RPG-HATPRO-G5 series

High-precision microwave radiometers for continuous atmospheric profiling

Applications

Tropospheric Profiling
of temperature, humidity, and liquid water

Water Vapour Monitoring
e.g. at astronomical sites

Nowcasting
• Atmospheric stability
• Severe weather

Atmospheric Attenuation
for satellite communication

Boundary Layer Profiling
• High-resolution temperature profiles (better than balloons)
• 24/7 monitoring of temperature inversions
• Fog detection
• Air pollution applications

Data Assimilation
Input for weather and climate models

Satellite Tracking
Tropospheric delay and attenuation along line of sight

Absolute calibration of Cloud Radar receivers
Design

- **Direct Detection Filter-Bank Receivers**
- **Narrow Antenna Beams** (\(\sim 2^\circ - 5^\circ\) HPBW)

- **Parallel Detection** at all channels
- **Immune to RFI** < 18 GHz*

- **Fast Data Acquisition**
- **100% Duty Cycle**

- **High Temporal Resolution**
  - 1 second resolution
  - Ideal for fast LWP sampling applications

- **High Spatial Resolution**
  - 2D sky mapping**

* e.g. radio transmitters or mobile phones, ** only with azimuth positioner

RPG-HATPRO-G5 radiometer during the absolute calibration procedure.
Improvements with Generation 5

High Precision Calibration Target
providing ±0.15 K absolute accuracy

Data Sampling Rate
increased by a factor 20

Rapid Noise Switching
16x faster than with G4

Complete removal of 1/f noise contributions

Integration to noise levels < 50 mK within 10 seconds

Improved Performance of Atmospheric Products - e.g. factor 3 for IWV (Integrated Water Vapour):

Left: IWV time series with 1 second sampling, right: IWV time series with 30 seconds sampling.

Even humidity fluctuations of 20g/m² become visible!

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>90</td>
<td>0.347</td>
<td>0.125</td>
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<tr>
<td>75</td>
<td>0.356</td>
<td>0.129</td>
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<tr>
<td>60</td>
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<tr>
<td>42</td>
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<td>36</td>
<td>0.580</td>
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<td>30</td>
<td>0.640</td>
<td>0.309</td>
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<td>24</td>
<td>0.759</td>
<td>0.418</td>
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<tr>
<td>19.2</td>
<td>0.861</td>
<td>0.521</td>
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<tr>
<td>10.2</td>
<td>2.399</td>
<td>1.233</td>
</tr>
</tbody>
</table>

IWV Accuracies at different elevation angles for generations G4 and G5 (1 second sampling).
Hardware Features

- Integrated Automatic Weather Station
  Vaisala® WXT536 to measure surface wind, rain rate, pressure, temperature, and relative humidity

- Mitigation System for Rain / Fog / Dew
  - Powerful blower
  - Radome with hydrophobic coating
  - Efficient heater system

- Azimuth Positioner
  for full sky scanning *

- Data Backup
  on embedded Radiometer-PC

- IR Radiometer
  for cloud base height detection **

- Ethernet Interface
  for network capability

- Optical Fibre Data Cable
  for lightning protection and secure data transmission

- Interference mitigation
  High frequency RFI (G5 and G6 mobile network) mitigated by channel redundancy.

- IR Scanner
  for synchronous IR and microwave observations **

* only with azimuth positioner, **optional
Software Features

State-of-the-art Retrievals
- Neural Network (NN)
- Customized

Atmospheric Data Products
- Profiles of temperature / humidity / liquid
- Integrated Water Vapour (IWV)
- Integrated cloud liquid
- Atmospheric attenuation
- Cloud base height*
- Wet/dry atmospheric delay

Accurate North-Alignment
via sun-scanning* and positioning with the integrated GPS receiver

Detailed Housekeeping Data
- Instrument status / control
- Data quality flags
- Data flagging

Thermodynamic Diagrams and Stability Indices

Free Software Updates

Satellite Tracking
with navigation files

Automatic Recovery
after power failures

Output Data
- Level 1 (brightness temperatures)
- Level 2 (retrieved products)
- Automatic conversion to netCDF, ASCII, RAOB®

Calibration
- Short calibration cycles
- Automatic skytipping
- Automatic internal calibrations including noise sources
- Manual liquid nitrogen calibration (every 6 months)

