Final Report on “Microwave and Millimeter-Wave Radiometric Studies of Temperature, Water Vapor, and Clouds”

Project ID: *0011106*

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Overview of Project

The importance of accurate measurements of column amounts of water vapor and cloud liquid has been well documented by scientists within the Atmospheric Radiation Measurement (ARM) Program. At the North Slope of Alaska (NSA), both microwave radiometers (MWR) and the MWRProfiler (MWRP), been used operationally by ARM for passive retrievals of the quantities: Precipitable Water Vapor (PWV) and Liquid Water Path (LWP). However, it has been convincingly shown that these instruments are inadequate to measure low amounts of PWV and LWP. In the case of water vapor, this is especially important during the Arctic winter, when PWV is frequently less than 2 mm. For low amounts of LWP (< 50 g/m^2), the MWR and MWRP retrievals have an accuracy that is also not acceptable. To address some of these needs, in March-April 2004, NOAA and ARM conducted the NSA Arctic Winter Radiometric Experiment - Water Vapor Intensive Operational Period at the ARM NSA/Adjacent Arctic Ocean (NSA/AAO) site. After this experiment, the radiometer group at NOAA moved to the Center for Environmental Technology (CET) of the Department of Electrical and Computer Engineering of the University of Colorado at Boulder. During this 2004 experiment, a total of 220 radiosondes were launched, and radiometric data from 22.235 to 380 GHz were obtained. Primary instruments included the ARM MWR and MWRP, a Global Positioning System (GPS), as well as the CET Ground-based Scanning Radiometer (GSR). We have analyzed data from these instruments to answer several questions of importance to ARM, including: (a) techniques for improved water vapor measurements; (b) improved calibration techniques during cloudy conditions; (c) the spectral response of radiometers to a variety of conditions: clear, liquid, ice, and mixed phase clouds; and (d) forward modeling of microwave and millimeter wave brightness temperatures from 22 to 380 GHz. Many of these results have been published in the open literature. During the third year of this contract, we participated in another ARM-sponsored experiment at the NSA during February-March 2007. This experiment is called the Radiative Heating in Underexplored Bands Campaign (RHUBC) and the GSR was operated successfully for the duration of the campaign. One of the principal goals of the experiment was to provide retrievals of water vapor during PWV amounts less than 2 mm and to compare GSR data with ARM radiometers and radiosondes. A secondary goal was to compare the radiometric response of the microwave and millimeter wavelength radiometers to water and ice clouds.

In this final report, we will include the separate progress reports for each of the three years of the project and follow with a section on major accomplishments of the project.

2005 Progress report on “Microwave and Millimeter-Wave Radiometric Studies of Temperature, Water Vapor, and Clouds”

2005-1. Data cleaning and outlier removal

We have analyzed the 30 days of data taken at the NSA/AAO in March-April 2004, including data cleaning and calibration of the GSR data. This includes removal of radio frequency interference and taking into account beginning and end points of discrete scanned data. We now have at our disposal a data set that includes the GSR, MWR, and MWRP, all interpolated to a basic time interval of about 1 min. In addition to editing by visual inspection of time series of all data, we have also developed a statistical method for flagging potential outliers and removing them if appropriate. An example of the application of our statistical quality control method is shown in Figure 1.

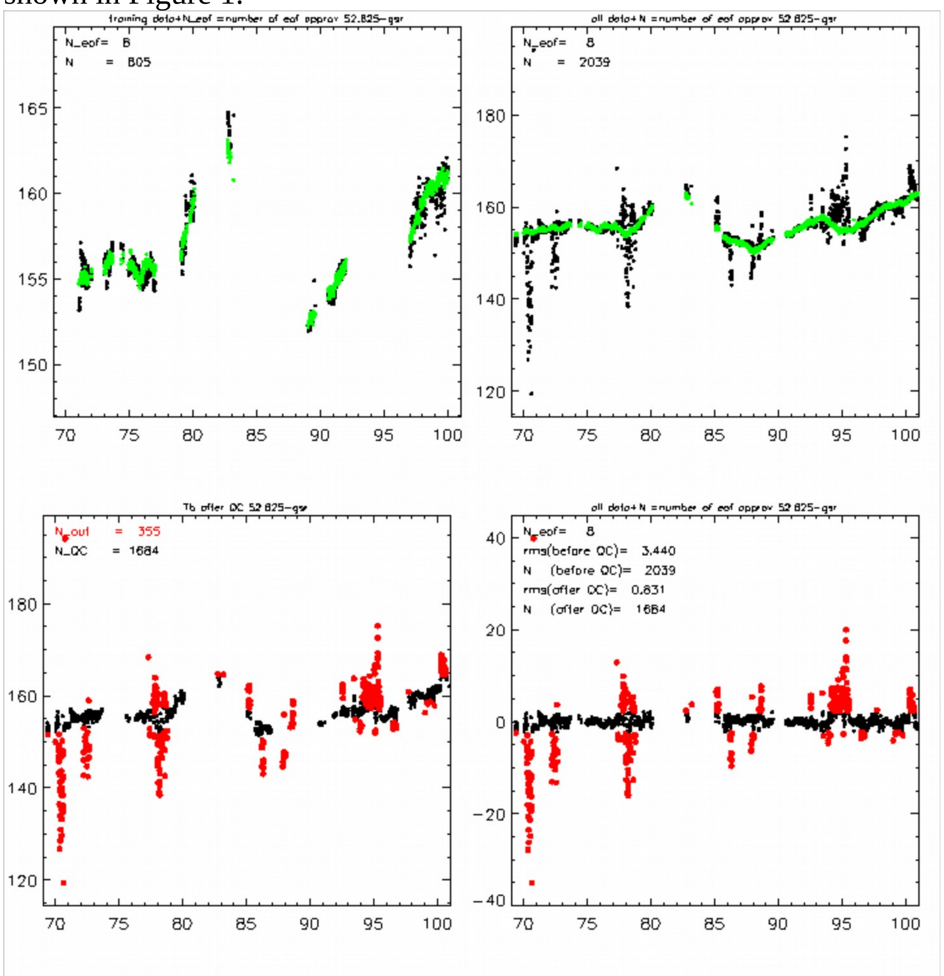


Figure 1. Quality Control of clear data at 52.625 GHz. Top_left. Training set used to develop eof’s and regression coefficients. Top_right. All clear data with eof predictions. Bottom_left. QC data-black, outliers-red. Bottom_right Difference plot with statistics.

2005-2. GSR Calibration

Because of the flexibility of the GSR data acquisition system, we have developed and compared several calibration alternatives. During a single scan from horizon to horizon, the GSR performs a dwell at six air masses (1, 1.5, 2, 2.5, 3, and 3.5) and two external targets while giving continuous data over the rest of the scan. In addition, the radiometer is electronically switched between two internal calibration targets on a rapid basis. Thus, the GSR is calibrated continuously during all sky conditions, even when tipcals are not possible, because of lack of horizontal stratification. Our results on calibration methods were presented at the 2005 ARM Science Team Meeting (ARM_STM_05) by Cimini et al. [1] and examples of our calibrated data are shown in Figure 2.

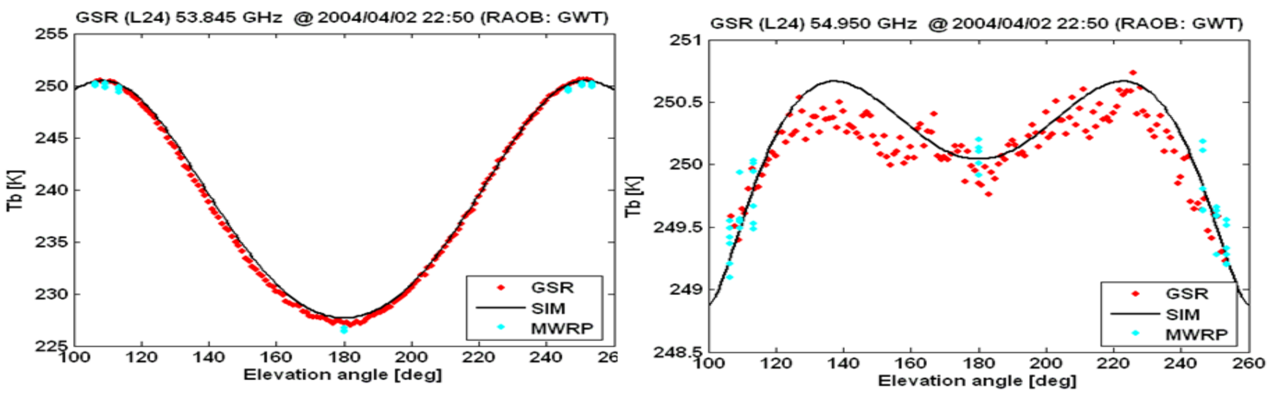


Figure 2. Comparison between simulated and measured Tbs during elevation scans. The black line indicates the simulations based on radiosonde observations, while red and cyan dots represent simultaneous GSR and MWRP measurements, respectively.

Publications

[1] Cimini, D., A. J. Gasiewski, M. Klein, E. R. Westwater, V. Leuski, and S. Dowlatshahi: Ground-based Scanning Radiometer Measurements during the Water Vapor IOP 2004: a valuable new data set for the study of the Arctic atmosphere. Proc. of the 15th. ARM Science Team Meeting, Daytona Beach, FL, March 14-18 2005.

2005-3. Millimeter Wavelength clear-sky forward model comparisons

Using calibrated GSR-data and Vaisala RS90 radiosonde data, we have compared clear-sky forward model calculations based on five contemporary models. Preliminary results from these comparisons were given at the ARM_STM_05 by Westwater et al. [2] and at the November 2-4, 2005 meeting of the ARM Instantaneous Radiative Flux Working Group. An example of these calculations is shown in Figure 3.

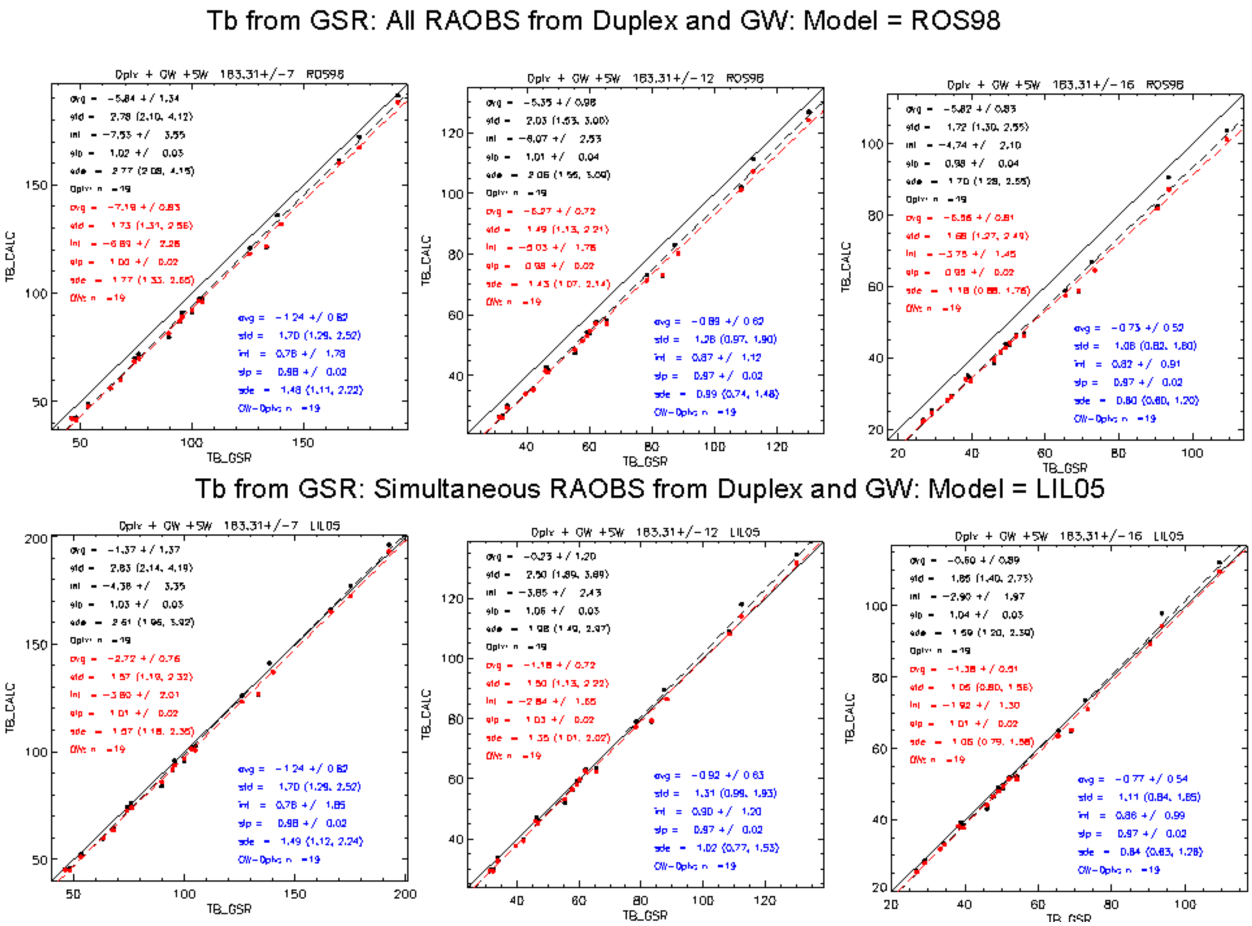


Figure 3. Comparison of forward model calculations based on Rosenkranz 1998 (upper three panels) and Liljegren 2005 (lower three panels) with GSR measurements. The GSR measurements are all calibrated by a combination of internal and external targets as well as by the tipcal method.

Finally, a paper describing the 1999 IOP was published by Racette et al;. [3].

Publications

[2] Westwater, E. R., D. Cimini, V. Mattioli , M. Klein, V. Leuski, A. J. Gasiewski, S. Dowlatshahi, J. S. Liljegren , B. M. Lesht and J. A. Shaw Microwave and Millimeter Wave Forward Modeling Results from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment Proc. of the 15th. ARM Science Team Meeting, Daytona Beach, FL, March 14-18 2005.

[3] Racette, Paul E. Ed R. Westwater, Yong Han, Albin J. Gasiewski, Marian Klein, Domenico Cimini, David C. Jones, Will Manning, Edward J. Kim, James R. Wang, Vladimir Leuski, Peter Kiedron: Measurement of Low Amounts of Precipitable Water Vapor Using Ground-Based Millimeterwave Radiometry, *J. Atmos. Ocean. Tech*., Vol. 22, No. 4, pp. 317 - 337, April 2005.

