Analysis of Tip Cal Methods for Ground-Based Microwave Radiometric Sensing of Water Vapor and Clouds

Y. Han and E. R. Westwater
CIRES, University of Colorado
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

Introduction

Ground-based Microwave Radiometers (MWRs) have been widely used to measure atmospheric water vapor and cloud liquid water. Frequencies on the 22.235-GHz water vapor absorption band and in the 31-GHz absorption window region are commonly used in these systems. These frequency channels differ in their response to water vapor and cloud liquid water and provide brightness temperature measurements from which precipitable water vapor (PWV) and integrated cloud liquid water are derived. Absolute calibration of the radiometer is fundamental in determining the accuracies of these retrievals. For a dual-channel radiometer at 23.8 GHz and 31.4 GHz, numerical simulations show that a 1.4 K calibration error will cause a 1-mm error in PWV.

The importance of the PWV measurements and, thus, the importance of the system calibration, has increased in recent years as the MWR measurements are often served as references and comparison standards for other water vapor measuring instruments, such as radiosondes, Raman water vapor lidars, and Global Positioning Systems (GPSs). One of the goals of the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) Program is to evaluate various techniques for determining PWV. During September 15-30, 1996, and September 15-October 5, 1997, Water Vapor Intensive Observation Periods (WVIOPs) were conducted at the ARM Cloud And Radiation Testbed (CART) site. Various calibration uncertainties that were noticed during these WVIOPs are the motivation of our work.

Tipping Calibration Method

The tip cal method has been commonly used throughout the microwave community. In this method, brightness temperatures are measured as a function of elevation angle θ, and are then converted to opacity $\tau(\theta)$ using the mean radiating temperature approximation (Westwater 1993). If the system is in calibration, then the plot of $\tau(\theta)$ as a function of (normalized) air mass a (= csc (θ)), will pass through the origin; conversely, if $\tau = \tau(a) = \tau(1)a + b$ does not pass through the origin, then a single parameter in the radiometer equation is adjusted until it does. Note that when the calibration is achieved, then the slope of the line is equal to the zenith opacity. Here, we will refer to scanning data taken for calibration simply as tipping data.

Calibration Uncertainties and Methods to Reduce Them

Calibration uncertainties may be caused either by the radiometer system or by violations of the assumptions in the theory on which the calibration is based. The former include the effects of radiometer antenna pattern, radiometer pointing error, and system random noise. The latter include the uncertainty in the mean radiating temperature T_{mr} and the uncertainties in the fundamental relationship between the airmass and the observation angle, which can be affected by non-stratified atmospheric conditions and the earth's curvature. We simulated these error sources and developed and tested effective techniques to reduce them. The simulations were performed for a clear-sky atmosphere by using a radiative transfer model (Westwater 1993), pressure, temperature, and humidity profiles, and a radiometer equation that could describe either an Environmental Technology Laboratory (ETL) or an ARM MWR. A statistical ensemble of radiosonde data with a size of 16,380 soundings were collected from five stations around the area of Oklahoma City, Oklahoma, from 1966 to 1992. We summarize the results of our simulations below, following Han and Westwater (1999). Only air masses ≤ 4 are considered.

Effect of Earth Curvature and Atmospheric Refractive Index

Our simulations showed that the effect of the refractive index profile on system calibration is negligible and that earth curvature has a relatively large effect that can be conveniently corrected to less than 0.05 K for air mass ≤ 4.

Errors Caused by Uncertainties in Radiometer Pointing Angle

Our simulations showed that pointing errors could have serious impact on the performance of the tip cal if only one-sided scans are used. Experience and simulations strongly suggest that antenna scans used for calibration should be taken in pairs at symmetric elevation angles.

Effect of Antenna Beam Width

The antenna temperature $T_a(\theta)$ of a radiometer at a specified frequency is a weighted average of incoming brightness temperature $T_b(\theta,\varphi)$ over all directions (θ,φ). Under normal atmospheric conditions and at the weakly absorbing frequencies considered here, due to the non-linear increase of the brightness temperature when lowering the elevation angle, $T_a(\theta)$ is larger than that of the brightness temperature $T_b^c(\theta)$ at the cone-like antenna beam center direction. Based on the assumption of a Gaussian beam antenna pattern, we derived an adjustment $\delta T_a(\theta)$,

$$\delta T_a(\theta) = \frac{\theta_{1/2}^2}{16\mathrm{Ln}(2)}\left(T_{mr}(\theta) - T_{bb}\right)\exp\left(-\tau(\theta)\right)\left[2 + \left(2 - \tau(\theta)\right)\tan^{-2}(\theta)\right]\tau(\theta), \tag{1}$$

where $\theta_{1/2}$ is the full width (in radians) at half-maximum power of the power pattern. Note that $\tau(\theta)$ in Eq. (1) is the slant path opacity at an elevation angle θ. The observed antenna temperatures should be corrected by the amount given by Eq. (1) before being used in the calibrations: $T_b(\theta) = T_a(\theta) - \delta T_a(\theta)$. Calculations of T_a and T_b^c are shown in Figure 1.

