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FINAL REPORT OF FY 1999, 2000, AND 2001 ACTIVITIES: CONTINUED DEVELOPMENT OF AN INTEGRATED SOUNDING SYSTEM IN SUPPORT OF THE DOE/ARM EXPERIMENTAL PROGRAM

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Title: Continued Development of an Integrated Sounding System of the DOE/ARM Experimental Program

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SCIENTIFIC GOALS OF RESEARCH

The basic goals of the research are to develop and test algorithms and deploy instruments that improve measurements of atmospheric quantities relevant to radiative transfer and climate research. Primary among these atmospheric variables are integrated amounts of water vapor and cloud liquid, as well as profiles of temperature, water vapor and cloud liquid. A primary thrust of this research is to combine data from instruments available to ARM to maximize their importance in radiative transfer and climate research. To gather data relevant to these studies, participation in field experiments, especially intensive operating periods, as well as the subsequent analysis and dissemination of collected data, is of primary importance. Examples of relevant experiments include several Water Vapor Intensive Operating Periods at the Southern Great Plains Cloud And Radiation Testbed site, experiments in the Tropical Western Pacific such as PROBE and Nauru'99, and experiments at the North Slope of Alaska/Adjacent Arctic Ocean site.

MAJOR ACCOMPLISHMENTS DURING THE PERIOD FEBRUARY 1, 1999 TO JANUARY 31, 2002

- Joint Participation with NASA Goddard Space Flight Center in the Arctic Winter Radiometric Experiment held at the North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) site near Barrow, Alaska in March, 1999. Significant results include the first time operation of 30 microwave, millimeter and sub-millimeter radiometric channels, the correction of the ARM Microwave Radiometer (MWR) to derive accurate measurements in an extreme environment, and the comparison of contemporary absorption models in modeling downwelling radiance.

- The development and publication in the open literature of a flexible diagnostic "tipcal" algorithm for MWR's. (Han and Westwater, 2000). This algorithm has played a crucial role in the analysis of MWR data from the SPG CART site, the NSA/AAO experiment, and also in data taken during the NAURU'99 experiment. The algorithm was transferred to ARM in June, 2000.

- Participation in the NAURU'99 experiment, primarily through the analysis of ARM MWR and radiosonde data. First, it was shown that the MWR was in excellent calibration by two independent methods. Next, the necessity of a correction algorithm for ARCS2 radiosonde data was shown using the MWR data, and finally the Vaisala radiosonde correction algorithm was evaluated, using the MWR data as comparison. Data from the R/V Ron H. Brown and the MIRAI were also used in the radiosonde evaluations.
- A special session devoted to the Atmospheric Radiation Program was organized at the July 2000 meeting of the International Geoscience and Remote Sensing Society (IGARSS'2000) and several prominent ARM scientists are included as invited speakers.
- The ARM-sponsored paper "Ground-Based Remote Sensor Observations during PROBE in the Tropical Western Pacific", by E. R. Westwater et al., received the 15th V. Vaisala Award from the World Meteorological Society, 2001.
- Participation in the Water Vapor Intensive Operating Period 2000 at the Southern Great Plains CART site with a variety of ground-based microwave radiometers, together with the analysis of Liquid Nitrogen calibration sources and "instantaneous" tipcal applied to MWR data.
- Reanalysis of the MWR data taken during SHEBA (Westwater et al., 2001) lead to an investigation of both clear and cloudy absorption algorithms in vapor and liquid retrievals. This study indicated that updates of cloud liquid absorption algorithms were required, especially for cold conditions.
- The ETL scanning 5-mm wavelength radiometer has successfully operated at CART sites in the Tropics, NSA/AAO, and the SGP. This instrument has been demonstrated to be an excellent tool for monitoring sea-air temperature differences, as well as low-altitude temperature profiles.

PROGRESS AND ACCOMPLISHMENTS FROM FEBRUARY 1, 2001 TO JANUARY 31, 2002.

Water Vapor Intensive Operating Period'2000

During September 15-October 5, 2000, the Environmental Technology Laboratory (ETL) participated in the Water Vapor Intensive Operating Period experiments at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART). The principal objective of our portion of the experiment was to evaluate the possibility that microwave radiometers could provide an absolute standard for water vapor measurements. During this experiment, ETL operated its Circularly Scanning Radiometer (CSR) that operated at 20.6 and 31.65 GHz. In addition to ETL instruments, several other Microwave Radiometers (MWRs) were operating during the experiment: these included two ARM MWRs operating at 23.8 and 31.4 GHz and a three channel instrument operating in the same wavelength band (Jet Propulsion Laboratory). We also performed black-body reference calibration test with all radiometers; examples of the data are shown in Figure 1. We analyzed our CSR data and have given the data to the ARM data archive. In addition, we applied the ETL tipcal (Han and Westwater, 2000) calibration method to both of the ARM MWR instruments and have shown that our method reduces the clear-air fluctuation levels in brightness temperature (T_b) by about a factor of two over the original ARM-operational method (Liljegren, 2000) (See Figure 2.) We have applied to all of the data sets contemporary microwave absorption algorithms (Liebe 1989; Liebe et al. 1993; and Rosenkranz, 1998) and have compared the following quantities:

(a) T_b calculated from Vaisala radiosondes vs. radiometer measurements (See Figure 3).
(b) T_b referenced to the common frequency of 23.8 and 31.4 GHz (See Table 1)
(c) Precipitable Water Vapor (PWV) vs. radiosondes
(d) The quantities (a), (b), and (c) for the two Vaisala radiosonde types RS80 and RS90.

Our results were reported at the WVIOP'2000 meeting in Madison, Wisconsin, November, 27-28, 2001. The main conclusions of our study are that

(a) MWR's can provide T_b with an accuracy of 0.5 K; this accuracy should be accurate enough to provide PWV with an accuracy of about 0.3 mm.
(b) Of the absorption algorithms that we evaluated, Rosenkranz (1998) provides the best overall consistency
(c) The ETL "instantaneous tipcal" method should be considered for clear air MWR analysis.

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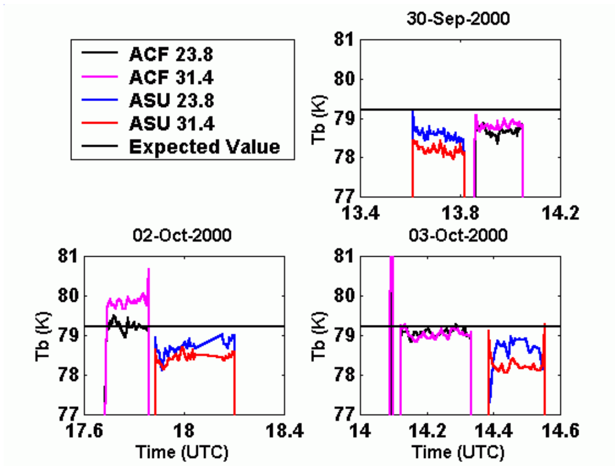


Figure 1. LN2-based absolute calibration tests performed on ARM CF and SU.

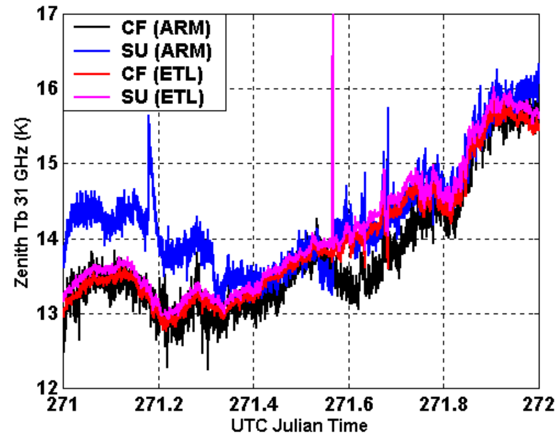


Figure. 2. Time series of 31.4 GHz Tb measured by ARM CF and SU, calibrated following the procedures explained in [2] (ETL) and [3] (ARM).

