Remote Sensing of Column Integrated Water Vapor by Microwave Radiometers and GPS During the 1997 Water Vapor Intensive Observation Period

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Introduction

Due to recent applications of Line-By-Line Radiative Transfer Models (LBLRTM) to climate models (Clough 1995) and to assimilation of satellite data in weather forecasting (Eyre et al. 1993), high accuracy is required of forward models to calculate absorption and emission spectra during clear sky conditions. With the increasing deployment of Fourier Transform Interferometric Radiometers (FTIR) (Revercomb et al. 1988, Han et al. 1997) at observation sites around the world, an excellent data base of well calibrated radiance data is becoming available through the Atmospheric Radiation Measurement (ARM) Program. The conventional way of evaluating and improving models is to measure vertical profiles of temperature and emitting constituents, use these measurements as input to LBLRTM, and compare measured and calculated radiance. Currently, a limiting factor in evaluating LBLRTM is the accuracy of the humidity profiles used as input to the model. Recognizing this limitation, two Water Vapor Intensive Observation Periods (WVIOPs) have been conducted at the ARM Cloud and Radiation Testbed (CART) site in 1996 and 1997. This paper focuses on the 1997 observations obtained by the National Oceanic and Atmospheric Administration (NOAA) and ARM instruments at or near the ARM Southern Great Plains (SGP) Central Facility (CF) near Lamont, Oklahoma. Results obtained during WVIOP'96 are discussed by Liljegren et al. (1998).

During WVIOP'97, the NOAA Environmental Technology Laboratory (ETL) operated two microwave radiometers (MWRs) at the SGP CF. At the same time, NOAA's Forecast Systems Laboratory (FSL) operated two Global Positioning Systems (GPSs) - one at the SGP CF and one at NOAA's wind profiler site, also near Lamont, a distance of about 9 km away from the CF. In addition, data from the ARM MWR were also available for intercomparison. The primary goal of these observations was to quantify the absolute accuracies of the MWRs and GPSs in measuring precipitable water vapor (PWV) and to compare these measurements with each other and with in situ measurements made every 3 hours by ARM's Balloon-Borne Sounding Systems (BBSSs). Vaisala HUMICAP RS-80 sensors were used for humidity profile measurements. Part of the motivation for these comparisons was the suggestion by Clough et al. (1997) that MWR measurements of PWV could be used to scale radiosonde observations to more realistic values; the possibility also exists of using the MWR or the GPS to help calibrate Raman lidar measurements of mixing ratio profiles.

Microwave Radiometers

Three MWRs were used in our PWV comparison study; the first operates at 20.6 GHz and 31.65 GHz (MWR ETL1), the second at 23.87 GHz and 31.65 GHz (MWR ETL2), and the third is the ARM MWR at 23.8 GHz and 31.4 GHz (MWR ARM). The temporal resolutions of the ETL instruments were 30 s and that of ARM was 20 s. The basic design of the ETL radiometers is described by Hogg et al. (1983); however, a useful modification to the antenna systems was introduced, following Jacobson and Nunnelee

(1997). This configuration was designed to minimize the adverse effects of rain and snow and uses a rapidly rotating flat antenna that is viewed by an offset parabolic horn. The rotating flat rotates at about 300 rpm and thus deflects rain and snow from the structure by centrifugal force. The MWR ARM is described by Liljegren (1994), and it differs from the ETL instruments in receiver designs as well as in antenna and instrument housing. However, the basic method of calibration—the "tip cal" method—is the same for all instruments.

Calibration and Retrieval Method

The "tipping curve" or "tip cal" method (Hogg et al. 1983) has been used extensively by the microwave radiometric community. Basically, the method consists of a) taking brightness temperature (T_b) observations at a set of elevation angles θ or, equivalently, at a set of air masses, m, where m = csc(θ); b) converting the T_b(m) observations to attenuation τ(m) by means of the mean radiating temperature approximation; and c) adjusting the parameters in the radiometer equation such that the attenuation τ(m) when extrapolated to m = 0 is zero. The following two assumptions of the "tip cal" method are paramount: a) the atmosphere is horizontally stratified; and b) the radiometer equation that is used is valid over the range of atmospheric conditions that are encountered. If "tip cals" are taken at opposing angles relative to zenith, then condition (a) can be checked by comparing T_b(m) with T_b(-m) over the set of m's. We took observations at m = ±1, ±2, and ±3, and rejected "tip cals" if $| T_b(m) - T_b(m) | \geq 3$ K for any m. The verification of the radiometer equation is more difficult; for ETL radiometers, we adopted a one-parameter equation (Han et al. 1994) that relates measured voltages from the sky and two internal loads (at known temperatures) to T_b. The radiometer equation that is used for MWR ARM is based on similar physics and is described by Liljegren (1994). However, MWR ARM uses noise diodes rather than internal loads and also views an internal reference target. Finally, we note that MWR ETL2 experienced occasional problems associated with electrical grounding. All uncertain data from this instrument were removed from this analysis.

