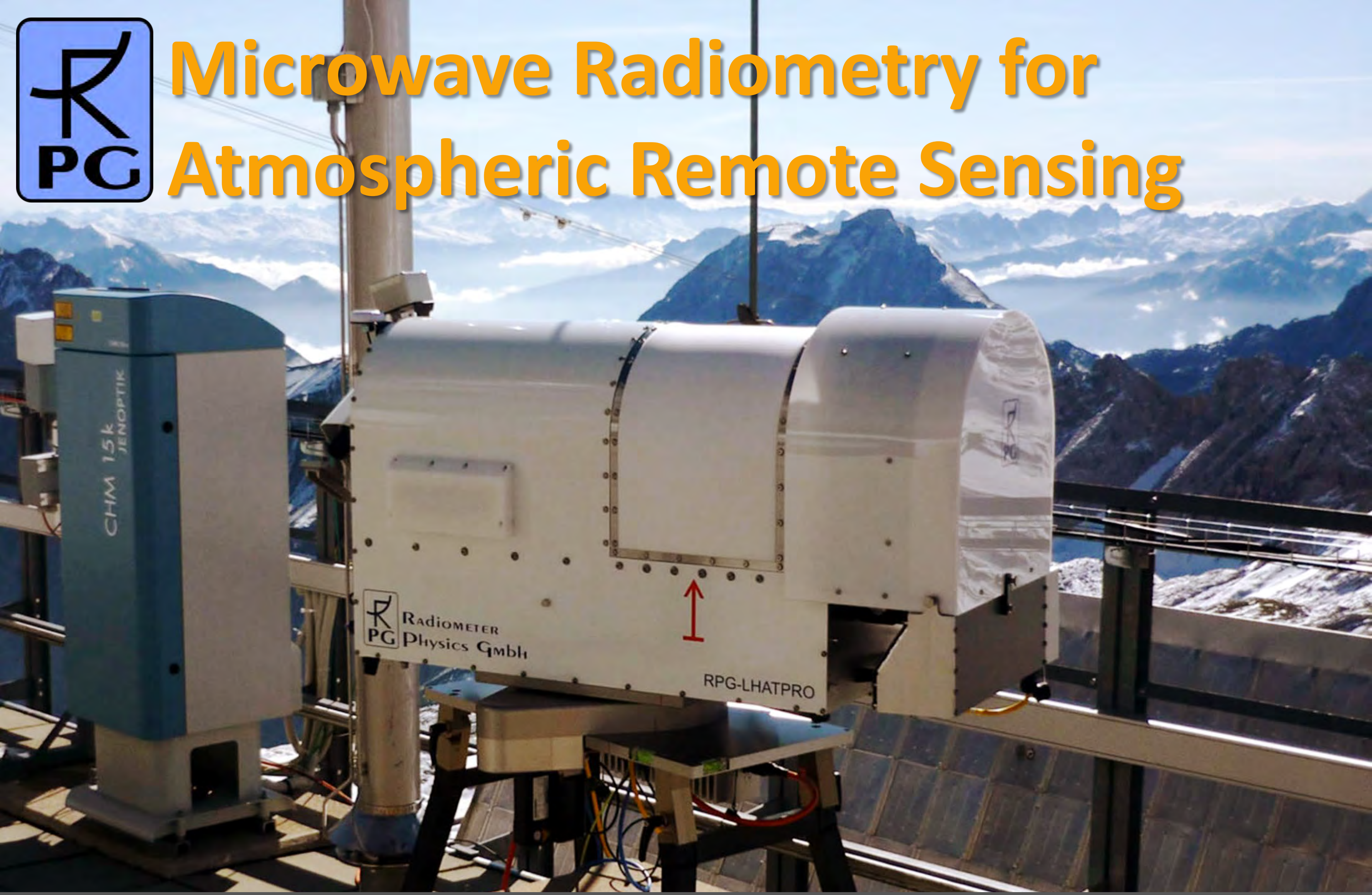
Microwave Radiometry for Atmospheric Remote Sensing



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Topics in the next 15 minutes…

1. Intro
2. Nature/Source of observed signal (thermal radiation, TB)
    - Planck‘s law
    - Conversion of energy units to brightness temperature TB
3. Link between MW spectrum and atmospheric state
    - Absoption lines, transmission windows, information content
4. Measurement devices, radiometer technology
    - Heteroydyne + Direct Detection
    - Calibration
5. Retrieval of atmospheric data from microwave data
    - Formulation of the problem
    - Simulation of the MW data by RTM
    - Adding instrument imperfection
    - Regression or iterative
6. Examples…

Remote Sensing: The general perspective

What is „Remote Sensing“?

