Microwave Radiometer Systems for Profiling of Low Water Vapour Concentrations and Temperature in Antarctica and for Polarized Observations of Rain: Instruments, Retrievals and Results

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ABSTRACT

The monitoring of low humidity levels at dry and cold locations like Antarctica is of interest for the modelling of earth's climatology. Global warming leads to increased concentrations of atmospheric water vapour and the strongest gradients can be measured in polar areas where warming effects are more dramatic than elsewhere.

Accurate cloud liquid measurements are essential for the understanding of cloud physics and the atmosphere's water cycle. LWP measurements with reasonable accuracy under raining conditions are complicated due to the presence of a mixture of Rayleigh and Mie scattering hydro-meteors. Polarized microwave observations offer the possibility to distinguish between cloud and rain liquid, and therefore to determine the total amount of liquid water more precisely. This contribution is a description of design concepts and built instruments for the stated applications, as well as methods of improving the water vapour profile vertical resolution.

1. INTRODUCTION

A. Low Humidity Profiler

In order to measure low atmospheric humidity concentrations at microwave frequencies, the strong 183.31 GHz water vapour line is the most useful spectral feature. Below humidity levels of 2 mm integrated water vapour (IWV) the much weaker water vapour line at 22.24 GHz almost disappears and humidity profiling is not possible.

The combination of a 183 GHz, 7 channel DSB (double side band) filter bank system with a 50-60 GHz temperature profiler (the RPG-LHATPRO, Low Humidity and Temperature Profiler) turns out to be an ideal tool to resolve the vertical humidity distribution in particular for the boundary layer with a water column of less than 4 mm down to 0.05 mm. The applied boundary layer scanning method resolves the low level extreme temperature inversions present in Antarctica. Inversions of >20 K over 200 m vertical extension are common and their detection requires a high spatial resolution of the 50 GHz antenna beam to be able to scan at low elevation angles down to 5°.

At remote places like Antarctica, the supply with liquid nitrogen for calibration purposes can be problematic. Calibration intervals of > 6 month are desirable to reduce logistic costs. In order to maintain the radiometric accuracy over such long periods, the radiometer's receivers are equipped with switchable secondary precision noise standards for gain drift compensation. In combination with an internal ambient temperature calibration target, the noise standards allow for a continuous complete auto-calibration of both receivers. This concept has been applied to many radiometer systems in the past, in particular at lower frequencies <60 GHz. The challenge in the design of the RPG-LHATPRO's water vapour radiometer was the development of a 170-200 GHz noise source with an output power of >7000 K equivalent noise temperature (excess noise ENR=13.7 dB). The noise source power is injected into the receiver via a 10 dB coupler and therefore adds about 700 K calibration noise at the receiver input. Such powerful noise sources at frequencies >170 GHz are currently not commercially available. Other calibration systems using cooled or heated absorber targets instead of a semi-conductor noise source are suffering from well known disadvantages like relatively small temperature difference to ambient temperature T_A, thermal gradients across the absorber cross section, high power consumption and poor long term stability. In particular the relatively small temperature difference of these targets with respect to T_A leads to a lower calibration accuracy compared to a calibration system with a 700 K hot target.

B. Polarized Multi-Frequency Radiometer

Polarized instruments cannot use scanning mirrors for elevation scans because the rotating mirror changes the E-field polarisation plane at different reflection angles. Consequently, the radiometers have to be rotated in elevation together with their antennas. In this configuration, external calibration targets for automatic calibration procedures are not practical, at least at frequencies < 40 GHz. Internal auto-calibration systems have been designed to achieve the required radiometric long term stability. The calibration system comprises noise sources and magnetically switched Dicke reference devices of the Y-junction type. Allan variance tests are presented to demonstrate the performance of this calibration approach. External calibration targets are no more required, except for a clear sky in the case of regular automatic sky tipping.

The discrimination of cloud and rain liquid during a rain event requires dual polarized receivers at different frequencies for different rain rates. A three frequency dual polarized radiometer, ADMIRARI, has been built by RPG for rain observations. ADMIRARI comprises receivers operating at 10.7, 21.0 and 36.5 GHz for strong, medium and light rain detection.

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2. INSTRUMENT AND MEASUREMENTS

A. RPG-LHATPRO

Fig.1a) and 1b) show the principle receiver layout of both RPG-LHATPRO profilers. The oxygen line temperature profiler (51-59 GHz, a)) is a direct detection receiver without mixer and local oscillator (LO) and therefore a purely passive system. The input signal is amplified, split, boosted, filtered and detected in the reception band without down-conversion to a low frequency (IF) band. The advantage is that the direct detection receiver is immune to low frequency interferences caused by strong radio transmitters or other sources. The filter bank concept reflects a parallel design with 100% measurement duty cycle for each channel. The oxygen line shape, which is used to derive the temperature profile, is captured in a single integration step which is much more efficient than using sequentially scanning synthesizers in heterodyne receivers. Typical system noise temperatures in the 51-59 GHz band are about 550 K.