* only with azimuth positioner
** only with optional IR Radiometer
Boundary Layer Temperature Profiling

Temperature profiles are continuously retrieved from zenith measurements for the entire troposphere (0-10 km). In addition, the boundary layer observation mode, based on frequent elevation scans, provides an enhanced vertical resolution below 2 km. Temperature inversions are much better resolved by the boundary layer scanning mode (left). The vertical resolution improves by a factor of 10 compared to the zenith observation mode (right):

The boundary layer mode allows for monitoring the formation and decay of temperature inversions in time:
Inter-comparison with meteorological tower

Boundary layer temperatures retrieved from RPG-HATPRO measurements were, for example, validated by an inter-comparison with a 100 m meteorological tower operated by the German Weather Service (DWD) in Lindenberg / Germany. The tower is equipped with in-situ temperature sensors every 10 height meters. The HATPRO radiometer was located right next to the tower.

![Temperature measurements comparison](image)

A 2-week time series of temperature measurements. Black: Meteorological tower temperature sensor readings. Red: Radiometer readings in boundary layer scanning mode. Top: Temperature in 10 m altitude. Center: Temperature in 100 m altitude, Bottom: Temperature gradient resolving inversions. The radiometer data are in excellent agreement with the in-situ measurements (Courtesy of S. Crewell, University of Cologne).

Tropospheric Profiling

Humidity Profiling:

![Humidity profile comparison](image)

Improvement example of G5 absolute humidity profile over previous radiometer generations. Black: radio sounding for comparison, light blue: G4 retrieval noise, orange: G5 retrieval noise.
Temperature Profiling:

Boundary layer temperature profiling inter-comparison example.

Full troposphere temperature profiling inter-comparison example.
Thermodynamic Diagrams

RPG’s operating software offers a number of common thermodynamic diagrams. Apart from the most recent profiles of temperature and dew point (retrieved from humidity and temperature profiles), the history of mean hourly temperature profiles is displayed. Additionally, vertical profiles from radiosondes and wind profilers in ASCII format (e.g. RAOB®) can be uploaded and displayed. Common stability indices (Lifted Index (LI), Showalter Index (SI), K Index (KI), Total Totals Index (TTI), Convective Index (KOI), CAPE) and characteristic levels (LFC, LCL) are calculated.
Integrated Water Vapour (IWV) and Liquid Water Path (LWP)

Full Sky IWV and LWP maps* below show inhomogenous water vapour distributions and cloud coverage:

IWV measurements remain accurate even with an LWP of 1000g/m²:

The figure below shows that accurate measurements of IWV and LWP are recorded simultaneously. IWV accuracy is maintained even in case of thick cloud and light rain. Retrieved IWV is plotted against IWV calculated from 2 months of radiosonde profiles.

* only with azimuth positioner
Attenuation Measurements

HATPRO measurements at 14 radiometer channels allow for an accurate retrieval of total atmospheric attenuation spectra between 1 and 100 GHz.
Accuracy examples: 0.0025 dB RMS @13 GHz, 0.0050 dB RMS @27 GHz.

Attenuation spectrum between 1 and 100 GHz retrieved from HATPRO observations (blue) compared to „true“ values (red).
Profiling Radiometer Models

• **RPG-HATPRO**
  - Humidity And Temperature PROfiler (standard profiling radiometer)
  - 7 channels: 22.24 GHz to 31.40 GHz
  - 7 channels: 51.26 GHz to 58.00 GHz
  - over-sampling for redundancy
  - customized direct detection channels for precise boundary layer mode
  - temperature profiles in elevation scanning mode

• **RPG-LHATPRO**
  - Low-Humidity And Temperature PROfiler
  - 7 channels: 51.26 GHz to 58.00 GHz
  - 6 channels: 183.31 ± 0.6 GHz to ±7.5 GHz
  - Designed for arctic conditions and/or high altitudes
  - Water vapour sounding at 183 GHz
  - 6 DSB channels with individual bandwidth

• **RPG-HUMPRO**
  - HUMidity PROfiler
  - 7 channels: 22.24 GHz to 31.40 GHz
  - over-sampling for redundancy

