Raman Lidar Measurements of Aerosols and Water Vapor During the May 2003 Aerosol IOP

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Abstract

Raman lidar water vapor and aerosol extinction profiles acquired over the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in northern Oklahoma (36.606 N, 97.50 W) are evaluated using profiles measured by ground-based and airborne in situ and remote sensing instruments deployed during the May 2003 Aerosol Intensive Operations Period (IOP). Automated algorithms used to derive aerosol and water vapor profiles from the CART (Cloud and Radiation Testbed) Raman lidar (CARL) data were modified to reduce or remove the adverse effects associated with a general loss of sensitivity of the Raman lidar since early 2002. These modifications reduced but could not eliminate these adverse effects. The Raman lidar water vapor (aerosol extinction) measurements produced by these modified algorithms were, on average, 0 to 15% (30 to 50%) higher than the other measurements. The high bias of the Raman lidar aerosol extinction measurements is due primarily to several issues associated with this loss of sensitivity of the Raman lidar.

Introduction

Measurements of water vapor and aerosol optical properties are required to meet two of the primary objectives of ARM, which are: 1) relate observations of radiative fluxes and radiances to the atmospheric composition and, 2) use these relations to develop and test parameterizations to accurately predict the atmospheric radiative properties. Measurements of water vapor are especially important in characterizing the clear-sky atmospheric state because uncertainties in the water vapor field dominate the spectral effects in the atmospheric window region of 800-1200 cm^{-1} (8.3-12.5 um). Vertical profiles of aerosol properties are required for the computation of radiative flux profiles.

ARM has aggressively pursued new technologies for systematic and routine measurements of water vapor and aerosols at the ARM SGP site. One such example is the CARL, which operates as a turnkey, automated system for unattended, around-the-clock profiling of water vapor and aerosols (Goldsmith et al. 1998). Although water vapor profiles acquired by CARL during nighttime operations have been extensively evaluated (Revercomb et al. 2003), water vapor and, in particular, aerosol profiles acquired during daytime operations have not been similarly evaluated. In this study, we assess the daytime CARL water vapor and aerosol extinction profiles using measurements acquired by additional ground-based and airborne in situ and remote sensing instruments that were deployed during the May 2003 Aerosol IOP.[a]

CART Raman Lidar

CARL autonomously measures profiles of aerosols, clouds, and water vapor in the low- to mid-troposphere throughout the diurnal cycle (Goldsmith et al. 1998). A tripled Nd:YAG laser, operating at 30 Hz with 350-400 millijoule pulses, is used to transmit light at 355 nm. A telescope collects the light backscattered by molecules and aerosols at the laser wavelength and the Raman scattered light from water vapor (408 nm) and nitrogen (387 nm) molecules. Profiles of water vapor mixing ratio, relative humidity (RH), aerosol backscattering, and aerosol extinction are derived routinely using a set of automated algorithms (Turner et al. 2002). Water vapor mixing ratio profiles are computed using the ratio of the Raman water vapor signal to the Raman nitrogen signal. Relative humidity profiles are computed using these profiles and the temperature profiles from a collocated Atmospheric Emitted Radiance Interferometer (AERI). The water vapor mixing ratio profiles are integrated with altitude to derive precipitable water vapor (PWV). Profiles of aerosol scattering ratio are derived using the Raman nitrogen signal and the signal detected at the laser wavelength. Aerosol volume backscattering cross section profiles are then computed using the aerosol scattering ratio and molecular scattering cross section profiles derived from atmospheric density data. Aerosol extinction profiles are computed from the derivative of the logarithm of the Raman nitrogen signal with respect to range. Aerosol optical thickness is derived by integration of the aerosol extinction profile with altitude.

