Radiometer Physics GmbH

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Radiometer Description and Performance

1.2 General Features

1.2.2 The RPG-HATPRO saves all measurement and housekeeping data on an embedded PC inside the radiometer for safety purposes and in addition on the external control PC (Host) that performs an online monitoring of that data.

1.2.3 The radiometer can be remotely controlled via remote desktop software (LAN interface of the host PC). Supported data formats are binary, ASCII and netCDF. Other data formats can be implemented if required.

1.2.4 The HATPRO software source code is written in C. It can be provided and the code is implemented for Windows NT, Windows 2000 and Windows XP operating systems.

1.2.5 The monitoring host software performs data quality checks like possible signal interference, retrieval limitations due to scattering on rain drops, thermal drifts during warm up etc. The data quality flags are stored in a separate file and are displayed online for warnig purposes.

1.2.6 Software updates are performed on a regular basis (approx. every 3 month) and are available free of charge for all RPG-HATPRO customers. The operating systems installed on the delivered PCs are licenced.

1.2.7 HATPRO data and software does not require a license.

3. Specifications

3.1 Microwave radiometer

3.1.1 The radiometer continuously measures humidity and temperature profiles with typical temporal resolution of 30 seconds. A boundary layer scanning mode provides 50 m vertical resolution for temperature profiling to resolve low level temperature inversions. The system is shipped with a set of retrievals for LWP, IWV, humidity profiles (full troposphere), temperature profiles (full troposphere), temperature profiles with high vertical resolution (boundary layer), stability indices (lifted index, Showalter, K-index, CAPE, Total Totals) and cloud base height. These retrievals do not require any external input except for the microwave brightness temperature, IR radiometer information and time / date. The time / date information is used for a continuous inclusion of seasonal effects to improve the a-priori

information accuracy. The minimum time resolution for most level 2 data products is 1 second. The minimum time resolution for boundary layer temperature profiling is 120 seconds since it requires an elevation scan.
RMS errors: Temperature profiles: 0.45 K (0-1000 m, vertical resolution 50-100 m, boundary layer mode), < 1 K (1000-4000 m, vertical resolution 100-500 m, zenith mode), < 2 K (4000 – 10000 m, vertical resolution 500-1000 m, zenith mode). Rel. humidity profiles: < 10% (0-1000 m), < 20% (1000-4000 m). IWV: < 0.3 kg/m^2. LWP: < 20 g/m^2.

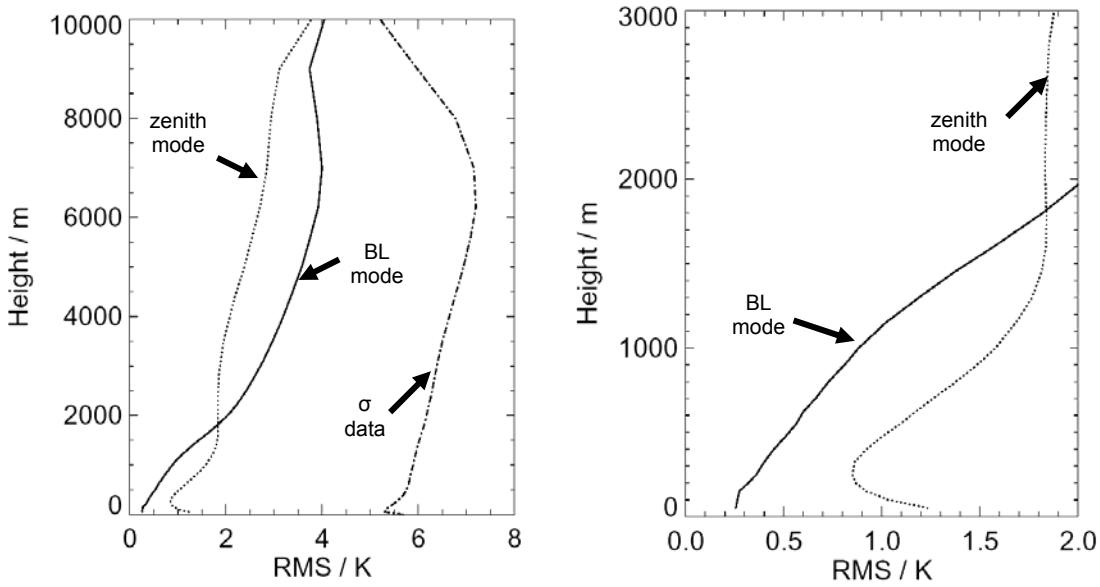


Fig.1: RMS accuracy of both temperature profiling modes.

The high vertical resolution capability of the BL mode is in particular important for the resolution of low level temperature inversions. The next figure shows an example of direct comparison between HATPRO measured temperatures at 200 m altitude and the temp. sensor reading of a meteorological tower in Cabauw/Netherlands (KNMI).