2005-4. Analysis of Radiosondes launched during the 2004 Arctic Winter Radiometric Experiment

Several radiosonde packages were deployed during the experiment: Vaisala RS90 radiosonde launched at the ARM duplex and at the Great White, and Sippican VIZ-B2 radiosondes operated by the National Weather Service. In addition, eight dual-radiosonde launches were conducted at the ARM duplex, with Vaisala RS90 and Sippican GPS Mark II carried on the same balloon. This last radiosonde was modified to include a Meteolabor "Snow White" chilled mirror humidity sensor. Analyses of the temperature and relative humidity measured by those radiosondes have been made. Comparisons between temperature measurements have shown a bias in night-time temperature soundings between the VIZ-B2 and the RS90, which reached about 5ºC at 20 hPa (see Figure 4).

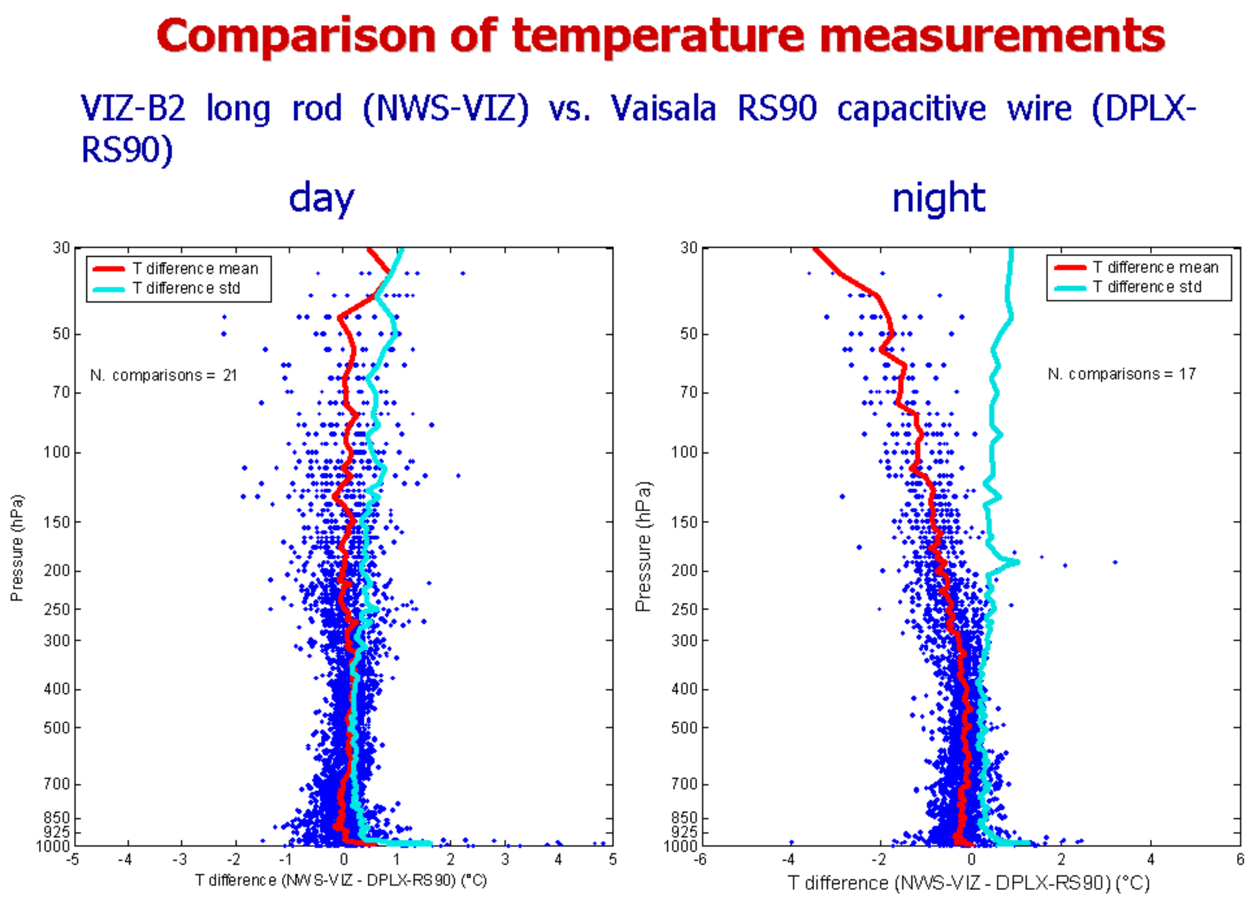


Figure 4. Temperature difference profiles between the NWS-VIZ radiosondes and the DPLX-RS90. (Left) Dataset taken at night (at 1100 UTC, 2 a.m. local time); (right) dataset taken during the day (at 2300 UTC, 2 p.m. local time). After Mattioli et al. [4,5].

Relative humidity comparisons have indicated good agreement between the RS90 and the chilled mirror. Conversely, large differences of the order of 20%, for upper-tropospheric and lower-stratospheric humidity, were found in the comparison of the VIZ-B2 and the Mark II carbon hygristors with both the RS90 and the chilled mirror (See Figure 5). These results, which have implications for ARM and for the long-term climate records at Barrow, were presented at the ARM_STM_05 (Mattioli et al., [4]), at the International TOVS Study Conference 2005 (Cimini et al., [6]), and have now been published in the open literature (Mattioli et al., [5]).

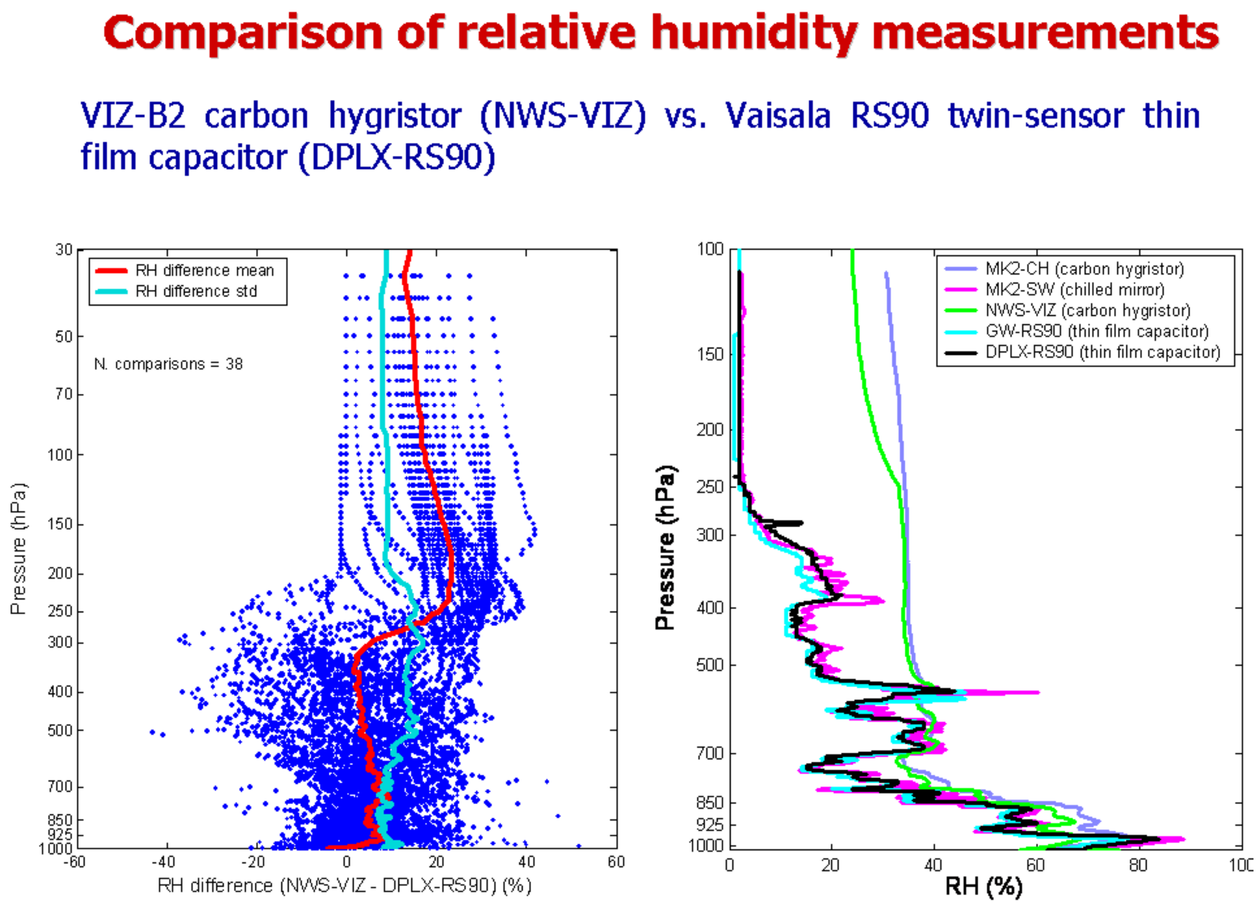


Figure 5. Left: RH difference profiles between the NWS-VIZ radiosondes and the DPLX-RS90, the comparison performed for the entire dataset. Right: Comparison of five simultaneous humidity soundings. After Mattioli et al. [4,5].

Publications

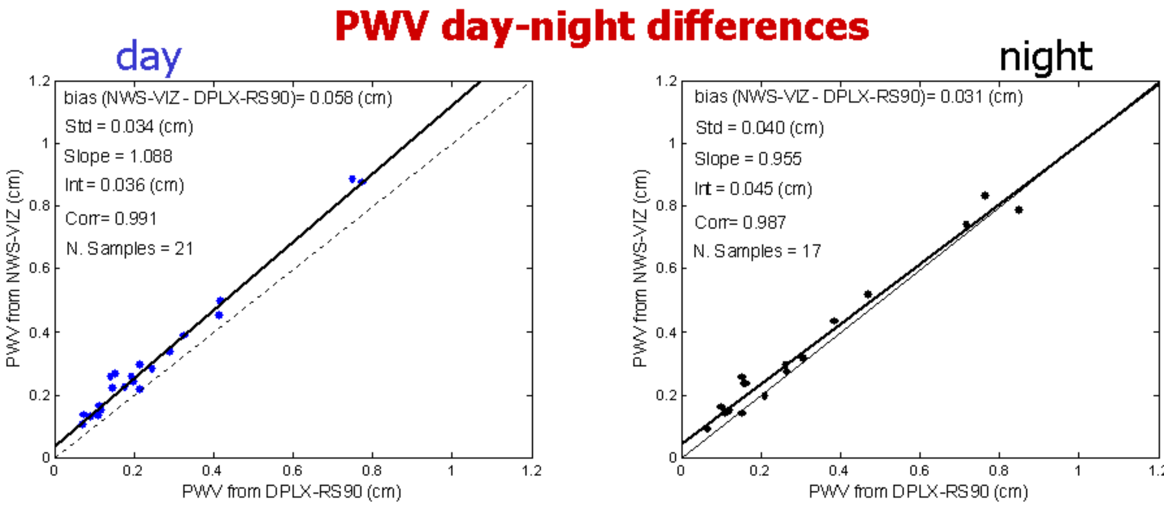
[4] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. Gutman, and F. Schmidlin, “Analysis of Radiosonde and PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment,” Proc. of the 15th. ARM Science Team Meeting, Daytona Beach, FL, March 14-18 2005.

[5] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin(2007a): “Analysis of Radiosonde and ground-based remotely sensed PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment” *Journal of Atmospheric and Oceanic Technology*, Vol. 24, March 2007, pp. 415-431.

[6] Cimini D., E.R. Westwater, V. Mattioli, A.J. Gasiewski, M. Klein, F. Romano, and V. Cuomo, Analysis of radiosonde measurements by ground- and satellite-based simultaneous observations during the Water Vapor IOP 2004 experiment, Proceeding of 14th International TOVS Study Conference, May, 2005.

2005-5. Analysis of PWV measurements during the 2004 Arctic Winter Radiometric Experiment

Remote sensing data were also used to examine the validity of the radiosondes. Comparisons in PWV have been made between data taken by the ARM MWR and MWRP, a GPS receiver, and each of the various radiosonde types. Diurnal differences have also been investigated. In general, the VIZ-B2 and the Mark II radiosondes measured higher values of PWV with respect to the RS90 and the Snow White, and with respect to the remote sensors. Good agreement on the order of 0.034 cm rms was found between the dual-channel radiometer and the profiler, when the five K-band channels were used for the PWV retrievals. Generally good agreement was also found between the radiometers and the GPS, although both near real-time and reprocessed PWV data were affected by a substantial scatter compared to the radiometers and the radiosondes. A typical result is shown in Figure 6.



	DPLX-RS90		NWS-VIZ		GW-RS90
	day	night	day	night	day
MWR	Bias=0.045 Slope=1.065 Int=0.027 Samples= 27	Bias=0.020 Slope=0.947 Int=0.037 Samples= 26	Bias=-0.019 Slope=0.954 Int=-0.005 Samples= 23	Bias=-0.009 Slope=0.978 Int=-0.001 Samples= 19	Bias=0.048 Slope=1.077 Int=-0.025 Samples= 25
GPS	Bias=0.081 Slope=1.021 Int=0.075 Samples= 30	Bias=-0.0004 Slope= 0.936 Int=0.025 Samples= 28	Bias=0.009 Slope=0.891 Int=0.047 Samples= 24	Bias=-0.038 Slope=0.954 Int=-0.021 Samples= 20	Bias=0.025 Slope=1.097 Int=-0.005 Samples= 26
MWRP	Bias=0.022 Slope=1.075 Int=0.001 Samples= 29	Bias=0.006 Slope=0.933 Int=0.024 Samples= 23	Bias=-0.037 Slope=0.966 Int=-0.026 Samples= 23	Bias=-0.035 Slope=0.867 Int=0.003 Samples= 17	Bias=-0.092 Slope=1.111 Int=0.058 Samples= 26

Figure 6. Comparison of Radiosonde and Remote Sensor diurnal differences in PWV measurements. After Mattioli et al. [4,5].

Publications

[4] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. Gutman, and F. Schmidlin, "Analysis of Radiosonde and PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment," Proc. of the 15th. ARM Science Team Meeting, Daytona Beach, FL, March 14-18 2005.

[5] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin: "Analysis of Radiosonde and ground-based remotely sensed PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment" *Journal of Atmospheric and Oceanic Technology*, Vol. 24, March 2007, pp. 415-431.

2005-6. Measurements of Water Vapor during Arctic Conditions

We have conducted preliminary comparisons of the response of MWR, MWRP and GSR channels to water vapor content during the coldest and driest of the conditions that we encountered. The comparisons indicated greatly enhanced sensitivity to water vapor in the 0.8 to 8.0 mm region of PWV. Depending on the channel, this sensitivity can be 50 times as great as that of the MWR to these changes. Figure 7 and Table 1 show selected results that were presented at the November 2-4, 2005 ARM Instantaneous Radiative Flux Working Group meeting.