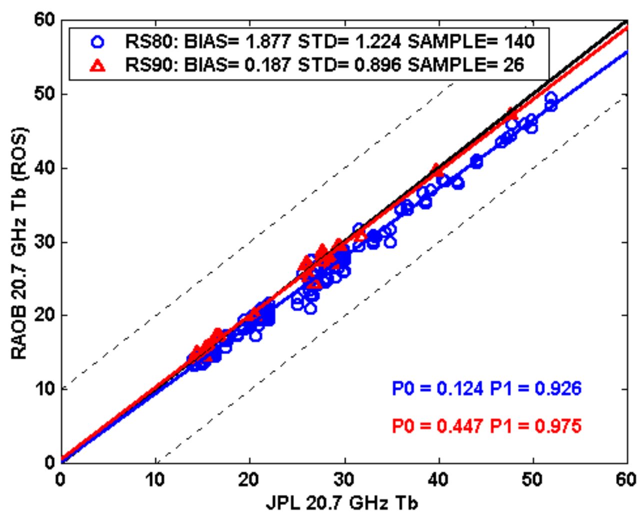


Figure 3. 20.7 GHz Tb measured by JPL vs. computed from RAOBs.

Table 1. Statistical Comparison between Tbs from Different Radiometers during WVIOP 2000. CF = ARM Central Facility; SU = ARM Spare Unit; CSR = ETL Circularly Scanning Radiometer; JPL = Jet Propulsion Laboratory

		23.8 GHz Tb (K)			**31.4 GHz Tb (K)**		
		BIAS	**STD**	**RMS**	**BIAS**	**STD**	**RMS**
CF	**SU**	0.62	0.17	0.64	-0.15	0.08	0.17
CF	**JPL**	-0.27	0.36	0.45	-0.43	0.23	0.49
CF	**CSR**	-0.63	0.53	0.82	-0.56	0.27	0.62
SU	**JPL**	-0.89	0.32	0.94	-0.28	0.23	0.36
SU	**CSR**	-1.25	0.44	1.32	-0.42	0.25	0.48
CSR	**JPL**	0.36	0.47	0.59	0.13	0.33	0.36

Millimeter-wavelength Radiometric Experiment at the NSA/AAO

In March of 1999, ETL and NASA/Goddard Space Flight Center conducted an experiment to evaluate the potential of using millimeter-wavelength radiometers, centered around the water vapor spectral line at 183.31 GHz, to supplement the existing ARM MWR during cold and extremely dry conditions. Based on our analysis of the data obtained during this experiment (both ETL and NASA/GSFC data have been delivered to the ARM archives), our conclusions and recommendations are (Westwater et al. 2001):

(a) The theoretical basis of using 183 GHz radiometers to improve MWR retrievals of PWV at low amounts is sound. A variety of simulations and theoretical considerations all suggest that about 4% accuracy can be obtained during clear conditions, for PWV less than about 20 mm. We show examples of ARM MWR the ETL Circularly Scanning Radiometer (CSR), and the NASA Microwave Imaging Radiometer (MIR) data in Figures 4 and 5 below. Note the significantly enhanced signal to noise radio at low PWV from the millimeter-wavelength radiometers. However, retrieval of PWV using millimeter-wave radiometric measurements is complicated by uncertainties that we outline below.

(b) Ground-based measurement experience of 183 GHz brightness temperatures is much less than that in the 22.235 GHz region. Forward-modeled Tbs differ when different absorption models are used. Our calculations showed that substantial (~10 - 15 K) differences existed between the various models at some of the sub millimeter frequencies. Our estimated radiometric calibration accuracy allowed us to resolve some, but not all, of the problems. For the MWR channels, the Liebe 1993 model agreed with better than 0.1 K bias and a standard deviation of better than 0.2 K rms. However, for the millimeter wave channels, the Liebe 93 model significantly over-predicted Tb by 5.9, 8.8, and 13.3 K. The uncertainties in RAOB measurements of water vapor, coupled with MIR and CSR calibration uncertainties of perhaps 3

K, did not allow us to make a clear choice between the Liebe 89 and the Rosenkranz 98 absorption models. This is not a fundamental limitation of the 183 GHz region, but reflects the fact that a more comprehensive database of Tb and high quality radiosonde measurements is needed.

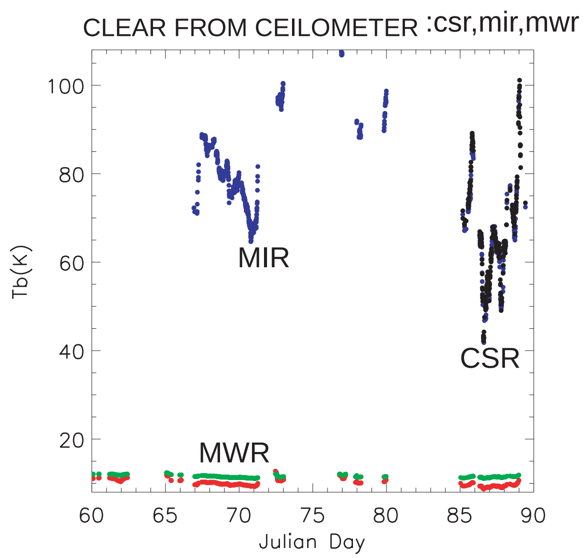
(c) Comparisons of NWS radiosondes launched at Barrow with those of ARM launched at the CART site showed agreement in PWV usually in the range of about 0.05 cm, although simultaneous radiosondes were not available. Because of the long database of NWS radiosondes, and because currently, only one radiosonde per day is launched at the NSA/AAO CART site, a more definitive radiosonde comparison is recommended. Because of the excellent data that is produced by the ARM MWR, perhaps the simultaneous operation of MWRs at the CART site and at the NWS facility, could aid in such a study.

(d) It was discovered during the experiment, that the initial calibration of the ARM MWR was spurious because of poor thermal control. However, as was shown by Han et al. (2000) much of this problem was overcome by the use of instantaneous, rather that averaged, calibration factors were used. Again the crucial importance of tipcal was demonstrated.

(e) For window frequencies and channels beyond perhaps 5 GHz from the absorption line center, sub-millimeter wave radiometer calibration can benefit by the tipcal method. Unfortunately, for the MIR radiometer during our experiment, two-sided tipcals were not possible, and hence some residual uncertainties existed. Again, this is not a fundamental limitation, but is one that can be overcome by equipment design.

We also did an evaluation of a 5-mm scanning radiometer that was operated by ETL during the 1999 experiment. Our report to the presented at the ARM Science Team Meeting (Leuski et al. 2001) indicates that excellent temperature profiles can be derived from a scanning 5-mm radiometer if a radiosonde temperature profile is used for an initial guess. The availability of such data can improve sub-millimeter wave measurement-based retrievals in two ways: the derived profiles can be used to determine real-time mean radiating temperatures for tipcals. Second, the derived profiles can be scaled by MWR PWV measurements to provide a high quality first guess for 183 GHz radiometers. We show in Figure 7 an example of the time-height temperature cross-sections derived from the ETL 5-mm radiometer.

Finally, we have drafted an open literature paper, describing the results of our NSA/AAO experiment, that will be submitted to the Journal of Atmospheric and Oceanic Technology.