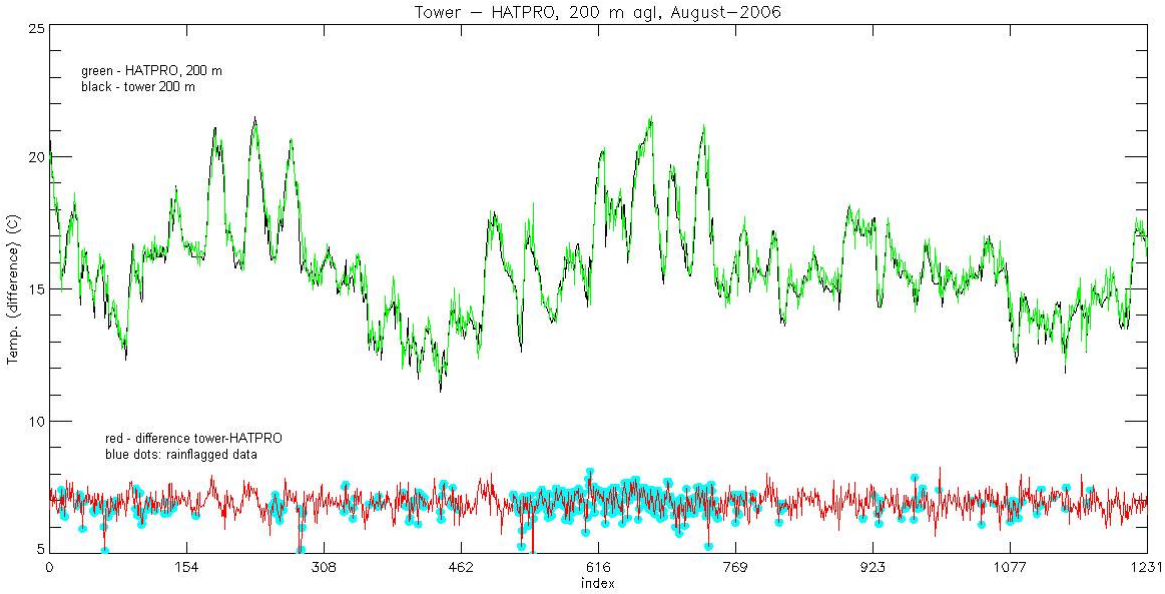


Fig.2: Comparison of retrieved HATPRO temperature at 200 m with 200 m temperature sensor reading of met. tower in Cabauw (KNMI) in August 2006. Total

number of samples: 1232, no-rain: 836 samples (RMS: 0.36 K, bias: -0.04 K); 396 rain samples (RMS: 0.45 K, bias: -0.13 K).

Humidity retrieval accuracy:

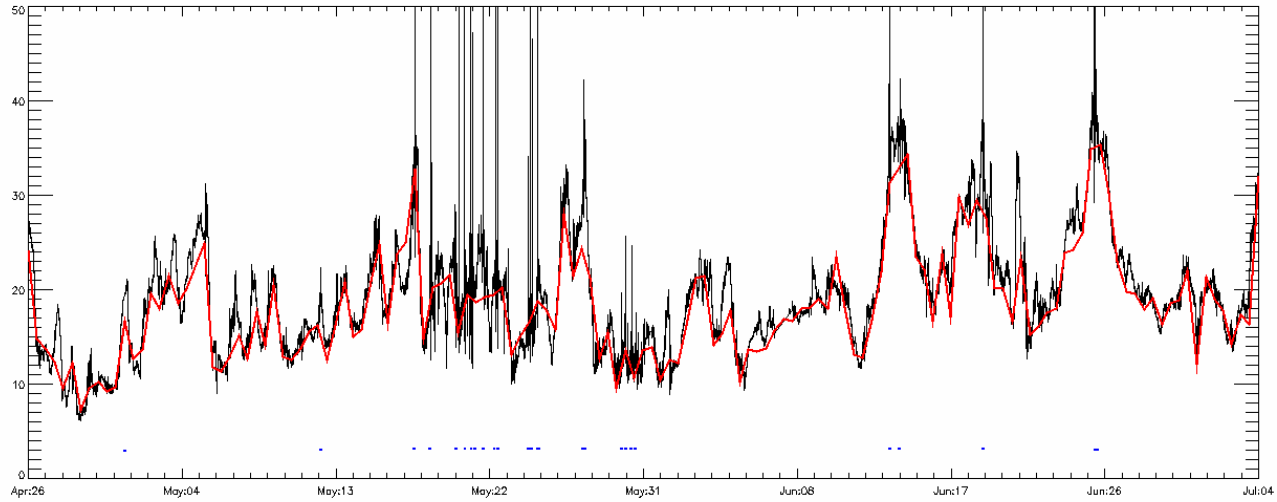


Fig.3: Comparison of retrieved HATPRO IWV (black) with one month radiosonde data (red). 140 radio sondings (26. April to 4. July, Cabauw, KNMI), radiosonds: Vaisala RS-92, no-rain RMS: 0.43 kg/m^2, bias: 0.05 kg/m^2