Radiometric retrievals of PWV were based on Liebe's MPM (1989) and a priori linear statistical inversion of absorption τ derived from T_b (Westwater 1993). Mean radiating temperatures and retrieval coefficients were derived from an a priori ensemble of radiosonde data taken in the Oklahoma region from August-October 1966-1992 (N = 1744). By using the a priori inversion method, all retrievals of PWV were independent of WVIOP'97 or WVIOP'96 radiometric and radiosonde data. Two methods of quality control were imposed as follows: a) we used a 3-point median filter to eliminate occasional spikes from RF interference, and b) for PWV determinations, we rejected all data for which T_b at 31.65 GHz was greater than 125 K. We have determined empirically that retrievals of PWV at the SGP for T_b (31.65 GHz) > 125 K are degraded.

GPS Measurements of PWV

GPS measurements of excess zenith path delay, together with surface pressure and temperature measurements can be used to determine PWV with an accuracy of 0.1 cm to 0.15 cm root mean square (rms) (Duan et al. 1996). The temporal resolution of the GPS measurements is 30 min. Because of their relatively low cost, extensive deployment of these systems over land is envisaged. During WVIOP'97, two GPS units were used. The first was located at the NOAA Profiler Network (NPN) wind profiler site near Lamont; the second was operated by the FSL at the SGP CART site. Data from the two systems were processed by two different groups, both of whom used the GAMIT processing package (King and Bock 1994). The first processing method was by the NOAA Environmental Research Laboratories (ERL) who used their operational method; the second was by the Scripps Institution of Oceanography (SIO) who used improved antenna mapping functions (Niell 1996). The accuracy of the retrievals depends on a variety of factors including the cutoff elevation angle that is used, the zenith delay mapping function, and the accuracy of the GPS satellite orbit determinations.

Results

Time Series

Figure 1 shows a time series of PWV derived from the ETL1 system (20.6 GHz and 31.65 GHz) and BBSS radiosondes. Because of the close agreement between all of the measurements, roughly within 2 mm, and because of clarity, only ETL1 and the BBSS are shown. Although WVIOP'97 only lasted 20 days, there was a wide range of PWV, from less than 1.0 cm to more than 5.0 cm. The temporal resolutions of the MWR ETL1 was 30 s and that of the GPS was 30 min. The differences in temporal resolution were apparent, especially during times of clouds, with sharper changes in PWV being observed by the radiometers.

MWR ETL1 versus MWR ETL2

The two ETL MWRs were closely located and independently operated. The performance of the two radiometers differed greatly during the course of the

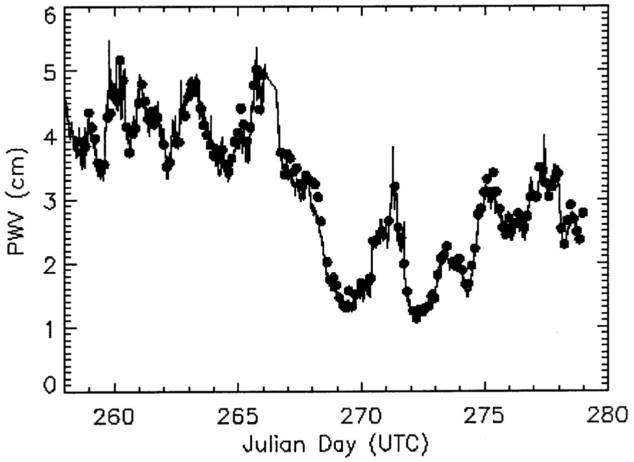

Figure 1. Time series of PWV data from MWR ETL1 during WVIOP'97. The solid circles are soundings from the ARM BBSS.