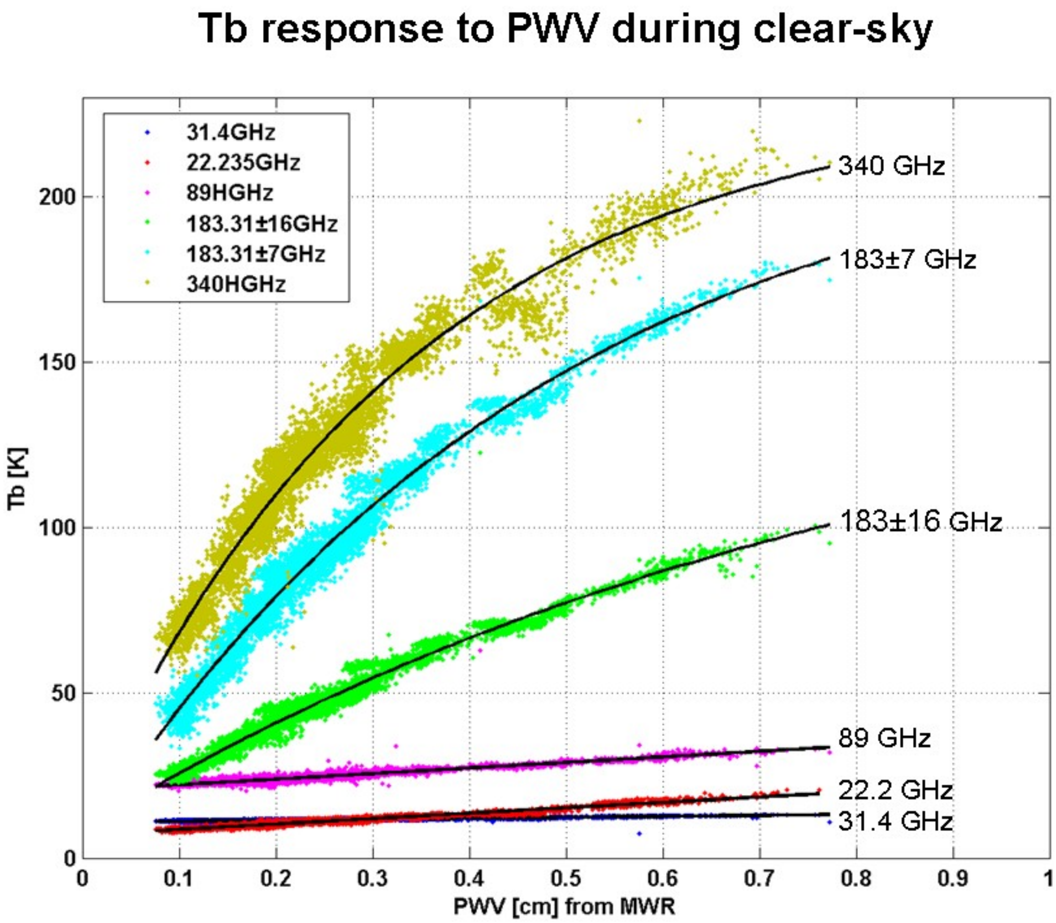


Figure 7. Response of several transparent window channels to PWV, as measured by the MWR. After Cimini et al. [18,20].

PWV sensitivity for MW- and mm-wave channels (PWV<1.5 mm)

After Racette et al.*		WVIOP2004 (measured)	
f(GHz)	S_{sim}(K/mm)	S_{meas}(K/mm)	99%CI(K/mm)
23.8	1.25	1.28	0.05
31.4	0.34	0.29	0.07
89.0	1.81	1.84	0.21
150.0	6.95	NA	NA
183.3±1	78.60	87.13	3.93
183.3±3	75.00	68.04	3.04
183.3±7	39.20	31.78	1.94
183.3±16	NA	13.84	0.69
220.0	14.60	NA	NA
340.0	44.50	42.04	2.36
0.5<PWV<1.5 mm		0.8<PWV<1.5 mm	

*simulations based on Rosenkranz 1998 model

Table 1. Theoretical and measured response of several microwave and millimeter wave channels to low amounts of PWV. After Cimini et al. [18,20].

2005-7. Measurements of Cloud Liquid during Arctic Conditions

We have conducted preliminary comparisons of the response of MWR, MWRP and GSR channels to liquid water during our experiment. We focused on GSR channels that are close to the 89 and 150 GHz radiometers that ARM is purchasing. The comparisons indicated greatly enhanced sensitivity to Liquid Water Path in the 0.1 to 0.5 mm region of LWP. This sensitivity is some 3 to 4 times as great as that of the MWR to these changes. Figure 9 and Table 2 show selected results that were presented at the November 2-4, 2005 ARM Cloud Working Group meeting. The type of improvements in sensitivity to cloud liquid from higher frequency window channels is shown in this figure. Here we plot δTb ≡ Tbcloudy-Tbclear as a function of LWP derived from the MWR. First, from the slopes of the derived regression lines, it is clear that there is large increase in sensitivity of 89/183.31±16 relative to 22 and 30 GHz. However, there is increased scatter in the GSR data: at least three things contribute: (1) uncertainty in LWP from the MWR, especially at the very lowest levels of LWP. (2) errors in subtracting PWV from the total signal; (3) the GSR samples only 1-sec at zenith every 2 minutes, because of its continuous scan and internal calibration switching. However, it is encouraging that the intercepts of all of the curves approach zero.

We also have started to investigate the response of the channels to Ice Water Path (Dowlatshahi et al., 2005)

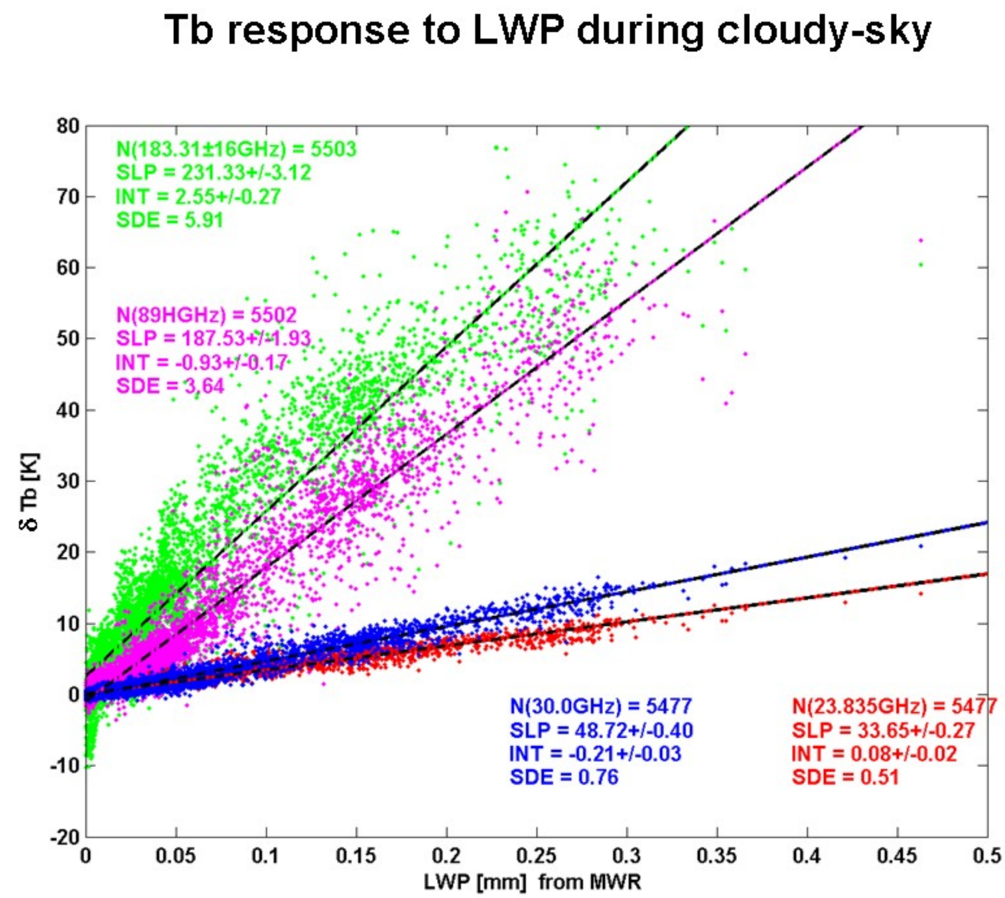


Figure 8. Response of several transparent window channels to LWP as measured by the MWR. After Cimini et al. [18,20].

LWP sensitivity for MW- and mm-wave channels
(0.0<LWP<0.5 mm)

f(GHz)	Slope(K/mm)	99%CI(K/mm)	Intercept(K)	99%CI(K)
22.235	28.34	0.32	0.34	0.03
23.035	32.79	0.30	0.27	0.03
23.8	32.28	0.08	0.14	0.01
23.835	33.65	0.27	0.08	0.02
26.235	39.85	0.35	-0.11	0.03
30.0	48.72	0.41	-0.21	0.03
31.4	55.61	0.08	0.14	0.01
89 H	187.53	1.93	-0.93	0.17
89 V	187.89	1.92	-0.82	0.16
183±16	231.33	3.12	2.55	0.27
183±12	195.61	3.25	2.89	0.28
183±7	95.39	4.40	1.78	0.38

Table 2. Measured response of several microwave and millimeter wave channels to low amounts of PWV. After Cimini et al. [18,20].

Publications
[7] Dowlatshahi, S.G., A.J. Gasiewski, T. Uttal, M. Klein, E.R. Westwater, and D. Cimini, Detection of Arctic Cloud Ice Properties Using Submillimeter-wave Radiometers, Proc. of the 8th Conference on Polar Meteorology and Oceanography, 85th AMS Annual Meeting, January, 2005.

[18] Cimini, E. R. Westwater, A. Gasiewski, M. Klein, V. Leuski, J. Liljegren, Ground-based millimeter- and submillimiter-wave observations of low vapor and liquid water contents, *IEEE Transaction on Geosciences and Remote Sensing*, **Vol. 45, No. 7**, Part II. July 2007, pp.2169-2180.

[20] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leuski, and J.C. Liljegren, "Millimeter- and submillimeter-wave Observations of Low Vapor and Liquid Water Amounts in the Arctic Winter". Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006D.

2005-8. Instrument development

In the third year of our effort, we will deploy the GSR either at the SGP or at Barrow. We thus are continuing to improve the instrument for this deployment.

1 380 GHz radiometer. Two frequency channels were added: a 380.6 GHz channel with a 200MHz frequency bandwidth and a 381.7 GHz channel with a 500 MHz frequency band.
2 A radiometer at 31-32 GHz is under development. This will be a super heterodyne receiver with Low Noise Amplifier in the front end. The radiometer will have a 9 deg beam width lens-horn antenna. A ferrite switch with an ambient-temperature reference load and a noise diode will be used for radiometer calibration. The radiometer has three frequency channels: 31-32 GHz, 31.4GHz with 200 MHz frequency band width, and 31.65 with 300 MHz band width. The estimated receiver SSB noise temperature is 440 K. During November 2005, an antenna, electronic, and microwave components were purchased, tested, and assembled. The radiometer base board, enclosure, and details for electronic component support were manufactured. Wiring and complete radiometer assembly is under development.

3 A five-channel radiometer at 18.6-24 GHz is under development. This is a direct detection receiver with a low noise transistor amplifier and detector. A lens-horn antenna with 8.5 degree beam width will be deployed. A ferrite switch with ambient-temperature reference load and noise diode will be used for the radiometer calibration. The radiometer has 5 frequency channels: 18.6-18.8 GHz, 21.3-21.6 GHz, 22.135-22.335GHz, 22.9-23.1GHz, 23.6-24GHz. The estimated receiver Single Side Band noise temperature is 360 K. During November 2005, electronic and microwave components were purchased, tested, and assembled. The antenna is being manufactured. The radiometer base board, enclosure, and supporting details were produced.

2005-9. Cloud Intercomparison Experiment

We participated in the 2003 Cloud Intercomparison Experiment that was held at the SGP Central Facility in February-March 2003. Brightness temperatures computed from five absorption models and radiosonde observations were analyzed by comparing them with measurements from three microwave radiometers at 23.8 and 31.4 GHz. The radiometers were calibrated using two procedures, the so-called instantaneous “tipcal” method and an automatic self-calibration algorithm. Measurements from the radiometers were in agreement, with less than a 0.4-K difference during clear skies, when the instantaneous method was applied. Brightness temperatures from the radiometer and the radiosonde showed an agreement of less than 0.55 K when the most recent absorption models were considered. Precipitable water vapor (PWV) computed from the radiometers were also compared to the PWV derived from a Global Positioning System station that operates at the ARM site. The instruments agree to within 0.1 cm in PWV retrieval. These results were published in the open literature by Mattioli et al. [8].

Publications

[8] Mattioli ,V., Ed R. Westwater, Seth I. Gutman, and Victor R. Morris,": Forward Model Studies of Water Vapor using Scanning Microwave Radiometers, Global Positioning System, and Radiosondes during the Cloudiness Inter-Comparison Experiment", *IEEE Transactions on Geoscience and Remote Sensing* Vol. 43, issue 5, May 2005, pp.1012-1021.

2005-10. Additional activities

We also contributed articles in cloud research (Zuidema et al, [9]), atmospheric profiling (Cimini et al.,[26]and [27]; Bianco et al., [28]), Numerical Weather Prediction model evaluation (Memmo et al., [30]), passive ground-based measurement of rainfall (Marzano et al., [29]), and to a widely circulated overview on Radiometry (Westwater et al, [10]).

Publications

[9] Zuidema, Z., C. Fairall, E. Westwater, D. Hazen, "Ship-based liquid water path estimates in marine stratus, *J. Geophys. Res.*,**110, D20206,** dor:10:1029/2005/2005JD005833,2005

[10] Westwater, Ed. R.,Susanne Crewell, and Christian Matzler, "Surface-based Microwave and Millimeter wave Radiometric Remote Sensing of the Troposphere: a Tutorial", *IEEE Geoscience And Remote Sensing* Newsletter, March 2005, **16-33**. ISSN 0161-7869.

[26] Cimini D., T. J. Hewison, and L. Martin, Comparison of brightness temperatures observed from ground-based microwave radiometers during TUC, Meteorologische Zeitschrft, 2005..

[27] Cimini D., T. J. Hewison, L. Martin, J. Güldner, C. Gaffard, and F. Marzano, Temperature and humidity profile retrievals from ground-based microwave radiometers during TUC, Meteorologische Zeitschrft, 2005.

