Initial Results from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment

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Abstract-**A multi-instrument radiometric experiment was conducted on the North Slope of Alaska near Barrow, Alaska, during March 9 to April 9 2004. Initial radiometric and radiosonde data from this experiment are presented.**

I. INTRODUCTION

The importance of accurate measurements of column amounts of water vapor and cloud liquid has been well documented [1]. Although several technologies have been investigated to measure these column amounts, microwave radiometers (MWR) have been used operationally by the Department of Energy's Atmospheric Radiation Measurement (ARM) program for passive retrievals of these quantities, which we call precipitable water vapor (PWV) and integrated cloud liquid (ICL). The technology of PWV and ICL retrievals has advanced steadily since the basic 2-channel MWR was first deployed at ARM observation sites [2]. Two important advances are the development and refinement of the tipcal calibration method [2, 3] and improvement of forward-model radiative transfer algorithms [4]. However, the concern still remains that current instruments deployed by ARM may be inadequate to measure low amounts of PWV and ICL. In the case of water vapor, this is especially important because of the possibility of scaling and/or quality control of radiosondes by the water amount [1]. Extremely dry conditions, with PWV less than 3 mm, commonly occur in Polar Regions during the winter months. Accurate measurements of the PWV during such dry conditions are needed to improve our understanding of the regional radiation energy budgets. Reference [5] shows that the strength associated with the 183 GHz water vapor absorption line makes this frequency regime suitable for measuring such low amounts. To investigate the promise of 183 GHz radiometry for measuring low amounts of PWV, an experiment was conducted by the NASA Goddard Space Flight Center (NASA/GSFC) and the NOAA Environmental Technology Laboratory (NOAA/ETL) at the ARM North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) site during March of 1999. The recent experiment (Arctic Winter Water Vapor Intensive Operating Period 2004-WVIOP'04) was an outgrowth of these earlier theoretical considerations and experimental experiences. In addition to quantitative improvement of water vapor measurements at cold temperatures, the data will allow us to evaluate the sensitivity of millimeter-wave window channels to Arctic clouds.

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The WVIOP'04 was conducted at the NSA/AAO field site near Barrow, Alaska, during March 9 to April 9 2004. The major goal was to demonstrate that millimeter wavelength radiometers can substantially improve water vapor observations during the Arctic winter. Secondary goals included forward-model studies over a broad frequency range, demonstration of recently developed calibration techniques, the comparison of several types of *in situ* water vapor sensors, and the application of infrared imaging techniques. During this IOP, radiometers were deployed over a broad frequency range (22.235 to 380 GHz), including several channels near the strong water vapor absorption line at 183.31 GHz. These radiometers were supplemented by frequent radiosonde observations and other *in situ* observations, including several "Snow White" Chilled Mirror radiosondes. The radiometers deployed were also useful for measuring clouds during these cold conditions. Radiometers that were deployed include the Ground-based Scanning Radiometer (GSR) of NOAA/ETL, the MWR and the Radiometric Profiler of ARM, and an infrared cloud imager (ICI) operated by Montana State University. In addition, all of the ARM active cloud sensors (radar and lidars) were operating.

II. INSTRUMENTS DEPLOYED AT THE NSA 2004 ARCTIC WINTER RADIOMETRIC EXPERIMENT

NOAA/ETL designed and constructed a multi-frequency scanning radiometer operating from 50 to 380 GHz. The radiometers are installed into a scanning drum or scanhead (see Figure 1). The Ground-based Scanning Radiometer (GSR) uses the sub-millimeter scanhead with 11-channels in the 50-56 GHz region, a dual-polarization measurement at 89 GHz, 7-channels around the 183.31 GHz water vapor absorption line, a dual-polarized channel at 340 GHz, and three channels near 380.2 GHz. It also has a 10.6 micrometer infrared radiometer within the same scanhead. All of the radiometers use lens antennas and view two external reference targets during the calibration cycle. In addition, each of the radiometers' design includes two internal reference points for more frequent calibration. The GSR instrument is a modification of the CSR that operated at the NSA/AAO site in 1999 [6]. A substantial improvement in radiometer calibration for ground observation in the Arctic environment has been achieved. Based on our experience from the 1999 IOP, a new set of thermally stable calibration targets with high emission coefficients were also designed, constructed, and deployed. The primary use of the instrument is to measure temperature, water vapor, and clouds, at cold (-20 to -55 °C) and dry (PWV < 5 mm) conditions. A schematic of the GSR is shown below in Figure 1. The beam widths of the GSR channels are 1.8 ° and can be averaged to given beam-widths that are consistent with the ARM MWR (4.5 to 5.5 °).