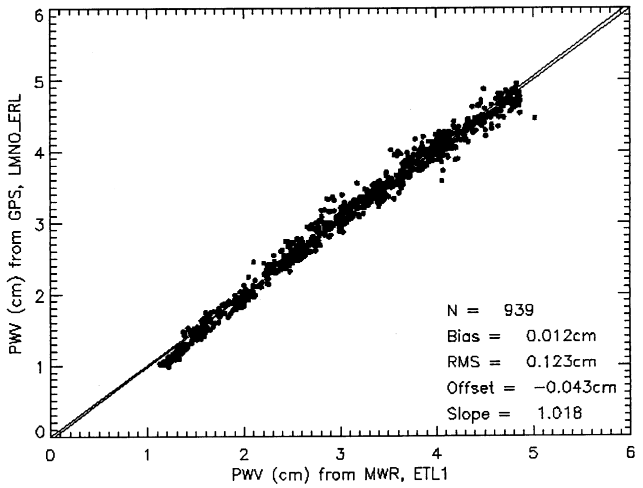

Figure 2. Scatter plot of 30-min. averages of PWV (cm) derived from the MWR ETL1 (20.6 GHz and 31.65 GHz) and NPN GPS (with NOAA/ERL processing).

experiment. The MWR ETL1 suffered occasional spikes at the 20.6-GHz channel, which were presumably due to radio frequency interference. However, these spikes were easily removed from the data by the 3-point median filter. The MWR ETL2 however, had a substantial number of occurrences in which there were calibration shifts, which were due to grounding problems. Because two of the major goals of the experiment were to compare radiometric calibration techniques and the evidence of possible biases between the GPS, BBSS, and the MWRs, all suspicious ETL MWR2 data were discarded. Unfortunately, these shifts occurred when the PWV was below about 3 cm. The statistical comparisons of the two ETL radiometers are included in Table 1.

GPS versus MWR ETL1

After quality control, the ETL1 soundings were averaged to 30 min. for comparison with those of the Lamont GPS. A scatter plot of the comparisons, with ERL GPS processing, is shown in Figure 2. In general, there is excellent agreement between the two sets of measurement in a variety of statistical measures. Note, however, that there is a slight departure from the straight line fit at lower values of PWV (around 1.2 cm) and a slight evidence of general curvature in the comparisons. We are still investigating these effects, which are believed to be due to uncertainties in radiometric calibration.

MWR ETL1 versus MWR ARM

Since the performance of the MWR ETL1 was far superior to that of MWR ETL2, we based our comparison with the GPS and MWR ARM on the data from MWR ETL1. The ETL radiometers had rotating flat reflectors that minimize the effects of falling rain and quickly disperse rain drops after rain has ceased. When comparing time series between ETL and ARM systems, we noticed that there was a much larger time interval during which the ARM radiometer was adversely affected by rain (and its residual) on the window covering the antennas. We applied strict quality control methods to all radiometric data and eliminated data during periods of rain or moisture. A scatter plot of the results is shown in Figure 3. Note that there is a bias of about 2 mm between MWR ETL1 and MWR ARM (ARM is the higher), but that again (see MWR ETL1 versus GPS comparisons) there is evidence of curvature in the ETL data. The causes of this behavior is still under investigation by ARM and ETL scientists.

GPS Processing by ERL versus GPS Processing by SIO

We also compared retrievals of PWV by the GPS system at Lamont by both the ERL and SIO processing algorithms. The primary difference between the two algorithms was the zenith delay mapping function (Neill 1996). The ERL algorithm used an elevation cutoff angle of 7° and that of SIO was 15°. The statistics of the GPS-GPS comparisons are included in Table 1 and are comparable with the ETL MWR1-MWR2 comparisons.

Table 1. Statistical summary of PWV (cm) determinations during WVIOP'97 GPS notation: (LM_E)-Lamont, ERL processing; (LM_S)-Lamont, SIO processing; (CF_S)-SGP Central Facility, SIO processing. Data are ranked in increasing order of rms difference.