Liquid water profiles:
It is not possible to measure liquid water profiles with reasonable accuracy by using passive microwave radiometry (for this reason cloud radars with ten times the cost of a passive instrument are still built and sold). The reason for this fact is that liquid water does not emit a spectral line like water vapour or oxygen but only a continuum component instead (a water droplet is not a molecule!). The water vapour line does not contain any information about liquid water, so only the ratio between the water vapour line centre brightness temperature relative to the window channel TB at 31.4 GHz measures the **total amount** (LWP) of liquid water. This is just a single number! Even if one uses an infrared radiometer to determine the cloud base height (combining the IRR data with the temperature profile) this adds another number. It should be mathematically clear that it is not possible to derive a profile from two numbers (the oxygen line TBs do not help either). The most important parameter that is missing for a coarse liquid water profile estimate is the cloud top height (then one could estimate a profile by using an adiabatic approach or the Salonen model). It is scientifically not respectful to claim that liquid water profiling can be done with passive microwave radiometry and clearly criticized by experts who develop retrieval algorithms for atmospheric parameters. Nobody has ever proven or published (e.g. by comparison with radar and ceilometer data) that 'liquid water profiles' derived from observations of the water vapour line and window channels around 31 GHz (in combination with IRR data) are consistent with active microwave observations of clouds. The RPG-HATPRO provides even more channels than other competitive instruments and would be used for liquid water profiling, if it would be scientifically justified.

3.1.2.1 The RPG-HATPRO operating environmental temperature is -30°C to +45°C. Over this range the receivers and optics are thermally stabilized to 30 mK!

3.1.2.2 operating humidity is <=100%

3.1.2.3 The RPG-HATPRO is firmly mounted to its stand which can be anchored to the ground or loaded with sand sacks or concrete plates. The system withstands wind speeds up to 70 m/sec (ca 250 km/h).

3.1.2.4 The radiometer provides a wide range AC voltage input (90-240 Volts AC), 50-60 Hz with maximum power consumption of 350 Watts at warm-up. When the radiometer is in equilibrium state (after warm-up), its power consumption is approx. 120 Watts. The blower system operates on two speeds: low speed (70 Watts) for rel. humidity e.g. < 70% (user selectable) and no-rain, high speed for rain conditions and rel. humidity e.g. >= 70% (user selectable). The blower heater (1350 Watts) is only turned on during rain and rel. humidity levels above 90% (fog!) or can be disabled. The heater is a removable unit. Heater and blower can be powered separately from the radiometer to allow for by-passing of UPS systems. The average total power consumption of the system is estimated to be <500 Watts.

3.1.3 Center frequencies & BW: K-band: 22.24 GHz (230 MHz), 23.04 GHz (230 MHz), 23.84 GHz (230 MHz), 25.44 GHz (230 MHz), 26.24 GHz (230 MHz), 27.84 GHz (230 MHz), 31.40 GHz (230 MHz). V-band: 51.26 GHz (250 MHz), 52.28 GHz (250 MHz), 53.86 GHz (250 MHz), 54.94 GHz (250 MHz), 56.66 GHz (600 MHz), 57.30 (1000 MHz), GHz, 59 GHz (2000 MHz).
All bandpass filters are waveguide resonator filters. The frequency stability is better than 100 Hz / year for both bands since no dielectrics (except dry air) are used and mechanical stability of waveguide filters is high. The filters are thermally stabilized to better than 30 mK.
All channels are realized in direct detection technology without using mixers for frequency down-conversion. The radiometer is immune to low frequency interference below 18 GHz. The direct detection receivers do not comprise local oscillators that might emit leakage power out of the system. The direct detection technology implies 100% passive radiometry.
The channel selection is optimized due to protected bands, lowest channel correlation and thus highest information content.
Channel over-sampling of the water vapour and oxygen lines allows for omitting single channels in the case of signal band interference without significant loss of retrieval accuracy.
RFI below 18 GHz (e.g. by cell phone transmitters, radio / TV transmitters, wind profilers) is not possible due to direct detection technology.