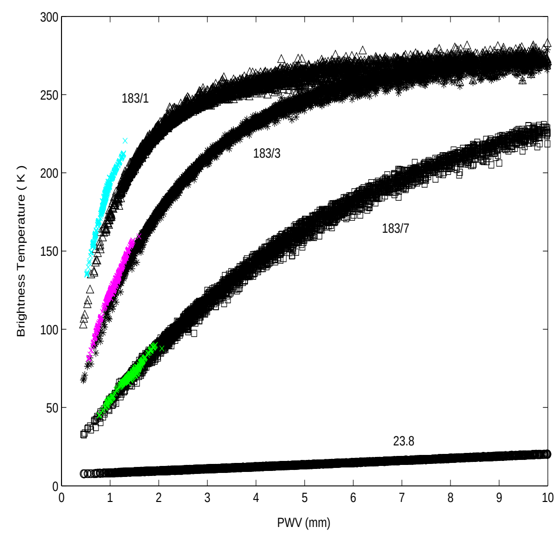


Figure 4. Time series of measured Tb from the ARM MWR, the NASA MIR, and the ETL CSR during March 1999. Clear conditions as determined from ARM ceilometer.

Figure 5. Measured (colored) and calculated (black) Tb vs. PWV for MWR (23.8) and MIR (183 ±1,±3,±7) frequencies.

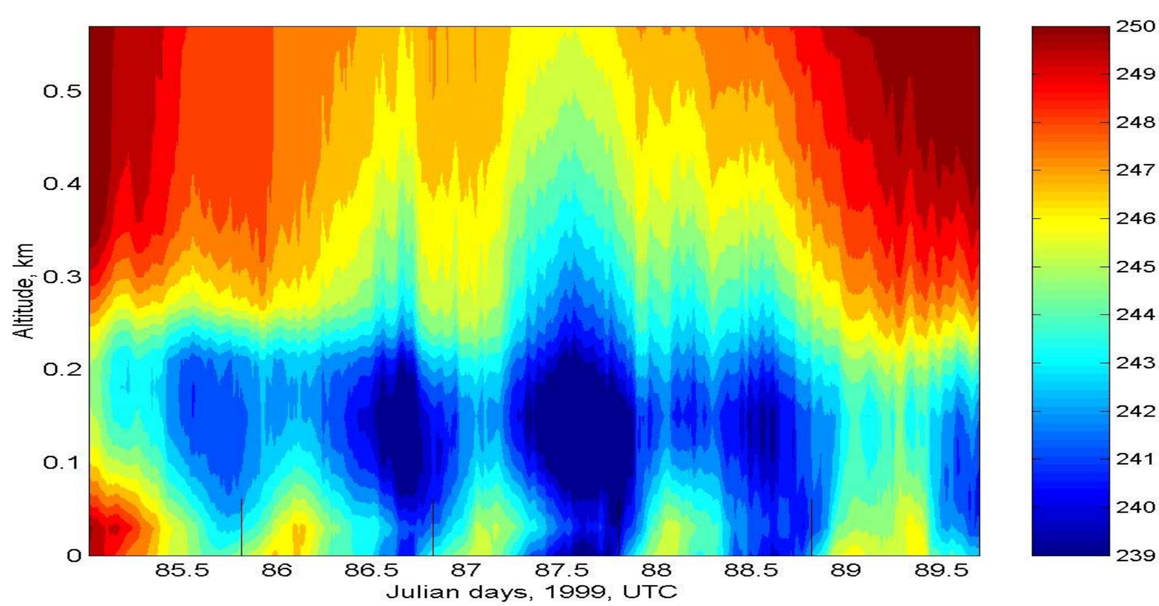


Figure 6. Temperature time-height cross sections derived from the ETL 5-mm radiometer with a first guess derived from RAOBS

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Reanalysis and evaluation of MWR data taken during SHEBA

Because of several concerns raised within the ARM community about differences between MWR and aircraft data taken during SHEBA, we analyzed the most important factors involved in deriving Integrated Cloud Liquid (ICL) from MWR data. This work was published in the open literature (Westwater et al., 2001)

We investigated a variety of factors that enter into the determination of precipitable water vapor and integrated cloud liquid by the ARM dual-channel microwave radiometer that was operated during SHEBA. We first carefully examined the radiometer calibration and concluded it was well calibrated with a 0.3 K rms error. Our main finding is the degree to which both clear air and cloud liquid models have an effect on the retrievals, especially on ICL retrievals. The most significant changes we saw were due to the dry opacity and the cloud liquid absorption coefficient. The dry opacity is best modeled by the Rosenkranz98 since the use of this model resulted in the smallest L retrievals during clear-sky conditions. The cloud liquid absorption is best modeled either by Liebe91 or Rosenberg72 since these two models used experimental data at temperatures below 0 ^{o}C, while Grant57 used data above 0 ^{o}C. Although we found nothing in the original ARM data that was grossly incorrect application of these more recent models reduced the original ARM retrievals of ICL by roughly 20 to 30 %. For the MWR parameters of the SHEBA experiment, we determined that an accuracy of 2.5 K in cloud temperature would result in a 10 g/m^2 accuracy in ICL. The statistical method, used as a default when only *a priori* data are available, yields an accuracy of about 25 g/m^2. Thus, the use of cloud temperature information, derived from both in situ and remote sensors, is important.

We also investigated the use of a single-channel retrieval of L when radiosonde data, interpolated in time, were used to provide measurements of ρ_V, pressure (P), and Temperature (T). In this case, the temporal variability of ρ_V (or PWV) was a limiting factor in retrieval accuracy. In general, the accuracy of the physical retrieval technique depends on the accuracy of background profiles of T, P, and ρ_V, as well as the availability of cloud radar/lidar data.

The change of clear-air absorption models from Liebe87 to Rosenkranz98 has little impact on PWV retrievals except when PWV is low. For PWV < 0.5 cm, the PWV retrievals using Rosenkranz98 may be more than 10% lower than those retrieved using Liebe91.

Uncertainties in the retrieved LWP have a significant impact on cloud microphysical retrievals that combine radar and MWR measurements to determine profiles of liquid water content and cloud droplet effective radius [eg. Frisch et al. 1998]. For microphysical retrievals of single phase liquid clouds, a 20% error in LWP would lead to errors of 20% and ~8% in ρ_L and in effective radius, respectively.

In addition to the algorithm and calibration contributions to radiometer-aircraft differences, spatial variability, even in pure phase stratus clouds, is important. As an example, we looked at an (almost) pure liquid cloud on May 18, 1998, during which there was only a very small variability in radar reflectivity, from a very stable stratus cloud of approximately 500 m thickness. However, even for this case, the 5-min variability in radiometrically-measured L was about 25 to 30 g/m^2, and, for the day, a range of 80 g/m^2 was observed. The 5-min differences are at least as large as the differences between the MWR and the aircraft measurements of L. Thus, although aircraft measurements of cloud liquid profiles are currently the only practical way of verifing L retrievals, the limitations of this validation method are evident.

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Observations from microwave radiometers and radiosondes during Nauru' 99

In our progress reports for 2000 and 1999, we presented our results on comparing data from the ARM MWR and radiosondes from the Ron H. Brown and from the ARCS2 site on the island of Nauru. These results have been collected and an open literature paper has been submitted to the Journal of Atmospheric and Oceanic Technology.

During Nauru'99, we also operated scanning infrared and microwave radiometers for measuring temperature profiles and sea-air temperature difference. We collected MWSR and IRSR measurements with the same time stamp, but we calibrated and processed them independently, obtaining two completely independent retrievals.

Air Temperature profiles

During Nauru99, balloons were launched from 4 up to 8 times per day, while scanning radiometers were working continuously. In order to determine the air temperature profile retrieval accuracy, we compare radiometric estimates with *in situ* measurements. Considering the whole set of RAOBs launched from RHB R/V between 1999/07/03 and 1999/07/07, we can compute statistics of the overall comparison. In Figure 7, we plot the mean value (BIAS), the standard deviation (STD) and the root mean square (RMS) of the difference between radiometric estimations and *in situ* measurements for the whole sample. The MWSR (left panels) shows an air temperature profile retrieval accuracy comparable with the predicted error estimated from the *a priori* data set. The RMS is smaller than 0.35 K up to 500 m, while the BIAS does not exceed 0.16 K. The IRSR (right panels) shows a STD profile that increases with height, reaching almost 0.6 at 500 m, which is consistent with the prediction from the *a priori* data set. On the other hand it is affected by a fairly high BIAS (up to 0.3 K). This might be related to the relatively small sample (22 cases), but also to the IRSR calibration procedures, which relays on simultaneous measurements from a Fourier Transform IR (FTIR) interferometer.

