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Final Report

Millimeter-Wave Radiometer for High Sensitivity Water Vapor Profiling in Arid Regions


DOE Contract#: DE-FG02-02ER83440

EXECUTIVE SUMMARY

The Department of Energy (DOE) awarded a Phase II SBIR contract to ProSensing on July 1, 2003 to develop an operational 183 GHz water radiometer for ultra sensitive measurement of atmospheric water vapor column and integrated liquid water content in arid climate. The instrument is intended to be deployed at the North Slope of Alaska DOE ARM (Atmospheric Radiation Measurement) program site to extend radiometric water vapor monitoring through the driest, winter months. This report summarizes the results and accomplishments of this project.

As part of this Phase II SBIR contract, ProSensing Inc. developed a ground-based and an airborne version of a four-channel 183 GHz (G-band) water Vapor Radiometer (GVR). The ground-based unit (Ground GVR) was completed in early 2005 and in April that year was deployed at the Great White DOE North Slope of Alaska ARM site, where it continuously collected data for over a year. In June 2006 the instrument was returned to ProSensing for minor maintenance and improvements and was returned in August for a second year of continuous operation. At the time of this report, the instrument was collecting data at the Barrow, AK ARM site. A more compact airborne 183 GHz radiometer (Airborne GVR) was completed and ground-tested in early 2006 and was successfully test flown onboard the National Research Center (NRC) of Canada Convair aircraft in August 2006. The Airborne GVR was returned to ProSensing for calibration in September, but was returned in October to be reinstalled in the NRC Canada Covair to participate in the NASA CloudSat satellite validation flights through the spring of 2007. Details of the radiometer design and example data were documented in a paper that has been accepted to be published in the TGARS (Transactions on Geoscience and Remote Sensing) journal (original manuscript attached). The validation of the data collected in Barrow, AK was described in a separate TGARS article (also attached), written by Cadeddu et al, and also accepted for publication. The ground instrument is planned to be permanently installed at the NSA ARM site in the fall of 2007.

Through November 10, 2006, \$119,649 has been spent on parts, \$192,579 on direct salaries with total of \$683,946 out of the budgeted \$683,845 spent including over-head and administrative expenses. ProSensing also invested additional company funds to support the project. A Thermotron environmental chamber was purchased and installed for \$20,583.62 and since August 2006, \$13,329 company R&D funds have been spent to publish a refereed journal paper on the Ground GVR, to support the Barrow measurements with the Ground GVR, and on the calibration and the airborne campaign with the Airborne GVR onboard the NRC Canada Convair aircraft.

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Manuscript submitted to the Transaction on Geoscience and Remote Sensing Journal:

Compact 183 GHz Radiometer for Airborne and Ground-Based Water Vapor and Liquid Water Sensing

Andrew L. Pazmany


Abstract - ProSensing Inc. has developed a G-band (183 GHz) water Vapor Radiometer (GVR) for long-term, unattended measurements of low concentrations of atmospheric water vapor and liquid water. Precipitable water vapor and liquid water path are estimated from zenith brightness temperatures measured from four double-sideband receiver channels, centered at 183.31 ± 1 , ± 3 and ± 7 , and ± 14 GHz. A prototype ground-based version of the instrument was deployed at the DOE ARM program's North Slope of Alaska site near Barrow AK in April 2005, where it collected data continuously for one year. A compact, airborne version of this instrument, packaged to operate from a standard 2-D PMS probe canister, has been tested on the ground and is scheduled for test flights in the summer of 2006. This paper presents design details, laboratory test results and examples of retrieved precipitable water vapor and liquid water path from measured brightness temperature data.

Index Terms—Millimeter wave radiometry, remote sensing, precipitable water vapor and liquid water path retrieval.

1. I. Introduction

Most ground-based atmospheric water vapor radiometers are designed to measure blackbody radiation near the 22 GHz water vapor absorption line, despite the fact that the 183 GHz line is about 50 times more sensitive to changes in precipitable water vapor (PWV) and over 10 times more sensitive to liquid water path (LWP). This preference is primarily because the center of the 183 GHz line saturates at a relatively low 2 mm PWV, making this frequency unsuitable for general purpose, year round observations. Furthermore, 183 GHz instruments have been considerably more difficult and expensive to build due to the historic lack of off-the-shelf microwave components above 100 GHz.

In arid regions—including high latitudes, deserts, or above the atmospheric boundary layer, PWV measurement accuracy of a few tenth of a millimeter is required to monitor changes in humidity. In dry conditions, 183 GHz brightness temperature changes by approximately 20 K for each millimeter change in total water vapor, so an instrument with a 1 K radiometric measurement precision can detect 0.05 mm change in the vapor column. This same measurement resolution would require a precision of less than 0.02 K with a 22 GHz radiometer—a level of precision that only a handful of radiometers have been able to approach, requiring an expensive development effort [1]. On the other hand, the 1 K precision needed at 183 GHz is a routine radiometer design goal. Nevertheless, at millimeter wavelengths, front-end losses, effects of radome reflections and the complexity of incorporating stable calibration loads in the design, present significant design challenges. Several recent advances however make the development of a 183 GHz radiometer more practical today. These include the commercial availability of subharmonically

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pumped Schottky mixers and conical feed horns, and an ultra stable radiometer design developed at K-band by Tanner [1].

The majority of 183 GHz radiometers constructed to date were custom designed and developed for spaceborne operation (e.g., one channel of the NOAA-15 Advanced Microwave Sounding Unit, AMSU) or were built to operate as part of ground-based millimeter wave interferometric telescopes such as the James Clark Maxwell Telescope (JCMT) [2] and the Atacama Large Millimeter Array (ALMA) telescope to track optical path variations. A ground-based instrument was also constructed in the late 90s and was operated jointly by ETL and NASA in March 1999 in Barrow, Alaska to compare the ability of 22 GHz and 183 GHz radiometers to measure water vapor in winter arctic conditions [3]. More recently, the Ground-based Scanning Radiometer [4] participated in a late winter Intensive Observation Period (IOP) at the DOE North Slope of Alaska ARM site in 2004.

This paper describes a compact, turn-key, four-channel G-band (183 GHz, 3 mm wavelength) water vapor radiometer, designed for long-term unattended operation on the ground (Ground GVR), or to operate from an aircraft in a standard 2-D PMS probe canister (Airborne GVR).

2. II. Ground-Based GVR Description

A simplified block diagram of the GVR receiver is shown in Fig. 1. The downwelling atmospheric radiation is captured by a 10 cm diameter, 1.7° beamwidth, 90 degree parabolic metal mirror and focused to a corrugated feed horn. A subharmonically pumped mixer, using a 91.655 GHz LO signal, downconverts the upper and lower sidebands to baseband, where a broad-band low-noise amplifier increases the noise signal power and sets the receiver noise temperature. A broadband power splitter divides the amplified signal between four channels before filtering. The center frequency and bandwidth of the filters are 1/0.5, 3/1, 7/1.4 and 14/2 GHz respectively. The band-limited noise signals are square-law detected, converted to a TTL pulse-train using highly linear Analog Devices AD650 voltage-to-frequency converters (20 ppm nonlinearity and less than 0.3 ms response time to a step input as configured), and frequency-counted using an FPGA processor. This frequency counting effectively integrates and measures the square-law detector voltage, or equivalently the noise power. The measured noise power from the four channels together with the instrument temperature readings are time stamped and transmitted to a data logger PC via an RS232 (or optional RS422) bus.

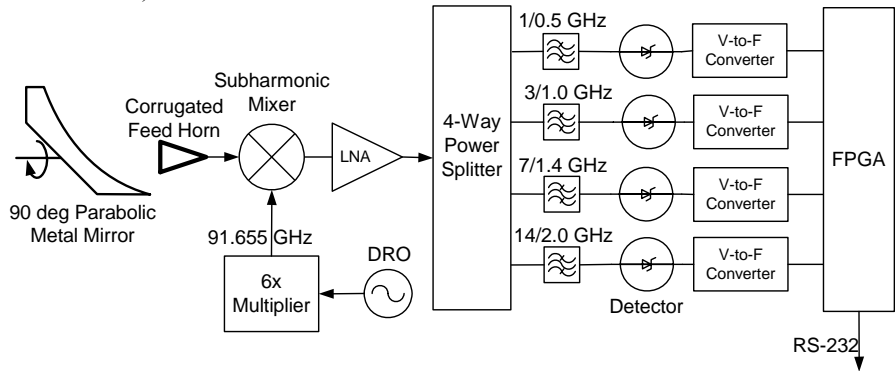



Fig. 1. GVR simplified component level block diagram.

The sensitivity of the GVR receiver to physical temperature changes is approximately 80 K/K, meaning that the perceived scene temperature changes 80 K if the temperature of the broadband amplifiers (component plate) changes by 1 K. Consequently, stabilizing the receiver components, particularly the amplifiers, and frequently monitoring receiver gain and offset, is essential.