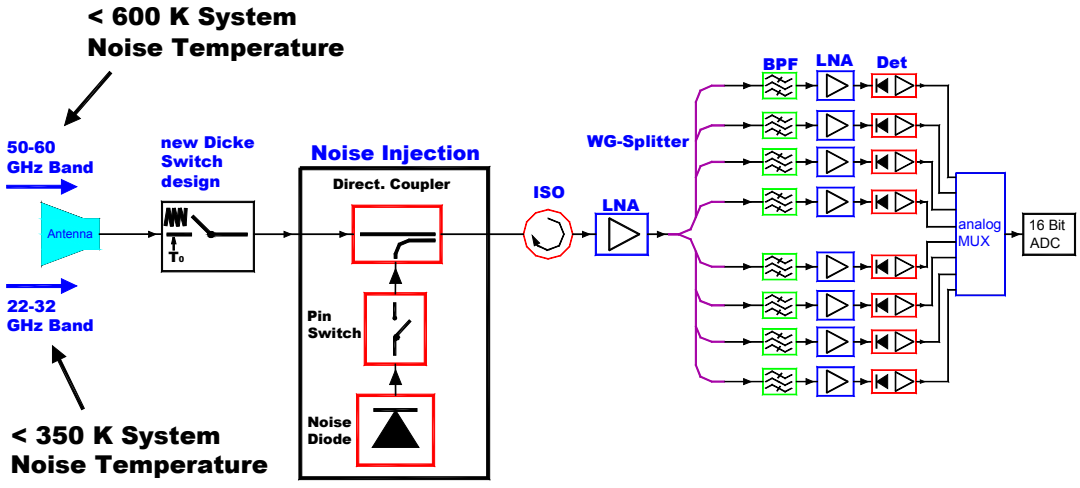


Fig.4: RPG-HATPRO direct detection filter-bank receiver layout with parallel data acquisition of all channels (100 % duty cycle). The design does not use local oscillators or mixers and is neither immune to RFI < 18 GHz nor does it emit any spurious leakage power at signal band frequencies (like synthesizers do). Its parallel configuration scans both spectral lines in one step without the need for switching frequency channels (temporal resolution: 1 sec.).

Radiometers with synthesizer local oscillators (heterodyne systems) do not have the sensitivity of a parallel detection system like the RPG-HATPRO. They work like a spectrum analyzer and sample the atmospheric line channels sequentially (one after the other) with a very poor duty cycle of < 10% per channel. This results in less integration time / channel and much higher noise levels. A synthesizer controlled radiometer would not be capable of fulfilling the high radiometric demands of the boundary layer temperature profiling mode (RMS noise < 0.1 K) and is thus not able to retrieve temperature inversions accurately. Even though such a system can change its RF frequency set (e.g. to avoid interferences) it is **not** able to change its IF frequency (its down-converted frequency) band. It is well known that IF interferences are quite common close to radio transmitters in the 50 to 100 MHz range or can be emitted by digital systems (PCs) or other fast switching devices (or e.g. by wind profilers). In field experiments it was found that synthesizers in radiometers can easily leak out of the system and interfere with other instruments. Thus such systems cannot be considered as purely passive.
The RPG-HATPRO avoids all these possible interference problems by not using a down conversion. The receivers provide a cut-off for all frequencies < 18 GHz. If an RFI is encountered in one of the channels the jammed channel is simply not used in the retrieval algorithm. This can be done without affecting the retrieval output quality because the spectral lines are both over-sampled by the RPG-HATPRO radiometer. This means that the HATPRO frequency set contains redundant information (the channels are highly correlated) which slightly improves the retrieval noise. E.g. by losing one channel as retrieval input the retrieval output noise is slightly increased which is mostly compensated by the systems' overall low TB noise level related to its 100% duty cycle channel integration.

3.1.4 The radiometer is absolutely calibrated twice per year (using liquid nitrogen) to calibrate its internal secondary noise standards. This way its accuracy does not degrade over years and is maintained constant.

3.1.5 The requirement of measuring accurate humidity profiles at 20 mm / h rain rate is not realistic. Boundary layer temperature profiling is still quite accurate at rain rates of 20 mm/h (see Fig.2) but due to scattering on rain droplets the water vapour line is drastically distorted (see Fig.5a below). The line is relatively weak and at rain rates of 20 mm/h or more the liquid water continuum dominates the spectrum. A more realistic threshold for reasonably accurate humidity profiling and IWV measurements is 5 mm/h rain rate. Under these conditions the droplet diameter is quite small and scattering effects can be handled by the retrieval (scattering on droplets is proportional to the 6^{th} power of the droplet radius), see Fig.5c. The problem is not caused by droplets on the microwave window because the strong blower system is capable of removing these drops effectively. The radiative transfer calculations required to develop the retrieval algorithm for the humidity products cannot distinguish between different drop size distributions during rain events and are only able to retrieve accurately when droplet scattering can be neglected. This situation can be improved when the radiometer data is combined with a MRR (microwave rain radar) that provides the drop size distribution that can be fed into the profile retrieval.

