Comparison of Water Vapor Measurements by Airborne Sun Photometer and Diode Laser Hygrometer on the NASA DC-8

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For submittal to J. Atmos. Oceanic Technol.

13 July 2007

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ABSTRACT

In January-February 2003 the 14-channel NASA Ames Airborne Tracking Sunphotometer (AATS) and the NASA Langley/Ames Diode Laser Hygrometer (DLH) were flown on the NASA DC-8 aircraft. AATS measured column water vapor on the aircraft-to-sun path, while DLH measured local water vapor in the free stream between the aircraft fuselage and an outboard engine cowling. The AATS and DLH measurements were compared for two DC-8 vertical profiles by differentiating the AATS column measurement and/or integrating the DLH local measurement over the altitude range of each profile (7.7-10 km and 1.2-12.5 km). These comparisons extend, for the first time, tests of AATS water vapor retrievals to altitudes >~6 km and column contents <0.1 g cm\(^{-2}\). To our knowledge this is the first time suborbital spectroscopic water vapor measurements using the 940-nm band have been tested in conditions so high and dry. For both profiles layer water vapor (LWV) from AATS and DLH were highly correlated, with \(r^2\) 0.998, rms difference 7.2% and bias (AATS minus DLH) 0.9%. For water vapor densities AATS and DLH had \(r^2\) 0.968, rms difference 27.6%, and bias (AATS minus DLH) -4.2%. These results compare favorably with previous comparisons of AATS water vapor to in situ results for altitudes <~6 km, columns ~0.1 to 5 g cm\(^{-2}\) and densities ~0.1 to 17 g m\(^{-3}\).

1. Introduction

Water vapor measurements by sunphotometry using the 940-nm water vapor absorption band have been compared to in situ and other remote (e.g., microwave) measurements in several previous publications (e.g., Schmid et al. 2000, 2001, 2003a,b, 2006; Redemann et al. 2003; Livingston et al. 2000, 2003, 2007). Those comparisons were all restricted to sunphotometer
altitudes <~6 km, with water vapor columns ~0.1 to 5 g cm\(^{-2}\) and water vapor densities ~0.1 to 17 g m\(^{-3}\).

In January-February 2003, the 14-channel NASA Ames Airborne Tracking Sunphotometer (AATS) flew on the DC-8 along with the NASA Langley/Ames Diode Laser Hygrometer (DLH). The flights were part of the second SAGE (Stratospheric Aerosol and Gas Experiment) III Ozone Loss and Validation Experiment (SOLVE II). They provided an opportunity to test AATS water vapor measurements in higher, drier environments, including altitudes up to 12 km and water vapor columns ~0.002 to 0.1 g cm\(^{-2}\) above 4 km. The availability of DLH measurements on the same aircraft as AATS provided an especially good comparison opportunity, since the DLH was designed and built to perform well in environments this high and dry, and previous DLH measurements had been compared to other state-of-the-art water vapor measurements in such regions (e.g., Podolske et al. 2003). To our knowledge there had not been any previous tests of suborbital spectroscopic water vapor measurements using the 940-nm band in conditions so high and dry.

It should be noted, however, that several satellite instruments that view the sun through the Earth’s atmospheric limb do use the 940-nm band for water vapor measurements, and they have been validated. These instruments include the Stratospheric Aerosol and Gas Experiment (SAGE) and Polar Ozone and Aerosol Measurement (POAM) families of sensors, validations of which have been published by, e.g., Nedoluha et al. (2002), Taha et al. (2004), Thomason et al. (2004), and Lumpe et al. (2006). The SAGE and POAM measurements benefit from the long viewing path of their limb-viewing geometry (e.g., ~200 km in a 1-km thick atmospheric shell, resulting from local solar zenith angle ~90\(^{\circ}\)), which produces measurable absorption in the 940-
nm band even for stratospheric concentrations of water vapor (typically 3-8 ppmv). The AATS DC-8 measurements reported in this paper had true solar zenith angle ranging from 68.6° to 89.1°, which includes viewing paths (hence airmass factors) considerably less than those for the SAGE and POAM viewing geometries.

2. Instruments and Data Analysis Techniques

a. 14-channel Ames Airborne Tracking Sunphotometer (AATS)

The 14-channel NASA Ames Airborne Tracking Sunphotometer (AATS-14 or simply AATS in this paper) has been described previously in the literature (e.g., Russell et al. 2005, 2007), so we give only a brief synopsis here. AATS measures the direct beam solar transmission in 14 channels with center wavelengths from 354 to 2138 nm, including a channel centered at 941 nm. Azimuth and elevation motors rotate a tracking head to lock on to the solar beam and maintain detectors normal to it.