- Observing radiation (more general: energy) reaching a „receiver“ device to learn something about a remote object

Examples:

- The human eye
  (binocular total power receiver, multi-pixel focal-plane array,
  recording of mostly back-scattered light in the 500 nm to 800 nm region…)
- Radar, Lidar, Sonar, Sodar, ….
- IR fever thermometer…
- Microwave specrometers
- Microwave radiometers

What are we focussing on? Microave Radiometry…

- Passive total power radiometers in the centimer to millimeter wavelength regime (10 GHz to 300 GHz)
- Retrieval algorithms to invert observed microwave sky brightness into something meteorological (meaningful) data

Basic Concept in one Slide

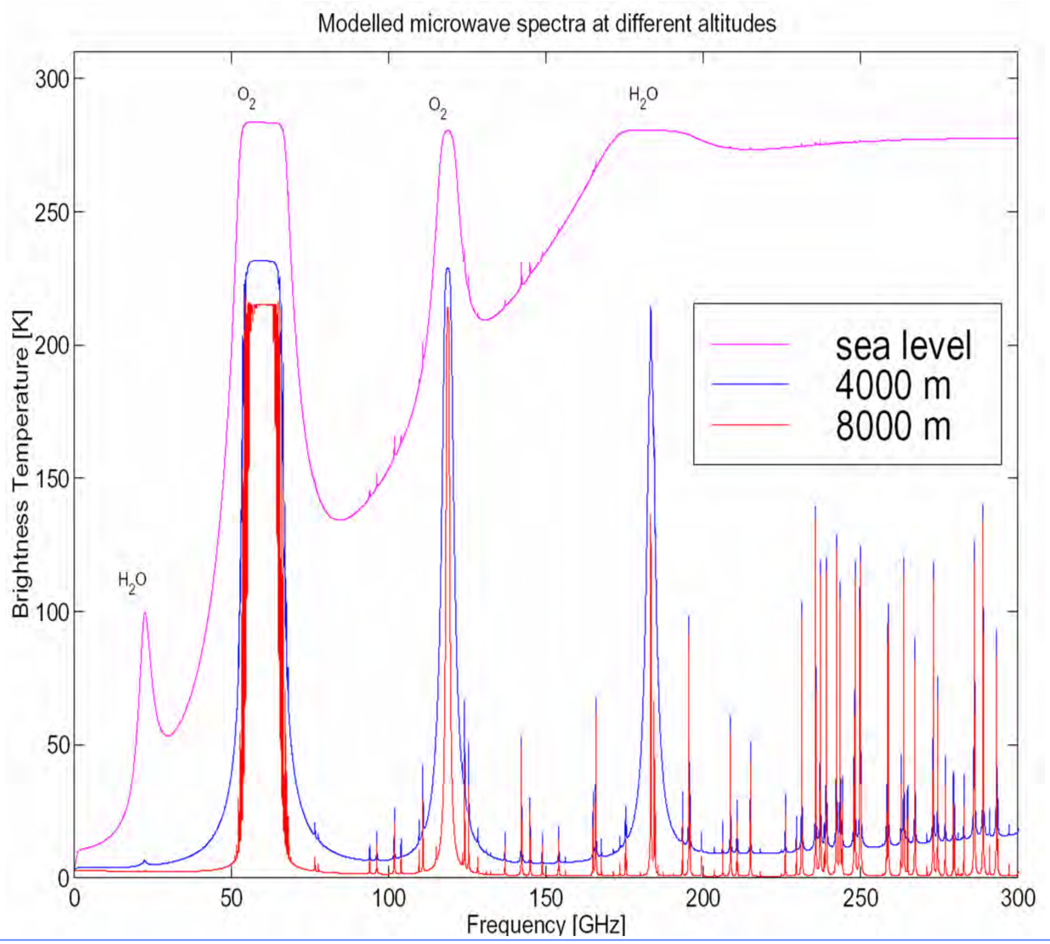
- **Passive:** detection of microwave **Thermal Radiation** *(no power emitted by MWR!)*
  - Emission (+absorption, scattering) from atmospheric components:
  - Gases (H2O, O2, N2,… line emission)
  - Hydrometeors (clouds, precipitation, frequency dependent continuum)
- **Radiometric observation:**
  Intensity (sky brightness) in units of brightness temperatures (TB)
  - At several fixed frequencies
  - At several elevation angles
- **Meteorological Variables**
  Calculated by retrievals
  - Solving the „forward problem“ (radiative transfer for a given atmosphere)

$$TB = F(T(z), Q(z), P(z), LWC(z))$$

  - Inversion of **F** is the „retrieval“

$$T(z) = F^{-1}(TB)$$

  - Inversion problem is ill-posed
  - Data set statistics important!