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To stabilize the temperature of the receiver components, the packaging technique described in [1] was employed, consisting of an insulated cold-plate in a box, in a temperature controlled enclosure. The resulting component plate temperature stability limited the effect of receiver-gain rate-of-change to below 100 K/Hr, requiring system gain and offset calibrations only a few times a minute to achieve a sub-K measurement precision.

Since neither noise sources nor low-loss fast switches are readily available at G-band, external (to the antenna horn) hot and warm calibration absorbers were required to track the receiver gain and offset. The metal mirror of the Ground GVR is rotated with a stepper motor to point the radiometer antenna beam to the calibration loads. The hot and warm calibration absorbers were constructed using the Firam-160 absorber, with the hot load packed in an insulated box covered with a 1 mil Mylar window (~0.03 dB loss factor) tilted by 4°. The Mylar window is tilted by about twice the antenna beamwidth to minimize the reflection of the receiver emitted radiation back to the receiver. The hot load is convection heated to a uniform temperature of 343 +/-0.5 K, while the warm load is left to soak to the temperature of the outer enclosure, which is heated with a PID controller to 293 K. The temperature of the absorbers is monitored with RTD temperature sensors and the readings are recorded along with the receiver noise power data. The temperature sensors are calibrated with a laboratory calibration certified Hart Scientific 1502A meter and 5623A probe to better than 0.1 K accuracy.

Special care was also taken to maximize the antenna beam efficiency. The 10 cm diameter 90° optical quality metal collector mirror has an RMS surface roughness of less than 175 Angstroms (175×10^{-10} m), a negligible 0.001% of the radiometer wavelength. Since there is no feed-horn or sub-reflector blockage with a 90° mirror, the only other critical factor for maximizing beam efficiency was the mirror illumination. The GVR feed is a copy of the space qualified AMSU-B satellite instrument feed, with a well characterized, low sidelobe pattern (23° 3 dB beamwidth, -30 dB first sidelobe). When placed at the mirror focal point, 99.5% of the feed pattern is intercepted by the mirror surface, and the 3 dB footprint of the feed illuminates roughly half of the mirror's overall diameter. The cost of this under-illumination is that the radiometer beam 3 dB width is broadened to 1.7° compared to about 1.1° beamwidth of a same size antenna designed to maximize gain.

The filter-bank type receiver was chosen over a variable LO type design to increase data rate, which is particularly important with the Airborne GVR, and to keep the high frequency portion of the instrument as simple as possible. A variable LO type design potentially has a better receiver noise temperature since a narrower IF bandwidth is sufficient and thus a lower noise figure low noise amplifier may be used. Furthermore, the variable LO design should have a smaller sensitivity imbalance between the upper and lower sidebands. Nevertheless characterizing the radiometer receiver passband is essential for accurate retrieval, particularly for estimating LWP, due to the asymmetry of the absorption spectrum of liquid water around 183 GHz. The passband of the four GVR receivers were measured with a calibrated G-band synthesized signal source. The resulting receiver frequency response relative to 183.31 GHz is shown in Fig. 2. The rapidly diminishing noise figure of the harmonic mixer above 14 GHz is evident in the skewed outside passbands.

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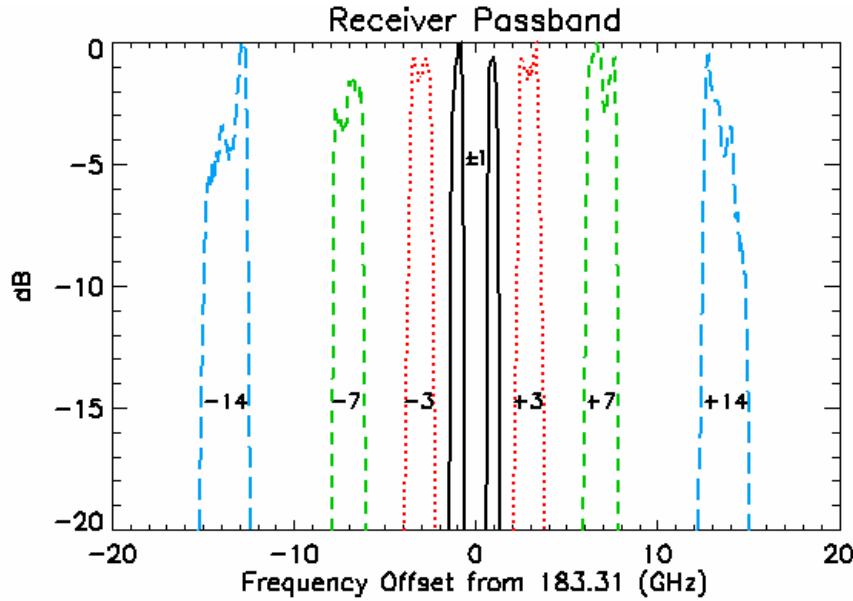



Fig. 2. Frequency response of the four GVR double sideband receiver channels. The G-band source output power over the 163 to 203 GHz band is flat to within 0.5 dB. This measured frequency response is needed to optimize the LWP and PWV retrieval algorithms.

3. III. Test Results

A prototype ground-based version of the radiometer was completed in late 2004. In early 2005 the instrument was tested over a temperature range of -40 C to $+25$ C in an environmental chamber. The stability of the instrument was also characterized by measuring the brightness temperature of a constant temperature external absorber in the chamber. Rau et al. [5] recommends the use of Allan Deviation for measuring the stability of radiometers. Allan Deviation (AD_N) for a radiometer is defined as the $\sqrt{0.5} \times RMS$ difference between non-overlapping adjacent N-point averages of a series of measured brightness temperatures $T(i)$, $i=1, \dots, M$ such that

$$AD_N = \sqrt{\frac{1}{2} \left(\sum_{i=1}^{j=(M/N)-1} \left[\frac{\bar{T}_N(Ni+i-N) - \bar{T}}{M/N-1} \right]^2 \right)^{1/2}}, \quad \text{where} \quad \bar{T}_N(i) = \sum_{j=i}^{j=i+N-1} \frac{T(j)}{N} \quad \text{and}$$

$$\bar{T} = \sum_{j=1}^{j=M} \frac{T(j)}{M}$$

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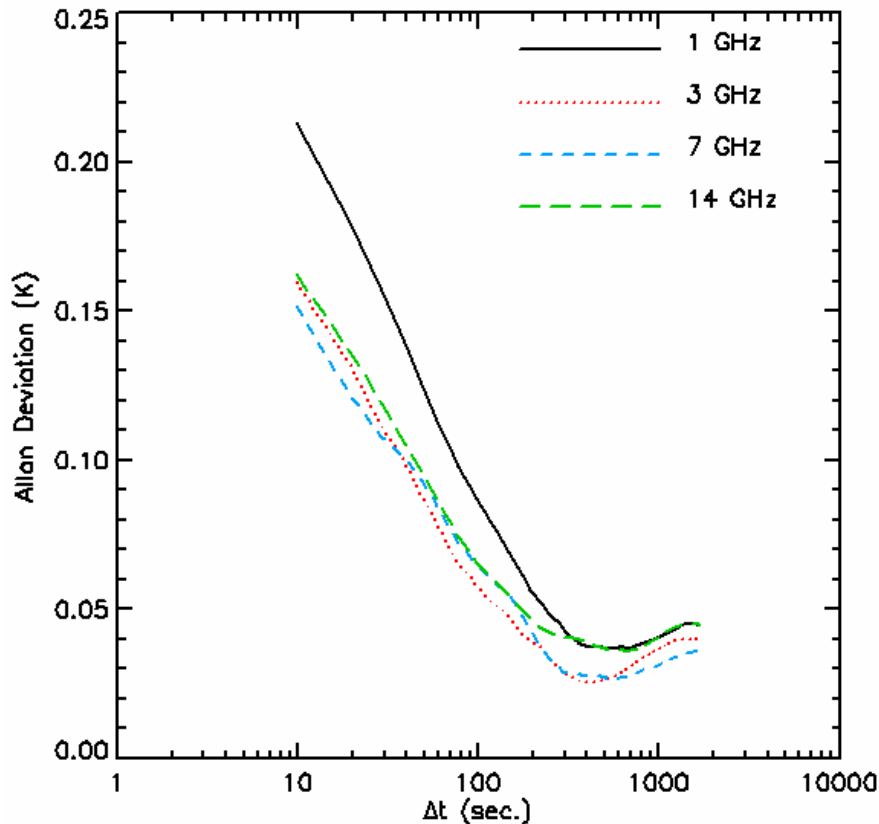



Fig. 3. Allan Deviation of the Ground GVR measured in a temperature stable chamber.

