. OSTI ID 762789

AI03-97 ER 62343

PROGRESS REPORT OF FY 1999 ACTIVITIES: The Application of Kalman Filtering to Derive Water Vapor Profiles from Combined Ground-Based Sensors: Raman Lidar, Microwave Radiometers, GPS, and Radiosondes

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ABSTRACT

Previously, the proposers have delivered to ARM a documented algorithm, that is now applied operationally, and which derives water vapor profiles from combined remote sensor measurements of water vapor radiometers, cloud-base ceilometers, and radio acoustic sounding systems (RASS). With the expanded deployment of a Raman lidar at the CART Central Facility, high quality, high vertical-resolution, water vapor profiles will be provided during nighttime clear conditions, and during clear daytime conditions, to somewhat lower altitudes. The object of this effort is to use Kalman Filtering, previously applied to the combination of nighttime Raman lidar and microwave radiometer data, to derive high-quality water vapor profiles, during non-precipitating conditions, from data routinely available at the CART site. Input data to the algorithm would include: Raman lidar data, highly quality-controlled data of integrated moisture from microwave radiometers and GPS, RASS, and radiosondes. While analyzing data obtained during the Water Vapor Intensive Operating Period'97 at the SGP CART site in central Oklahoma, several questions arose about the calibration of the ARM microwave radiometers (MWR). A large portion of this years effort was a thorough analysis of the many factors that are important for the calibration of this instrument through the tip calibration method and the development of algorithms to correct this procedure. An open literature publication describing this analysis has been accepted.

TIPPING CURVE CALIBRATION METHOD FOR MICROWAVE RADIOMETER

To combine data by Kalman filtering, it is necessary to know the error characteristics of each data source and to eliminate, as far as possible, sources of internal inconsistency between the data. The input data for our Kalman algorithm will be mixing ratio profiles from the ARM Raman lidar, precipitable water vapor (PWV) from the ARM microwave radiometer (MWR) and possibly PWV from the Global Positioning System (GPS) that is operated by the National Weather Service at Lamont, Oklahoma, and Vaisalla type radiosondes that are operated on the Balloon Borne Sounding System (BBSS) at the Southern Great Plains CART Central Facility. Previously, ARM scientists have used the PWV derived by the ARM MWR to scale soundings from the BBSS and the Raman lidar. In our analysis of the data from the 1997 Water Vapor Intensive Operating Period, we found, in contrast to the 1996 experiment, that there was now a significant bias between the ARM MWR, and a variety of other independent instruments, including two ETL MWR's, GPS, ARM radiosondes (BBSS), and a Raman lidar that was calibrated by the CART in situ instruments on the 60 -m tower. Later work, principally by

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B. Lesht showed how the BBSS data could be re-calibrated. However, our work on the ARM MWR is still of general relevance to ARM and to the Kalman filter development, in particular.

MWR Calibration Uncertainties and Methods to Reduce Them

We examined a large number of factors that effect the calibration. The three most important are:

A. 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.

B. Effect of Antenna beam width

It was shown that the relatively wide beam of the ARM MWR (6°) could lead to a significant bias in the calibration, and we derived and will supply to ARM an effective method of correction. Figure 1 shows the magnitude of this effect for the ARM MWR and the results of our method of correction.