Navigation

2. Thermal Radiation and the Microwave Spectrum

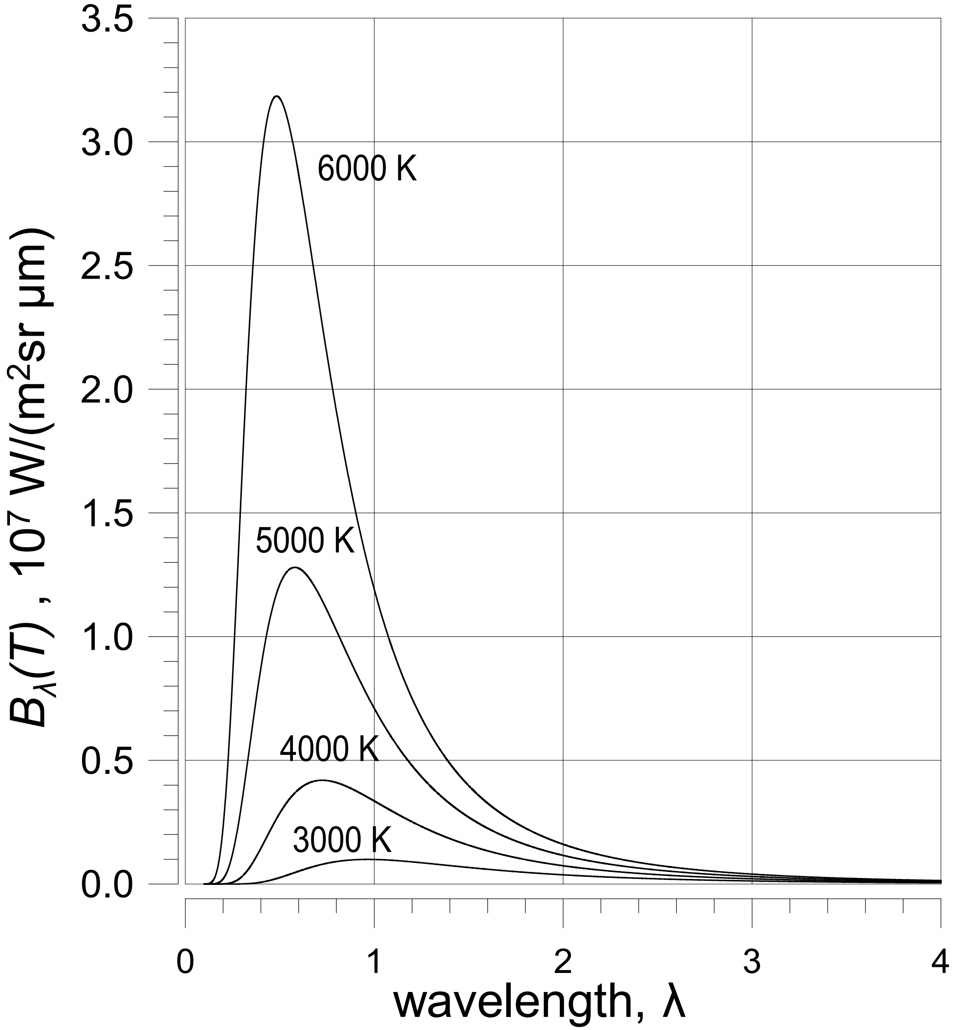
Thermal Radiation: Planck‘s Law

- Source of detected signal: Thermal radiation (Planck , 1901)
- All bodies of with T>0 emit EM radiation at all wavelengths

B_λ	spectral power density [W m^{-2} sr^{-1} m^{-1}]	
h =	6 626·10^{-34} J s	Planck's constant
k_B=	1.38·10^{-23} J/K	Boltzmann const.
c =	2.99792·10^8 m/s	speed of light

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp\left(\frac{hc}{k_B\lambda T}\right)-1}$$