	Offset	Slope	Bias	rms	N
ETL1-ETL2	0.189	0.954	0.006	0.051	20129
GPS:(LM_S)-(LM_E)	0.050	0.966	0.056	0.080	1056
GPS(LM_E)-ETL1	-0.043	1.018	0.012	0.123	939
GPS(LM_S)-ETL1	0.006	0.985	-0.040	0.125	968
BBSS-ETL1	0.145	0.970	0.052	0.145	146
GPS(CF_S)-ETL1	0.001	0.976	-0.074	0.154	968
BBSS-GPS(LM_E)	0.172	0.957	0.042	0.160	145
ETL1-ARM	-0.133	0.978	-0.207	0.218	42587
GPS(LM_E)-ARM	-0.141	0.983	-0.198	0.225	788

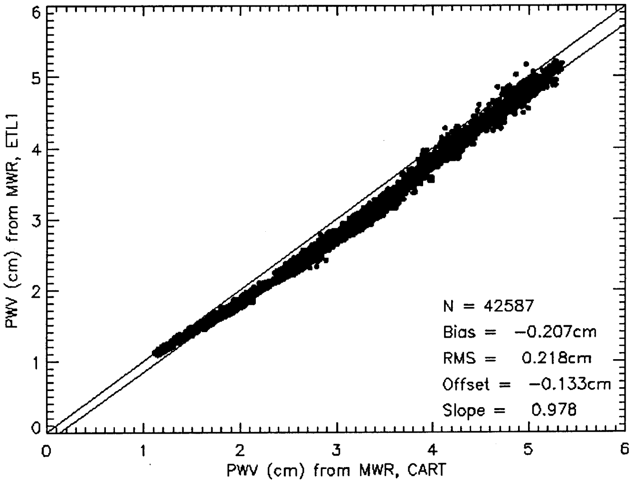

Figure 3. Scatter plot of MWR ARM versus MWR ELT1 data taken during WVIOP'97.

Statistical Summary

In all, we made scatter plots and derived regression parameters for various combinations of GPS (ERL versus SIO), MWR ETL (ETL1 versus ETL2), MWR (ARM versus ETL1), and radiosonde soundings made by the BBSS. Table 1 shows representative results, ranked in order of increasing rms difference. It is apparent from these results that, except for the consistent 2-mm bias difference between the MWR ARM instrument and all of the others, there are only modest differences among the remaining methods for determining PWV. Many of the differences illustrated in this table are surely due to sampling different volumes of air by the two techniques: the GPS effectively samples a volume of some 20 km to 30 km; the volume sampled by the BBSS depends on its trajectory, which, in turn, depends on the vertical profile of wind. The smallest rms difference is between the two ETL radiometers, which are collocated with their antennas only 3 m apart. The next smallest is between the two GPS receivers at Lamont, with the differences coming between two methods of processing. The two largest differences are between the MWR ARM and MWR ETL1 or GPS. As stated before, the ETL-ARM differences are surely the results of radiometric calibration and their causes are under investigation. We note that Table 1 shows rms statistics that are based on the usual assumption of a linear relationship between variables; however, as is evident from Figure 3, which is derived from a sample size of 42,586, there is evidence of curvature. This and comparison with data from all of the independent sensors suggest a modest nonlinearity in the ETL1 radiometer. In addition, the excellent correlation of the ARM radiometer with all other sources suggests that there is probably only a calibration offset in the ARM data.

Summary and Conclusions

Two GPS instruments (Lamont, Oklahoma, and the SGP CART CF) and two processing algorithms (ERL and SIO) were internally consistent in determining PWV with a bias of 0.056 cm and rms differences of 0.08 cm. Two ETL radiometers were also internally consistent (bias = 0. 006 and rms = 0.051 cm). Small non-linearities in one radiometer required a modified "tip cal" method. The GPS, MWR, and BBSS measurements were all in excellent agreement, with a maximum rms difference of 0.16 cm. The state of accuracy of all three measurements has approached the level that an independent and highly accurate technique is required for further improvement in algorithms and establishment of ultimate accuracy of each of the frequently used measurements. A promising candidate for the independent technique is that of Raman lidar, routinely operated at the SGP CART site.

To improve radiometric determinations of PWV, at least once-a-day, high quality "tip cals" are necessary. Because of the frequent occurrence of conditions of non-stratified atmospheres, perhaps frequent "tip cals" could be continuously performed during known clear conditions. In addition, we are investigating the use of high-quality calibration targets as a complement, not a replacement, to the "tip cal" technique.

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