[28] Bianco, L., D. Cimini, F. S. Marzano, and R. Ware, Combining Microwave Radiometer and Wind Profiler Radar Measurements for High-Resolution Atmospheric Humidity Profiling, Journal of Atmospheric and Oceanic Technology, Vol. 22, pp. 949-965, July 2005.

[29] Marzano F. S., D. Cimini, P. Ciotti, and R. Ware: Modeling and Measurement of Rainfall by Ground-based Multispectral Microwave Radiometry, IEEE Transactions on Geoscience and Remote Sensing, Vol. 43, n. 5, pp. 1000-1011, May 2005.

[30] Memmo, A., E. Fionda, T. Paolucci, D. Cimini, R. Ferretti, S. Bonafoni, and P. Ciotti: Comparison of MM5 Integrated Water Vapor with Microwave Radiometer, GPS, and Radiosonde Measurements, IEEE Transactions on Geoscience and Remote Sensing, Vol. 43, n. 5, pp. 1050-1058, May 2005.

PLANS FOR 2006

We plan to investigate how tipcal can be improved by deriving the mean radiating temperature for the GSR channels from the temperature and humidity retrievals from the MWRP. This improvement in accuracy will allow us to use tipcal on increasingly more opaque channels.

After our calibration and data cleaning on all GSR channels is complete, we will submit a final data set to the ARM archive that includes brightness temperature at all of our air mass dwell angles.

We will investigate retrieval methods using the GSR data to derive temperature and humidity profiles, as well as improved estimates of LWP. We will also investigate the combined use of active-passive retrievals to derive profiles of cloud liquid density. Our retrieval methods will be physical in the sense that radiative transfer models will be used in each step of the retrieval process. We also will investigate the information content of angular vs. zenith-only measurements.

During our research into the use of the MWR and the MWRP, we found several differences in the estimation of PWV and LWP from estimates based on each of the instruments. We plan to perform both calibration and forward model studies to analyze the problem. This is especially important, because some of the PWV and LWP retrievals are the best source of “ground truth” for our GSR data.

We will investigate the effect of scattering from both liquid and ice clouds on our data. Theoretically, we will perform calculations using a state-of-the-art radiative transfer model. With our data, we will continue to use the MMCR to derive ice parameters, and to help identify data types: pure liquid, pure ice, and mixed phase.

We plan to present our results at the 2006 Microwave Radiometry Conference to be held in San Juan, Puerto Rico, and to develop open literature papers based on these presentations. We are presenting two invited talks at this meeting.

We plan to complete the development of the three-channel radiometer the in the 31-32 GHz band, and to complete the 5-channel 18.6-24 GHz radiometer. Final testing of these radiometers will be done.

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2006-1. GSR Final Calibration and Delivery of Data to ARM

The GSR has a very flexible data acquisition system that allows several calibration alternatives. During a single scan from horizon to horizon, the GSR performs a dwell, on both sides of zenith, at six air masses (1, 1.5, 2, 2.5, 3, and 3.5) while giving continuous data over the rest of the scan. At the end of the scan, the GSR moves into a calibration shelter where it observes two external blackbody targets. In addition, depending on the frequency band, the radiometer is electronically or mechanically switched between two internal calibration targets on a rapid basis. In addition, atmospheric conditions permitting, tipcal calibrations can also be used. Thus, the GSR is calibrated continuously during all sky conditions, even when tipcals are not possible. During this year, we refined our calibration method, applied it to the 30 days of GSR data, and delivered a recalibrated data set to the ARM data archives. In addition, we prepared a paper that is now published in the open literature (Cimini et al., [11]). Examples of our calibrated data are shown in Fig. 1.

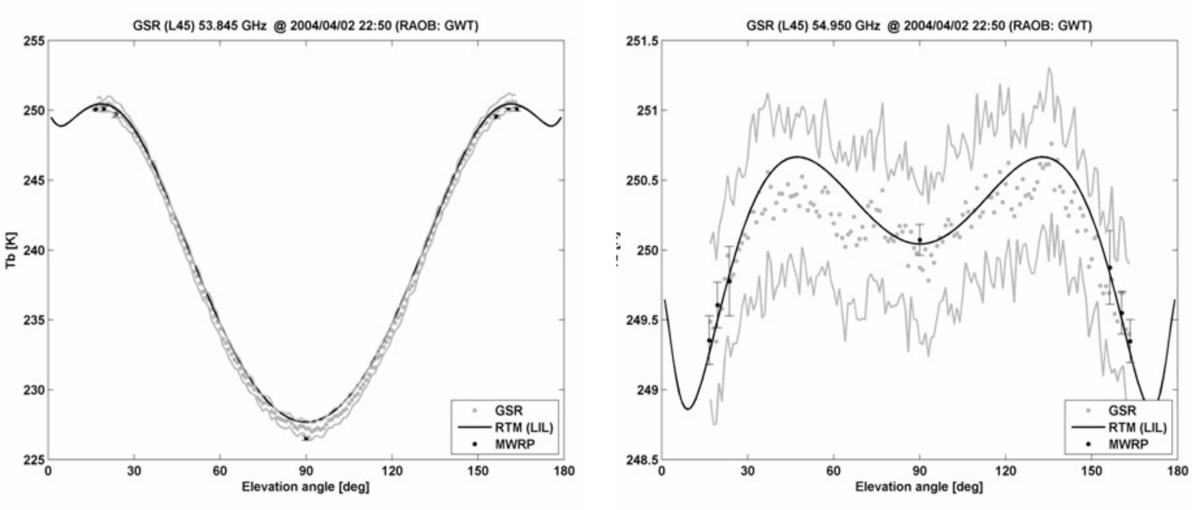

Fig. 1. Comparison of simulated and measured Tb for elevation scan. Only the two GSR channels that overlap in requency with two MWRP channels are shown. The black line indicates the simulations (absorption model in Liljegren et al, 2005) based on the RAOB launched on 2004/04/02 at 2300 UTC, while grey and black dots represent simultaneous GSR and MWRP measurements. Also, std of MWRP and GSR measurements during the first 30 min of the balloon ascent are shown with black bars and grey solid line, respectively. [After Cimini et al., 2006A].

After Cimini et al., [11].

Publications

[11] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leusky, and J. C. Liljegren, „The Ground-based Scanning Radiometer (GSR): a powerful tool for the study of the Arctic Atmosphere", *IEEE Transaction on Geosciences and Remote Sensing*, **Vol. 45, No. 9**, September 2007, pp. 2759-2777

[12] Westwater, E. R, D. Cimini, V. Mattioli ,A. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren, "The 2004 North Slope Of Alaska Arctic Winter Radiometric Experiment: Overview And Highlights", Proc. MicroRad'06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico. pp. 247-251, http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[13] Westwater, E. R., D. Cimini, V. Mattioli ,A. J. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren, "The 2004 North Slope of Alaska Arctic Winter Radiometric Experiment: Overview and Recent Results", Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

2006-2. Millimeter Wavelength clear-sky forward model comparisons

Using the recalibrated GSR-data and Vaisala RS90 radiosonde data, we have compared clear-sky forward model calculations based on five contemporary models. These results of these comparisons were given at MicroRad'06 (Westwater et al.,[12]), at the ARM_STM_06 by Westwater et al. [13], and at the ITSC-15 (Westwater et al., [14]). An example of these calculations is shown in Fig.2.

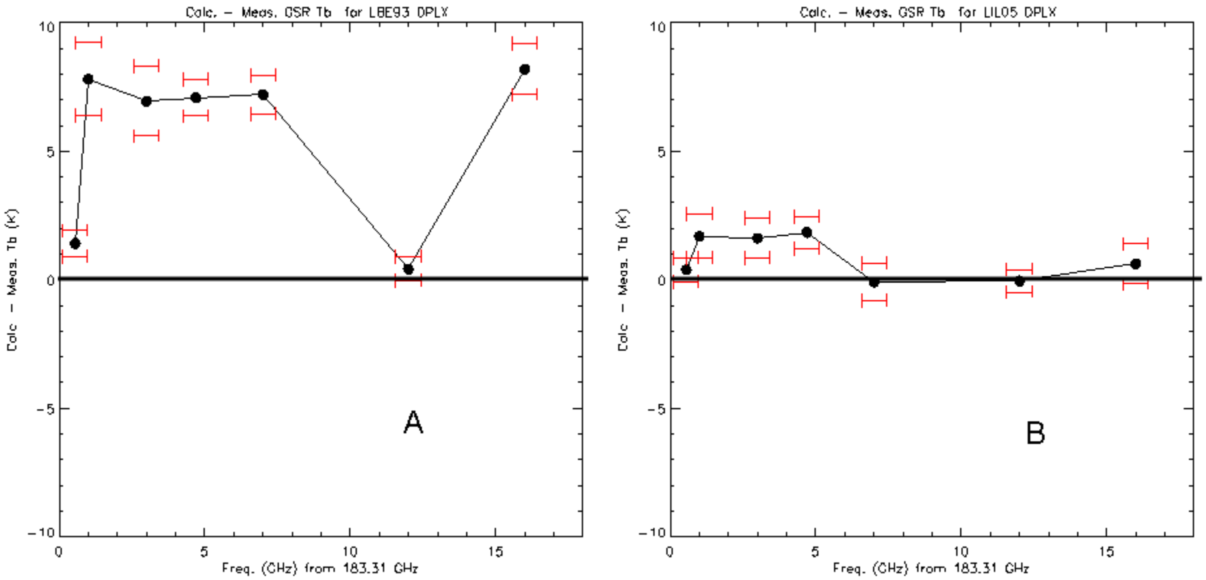

Fig. 2. Comparison of recalibrated GSR Tb data near 183.31 GHz vs. two contemporary absorption models. (A) Forward model of Liebe (1993). (B) Forward model of Liljegren (2005). Radiosonde data: 85 Vaisala RS90 sondes launched from the ARM NSA Duplex. Note the excellent agreements with the Liljegren model. [After Westwater et al., 2006C]

Publications

[12] Westwater, E. R, D. Cimini, V. Mattioli, A. Gasiewski, M. Klein, V. Leuski, and J. C. Liljegren, "The 2004 North Slope Of Alaska Arctic Winter Radiometric Experiment: Overview And Highlights", Proc. MicroRad'06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico. pp. 247-251. http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[13] Westwater, E. R., D. Cimini, V. Mattioli ,A. J. Gasiewski, M. Klein, V. Leuski, and J. C. Liljegren, "The 2004 North Slope of Alaska Arctic Winter Radiometric Experiment: Overview and Recent Results", Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

[14] Westwater, E., R., D. Cimini, V. Mattioli, ,M. Klein, V. Leuski, A. J. Gasiewski Clear-Air Forward Microwave and Millimeterwave Radiative Transfer Models for Arctic Conditions, , International TOVS Study Conference-15, Maratea, Italy, Oct. 4-11, 2006.

2006-3. Analysis of Radiosondes launched during the 2004 Arctic Winter Radiometric Experiment

In order to conduct accurate forward model radiative transfer studies, both in the microwave and infrared spectral regions, it is necessary to have accurate measurements of profiles of temperature, pressure, and water vapor. To evaluate several types of radiosonde sensors, several radiosonde packages were deployed during the experiment: Vaisala RS90 radiosondes launched at the ARM Duplex in Barrow, and at the principal ARM field site (the Great White), and Sippican VIZ-B2 radiosondes operated by the National Weather Service. In addition, eight dual-radiosonde launches were conducted at the Duplex, with Vaisala RS90 and Sippican GPS Mark II carried on the same balloon. This last radiosonde was modified to include a Meteolabor "Snow White" chilled mirror humidity sensor. Analyses of the temperature and relative humidity (RH) measured by those radiosondes have been made. These results, previously reported in the ARM Science Teams meeting of 2005, and presented orally by E. R. Westwater in the Plenary Session of the ARM Science Team Meeting'06, formed the basis of an open literature publication that has been accepted for publication (Mattioli et al.,[5]). A major point of the paper was that the relative humidity (RH) profiles of the NWS had substantial biases (~ 20 %) in the upper troposphere and lower stratosphere, and also when the surface temperature was less than – 35 °C. We quote from the conclusions of the Mattioli et al. paper: "*Given that surface temperatures are frequently less that – 35ºC, this lack of reliability is a serious problem for the climate record at Barrow*."

Publications

[5] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin(2007a): "Analysis of Radiosonde and ground-based remotely sensed PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment" *Journal of Atmospheric and Oceanic Technology*, Vol. 24, March 2007, pp. 415-431.

[12] Westwater, E. R, D. Cimini, V. Mattioli ,A. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren, "The 2004 North Slope Of Alaska Arctic Winter Radiometric Experiment: Overview And Highlights", Proc. MicroRad'06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico. pp. 247-251, 2006. http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[13] Westwater, E. R., D. Cimini, V. Mattioli ,A. J. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren: "The 2004 North Slope of Alaska Arctic Winter Radiometric Experiment: Overview and Recent Results", Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

2006-4. Analysis of MWR and MWRP Tb measurements during the 2004 Arctic Winter Radiometric Experiment

The Mattioli et al. paper above, also presented analyses of the ARM MWR and MWRP for their accuracy in measuring PWV. Comparisons in PWV were made between data taken by the MWR and MWRP, a GPS receiver that belongs to the Suominet network, and each of the various radiosonde types. In general, the VIZ-B2 and the Mark II radiosondes measured higher values of PWV with respect to the RS90 and the Snow White, and with respect to the remote sensors. Good agreement on the order of 0.034 cm rms was found between the dual-channel radiometer and the profiler, when the five K-band channels were used for the PWV retrievals. Generally good agreement was also found between the radiometers and the GPS, although both near real-time and reprocessed PWV data were affected by a substantial scatter compared to the radiometers and the radiosondes. However, because of the substantial bias in the NWS VIZ-B2 upper atmospheric humidity soundings, we compared radiosonde soundings with measurements of the 22.235 GHz MWRP channel. This channel is sensitive to upper altitude water vapor, as shown in Fig. 3. As an independent confirmation that the NWS radiosondes were biased in the upper atmosphere, we show in Fig. 4. the comparisons between calculations using Vaisala RS90 (accurate) and NWS VIZ-B2 (inaccurate) radiosondes. vs. MWRP 22.235 GHz Tb measurements. We note the excellent agreement between measurements and the calculations based on Duplex radiosondes (RS90) and the Liljegren et al. (2005) model, but very poor agreement when using the same model with the NWS VIZ-B2 radiosondes.