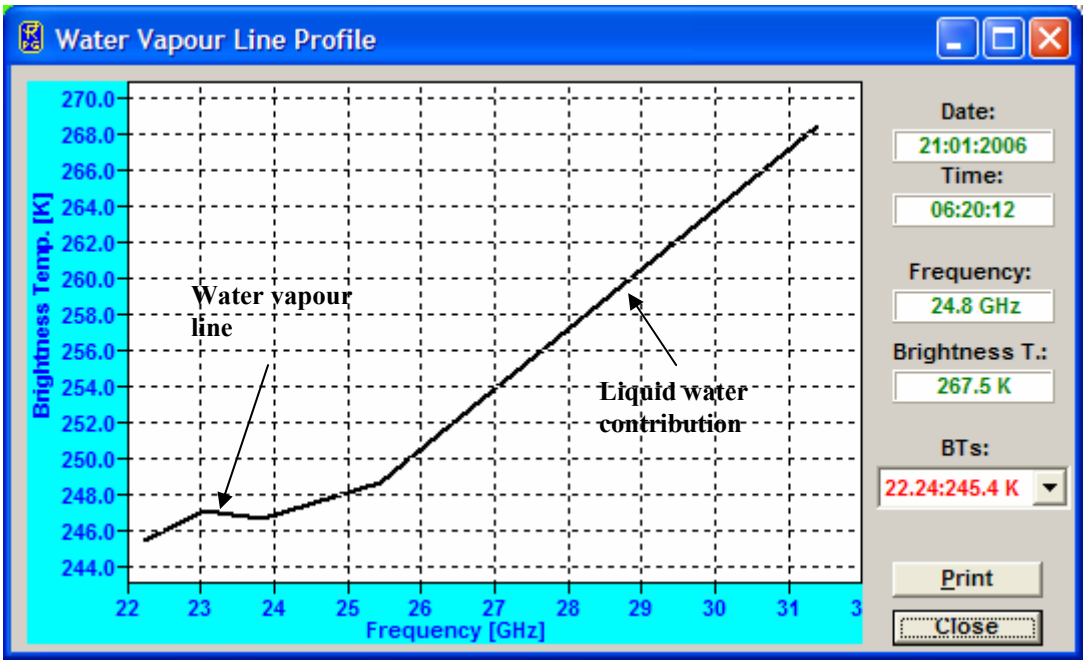


Fig.5a: Water vapour line profile measured in Darwin /Australia at a rain rate of 20 mm/h. IWV retrieval: 86 kg/m^2, radio sounding: 66 kg/m^2.

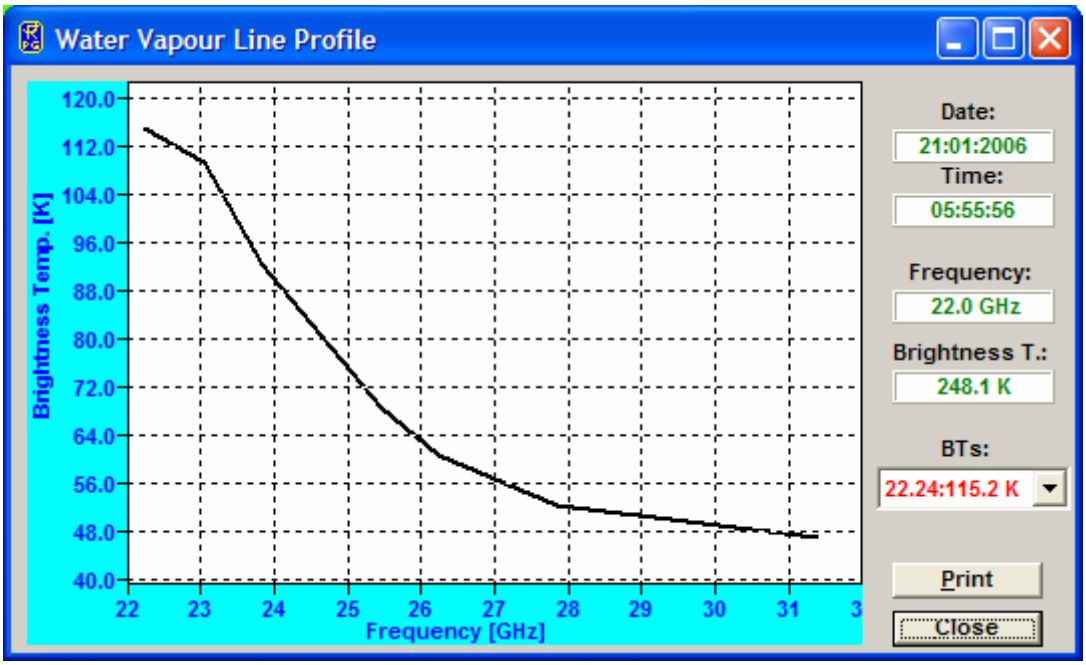


Fig.5b:Undisturbed (no rain) water vapour line profile measured in Darwin /Australia 25 minutes before. IWV retrieval: 68 kg/m^2, radio sounding: 66 kg/m^2.

