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Measurements of Integrated Water Vapor and Cloud Liquid Water from Microwave Radiometers at the DOE ARM Cloud and Radiation Testbed in the U.S. Southern Great Plains

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Abstract -- The operation and calibration of the ARM microwave radiometers is summarized. Measured radiometric brightness temperatures are compared with calculations based on the model of [1] using co-located radiosondes. Comparisons of precipitable water vapor retrieved from the radiometer with integrated soundings and co-located GPS retrievals are presented. The three water vapor sensing systems are shown to agree to within about 1 mm.

INTRODUCTION

In order to quantify the spatial and temporal variations of water vapor and clouds, the U. S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program has deployed five dual-frequency microwave water radiometers at its Cloud and Radiation Testbed (CART) in Oklahoma and Kansas, as illustrated by the map in Fig. 1.

The microwave radiometers are used to derive the integrated ("precipitable") amount of water vapor and cloud liquid water overhead of the instrument as defined by

$$PWV = \int \rho_V(z)\,dz \tag{1}$$

$$LWP = \int w(z)\,dz \tag{2}$$

where $\rho_V(z)$ is the vertical distribution of water vapor density and $w(z)$ is the vertical distribution of cloud liquid water content. It is common practice to normalize these by the

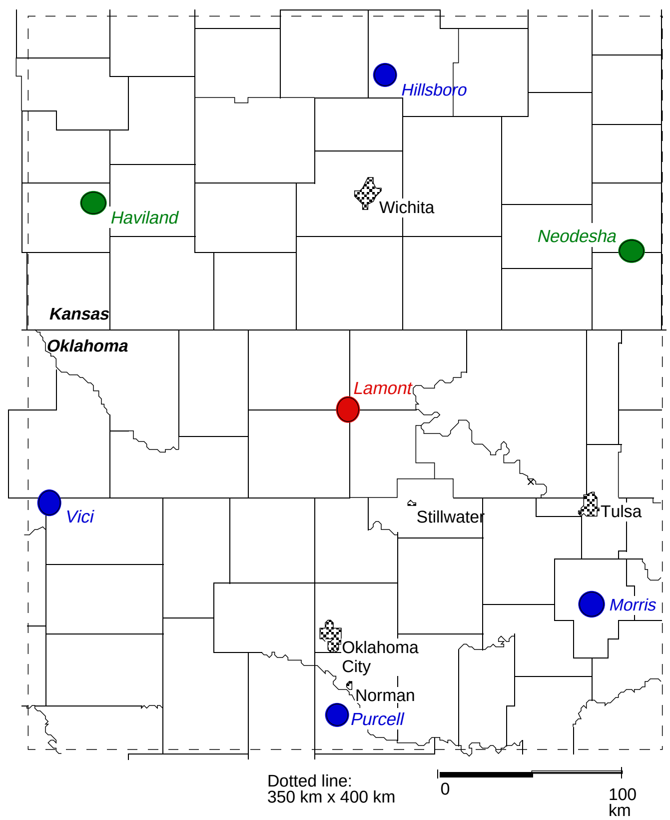

Fig. 1. The ARM Cloud and Radiation Testbed (CART). Microwave radiometers and balloon-borne sounding systems are co-located at each of the Boundary Facilities and at the Central Facility; NOAA wind profilers and GPS receivers are located within a few kilometers of these facilities. NOAA wind profilers are also located at Haviland and Neodesha, KS.

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nominal density of liquid water, 10^6 g/m^3, and to express precipitable water vapor or PWV in centimeters and the liquid water path or LWP in millimeters.

THE MICROWAVE RADIOMETERS

The microwave water radiometers (MWRs) that ARM has deployed are Radiometrics™ model WVR-1100. These instruments have a vapor-sensing channel at 23.8 GHz and a liquid-sensing channel at 31.4 GHz. The instruments use a common antenna and wave guide for both channels with individual Gunn diode oscillators for each frequency. Consequently the beam widths are unequal: 5.5° at 23.8 GHz and 4.6° at 31.4 GHz.

Radiometric Measurements

At the beginning of each 20-second observing cycle the radiometer first measures the microwave sky signal V_{sky} at each frequency for a 1-second integration period. Its elevation mirror is then rotated to measure the signal from an internal blackbody target V_{ref}. The target temperature T_{ref} is also measured. The signals are converted to a sky brightness temperature T_B using the radiometer equation

$$T_B = X\left[T_{ref} + \overline{G}\left(V_{sky} - V_{ref}\right)\right] + (1 - X)T_{ref} \qquad (3)$$

where the factor X = 1+ε accounts for the contribution of the Teflon™ foam window that protects the mirror. While viewing the blackbody target a noise injection source is energized and the corresponding signal V_{ref+n} measured at each frequency. The instantaneous gain G is then determined according to

$$G = \Delta T_n / \left(V_{ref+n} - V_{ref}\right) \qquad (4)$$

where ΔT_n is determined by prior calibration. The instantaneous gain is then low-pass filtered to yield the central tendency $\overline{G}$.