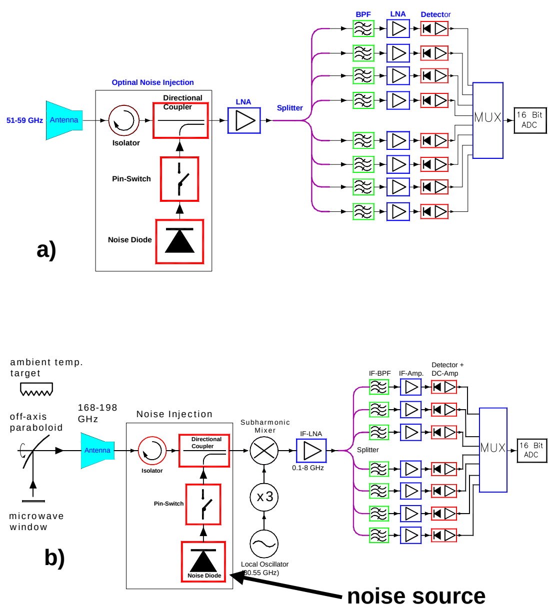

Figure 1. *a): 8 channel direct detection filter bank receiver (temp. profiler 51-59 GHz) and b) 7 channel DSB 183.31 GHz humidity profiler layout..*

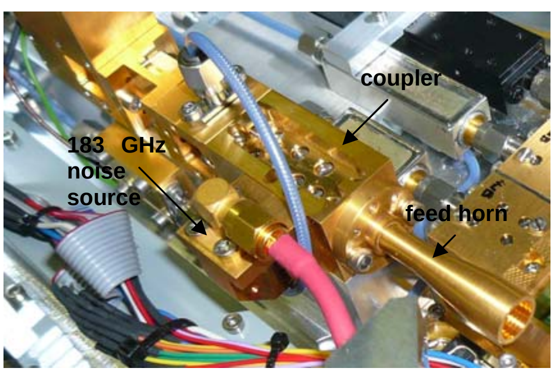

Figure 2. *183 GHz RF front end with feedhorn, directional coupler and 7000 K noise source.*

The humidity profiler is a 7 channel 183 GHz double sideband (DSB) heterodyne receiver with sub-harmonic mixer and parallel filter bank architecture (Fig.1b)). The highlight of this design is a powerful 7000 K precision noise source for long term gain stabilization, operating in the 170-200 GHz range. In combination with an ambient temperature calibration target, the noise sources eliminate the need for frequent absolute calibrations using liquid nitrogen and help to make this instrument well suited for remote sites like Antarctica.

The RPG-LHATPRO has been deployed at Concordia station, a French / Italian research facility at Dome C / Antarctica since January 2009 (Fig.3). It is operated by the French Laboratoire d'Aerologie, Observatoire Midi-Pyrenees in Toulouse [1] combined with a strato-spheric water vapour radiometer. During the summer season, LHATPRO was used outside at environmental temperatures down to -40°C. The Concordia station's altitude is 3300 m asl.

Figure 3. *RPG-LHATPRO deployed at Dome-C in Antarctica.*

In Fig.4 a comparison between a radiometer temperature profile and a radio sounding is shown. Within the troposphere up to 5 km above the station, the two profiles match quite well and the tropo-pause altitude is in good agreement.

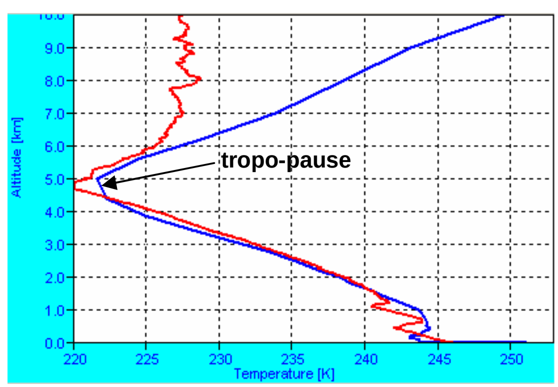

Figure 4. *Typical temperature profile over Dome C in summer time, blue: Radiometer Retrieval, red: Radio Sounding (courtesy of P.Ricaud, Laboratoire d'Aerologie, Observatoire Midi-Pyrenees).*

In contrast to winter profiles, when low inversions of 30 K can be observed (radiative surface cooling dominates), there are no pronounced temperature inversions close to the ground during the summer season (radiative cooling is balanced by infrared warming of the snow surface). Beyond the tropo-pause, the radiometer profile temperatures are unrealistically warm. The temperature profiler retrievals do not include radiative transfer calculations for the stratosphere and therefore this discrepancy is not surprising. The main purpose of the RPG-LHATPRO at Dome C is to continuously monitor the tropospheric boundary layer temperature and humidity profile structure for at least 10 years.