The measured $AD_{\Delta t}$ as a function of Δt is shown in Fig. 3, where Δt is the acquisition time of N brightness temperature samples. The AD curves indicate that the precision of the GVR brightness temperature measurements can be reduced to a lower limit of about 0.05 K by averaging for 8 min. Due to the slow (0.1 Hz) measurement rate of the Ground GVR, with the mechanically rotated reflector mirror, this time interval corresponds to averaging only 43 data points. The radiometer was configured such that each of these data points was acquired by integrating the detected signal for about 0.3 sec. The difference in the precision of the various channels is due to receiver bandwidth (500 MHz @ 1GHz compared to 2 GHz @ 14 GHz) and due to differences in the subharmonic mixer noise figure and IF port matching, which rapidly degrades above 12 GHz, as shown in Fig. 4. The resulting instrument precision and stability is more than sufficient in practice however, since the temporal variability of the atmosphere is usually several K in less than a minute, even in clear, calm and non-convective conditions.

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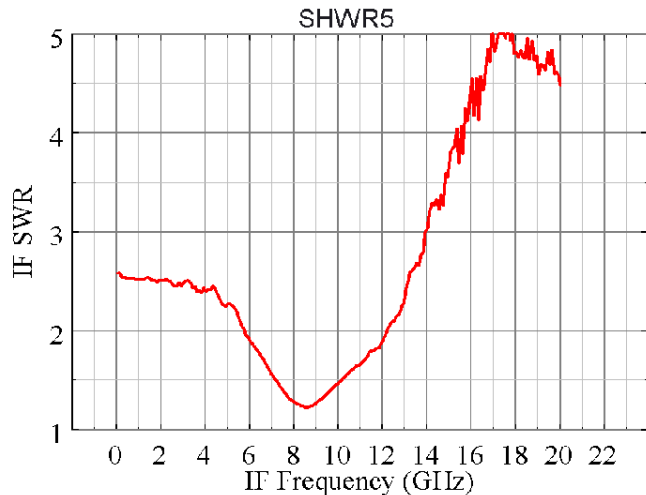


Fig. 4. IF port matching of the Virginia Diodes Inc. 183 GHz sub-harmonically pumped front-end mixer.

In February 2005, after a series of tests, the Ground GVR was installed on the roof of ProSensing facility in Amherst, MA, and left to collect data continuously for three weeks. The antenna was kept clear of snow and debris using a combination of a tilted 1 mil Mylar film window and a 500 Cubic Feet per Minute (CFM) blower and hood. In mid-April 2005, the instrument was deployed at the DOE ARM program's North Slope of Alaska site near Barrow, Alaska, shown in Fig. 5., where it collected data continuously for one year.


4. IV. Airborne GVR

A compact airborne version of the GVR, shown in Fig. 6 through Figure 8, was designed to operate from a standard 2-D PMS probe. The Mylar film window was replaced with a more rugged flat TPX (Polymethylpentene) radome, matched on both surfaces with grooves aligned perpendicular with the E-field, according to [6], as shown in Fig. 6. The optimal depth (D) of the quarter wave surface matching grooves are a function of the TPX dielectric constant ($\epsilon_r \approx 2.127$) and the radiometer free space

wavelength, λ , such that $D = \frac{\lambda}{4\epsilon_r^{1/4}} \approx 0.34$ mm. The groove spacing to free space wavelength ratio

should be as small as possible, but a practical maximum ratio is $\frac{L}{\lambda} \approx 0.4$, suggesting a $L \approx 0.65$ mm groove spacing, a non-trivial machining task. According to [6], for this spacing, the ratio of the groove spacing to W should be approximately $\frac{W}{L} \approx 0.34$, resulting a $W \approx 0.22$ mm for the 183 GHz TPX radome.

The overall thickness (T) of the radome was designed to be a multiple half wavelength in the TPX material, at the center of the vapor line according to

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$$T = \frac{n\lambda}{2\sqrt{\epsilon_r}}$$

. For mechanical considerations n was chosen to be 8, resulting in a radome thickness of

0.45 cm. While the surface matching is broad-band, the thickness is only close to multiple half wavelength near the 183.31 GHz design frequency, so the farther off-line channels are not matched as well as the 1 GHz channel. The resulting equivalent Loss Factor of the TPX radome was measured to be 0.1 dB using the 14 GHz channel. The portion of this loss due to absorption is 0.06 (based on a TPX loss tangent of 8.1E-4), so the effect of reflection on measurement bias is relatively small, but not negligible.



Fig. 5. The prototype Ground-based GVR at the DOE North Slope of Alaska "Great White" site near Barrow, Alaska. A tilted 1 mil. Mylar film radome window is kept clear from rain or snow with a 500 CFM blower and hood.



Fig. 6. Airborne GVR packaged and wired to operate from a standard 2-D PMS probe canister. The weight of the instrument is 22 lb; 38 lb total with canister and cable as shown. Maximum sampling rate is about 10 Hz with 0.25 sec calibration gaps a few times a minute.


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Figure 7. The Airborne GVR installed on the NRC Canada Convair aircraft in September 2006.



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Figure 8. The Airborne GVR installed on the outer PMS probe canister for test flights in September 2006.

In the Airborne GVR, the large calibration loads also had to be replaced with much smaller, RAM tiles by Terahertz Co., and instead of rotating the parabolic reflector mirror, the loads are moved in front of the antenna horn using solenoids.

Key system parameters for the Ground and Airborne GVR instruments are summarized in Table 1.

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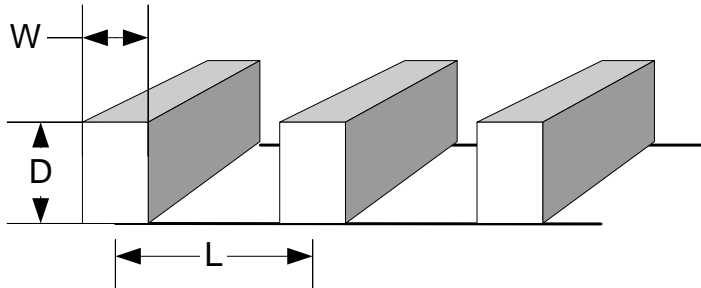



Fig. 9. Surface matching of the TPX radome window of the Airborne GVR instrument. The grooves are aligned perpendicular to the antenna E-field.

**TABLE I
GVR KEY PARAMETERS**

Frequency:	183.31 ± 1 , ± 3 , ± 7 and ± 14 GHz
Bandwidth:	0.5 (1), 1.0 (3), 1.4 (7) and 2.0 (14) GHz
T_{Rec} :	1750 K (1), 1610 K (3), 1600 K (7) and 2170 K (14)
ΔT :	0.2 K @ 200 ms integration (5 Hz data rate)
Allan Deviation:	0.05 K @ 500 sec.
Measurement Rate:	~4/minute including calibration (Ground), up to 20 Hz (Airborne) with 0.25 sec calibration gaps
Antenna:	4" Aperture, 90 deg Parabolic Metal Mirror, 1.7° BW
Radome:	1 mil. Mylar film w. blower and hood (Ground) Matched 0.177" TPX window (Airborne)

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5. III. Example Data


Ground-based GVR:

On February 18, 2005, the Ground-based GVR was operating from the roof of the ProSensing facility in Amherst, MA. In early afternoon, broken clouds, shown in Fig. 10, containing super cooled liquid passed above the zenith pointed radiometer. The surface temperature was about +5 deg C and the clouds were approximately 1 to 2 km above the instrument. The corresponding hour-long brightness temperature data from the four channels is shown in Fig. 11. The PWV and LWP, shown in Fig. 12, were estimated with two separate neural networks using the four brightness temperatures and the surface air temperature as inputs. The neural networks used for this retrieval were trained with PWV and LWP computed from an atmospheric model generated using simulated liquid clouds combined with radiosonde data that was collected over a seven-year period in Albany, NY. For each computed PWV and LWP, the corresponding brightness temperature training data at the four radiometer channels were calculated using the atmospheric absorption models compiled by Ulaby et al. [7]. Validation of the data collected with the Ground GVR in Barrow, Alaska using coincident radiosonde data and the Rosenkranz corrected vapor absorption model [8] is presented by Cadeddu et. al, [9].

The data presented here is a qualitative example of GVR sensitivity to PWV and LWP. Atmospheric conditions were quite favorable for precise PWV and LWP retrieval since the atmosphere was sufficiently dry that none of the channels were saturated. The resulting precision of the retrieved LWP was less than 0.005 mm and the precision of the estimated PWV was about 0.1 mm. Cadeddu et al. [9] have investigated the absolute calibration of Ground GVR data. That study concluded that the brightness temperatures measured during the dry winter months are in good agreement (within a few K) with brightness temperatures calculated based on radiosonde data.



Fig. 10. Winter-time fair weather cumulus clouds passed over the Ground-based GVR on February 18, 2005 in Amherst, MA. Based on a +5 deg. C surface temperature and an estimated cloud altitude of 1-2 km, it is assumed that these clouds contained super cooled liquid. The retrieved

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Liquid Water Path (LWP) data, shown in Fig. 9, demonstrates the sensitivity of the instrument to the passing clouds.