Air-Sea Temperature differences

In Fig.8a we show a five-day time series of air-sea temperature difference retrieved from downward looking MWSR and IRSR scans. For the same time interval, in Fig.8b we show the interface effect, which is the difference between the radiometric skin temperature (from MWSR and IRSR) and the *in situ* bulk temperature measured at 5 m depth. Although there are some differences, the interface effect measured by MWSR and IRSR show a similar behavior. The main departures happen during local daytime (around midnight UTC), remaining qualitatively within the values predicted by the theory. During local nighttime (around noon UTC) the agreement is impressive. We computed statistics that rm that MWSR and IRSR retrievals are in good agreement during nighttime. Both of them appear to measure a sea skin colder then the bulk, with a difference ranging from 0.1 to 0.5 K, except sharp spikes. These are qualitatively and quantitatively in agreement with the theory of cooling heat flux, which predicts a cool skin during nighttime [Fairall et al., 1996; Wick et al., 1996]. Comparing the radiometric estimations with each other we obtain an RMS difference of about 0.15 K. During daytime the situation is much different, with a BIAS and a STD between MWSR and IRSR measurements twice as large than during nighttime. The strong solar radiation causes a “warm layer” at the top of the sea, which leads to a temperature difference between the skin and the bulk (5 m depth) ranging from 0 to 3 K, depending on wind speed and solar flux. This effect has diurnal time scale and so can compensate the cool skin during daytime [Fairall et al., 1996]. Considering the total set, we obtain an RMS difference of 0.28 K.

Conclusions

To our knowledge this experiment was the first comparing two independent scanning radiometers. We have demonstrated that scanning radiometry can provide accurate, continuous, simultaneous estimates of air temperature profile and air-sea temperature difference, and so we believe that scanning radiometry represents a powerful tool to study marine boundary layer environment [Cimini et al., 2001].Future plans rely on the feature of this technique to allow measurements of the water skin temperature without disturbing the skin layer (magnitude orders of microns) at different optical depths (two full magnitude orders: 3 microns for IRSR and 300 microns for MWSR). It might be possible to use simultaneous MWSR and IRSR measurements to examine small-scale skin-temperature gradients, providing precious information for air-sea interaction studies.

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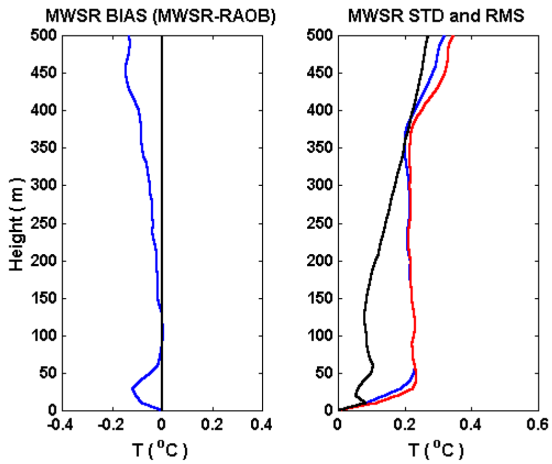

Figure 7a. Statistics of the difference between radiometric estimates of air temperature profile derived by the MWSR and RAOBs.

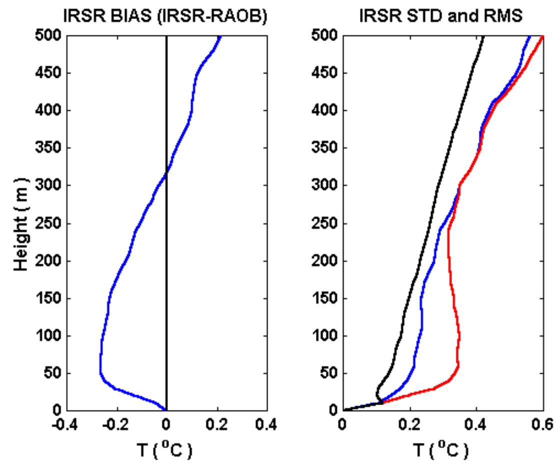

Figure 7b. Statistics of the difference between radiometric estimates of air temperature profile derived by the IRSR and RAOBs.

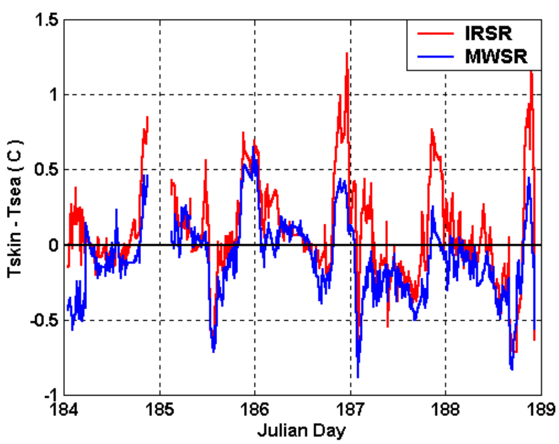

Figure. 8a. Time series of the difference between the skin and the bulk temperature.

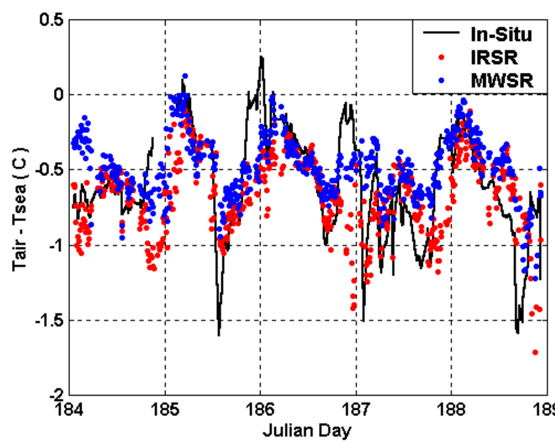

Figure. 8b. Time series of the difference between the air-sea temperature as measured by the radiometric and in situ techniques.

PUBLICATIONS FROM FEBRUARY 1, 2001 TO JANUARY 31, 2002

OPEN LITERATURE PAPERS AND SUBMISSIONS

Ed R. Westwater, Yong Han, Matthew D. Shupe, and Sergey Y.Matrosov (2001): Analysis of integrated cloud liquid and precipitable water vapor retrievals from microwave radiometers during SHEBA, J. Geophysical Research, December 16 issue (volume 106, issue 23, pages 32,019--32,030).

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PRODUCTS DELIVERED

(1) 20.6 and 31.65 GHz Radiometer data taken by the Environmental Technology Laboratory during the 2000 Water Vapor Intensive Operating Period at the SPG CART site

(2) Calibrated submillimeter wavelength Radiometer data taken by the Environmental Technology Laboratory during the 1999 Radiometer Experiment at the NSA/AAO CART site.

(3) Retrievals of temperature profiles derived from 5-mm wavelength scanning radiometer data taken by the Environmental Technology Laboratory during the 1999 Radiometer Experiment at the NSA/AAO CART site.