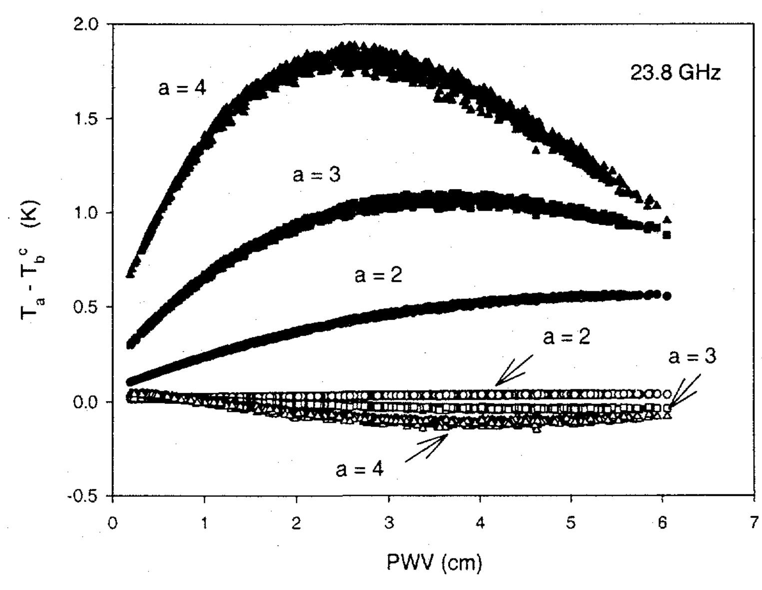

Figure 1. Differences between antenna temperature ($\theta_{1/2}$ = 6 °) and the brightness temperature at the beam center direction as a function of PWV. The filled symbols are those without beam effect corrections; the open symbols are those with the corrections in which the antenna temperature is adjusted by the ETL method. The airmasses at which the differences are calculated are indicated in the figure. After Han and Westwater (1999)

C. Errors caused by non-stratified atmospheric conditions

Using scanning radiometer data obtained during WVIOP'99, we were able to observe the effects on the tipping method of non-stratified conditions. An example of these data is shown in Figure 2.

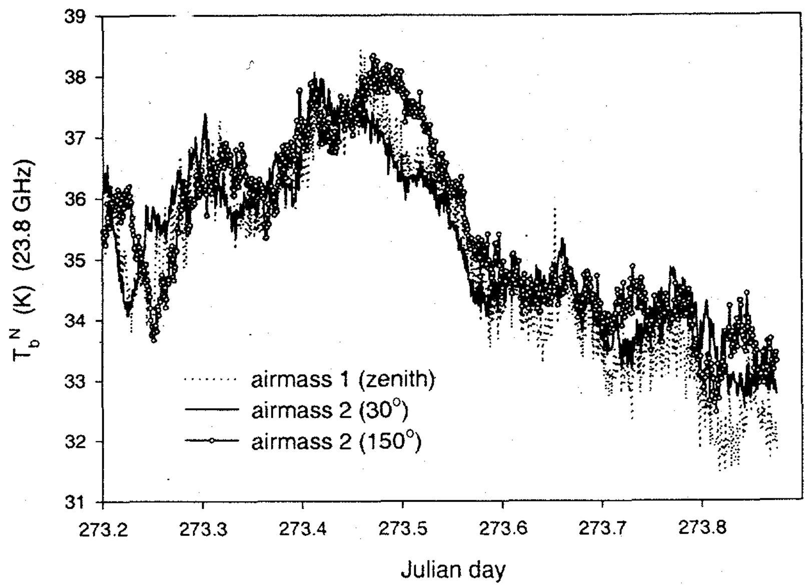

Figure 2. Brightness temperature measurements, normalized to zenith, taken during WVIOP'97. The three curves correspond to brightness temperatures observed at airmass 1 and a pair of symmetric elevation angles with airmass 2. The figure demonstrates the horizontal inhomogeneity even under clear-sky conditions, in contrast to a stratified atmosphere, which should result in an agreement among the three curves. After Han and Westwater (1999).

We recommended in our 1999 papers several ways to identify and eliminate these fundamental limitations to the tipping calibration method.

The results demonstrate that ARM MWR data must be corrected for several effects before they can be used in Kalman filtering algorithms or scaling of radiosonde data. However, with these corrections, it is still recommended that ARM MWR data be used as a consistency measure of water vapor sounding data.

PLANS FOR FY 1999

- To deliver to ARM our tipping calibration method correction algorithms for the MWR.

- To develop the error covariance matrices and transition matrices that are required for the Kalman filter algorithm from a subset of the WVIOP'96 and WVIOP'97 data and apply the algorithm to independent data taken from SGP instruments.
- Deliver a Kalman filter algorithm to ARM
- Submit the results of the Kalman analysis to the open literature.

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