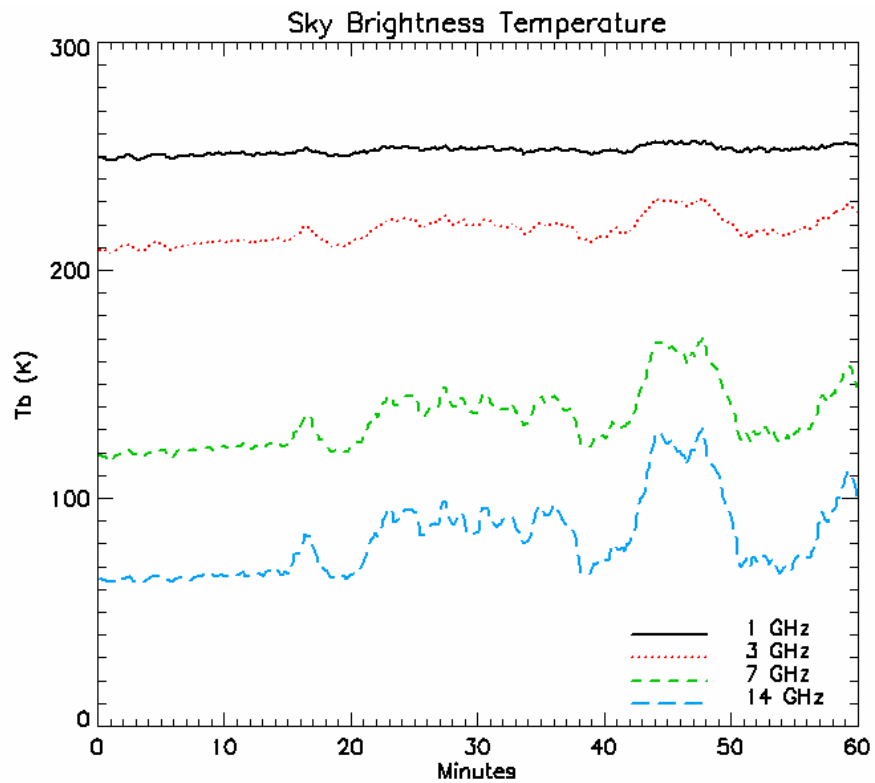



Fig. 11. Data collected with the ground-based GVR from clouds containing super cooled liquid water, shown in Fig. 10.

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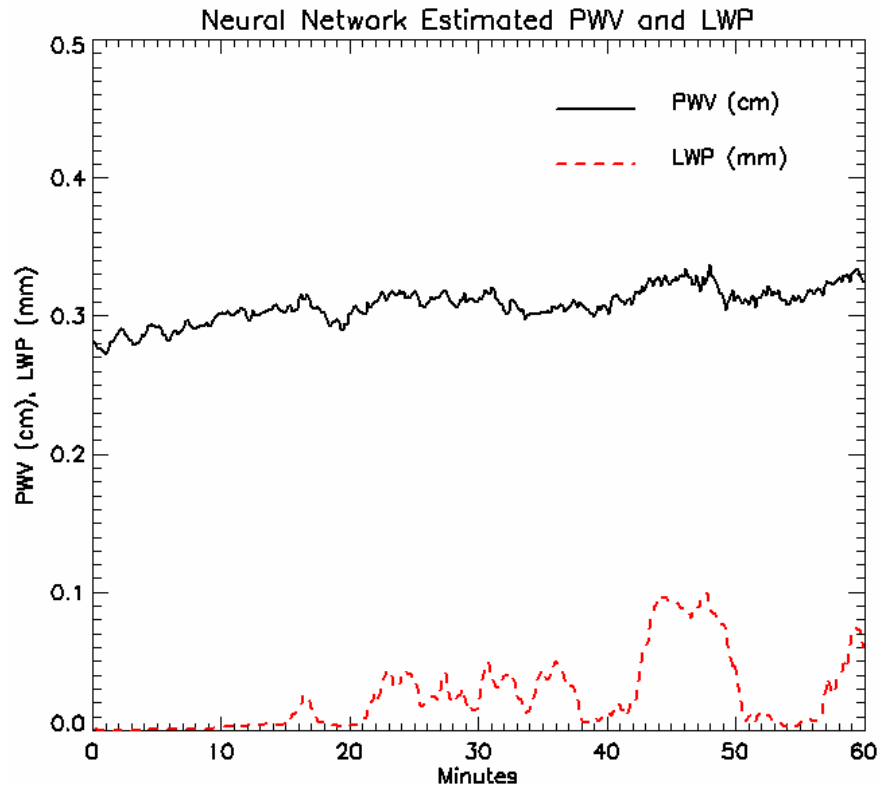



Fig. 12. Retrieved precipitable water vapor and liquid water path of the fair weather cumulus clouds shown in Fig. 10. Data products were estimated using a neural network algorithm from the measured brightness temperatures of Fig. 11. and surface temperature.

Airborne GVR:

On October 26, 2006 the NRC Canada Convair aircraft, with the Airborne GVR installed in one of its PMS probe wing pods, descended into a liquid cloud for a 50 minute level flight leg, then ascended out of the cloud layer. The recorded Zenith brightness temperature from the four receiver channels are shown in Figure 13 and the corresponding retrieved Precipitable Water Vapor (PWV) and Liquid Water Path (LWP) are shown in Figure 14.

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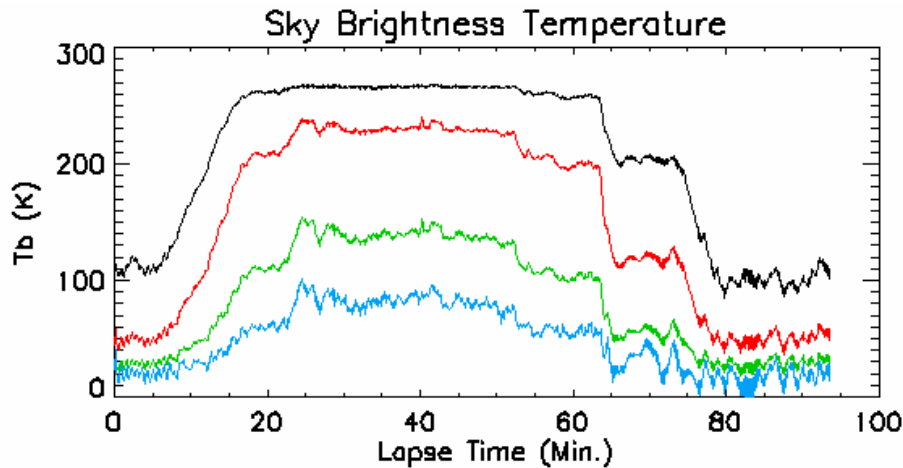


Figure 13. Data collected with the Airborne GVR during a CloudSat validation flight near Ottawa, Canada on October 26, 2006. Zenith brightness temperature data is shown from the four double sideband receiver channels: Black=183.31 +-1 GHz, Red=+-3 GHz, Green=+-7 GHz and Blue=+-14 GHz.

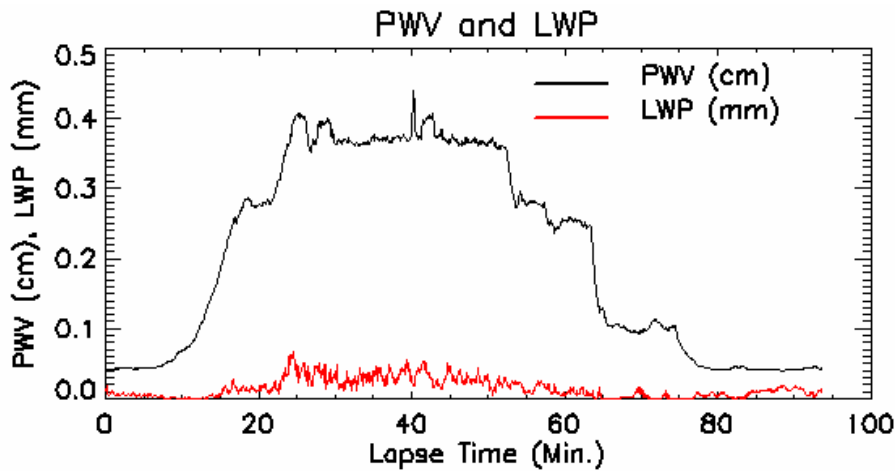



Figure 14. Precipitable Water Vapor (PWV) and Liquid Water Path (LWP) estimated using a neural network algorithm from the measured brightness temperature data of Figure 3 and flight level air temperature. The neural network was trained with a combined multi-year radiosonde data-set from Albany, New York and Barrow, Alaska. The sounding data was processed to a data set of brightness temperatures at the four radiometer frequencies, air temperature at the instrument and corresponding PWV and LWP. This simulated data set was used to train and test the neural network.

6. V. Discussion

The potential high sensitivity of radiometers operating near the 183 GHz vapor line to PWV and LWP has been convincingly demonstrated by previous instruments and field campaigns [2][3][4]. The novelty of

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the two radiometers described in this paper is that they realize this potential in a simple and compact design.