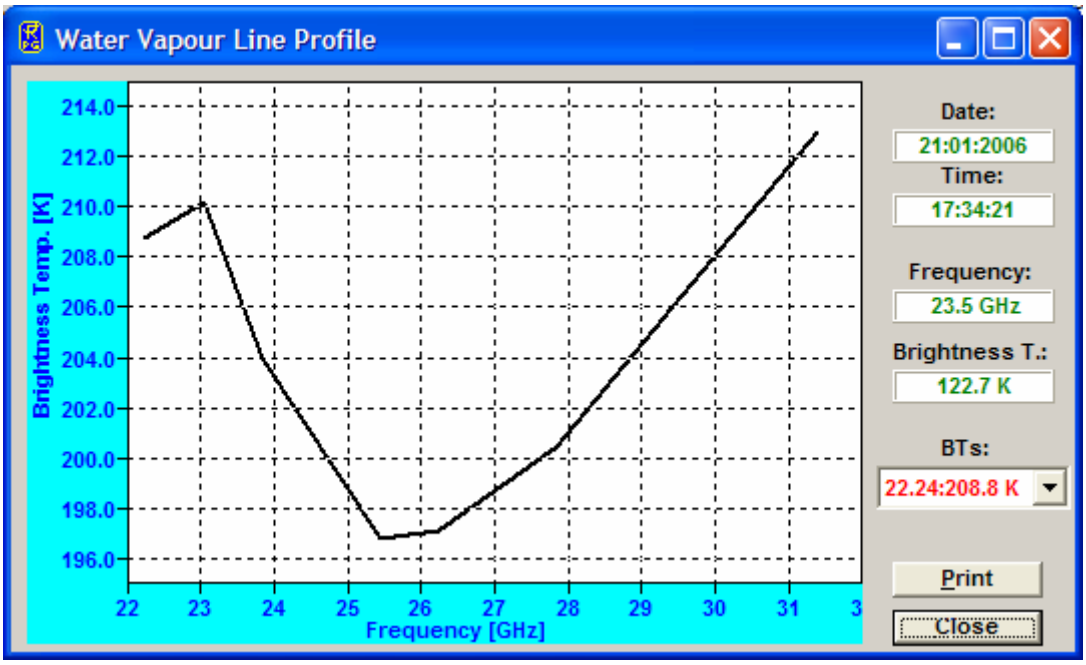


Fig.5c: Water vapour line profile measured in Darwin /Australia at a rain rate of 6 mm/h. IWV retrieval: 72 kg/m^2, radio sounding: 70.5 kg/m^2.

3.1.6 The RPG-HATPRO is equipped with a powerful azimuth drive and controller unit.This unit is controlled by the host software package.

3.1.7 The radiometer is mounted on a stable stand construction which is loadable (e.g. with sand sacks). The stand can be tied down to ground. The system withstands wind speeds up to 250 km/h. The instrument stand is equipped with 4 levellers and can be horizontally adjusted to a precision of +/- 0.1°. The prop weight is 35 kg and the stand is transportable.

4.1.1 RPG has more than 10 years experience in the installation of radiometer systems at research institutes all over the world. The RPG-HATPRO radiometer has been operated under various conditions by the following users:

University of Salford, UK
Instrumentation: RPG-HATPRO, lidar, radiation detectors
Application: Boundary layer and full troposphere temperature profiling, high temporal resolution LWP

ARPAV, Weather Service of Veneto / Italy
Instrumentation: RPG-HATPRO, METEC wind profiler, cloud radar
Application: Weather modelling and prediction, now casting, air pollution in the Po plain

Regione Marche Civil Protection Centre / Ancona, Italy
Instrumentation: RPG-HATPRO, weather stations, cloud radar
Application: study of atmospheric instabilities

Meteorological Institute, University of Bonn / Germany
Instrumentation: RPG-HATPRO, cloud radar, lidar, wind profiler
Application: T/H Profiling, LWP, convection in the tropics (AMMA Project)

KNMI, Weather Service of the Netherlands, Cabauw
Instrumentation: RPG-HATPRO, ceilometer, 200 m met. tower, cloud radar

Application: Weather modelling and prediction, climatology, LWP calibration of cloud radar data

Tokyo University / Japan

Instrumentation: RPG-LWP, RPG-TEMPRO90, wind profiler
Application: Validation of satellite data, cloud modelling, rain

University of Munich / Germ.