The AATS channel wavelengths are chosen to permit separation of aerosol, water vapor, and ozone transmission along the measured slant path. Our methods for data reduction, calibration, and error analysis have been described in detail previously (Russell et al. 1993a, 1993b; Schmid and Wehrli 1995; Schmid et al. 1996, 2001, 2003). Water vapor analysis methods are briefly reviewed below. Results for AATS aerosol optical depth and ozone measurements from the DC-8 in SOLVE II are described by Russell et al. (2005) and Livingston et al. (2005).

AATS was calibrated by analysis of sunrise measurements acquired at Mauna Loa Observatory (MLO), Hawaii, for six sunrises in November 2002 prior to SOLVE II and for
seven sunrises in March 2003 after SOLVE II. Exoatmospheric detector voltages, \( V_0 \), were derived using the Langley plot technique (e.g., Russell et al. 1993a, 1993b; Schmid and Wehrli 1995) for all channels except 941 nm, for which a modified Langley technique (Reagan et al. 1995; Michalsky et al. 1995; Schmid et al. 1996, 2001) was employed to account for water vapor absorption.

Because absorption by water vapor varies strongly within the 5-nm FWHM bandpass of the AATS-14 channel centered at 941 nm, the usual Beer-Lambert-Bouguer expression must be modified to describe correctly the relationship between the output detector voltage, \( V(941) \), and the atmospheric attenuators on the sun-to-instrument path. In particular,

\[
V(941 \text{ nm}) = V_0(941 \text{ nm}) d^{-2} \exp \left[- \sum_i m_i \tau_i(941 \text{ nm}) \right] T_w, \tag{1}
\]

where \( V_0(941 \text{ nm}) \) is the exoatmospheric calibration voltage, \( d \) is the Earth-Sun distance in astronomical units at the time of observation, \( m_i \) is the airmass factor (ratio of slant path optical depth to vertical optical depth) for attenuating species \( i \) (where \( i \) represents gas scattering, non-water vapor gas absorption, or aerosol extinction), \( \tau_i \) is the optical depth for the \( i \)th attenuating species other than water vapor, and \( T_w \) is the water vapor transmittance (weighted by absorption strength, source intensity and filter function). Consistent with the approach followed by Livingston et al. (2007), we used the three-parameter expression of Ingold et al. (2000) to parameterize \( T_w \) as a function of the amount of water vapor, \( w_s \), along the slant path:

\[
T_w = c \exp(-aw_s^b). \tag{2}
\]
In this expression, the coefficients \( a \), \( b \), and \( c \) are least squares fitting parameters. In particular, calculations were performed using the radiative transfer code LBLRTM V9.2 (Clough et al. 2005) for a variety of model atmospheres and a range of solar zenith angles to extend the Livingston et al. (2007) Table 2 results to include all altitudes (maximum of \(~12.5\) km) flown by the DC-8 during SOLVE II. These results are shown in Fig. 1 and the complete set of fitting coefficients is given in Table 1.

As noted by Livingston et al. (2007) and illustrated here in Fig. 1, a retrieval that ignores the instrument altitude can result in an incorrect determination of slant path (hence, column) water vapor. In particular, if it is assumed that the instrument is located at sea level, then column water vapor (CWV) would be underestimated for instrument altitudes above sea level, and the errors would be greatest for large solar zenith angles, SZA (high airmass values), and high CWV (hence, high slant water vapor) amounts.

Column water vapor is calculated from the slant amount by dividing by an appropriate water vapor airmass factor. These airmass factors were calculated using the methodology reported in Russell et al. (2005) and Livingston et al. (2005) by assuming a vertical water vapor distribution corresponding to the subarctic winter atmospheric model for the 21 January 2003 measurements and the midlatitude winter atmospheric model for the 6 February 2003 data. The uncertainty in CWV is computed following Schmid et al. (1996). The calculated CWV values are averaged within 50-m vertical bins, and a smoothing spline is then fit to the resultant CWV profile. Water vapor density \( \rho_w \) is obtained as the derivative of the spline fit.

b. **Diode Laser Hygrometer**
The NASA Langley/Ames Diode Laser Hygrometer (DLH) was designed and built to measure gas-phase water in the free-stream region of the NASA DC-8 aircraft, between the fuselage and the cowling of an outboard engine. The instrument is described in detail elsewhere (Vay et al. 1998; Diskin et al. 2002; Podolske et al. 2003), so only a brief description is given here.

