Comparison of Measurements by the NASA/GSFC Scanning Raman Lidar and the DOE/ARM CART Raman Lidar

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Introduction

Latent heat transfer through evaporation and condensation of water vapor is the most important energy transport mechanism in the atmosphere. In addition, water vapor is the most active greenhouse gas. Any global warming scenario must take accurate account of the spatial and temporal variation of water vapor in order to account for both of these effects.

Due to the great importance of water vapor in atmospheric radiation studies, specific intensive observation periods (IOPs) have been hosted by the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) program. One of the goals of these IOPs has been to determine the quality of and explain any discrepancies among a wide variety of water vapor measuring instruments. Raman lidar systems developed by the National Aeronautics and Space Administration (NASA)-Goddard Space Flight Center (GSFC) and DOE/Sandia National Laboratories have participated in the two Water Vapor IOPs (WVIOPs) held at the Southern Great Plains (SGP) Cloud and Radiation Testbed Site (CART) site during 1996 (WVIOP1) and 1997 (WVIOP2). A detailed comparison of these two systems is ongoing but this effort has already resulted in numerous improvements in design and data analysis for both lidar systems.

Lidar System Descriptions

The NASA/GSFC scanning Raman lidar (SRL) (Ferrare et al. 1995) is a mobile system that uses two laser transmitters: a XeF excimer laser (24 Watts to 351 nm) for nighttime measurements and a tripled Nd:YAG (9 Watts to 355 nm) for daytime measurements. Using a 0.76 m telescope, Rayleigh and Mie scattering from molecules and aerosols as well as Raman shifted signals from oxygen (1555 $\mathrm{cm^{-1}}$), nitrogen (2329 $\mathrm{cm^{-1}}$) and water vapor (3654 $\mathrm{cm^{-1}}$) are measured. Interference filters and photomultiplier tubes (PMTs) are used to select and detect the desired wavelengths. Two PMTs are used for each signal: one for low altitude returns and the other for high altitude. A large scan mirror allows profiles to be acquired at any angle in a single scan plane and also allows improved measurements at low altitudes for comparison with tower or surface-based instruments.

The CART Raman lidar (CARL) (Goldsmith et al. 1998) is an autonomous, operational lidar system permanently deployed at the SGP site. It has advanced the state-of-the-art in Raman lidar system automation with its demonstrated ability to make unattended measurements for days at a time. It uses a tripled Nd:YAG laser (12 Watts to 355 nm), a 0.61-m telescope and interference filters and PMTs. In addition to the Rayleigh/Mie, Raman water vapor and nitrogen signals, CARL also has the capability to measure depolarization in the Rayleigh/Mie channel. As in the SRL, CARL uses high and low channels for each signal.

Water Vapor Mixing Ratio Bias Versus Height

The ARM WVIOP held during September 1996 provided the first opportunity for the Raman lidar systems from NASA and DOE to be carefully intercompared. Water vapor measurements were compared as a function of height using all times when both lidar systems were operated together and when radiosonde launches occurred. This allows the radiosondes to be used to determine the source of any systematic differences that might be found between the lidar systems. The first comparison of the lidars was performed shortly after WVIOP1 in 1996 and showed significant bias changes with height (Turner and Goldsmith 1998). Work done since then has identified the sources of most of these differences. The most recently processed data from WVIOP1 implements a new lidar system overlap (Goldsmith et al. 1998) correction for the CARL analysis, which has removed most of the bias variation with height. The lidar systems now are in agreement to generally better than +/- 5% from near the surface to about 7 km. The results from both IOPs are presented in Figure 1.

The left panels of Figure 1 present the average profiles of the SRL, CARL and Vaisala radiosondes for 12 cases during WVIOP1 and 14 cases during WVIOP2. These are the profiles used in the comparisons shown in the other panels of the figure. The results from WVIOP1 shown in the lower panels will be discussed first.

The lower right-hand panel gives the water vapor mixing ratio bias versus height for WVIOP1 using the new overlap correction in the CARL analysis that has removed most of the height bias seen in earlier results (Turner and Goldsmith 1998). There still remains up to a 5% bias between the two lidar systems between 0 km to 4 km. The panel in the lower center of the figure presents the ratio of the average lidar profile (both CARL and SRL) to the average radiosonde profile. This comparison shows that the lidars disagree with the radiosonde in the lowest part of the profile. Both the CARL and SRL curves slope toward the average radiosonde profile from the surface up to about 1.5 km in the case of the SRL and about 3.0 km in the case of the CARL. These differences require further study but are perhaps due to an equilibration time for the radiosondes or an incorrect lidar system overlap (Goldsmith et al. 1998) in both lidar systems.