Calibration

Calibration of the noise injection is achieved using "tipping curves" [2]. Using the true zenith brightness temperature from each tipping curve, (3) and (4) are combined and solved for ΔT_n. We use ten angles on both sides of zenith (cosec(elev) = 1, 1.5, 2, 2.5, 3) and reject tips for which the correlation coefficient of the fit is less than 0.998. We can acquire a tip curve every 60 seconds; we typically acquire about 1000 tips in a calibration period. We use a robust fitting scheme to regress ΔT_n on T_{ref} to account for a slight dependence on ambient temperature. The calibration of S/N 10 in effect 5 January - 12 September 1995 differed by less than 1% from that in effect 12 September - 30 November 1995.

COMPARISON WITH RADIOSONDES AND GPS

In Fig. 2 we compare brightness temperatures measured with MWR S/N 10 against those calculated using co-located radiosondes and a radiation transfer model [3] based on the microwave absorption model of [1]. ARM uses Vaisala Balloon-Borne Sounding Systems (BBSS) and RS-80 radiosondes with H-Humicap® relative humidity sensors. The MWR T_B values are 40-minute averages centered on the time of sonde launch.

To assure a valid comparison we included only those cases for which the 40-minute standard deviation of T_B was less than 0.3 K in the liquid sensing channel (clear sky) and less than 0.35 K in the vapor channel (homogeneous sky). These values are twice the RMS noise level of the instrument. As shown in Fig. 2 we identified many soundings for which the

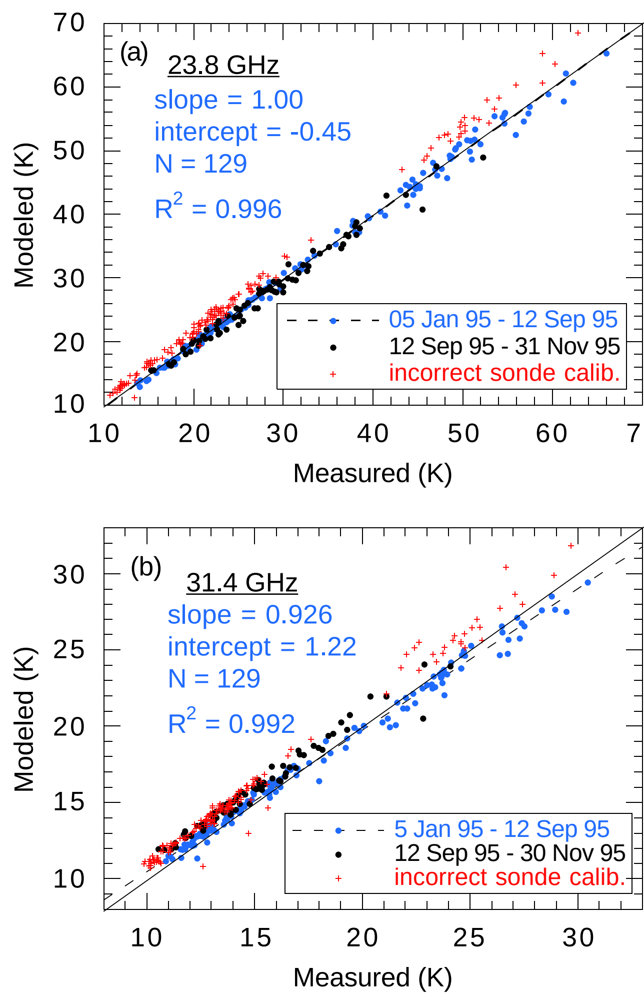

Fig.2. Model-calculated and measured brightness temperatures at (a) 23.8 GHz and (b) 31.4 GHz for 5 Jan - 12 Sep 1995 and 12 Sep - 30 Nov 1995. Incorrectly calibrated radiosondes are also indicated.

manufacturer's calibration appeared incorrect; this finding was later confirmed by Vaisala.

We use a statistical retrieval [4] to obtain the precipitable water vapor (PWV) and liquid water path (LWP) from the measured brightness temperatures. Because the retrieval is based on the radiation transfer model [3], we must apply the regression of modeled T_B on measured T_B as a correction or tuning function to the measured T_B values in order to obtain accurate estimates of PWV and LWP with the retrieval.