Instrumentation: RPG-HATPRO, RPG-DP150-90 (dual pol. 150 GHz + 90 GHz channel), ceilometer, wind profiler, lidar, radiation sensors
Application: High altitude atmospheric modelling, boundary layer temperature profiling in alpine locations (Zugspitze area)

Meteo Swiss / Switzerland

Instrumentation: 1x RPG-HATPRO, 2 x RPG-TEMPRO (single temp. profiler), ceilometer, wind profiler, lidar, radiation sensors, radiosondes
Application: boundary layer temperature profiling in the Mittelland area, convective processes in the lower troposphere

Aerospace Corporation / USA

Instrumentation: 1x RPG-HATPRO, radiosondes
Application: boundary layer temperature profiling (Los Angeles area, Hawaii), study of atmospheric changes over the ocean, calibration of satellite data

Institut für Meereskunde in Kiel / Germany

Instrumentation: 1x RPG-HATPRO
Application: instrument will monitor humidity and temperature profiles over the ocean (between Antarktika and Spitzbergen) on board of the German research ice breaker 'Polarstern'

University of Wisconsin, Medison / USA

Instrumentation: 1x RPG-HATPRO, IR lidar,
Application: long term campaigns at ARM (Atmospheric Radiation Monitoring system) Southern Great Plains site (Oklahoma / USA).

A certificate of sales is attached to this proposal.

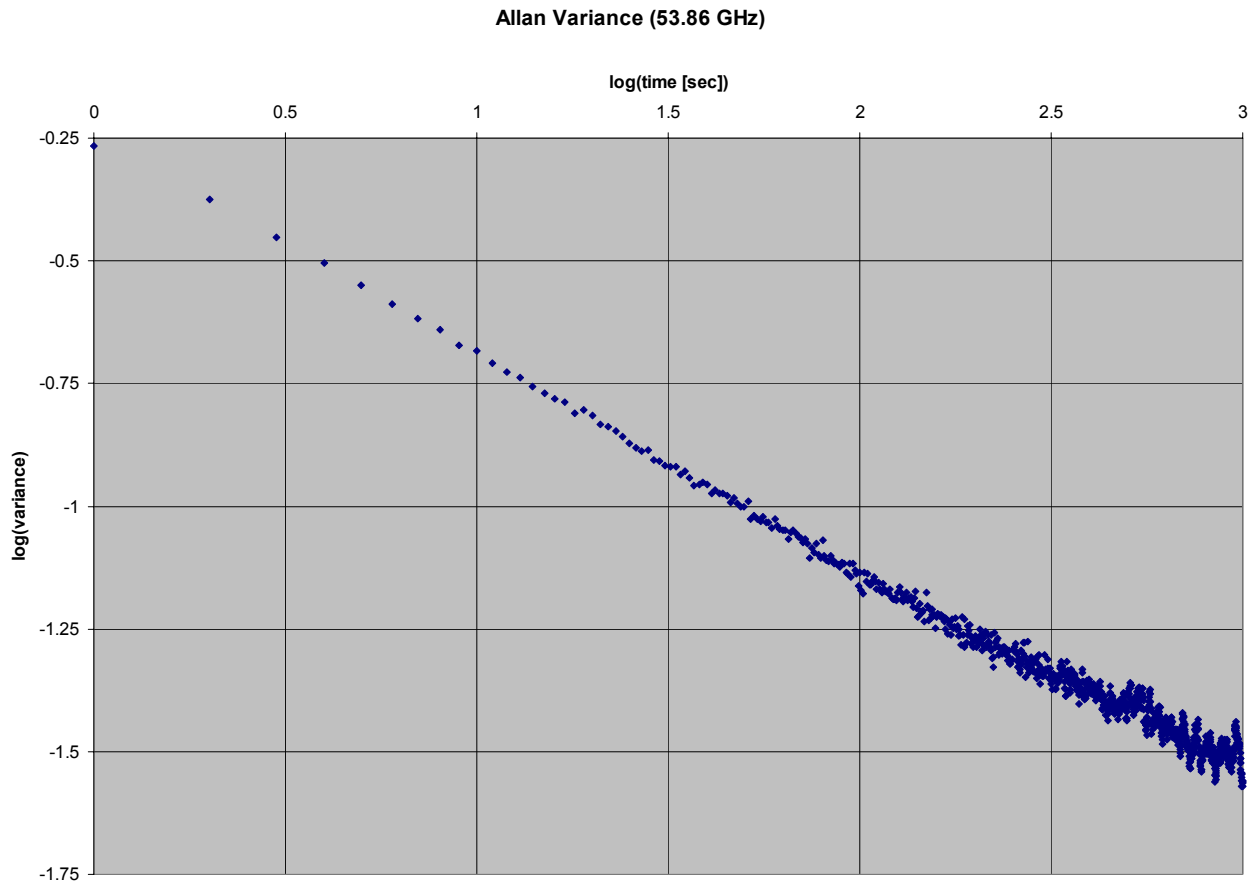
4.2.2 See separate offer document.

4.3.2 A measurement is initiated by sending a measurement definition file (MDF) to the radiometer. This file is stored on the embedded PC as long as the measurement is terminated by the user. In the case of a power failure and power return this MDF is not deleted and the embedded PC first checks for an undeleted MDF to be continued after a power failure. It automatically restarts the radiometer operation with the same measurement parameters as it used when the measurement was interrupted. The host PC software features an auto-connect option to connect automatically to the radiometer after the power return. This way also the online monitoring is restarted.