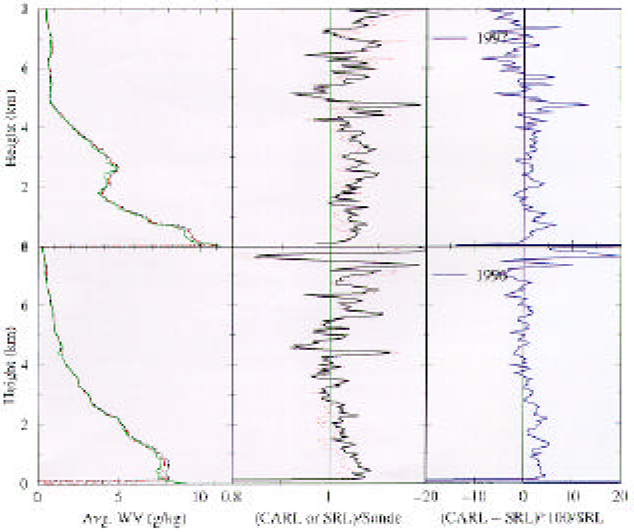

Figure 1. Synopsis of water vapor mixing ratio measurements versus height for both lidar systems and the Vaisala radiosondes averaged over both WVIOPs. In the left panels, the average radiosonde profile is represented by a solid curve, average SRL by a dashed curve, and the average CARL by a dotted curve. The overall agreement is excellent. In the center panel the ratio of these SRL and CARL averages to the average radiosonde profile is shown. The SRL ratio is represented by a dotted line, the CARL ratio by a solid line. The right panels are a comparison of average SRL to CARL percentage difference. The lower three panels present the most recently processed results from WVIOP1 (1996) while the results from WVIOP2 (1997) are presented on top. As explained in the text, the current analysis of SRL to CARL bias versus height for both WVIOPs shows that the lidars agree to within +/- 5% up to about 7 km for both experiments. The comparison with the average radiosonde profiles, which is shown in the center panels, indicates that there were small biases for both lidar systems during both WVIOPs; a sloping height-dependent bias during 1996 and a constant offset bias during 1997. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/whiteman-98.pdf*.)

The results from WVIOP2 are presented in the upper panels of Figure 1. In general, these comparisons indicate excellent agreement between the lidars. There is, however, an indication of a consistent difference of up to 5% between the lidars at about 1 km (upper right), which may be due to errors in the merging of the high and low channels. Otherwise, the average lidar profiles show little height-dependent bias. The comparison of the lidars with radiosonde (upper middle), however, displays a consistent bias because the lidars are calibrated with respect to the CART microwave radiometer (MWR), which, in general, measures a higher value of precipitable water (PW) than the radiosondes.

PW Comparisons

For the PW comparisons, the final calibration of the lidar mixing ratio for both systems has been performed by forcing the lidar integrated PW to agree with that measured by the CART MWR. A single calibration constant for the entire IOP has been derived for each lidar system. Figure 2 shows the comparison of PW values for the two lidar systems over seven nights of measurement. The bias and root mean square (rms) differences between the two systems were -0.06 cm and 0.13 cm, respectively, indicating that the lidars show good agreement with each other. The non-zero bias indicates that the calibration constants for the two systems were determined using a larger dataset than presented in these figures. On the evenings of September 26 and October 1, the SRL PW measurements were lower than the CARL measurements. On September 26, the differences are due to substantially different mixing ratio profiles for both lidar systems. The radiosonde measurement made at this time did not agree with either lidar in the lowest 1 km as shown in Figure 3.

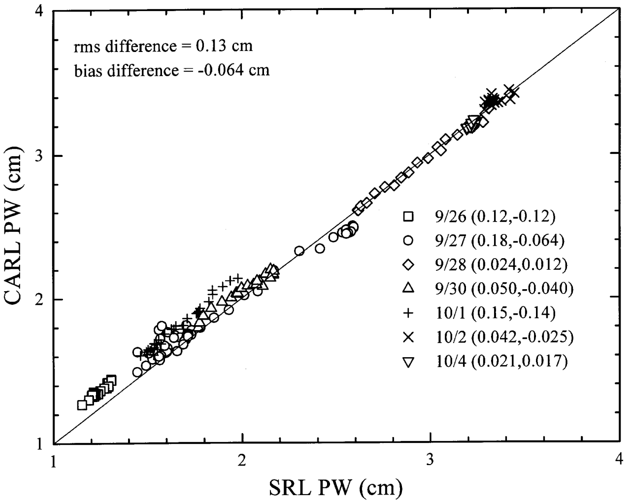

Figure 2. PW comparison of the CARL and the SRL from the 1997 WVIOP. Both lidars were calibrated with respect to the CART MWR precipitable water measurements. The agreement of the two systems is in general quite good. Discrepancies on the nights of September 26 and October 1 are under investigation.

These differences in measurement have yet to be explained. On October 1, the SRL used a Nd:YAG laser for the transmitter due to an electrical problem in the excimer laser, which is normally used for nighttime measurements. The differences on this night can be attributed to this substitution and the different calibration required.

