A Comparison of Integrated Water Vapor from Microwave Radiometer, Balloon-Borne Sounding System, and Global Positioning System

J. C. Liljegren
Ames Laboratory
Ames, Iowa

B. M. Lesht
Argonne National Laboratory
Argonne, Illinois

T. VanHove and C Rocken
University Corporation for Atmospheric Research
Global Positioning System Science and Technology
Boulder, Colorado

Introduction

Comparisons of integrated water vapor (IWV) derived from the Atmospheric Radiation Measurement (ARM) Microwave Radiometer (MWR), ARM Balloon-Borne Sounding System (BBSS), and the global positioning system (GPS) receivers near Lamont, Oklahoma, during the 1997 ARM Water Vapor Intensive Observation Period (IOP) exhibited conflicting levels of agreement. In an effort to resolve the discrepancies, we have carried out a more extensive comparison of IWV from MWR, BBSS, and GPS at several ARM facilities in Oklahoma and Kansas. These comparisons revealed increased bias and variability between the MWR and both the BBSS and GPS during the summer months that are consistent from year to year and site to site.

MWR-BBSS Comparisons

The correction to the RS-80 radiosonde relative humidity measurement developed by Vaisala results in increased relative humidity. The relationship between the resulting correction to the IWV and the sonde age and IWV amount are presented in Figure 1.

Because this correction depends on the age of the sonde (i.e., the difference between the time it was calibrated and the time it was launched), it accounts for much of the batch dependence. Because it corrects the relative humidity, the effect on the IWV is largest in the summer when the largest biases between MWR and BBSS were observed, as shown in Figure 2.

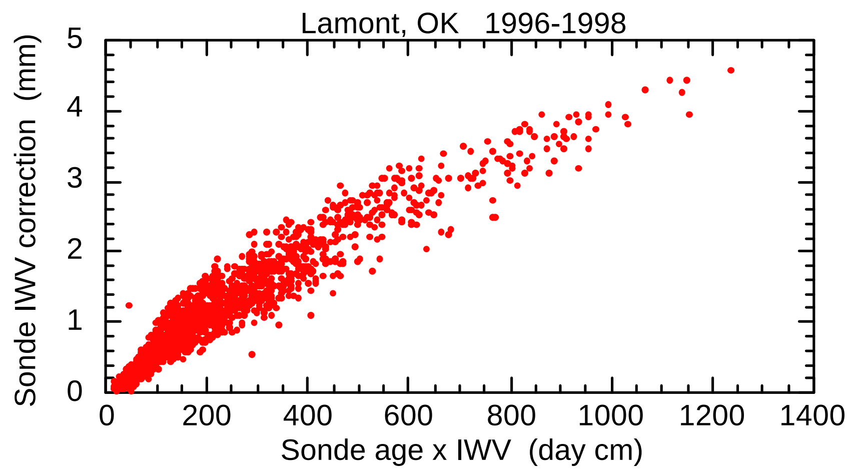

Figure 1. The IWV correction resulting from the Vaisala relative humidity correction as a function of the product of sonde age and IWV.