(a) (http://www.db.arm.gov/cgi-bin/IOP/selectExecSummary.pl?iopName=sgp2003aerosol&person_id=)

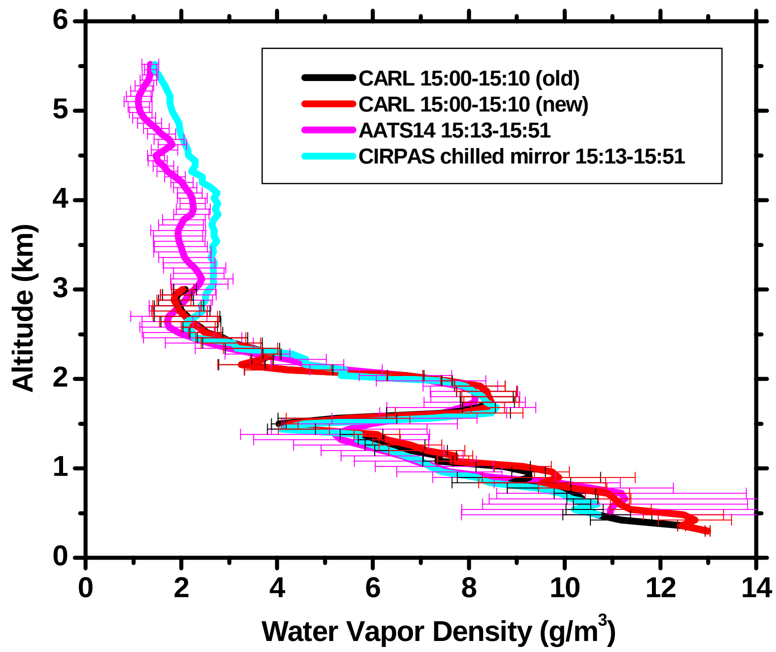
May 2003 Aerosol IOP

One of the goals of the May 2003 Aerosol IOP that was conducted over the SGP site was to characterize the routine aerosol extinction profile measurements acquired by CARL. Additional ground-based and airborne in situ and remote sensing instruments were deployed during this IOP to help assess these and other SGP measurements. Comparisons of the CARL aerosol and water vapor profiles with these additional datasets acquired during the IOP as well as trends derived from long-term CARL measurements revealed several issues with the CARL data that adversely impacted retrievals of both aerosol and water vapor profiles. The sensitivity of the CARL has been significantly declining since the end of 2001. This loss of sensitivity has greatly impacted the quality of the CARL aerosol backscattering and extinction profiles derived since this time and during the Aerosol IOP. Therefore, the automated algorithms used to derive aerosol and water vapor profiles from the CARL data were modified in an attempt to reduce or remove these adverse effects. The modifications to the aerosol retrievals: 1) lowered the low/high channel merge region, 2) increased the vertical smoothing of low N2 channel, 3) updated the overlap correction functions, 4) developed new procedures for detecting gross alignment changes, and 5) improved the logic associated with the retrieval and use of the aerosol extinction/backscatter ratio. Modifications to the water vapor retrievals updated the overlap correction functions and changed the calibration procedure to use a single water vapor calibration constant for the entire IOP. Turner et al. (2003a) provide a more complete description of how the loss of sensitivity impacts the Raman lidar retrievals and the modifications made to alleviate these adverse effects.

Several comparisons were made to assess the CARL water vapor and aerosol extinction retrievals. Some comparisons used measurements acquired from an extensive suite of instruments deployed on board the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft. The Twin Otter performed 16 daytime research flights over the SGP site during the IOP. The aircraft carried instrumentation to perform in-situ measurements of aerosol absorption (Particle Soot Absorption Photometer [PSAP]) and scattering (nephelometer) and water vapor density (chilled mirror). Aerosol extinction and water vapor density were measured with the National Aeronautics Space Administration (NASA) Ames Airborne Tracking 14-channel Sun photometer (AATS14) (Schmid et al. 2004). Additional measurements were acquired as part of the ARM In Situ Aerosol Profiling (IAP) measurement program. In this program, measurements of aerosol sub-micrometer scattering (nephelometer), backscattering, and absorption (PSAP) and water vapor are acquired by in situ instruments on a small aircraft flown 2 to 3 times per week on a long-term (i.e., multi-year) basis (Andrews et al. 2004). The IAP instrument suite includes a Vaisala Humicap 50Y capacitive sensor to measure ambient RH. Additional IOP water vapor comparisons include both the standard Vaisala RS-90 radiosonde water vapor profiles, as well as the radiosonde water vapor profiles that have been scaled to match the PWV measured by the ARM SGP microwave radiometer (MWR). These MWR scaled radiosonde profiles have been adopted by ARM because this scaling has significantly reduced the sonde-to-sonde variability and has reduced the residuals between measurements and models of high spectral infrared radiance (Turner et al. 2003b). These water vapor comparisons were performed for altitudes between 0.1 to 3.0 km to match the nominal daytime altitude range of CARL.