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{k_B T}\right)-1}$$

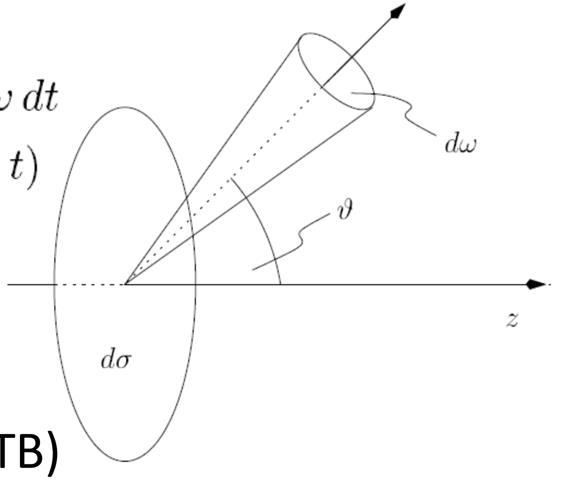


Observables: Intensity → Brightness Temperature

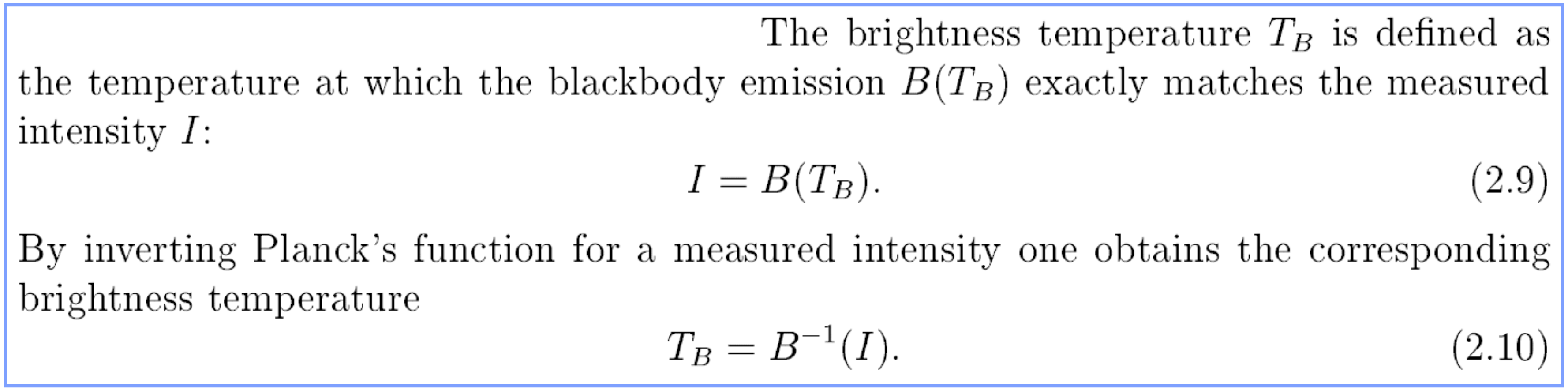
- Radiometers observe „sky brightness“
  or: radiant energy
  or: specific intensity, …

$$dE_\nu = I_\nu \cos\theta \, d\nu \, d\sigma \, d\omega \, dt$$

$$I_\nu \equiv I_\nu(x, y, z, \gamma, \delta, \mu, t)$$



- Units: $\mathrm{Wm^{-2}sr^{-1}Hz^{-1}}$
- Extremely small power levels: P=~10^{-13} W
  (demands high amplification, 100 dB)
- More „human readable“ units: Brightness Temperature (TB)



The brightness temperature T_B is defined as the temperature at which the blackbody emission $B(T_B)$ exactly matches the measured intensity I:

$$I = B(T_B). \tag{2.9}$$

By inverting Planck's function for a measured intensity one obtains the corresponding brightness temperature

$$T_B = B^{-1}(I). \tag{2.10}$$

- Optically thick (solid) objects have TB = ε·(T_{physical}) (with emissivity ε=0.0 …. 1.0)
- Optically thin media: translucent, optical thickness τ
  absorption & emission proportional to presence
  of absorbing matter → **RTM (Radiative Transfer Model)**