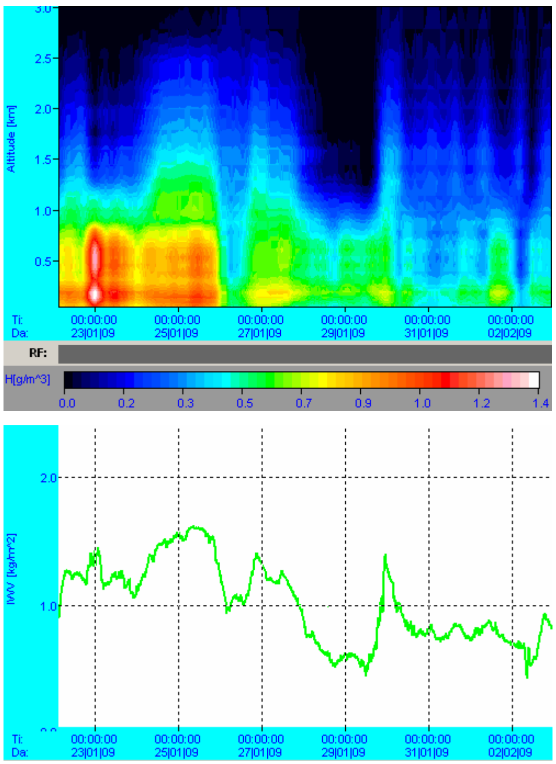

Figure 5. *Humidity profile time series and IWV for the period 22.1.2009 to 3.2.2009 (courtesy of P.Ricaud, Laboratoire d'Aerologie, Observatoire Midi-Pyrenees).*

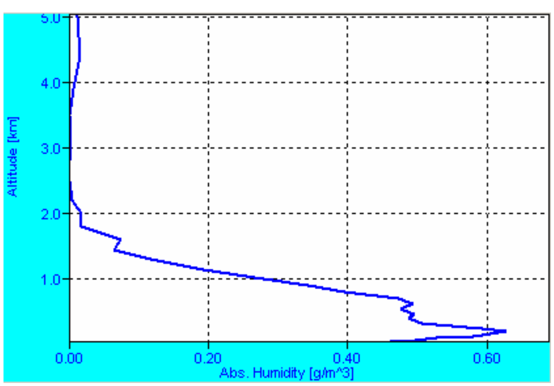

Figure 6. *Single humidity profile with humidity concentrated below 1000 altitude above ground level (courtesy of P.Ricaud, Laboratoire d'Aerologie, Observatoire Midi-Pyrenees)..*

Fig.5 is a time series of humidity profiles and IWV over a period of 10 days. The IWV variability is significant and ranges between 0.5 and 1.5 mm which is typical for the summer season. During winter time, the humidity level drops down to an order of magnitude less compared to summer time. Fig.6 illustrates that almost 90% of the total water vapour is concentrated in the lowest 1000 m layer.

B. Polarized Multi-Frequency Radiometer

The discrimination of rain liquid water and cloud liquid during rain events is possible because falling rain droplets flatten horizontally (almost elliptical shape) and therefore show a stronger microwave emission at horizontal polarisation than at vertical. In contrast, cloud droplets with their small diameters in the order of 10 µm are perfectly spherical and do not lead to polarisation effects. Because the scattering of large rain droplets exceeds the scattering of an ensemble of small cloud droplets of the same volume, un-polarized measurements tend to over-estimate the total amount of liquid water during rain [2],[3]. The additional measurement of polarisation differences caused by rain droplets implies a much more accurate LWC (liquid water content) estimate, which is the major motivation for this observation technique.

As discussed before, polarized measurements of atmospheric emission under lower elevation angles necessitate to rotate the radiometers in elevation together with their antennas, in order to avoid a polarisation change of the received signal by scanning mirrors. Fig.7 shows an example, the ADMIRARI radiometer, which has been optimized for rain observations [4].

Figure 7. *ADMIRARI instrument: Three frequency (10.7 / 21.0 / 36.5 GHz), dual polarized radiometer, optimized for rain observations.*

The required scanning configuration has certain consequences for the receiver calibration techniques because it is not practical to use quasi-optical calibration targets which have to be scanned during observations. Therefore the receivers do not only comprise noise standards for gain drift compensation, but also have to replace the standard ambient target by a smaller internal device, a magnetically switchable Dicke reference for receiver noise temperature long term drift corrections. These devices can switch the receiver input to a waveguide termination within milliseconds and allow for a continuous observation mode without calibration interruptions (see Fig.8).