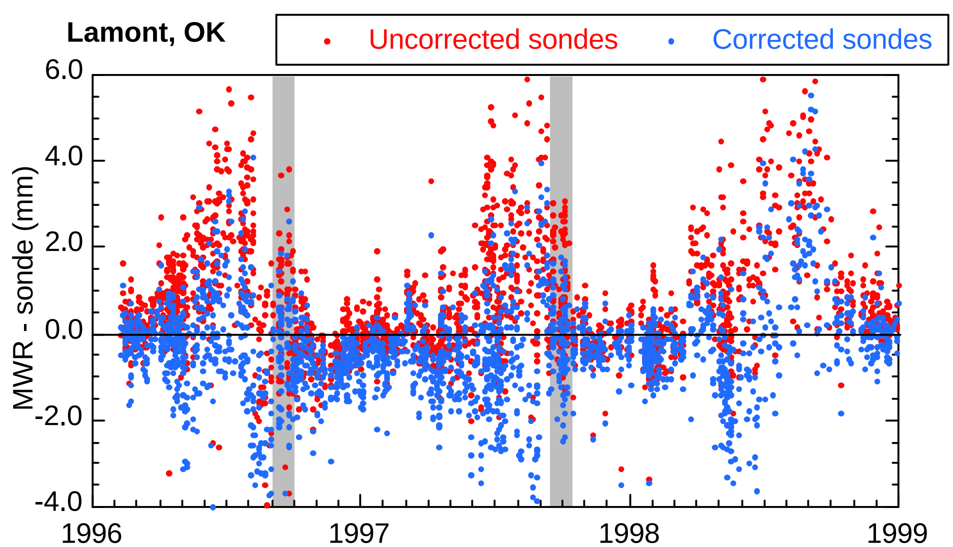

Figure 2. The IWV difference (MWR-sonde) for clear-sky conditions at Lamont, Oklahoma, 1996 to 1998 for uncorrected and corrected sondes. The shaded areas indicate the 1996 and 1997 Water Vapor IOP periods.

The dramatic reduction in the seasonal bias and variability is evident in Figure 3 and Table 1. The substantial bias that existed during the "wet season" from mid-March to mid-October has been essentially eliminated. The net result of the sonde correction is to substantially improve the overall agreement between the MWR and sondes, as demonstrated by Figure 4. The slope of the regression of MWR IWV on the sondes is now unity, the bias is now ~0.3 mm (sonde > MWR) and the variability has been significantly reduced.

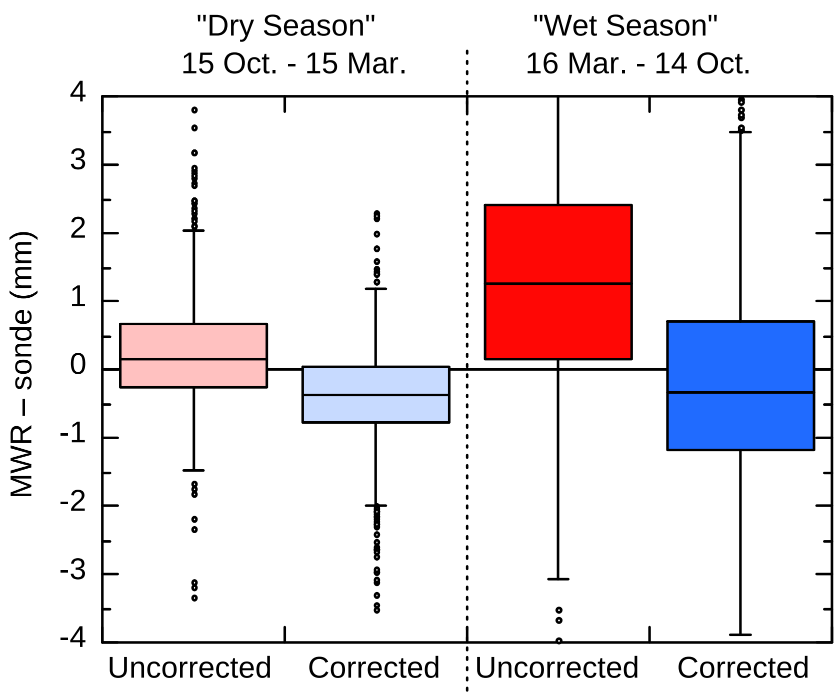

Figure 3. Box plots of IWV difference (MWR-sonde) for the "dry season" (mid-October to mid-March) and "wet season" (mid-March to mid-October).

Table 1. Statistics from the box plots of Figure 3.

MWR-sonde	Median (mm)	Inter-Quartile Range (mm)
Dry Season		
Uncorrected	0.15	0.92
Corrected	-0.37	0.81
Wet Season		
Uncorrected	1.22	2.25
Corrected	-0.33	1.87

MWR-GPS Comparisons

We examined the effects of two changes to the Bernese processing of the GPS data used to derive IWV estimates. First, the minimum elevation angle between the GPS satellites and the ground-based receiver was reduced from 15° to 7° in order to improve the sensitivity to water vapor. To facilitate this, the Hopfield (1971) wet mapping function was replaced with the more accurate Niell (1996) wet mapping function. Second, the mean vapor temperature T_{vapor}, was interpolated in time between exact calculations using radiosondes:

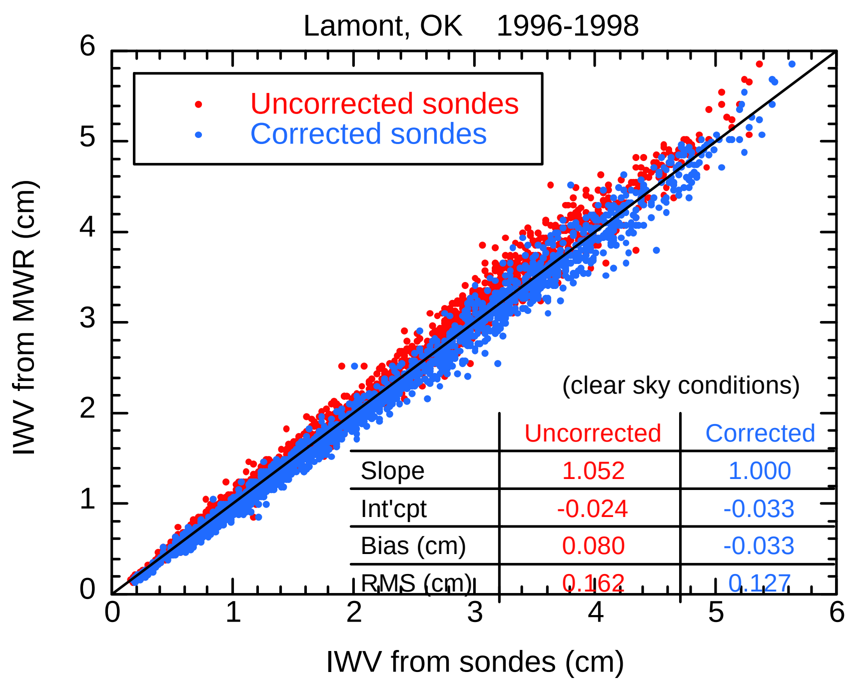

Figure 4. Comparison of IWV from MWR with uncorrected and corrected sondes for clear-sky conditions at Lamont, Oklahoma, for 1996 to 1998.

$$T_{vapor} = \int (e / T)\, dz \,/ \int (e / T^2)\, dz \qquad (1)$$

rather than estimated from surface temperature using the relationship

$$T_{vapor} = 70.2 + 0.72\, T_{surface} \qquad (2)$$

due to Bevis et al. (1994). T_{vapor} is needed to determine the conversion factor Π between the zenith wet delay (ZWD) measured by the GPS and the IWV

$$IWV = \Pi\, ZWD. \qquad (3)$$

Figure 5 presents values of T_{vapor} computed from both Eq. (1) and Eq. (2) for Lamont, Oklahoma, for 1996 to 1998. The estimator (Eq. 2) predicts these data reasonably well. However, because Π is a multiplicative factor, small errors will become more significant as the IWV amount increases. This is evident in Figure 6, which presents the errors in IWV arising from errors in Π due to using Eq. (2) rather than Eq. (1).

The effect of the changes in GPS processing are evident in Figure 7. For the 7° minimum angle with Π computed using T_{vapor} from soundings, the bias and seasonal variation is clearly reduced. This is borne out by the statistics for the wet and dry seasons summarized in Table 2. The dry season bias is essentially eliminated. For the wet season, the bias and the variability are substantially reduced.