The DLH instrument is a near-infrared (NIR) spectrometer operating at wavelengths near 1.4 µm to detect individual rotation-vibration lines of H₂O in either the (101) combination band or the (200) overtone band. Second harmonic detection (Sachse et al. 1977, 1987; Reid and Labrie 1981; Podolske and Loewenstein 1993, and references therein) and long path length are utilized to achieve high sensitivity, and two or more lines of different strengths are used to meet the dynamic range requirements for atmospheric water. The beam of a NIR diode laser is quasicollimated and transmitted through a quartz window secured in a DC-8 window plate, toward the cowling of the right (starboard) side outboard engine. There it strikes a sheet of retroreflector material and returns to the fuselage window from which it originally emerged. Inside the window a portion of the return beam is passed through a narrowband interference filter, collected by a Fresnel lens, and focused onto a detector. The sample volume of the external path is completely exchanged every 40–70 ms, depending on aircraft velocity. The laser wavelength is modulated, and the signal detector output is synchronously demodulated to produce the second harmonic signal. The second harmonic (2F) and DC components from the signal detector are recorded to allow power normalizing of the (2F) signal.

The laser radiation emitted from the rear facet of the diode laser is sent through a short (50 mm) reference cell containing pure water vapor and onto a second detector. The reference
detector output is synchronously demodulated at the third harmonic (3F), the central zero crossing of which is subsequently used to lock the laser wavelength to the center of the chosen absorption line.

DLH calibration and data retrieval algorithms are described by Podolske et al. (2003). During SOLVE-II and subsequently, efforts to quantify DLH accuracy have yielded a typical uncertainty of ±5%, with a precision at 5 ppmv water vapor of approximately 1%.

3. Results

Results from the first comparison profile, which was flown 21 January 2003 on a DC-8 ascent out of Kiruna, Sweden, are presented in Fig. 2. AATS was able to view the sun at DC-8 altitudes between ~7.7 and 10 km, thus allowing calculation of CWV at each altitude in that range. The AATS and DLH CWV profiles are overplotted in Fig. 2a, in addition to the ambient atmospheric temperature profile. Because DLH measures local (not column) water vapor, the DLH CWV value at profile top is set equal to the AATS value there, and DLH CWV values below that altitude are obtained by integrating DLH local values downward. Corresponding AATS and DLH water vapor densities are overplotted in Fig. 2b. As noted in Section 2a, AATS $\rho_w$ is obtained as the vertical derivative of a spline fit to the AATS CWV profile that results after averaging the CWV values within 50-m vertical bins.

Scatter plot comparisons of AATS and DLH CWV and $\rho_w$ for the 21 January profile are shown in Fig. 2c and 2d. The statistics shown on each scatter plot quantify the correlation and agreement between the AATS and DLH results. For CWV, AATS and DLH have $r^2$ 0.977, rms difference 13.0% and bias (AATS minus DLH) 8.1%. Corresponding values for $\rho_w$ are $r^2$ 0.887,
rms difference 92.1% and bias (AATS minus DLH) 37.3%. This agreement is noteworthy in
light of the very dry conditions: maximum AATS CWV of 0.007 g cm\(^{-2}\) and maximum \(\rho_w\) of 0.1 g m\(^{-3}\).

Fig. 3 shows results from the second comparison profile, which was flown 6 February 2003
as the DC-8 descended into Edwards Air Force Base, California, on its return from Sweden. In
this case, AATS was able to view the sun at DC-8 altitudes from \(\sim\)12.5 km to the surface. This
profile is noteworthy for combining very dry conditions above \(\sim\)6 km (similar to those in the 21
January case, cf. Fig. 2) with significantly increased CWV and \(\rho_w\), and strong vertical structure,
below \(\sim\)6 km (though values are still small compared to the previous AATS comparisons cited in
Section 1). Another significant feature of this profile is the availability of water vapor data from
the radiosonde released from Edwards at 1500 UT (1.5 to 1.9 h before the DC-8 descent profile).
Frames 3a and 3b overplot the results for the entire range of measurement altitudes; frames 3c
and 3d expand the results between 7.5 and 12.5 km. For this case, in order to minimize the effect
of horizontal inhomogeneities on the calculated AATS CWV profile, the AATS CWV values
above 4.5 km were smoothed more than the values below 4.5 km in applying the spline fit.

