreed to within 0.25% of each other and to within 3% of the MWR PWV.

## 5. CONCLUSION

Initial comparisons with LASE upper troposphere (UT) water vapor measurements acquired during AFWEX showed the CART Raman lidar (CARL) UT water vapor profiles were about 6% wetter than LASE in the upper troposphere, and the Vaisala RS80-H and chilled mirror sondes were about 8-10% drier than LASE. The differences between the CARL and Vaisala radiosonde profiles are reduced to about 5% by accounting for altitude and temperature dependencies of the CARL water vapor profiles, and by employing a correction scheme designed to correct the Vaisala RS80-H calibration method. The LASE and DC-8 in situ DLH UT water vapor measurements generally agreed to within about 3%, although the DC-8 in situ cryogenic hygrometer measurements were generally 10-20% drier than the LASE measurements. Precipitable water vapor (PWV) derived from the LASE profiles agrees within about 3% on average with PWV derived from the ARM SGP microwave radiometer. The agreement between the LASE and MWR PWV and the LASE and CARL UT water vapor measurements supports the hypotheses that MWR measurements of the 22 GHz water vapor line can accurately constrain the total water vapor amount and that the CART Raman lidar, when calibrated using the MWR PWV, can provide an accurate, stable reference for characterizing UT water vapor.

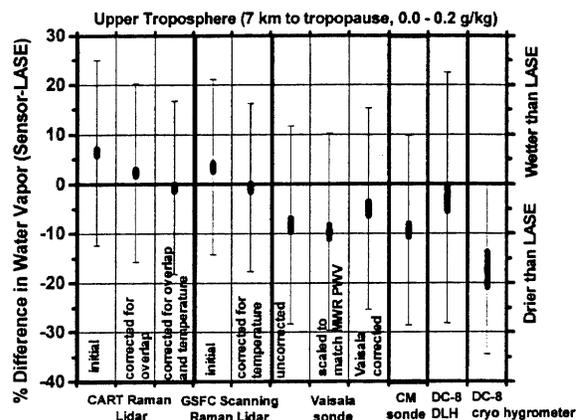


Figure 2. Average differences in UT water vapor measurements referenced to the LASE measurements. Boxes represent  $\pm 2$  st. deviations of the average and error bars represent standard deviations of the measurements.

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