The method of using external calibration loads to track receiver gain and offset drifts appears to be very accurate, even at a low (~0.1 Hz) calibration rate. The convection-heated enclosure of the Ground GVR hot load is quite large compared to the rest of the instrument, but it is necessary for absolutely calibrating the measurements. The much smaller calibration loads of the Airborne GVR are stable and precise, but must be independently calibrated using an external hot load, due to the significant temperature gradients in the heated load.

Interference caused by a nearby high power radar was found to be a problem while operating at the Barrow, AK site. Metal shielding around the IF section reduced the interference, but did not eliminate it. Fortunately, the interference was only strong enough to be noticeable when the scanned radar beam was pointed directly at the radiometer, which only occurred once every 2-3 minutes and affected only one data point per radar scan. Consequently, those corrupted data points could be reliably detected and eliminated using the Conservative Smoothing algorithm [10]. No other interference problems have been encountered to date with GVR.

The combination of high performance blower and Y-shaped pipe hood solved the problem of keeping the Mylar window of the Ground GVR clean from ground debris and precipitation. Conventional radiometer fan designs, which blow horizontally over the radome, would have ripped the 1 mil. thin Mylar film in a few days, while in spite of the over 10 m/s updraft in the Y-pipe, the Mylar film at the base stayed intact after a full year of continuous operation. The 15 cm (6") diameter Y-pipe also did not have a detectable effect on the measured data; likely due to the narrow beam and high beam efficiency of the radiometer antenna. Nevertheless, the final system calibration, using external high precision hot and warm loads, was conducted with the Y-pipe hood in place.


Two other technical issues with the Airborne GVR are the effect of aircraft vibration and preventing ice and water buildup on the radome. To minimize potential errors due to vibration, all the components were securely fastened to a solid frame, coaxial cables were kept to a minimum length and all SMA connectors were secured with Loctite Prism adhesive. To reduce radome icing potential, the radiometer head was designed with a smooth exterior surface to minimize turbulence and to promote laminar airflow. Additionally, the radome may be heated near the edge to further reduce icing.

ACKNOWLEDGMENT


Many individuals have contributed to this instrument development effort. The author is grateful to Allen Tanner for his technical guidance during the design phase, to James Mead for technical discussions throughout the project and for editing the manuscript, to James Liljegren for organizing the deployment of the Ground GVR to the Barrow AK ARM site and to Walter Brower for maintaining and helping to calibrate the instrument in Alaska. The author also wishes to thank Richard Cochran, Tristan Chambers and Eric Black for developing software, Mike Cunningham, Richard Lamoureux and Frank Leaf for constructing the instruments, Geoffrey Lee for mechanical design of the Airborne GVR and to Barry Volain for designing and programming the FPGA data acquisition board.

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Measurements and Retrievals from a New 183-GHz Water Vapor Radiometer in the Arctic

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Abstract— A new G-band (183.31-GHz) vapor radiometer (GVR) developed and built by ProSensing Inc. was deployed in Barrow, Alaska, in April 2005. The radiometer is part of a suite of instruments maintained by the Atmospheric Radiation Measurement (ARM) Program. The instrument measures brightness temperatures from four double sideband channels centered at ± 1 , ± 3 , ± 7 , and ± 14 GHz from the 183.31-GHz water vapor line. Atmospheric emission in this spectral region is primarily due to water vapor, with some influence from liquid water. The GVR will remain in Barrow through the winter and will collect data for several months in a dry and cold environment, when its sensitivity is best.


In this paper, data collected in November 2005, December 2005, and January 2006 are shown. Measurements are compared with simulations obtained by using a radiative transfer model. We show that the measurements agree well with model simulations. Precipitable water vapor (PWV) and liquid water path (LWP) are retrieved with a nonlinear physical algorithm, and results are compared with those from the co-located dual-channel microwave radiometer (MWR) and radiosondes. Retrieval errors are estimated to be better than 5% for precipitable water vapor and of the order of 0.006 mm for LWP.

Index Terms—Microwave radiometry, remote sensing, water vapor retrieval.

1. INTRODUCTION

The GVR is part of a suite of instruments deployed by the ARM Program to improve observations of low amounts of PWV (< 5 mm) and low amounts of liquid water ($LWP < 50 \text{ g/m}^2$). Water vapor, as one of the most variable atmospheric constituent, plays a crucial role in the analysis of local weather patterns, as well as in the validation of global climate models. Accurate water vapor measurements are essential in assessing the performance of clear-sky radiative flux models. PWV retrieval errors achieved with traditional linear statistical retrievals from microwave measurements are around 0.4 mm. Microwave radiometry is also an established method to retrieve accurate liquid water path that is necessary to the study of the role of clouds in the Earth radiation balance. LWP retrieval errors are around 0.02 mm (or 20 g/m^2) however, as shown in [1], a large percentage of clouds have LWP of less than 100 g/m^2 . Traditional

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ground-based measurements employ two or more channels located in the spectral region of water vapor absorption at 22 GHz and one channel in the liquid absorption region around 30 GHz. In particular, the ARM Program has been operating for several years a two-channel microwave radiometer, the MWR, with frequencies at 23.8 and 31.4 GHz. During the cold Arctic winter, the amount of PWV is often less than 3 mm and clouds with LWP of less than 50 g/m² are common. In these conditions the dual-channel MWR is operating at the limit of its capabilities with a very low signal-to-noise ratio. Several authors, [1], [2], and [3] to mention just some examples, have analyzed the origin of uncertainties in MWR retrieval. Besides calibration issues and the effect of measurement noise, uncertainty in the liquid water retrieval can be attributed to the modeling of the dry opacity term and to the cloud liquid absorption coefficient. One result of these uncertainties is the fact that the MWR can retrieve LWP significantly higher than zero, when the sky is clear (i.e. there are no liquid clouds).

Because of its increased sensitivity to water vapor the 183.31-GHz absorption line can help improve water vapor retrievals during the dry Arctic winter. However, the dependence of brightness temperatures on precipitable water vapor and liquid water is linear only in a limited region, and a nonlinear retrieval algorithm is needed. An additional layer of complexity is added by the fact that the radiometer response saturates at a PWV of ~ 5 mm [4] for the most sensitive channels. The absorption line centered at 183.3 GHz has been extensively used from satellites [5] and aircraft [6], however very few measurements ([7], [4]) have been reported from the ground. The GVR has been operating in Barrow, Alaska for one year and is the first ground-based radiometer operating at 183.3 GHz permanently deployed at an Arctic location with the purpose of improving PWV and LWP retrievals.

The purpose of this paper is to analyze the data from the GVR and to assess the capability of this instrument to supplement the MWR retrievals in very dry conditions. The considerable length of time during which the radiometer has been operating has been very important to assess the stability of the instrument and the quality of the calibration. The paper is organized as follows: In section II is given a brief description of the instrument. In section III and IV measured brightness temperatures are compared to model computations and their sensitivity to water vapor and cloud liquid water are assessed. The retrieval algorithm is described in section V and, in section VI, PWV and LWP retrievals are discussed, retrieval errors are theoretically quantified and their dependence on the amount of PWV is shown. The large dataset has also provided us with the opportunity to carry an extensive comparison with retrievals from the MWR and Vaisala R90 radiosonde under a range of water vapor conditions. Specific attention is devoted in section VII to the analysis of retrieved LWP under clear sky conditions and its comparison with the MWR. A brief summary of results is given in the conclusive section. We conclude that PWV retrievals from the GVR can achieve an accuracy of better than 5% for PWV amounts of less than 8 mm. Expected clear-sky retrievals of LWP have standard deviations of less than 0.002 mm.

2. The Instrument

The GVR, developed and built by ProSensing Inc. (<http://www.prosensing.com>) [8], measures brightness temperatures from four double sideband channels centered at ± 1 , ± 3 , ± 7 , and ± 14 GHz from the 183.31-GHz water vapor line. Atmospheric emission in this spectral region is primarily due to water vapor, with some influence from liquid water. The 183.3 ± 14 GHz channel is particularly sensitive to the presence of liquid water. Bandwidths for the four channels are 0.4, 1.0, 1.4, and 2.0 GHz. The radiometer uses a hot (~ 330 K) and warm (290 K) calibration target. ProSensing expects a calibration accuracy of better than 1 K. The GVR started collecting data successfully immediately after deployment. On the first day of collection, it was found that a radar operated by the U.S. Air Force in the vicinity of the radiometer was causing a strong interference with the 183.3 ± 1 GHz channel. To eliminate this effect, a conservative filter was applied to all frequencies. Apart from intermittent high noise due to thermal instability, instrument operations have been stable. For the purpose of this analysis, data during cold days (surface temperatures of less than 255 K) were chosen in order to avoid excessive noise.

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3. Measurement-Model Comparison

The GVR has been operating at the North Slope of Alaska (NSA) site since April 2005. Although operations have been continuous, this data analysis will cover only data collected during the cold winter months, when low-humidity conditions prevail. A time series of data collected in January 2006 is shown in Fig. 1. Some periods of enhanced noise are visible on days 13-19. Temperature instability in the radiometer was responsible for the noisy data. Additional periods of enhanced noise (not shown) are present during the months of November and December.

