A COMPACT 183 GHZ RADIOMETER FOR WATER VAPOR AND LIQUID WATER SENSING

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***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 using 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 Department of Energy Atmospheric Radiation Measurement program's North Slope of Alaska site near Barrow AK in April 2005, where it collected data continuously for one year. 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.**

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) [1]. 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 (few mm PWV) conditions, 183 GHz brightness temperature changes by over 20 K, as shown in Fig. 1., 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 [2]. 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 radiometer, 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 pumped Schottky mixers, a high beam efficiency conical feed horn developed for a satellite radiometer and a temperature stable packaging technique developed by Tanner for an ultra stable K-band radiometer [2].

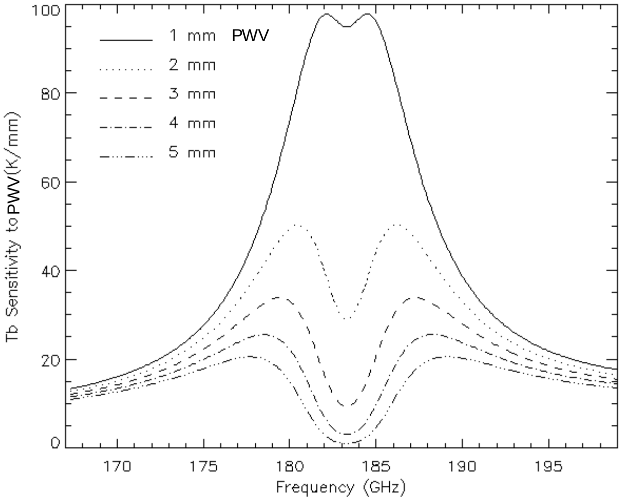

Fig. 1. Sensitivity of brightness temperature to changes in PWV $\left(\Delta Tb / \Delta PWV\right)$ as a function of frequency and total vapor near the 183.31 GHz vapor line. In very dry conditions, Tb measurements close to the vapor line are most sensitive water vapor, but with increasing PWV, the optimum frequency shifts away from the line (calculated using the radiative transfer models compiled in [7]).

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) [3] and the Atacama Large Millimeter Array (ALMA) telescope to track optical path variations. Two research ground-based instruments were also constructed by the Environmental Technology Laboratory (ETL) and by NASA and were both operated 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 [1]. More recently, the Ground-based Scanning Radiometer [4] participated in a late winter Intensive Observation Period (IOP) at the Department of Energy (DOE) North Slope of Alaska Atmospheric Measurement Program (ARM) site in 2004.

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This paper describes a compact, turn-key, four-channel G-band (183 GHz, 3 mm wavelength) water Vapor Radiometer (GVR), designed for long-term unattended operation on the ground.

II. GVR DESCRIPTION

A simplified block diagram of the GVR receiver is shown in Fig. 2. The downwelling atmospheric radiation is captured by a 10 cm diameter, 1.7° 3 dB (half power relative to maximum gain) beamwidth, 90 degree parabolic metal mirror and focused to a corrugated feed horn. A subharmonically pumped mixer, using a six times multiplied 15.276 GHz Dielectric Resonant Oscillator (DRO) LO signal, down-converts the upper and lower sidebands to baseband, where a broad-band Low-Noise Amplifier (LNA noise figure <2.3 dB) 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 (Transitor-Transitor Logic) 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 (Field Programmable Gate Array) 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 Personal Computer (PC) via an RS422 serial bus.

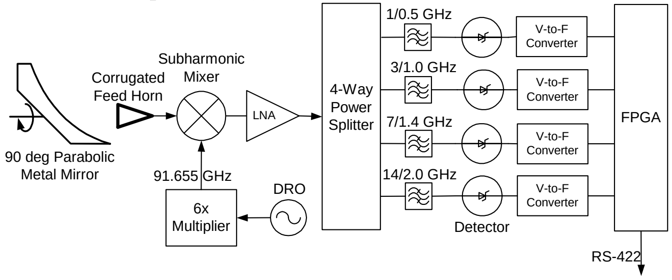

Fig. 2. GVR simplified component level block diagram.

Since neither noise sources nor low-loss fast switches are readily available at G-band, GVR is operated as a total power radiometer and external (to the antenna horn) hot and warm calibration absorbers are periodically observed to track changes in 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 3 dB 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 Proportional Integral Derivative (PID) controller to 293 K. The temperature of the absorbers is monitored with Resistance Temperature Detectors (RTD) 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 beamwidth of the feed illuminates roughly half of the mirror's overall diameter. The cost of this under-illumination is that the GVR antenna 3 dB beamwidth is broadened to 1.7° compared to about 1.1° beamwidth of a same size antenna designed to maximize gain.

This mechanical method of calibration can only be repeated a few times a minute, so the receiver gain must remain stable on this timescale. For each K change in physical temperature of the GVR amplifiers (component plate), the receiver gain changes by about 0.1 dB, or equivalently an 80 K change in the perceived scene brightness temperature. Consequently, temperature stabilizing the receiver components, particularly the amplifiers is essential.