As mentioned above, the calibration for both lidars is determined through comparisons with the CART MWR. Comparisons of the lidars with the CART radiometer thus show very good agreement and will be presented at the meeting. Figure 4 shows PW data from both lidars compared to NOAA/ETL (National Oceanic and Atmospheric Administration/Environmental Technology Laboratory) MWR. The measurements are very consistent but show a bias that changes either as a function of PW or as a function of day of measurement. As will be shown at the meeting, this same bias change is present when a comparison of CART MWR PW versus this same ETL MWR is performed. It is clear

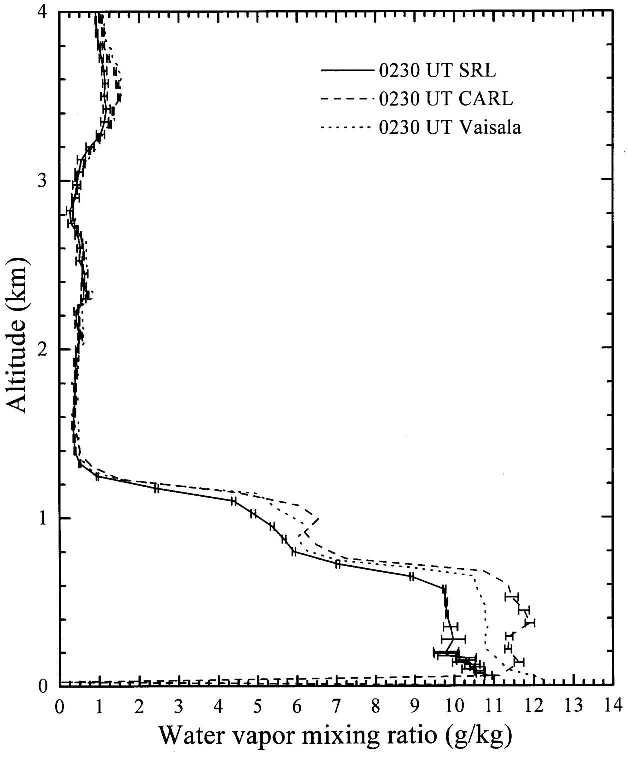

Figure 3. CARL, SRL and Vaisala radiosonde measurements of water vapor mixing ratio on the night of September 26. There are significant differences among all instruments in the first kilometer.

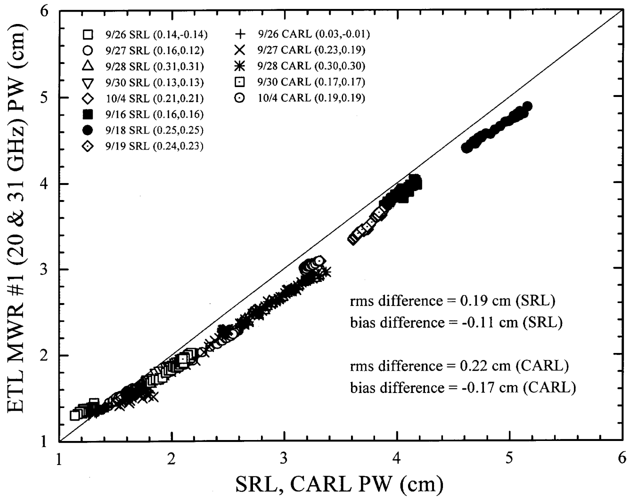

Figure 4. CARL and SRL measurements of PW compared with the ETL MWR. Notice the bias that changes as a function of PW. As the lidars are calibrated against the CART MWR, this curve reveals a PW-dependent bias between the CART MWR and the ETL MWR.

from these comparisons that the standard to which the Raman lidar water vapor measurements is tied is crucial.

Other Comparisons and Testing

Comparisons have also been made between water vapor mixing ratio measurements at the 60-m height by both lidars as well as the Vaisala in situ sensor on the 60-m tower at the CART site. These will be presented along with the results of other work that is ongoing between the two lidar groups, including 1) linearity testing of both the CARL and the SRL photomultiplier tubes, and 2) influence of high count rates on derived water vapor amount and improved techniques for processing these data.

Summary

Detailed comparisons of the water vapor measurements made by two Raman lidar systems during the two WVIOPs have been made. These comparisons have resulted in improvements in both the way that data are acquired and the way that the data are processed. Discrepancies in water vapor mixing ratio measurements between the two systems have been addressed and to a large degree resolved yielding excellent agreement between the lidar instruments. The small residual discrepancies between the lidars, which are on the order of 5% or less, are still under investigation. In addition, several other areas still require further study including 1) PMT detector linearity, and 2) the influence of high signal levels and lidar system overlap function on derived water vapor values. Examples of this work will be presented at the meeting.

References

Ferrare, R. A., S. H. Melfi, D. N. Whiteman, K. D. Evans. F. J. Schmidlin, and D. O'C. Starr, 1995: A comparison of water vapor measurements made by Raman lidar and radiosondes. *J. Atmos. Oceanic Technol.*, **12**, 1177-1195.

Goldsmith, J. E. M., F. H. Blair, S. E. Bisson, and D. D. Turner, 1998: Turn-key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols. *Applied Optics*, accepted.

Turner, D. D., and J. E. M. Goldsmith, 1998: CART Raman lidar water vapor measurements during the ARM 1996 Water Vapor IOP. In *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting*, CONF-970365, pp. 131-134. U.S. Department of Energy, Washington, D.C.