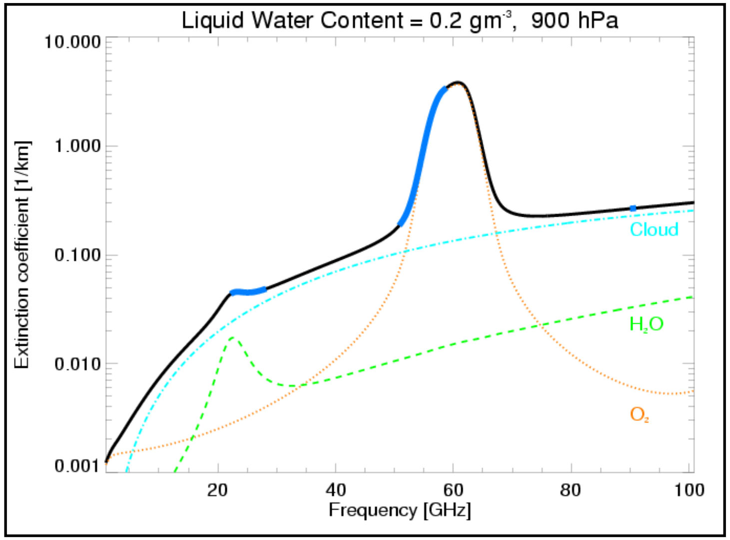
$$\tau = \int_0^\infty \alpha(s)\, ds$$

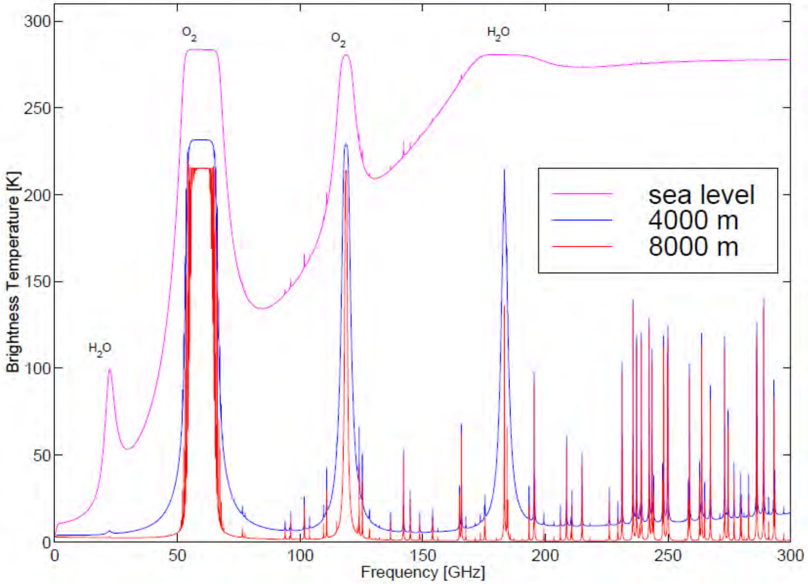
Navigation

3. How the MW Spectrum is defined by the Atmosphere

Impact of Atmosphere on MW Spectrum (I)

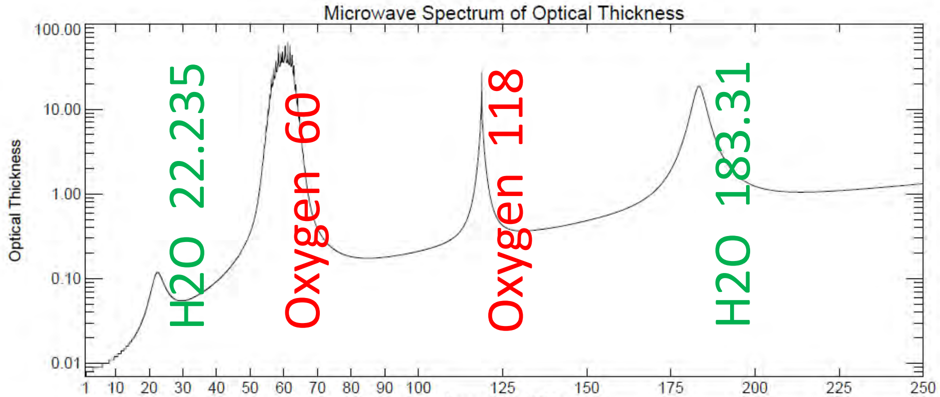
- Emission proportional to absorption (**Kirchhoff**'s radiation law)
- Atmosphere is made from gas and small particles
  ➔ discrete absorption lines rather than continua (quantum mechanics)
- Atmospheric constituents define the observed spectrum



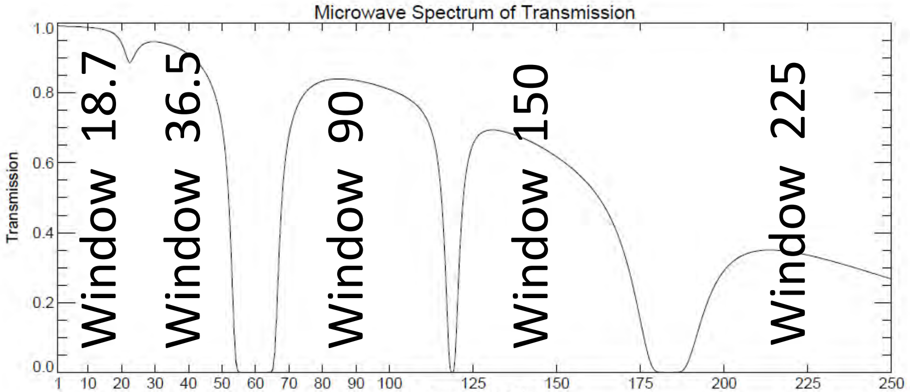


- Emission lines of water vapour (vary with H_2O Mixing ratio, and Temperature)
- Emission lines of Oxygen (vary with T, but mixing ration is fixed)
- Window channels in between lines: mostly affected by liquid water and the far wings of other lines
- At higher frequencies: trace gases