Simulated brightness temperatures shown in Fig. 1 are computed by using the radiative transfer code MonoRTM [9] with the HITRAN database line parameters [10] and the so-called CKD 2.4 continuum [11]. Only radiosonde data collected during clear conditions were used to compute brightness temperatures. The clear-sky screening dramatically decreased the amount of data available for the comparison. Radiosondes (Vaisala RS90) are launched at the NSA site once a day, five days a week. The original number of radiosondes available was 55 (17 in November, 18 in December, and 20 in January). Once data were screened for clouds, only 30 cases were left (10 in November, 11 in December, and 9 in January). The agreement between measurements and observations is satisfactory at all frequencies. Large discrepancies between measured and modeled brightness temperatures at similar frequencies were recently reported in [4]. The improved agreement observed in this comparison can be attributed, at least in part, to improved radiosonde measurements. Mean and standard deviation of measurements-minus-model computations is displayed in Table 1. A scatter plot of measured and modeled brightness temperature is shown in Figure 2. From this comparison it appears that the model is in acceptable agreement with the measurements. The larger discrepancies are observed at 183.3 ± 1 GHz where the model overestimates the measurements of about 4 K. The overestimation has a slight dependence on the brightness temperature itself.

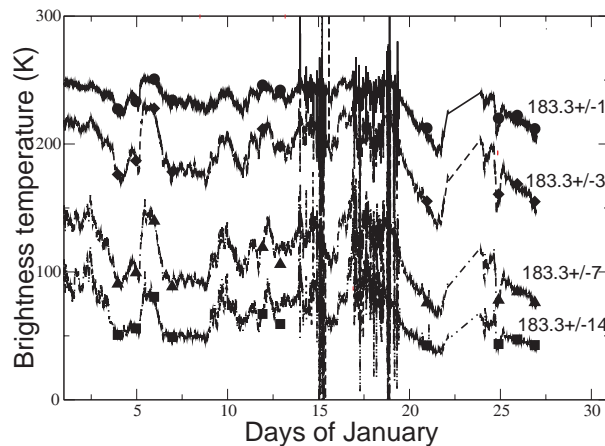



Fig. 1. Brightness temperatures measured by the GVR during the month of January. Model computations during clear-sky conditions are shown as circles, diamonds, triangles and squares. High noise level between day 15 and 20 are due to thermal instability of the instrument.

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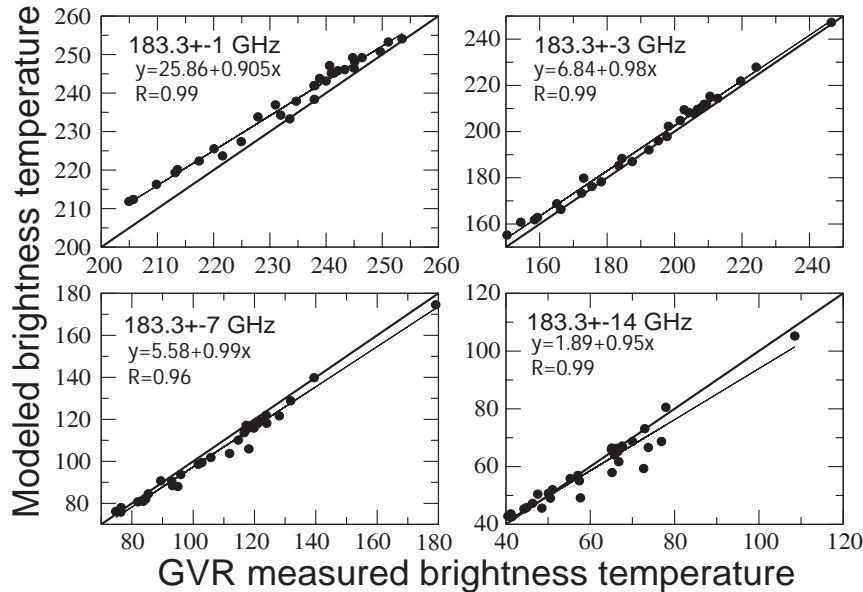



Fig. 2. Scatter-plot of clear-sky measured (x-axis) and modeled (y-axis) brightness temperatures. Data were collected during November, December and January (N=31)

TABLE I
MEAN AND STANDARD DEVIATION OF MEASURED-MINUS-MODELED BRIGHTNESS TEMPERATURES FOR THE MONTHS OF NOVEMBER, DECEMBER, AND JANUARY AT THE NSA (N=31).

Frequency GHz	Mean K	Standard deviation K
183.3 ± 1	-	2.03
183.3 ± 3	3.81	2.08
183.3 ± 7	2.77	2.90
183.3 ± 14	3.0	3.87
	3	
	1.4	
	9	

4. Sensitivity to PWV and LWP

The sensitivity of the GVR channels to the presence of water vapor is much stronger than the 22 GHz water vapor line [4]. In Figure 3 the dependence of GVR-measured brightness temperatures on PWV is shown. The PWV is retrieved from the MWR. The circles, diamonds, triangles and squares, are model computations from one year of radiosonde data. Fig. 3 shows the non-linear response of the GVR to water vapor as well as the saturation of the channels close to the line center. These results are consistent with those of [4] who estimated the sensitivity to PWV at these frequencies to be approximately 30 times higher than at the frequencies of the MWR. To assess the sensitivity to LWP, three months of radiosonde data (clear and cloudy) were used to compute brightness temperatures. Since the radiosondes do not measure liquid water, differences between model and measurements were attributed to the presence of LWP. In Fig. 4 is shown the difference between measured and modeled brightness temperatures as a function of LWP retrieved with the MWR. Since the uncertainty in MWR retrievals is about 20 g/m², data with LWP < 0.02 mm were considered clear. For comparison, the same difference is shown for brightness temperatures

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measured by the MWR. The ratio $\Delta T_b / \Delta LWP$, the slope of the linear fit, is an indication of the sensitivity to LWP. In Table 2 the slope is displayed for the two MWR channels and for two of the GVR channels. The 183.3 ± 14 GHz channel has a sensitivity that is about 3.5 times higher than the 31.4 GHz channel of the MWR.

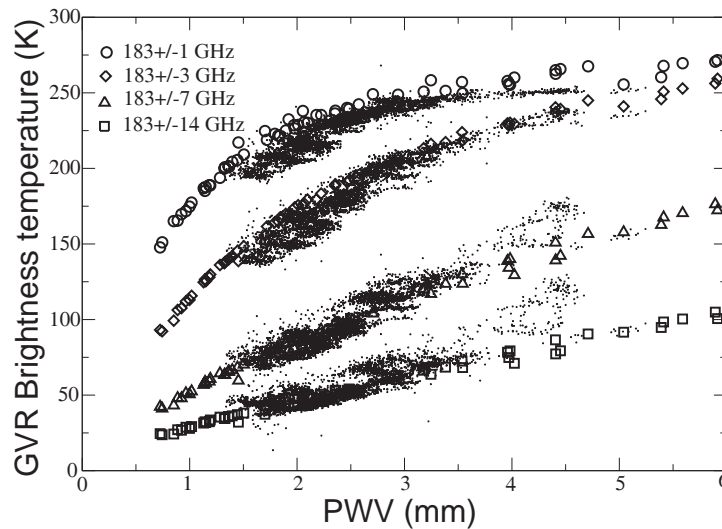


Fig. 3. GVR-measured brightness temperatures as a function of PWV retrieved from the collocated MWR. Data are for non-cloudy conditions only. The circles, diamonds, triangles, and squares are model computations from one year of radiosonde data. The non-linear response to PWV is evident in the ± 1 and ± 3 channels.

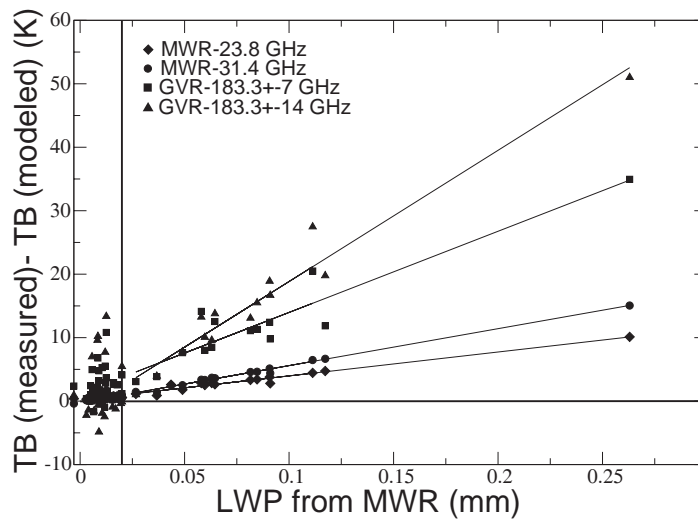


Fig. 4. Sensitivity of GVR-measured brightness temperatures to LWP. The LWP on the x-axis is retrieved from the co-located MWR.