Figure 1 shows examples of water vapor and aerosol extinction profiles acquired on May 22. The water vapor profiles derived using normal (“old”) processing are shown as well as those derived using the modified (“new”) algorithms. Enhanced background skylight limits CARL water vapor retrievals

(a)



(b)

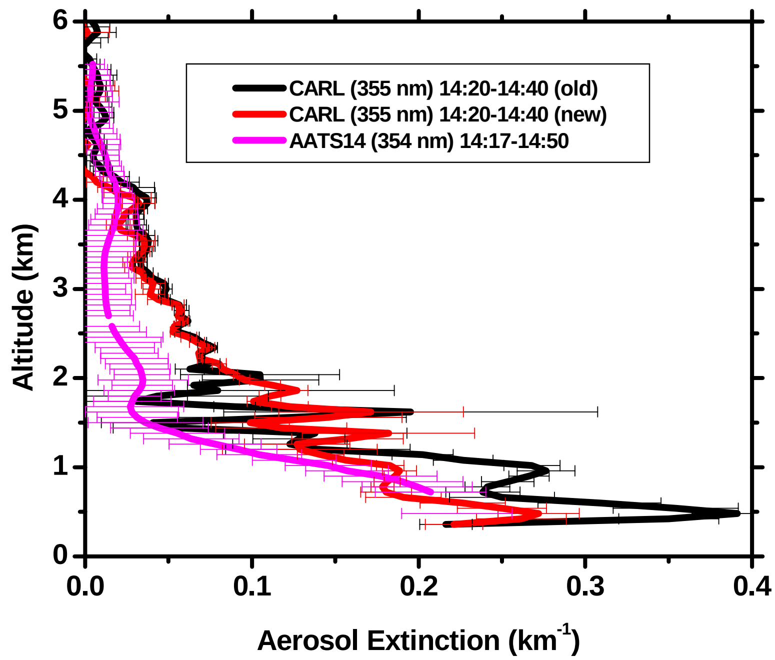


Figure 1. (a) Water vapor profiles acquired on May 22 during the May 2003 Aerosol IOP. Error bars represent standard deviations during the averaging periods. (b) Same except for aerosol extinction profiles.

during daytime operations to altitudes below about 3 km. Also shown in Figure 1a are water vapor profiles derived from the AATS14 and from a chilled mirror hygrometer on board the CIRPAS Twin Otter (Schmid et al. 2004). Differences among the water vapor profiles are generally less than 10%. Updates to the CARL water vapor overlap function that are included in the modified algorithm slightly increased water vapor below about 1 km. Figure 1b shows that relative differences between the CARL and AATS14 aerosol extinction profiles are larger than in the case of the water vapor. Uncertainties in system alignment and overlap correction functions and larger random noise levels, which were associated with the reduced signal levels, all contributed to these larger relative differences. The aerosol extinction profile produced by the modified algorithm shows better overall agreement with the AAT14 profile than the profile produced by the standard processing.

Table 1 shows the results of the water vapor comparisons. The CARL profiles were generally in good (<5% bias difference) agreement with the MWR scaled radiosonde measurements but were 5 to 17% wetter than the other measurements. The largest differences were generally found for low RH conditions. The reasons for such large differences are not presently clear, but may be related to the use of the MWR PWV as a calibration standard since both the CARL and scaled radiosonde water vapor profiles are calibrated to match the MWR PWV. Previous nighttime comparisons found that scaling Raman lidar water profiles to match a chilled mirror sensor on the SGP tower produced profiles that were 3 to 4% drier than the profiles scaled to match the MWR PWV (Revercomb et al. 2003). Previous comparisons have also found better agreement between the CARL and IAP water vapor measurements (Ferrare et al. 2003).