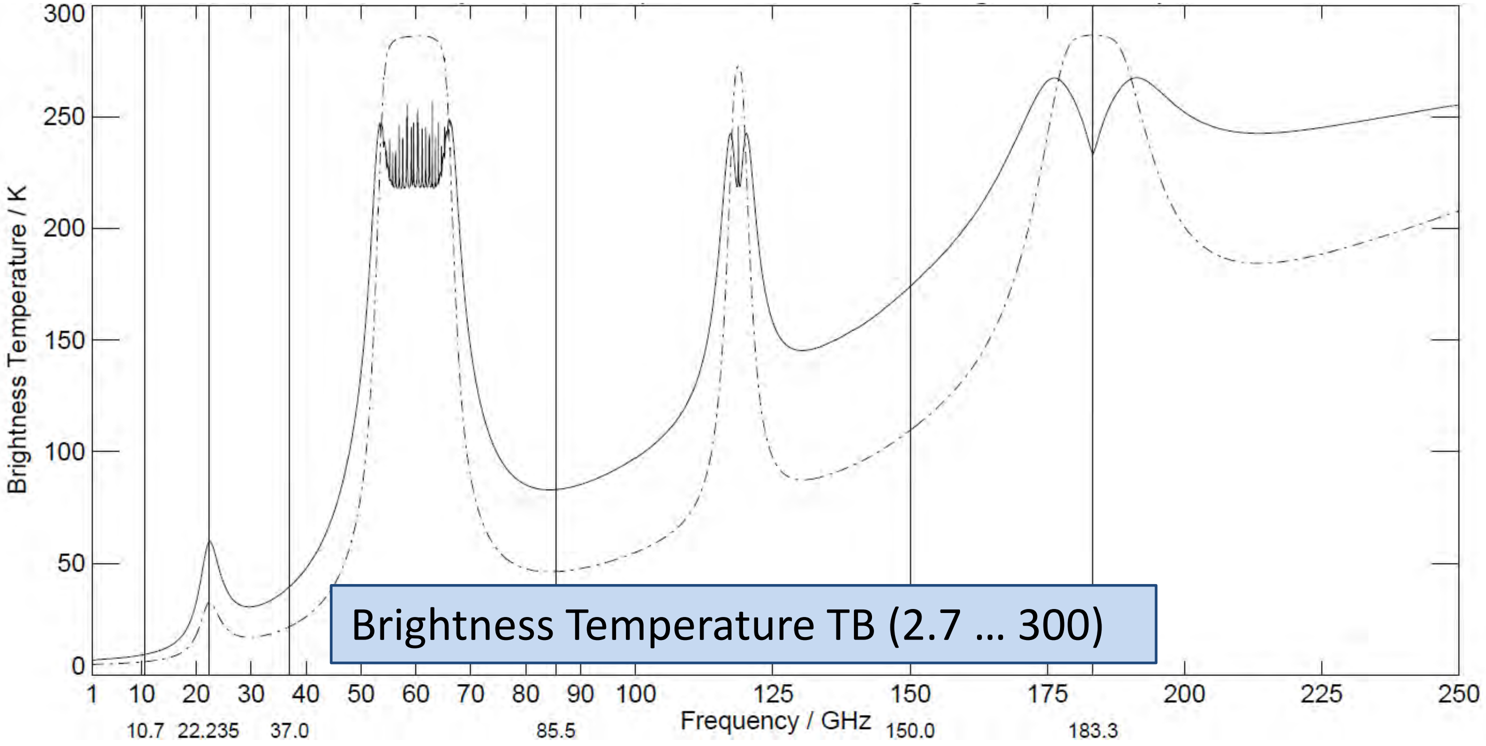
Different views of the MW Spectrum



Optical thickness (0 … 100, or more)



Transmission (0 … 1)



Brightness Temperature TB (2.7 … 300)

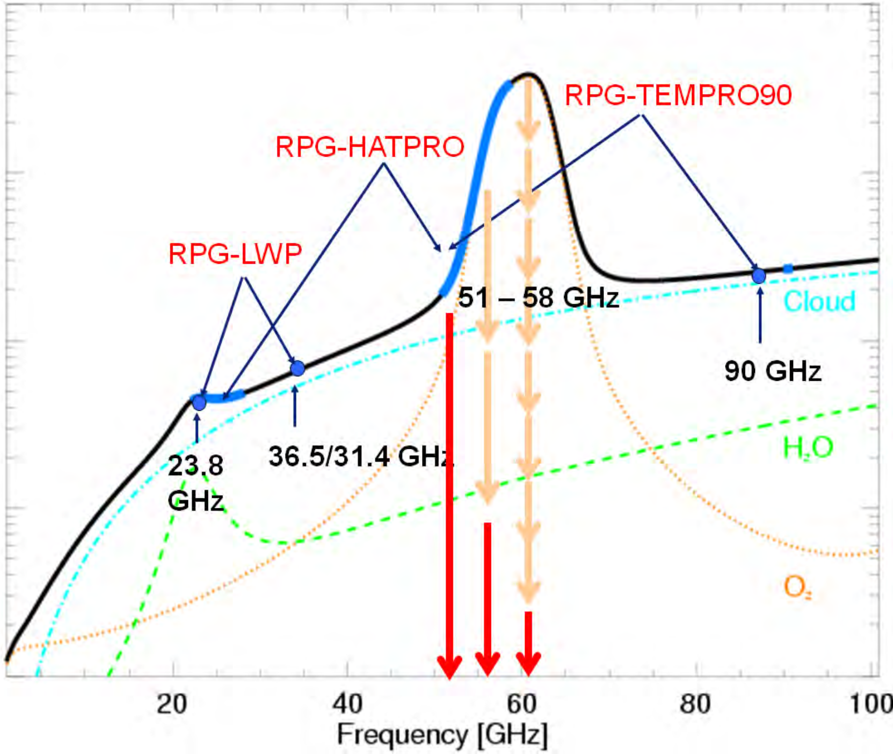
Source of Information: Basic Concepts (I)