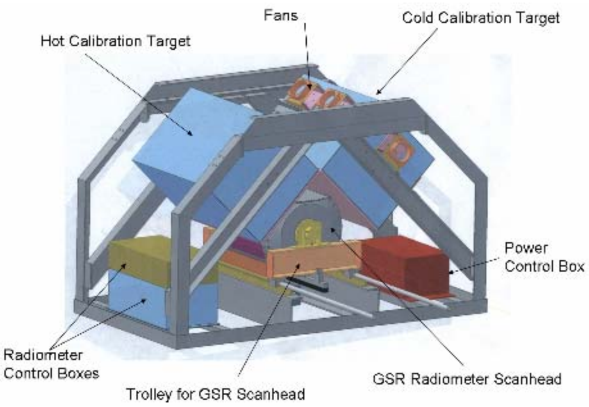

Figure 1. Schematic diagram of the GSR calibration and scanner system. The GSR scanhead periodically moves out of the framework for atmospheric viewing on a trolley system, and shares time observing the atmosphere and the two thermally controlled blackbody reference targets.

In addition, the ARM MWR and the ARM Radiometric Profiler MWPR [7] were also operated. The channels of the MWPR, in addition to providing temperature and humidity profiles, are also useful in forward model studies. A summary of primary instruments that were deployed is shown in Table 1.

Table 1. Instruments deployed during the NSA/AAO Arctic Winter Radiometric Experiment

Platform	Parameters Derived	Frequencies (GHz)
ARM MWR	PWV, ICL	23.8, 31.4 GHz
GSR	PWV	183.31 ± (0.5, ± 1, ± 3, ± 5, ± 7, ± 12, ± 15 GHz)
GSR	T, ICL	50.3, 51.76, 52.625, 53.29, 53.845, 54.4, 54.95, 55.52, 56.025, 56.215, 56.325 GHz
Microwave Profiler	T, PWV, ICL	22.235, 23.035 ,23.835, 26.235, 30.000, 51.250, 52.280, 53.850, 54.940, 56.660, 57.290, 58.800 GHz
GSR	ICL	89 GHz (dual-polarization)
GSR	PWV, ICL	340 GHz (dual-polarization)
GSR	PWV, ICL	380.2 ±4, ±9, ± 17 GHz
Infrared Cloud Imager	Spatial cloud coverage	8-14 microns
GSR	Cloud presence	10 microns
GPS	PWV	
Vaisala RS90 Radiosondes	T, P and ρ profiles	
Chilled Mirror Radiosondes	T, P and ρ profiles	
VIZ Radiosondes	T, P and ρ profiles	

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III. PRELIMINARY DATA

A. *Radiosondes*

During the experiment a number of radiosondes were launched. The ARM Operational Balloon Borne Sounding System radiosondes (BBSS) were launched daily at 2300 UTC at the Great White-the name of the site where basic radiation measurements are taken. These systems used the Vaisala RS90 humidity elements. In addition, at the ARM Duplex, about 1 mile to the north from the Great White, BBSSs were launched four-times daily (500, 1100, 1700, and 2300 UTC). Raw data from synoptic radiosondes from the NWS (1100 and 2300 UTC) were also archived. Finally, during clear conditions, ten dual-sonde launches were conducted at the ARM Duplex. For these releases, five during the day and five during the night, the Chilled Mirror "Snow White" sondes were attached to the same balloon that carried the BBSS sensor. For the month of the experiment, a total of 220 soundings were taken. Figure 2 shows one result when four systems were launched at the same time. We think that the availability of the 220 radiosondes overcomes one of the principal limitations of the 1999 NSA/AAO experiment.

