Millimeter-Wave Radiometric Measurements of Low Amounts of Precipitable Water Vapor

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Introduction

Extremely dry conditions commonly occur in polar regions during the winter months. Accurate measurements of the precipitable water vapor (PWV) during such dry conditions are needed to improve our understanding of the regional radiation energy budgets. The strength associated with the 183-GHz water vapor absorption line makes radiometry in this frequency regime promising for measuring low amounts of PWV. However, retrievals using these frequencies are complicated by the uncertainties in the absorption models and the fact that these frequencies also respond to the vertical temperature distribution as well as liquid and ice clouds. Pacific Northwest National Laboratory and the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program sponsored National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory to conduct an experiment to investigate the application of millimeter wave radiometry for making ground-based estimates of PWV during the dry conditions. The data set obtained during this experiment is applicable to assessing the potential limitations of millimeter-wave radiometry to retrieving very low amounts of PWV. The data are also valuable for studying discrepancies in the different absorption models for water vapor, oxygen, and super cooled liquid water. In this paper, an overview of the experiment is presented, a summary of the data collected is given, and single-channel clear-air retrievals are shown.

The Arctic Winter Experiment

NASA and NOAA deployed a suite of radiometers covering 25 channels in the frequency range of 20 GHz up to 340 GHz. Twenty-three days of nearly consecutive radiometer data were collected during

March 1999 at the DOE's ARM Program's North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) site located just outside Barrow, Alaska. Table 1 summarizes the millimeter-wave radiometers and the measurement channels deployed for the experiment. In addition to the usual CART site instrumentation, the NOAA depolarization and backscatter unattended lidar (DABUL), the State University of New York (SUNY) rotating shadowband spectroradiometer (RSS), and other surface-based meteorological instrumentation were deployed during the intensive observation period. Vaisala RS-80 radiosondes were launched daily, and the nearby National Weather Service (NWS) station launched VIZ sondes twice daily.

Table 1. Millimeter-wave radiometers deployed during the arctic winter experiment.

Radiometer	Channels (GHz)
Millimeter-wave Imaging Radiometer (MIR)	89, 150, 183.31 ± 1, 183.31 ± 3, 183.31 ± 7, 220, 340
DOE Multichannel Microwave Radiometer (DOER)	20.735, 21.485, 22.235, 22.985, 23.735, 36.5, and 89.0
Scanning-O2	60.5 GHz
Circularly Scanning Radiometer (CRS)	20.6, 31.65, 183 ± 0.5, 183 ± 1, 183 ± 3, 183 ± 5, 183 ± 7, 183 ± 12, 183 ± 15, 325 ± 1, 325 ± 3, 325 ± 8, 340

The experiment benefited from a wide variety of artic-winter atmospheric conditions ranging from clear, calm skies to blowing snow and heavy multi-layer cloud coverage. Measurements made by the CART site microwave radiometer (MWR) indicate the PWV varied from ~0.9 mm to ~5.7 mm during the experiment. The near-surface temperature varied between about -42°C to -18°C. The driest conditions were experienced during periods of clear skies. Two periods of prevailing clear skies occurred during the experiment, Julian Day 67-71 and Julian Day 85-89, during which time the PWV was about 2 mm or lower. During the first period, the surface temperature was ~10°C colder than during the later period, though the PWV was about the same. The differing conditions allow us to study how the atmospheric temperature affects PWV retrievals using millimeter wave radiometry.

Radiometric Observations

Figure 1 shows brightness temperature (TB) measurements made by the MIR during the experiment. Overlaid on the measurements are forward model calculations derived from radiosonde measurements; the NWS sondes are from the nearby Barrow NWS station; GWo (original sondes) and GWc (corrected sondes) are derived, respectively, from the original and corrected Vaisala RS-80 sondes launched at the NSA/AAO site. Forward model calculations were made using two absorption models, Liebe-87 (-87) (Liebe and Layton 1987) and Rosenkranz-98 (-Ros) (Rosenkranz 1998). Significant differences between the forward modeled TBs and those measured by the MIR are observed for all the sonde calculations (Westwater et al. 2000). The measurements made near the 183-GHz absorption line are generally lower than the forward modeled TBs. Whereas, in the window regions near 150 GHz,