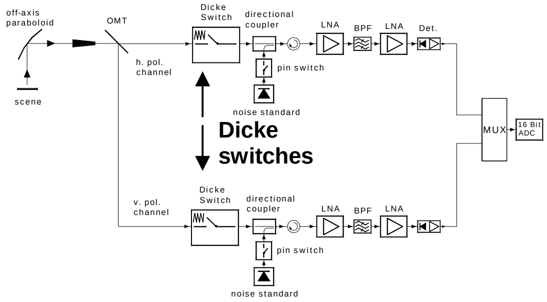

Figure 8. *Dual polarised ADMIRARI receivers with noise injection and Dicke switch calibration standards.*

All receivers are realized in direct detection technology. An ortho-mode transducer (OMT) splits the feed horn signal into orthogonal polarizations (see Fig.9).

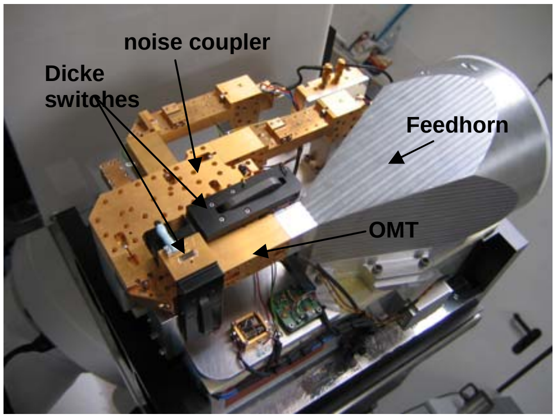

Figure 9. *21.0 GHz dual polarized receiver.*

The 1/f noise stability of the calibration system was checked by Allan Variance measurements and showed a stability of better than 3000 seconds. This makes these receivers ideal for applications where no external calibration targets are available.

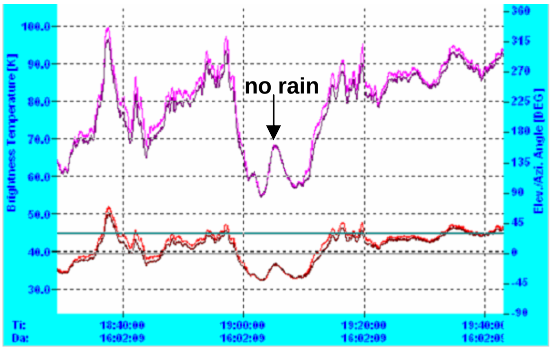

Figure 10. *Brightness temperatures at 36.5 and 21 GHz during a rain even, elevation angle: 30°.*

In fig.10 a time series of brightness temperatures (21.0 and 36.5 GHz) clearly identifies periods with rain droplets (polarisation difference visible) and without rain.

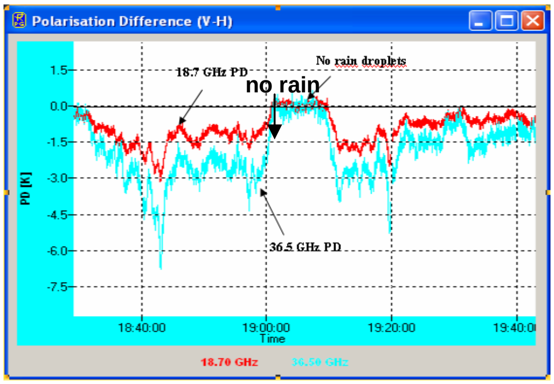

Figure 11. *Polarisation difference of the time series in fig.10.*

A first simple retrieval set has been developed at RPG based on radiative transfer calculations taking one-dimensional scattering into account, to quantify LWC in terms of cloud and rain contributions. Fig.12 shows the different components.

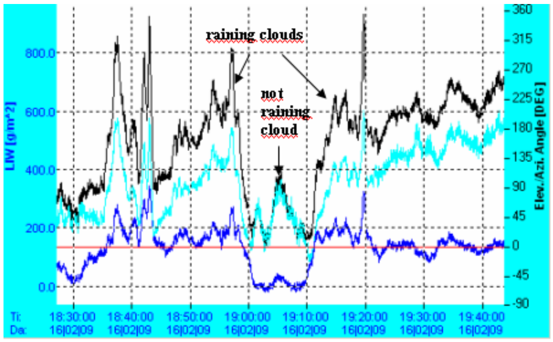

Figure 12. *A rain event split into cloud liquid (light blue) and rain liquid (dark blue), black is the total LWC.*

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