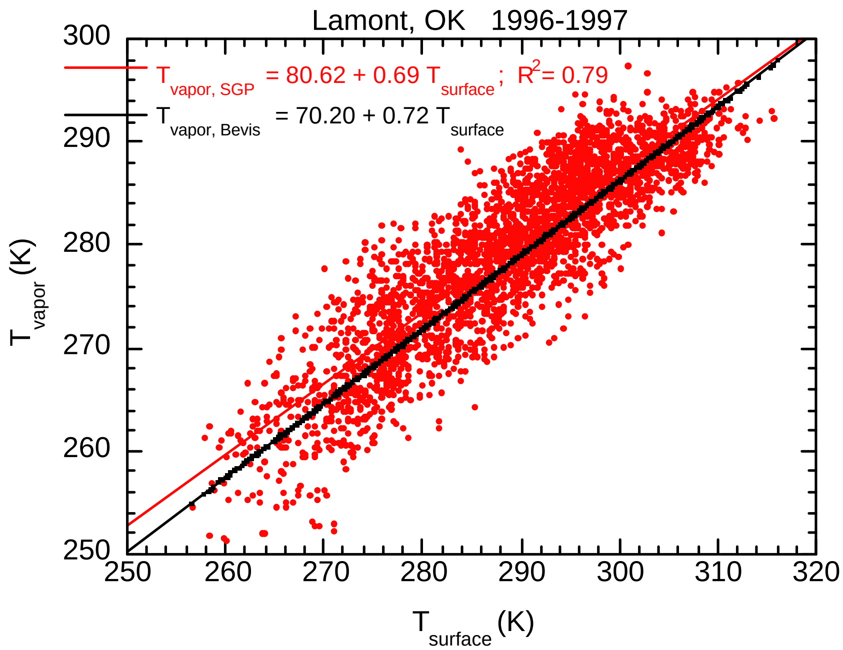

Figure 5. Mean vapor temperature calculated from radiosondes and estimated from surface temperature as a function of surface temperature.

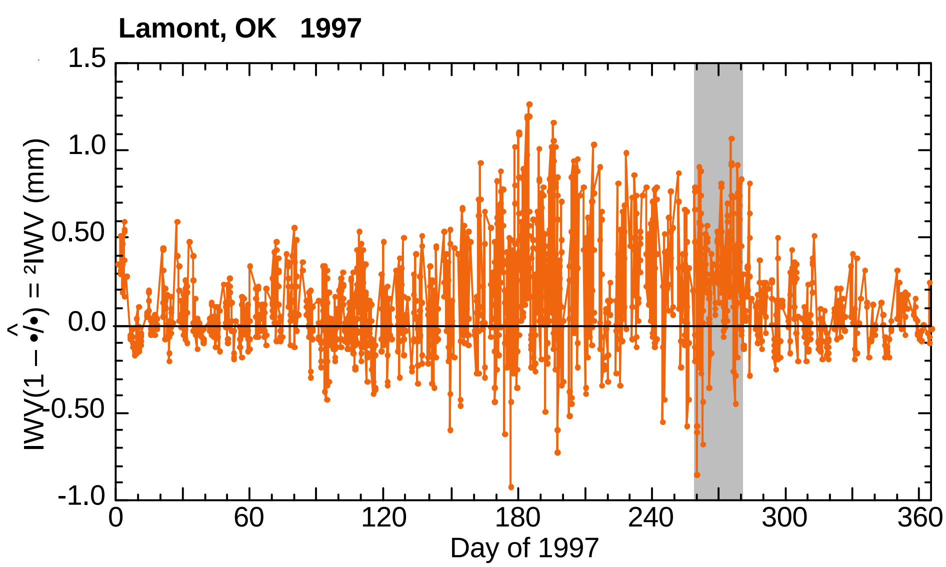

Figure 6. Error in IWV arising from errors in the conversion factor ∏ due to errors in mean vapor temperature. The shaded region indicates the 1997 Water Vapor IOP.