4.4 See attached document about RPG-HATPRO measurements

Additional Information

Calibration and stability of the system:



Example of Allan Variance for V-band channel at 53.86 GHz. The radiometer calibration system enables the receivers to obey the radiometer formula up to at least 1000 seconds.

All routine operations are automatically controlled without user intervention. These operations include: gain calibration with internal calibration target, system noise calibration with internal noise standard, sky-tipping calibration of noise standards, timing for all products (integration, sample rate, minimum sample rate = 1 second), automatic file backup of all measurement data and housekeeping on internal embedded PC memory (1 GB), acquisition of all sensors, elevation scanning, blower and heater control, interfacing with external PC etc.

The automatic relative calibration using the internal ambient temperature target is provided by the instrument.

The accuracy of the ambient temperature target BT is better than +/- 0.1 K.

The medium-term stability of the system is achieved by periodic automatic calibrations with both built-in standards and regular sky-tipping procedures. An example is giving above as an Allan Variance measurement at 53.86 GHz over 20000 seconds. The standard deviation of the radiometric response obeys the radiometer equation up to at least 1000 seconds reflecting the high system stability. The BT uncertainty of the automatic

calibration system within a time frame < 1000 hr is estimated to be < +/-0.3 K for channels under 54 GHz and < +/- 0.15 K for channels >54 GHz.
Long-term stability: Controlled by absolute calibration with external standards (LN) every 6 month and sky-tipping calibration method. The calibration uncertainty is < +/- 0.3 K for calibration with LN and < +/- 0.25 K for sky-tipping (f < 54 GHz) and < +/- 0.2 K for f > 54 GHz.
These figures apply for ambient temperature changes of less than 10 K / hr.
The radiometer software routinely compares the accuracy of the K-band noise standard by comparison with successful automatic sky-tipping (absolute) calibrations to derive a quality flag for the noise standard. This quality flag recommends when an absolute calibration with external standard (LN) is due. Although the K-band noise standard is re-calibrated by each successful sky-dip, its initial equivalent brightness temperature determined by the last absolute calibration with LN is stored for the quality control check to determine the next required absolute calibration with LN also for the temperature profiler noise standard. This standard cannot be re-calibrated by sky-tipping because the atmosphere is not transparent at oxygen line channels which is a major requirement for sky-tipping.
Rain is detected by a rain sensor that immediately responds to the start of rain. The average recovery time after a rain event is 5-10 minutes. Due to the effective removal of rain drops from the microwave window and the heating capabilities of the high power blower system, an unbiased operation is achieved within 2 minutes after the rain event.
During fog conditions the blower heater prevents the formation of liquid water condensation on the microwave window. This also works quite effectively for drizzle. The retrievals are thus not biased in these conditions, also because there are no big droplets in the air like with medium / heavy rain.

Retrieval Algorithms:

The system is shipped with a set of retrievals for LWP, IWV, humidity profiles (full troposphere), temperature profiles (full troposphere), temperature profiles with high vertical resolution (boundary layer), stability indices (lifted index, Showalter, K-index, CAPE, Total Totals) and cloud base height. These retrievals do not require any external input except for the microwave brightness temperature, IR radiometer information and time / date. The time / date information is used for a continuous inclusion of seasonal effects to improve the a-priori information accuracy. The minimum time resolution for most level 2 data products is 1 second. The minimum time resolution for boundary layer temperature profiling is 120 seconds since it requires an elevation scan.

Software and Data Archiving:

Sampling schedule is controlled by the user by sending a measurement definition file to the radiometer before measurement start (integration times, calibration intervals, observing angles and duration, scene dwell times).
Full remote control of the radiometer is achieved by remote desktop operation on the external PC. A command line version of the host PC software is provided for using scripts or schedulers for an automated re-configuration
The host software includes a post-processor to generate level 2 data from brightness temperature data files. All level data files are archived and automatically named (date/time information). Automatic concatenation of hourly files to one day files possible.

The host PC software provides a sophisticated graphical display package for level 1 / 2 data. Several data formats are selectable like binary, ASCII, netCDF, JPG or BMP.
Each data sample is time stamped. If the integration times for all data products are identical the synchronization of these samples is better than +/-2 seconds.
RPG offers support for software adaptation to other instrumentation. This includes the data output in user defined formats, data exchange on operating system basis, display of other instrumentation data within the radiometer display or direct interfacing.
The source code is available for customers. Detailed information about calibration algorithms, retrievals or instrument control features is provided if requested. The host software includes a retrieval file editor for easy implementation of user specified retrievals.
The sky-tipping algorithm uses two quality flags to separate good conditions from unusable ones. All sky tips together with these quality flags and fit information are archived, no matter if the sky-dip is successful or not. BT thresholds and relations are used to distinguish between degraded humidity profiles and reasonably accurate once during rain.