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TABLE II
SLOPE OF LINEAR REGRESSION FIT

Frequency GHz	Slope $\Delta T_b / \Delta LWP$ (K/mm)
23.8	38.53
31.4	58.71
183.3 \pm 7	130.39
183.3 \pm 14	205.92

5. Retrieval Algorithm

A non-linear algorithm was used to retrieve LWP and PWV from GVR measurements. The algorithm is a Gauss-Newton method [13] that finds the zeroes of the gradient of the cost function:

$$\mathbf{J} = [\mathbf{y} - \mathbf{F}(\mathbf{x})]^T \mathbf{E}^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x})] + [\mathbf{x} - \mathbf{x}_a]^T \mathbf{S}_a^{-1} [\mathbf{x} - \mathbf{x}_a] . \quad (1)$$

In (1) \mathbf{x} is a 27-element vector whose first element is LWP and whose remaining 26 levels constitute a relative humidity profile between 0 and 10 km. The ‘*a priori*’ constraint \mathbf{x}_a is computed from one year of radiosonde data with covariance \mathbf{S}_a . The vector of computed brightness temperatures is $\mathbf{F}(\mathbf{x})$ and \mathbf{y} is the vector of the measurements with error covariance \mathbf{E} . The minimization is achieved by successive iterations starting from a first guess profile of temperature and relative humidity. The first guess profiles are retrieved by linear statistical regression from measurements collected by the 12-channel microwave profiler (MWRP) [12]. The criteria for convergence is that the difference between two successive estimations be smaller than a predetermined threshold: $x_{n+1}(1) - x_n(1) < 0.005$ mm and $x_{n+1}(i) - x_n(i) < 20\%$ for $i = 2, 27$. Upon convergence the algorithm returns the estimated vector $\hat{\mathbf{x}}$ and its error covariance \mathbf{S}_x . The post-measurements covariance matrix \mathbf{S}_x is defined as


$$\mathbf{S}_x = (\mathbf{K}^T \mathbf{E}^{-1} \mathbf{K} + \mathbf{S}_a^{-1})^{-1}, \quad (2)$$

where \mathbf{K} is the Jacobian $K_{ij} = \partial f_i(x) / \partial x_j |_{x=x_n}$ and the superscript ‘‘T’’ indicates the transpose matrix. The matrix \mathbf{S}_x is an indication of how well the retrieval is performing with respect to the climatologic average used as statistical constraint. The square roots of its diagonal elements are the standard deviation of the retrieval at each layer. In Fig. 5 an example of $\sqrt{S_x(i,i)}$ is shown together with $\sqrt{S_a(i,i)}$, the prior standard deviation. In the region where the measurements are not contributing to the retrieval the standard deviation tends to the ‘*a priori*’. This is noticeable at the very top and bottom layers. Where the measurements are contributing the post-measurement standard deviation is smaller than the prior. Contributing factors to the total retrieval covariance are measurement noise, forward model errors and errors deriving by the use of a low-resolution atmospheric profile. In addition, any error in the instrument calibration will appear as a bias in the final result. Calibration may be affected by the thermal stability of the warm target. The estimated calibration accuracy for the instrument is in the range of 1 K. The retrieved relative humidity vector is first converted to specific humidity and then integrated to obtain PWV. The retrieved PWV error covariance is estimated following [13], by applying a linear transformation \mathbf{h} to \mathbf{S}_x :

$$s_{PWV} = \mathbf{h}^T \mathbf{S}_x \mathbf{h}, \quad (3)$$

and the retrieval standard deviation is

$$\mathcal{E}_{PWV} = \sqrt{s_{PWV}} . \quad (4)$$

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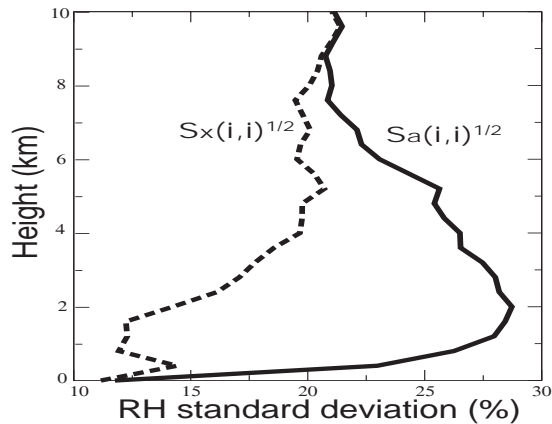



Fig. 5. An example of standard deviation for a relative humidity (RH) profile. The solid line is the prior standard deviation. Where measurements are not contributing to the retrieval the post-measurement covariance is the same as the prior.

6. Retrieval Results

A time-series of retrieved PWV and LWP for January 2006 is shown in Fig. 6. Data were collected during prevailing low-humidity conditions. GVR retrievals have the same time resolution (5 minutes) as the MWRP retrievals used to initialize the algorithm. The temporal resolution is therefore 5 minutes. The top panel is the retrieved LWP, while the middle pane is the retrieved PWV. In the bottom panel infrared temperature measured by a Wintronics KT-19.85 infrared thermometer located at the site is shown. When the measured temperature is 223 K, the sky can be considered free of liquid clouds. On the two top panels the solid and dashed lines are the GVR and MWR retrievals respectively. The MWR retrievals are based on an ‘a priori’ linear statistical retrieval trained with several years of in-situ radiosonde measurements. A Gaussian noise with a standard deviation of 0.5 K is used to simulate a real instrument noise. The radiative transfer model MonoRTM is used in both retrievals. In the non-linear physical algorithm for the GVR, the liquid water layer is added between 0 and 1 km. The first noticeable feature of the comparison is that the GVR retrieves less LWP than the MWR. This is generally true during clear-sky conditions, as it will be shown later, however it is also true under cloudy conditions. In the absence of additional LWP measurements it is difficult to assess the accuracy of the LWP retrievals. The theoretical LWP accuracy computed from (4) (not shown here) varies linearly between 0.004 and 0.012 mm as a function of PWV while the difference between MWR-retrieved and GVR-retrieved LWP increases linearly with the LWP. Although previous studies have shown that MWR retrievals of liquid water may be too high at times, it is not excluded that the differences in the retrievals may be due to issues in the iterative retrievals used for the GVR. Additional investigation is needed to clarify this point, especially on the role of the prior information and statistical constraints. The PWV retrievals from the two instruments are in satisfactory agreement. When the PWV is very low ($PWV < 4$ mm) it appears that the GVR retrieves less PWV. In Fig. 7 is shown a scatter plot of MWR and GVR-retrieved PWV for cloudy and clear-sky cases during two weeks in December 2005 and two weeks in January 2006. The scatter plot confirms that the PWV from the MWR is slightly higher when the PWV amount is less than 4 mm. In Fig. 8 is shown that the PWV error percentage as estimated from (4), varies approximately between 2 and 4.5% for a range of retrieved PWV between 1.5 and 7.5 mm. In Fig. 9 is shown a comparison of retrieved PWV with measurements from Vaisala R90 radiosondes during the months of November, December and January for clear-sky cases only. Vaisala RS90 radiosonde expected accuracy of relative humidity measurements is estimated at about 5%. This translates in a PWV accuracy of better than 1 mm. The diamonds are the MWR retrievals, empty circles are

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the GVR retrievals using the MWRP-retrieved profile to initialize the algorithm, and the full circles are GVR retrievals initialized using the radiosonde profiles. For the 41 cases shown in Fig. 8 the MWR slightly overestimated water vapor when radiosonde measurements were below 3 mm. On the other side GVR retrievals display a slight 0.1-mm bias in the other direction. In addition to the total retrieval error defined in (2) and shown in Fig. 8, we examined the influence of the first guess. This was done by running the retrieval in proximity of radiosonde launches and by using the radiosonde profiles, as the first guess, instead than the MWRP-retrieved profiles. The results of this exercise are show in Fig. 9 as black filled circles and they suggest that the uncertainty related to the prior information is not a large source of error. As the PWV amount increases, however, it appears that uncertainties in the prior information have a larger impact on the retrieval. This could be explained by the fact that, as the non-linearity of the retrieval increases, the choice of prior information becomes important for the proper convergence of the algorithm.

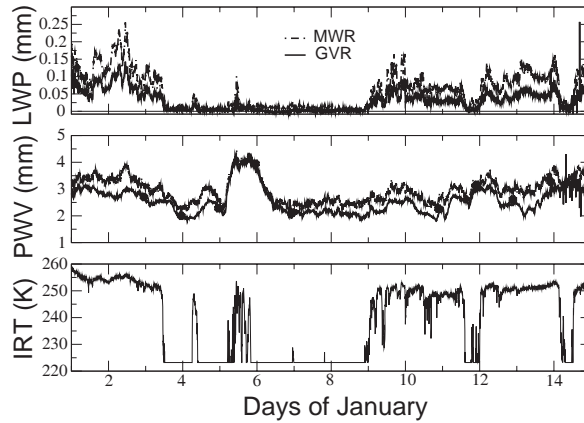


Fig. 6. Time series of PWV and LWP retrieved by the MWR and the GVR in January 2006. The MWR-retrieved parameters are slightly higher than the GVR's. The bottom panel is the infrared temperature measured by the infrared thermometer located on top of the MWRP.