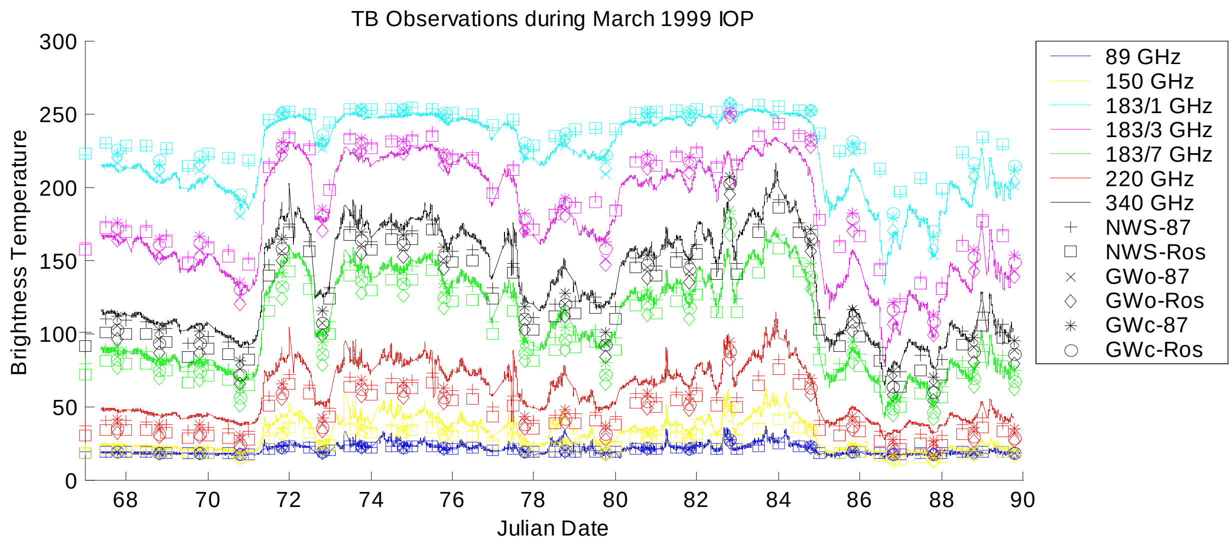

Figure 1. Brightness temperatures measured in Kelvin by the MIR throughout the course of the experiment. Overlaid on the plot are forward modeled TBs based upon radiosonde measurements.

220 GHz, and 340 GHz, the measured TBs are higher than the forward modeled TBs. Thus, the discrepancies between the forward modeled and measured TBs cannot be explained by a simple bias of the radiosonde humidity profile.

Figure 2 shows a time series comparison of TB measurements made by the MIR and CSR instruments. Forward-modeled TBs using Liebe-87 for the original (GWo) and corrected sondes (GWc) are also shown. The MIR and CSR were independently calibrated (Han et al. 2000). The MIR used two internal

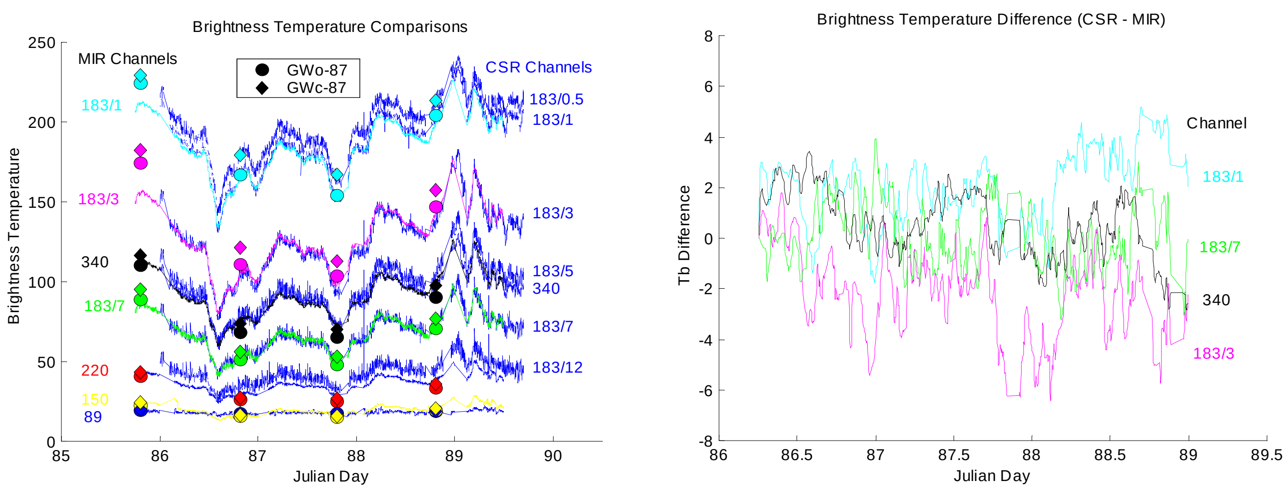

Figure 2. Time series comparison of MIR and CSR measurements. To the left are TB measurements in Kelvin made by the two instruments with forward modeled radiosonde calculations overlaid. To the right are time-averaged (30-minute) differences in measured TBs.