Corresponding values of AATS and DLH CWV and \(\rho_w\) for the 6 February profile are
compared in scatter plots in Fig. 4. For CWV calculated from the measurements obtained during
this profile, AATS and DLH have \(r^2\) 0.998, rms difference 6.6% and bias (AATS minus DLH)
0.8%. Corresponding values for \(\rho_w\) are \(r^2\) 0.965, rms difference 25.2% and bias (AATS minus
DLH) -4.8%. Even for comparisons between AATS and the sonde, which was flown 1.5-1.9 h
earlier, the overall agreement is striking: for AATS values interpolated to sonde-reported
altitudes, AATS and sonde CWV have \(r^2\) 0.997, rms difference 15.1% and bias (AATS minus
sonde) 6.3%. Corresponding values for $\rho_w$ are $r^2$ 0.897, rms difference 42.7% and bias (AATS minus sonde) 10.4%. The maxima of the scatter plots (CWV < 0.3 g cm$^{-2}$, $\rho_w$ < 1.1 g m$^{-3}$), though larger than those shown in Fig. 2, are still noteworthy for their small values. For example, in previous AATS comparisons to in situ and other remote water vapor measurements, CWV has ranged up to ~5 g cm$^{-2}$ and $\rho_w$ up to ~17 g m$^{-3}$.

Fig. 5 shows scatter plots that combine AATS and DLH results for the profiles on January and 6 February. AATS and DLH CWV (5a) have $r^2$ 0.998, rms difference 7.2% and bias (AATS minus DLH) 0.9%. Corresponding values for $\rho_w$ (5b) are $r^2$ 0.968, rms difference 27.6% and bias (AATS minus DLH) -4.2%. Results for altitudes > 7.5 km only are shown for CWV and $\rho_w$ in 5c and 5d, respectively. For CWV, values are $r^2$ 0.971, rms difference 9.4% and bias (AATS minus DLH) 26.5%.

These values are similar to those found in previous AATS-14 water vapor comparisons (as cited in the introduction) with much larger CWV and $\rho_w$. Most recently, Livingston et al. (2007) compared layer water vapor (LWV) between profile top and bottom as measured by AATS and an in situ sensor on the same aircraft during 35 vertical profiles acquired over the Gulf of Maine, with maximum LWV ~3.7 g cm$^{-2}$ and maximum $\rho_w$ ~16 g m$^{-3}$. They found $r^2$ 0.97, rms difference 8.8% and bias (AATS minus in situ) -7.1%. For 22 profiles within 1 h and 130 km of sonde ascents, they found AATS and sonde LWV had $r^2$ 0.90, rms difference 10.7%, and bias (AATS minus sonde) -5.4%. Previously, Schmid et al. (2006) reported an AATS dry bias of 5% relative to coincident $\rho_w$ measurements acquired with an Edgetech 137-C3 chilled mirror for 35 vertical profiles over the Atmospheric Radiation Measurement (ARM) Southern Great Plains.
(SGP) site. In each of these studies, AATS was equipped with the same 941-nm interference filter used during SOLVE II.

4. Summary and Conclusions

This paper has compared values of CWV and $\rho_w$ calculated from simultaneous measurements acquired by the AATS and DLH sensors on the DC-8 for two vertical profiles flown during SOLVE II. This study is unique because it includes data acquired at altitudes (above 6 km) where we had previously never taken measurements and where the amount of water vapor in the atmosphere was the lowest we have ever measured. To our knowledge this is the first time suborbital spectroscopic water vapor measurements using the 940-nm water vapor absorption band have been tested in conditions so high and dry.