B. *Comparisons of MWR, MWProfiler, and Tb's calculated from BBSS radiosondes*

As discussed above, we launched Vaisala RS90 radiosondes from the ARM Duplex and from the Great White. As a preliminary evaluation of the quality of the data from the radiosondes, the MWR, and the MWProfiler, we compared the T_b data measured by the two radiometers with T_b calculated from the

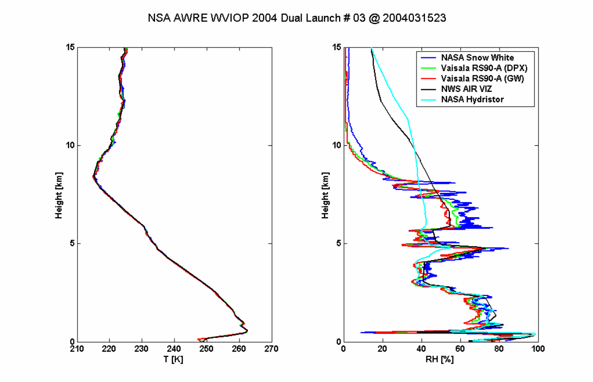

Figure 2. Comparisons of Radiosondes, including dual-sonde launch, on March 15 at 2300 UTC, Barrow, Alaska.

radiosondes, using the absorption algorithm of [12]. The results, shown in Figure 3, are promising.

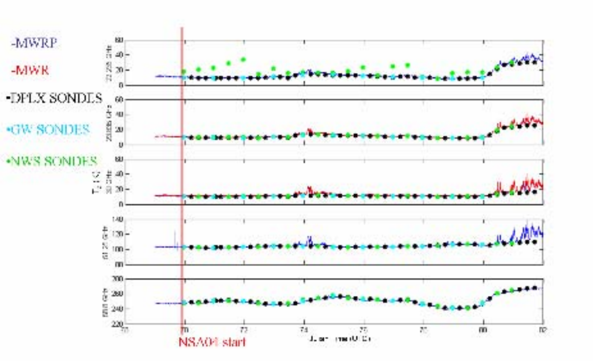

Figure 3. Comparison of T_b measured by ARM radiometers with calculations based on BBSS and NWS radiosondes and the absorption model of [12].

C. Typical target, continuous scan, and air-mass dwell for GSR.

The GSR has a flexible and software programmable angular-scanning sequence that is repeated every two minutes. The sequence starts with the GSR being inside the calibration house and viewing the hot calibration target for 3 seconds. During the next step, the GSR remains in the calibration house and views the cold target, again for 3-seconds. The scanhead then moves out of the calibration house and moves to the atmospheric-scanning position, where it moves from air mass = 3.5 to a sequence of air mass dwells of 2-seconds each (air mass dwells at 3.5, 3.0, 2.5, 2.0, 1.5, 1.0). Between the air mass dwells the radiometer moves continuously to the next scan position. Thus the radiometer acquires both continuous and dwell data for the atmosphere with two-point calibration data in between. For channels in the transparency windows, both 2-point and tipcurve calibration methods can be used. In addition to the external calibration, the radiometer also switches between hot and cold internal calibration loads. Figure 4 shows the calibration sequence of the GSR.

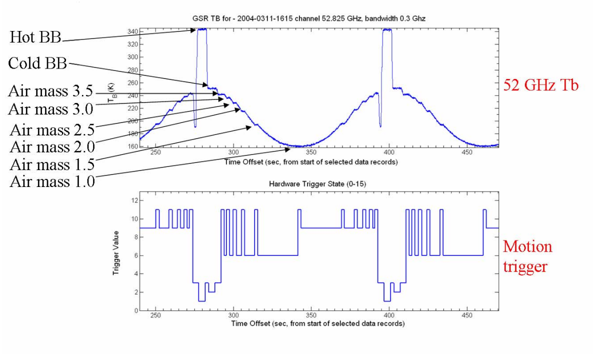

Figure 4. Calibration, dwell, and continuous scanning sequence of the GSR.