(4) Recalibrated brightness temperatures, precipitable water vapor and integrated cloud liquid from ARM MWR radiometer data processed by the Environmental Technology Laboratory from data taken during the 1999 Radiometer Experiment at the NSA/AAO CART site

PROGRESS AND ACCOMPLISHMENTS FROM FEBRUARY 1, 2000 TO JANUARY 1, 2001 (from Progress Report delivered to ARM on July 13, 2000)

The NSA/AAO arctic winter radiometric experiment

The Millimeter-wave Radiometric (MMWR)-Arctic experiment was conducted in March 1999 at the North Slope of Alaska/Adjacent Arctic Ocean Cloud and Radiation Testbed (NSA/AAO CART) site. During the experiment, the NASA Goddard Space Flight Center and the NOAA Environmental Technology Laboratory (ETL) deployed four microwave radiometer systems with a total of 24 radiometric channels ranging in frequency from 20.6 GHz to 340 GHz. One of the objectives of this experiment was to evaluate, during extreme cold conditions, the performance of the ARM dual-channel (23.8 and 31.4 GHz) microwave radiometer (MWR) that is routinely operated at the CART site to derive precipitable water vapor (PWV) and cloud liquid water. The

MWR measurements are compared with water vapor measurements using frequency channels around the much stronger 183 GHz water vapor absorption line. NASA's Millimeter-wave Imaging Radiometer (MIR) has three channels near the 183 GHz absorption line and ETL's Circularly Scanning Radiometer (CSR) has seven channels around 183 GHz. In our analysis, we focused on the evaluation of the performance of the ARM MWR by comparing its PWV retrievals with those derived from the 183 GHz channels and radiosondes, which were released at the NSA/AAO CART site.

CALIBRATION METHODS

The MIR and CSR systems both had two external blackbody reference targets, one at the ambient temperature of about -30 C and the other at 26 C. During each scan, the radiometers observed each of the reference targets once and the voltage measurements of the atmospheric portion of the scan were linearly interpolated or extrapolated using these two reference points. For channels with low atmospheric opacity, the measurements were also calibrated by the tipping-curve calibration procedure (Han and Westwater 2000) in which a calibration factor in the radiometer equation is adjusted to yield a straight line of opacity τ vs. airmass a that passes through the origin.

INTER-COMPARISONS OF BRIGHTNESS TEMPERATURE AND PRECIPITABLE WATER VAPOR MEASUREMENTS

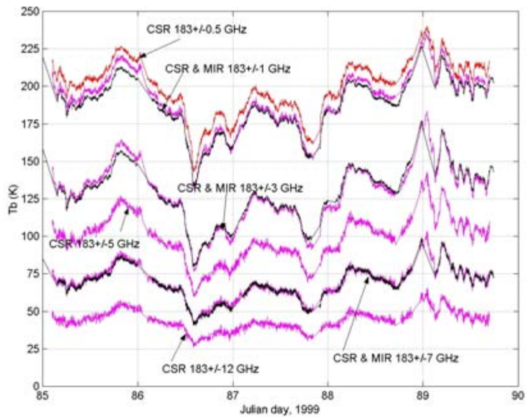
The CSR 183 channels were calibrated first using blackbody reference targets and then re-calibrated using the tipcal method because of a problem in the hot reference load. The MIR 183 channels were calibrated with blackbody references whose characteristics had been carefully evaluated in laboratory tests. The recently constructed CSR did not have the advantage of such testing. Both of the radiometers performed continuous elevation scans, but due to instrument differences, the scan patterns were different, the principal difference being that the CSR performed a symmetrical scan that yielded good data over roughly three air masses. The two MWR channels were initially calibrated and then re-calibrated, using different tipcal averaging methods. As shown in Figs. 1 and 2, the two 183 GHz radiometer systems agreed very well, especially the 183.31 +/- 7 channels, which are used to derive PWV in this study.

However, initial comparisons of the 183 GHz with the original archived ARM MWR brightness temperature Tb measurements showed substantial differences. These differences were the result of a software attempt to compensate for improper temperature regulation at low temperatures. These data were re-calibrated by ETL using an instantaneous calibration factor. Fig. 3 shows Precipitable Water Vapor (PWV) derived from original and ETL-corrected ARM MWR data. As shown in Fig. 4, the corrected ARM MWR data, when converted to is in excellent agreement with both MIR and CSR radiometer data. Comparisons with NWS radiosondes are about two tenths of mm wetter than both of the radiometric measurements.

CONCLUSIONS AND PLANS

The use of the instantaneous tip cal method dramatically improved ARM MWR retrievals, but the it is still an open scientific question whether a 183 GHz radiometer is needed to improve

PWV retrievals at concentrations from 0.8 to 3.0 mm. One stumbling block was the lack of radiosondes at the NSA/AAO site. In the future, we would like to repeat the experiment, but with a minimum of 4, and perhaps as many as 6 launches a day.



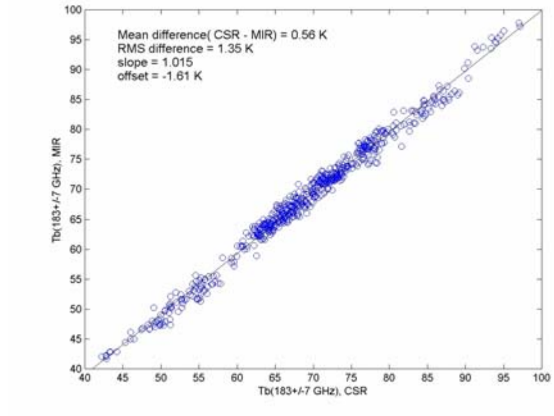
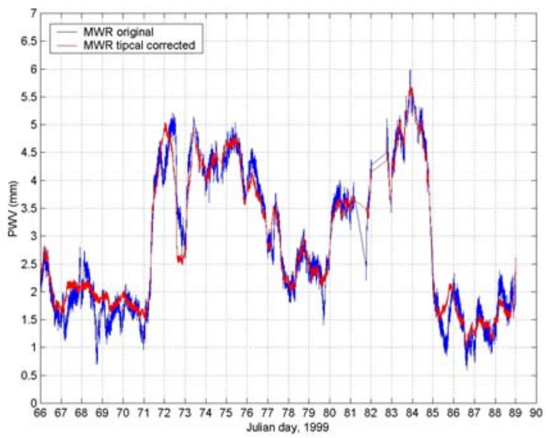


Fig. 1. Time Series of T_b around 183 GHz. Red-CSR; Black-MIR. PI's: Y. Han and E. Westwater, CIRES, Univ. of Colo./NOAA, 2000.

Fig. 2. Statistics of comparisons between CSR and MIR 183.31   7 channels. NSA/AAO March 7-30, 1999. PI's: Y. Han and E. Westwater



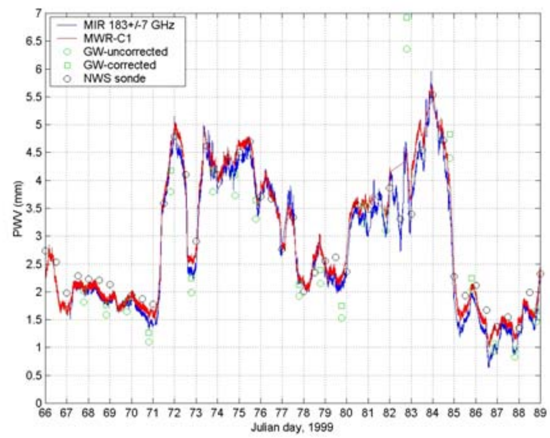


Fig. 3. Time series of PWV obtained from ARM original and re-calibrated data. NSA/AAO PI:s. Y. Han and E. Westwater (CIRES), 2000.

Fig. 4. Time Series of MIR (blue) and CSR (red). NSA/AAO. PI's: Y. Han and E. Westwater.