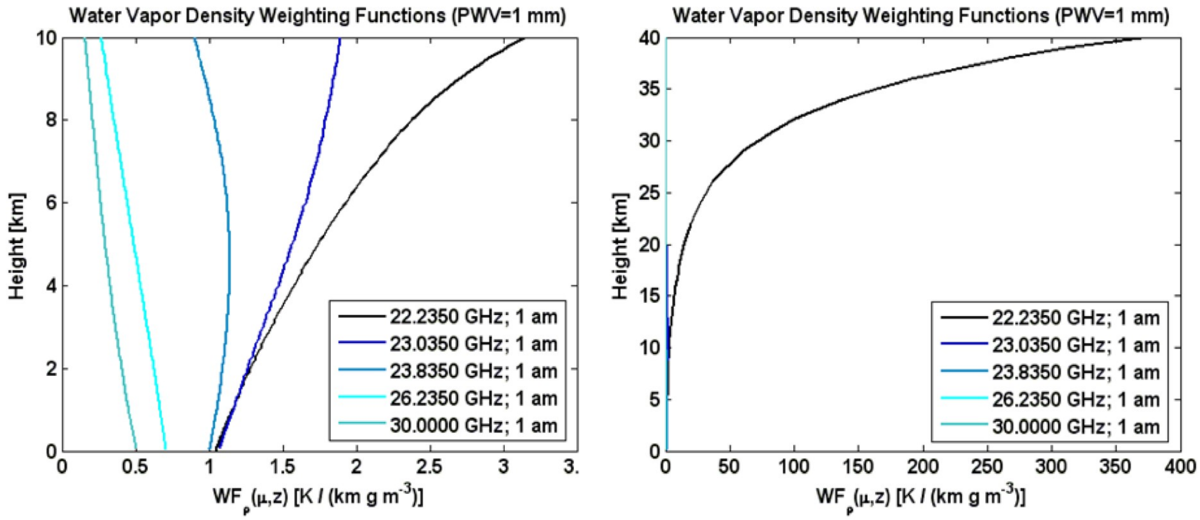

Fig. 3.Water Vapor Weighting Functions for Microwave Radiometric Profiler. (A): Tropospheric Weighting Functions. (B): Tropospheric and Stratospheric Weighting Functions. [After Westwater et al., 2006A].

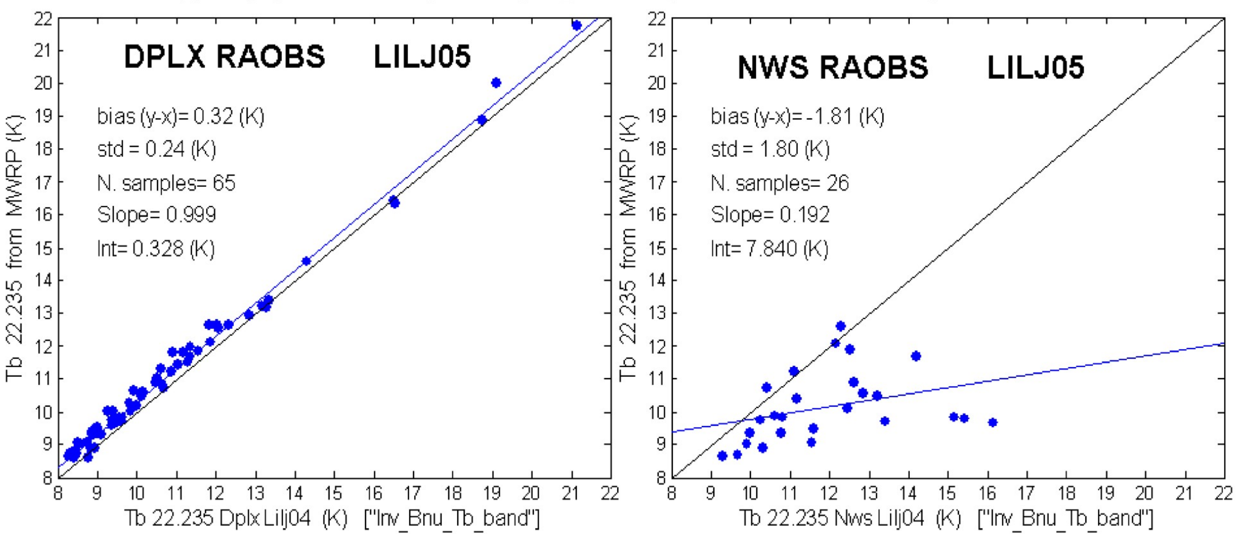

Fig. 4. Comparison of Measured vs. Calculated Brightness Temperature at 22.235 GHz.

After Mattioli et al., [15].

Publications

[15] Mattioli, V., E. R. Westwater, D. Cimini, A.J.Gasiewski, M. Klein, V.Y. Leuski, 2008:“Microwave and Millimeter-wave Radiometric and Radiosonde Observations in an Arctic Environment”, *Journal of Atmospheric and Oceanic Technology*, **Vol. 25, No. 10**. pp. 1768–1777.

[12] Westwater, E. R, D. Cimini, V. Mattioli ,A. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren, “The 2004 North Slope Of Alaska Arctic Winter Radiometric Experiment: Overview And Highlights”, Proc. MicroRad’06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico. pp. 247-251, 2006A. http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[13] Westwater, E. R., D. Cimini, V. Mattioli ,A. J. Gasiewski, M. Klein, V. Leuski ,and J. C. Liljegren, "The 2004 North Slope of Alaska Arctic Winter Radiometric Experiment: Overview and Recent Results", Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

Reference

Liljegren, J. C., S. A. Boukabara, K. Cady-Pereiria, and S. A. Clough, "The Effect of the Half-Width of the 22-GHz Water Vapor Line on Retrievals of Temperature and Water Vapor Profiles with a Twelve-Channel Microwave Radiometer," *IEEE Transactions on Geoscience and Remote* Sensing, **43**(5), pp. 1102-1108, 2005.

2006-5. Measurements of Water Vapor during Arctic Conditions

In our previous 2005 Progress Report, we conducted preliminary comparisons of the response of MWR, MWRP and GSR channels to water vapor content during the coldest and driest of the conditions that we encountered. The comparisons indicated greatly enhanced sensitivity to water vapor in the 0.8 to 8.0 mm region of PWV. Depending on the channel, this sensitivity can be 50 times as great as that of the MWR to these changes. The results have now been submitted to the open literature (Cimini et al., [18]). In Fig. 5, we show some time series comparisons between PWV derived by the MWR, the GSR, and by radiosondes. It is evident the enhanced sensitivity of the GRS improves the agreement with the radiosondes.

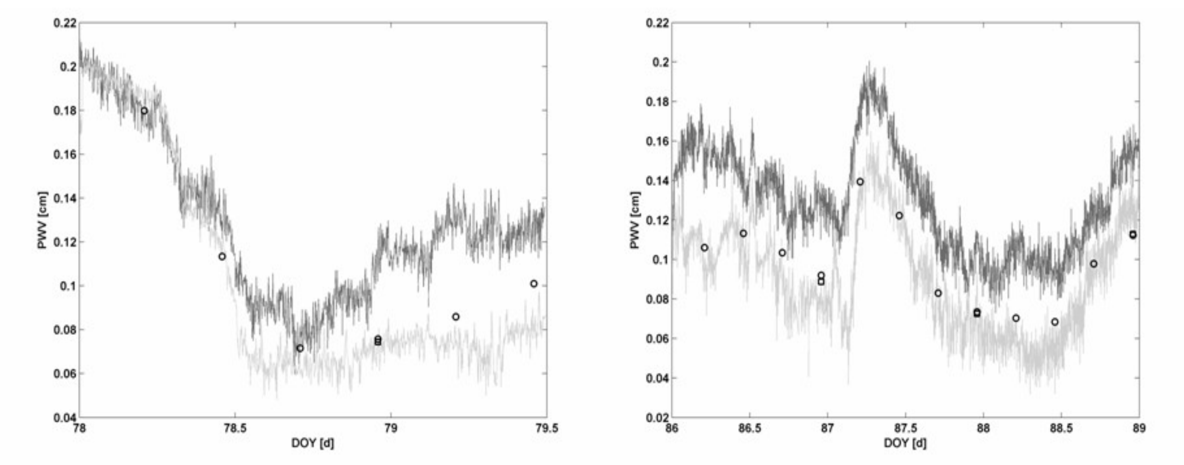

Fig. 5: Two examples of time series during very dry conditions. PWV from MWR is shown in dark grey, while GSR(89,183.2±7) PWV in light grey. Black circles and squares represent PWV measured by DRI X and GW sondes, respectively. [After Cimini et al., 2006B]

Publications

[18] Cimini, E. R. Westwater, A. Gasiewski, M. Klein, V. Leuski, J. Liljegren, Ground-based millimeter- and submillimiter-wave observations of low vapor and liquid water contents, *IEEE Transaction on Geosciences and Remote Sensing*, **Vol. 45, No. 7**, Part II. July 2007, pp.2169-2180.

[19] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leuski, V. Mattioli, S. Dowlatshahi, and J. Liljegren, "Ground-Based Millimeter- and Submillimeter-Wave Observations of the Arctic Atmosphere", Proc. MicroRad'06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico, pp. 7-81, 2006. http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[20] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leuski, and J.C. Liljegren, "Millimeter- and submillimeter-wave Observations of Low Vapor and Liquid Water Amounts in the Arctic Winter". Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

2006-6. Measurements of Cloud Liquid during Arctic Conditions

In our previous Progress Report (2005), we showed preliminary comparisons of the response of MWR, MWRP and GSR channels to liquid water during our experiment. We focused on GSR channels that are close to the 89 and 150 GHz radiometers that ARM is purchasing. The comparisons indicated greatly enhanced sensitivity to Liquid Water Path (LWP) in the 0.1 to 0.5 mm region of LWP. Our results have been submitted to the open literature (Cimini et al., [18]) and Table 1 shows our complete sensitivity comparisons. Examples of MWR and GSR retrievals of LWP during clear conditions. are shown in Fig. 6. We note the substantial variations of the MWR- retrieved LWP, while the GSR retrieval is much closer to the correct zero value.

Table 1: Measured sensitivity to low LWP amounts. After Cimini et al.,[18].

	WVIOP2004 (measured)		**ARM NSA HDB (simulations)**	
	0.0<LWP<0.5 mm		**0.0<LWP<0.5 mm**	
f (GHz)	**S ± 99%CI (K/mm)**	**I ± 99% CI (K)**	**S ± 99%CI (K/mm)**	**I ± 99% CI (K)**
23.8	32.28 ± 0.08	0.14 ± 0.01	35.50 ± 0.69	0.09 ± 0.09
31.4	55.61 ± 0.08	0.14 ± 0.01	57.00 ± 0.79	0.15 ± 0.10
22.235	28.34 ± 0.32	0.34 ± 0.03	32.53 ± 1.58	-0.13 ± 0.20
23.035	32.79 ± 0.30	0.27 ± 0.03	33.48 ± 0.68	0.05 ± 0.09
23.835	33.65 ± 0.27	0.08 ± 0.02	35.60 ± 0.69	0.09 ± 0.09
26.235	39.85 ± 0.35	-0.11 ± 0.03	42.47 ± 0.74	0.12 ± 0.09
30.0	48.72 ± 0.40	-0.21 ± 0.03	53.10 ± 0.78	0.14 ± 0.10
89 V	187.89 ± 1.92	-0.82 ± 0.16	191.84 ± 2.25	1.01 ± 0.29
89 H	187.53 ± 1.93	-0.93 ± 0.17	191.84 ± 2.25	1.01 ± 0.29
183.31±16	231.33 ± 3.12	2.55 ± 0.27	233.67 ± 9.53	3.76 ± 1.21
183.31±12	195.61 ± 3.25	2.89 ± 0.28	204.37 ± 10.20	3.69 ± 1.30
183.31±7	95.39 ± 4.40	1.78 ± 0.38	121.05 ± 11.11	3.40 ± 1.41
183.31±4.7	67.77 ± 3.18	2.85 ± 0.27	54.24 ± 9.62	2.73 ± 1.22
183.31±3.05	41.77 ± 2.56	1.80 ± 0.22	14.04 ± 6.88	1.66 ± 0.87
183.31±1	48.03 ± 2.41	0.36 ± 0.21	-4.25 ± 6.33	0.08 ± 0.80
183.31±0.55	49.76 ± 2.49	0.27 ± 0.21	-4.56 ± 6.71	-0.05 ± 0.85
340 V	108.71 ± 5.25	3.74 ± 0.45	104.01 ± 14.41	5.10 ± 1.83
340 H	141.10 ± 5.99	6.86 ± 0.52	104.01 ± 14.41	5.10 ± 1.83
380.197±4	78.12 ± 2.65	-0.16 ± 0.23	-9.42 ± 7.92	-0.25 ± 1.01
380.197±9	60.17 ± 2.62	0.51 ± 0.22	-7.61 ± 7.67	0.86 ± 0.97
380.197±17	37.23 ± 2.76	3.85 ± 0.24	15.79 ± 9.79	3.06 ± 1.24

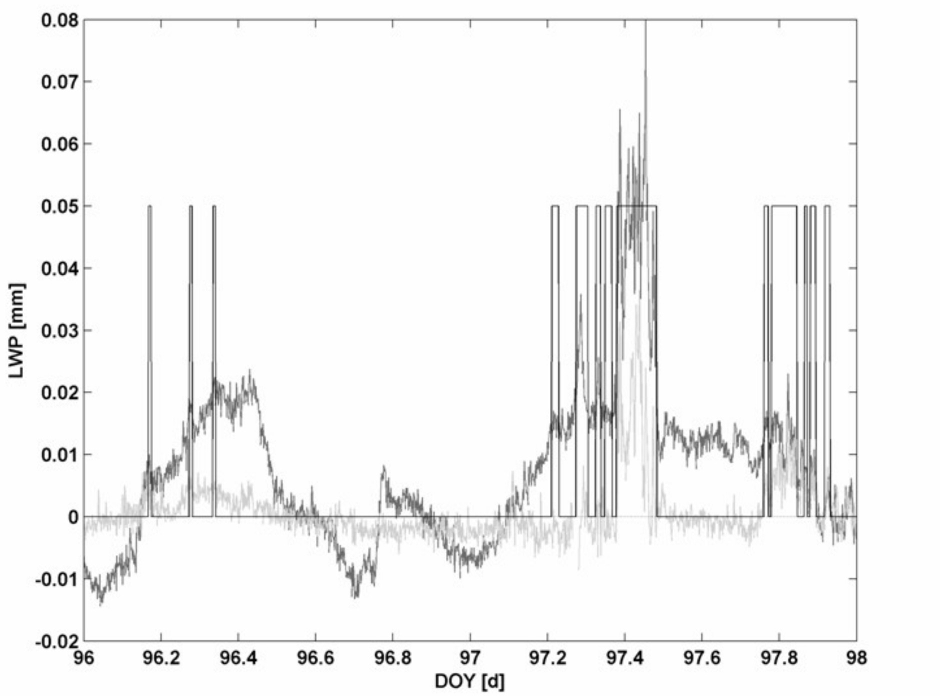

Fig.6: Time series of LWP as retrieved from MWR (dark grey) and GSR(89,183.2±7) (light grey). The black solid line represents cloud detection by the MWRP IR sensor; 0 means clear sky, while 0.05 indicates clouds overhead.