• **RPG-TEMPRO**
  - TEMperature PROfiler
  - 7 channels: 51.26 GHz to 58.00 GHz
  - over-sampling for redundancy
  - customized direct detection channels for precise boundary layer mode
  - temperature profiles in elevation scanning mode
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
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</table>
| **Height grid of atmospheric profiles** (temperature / humidity / liquid water) | Number of layers: 93  
Vertical Resolution:  
25 m (range 0-100 m)  
30 m (range 100-500 m)  
40 m (range 500-1200 m)  
60 m (range 1200-1800 m)  
90 m (range 1800-2500 m)  
120 m (range 2500-3500 m)  
160 m (range 3500-4500 m)  
200 m (range 4500-6000 m)  
300 m (range 6000-10000 m) |
| **Temperature profile performance**                                      | Accuracy:  
0.25 K RMS typical (range 0-500 m)  
0.50 K RMS typical (range 500-1200 m)  
0.75 K RMS typical (range 1200-4000 m)  
1.00 K RMS typical (range 4000-10000 m) |
| **Humidity profile performance**                                         | Accuracy:  
0.3 g/m³ maximum bias typical (absolute humidity)  
0.1 g/m³ RMS typical (absolute humidity)  
5% RMS typical (relative humidity) |
| **Liquid water profile performance** (only with IR radiometer)           | Cloud base height accuracy:  
50 m (range 0-300 m)  
100 m (range 300 - 1.000 m)  
200 m (range 1.000 - 3.000 m)  
400 m (range 3.000 - 5.000 m)  
600 m (range 5.000 - 10.000 m)  
Density: 0.03 g/m³ RMS  
Threshold: 50 g/m² LWP  
Only single layer clouds are modelled |
<p>| <strong>IR radiometer option</strong>                                                 | 9.6-11.5 µm band, accuracy 1 K, noise: 0.2 K RMS |
| <strong>LWP</strong>                                                                  | Accuracy: ± 10 g/m², sensitivity: 2 g/m² RMS |
| <strong>IWV</strong>                                                                  | Accuracy: ± 0.12 kg/m² RMS, sensitivity: 0.04 kg/m² RMS |
| <strong>Full sky IWV and LWP maps</strong> (only with azimuth positioner)             | More than 200 points in 8 minutes rapid scanning |</p>
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| Satellite tracking mode (only with azimuth positioner) | • Determines tropospheric wet delay and attenuation along line of sight for all visible GPS / Galileo satellites in a single scan (2 minutes)  
• Tracking via satellite navigation files (e.g. RINEX) or direct GPS vector readings from integrated GPS receiver |
| Channel centre frequencies | K-Band: 22.24 GHz, 23.04 GHz, 23.84 GHz, 25.44 GHz, 26.24 GHz, 27.84 GHz, 31.40 GHz  
V-Band: 51.26 GHz, 52.28 GHz, 53.86 GHz, 54.94 GHz, 56.66 GHz, 57.30 GHz, 58.00 GHz |
| Channel bandwidths | 2000 MHz @ 58.0 GHz, 1000 MHz @ 57.30 GHz, 600 MHz @ 56.66 GHz, 230 MHz @ all other |
| System noise temperatures | < 400 K typical for 22.24 – 31.40 GHz profiler  
< 600 K typical for 51.26 – 58.00 GHz profiler |
| Radiometric resolution | K-Band: 0.07 K RMS,  
V-Band: 0.07 – 0.15 K RMS (@ 1 second integration time) |
| Absolute brightness temperature accuracy | ±0.15 K |
| Absolute calibration | With internal ambient & external cold load |
| Internal calibration | • gain: with internal noise standard  
• gain + system noise: ambient temperature target + noise standard  
• abs. cal. of humidity profiler: sky tipping calibration |
| Receiver and antenna thermal stabilization | Stability better than 0.03 K over full operating temperature range |
| Gain non-linearity error correction | Automatic, 4-point method |
| Brightness calculation | Based on exact Planck’s radiation law |
| Integration time | ≥ 0.4 seconds for each channel (user-selectable) |
| Sampling rate for profiles | ≥ 1 second (user-selectable) |
| Rain / fog mitigation system | Highly efficient blower system (130 Watts), hydrophobic coated microwave transparent window, 2 kW heater module to avoid the formation of dew. |
| Integrated weather station | Vaisala® WXT536 on 1-m mast mounted to radiometer:  
• temperature, pressure, relative humidity  
• wind speed, wind direction, and rain rate |
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</thead>
<tbody>
<tr>
<td>Data interface / rate</td>
<td>Ethernet (TCP/IP)</td>
</tr>
<tr>
<td>Instrument control (external PC)</td>
<td>Windows™ System with Ethernet interface</td>
</tr>
<tr>
<td>Instrument control (internal)</td>
<td>Embedded PC controls internal calibrations, data acquisition, azimuth positioner, and communication with Host-PC. Can run measurements independently from Host-PC - with possible data file backup on 10 GB flash memory.</td>
</tr>
<tr>
<td>Housekeeping data</td>
<td>Detailed instrument status information, including health checks, data flagging, calibration history, and log files</td>
</tr>
<tr>
<td>Retrieval algorithms</td>
<td>Neural Network algorithms</td>
</tr>
<tr>
<td>Optical resolution</td>
<td>HPBW (frequency dependent): 3.9° - 4.6° for water vapour, 1.8° - 2.2° for temperature profiler</td>
</tr>
<tr>
<td>Side-lobe level</td>
<td>&lt; -30 dBC</td>
</tr>
<tr>
<td>Pointing range / resolution</td>
<td>Elevation: 0° to 180° (0.1° steps), full s/w control</td>
</tr>
<tr>
<td></td>
<td>Azimuth (optional): 0° to 360° (0.1° steps), full s/w control</td>
</tr>
<tr>
<td>Pointing speed</td>
<td>45°/sec (elevation), 20°/sec (azimuth, optional)</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-30°C to +45°C</td>
</tr>
<tr>
<td>Power consumption AC 1 (100 - 230 V~)</td>
<td>&lt; 120 Watts average, 650 Watts peak for warming-up (without dew blower), blower: 130 Watts maximum</td>
</tr>
<tr>
<td>Power consumption AC 2 (100 - 230 V~)</td>
<td>Heater Module: 2 kW @ 230 V/AC</td>
</tr>
<tr>
<td>Lightning protection</td>
<td>Power line: circuit breakers</td>
</tr>
<tr>
<td></td>
<td>Data line: optical fibre cable (max. length: 1400 m)</td>
</tr>
<tr>
<td>Input voltage</td>
<td>90-230 V AC, 50 to 60 Hz</td>
</tr>
<tr>
<td>Weight</td>
<td>60 kg (without dew blower)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>63 × 36 × 90 cm³</td>
</tr>
</tbody>
</table>
Remote Sensing for Weather and Climate