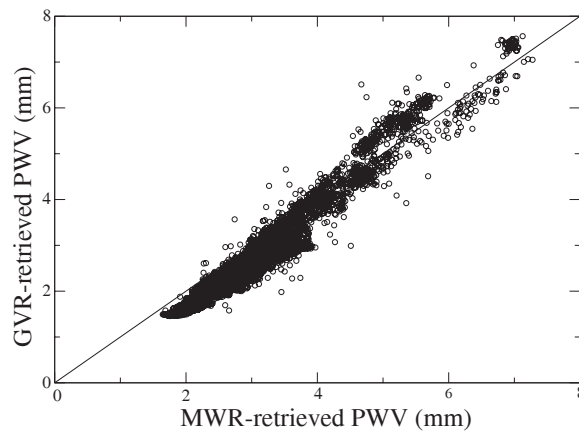



Fig. 7. Scatter plot of MWR-retrieved (x axis) and GVR-retrieved (y axis) PWV (data are from two weeks in December and January).

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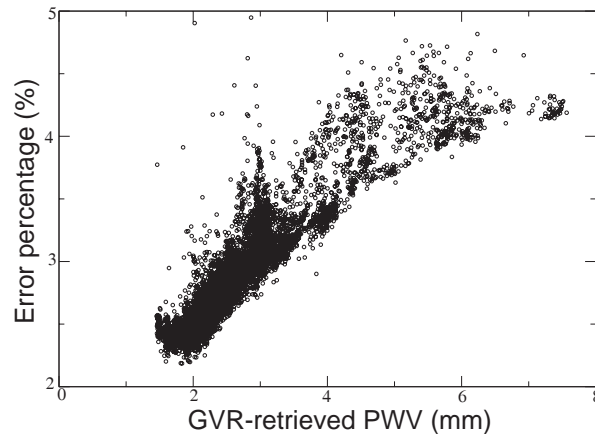


Fig. 8. Estimated error percentage of GVR-retrieved PWV as a function of PWV.

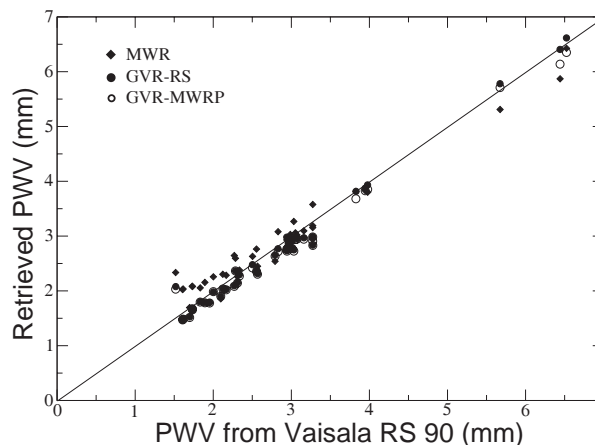



Fig. 9. Comparison of PWV retrieved from the MWR (diamonds) and the GVR(circles) with radiosonde measurements. Data are 41 cases of clear-sky measurements during the months of November, December and January.

7. Clear-sky LWP retrievals

The analysis of LWP retrieval under clear-sky conditions is important to assess uncertainties that will affect LWP retrieval under cloudy conditions. Theoretically, the LWP in the absence of clouds should be zero. However, because of the intrinsic nature of passive remote sensing and because of errors in the conversions from brightness temperature to physical quantities, most of the times the individual retrievals during clear sky will not be exactly zero. Uncertainties in the MWR clear-sky retrievals have been analyzed in [1] and [3] and have been attributed to modeling of the dry opacity term and to the cloud liquid absorption coefficient. This effect will lead to the retrieval of a positive amount of LWP even when the sky is clear. MWR retrieved amounts during clear days can be as large as 20 g/m^2 . In the 183.3 GHz line the effect of uncertainties in the oxygen modeling should be negligible, therefore uncertainties related to this term should not affect the retrieval. Both MWR and GVR retrievals use the same liquid water absorption model of [14]. From our studies it emerges that two factors will affect the clear-sky retrievals from the GVR: the modeling of the line absorption (most probably the line width parameter) and uncertainties in brightness temperature measurements. In Table 1 it can be seen that standard deviations of measured-minus-modeled clear sky brightness temperatures are around 3 and 4 K for the 183.3 ± 7 and 183.3 ± 14 GHz channel respectively. From the sensitivity study (see Table 2) it can be estimated that the corresponding uncertainty

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in the GVR-retrieved LWP can be as large as 0.02 mm in a worst-case scenario. Fig. 10 shows the retrieved LWP distribution for 500 clear-sky cases in January 2006. On the left panel are the MWR retrievals and on the right panel are the GVR retrievals. The mean (0.004 mm) and standard deviation (0.002 mm) for the LWP retrieved from the GVR suggest that the calibration accuracy for the 183.3 ± 7 and ± 14 GHz channel is better than 1 K. This was recently confirmed by an independent calibration that was performed on site with an improved thermal stabilization of the target. Assuming a stable calibration, we can say that the remaining uncertainty is related to the line modeling. On the other side, the MWR retrievals display the larger liquid amount already discussed.

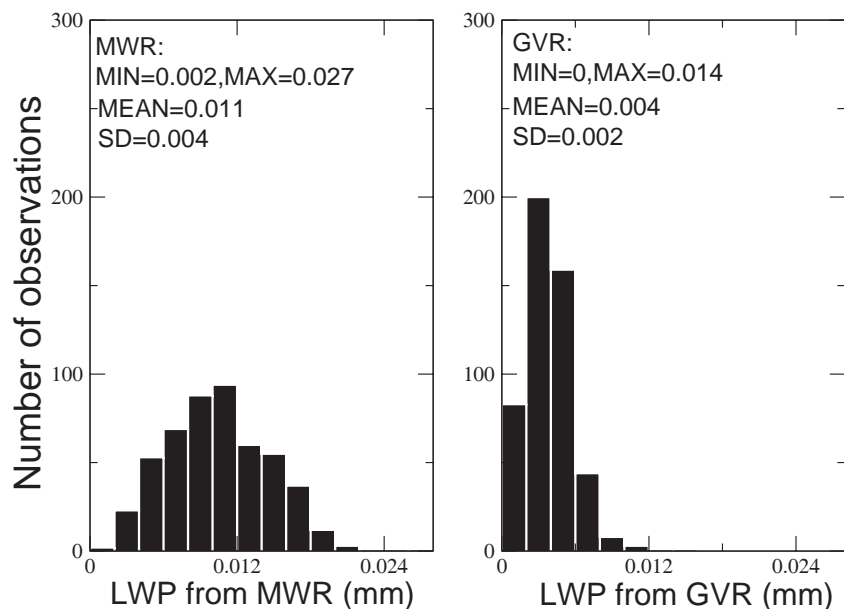



Fig. 10. Clear-sky LWP distributions retrieved by the MWR (left panel) and the GVR (right panel). N= 499 cases in January 2006.

8. Conclusions


In this paper we have analyzed an extensive set of measurements from a ground-based 183.3 GHz water vapor radiometer. The instrument was designed with the purpose of improving water vapor and liquid water retrievals that are greatly needed in radiance simulations and climate models. This is the first time such an extensive set of ground-based data has been available at these frequencies. It has enabled us to assess quality of calibration, the agreement with the model and the retrieval performance. From the analysis it appears that the quality of calibration was very good for the ± 7 and ± 14 -GHz channels. There may be the need for improved calibration improvement at 183.3 ± 1 and ± 3 GHz, but the error in the brightness temperature at this moment should not be larger than 2 K. Clear-sky model comparisons with MonoRTM simulations were satisfactory.

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A retrieval algorithm was developed for PWV and LWP and results were compared with the collocated MWR retrievals and with radiosonde measurements. The GVR generally retrieves less LWP than the MWR and the differences between the two instruments increase at larger LWP amounts. The origin for the discrepancy is not clear and is under investigation. Retrieved PWV from the two instruments are in good agreement. The GVR retrieves less PWV than the MWR during very dry conditions and it agrees better with radiosonde soundings. Retrieval errors have been estimated to be below 5% when the PWV is in the range of 1 to 8 mm. The effect of the first-guess profile in the retrieval can have some influence when the PWV is higher than 4 mm. In general, given the nonlinear nature of the problem a reasonably close ‘a priori’ and first-guess profile are important. The estimated LWP error is of 0.006 mm but it could reach 0.02 mm. Clear-sky LWP retrievals show that the main source of error is due to the modeling of the absorption line, but a stable calibration with uncertainties of less than 1 K is essential for good retrievals.

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DISCLOSURE:

No inventions were created under this project during the report period.

COMPUTER PROGRAMS:

Available upon request.

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