To stabilize the temperature of the receiver components, the packaging technique developed by Tanner [2] was employed, consisting of an insulated cold-plate in a box, in a temperature controlled enclosure. The resulting component plate temperature stability limited receiver-gain rate-of-change to below 10 dB/Hr (100K/Hr equivalent scene temperature drift rate), making the calibration cycle rate of a few times a minute sufficient to achieve a sub-K measurement precision.

The filter-bank type receiver was chosen over a variable Local Oscillator (LO) type design to increase data rate 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. 3. The rapidly diminishing noise figure of the harmonic mixer above 14 GHz is evident in the skewed outside passbands.

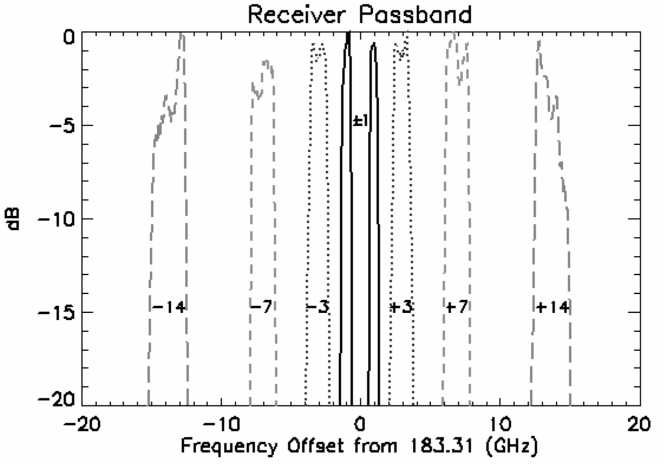

Fig. 3. Frequency response of the four GVR double sideband receiver channels. The output power of the G-band source used to make these measurements over the 163 to 203 GHz band was flat to within 0.5 dB. This measured frequency response is needed to optimize the LWP and PWV retrieval algorithms.

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 (~263 K) 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 the error series associated with the radiometer measured brightness temperatures $\widehat{T}(i)$, $i=1,\ldots,M$, relative to the true (error free) $T(i)$, such that

(1)

$$AD_N = \sqrt{\tfrac{1}{2}}\left(\sum_{i=1}^{j=\left(M/N\right)-1}\frac{\left[\overline{E}_N\left(Ni+i-N\right)-\overline{E}_N\left(Ni+i\right)\right]^2}{M/N-1}\right)^{1/2}$$

, where $\overline{E}_N\left(i\right)=\sum_{j=i}^{j=i+N-1}\frac{\widehat{T}\left(j\right)-T\left(j\right)}{N}$.

The measured $AD_{\Delta t}$ as a function of Δt is shown in Fig. 4, 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 by averaging up to about 8 minutes. 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. 5. The resulting instrument 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.

The instrument precision suggested by Fig. 4 is only valid when the sky temperature is close to the temperature of the GVR calibration loads. The temperature of the absorber used to measure the Allan Deviation of Fig. 4 was about –10 C (~263 K), not much colder than the 293 K GVR warm load. Measurement errors increase with colder temperatures, such that a 50 K sky measurement is expected to have close to six times the errors shown in Fig. 4.

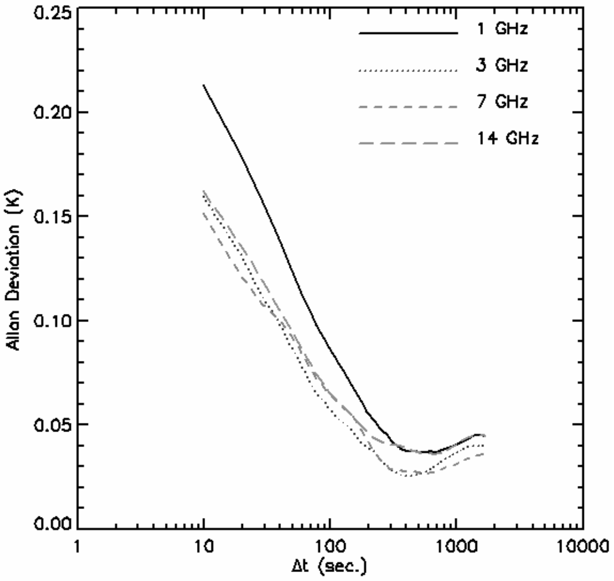

Fig. 4. Allan Deviation of the GVR measured in a temperature stable chamber while observing a –10 C absorber.