A histogram of LWP for cases where the standard deviation of the liquid sensing channel was less than 0.3 K (i.e. "clear sky") is presented in Fig. 3. This indicates the accuracy with which LWP can be determined by the system; it reflects the limiting accuracy of the instrument as well as the retrieval.

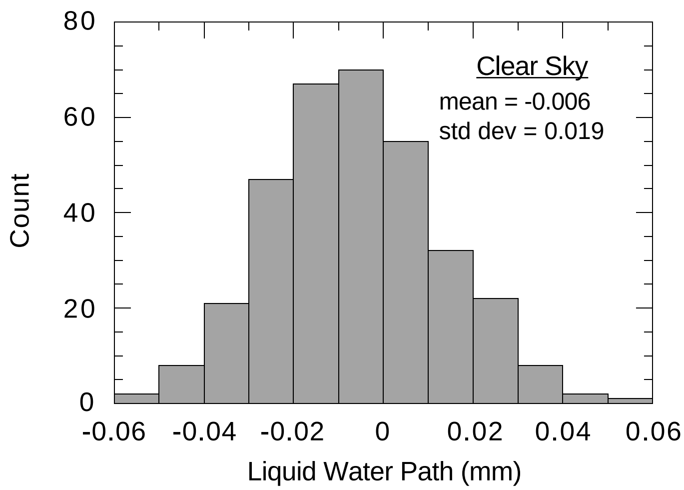

Fig. 3. Distribution of LWP for clear sky conditions (standard deviation of T_B at 31.4 GHz less than 0.3 K).

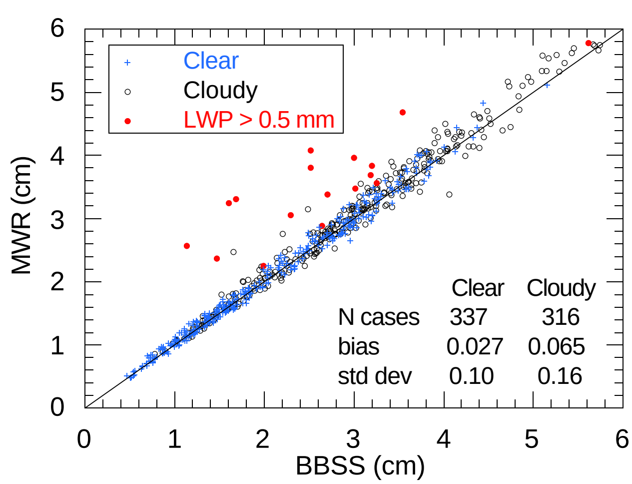

Fig. 4. Comparison of precipitable water vapor measured by microwave radiometer (40-minute averages) and balloon-borne sounding system at Lamont, OK for 5 Jan-30 Nov 1995.

The comparison of PWV from the MWR and the BBSS for clear and cloudy sky conditions is presented in Fig. 4. Although the agreement is good both for clear sky cases and for cloudy skies with LWP < 0.5 mm (50 g/m^2), as LWP increases above 0.50 mm the difference between the PWV reported by the two systems is essentially uncorrelated.

Retrievals of PWV are now possible using the Global Positioning System (GPS) [5]. In Fig. 5 we present comparisons of 30-minute averaged PWV from the MWR and GPS for clear sky conditions. Because the GPS measurement represents an average over nearly the entire sky, whereas the MWR has a relatively narrow field of view (~5^o), cloudy sky comparisons show considerably more variability.

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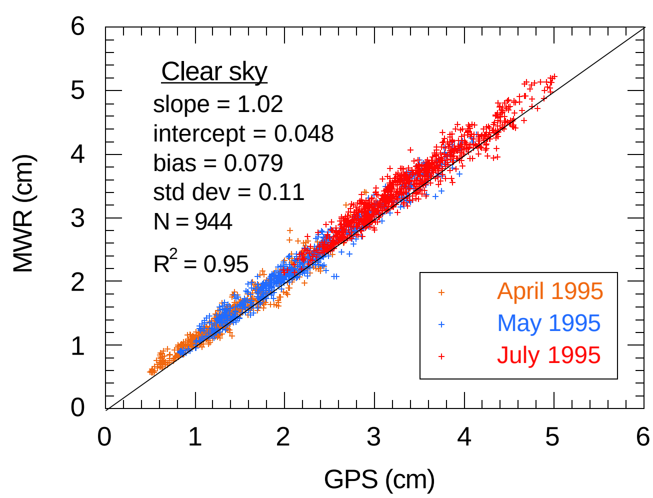

Fig. 5. Comparison of 30-minute averaged precipitable water vapor from microwave radiometer and Global Positioning System at Lamont, OK for clear sky conditions (LWP < 0.04 mm) during April, May and July 1995.