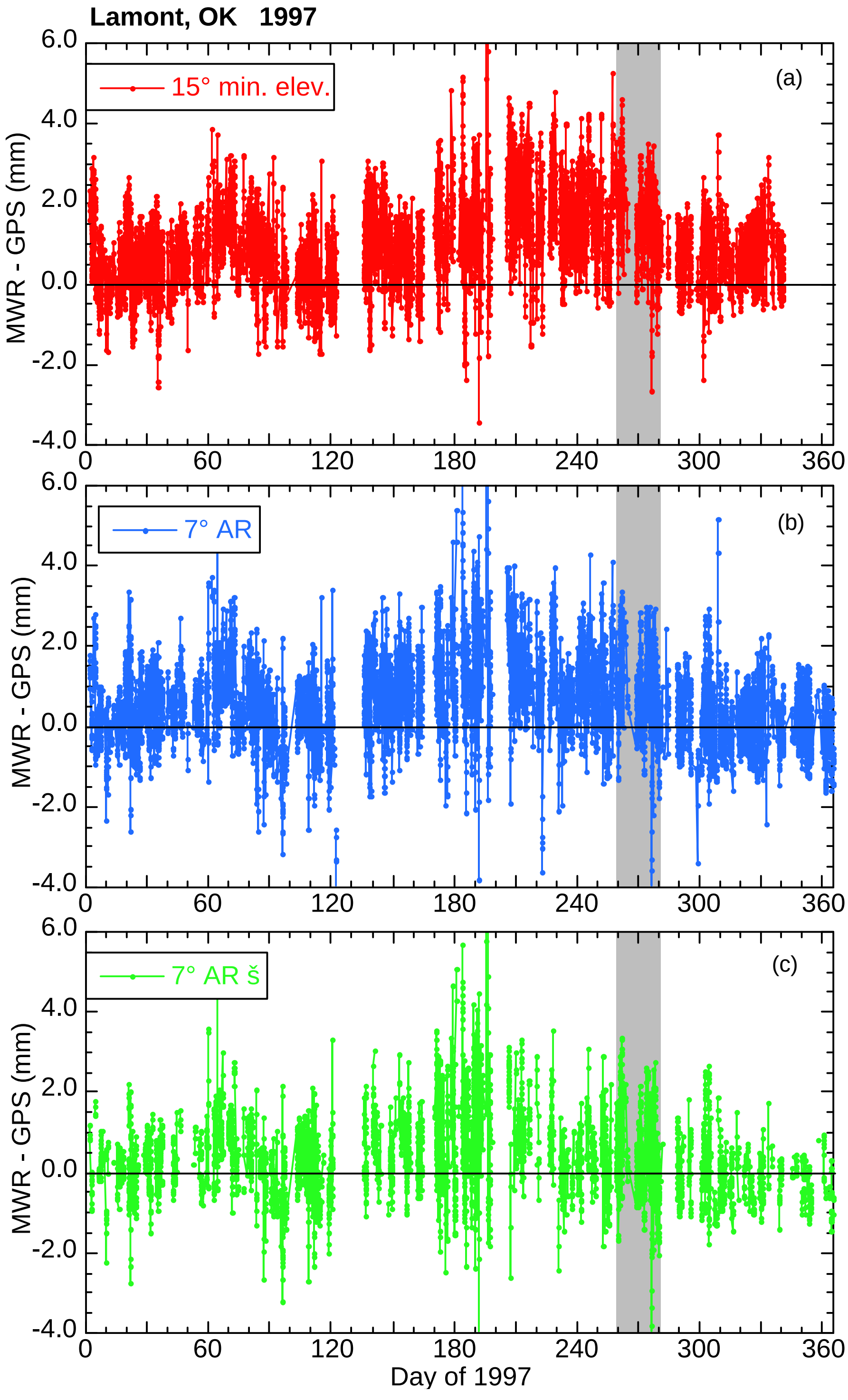

Figure 7. Plots of MWR-GPS differences for a) 15° minimum elevation angle, b) 7° minimum angles, ambiguity resolution enabled, and c) as in b) plus ∏ calculated from radiosondes. The 1997 Water Vapor IOP is indicated by gray shading.

Table 2. Statistical summary of MWR-GPS differences for "dry" and "wet" seasons (1997, clear-sky conditions) for 15° and 7° minimum angles and various GPS processing options. "AR" indicates ambiguity resolution enabled; "∏" indicates ∏ calculated from radiosondes.

MWR-sonde	Median (mm)	Inter-Quartile Range (mm)
Dry Season		
15° min. elev.	0.43	1.03
7° min. elev.	-0.06	0.99
7° AR	0.26	1.01
7° ∏	-0.16	0.97
7° AR ∏	0.17	1.02
Wet Season		
15° min. elev.	1.44	1.31
7° min. elev.	1.13	1.69
7° AR	1.05	1.37
7° ∏	0.70	1.65
7° AR ∏	0.64	1.36

Figure 8 shows that additional improvements in the GPS measurements may be possible. Diurnal variations in the MWR-GPS and BBSS-GPS differences during the 1997 Water Vapor IOP show significant correlation that may be due to GPS multi-path errors.