D. Sample data from 50-60 GHz channels

As shown in Table 1, the GSR takes data at 11 channels in the 50-60 GHz Oxygen band. In Figure 5, we show a short series of data from these channels taken during the IOP. We note that the strongest channels from 55.5 to 56.3 GHz clearly show the presence of a thermal inversion, i.e., T_b increases with increasing elevation angle. Conversely, the weakest channel at 50.3 GHz will allow tipcurve calibration. For all of the channels, the time spent dwelling at the separate air mass dwell points can be seen.

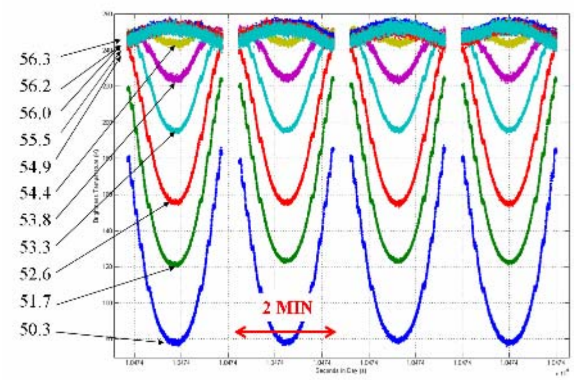

Figure 5. Time series of T_b between 50 and 60 GHz. See Figure 4 for date and time of data.

E. Sample data from 183.31 GHz channels

As shown in Table 1, the GSR takes data at 7 channels around the 183.31 GHz water vapor line. In Figure 6, we show a short series of data taken during the IOP. We note that the strongest channels from 183.31 ±0.5 and ±1 GHz are close to saturation; i.e., T_b is close to the kinetic temperature of the atmosphere. Conversely, the weakest channels from 183.31 ± 15, ±12, and ±7 GHz all will allow tipcurve calibration. Again, for all of these channels, the time spent dwelling at the separate air mass dwell points can be seen.

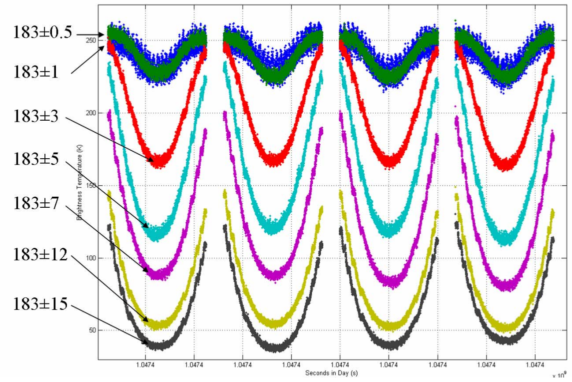

Figure 6. Time Series of T_b for channels around the 183.31 GHz water vapor line. See Figure 4 for date and time of data.

IV. SUMMARY, CONCLUSIONS, AND FURTHER WORK

The WVIOP-04 was conducted from March 9 to April 9, 2004. It is already evident that an exceptionally richdata set of microwave and millimeter wavelength radiometric observations, infrared cloud images, and a comprehensive set of radiosonde observations were taken. Below is a short summary of the relevant observations.

(a) Radiosondes. A total of 220 radiosondes were launched during the 30-day period.
(b) The GSR operated flawlessly during the experiment.
(c) Both the MWR and MWRP operated and produced high quality data.
(d) Both PWV from the MWR and temperature retrievals from the MWRP appear to be of high quality.
(e) The ICI operated continuously and yielded high resolution images of the sky every 2 minutes.
Further information on these data is available at: http://www.etl.noaa.gov/programs/2004/wviop/.