Measurements were acquired at altitudes between 7.7 km and 10 km during the 21 January aircraft ascent, and between 1.1 km and 12.5 km during the 6 February descent. AATS and DLH CWV values (where the DLH value was set equal to the AATS CWV value at the top of the profile) yielded $r^2$ of 0.997 for 21 January and 0.998 for 6 February. Comparison of AATS and radiosonde CWV values for sonde measurements (normalized to AATS CWV at the top of the profile) acquired 1.5-1.9 h before the AATS profile on 6 February yielded an $r^2$ of 0.997. For measurements taken at altitudes >7.5 km, the composite AATS and DLH data set gave an $r^2$ of 0.97, an rms difference of 9.4% (0.0004 g cm$^{-2}$), and a bias (AATS minus DLH) of 4.2% (0.0002 g cm$^{-2}$). Corresponding values for $\rho_w$ were $r^2$ of 0.91, an rms difference of 73.6% (0.01 g m$^{-3}$), and a bias (AATS minus DLH) of 26.5% (0.004 g m$^{-3}$). The large relative rms and bias differences reflect the dry atmosphere with $\rho_w <0.1$ g m$^{-3}$ at those altitudes.
The comparisons presented here included a very limited set of measurements at altitudes in the 7-12 km range, and additional comparisons between sunphotometer and in situ sensors are needed at these altitudes where the amount of water vapor in the atmosphere is so low to permit quantification of the uncertainty in the sunphotometer-calculated $\rho_w$ values. Nevertheless, the agreement we have found between the AATS and DLH retrievals of CWV (essentially, LWV) gives us hope that airborne sunphotometer measurements can provide useful data for validation of satellite water vapor retrievals not only for the full atmospheric column and for $\rho_w$ in the lowest few km of the troposphere, as has been shown in previous studies, but also at altitudes in the upper troposphere where water vapor is limited.

Acknowledgments. We thank James Eilers and Richard Kolyer for supporting AATS measurements, and Stephanie Ramirez for help with illustrations and formatting. The SOLVE II measurements were supported by NASA’s Upper Atmosphere Research Program. AATS analyses were supported by NASA’s Solar Occultation Satellite Science Team.
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Table 1. Coefficients of Ingold et al. (2000) 3-parameter functional fit (2-parameter at altitudes below 4 km) to LBLRTM_v9.2 calculations of water vapor transmittance as a function of slant path water vapor $w_s$ (where $w_s$ is in units of cm or g/cm$^2$) for the AATS-14 channel centered at 940.6 nm. Values for altitudes 0-8 km are the same as those shown in Table 2 of Livingston et al. (2007).

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Fig. 1. LBLRTM calculations of water vapor transmittance $T_w$ as a function of slant path water vapor and aircraft (instrument) altitude for the AATS-14 941-nm channel. Results are shown for altitudes from 0 to 13 km in (a) and on expanded axes for altitudes 9 to 13 km only in (b).
**Fig. 2.** For the 21 January 2003 DC-8 ascent out of Kiruna, Sweden, (a) profiles of AATS-14 unbinned (black xs) and binned (blue dots) CWV, AATS-14 one sigma CWV uncertainties (dashed blue lines), DLH CWV (red dots), and ambient atmospheric temperature (magenta dots); (b) corresponding profiles of AATS-14 and DLH water vapor density; (c) scatterplot of AATS-14 versus DLH CWV (blue dots), AATS-14 CWV uncertainties (dashed blue lines), and linear regression fit (red line); (d) scatterplot of AATS-14 versus DLH water vapor density, and linear regression fit (red line). For CWV, the DLH value at profile top has been set equal to the AATS value there. Black dashed line in (c) and in (d) represents the one-to-one correspondence.
Fig. 3. For the 6 February 2003 DC-8 descent into Edwards AFB, (a) profiles of AATS-14 CWV (blue dots), AATS-14 one sigma CWV uncertainties (dashed blue lines), DLH CWV (red dots), CWV (green squares) calculated from Edwards AFB 15 UT radiosonde, and ambient atmospheric temperature (magenta dots); (b) corresponding profiles of water vapor density; (c,d) same profiles shown in (a,b), but for altitudes above 7.5 km only with expanded axes limits. For CWV, the DLH and sonde values at profile top have been set equal to the AATS value there.
Fig. 4. For the 6 February 2003 DC-8 descent into Edwards AFB, scatterplots of AATS-14 versus DLH (a) CWV and (b) water vapor density, and AATS-14 versus Edwards AFB 15 UT radiosonde (c) CWV and (d) water vapor density. Black dashed lines represent one-to-one correspondence, and red dashed lines are the regression fits.
Fig. 5. Composite results for the 21 January 2003 ascent and the 6 February 2003 DC-8 descent: scatterplots of AATS-14 versus DLH (a) CWV and (b) water vapor density; scatterplots of AATS-14 versus DLH (c) CWV and (d) water vapor density for altitudes >7.5 km only.