Table 1. May 2003 Aerosol IOP Water Vapor Comparison Results

	Least Squares Regression							
	Bisector		Standard Linear					
	Slope	Intercept (g/m^3)	Slope	Intercept (g/m^3)	R	N	Bias Difference[a] (g/m^3) (%)	RMS Difference (g/m^3) (%)
Radiosonde (day)	0.89	0.23	0.85	0.45	0.96	2002	-0.48 (-7.6%)	1.1 (18%)
MWR-scaled radiosonde (day)	0.95	0.32	0.91	0.56	0.96	2002	0.0097 (0.15%)	1.0 (16%)
Radiosonde (night)	0.93	0.092	0.91	0.22	0.98	1650	-0.27 (-5.0%)	0.76 (14%)
MWR-scaled radiosonde (night)	0.96	0.067	0.93	0.20	0.98	1650	-0.17 (-3.1%)	0.72 (13%)
AATS14	0.91	-0.077	0.87	0.14	0.96	786	-0.65 (-11%)	1.2 (21%)
Chilled mirror	0.87	0.21	0.84	0.40	0.96	786	-0.59 (-10%)	1.2 (21%)
IAP	0.87	-0.34	0.86	-0.27	0.99	69	-1.25 (-17%)	1.5 (20%)

(a) difference = sensor - CARL

Table 2 shows results of comparing the CARL aerosol extinction profiles with other IOP sensors. The Twin Otter in situ aerosol extinction profiles were derived by combining the nephelometer aerosol scattering measurements with the PSAP aerosol absorption measurements. The nephelometer aerosol scattering measurements were converted to ambient RH using aerosol humidification factors derived from simultaneous aircraft measurements of aerosol scattering at high RH. The aerosol absorption measurements represent dry (<40% RH) conditions. In order to compare to the Twin Otter and IAP aerosol extinction profiles, the CARL aerosol extinction profiles at 355 nm were converted to 450 nm using Angstrom exponents computed from the aerosol extinction values derived from the in situ Twin Otter and IAP measurements. Results in Table 2 indicate that the CARL aerosol extinction profiles were, on average, significantly (33-50%) higher than the other measurements. Additional analyses indicate that the largest differences were found for low (<0.05 km^{-1}) aerosol extinction values and that the differences were significantly less (~10%) for higher (0.15-0.3 km^{-1}) values of aerosol extinction. The aforementioned reduction in CARL sensitivity led to increased calibration errors, larger random errors, and greater uncertainties in maintaining proper alignment, all of which contributed to these large differences. The extensive modifications made to the CARL automated algorithms reduced but could not eliminate these adverse effects. In addition, no attempt was made to account for the temperature dependence of Raman scattering and the potential impact on the derived aerosol backscattering and extinction profiles; modeling studies suggest that these impacts may introduce biases in the Raman lidar aerosol retrievals (Whiteman et al. 2003). Efforts are currently underway to characterize these effects and to modify CARL to restore and/or improve its sensitivity.

Table 2. May 2003 Aerosol IOP Aerosol Extinction Comparison Results

Least Squares Regression								
	Bisector		Standard Linear					
	Slope	Intercept (km^{-1})	Slope	Intercept (km^{-1})	R	N	Bias Difference[a] (km^{-1}) (%)	RMS Difference (km^{-1}) (%)
AATS14 (354 nm)	0.92	-0.020	0.74	-0.0056	0.81	537	-0.026 (-33%)	0.048 (61%)
Twin Otter (neph+PSAP) (450 nm)	0.70	-0.012	0.51	-0.00034	0.74	759	-0.031 (-50%)	0.049 (78%)
IAP (neph+PSAP) (450 nm)	0.76	-0.012	0.62	-0.00094	0.82	65	-0.032 (-40%)	0.051 (64%)

(a) difference = sensor - CARL

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