MICROWAVE RADIOMETERS AND RADIOSONDES DURING NAURU' 99

Previous experience, both in the PROBE experiment in the Tropical Western Pacific and during Water Vapor Intensive Operating Periods (WVIOPs) at the ARM Southern Great Plains CART site, indicated the need for adjustments to Vaisala Humicap RS80 humidity soundings. The need for such corrections has been identified by measurements of water vapor by microwave radiometers and the subsequent adjustments by scaling of water vapor profiles. During Nauru-99, a variety of ground- and ship-based instruments were available to test the quality of radiosonde (RAOB) soundings in the tropical environment around the island of Nauru. In particular, nearly simultaneous RAOB soundings from the Atmospheric Radiation and Cloud Station (ARCS-2) and from the R/V Ronald H. Brown (RHB) were available. In contrast to the earlier PROBE experiment, the lot numbers of the Vaisala RAOBs were available for subsequent analysis. A variety of remote sensing and *in situ* measurements were also available. These instruments at ARCS-2 include the Radiometrics Microwave Radiometer (MWR) and a Vaisala ceilometer. Of special interest to our analysis was our independent calibration of the MWR that used a blackbody calibration target cooled by Liquid Nitrogen (LN2). The RHB arrived at Nauru on July 5 and assumed a stationary position close to the ARCS-2 location approximately 1 km away. The first indication that there were substantial differences between ARCS-2 and RHB radiosondes was observed on the very first day that the ship was in close proximity to the island. Fig. 5 shows a time series of brightness temperatures (Tb) observed by the MWR at 23.8 and 31.4 GHz, and Tbs calculated from various radiosonde profiles. The Tb model used in these calculations was the latest Rosenkranz (1998) absorption model. Somewhat surprisingly, the RAOB data from the RHB agreed much better with the MWR than those from the co-located ARCS-2 soundings. The triangles show data that were calculated from corrected ARCS-2 soundings using a procedure described by Lesht (1999).

The results of Fig. 5 showed that, at the very least, there were significant differences between RAOBs that were launched at nearly the same time from the RHB and from the ARCS-2. A change in experimental plan was made and for five soundings, RAOB packages from the two sites were interchanged. This time, the original RHB radiosondes were in close agreement with the MWR, while the original ARCS-2 RAOBS, now launched from the RHB, were in substantial disagreement with the MWR. Thus, when the RAOBs were exchanged, the results were consistent with a RAOB problem, not a site problem. Again, using the procedure of Lesht (1999), the corrected RAOBs were in good agreement with the MWR Tbs. The reasons for the problem are now known to be associated with contamination of the RS80 humidity element as it ages. Later on in this report, we present results evaluating the accuracy of the RAOBS and their correction, as a function of RAOB age.

Many of our comparisons rely on the accuracy and consistency of the ARCS-2 MWR. During this experiment, the radiometer was run in a nearly continuous tip cal mode. When the sky conditions were favorable, as determined by symmetry of radiometry scans, the radiometer continued scanning at angles corresponding to the air masses 1, 1.5, 2.0, and 2.5 (elevation angles of 90, 41.8, 30, and 23.6 degrees). When clouds were present, angular symmetry was destroyed, and the radiometer went into a zenith-observing mode. Since, we can not calculate brightness temperatures from RAOBs during cloudy conditions, we will focus on clear conditions only; another reason for focusing on clear conditions is that during these conditions, calibration can be done on a nearly continuous basis. The original ARM calibration algorithm was used on the data and excellent data were obtained. We applied the ETL calibration method (Han and Westwater, 2000) to the same tip cal data, and nearly identical results were obtained. Our results, requiring beam width and angular-dependent mean radiating temperatures, use equivalent zenith brightness temperatures as a measure of calibration quality. Rms departures of this measure were frequently better than 0.2 K, indicating a high degree of atmospheric stratification and antenna beam symmetry. We also performed a LN2 calibration experiment, in which a blackbody reference target (or load) was filled with LN2 and placed over the MWR. The measured Tbs during this experiment are shown in Fig. 6. For the first two minutes after the load was inserted, the measured Tbs were about 79.6 K which is close to the expected value of 79.4 ± 1.9 K (F. Solheim, private communication). After the first two minutes, moisture condensed on the underside of the Styrofoam container and increasingly spurious observations were obtained. However, the few minutes of good measurements indicated that the MWR was accurate to within ±1K. This single target calibration measurement, together with the continuous high quality of tip cals, indicated that the MWR could be used as a comparison standard for the experiment.

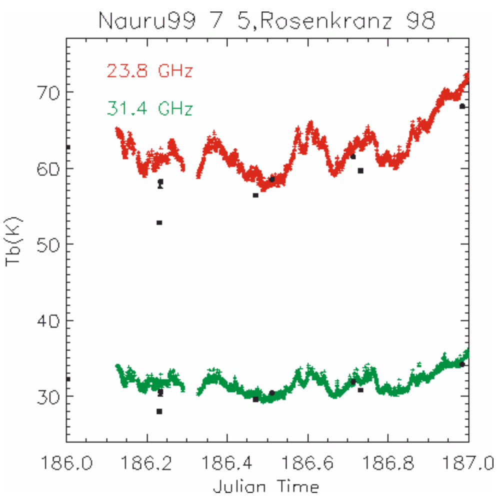


Fig. 5. Time series of MWR Tb during July 5, 1999. ■ - calculated from original ARCS2, RAOBS ► - calculated from corrected ARCS2 RAOBS, ˜ - calculated from Ron. H. Brown RAOBS. Absorption model: Rosenkranz (1998). PI: E. R. Westwater, CIRES/Univ. of. Colo/ NOAA-ETL, 2000.

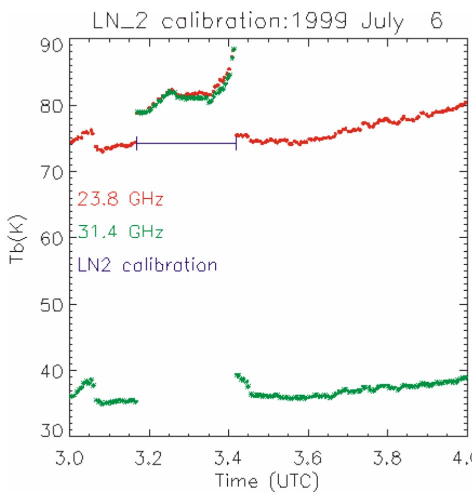


Fig. 6. Results of the LN2 calibration during Nauru'99, July 6, 1999. PI: E. R.. Westwater, CIRES/ Univ. of Colo./NOAA-ETL, 2000.

The manufacturers of Vaisala radiosondes have developed a proprietary algorithm to correct for the dry bias problem (Lesht, 1999). We have used a version of the algorithm that makes the correction based only on the age of the RAOB. Since we were also worried about diurnal effects, we divided our data samples into day and night subsets, and for these subsets compared Tbs measured by the ARM MWR with calculations, based on the Rosenkranz (1998) absorption model for both the original and corrected radiosondes. Our analysis showed that no statistically significant effects were present. Fig. 7 shows a scatterplot showing the comparison of corrected and uncorrected Tb calculations vs. the MWR Tbs for the period of June 15 to July 15, 1999. Since the performance of the algorithm as a function of RAOB age was an important issue, we plotted the differences between measurements and calculations as a function of RAOB age. The results, shown for ARCS-2 in Fig. 8, were surprising, and showed that although the algorithm, in general, improved the results, the improvement did not always occur for all RAOB lots. In fact, for the RAOB lots corresponding to the age around 360 days, the correction worsened the results.

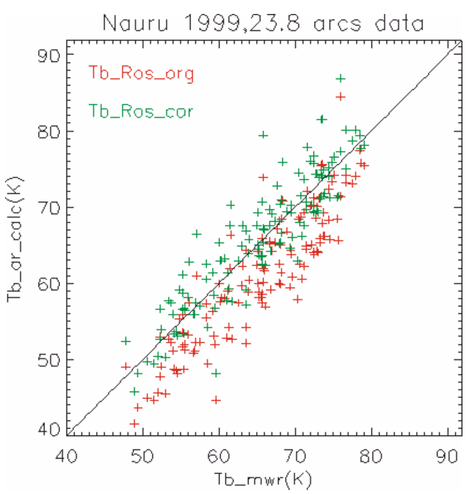


Fig. 7. Comparison of Tb calculated from original (red) and corrected (green) RAOBs vs. ARM MWR data at 23.8 GHz. Nauru'99 , June 15-July 15, 1999. Absorption model - Rosenkranz (1998). PI: E. R. Westwater, CIRES, Univ. of Colo./NOAA-ETL, 2000.