Conclusions

A correction to the sonde relative humidity measurement developed by Vaisala has eliminated the seasonal bias and reduced the mean BBSS-MWR difference to 0.3 mm. For the GPS, reducing the minimum elevation angle from 15° to 7°, and using more accurately calculated values of the mean vapor temperature and thus of the wet delay-to-integrated vapor conversion factor have been responsible for substantially improved agreement with the ARM MWR.

References

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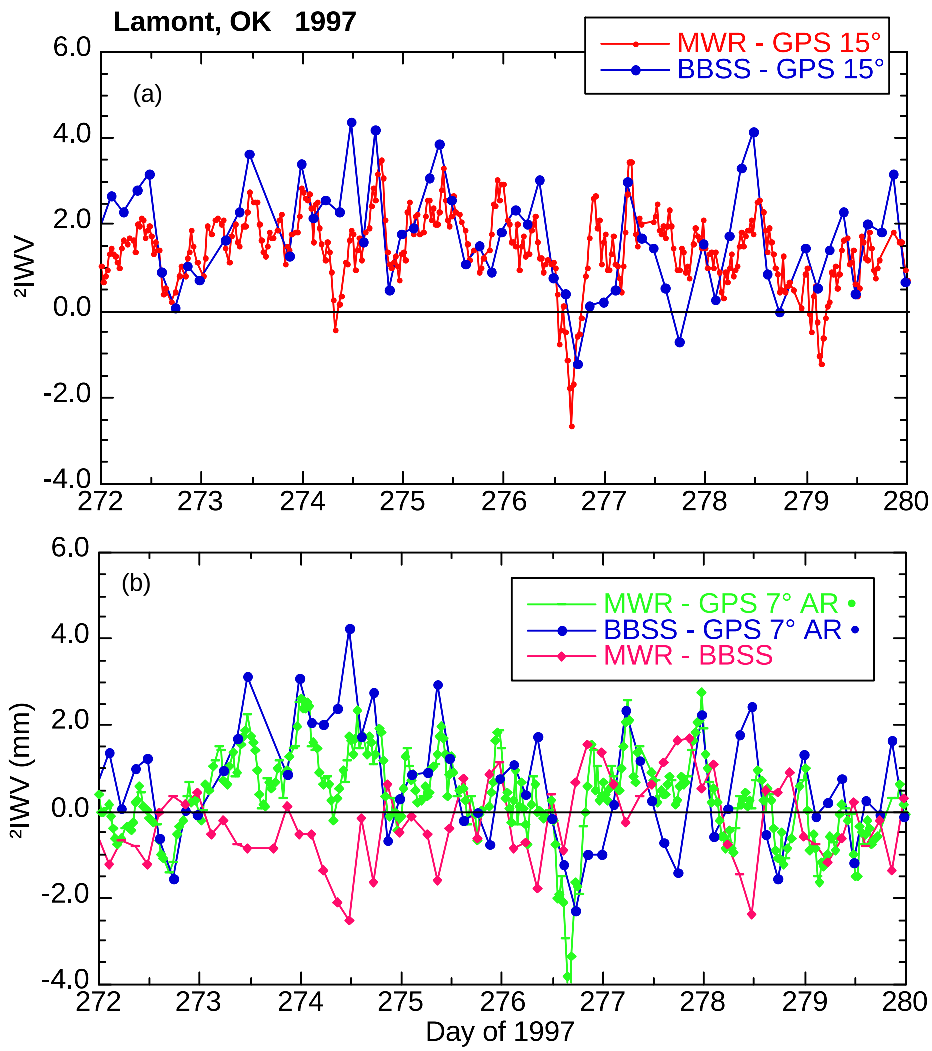

Figure 8. MWR-GPS and BBSS-GPS differences for a) 15° and b) 7° minimum angle, ambiguity resolution and ∏ calculated from radiosondes at Lamont, Oklahoma, during the 1997 Water Vapor IOP.