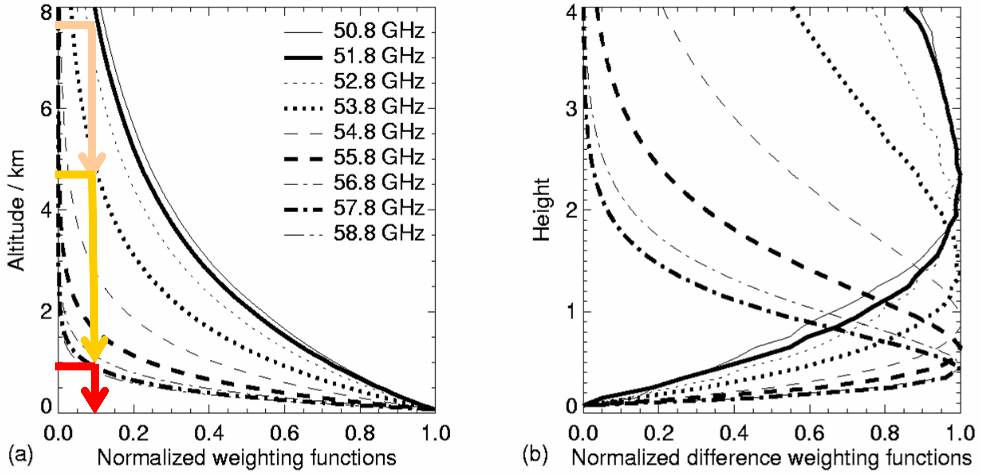
LWP/IWV:

- Compare a channel in the H2O line with a window channel
- Increase in H20 increases TB in line, not in the window
- Increase in LWP adds to both channels, (most in the window)

T-Profile:

- Frequency dependent absorption depth
- Contributions from upper atmosphere to total received signal are stronger for low absorption (absorption on the way down)
- Concept of weighting functions…