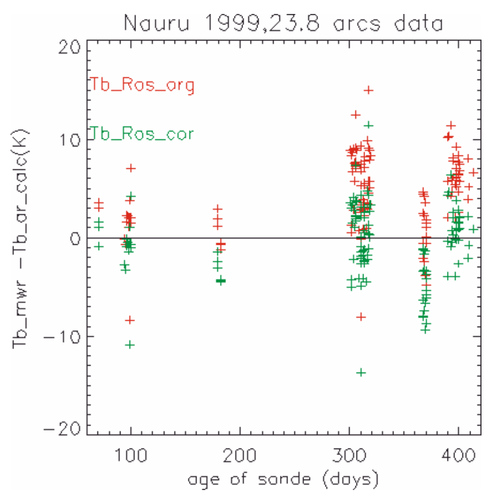


Fig. 8. Difference between measured and calculated Tbs from original (red) and corrected (green) RAOBs. Absorption model: Rosenkranz (1998). Nauru'99, June 15-July 15, 1999. PI: E. R. Westwater, CIRES, Univ. of Colo./NOAA-ETL. 2000.

CONCLUSIONS, DISCUSSION, AND PLANS

The ARM MWR operating at the ARCS-2 provided an excellent data set for the entire Nauru-99 experiment. The calibration accuracy was verified by a LN2 blackbody target experiment and by consistent high-quality tip cals throughout the experiment. The data thus provide an excellent baseline for evaluation of the quality and consistency of Vaisala RAOBs that were launched from ARCS-2. Our preliminary results indicate that substantial errors, sometimes of the order of 20 % in PWV, occurred with the uncorrected RAOBs. When the Vaisala correction algorithm was applied to the RAOBs, better agreement with the MWR was obtained. However, the improvement was noticeably different for different RAOB lots and was not a monotonic function of RAOB age.

We have also performed our brightness temperature calculations with two other absorption algorithms - Liebe 87 and Liebe 93. The Liebe 87 model was in close agreement with Rosenkranz 98, but neither was in agreement with Liebe 93. One task in completing this study will be to use scaled RAOB data using all of the models to calculate infrared radiance and then to compare these calculations with Atmospheric Emitted Radiance Interferometer (AERI) observations from the ARCS-2 site and Fourier Transform Infrared Radiometric observations from the Ron H. Brown. After completion of the statistical analysis of the comparisons with the infrared data, we plan to publish our results in the open literature.

We also plan to participate in the Water Vapor Intensive Operating Period'2000 to be held at the SGP CART site. The primary issues of interest are calibration of the ARM MWR, comparison with the ETL scanning radiometers, and the evaluation of several calibration targets using LN2 as a coolant. We have recently purchased a very high quality microwave calibration target and will deploy it during the experiment.

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PROGRESS AND ACCOMPLISHMENTS FROM FEBRUARY 1, 1999 TO JANUARY 31, 2000 (from Progress Report delivered to ARM on June 26, 1999)

1. Accomplishments in "Bulletized Form". Just a sentence or two description of specially significant results obtained in the previous twelve months.

- Joint Participation with NASA Goddard Space Flight Center in the Arctic Winter Radiometric Experiment held at the NSA/AAO site near Barrow, Alaska in March, 1999. Significant results include the first time operation of 30 microwave, millimeter and sub-millimeter radiometric channels, the correction of the ARM Microwave Radiometer (MWR) to derive accurate measurements in an extreme environment, and the comparison of contemporary absorption models in modeling downwelling radiance.

- The development, publication in the open literature, and application of a flexible diagnostic "tip cal" algorithm for MWR's. This algorithm has played a crucial role in the analysis of MWR data from the SPG CART site, the NSA/AAO experiment, and also in data taken during the nauru'99 experiment. The algorithm was transferred to ARM in June, 2000.

- Participation in the nauru'99 experiment , primarily through the analysis of ARM MWR and radiosonde data. First, it was shown that the MWR was in excellent calibration by two independent methods. Next, the necessity of a correction algorithm for ARCS2 radiosonde data was shown using the MWR data, and finally the Vaisala radiosonde correction algorithm was evaluated, using the MWR data as comparison. Data from the R/V Ron H. Brown and the MIRAI were also used in the radiosonde evaluations.

- A special session devoted to the Atmospheric Radiation Program was organized at the July 2000 meeting of the International Geoscience and Remote Sensing Society (IGARSS'2000) and several prominent ARM scientists are included as invited speakers.

Progress and accomplishments during last twelve months (or from beginning of the current effort whichever is shorter). Expectation here is no less than one page and no more than 5 pages double spaced not counting figures/graphics

Measurements of water vapor at the North Slope of Alaska and Adjacent Arctic Ocean (NSA/AAO) CART site in Barrow, Alaska, are a potential problem because of the difficulty of radiosondes to measure low amounts of vapor during cold and extremely dry conditions. The applicability of MWR scaling to radiosondes is questionable because of the low sensitivity of these instrument during dry conditions. It has been suggested by the ARM Instaneous Radiative Flux Working Group and others that measurements of brightness temperature around 183 GHz could be used to scale radiosondes during the coldest and driest periods. However, the millimeter wavelengths are vulnerable to cloud effects from both liquid and ice. During March 1999, we participated in the joint NASA/NOAA Millimeter wave Arctic Experiment to evaluate microwave and millimeter wave radiometers during extremely cold conditions.

ETL tested, both in an experiment at the Boulder Atmospheric Observatory and during the two Water Vapor Intensive Operating Periods in 1996 and 1997, a 5-mm scanning radiometer that measures low-altitude temperature profiles; both profiles of lapse rate and absolute temperature can be measured with the instrument. Results of these tests were published in the open literature. In addition, the ETL scanning radiometer was operated at the NSA/AAO in March 1999.

APPLICATION OF TIPPING CALIBRATION METHOD TO ARM MWR DATA

Results of the 1997 WVIOP (Westwater et al., 1998A; Westwater et al., 1998 B) indicated that the ARM MWR produced measurements of PWV that were about two millimeters higher than measurements from a variety of other independent instruments, such as two ETL MWR's, two Global Positioning Systems, and ARM Balloon Borne Sounding Systems (BBSS). These results were in contrast to results obtained during WVIOP'96, in which ETL and ARM MWR's were basically in agreement. Based on a newly developed correction algorithm to the tipping calibration method (Han and Westwater, 1999), we applied a variety of corrections to the ARM MWR data, and found that, in particular, the beamwidth correction accounted for a significant part of the bias. What was more surprising, we found that the ARM MWR tipping calibrations were inconsistent with each other; i.e., the data at 2, 2.5, and 3.0 airmasses, when normalized to zenith, were not in agreement. If the data at 1 and 2 airmasses were used, ARM and ETL radiometers agreed; if data at 2.5 and 3 airmasses were used, the radiometers did not agree. However, since the 1998 progress report, the BBSS data have been revised by Lesht (1999) and now agree better with corrected ARM MWR data.