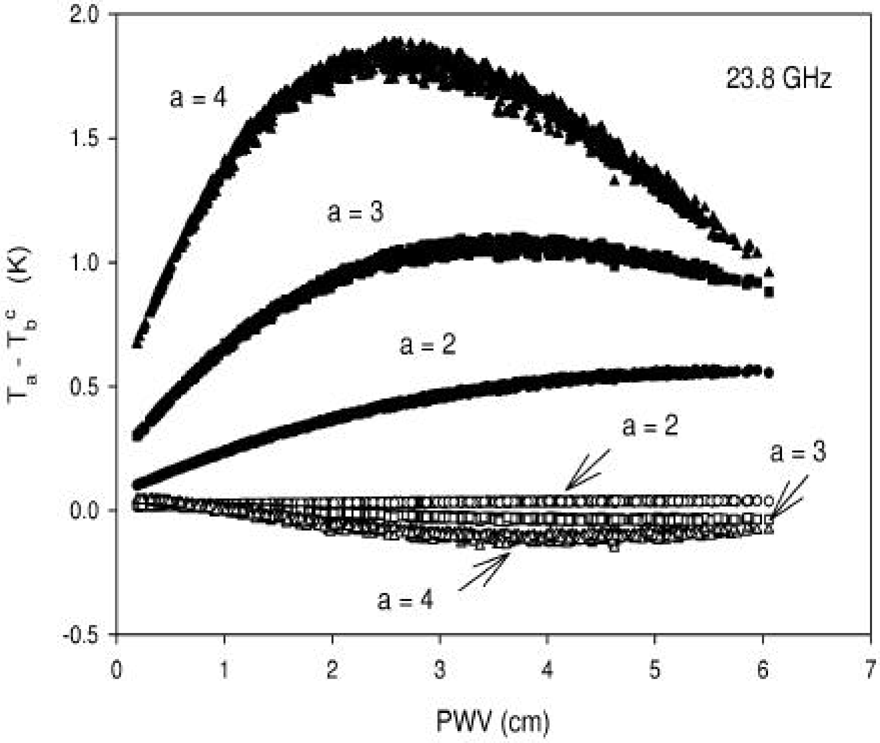

Figure 1. Differences between T_a and T_b^c as a function of PWV. The filled symbols are those without beam effect corrections; the open symbols are those in which T_a is adjusted by Eq. (1). The airmasses at which the differences are calculated are indicated. Data used in the simulations were from Oklahoma City, Oklahoma.

Effect of Mean Radiating Temperature

The quantity T_{mr} plays a role in mapping brightness temperature T_b to opacity τ. Our simulations suggest that by using T_{mr} that is a function of elevation angle and is estimated by surface meteorological measurements, is an effective way of reducing errors in T_{mr}. The prediction could also be improved significantly by using remote sensor observations.

Errors Caused by System Random Noise

The system random noise affects system precision, but with both the ETL and the ARM systems (root mean square [rms] noise ≈0.1 K), the calibration uncertainties are about 0.1 K to 0.4 K. We also found that the uses of larger airmasses suffer less than the uses of smaller ones due to larger signal to noise ratio at lower elevation angles. The impact of the system noise can usually be reduced by temporal averaging.

Errors Caused by Uncertainty in the Offset of the Radiometer Equation

If the offset uncertainty is less than 1 K, it will not cause serious calibration problems.

Errors caused by Non-Stratified Atmospheric Conditions

The airmass-angle relationship requires a horizontally stratified atmosphere. This is the reason why calibrations are usually performed under clear-sky conditions. However, even under these conditions, caution must be exercised due to spatial variations of the water vapor and temperature fields. Several instances were noted during the WVIOPs when there were significant differences and even phase shifts between these tip curves; an example is shown in Figure 2. We simulated the effects of horizontal inhomogeneity using angular scan data from a Raman Lidar and found that the magnitude of the difference reflects the degree of the horizontal inhomogeneity, and that the effects are frequently non-negligible. We suggest that temporal averaging, on the order of 2 to 3 hours, and careful screening of tipping data before applying them to the calibrations, may reduce this important source of error.