We also performed simulations to estimate the effects of scattering on the various channels used in the 2004 experiments. Figs. 6 and 7 show the results of these simulations for liquid and ice, respectively.

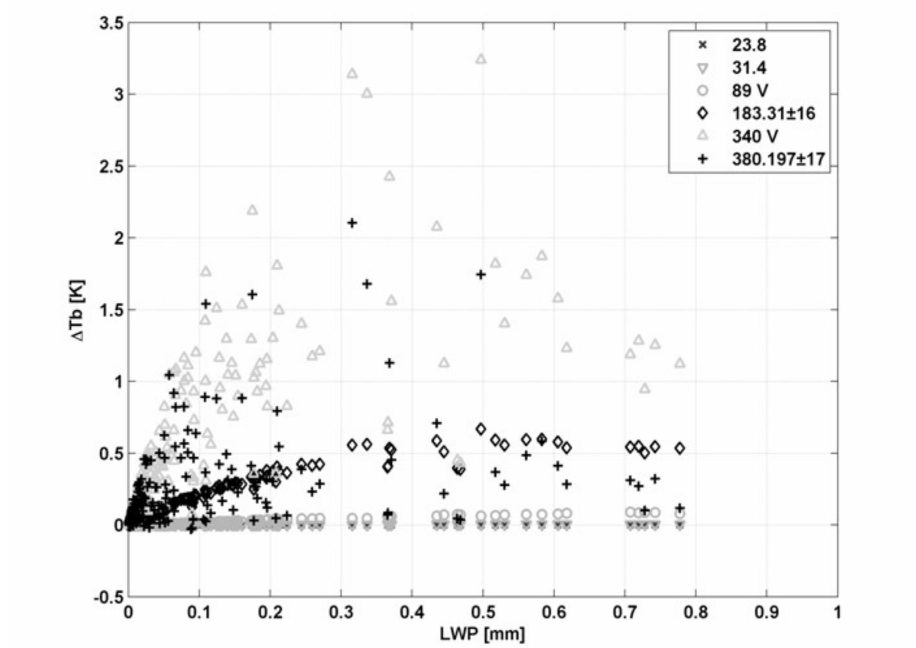

Fig. 7: Evaluation of the scattering effect using simulated data. Case of pure liquid clouds. [After Cimini et al., 2006B].

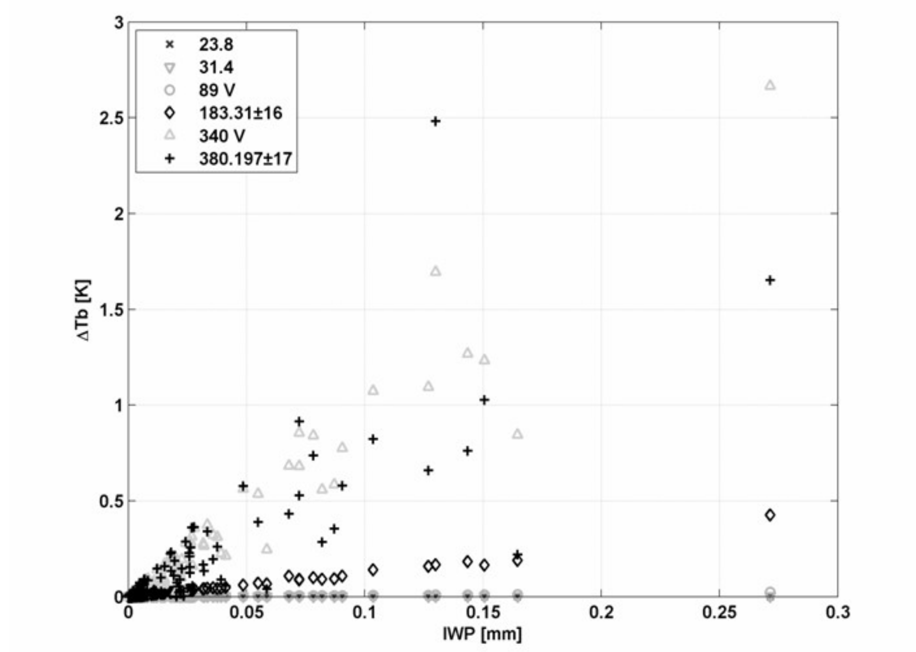

Fig. 8: Evaluation of the scattering effect using simulated data. Case of pure ice clouds. [After Cimini et al., 2006B]

Publications

[18] Cimini, E. R. Westwater, A. Gasiewski, M. Klein, V. Leuski, J. Liljegren, Ground-based millimeter- and submillimiter-wave observations of low vapor and liquid water contents, *IEEE Transaction on Geosciences and Remote Sensing*, **Vol. 45, No. 7**, Part II. July 2007, pp.2169-2180.

[19] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leuski, V. Mattioli, S. Dowlatshahi, and J. Liljegren, ”Ground-Based Millimeter- and Submillimeter-Wave Observations of the Arctic Atmosphere”, Proc. MicroRad’06, 28 Feb - 03 Mar 2006 San Juan, Puerto Rico, pp. 7-81, 2006. http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006

[20] Cimini, D., E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leuski, and J.C. Liljegren, ”Millimeter- and submillimeter-wave Observations of Low Vapor and Liquid Water Amounts in the Arctic Winter”. Proc. of the 16th. ARM Science Team Meeting, Albuquerque, NM, March 27-31, 2006.

2006-7. Instrument development

In this third year of our effort, we will deploy the GSR at Barrow. We thus are continuing to improve the instrument for this deployment.

1. 380 GHz radiometer. Two frequency channels were added: a 380.6 GHz channel with a 200MHz frequency bandwidth and a 381.7 GHz channel with a 500 MHz frequency band. The 5-channel measurements in the 380 GHz frequency band will complement the GSR channels centered around 183.31 GHz, and will be very responsive to very low amounts of water vapor (< ~ 1 mm).

2.The 18-24 GHz and 31 GHz radiometers were finished and tested as we planed, but we decided do not install them in GSR for 2007 experiment. If a volume scanning radiometer is deployed at a non-arctic site, these will be primary channels.

3. We improved the 55 GHz local oscillator frequency stability and made measurements of the frequency response of the channels.

4.-We modified and improved the 340 GHz radiometer's optics.

2006-8. Additional activities

At the invitation of the SIEM journal editor, we also contributed an overview on Radiometry (Westwater et al, [23]). E. R. Westwater was on the Steering Committees for Microrad'06 and IGARSS'06, and is a Guest Editor of the Special Issue of the Transactions of Geoscience and Remote Sensing that is devoted to MicroRad'06. Several ARM-sponsored and –related papers have been presented in these symposia and papers. E. R. Westwater also organized a Special Session of "Remote Sensing of Climate Variables" in the 2006 International Geoscience and Remote symposium that was held in Denver, Colorado, Jul – Aug. Several ARM scientists participated in this Special Session.

Data from the ARM NSA Winter Radiometric Experiment have been used by other investigators for satellite data analysis and validation; results have been showed at the last International TOVS Study Conference (Cimini et al, [32]; Romano et al., [36]). Also, D. Cimini participated to the data analysis of the Temperature, Humidity, and Cloud profiling (TUC) Campaign, a ground-based experiment founded by the European Community involving a suite of instruments including a MWRP unit. The main results, which have been published on the open literature (Cimini et al. [34], G; Hewison et al. [35]), are likely of interest to the ARM microwave community.

Using ARM data, we have been working with our Italian colleagues on the development of cloud models that will predict vertical profiles of cloud liquid from radiosonde data. The models have been trained using the following data from the ARM archive: MWR measurements of LWP, ceilometer measurements of cloud base height, and radiosonde measurements. These results have been published in several conference proceedings [Basili et al., [21], Mattioli et al., [22]], and an open literature publication is being prepared.

Publications to here

[21] Basili, P., S. Bonafoni, V. Mattioli, P. Ciotti, E. R. Westwater, "Analysis and improvement of cloud models for brightness temperature simulations", Proc. of the 9th Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, 28 February - 3 March, 2006, San Juan, Puerto Rico, pp. 296-300. (2006A). http://ieeexplore.ieee.org/xpl/tocresult.jsp?isnumber=35270&isYear=2006.

[22] Mattioli,V., P. Basili, S. Bonafoni, P. Ciotti, L. Pulvirenti, N. Pierdicca, F. S. Marzano, F. Consalvi, E. Fionda and E. R. Westwater: "Cloud Liquid Models for Propagation Studies: Evaluation and Refinements", Proc. of the 1st European Conference on Antennas and Propagation, 6 - 10 November 2006, Nice, France. (2006B)

[23] Westwater, E. R., S. Crewell, C. Mätzler, and D. Cimini, "Principles of Surface-based Microwave and Millimeter wave Radiometric Remote Sensing of the Troposphere", *Quaderni della Società Italiana di ElettroMagnetismo*, vol. 1, no. 3, pp. 50-90, 2005.

Publications

[31] Basili,P., S. Bonafoni, V. Mattioli, P. Ciotti, E. R. Westwater, “Cloud model studies for the simulation of brightness temperatures” Proc. of IGARSS 2006, July 31-August 04, Denver, CO. (2006)

[32] Cimini D., F. Romano, E. Ricciardelli, and V. Cuomo, “On the role of surface emissivity in polar night-time cloud detection”, *Proceeding of 15th International TOVS Study Conference*, October, 2006.

[33] Cimini, D., T. J. Hewison, L. Martin, “Comparison of brightness temperatures observed from ground-based microwave radiometers during TUC” , *Meteorologische Zeitschrift*, Vol.15, No.1, 2006, pp.19-25, 2006F.

[34] Cimini, D., T. J. Hewison, L. Martin, J. Güldner, C. Gaffard and F. S. Marzano, “Temperature and humidity profile retrievals from ground-based microwave radiometers during TUC:, *Meteorologische Zeitschrift*, Vol. 15, No. 1, 45-56, 2006.

[35] Hewison, T. J., D. Cimini, L. Martin, C. Gaffard and J. Nash, Validating clear air absorption model using ground-based microwave radiometers and vice-versa, *Meteorologische Zeitsc*hrift, Vol.15, No.1, 27-36, 2006.

[36] Romano F., D. Cimini, E. Ricciardelli, and V. Cuomo, “Analysis of day- and night-time Arctic clouds by means of hyperspectral infrared and ground-based observations”, *Proceeding of 15th International TOVS Study Conference*, October, 2006.

PLANS FOR 2007

We will continue to investigate retrieval methods using the GSR data to derive temperature and humidity profiles, as well as improved estimates of LWP. We will also investigate the combined use of active-passive retrievals to derive profiles of cloud liquid density. Our retrieval methods will be physical in the sense that radiative transfer models will be used in each step of the retrieval process. We also will investigate the information content of angular vs. zenith-only measurements.

We plan to participate in the ARM-sponsored IOP “Radiative Heating in Underexplored Bands Campaign (RHUBC) at the NSA site during 22 February to 14 March, 2007. Several GSR upgrades will be added in preparation for this experiment. These include:

Study of the 55 GHz radiometer stability during scanning process.
89 GHz radiometer antenna back sidelobes estimation
380 GHz radiometer mirror control improvement
340 GHz radiometer repair, assembling and testing.
Rebuild 183 unit.
Before shipping to Barrow, test the GSR on the roof of the CU Engineering Center.

We plan to submit an overview paper of the 2004 NSA IOP to the open literature.

We plan to submit an open literature paper on the comparison of forward models during Arctic conditions.

We plan to submit a short paper to the open literature on the 22.235 GHz observations at the NSA that confirm the bias in NWS humidity soundings. This will complement the Mattioli et al., 2006 paper on RAOB performance.

The GSR is being considered as a prototype for a volume scanning radiometer. We will continue work on the preliminary design of this instrument.

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2007-1. Participation of the GSR during RHUBC

As was demonstrated during the 2004 radiometric experiment, the GSR has a very flexible data acquisition system that allows several calibration alternatives (Cimini et al., [11]). During a single scan from horizon to horizon, the GSR performs a dwell, on both sides of zenith, at six air masses (1, 1.5, 2, 2.5, 3, and 3.5) while giving continuous data over the rest of the scan. At the end of the scan, the GSR moves into a calibration shelter where it observes two external blackbody targets. In addition, depending on the frequency band, the radiometer is electronically or mechanically switched between two internal calibration targets on a rapid basis. Finally, atmospheric conditions permitting, tipcal calibrations can also be used. Thus, the GSR is calibrated continuously during all sky conditions, even when tipcals are not possible. In preparations for RHUBC, several improvements were made to radiometers operating in the 60 GHz band and to the 340 GHz channel. We also conducted tests on the rooftop of our CET facilities to check out instrument performance and calibration improvements. During RHUBC, we performed a scan every minute, and, in addition to the one-month operating period, we continued operation of the instrument until July of 2007. The calibrated GSR data for the first month of the experiment have been calibrated and delivered the ARM data archives. Fig. 1 shows an example of the Quasi Real Time Display that was available during the experiment.