FMCW Cloud Radars
Radiometer Physics GmbH (RPG) has developed a line of polarimetric solid-state radars operating at 35 and 94 GHz for continuous cloud and precipitation observations.
- Accurate absolute calibration, hardware monitoring
- High spatial, temporal, and Doppler resolution
- Built-in passive radiometric channel for LWP estimation
- Rain mitigation system for keeping the radomes dry
- Data products: full spectra, moments, spectral polarimetry
- Optional scanner for volumetric processing
- Optional dual frequency configuration (35 + 94 GHz)
- Automated data exchange with RPG radiometers
- Turbulence, wind shear, fog, and cloud observations
- Particle size distribution, rain intensity, ice microphysics

Profiling Radiometers
The RPG-HATPRO (Humidity And Temperature PROfiler) is becoming the radiometer of choice for meteorological networks and forecasting systems all around the world.
- 14 channels (22 to 31 GHz, 51 to 58 GHz, 183 GHz optional)
- Superior direct detection technology: EMI / EMC, parallel
- Network suitable, control + data flow via Ethernet
- Data products: IWV, LWP, T + RH profiles, stability indices
- Better boundary layer T-profiling than radio-soundings
- Full-sky scanning (more than 200 directions 8 minutes)
- Ground-based: complementing the satellite view!
- All-weather proof, reliable, robust… proven!
- IR radiometer extension for cloud base height detection

Scintillometers
RPG is the only commercial supplier for scintillometers observing in the microwave spectral region.
- Microwave scintillometer RPG-MWSC operates at 160 GHz
- Synchronous observation of sensible and latent heat fluxes (combined with optical Large Aperture Scintillometer)
- Network suitable, control + data flow via Ethernet