blackbody references to achieve absolute calibration. The CSR used internal references and then tipping-curve calibration to achieve absolute calibration. The average difference between the CSR and MIR TBs (CSR-MIR) for the time period shown are 2.02 K, -2.25 K, 0.18 K, and 0.45 K for the 183 ± 1, 183 ± 3, 183 ± 7, and 340-GHz channels, respectively. The agreement between the two instruments gives a high degree of confidence in the calibration of the radiometer data. Though, the consistency between the measurements is not necessarily representative of their absolute error.

Clear-Air Retrieval Comparisons

Single-channel PWV retrievals were performed for six channels of the MIR data. The retrieval algorithm is based on one described by Jones and Racette (1998). The retrievals were limited for the two periods of predominantly clear conditions. Results are shown in Figure 3. Large discrepancies are observed between the retrieved values. The window channels yield higher values of PWV than those channels near the 183-GHz line. The retrieved values for the 183 ± 1 and 183 ± 3 agree very well for PWV less than ~3 mm. The differences in retrieved PWV are attributed to a combination of errors in the measured TBs and uncertainties in the absorption models.

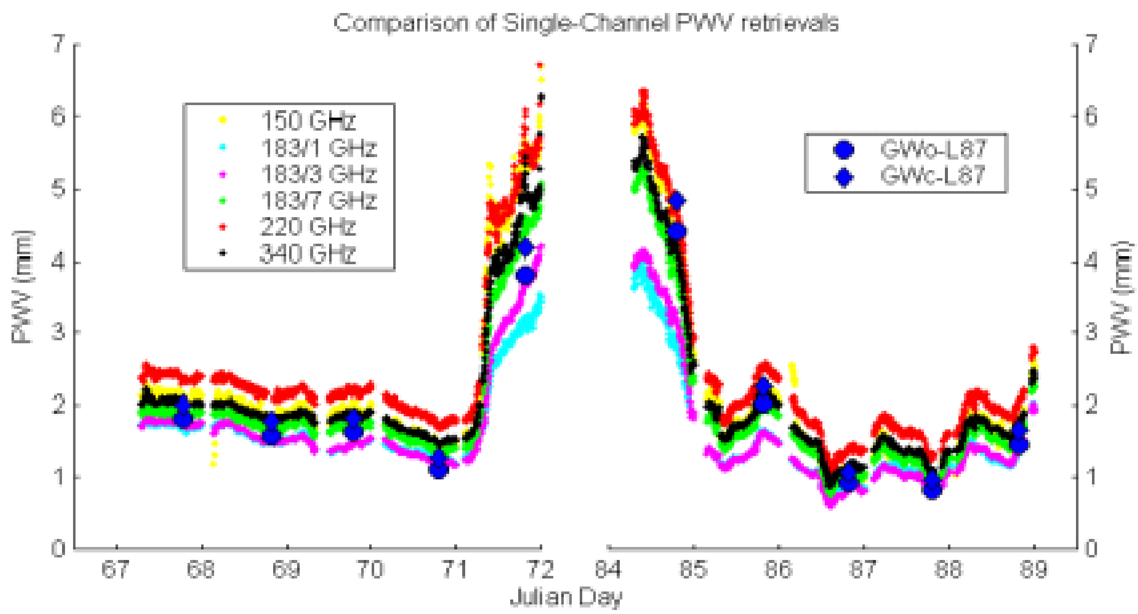

Figure 3. Comparison of single-channel PWV retrievals. Overlaid are PWV measured by Vaisala RS-80 radiosondes.

Discussion

Retrieval of PWV using millimeter-wave radiometric measurements is complicated by the uncertainties in nearly every facet of the analysis. Differences observed between radiosondes are indicative of the uncertainties associated with the radiosonde measurements. Forward-modeled TBs differ when different absorption models are used. Uncertainty in the measurements is small compared to the biases between different forward modeled TBs. The window channels (150 GHz, 220 GHz, and 340 GHz) yield TBs consistently higher than the forward-modeled TBs. In contrast, the 183 ± 1 and 183 ± 3 GHz channels yield TBs consistently lower than the forward-modeled TBs. The differences in the clear-air retrieved PWV are consistent with the differences in the forward-modeled TBs. Further analysis will focus on resolving the discrepancies between the measurements and models.

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