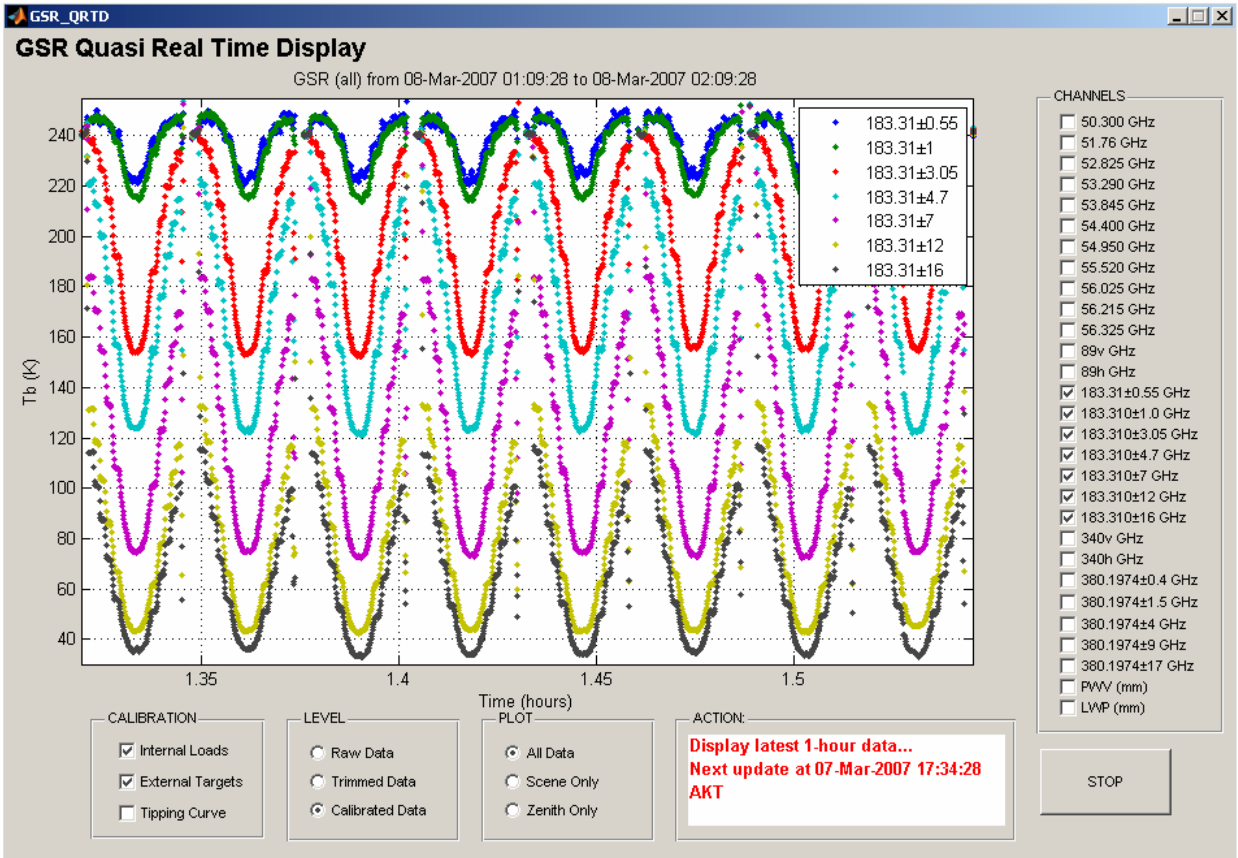

Fig. 1. Example of the GSR Quasi Real Time Display during RHUBC. The menu on the right hand portion of the figure shows the choices that the experimenters were able to access during the experiment. Note that GSR retrievals of PWV and LWP were used an aid to make decisions on when to launch radiosondes.

Publications

[11] Cimini, E. R. Westwater, A. J. Gasiewski, M. Klein, V. Leusky, and J. C. Liljegren,(2007a): "The Ground-based Scanning Radiometer (GSR): a powerful tool for the study of the Arctic Atmosphere", *IEEE Transaction on Geosciences and Remote Sensing*, Vol. 45, No. 9, September 2007, pp. 2759-2777.

2007-2. Millimeter Wavelength clear-sky forward model comparisons

As reported in our 2006 project report, we compared clear-sky forward model calculations based on five contemporary models. These results of these comparisons published in the Proceedings of IGARSS-07 (Westwater et al., [25]) and the Proceedings of the ITSC-15 (Westwater et al., [24]).

Publications

[24] Westwater, E. R., D. Cimini, V. Mattioli, ,M. Klein, V. Leuski, A. J. Gasiewski: "Clear-Air Forward Microwave and Millimeterwave Radiative Transfer Models for Arctic Conditions", Proc. of 15th International TOVS Study Conference, Maratea, Italy, Oct. 4-11, 2006. (http://cimss.ssec.wisc.edu/itwg/itsc/itsc15/proceedings/)

[25] Westwater, E. R., D. Cimini, A. J. Gasiewski, M. Klein, and V. Leuski: "The Ground-based Scanning Radiometer: a Tool for Arctic Atmospheric Research", Proc. IGARSS'07, Barcelona, Spain, July 23-27.

2007-3. Analysis of Radiosondes launched during the 2004 Arctic Winter Radiometric Experiment

In previous ARM progress reports, we presented our results from the 2004 NSA radiometric experiment that showed that radiosondes launched at Barrow, AK, by the U. S. National Weather Service were seriously in error in their measurements of upper tropospheric and lower stratospheric water vapor. The open literature paper containing these results was published (Mattioli et al., [5]). A major point of the paper was that the relative humidity (RH) profiles of the NWS had substantial biases (~ 20 %) in the upper troposphere and lower stratosphere, and also when the surface temperature was less than -35 deg C. We quote from the conclusions of the Mattioli et al. paper: "*Given that surface temperatures are frequently less that - 35 deg. C, this lack of reliability is a serious problem for the climate record at Barrow*."

Publications

[5] Mattioli, V., E. R. Westwater, D. Cimini, J. S. Liljegren, B. M. Lesht, S. I. Gutman, and F. J. Schmidlin(2007a): "Analysis of Radiosonde and ground-based remotely sensed PWV data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment" *Journal of Atmospheric and Oceanic Technology*, Vol. 24, March 2007, pp. 415-431.

2007-4. Analysis of GSR, MWR, and MWRP Tb measurements from the 2004 Arctic Winter Radiometric Experiment

The Mattioli et al. [5] paper, also presented analyses of the ARM microwave radiometers for their accuracy in measuring PWV. Comparisons in PWV were made between data taken by the MWR and MWRP, a GPS receiver that belongs to the Suominet network, and each of the various radiosonde types. Basically, the measurements showed good agreement on the order of 0.05 cm rms between the various sources of PWV retrievals. However both the ARM MWRP and the GSR have channels that are sensitive to upper-tropospheric and lower stratospheric water vapor. We show in Fig. 2, GSR channels that are sensitive to upper altitude water vapor. As an independent confirmation that the NWS radiosondes were biased in the upper atmosphere, as shown by Mattioli et al. [5]) in Fig. 3. we show comparisons between calculations using Vaisala RS90 (accurate) and NWS VIZ-B2 (inaccurate) radiosondes. vs. MWRP 22.235 GHz Tb measurements. Even more dramatic results are shown in Fig. 4, which shows the radiosonde comparisons with the three GSR channels. In both Figs. 3 and 4, we note the excellent agreement between measurements and the calculations based on Duplex radiosondes (RS90) and the Liljegren et al. (2005) model, but very poor agreement when using the same model with the NWS VIZ-B2 radiosondes. We believe that these results demonstrate the power of microwave and millimeter wavelength radiometers in identifying and possible correcting erroneous radiosonde data.

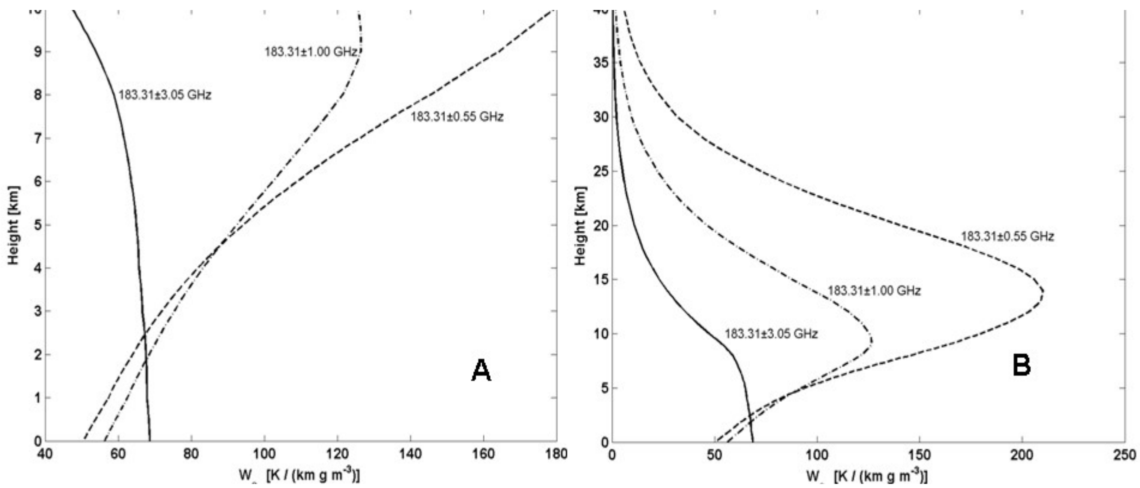

Fig. 1. Zenith Water Vapor Density weighting functions for three water vapor channels of the GSR for an average Arctic winter profile and a PWV of 1 mm. (A) Troposphere only, (B) troposphere and stratosphere. After Mattioli et al., [15].

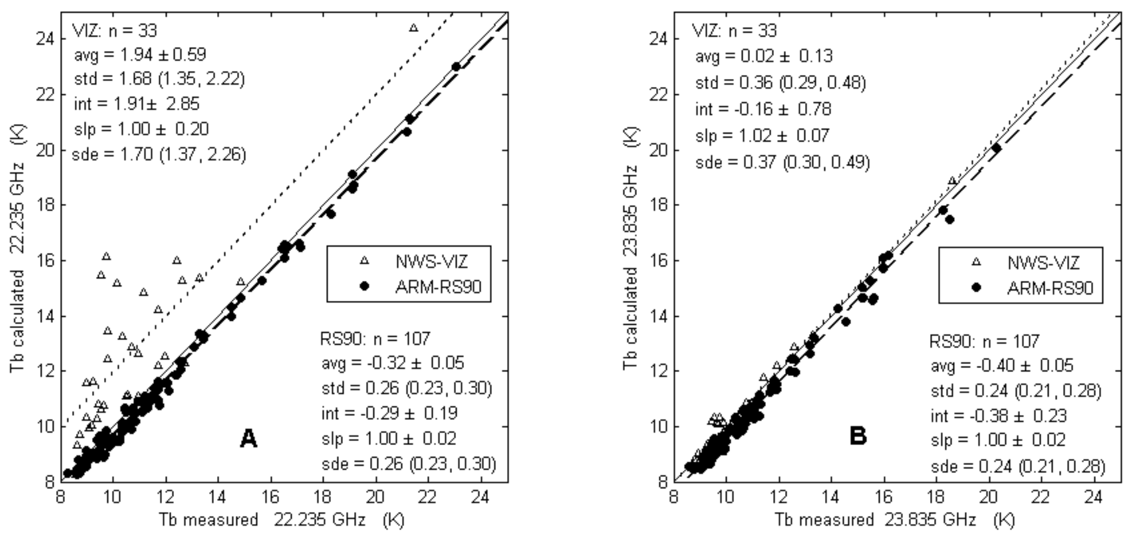

Fig. 3. Scatterplots of differences between calculations and MWRP measurements at (A) 22.235 GHz, and (B) 23.835 GHz. Note that the channel at 23.805 GHz is sensitive only to lower tropospheric water vapor and hence, does not show the large departures that are evident with the 22.235 GHz channel. After Mattioli et al., [15].

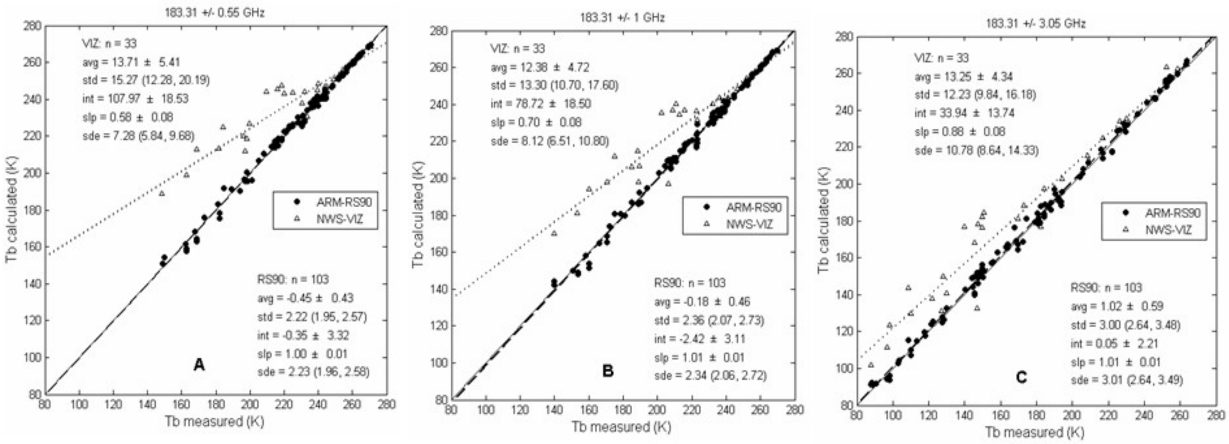

Fig. 4. Scatterplots of differences between calculations and MWRP measurements at (A) 183.31 ± 0.5 GHz, (B) 183.31 ± 1 GHz, and (C) 183.31 ± 3.05 GHz. After Mattioli et al., 2007b.

Publications

[15] Mattioli, V., E. R. Westwater, D. Cimini, A.J.Gasiewski, M. Klein, V.Y. Leuski: "Microwave and Millimeter-wave Radiometric and Radiosonde Observations in an Arctic Environment", *Journal of Atmospheric and Oceanic Technology*, **Vol. 25, No. 10**. pp. 1768–1777.

2007-5. Measurements of Water Vapor during RHUBC

In our previous 2006 Progress Report, we showed theoretical comparisons of the response of MWR, MWRP and GSR channels to water vapor content during the coldest and driest of the conditions that we encountered. The comparisons indicated greatly enhanced sensitivity to water vapor in the 0.8 to 5 mm region of PWV. Depending on the channel, this sensitivity can be 50 times as great as that of the MWR to these changes. The results have now been published in the open literature (Cimini et al., [18]). These results were demonstrated even further during RHUBC, an experiment that focused on PWV less than 2 mm. In Fig. 5, we show a typical example of GSR and MWR PWV retrievals. Note the excellent agreement between the GSR retrievals and the RS92 measurements.