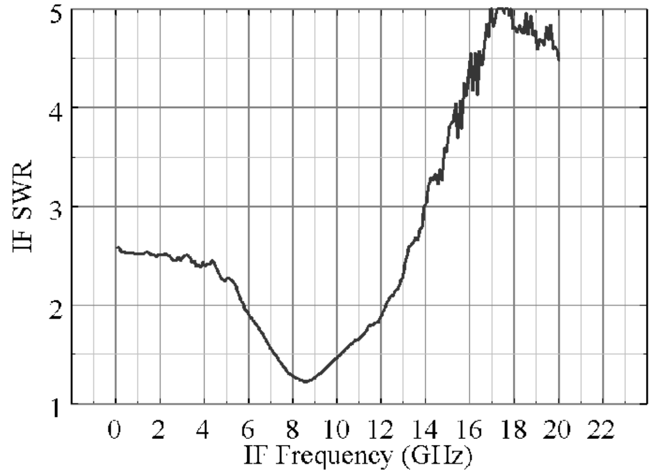

Fig. 5. IF port Standing Wave Ratio (SWR) of the Virginia Diodes Inc. 183 GHz sub-harmonically pumped front-end mixer.

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. 6., where it collected data continuously for one year.

Fig. 6. 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.

Key system parameters for the GVR instrument are summarized in Table 1.

TABLE I

GVR KEY PARAMETRERS

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
Antenna:	4" Aperture, 90 deg Parabolic Metal Mirror, 1.7° 3 dB BW
Radome:	1 mil. Mylar film w. blower and hood (Ground)

IV. EXAMPLE DATA

On February 18, 2005, the GVR was operating from the roof of the ProSensing facility in Amherst, MA. In early afternoon, broken clouds, shown in Fig. 7, 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. 8. The PWV and LWP, shown in Fig. 9, 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 GVR in Barrow, Alaska using coincident radiosonde data and the Rosenkranz corrected vapor absorption model [8] is presented by Caddedu et. al, [9].

Fig. 7. Winter-time fair weather cumulus clouds passed over the 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 supercooled liquid. The retrieved Liquid Water Path (LWP) data, shown in Fig. 9, demonstrates the sensitivity of the instrument to the passing clouds.

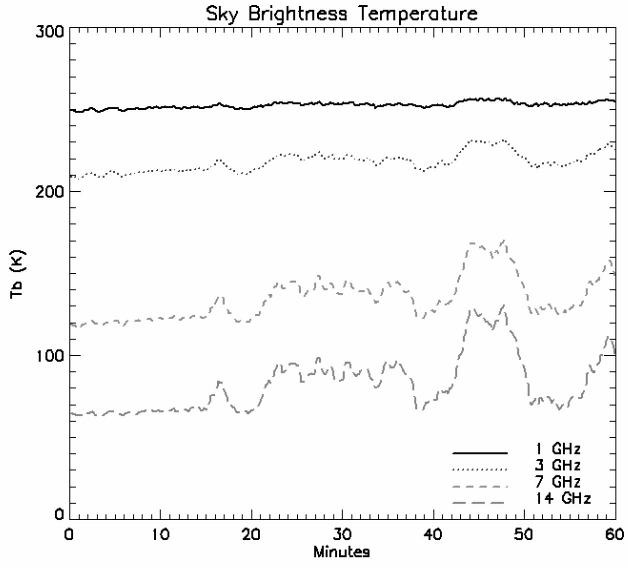

Fig. 8. Data collected with the GVR from clouds containing super cooled liquid water, shown in Fig. 7.

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 so 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 the 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.

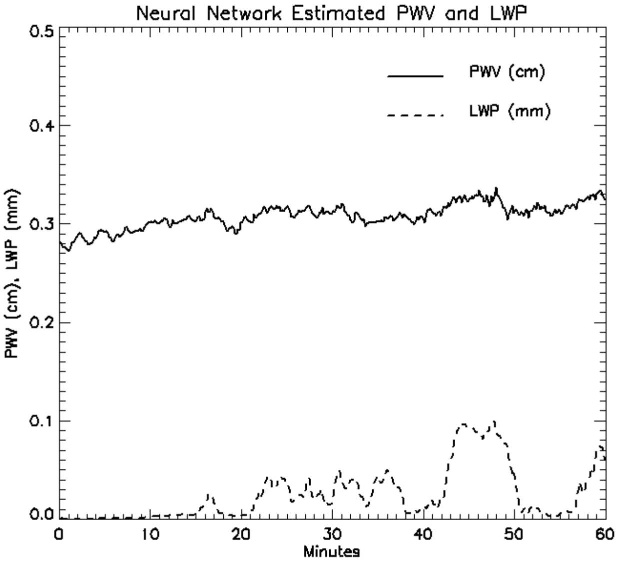

Fig. 9. Retrieved precipitable water vapor and liquid water path of the fair weather cumulus clouds shown in Fig. 7. Data products were estimated using a neural network algorithm from the measured brightness temperatures of Fig. 8 and surface temperature.

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 the radiometers described in this paper is that it realizes 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 is quite large compared to the rest of the instrument, but it is necessary for absolutely calibrating the measurements.

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 effected 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 clear 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.

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