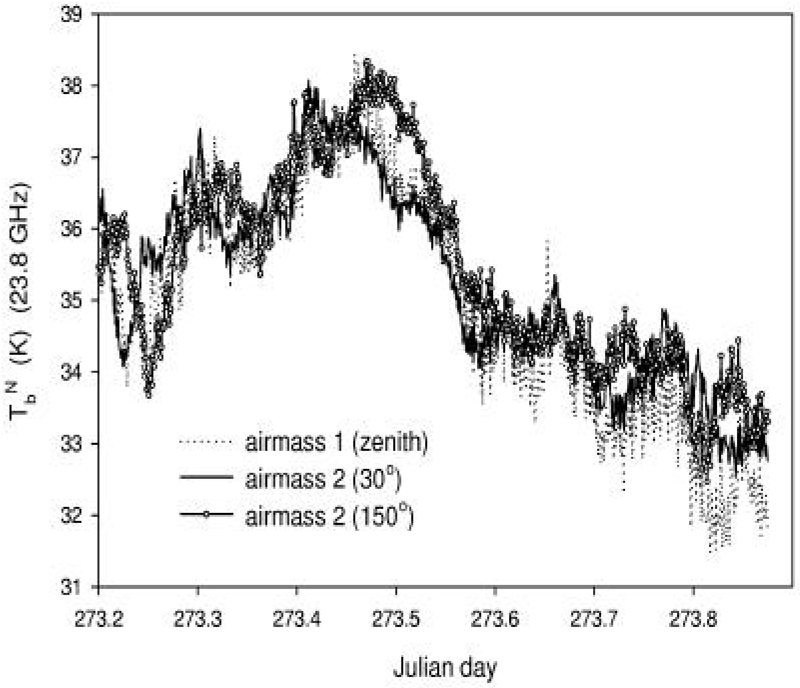

Figure 2. T_b, normalized to zenith, taken during WVIOP'97. The three curves correspond to T_b observed at a = 1 and a pair of symmetric elevation angles with a = 2. The curves demonstrate horizontal inhomogeneity during clear-sky conditions; for a stratified atmosphere, all curves would be coincident.

Further Discussion

We observed that calibrations using low elevation angles are more sensitive to the various error sources; however, for the same error, angles with larger separations give a mathematical advantage in least squares estimation. Thus, there is clearly a tradeoff on the choice of angles. From our experience and the earlier discussions, tipping data should not include airmass greater than 3, especially for antenna with beam widths ≥ 6 degrees. Quality control techniques applied to tipping data are also useful in reducing calibration errors. The technique of checking the symmetry of the tipping data taken at symmetric angles can be used to ensure a stratified atmosphere, or the correctness of system pointing angles. The standard deviation of normalized brightness temperature measurements, or airmass-opacity correlation coefficient (Liljegren 1994) can be used to screen out erroneous tipping data. The comparisons of calibration factors derived from different combinations of airmasses can be used as consistency checks.

As our investigation progressed, it became clear that there were significant advantages to having nearly continuous tipping calibrations. The presence of significant horizontal inhomogeneities as they pass overhead is easily revealed by a time series of tipping calibration data. If these tipping data are done frequently and in clear conditions, a representative time series of zenith T_b is still obtained. During cloudy conditions, the off-zenith scans can be used to identify cloudy data that are not necessarily overhead. This is important because cloud ceilometers or infrared radiometers usually only indicate clear conditions in the zenith direction. A large initial data set is also advantageous when applying rigorous quality control methods. For example, ARM radiometer, with its continuous scanning ability, generated roughly 3000 1-min. tipping calibration scans; during the same period, the ETL radiometers generated only about 30 15-min. scans.

References

Han, Y., and E. R. Westwater, 1999: Analysis and improvement of tipping calibration for ground-based microwave radiometers. *IEEE Trans. Geosci. Remote Sensing*. In press.

Liljegren, J. C., 1994: Two-channel microwave radiometer for observations of total column precipitable water vapor and cloud liquid water path. In *Proc. Fifth Symposium on Global Change Studies*, *Amer. Meteorol. Soc*., Nashville, Tennessee, January 23-28, 1994, pp. 262-269.

Westwater, E. R., 1993: Ground-based microwave remote sensing of meteorological variables. In *Atmospheric Remote Sensing by Microwave Radiometry*, Chapter 4, pp. 145-213, M. Janssen, Ed., New York, Wiley.