Our analysis plans using the data include:
(a) Careful editing of data to remove outliers and radio frequency interference.
(b) Investigation of calibration algorithms. Calibration opportunities include those using data from hot-cold targets, internal targets, and tip curves for the more transparent channels.
(c) To produce images of multi-channel data. For the GSR data, in which data were taken from a single platform and with a common time stamp, images of time series of these data can be produced. Images of the opacity of transparent channels may also be useful in determining cloud type, i.e., liquid, ice, or mixed-phase.
(d) To conduct forward model studies for clear-sky conditions. The models given in References [4, 7, 8, 9, 10, 11, and 12] will be investigated. We will also derive best fit absorption parameters from the calibrated T_b and radiosonde data.
(f) To conduct profile retrieval analysis. Because of the angular spectrum of multi-frequency radiometer data, the information content of several combinations of data can be analyzed. We will produce vertical profiles of temperature and humidity. Also, because of the multiplicity of radiosondes, many choices of several initial guess profiles are possible.
(g) Multi-sensor cloud studies. Using active remote sensing data from cloud radar and lidar, we will conduct case studies when ice clouds and mixed-phase clouds are present.

REFERENCES

[1] Clough, S. A., et al., 1999: "Effect on the Calculated Spectral Surface Radiances Due to MWR Scaling of Sonde Water Vapor Profiles," *Proc. of 9th Atmospheric Radiation Measurement (ARM) Science Team Meeting*.. [Available online at http://www.arm.gov/docs/documents/technical/conf_9903/index.html.]

[2] Liljegren, J. 2000: "Automatic self-calibration of ARM microwave radiometers," In *Microwave Radiometric Remote Sensing of the Earth's Surface*, P. Pampaloni and S. Paloscia (EDS), VSP2000, 443-441.

[3] Han, Y. and E. R. Westwater, 2000: "Analysis and improvement of tipping calibration for ground-based microwave radiometers," *IEEE Trans. Geosci. Remote Sensing*, **38**, 1260-1275, 2000.

[4] Rosenkranz, P. W., "Water vapor microwave continuum absorption: A comparison of measurements and models," *Radio Sci.*, **33**, pp. 919-928 (1998a). Correction, *Radio Sci.*, **34**, p. 1025 (1999).

[5] Jones, D. C. and P. Racette, (1998): "Ground-based Retrieval of Very Low to High Columnar Integrated Water Vapor Using Combined Millimeter-wave and Microwave observations," *Proc. IGARSS'98*.

[6] Westwater, E. R., P. E. Racette , and D. Cimini, 2001: "The Arctic Winter Millimeter-Wave Radiometric Experiment: Summary, Conclusions, and Recommendations," *Proc. of 11th Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 19-23, 2001 [Available online at http://www.arm.gov/docs/documents/technical/conf_0103/index.html.]

[7] Liljegren, J. C. 2004: "Improved retrievals of temperature and water vapor profiles with a twelve-channel radiometer," *Proc. 8th Symp. Integrated Observing and Assimilation Systems for Atmospheres, Oceans, and land surfaces* (IOAS-AOLS) Seattle, WA, Amer. Met. Soc., 11-15 January 2004.

[8] Liebe, H. J. and D. H. Layton, 1987: "Millimeter wave properties of the atmosphere: laboratory studies and propagation modelling," *NTIA Report 87-24*, 74 pp.

[9] Liebe, H. J. 1989: "MPM, an atmospheric millimeter wave propagation model," *Int. J. Infrared and Millimeter Waves*, **10**, 631-650.

[10] Liebe, H. J., G. A. Hufford, and M. G. Cotton, 1993: "Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000 GHz," in AGARD Conference Proceedings 542, Atmospheric propagation effects through natural and man-made obscurants for visible through MM-wave radiation, pp. 3.1 to 3.10, Available from NASA Center for Aerospace Information, Linthicum Heights, MD, 1993.

[11] Delamere, J. S., S. A. Clough, E. J. Mlawer, S. Boukabara, K. Cady-Peirera, and M. Shepard, 2002: "An update on Radiative Tranfer Model Development at Atmospheric and Environmental Research, Inc.," Proc. of 12th ARM Science Team Meeting, 2002. [Available on line at http://www.arm.gov/publications/proceedings/conf12/extended_abs/delamere-js.pdf]

[12] Rosenkranz, P. W., Private communication, 2004.