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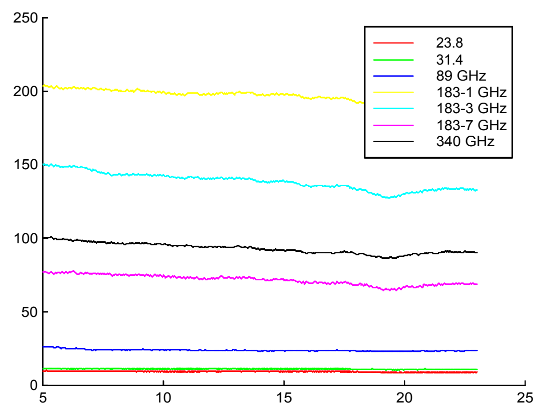
PARTICIPATION IN NSA/AAO WATER VAPOR EXPERIMENT

There are concerns about the ability of the ARM Microwave radiometer (MWR) to derive accurate measurements of Precipitable Water Vapor (PWV) during the coldest and driest of conditions, because of the relatively weak response of the 22 GHz emission to PWV amounts below about 5 mm. A theoretical analysis (Jones and Racette, 1998) indicated that measurements of atmospheric emission in the mm wavelength region can provide increased accuracy of PWV determination during these cold conditions. During March 1999, scientists from NASA/Goddard Space Flight Center and from NOAA/ETL participated in the Millimeter-wave Radiometric (MMWR)-Arctic experiments to determine if radiometric measurements around the much stronger 183 GHz absorption line can yield improved measurements of PWV during the extreme cold conditions. Instruments deployed are shown in Table 1.

Table 1. Instruments deployed during the Millimeter Wave Radiometric Arctic Winter Experiment

Instrument	Organization	Frequencies (GHz)
Millimeter-wave imaging Radiometer (MIR)	NASA/GSFC	89, 150, 183.31 ± (1, ± 3, ± 7), 220, 340
DOE Multichannel Microwave Radiometer (DoER)	NASA/GSFC	20.735, 21.485, 22.235, 22.985, 23,735, 36.5, and 89
Circularly Scanning Radiometer (CSR)	NOAA/ETL	20.6, 31.65, 183.31 ± (0.5, ± 1, ± 3, ± 5, ± 7, ± 12, ± 15), 325 ± (1, ± 3, ± 8), 340 H & V, 10 µm
Scanning O2 Radiometer	NOAA/ETL	60.5
Vaisala and chilled mirror surface met.	NOAA/ETL, NCAR	
Vaisala and chilled mirror radiosondes	ARM	



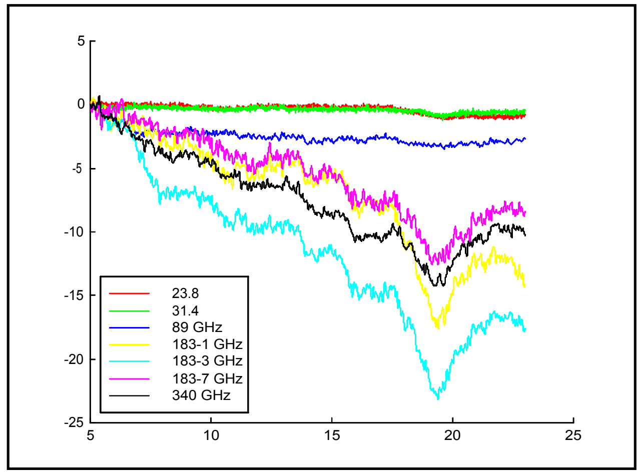


Figure 1: The response of seven of the channels are plotted as differences in brightness temperature referenced to 5:00 UTC on March 11. The microwave channels exhibit a small response whereas the mm-wave channels detect the changes in the atmosphere on this clear dry day.

Presently, ARM operates at their NSA/AAO CART site a MWR which measures downwelling radiation at 23.8 and 31.4 GHz from which PWV and LWP are retrieved. Data from this instrument represent the baseline from which millimeter-wave observations will be compared. For PWV amounts greater than 1 cm, this pair of frequencies is able to obtain accurate measurement. When the atmosphere becomes very dry the absorption around the 22.235 GHz water vapor line becomes weak. Thus, the relative uncertainty in retrieved PWV increases with decreasing water vapor. The 183 GHz absorption line is about 100 times stronger than that of the 22.231 GHz line. Improved estimates of low PWV can be obtained by taking advantage of the much stronger 183 GHz water vapor line. A preliminary look at our data demonstrates the greater sensitivity of the mm-wave frequencies. Responses of seven of the radiometer channels from March 11 are plotted in Figure 1. The PWV for this day is less than 2 mm and the temperatures were colder than -37 oC. The brightness temperature values at 5:00 UTC have been subtracted and the temperature differences for the remainder of the day are shown. The response of the channels at 23.8 GHz and 31.4 GHz vary by no more than ~1 degree. The mm-wave channels on the other hand exhibit variations of 10 to 20 degrees. Further analysis of this data will yield estimates of the errors associated with retrieving PWV using various combinations microwave and mm-wave frequencies. These observations confirm the greatly enhanced sensitivity of the millimeter wave observations, relative to the ARM MWR, at low temperatures and dry atmospheres.

References

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P. E. Racette, E. R. Westwater, Y. Han, Al Gasiewski, Ed Kim, M. Klein, K. Widener, B. Zak (1999): Millimeter Wave Radiometric Arctic Winter Experiment. Proc. 9th ARM Science Team Meeting, San Antonio, Texas, March 22-26, 1999 (in press).

TESTING OF 5-MM SCANNING RADIOMETERS AT NSA/AAO

An open literature paper was published describing the results of an experiment conducted from November 1996 to January 1997 at the Boulder Atmospheric Observatory (BAO) (Westwater et al., 1999). In this experiment, data from two scanning 5-mm radiometers and a Radio Acoustic Sounding System were compared against in situ tower data. In addition, we operated the ETL 5-mm scanning radiometer during the March 1999 experiment at the NSA/AAO. Data from the ATTEX 5-mm radiometer, purchased by ARM from a Russian firm, the ETL instrument, tower, and radiosondes, were taken and will be compared to determine the accuracy of the systems.

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E. R. Westwater, Y. Han, V. G. Irisov, V. Leuskiy, E. N. Kadygrov, and S. A. Viazankin (1999): Remote Sensing of Boundary-Layer Temperature Profiles by a Scanning 5-mm Microwave Radiometer and RASS: Comparison Experiment., J. Atmospheric Oceanic Technology, **16(7)**, 805-818.

FY 2000 PLANS

Southern Great Plains CART

A high quality calibration reference source for MWRs operating has been purchased and will shortly be delivered to ETL. We will take the calibration reference source to the SGP Central Facility and conduct calibration experiments with the ARM MWR.

We will change our focus from measurements of water vapor to those of clouds. The WVR has already been shown to measure liquid water path and, with the addition of ceilometer data, to yield a first-order profile of liquid water density (Han and Westwater, 1995). Although WVR data is widely used for the determination of liquid water path, only a very limited amount of *in situ* ground truth data has been used for verification. We propose to participate in cloud IOPs where *in situ* and other sources of cloud data will be available. The newest source of data will be that the CART cloud radar, which will add important information on cloud thickness. In addition, we plan to evaluate a technique using both GPS and MWR data to derive cloud liquid.

North Slope of Alaska

We will complete the analysis of the radiometer data taken during the March 1999 NSA/AAO Millimeter wave Arctic Experiment and make recommendations to ARM about 183 GHz deployment. An open literature article will also be submitted.

We will complete the analysis of the 5-mm scanning radiometer data taken during the March 1999 NSA/AAO and make recommendations to ARM about further operation with the ATTEX instrument.

We will also investigate the microwave radiative properties of arctic clouds, based on the wide variety of multi-frequency observations that were taken in March 1999.

Based partially on the results of the 1999 experiment, we will also recommend to ARM further experiments to study arctic clouds, temperature, and water vapor.

PUBLICATIONS FROM FEBRUARY 1, 1999 TO JANUARY 31, 2000

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E. R. Westwater, Y. Han, J. B. Snider, K. S. Gage, W. Ecklund, A. Riddle, J.H. Churnside, J. A. Shaw, M. J. Falls, C. N. Long, and T. P. Ackerman (1999):Ground-Based Remote Sensor Observations during PROBE in the Tropical Western Pacific. *Bull. Amer. Meteor. Soc.*, **80(2)**, 257-270. **(Received 15th V. Vaisala Award from the World Meteorological Society, 2001)**

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CONFERENCE PROCEEDINGS

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