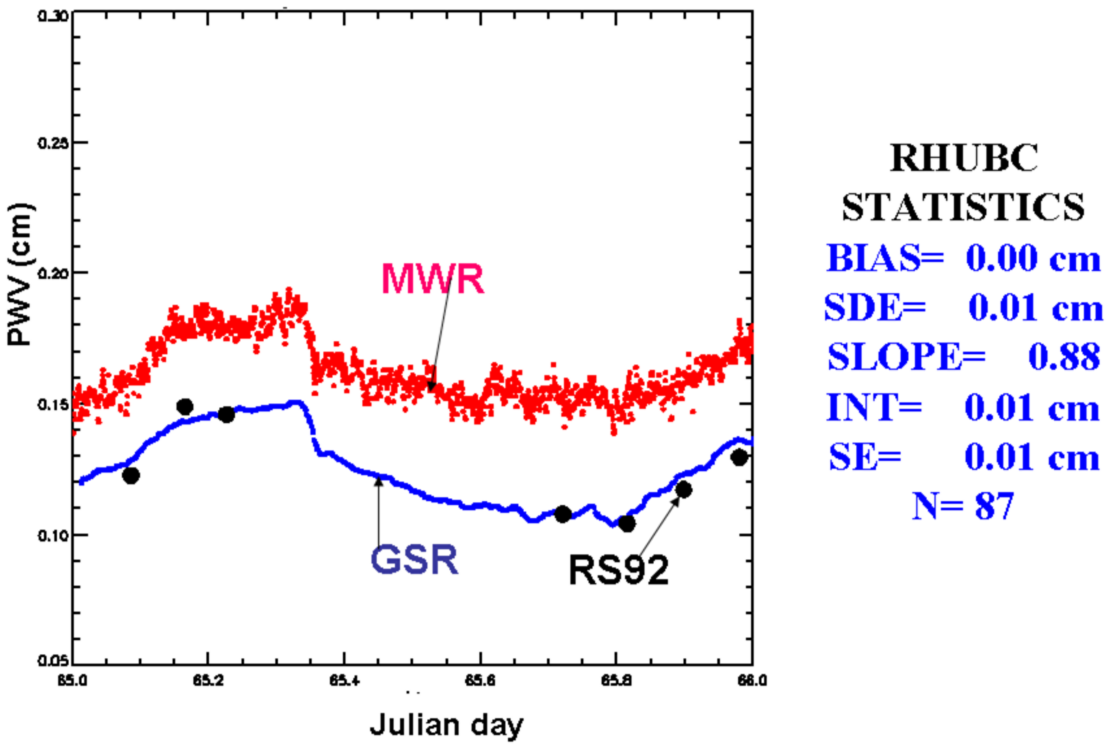

Fig. 5. Comparison of Precipitable Water Vapor Retrievals from the ARM MWR, the CET GSR, and Vaisala RS92 radiosondes launched during RHUBC on Julian Day 65, 2007, and the statistical comparisons of 87 data pairs.

Publications

[18] Cimini, D., E. R. Westwater, A. Gasiewski, M. Klein, V. Leuski, J. Liljegren, (2007b): “Ground-based millimeter- and submillimiter-wave observations of low vapor and liquid water contents”, *IEEE Transaction on Geosciences and Remote Sensing,* Vol. 45, No. 7, Part II, July 2007, pp. 2169-2180.

[25] Westwater, E. R., D. Cimini, A. J. Gasiewski, M. Klein, and V. Leuski: “The Ground-based Scanning Radiometer: a Tool for Arctic Atmospheric Research”, Proc. IGARSS’07, Barcelona, Spain, July 23-27.

2007-6. Measurements of Cloud Liquid during Arctic Conditions

In our previous Progress Report (2006), we showed preliminary comparisons of the response of MWR, MWRP and GSR channels to liquid water during our experiment. We focused on GSR channels that are close to the 89 and 150 GHz radiometers that ARM has purchased. The comparisons indicated greatly enhanced sensitivity to Liquid Water Path (LWP) in the 0.1 to 0.5 mm region of LWP. We also performed simulations to estimate the effects of scattering on the various channels used in the 2004 experiments. Our results have now been published in the open literature (Cimini et al., [18]). As an example from RHUBC, in Fig. 6. we show GSR and MWR retrievals of LWP during known clear conditions

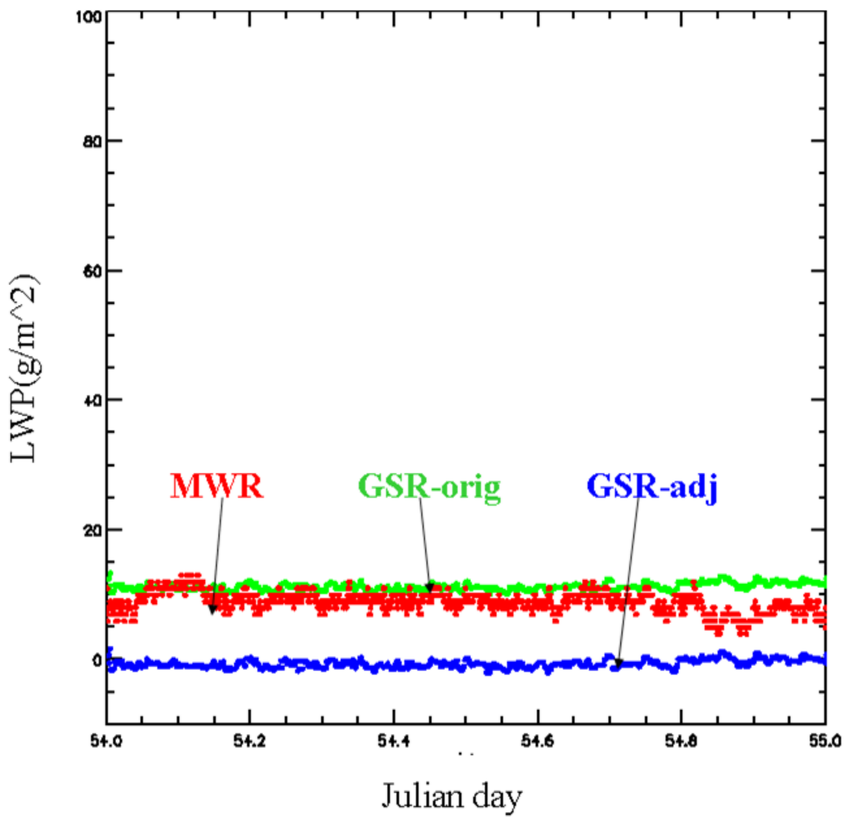

Fig. 6. MWR and GSR window channel LWP retrievals for Julian Day 54, 2007. The adjusted GSR retrievals used brightness temperatures that were adjusted to the Liljegren et al. (2005) model using GSR data from the 2004 NSA Arctic Winter Radiometric Experiment.

2007-7. Instrument development for RHUBC

1. 380 GHz radiometer. Two frequency channels were added: a 380.6 GHz channel with a 200MHz frequency bandwidth and a 381.7 GHz channel with a 500 MHz frequency band. The 5-channel measurements in the 380 GHz frequency band will complement the GSR channels centered around 183.31 GHz, and will be very responsive to very low amounts of water vapor (< ~ 1 mm). The new receiver worked during RHUBC and the data appear to be of high quality.

2. We improved the 55 GHz local oscillator frequency stability and made measurements of the frequency response of the channels. The improved radiometer worked well during RHUBC.

3. We modified and improved the 340 GHz radiometer's optics, and again, data taken during RHUBC appear to be of high quality.

2007-8. Additional activities

Ed Westwater has been a member of the ARM "Sunset Committee" and has participated in activities of this group. He is also a member of the ARM Radiative Processes Working Group and the Cloud Properties Working Group.

He also continues to be an Associate Editor of the IEEE Transactions on Geoscience and Remote Sensing and has handled several papers that were written by ARM researchers.

Several members of CET participated in the ARM Microwave Radiometer “Futures” meeting and made a presentation on the GSR.

SUMMARY OF PRINCIPAL RESULTS

(1) Analysis of Radiosondes launched during the 2004 Arctic Winter Radiometric Experiment [5,15]

During March 9-April 9, 2004, the North Slope of Alaska Arctic Winter Radiometric Experiment was conducted at the Atmospheric Radiation Measurement (ARM) Program’s “Great White” field site near Barrow, Alaska. The major goals of the experiment were to compare microwave and millimeter wavelength radiometers and to develop forward models in radiative transfer, all with a focus on cold (temperature 0 to -40ºC) and dry (Precipitable Water Vapor– PWV < 0.5 cm) conditions. To supplement the remote sensors, several radiosonde packages were deployed: Vaisala RS90 launched at the ARM Duplex and at the Great White, and Sippican VIZ-B2 operated by the NWS. In addition, eight dual-radiosonde launches were conducted at the Duplex, with Vaisala RS90 and Sippican GPS Mark II, the latter one modified to include a chilled mirror humidity sensor. Temperature comparisons showed a nighttime bias between the VIZ-B2 and the RS90, which reached 3.5ºC at 30 hPa. Relative humidity comparisons indicated better than 5% average agreement between the RS90 and the chilled mirror. A bias of about 20% for the upper-troposphere was found in the VIZ-B2 and the Mark II measurements relative to both the RS90 and the chilled mirror.
Comparisons in PWV were made between a Microwave Radiometer, a Microwave Profiler, a Global Positioning System receiver, and the radiosonde types. RMS agreement of 0.034 cm was found between the radiometer and the profiler, and better than 0.058 cm between the radiometers and the GPS. RS90 showed a daytime dry bias on PWV of about 0.02 cm.

A major point of the paper by Mattioli et al. [5] was that the relative humidity (RH) profiles of the NWS had substantial biases (~ 20 %) in the upper troposphere and lower stratosphere, and also when the surface temperature was less than – 35 °C. We quote: “*Given that surface temperatures are frequently less that – 35ºC, this lack of reliability is a serious problem for the climate record at Barrow*.”

In [5], a significant difference was observed between upper tropospheric-lower stratospheric water vapor profiles as observed by two radiosonde systems operating in the Arctic. The first was the Vaisala RS90 system as operated by the Department of Energy’s Atmospheric Radiation Measurements program; the second was the operational radiosondes launched by the U. S. National Weather Service that used the VIZ humidity sensor. Observations of Precipitable Water Vapor by ground-based microwave radiometers and GPS did not reveal these differences. However, both the Microwave Radiometer Profiler (MWRP) and the Ground-based Scanning Radiometer (GSR) contain channels that receive a significant response from the upper tropospheric region. Brightness Temperature observations from these instruments showed consistent agreement with calculations based on the RS90 data, but differed by several degrees with calculations based on the VIZ radiosondes. It was also shown that calculations of TB can serve as a gross quality control of upper tropospheric soundings [15].

(2) Successful operation of the GSR during 2004 and 2007 and delivery of the data to ARM [11,37]

Measurements of water vapor and clouds in the polar regions are difficult, because conventional instruments show little sensitivity (~1.3 K/mm) to low amounts. On the other hand, millimeter- and submillimeter-wavelength radiometry offers greatly enhanced sensitivity (up to 51.4 K/mm, depending upon frequency). For this reason, we designed and developed a new instrument, the Ground-Based Scanning Radiometer (GSR), for continuous and unattended observations at millimeter and submillimeter wavelengths (50-380 GHz). The GSR was deployed for the first time during the Arctic Winter Radiometric Experiment in March-April 2004. It was also deployed successfully during the Radiative Heating in Underexplored Bands Campaign (RHUBC), held in February-March 2007. The GSR calibration procedure, allows for accurate measurements during clear and cloudy skies. Error-budget analysis and comparison with independent measurements show an absolute accuracy on the order of 1-2 K. Complete GSR data sets from these campaigns were delivered to the ARM archives and have formed the basis of several papers that have been published in the ARM Science Team proceedings and in the open literature.

(3) Theoretical and experimental studies of the sensitivity of millimeter wavelength channels to water vapor and liquid [18]

Ground-based observations at millimeter (mm) and submillimeter (submm) wavelengths were collected by the GSR during both of the 2004 and 2007 Arctic campaigns. A weighting function analysis demonstrated the enhanced sensitivity of mm- and submm-wave (50-400 GHz) radiometers to low vapor and liquid water contents with respect to conventional instruments such as the ones operating at centimeter (cm) wavelengths (20-30 GHz). In addition, based on measurements, we carried out a quantitative analysis of mm- and submm-wavelength sensitivity, yielding improvement factors from 1.5 to 69 for precipitable water vapor (PWV) and 3 to 4 for liquid water path (LWP) when compared to 20-30 GHz radiometers. Furthermore, using a simulated data set, we evaluated the effect of hydrometeor scattering: given the conditions occurring during the experiment, the scattering contribution is within the instrumental noise for most, but not all, of the considered channels. With the same data set, we demonstrated that in the dry conditions of the Arctic, a simple linear regression yields satisfactory results when applied on selected mm- and submm-wave channels. For a dual-channel combination, the expected accuracy is ~0.23 (0.007) mm for PWV (LWP), when using mm- and submm-wavelengths, whereas it is 0.37 (0.012) mm using cm-wave channels. When the retrieval is applied to real observations, the accuracy is found in agreement with theoretical expectations.

(4) Forward Model Studies [38]

During RHUBC 2007, three millimeter-wave radiometers, including the GSR, were operated and compared [38]. These radiometers contained several channels located around the strong 183.31-GHz water vapor line, which is crucial for ground-based water-vapor measurements in very dry conditions, typical of the Arctic. Simultaneous radiosonde observations were carried out during conditions with very low integrated-water-vapor (IWV) content (< 2 mm). Observations from the three instruments are compared, accounting for their different design characteristics. The overall agreement during RHUBC among the three instruments and between instruments and forward model was discussed quantitatively. In general, the instrument cross-validation performed for sets of channel pairs showed agreement within the total expected uncertainty. The consistency between instruments allows the determination of the IWV to within around 2% for these dry conditions. Comparisons between these data sets and forward-model simulations using radiosondes as input showed spectral features in the brightness-temperature residuals, indicating some degree of inconsistency between the instruments and the forward model. The most likely cause of forward-model error is systematic errors in the radiosonde humidity profiles.

(5) Profile Retrievals [38,39]

The results in this item were developed after the completion of our contract but were based on GSR data obtained during our two major Arctic experiments. In addition, the method was also successfully applied to data from an instrument (developed by Radiometrics Corporation) identical to one operated by ARM. A 1-D variational (1DVAR) retrieval technique was developed for obtaining temperature and humidity profiles from observations of the GSR [38]. . Temperature and humidity profiles retrieved with the 1DVAR technique were compared with simultaneous radiosonde observations (RAOBs) during RHUBC. Examples and statistical results demonstrated the achieved retrieval accuracy and vertical resolution. The 1DVAR retrievals based on GSR observations improved the NWP background up to 5 km, particularly in the lower 3 km. The present implementation achieved a root-mean-square (rms) error with respect to RAOB within 1.5 K for temperature and 0.10 g/kg for humidity profiles of up to 5 km in height, with 2.9 and 2.0 degrees of freedom for signal, respectively. Using the interlevel covariance definition of the vertical resolution, the 1DVAR retrievals showed a < 1-km vertical resolution of up to 5 km for both temperature and humidity profiles. The integrated water vapor obtained from the retrieved humidity profiles showed an rms accuracy within 0.10 kg/m^2 , with small bias (< 0.01 kg/m^2) and excellent correlation (0.96). The method was also successfully applied to data taken by a Radiometrics instrument during the 2010 Winter Olympics [39].

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