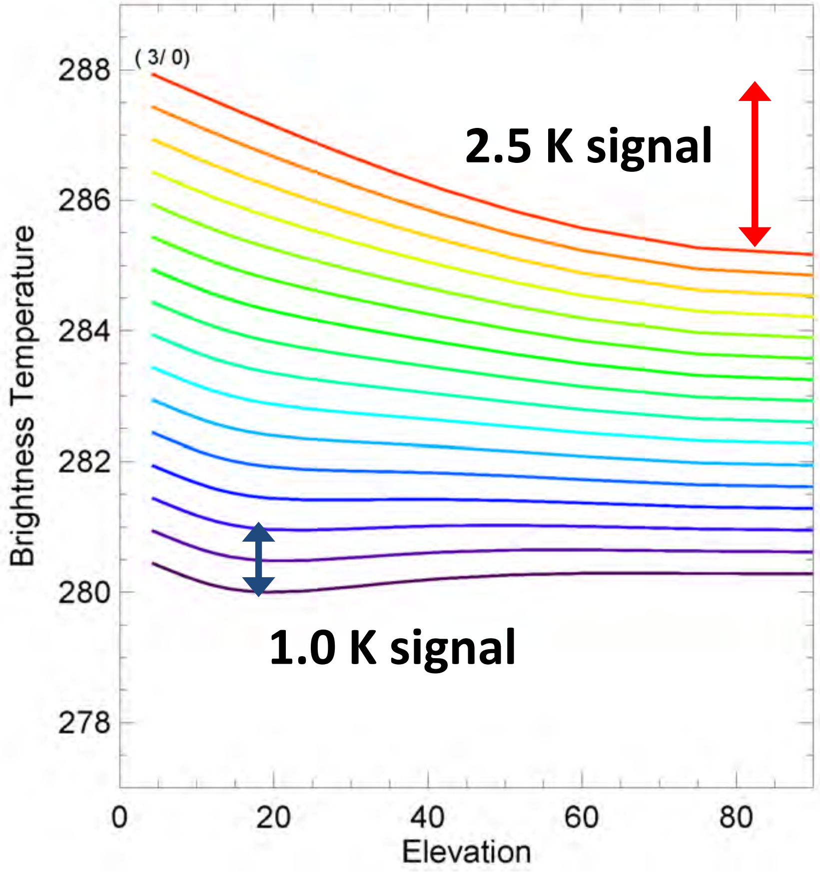
(a) Normalized weighting functions

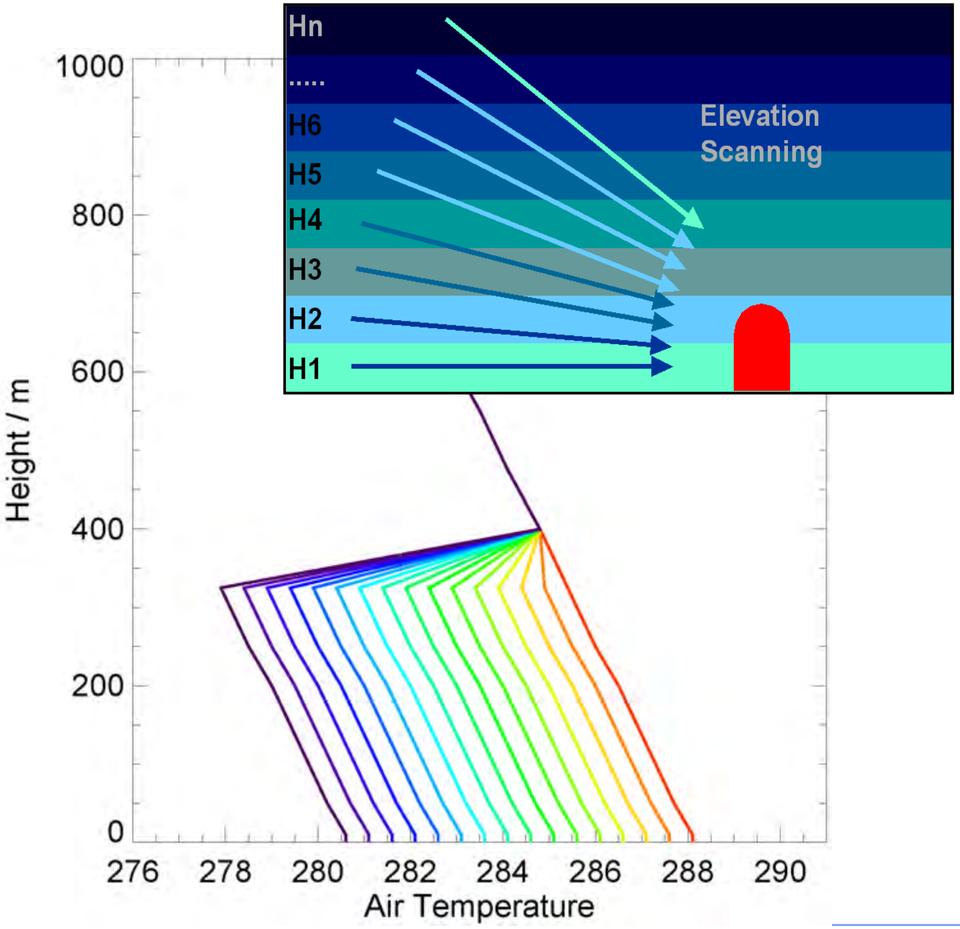
(b) Normalized difference weighting functions

Source of Information: Basic Concepts (II)

Boundary Layer T-Profile:

- Absorption length decreases for frequencies at line center (60 GHz)
- Limited (approx. 600 m) emission depth @ 58 GHz
- Weighting functions shifted towards surface by elevation scans





Navigation

Done so far:

- the source of the radiation, and
- the way the atmospheric conditions make an imprint on the microwave spectrum…

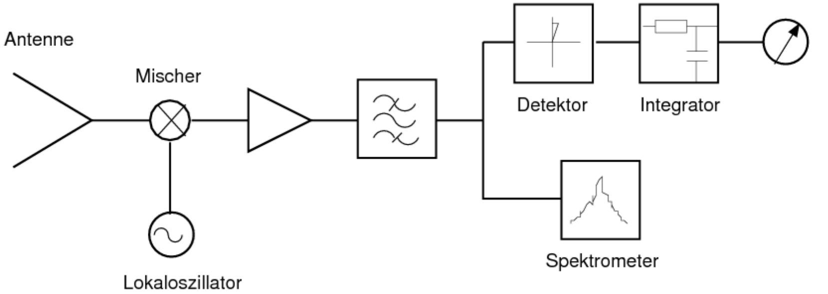
Remaining:

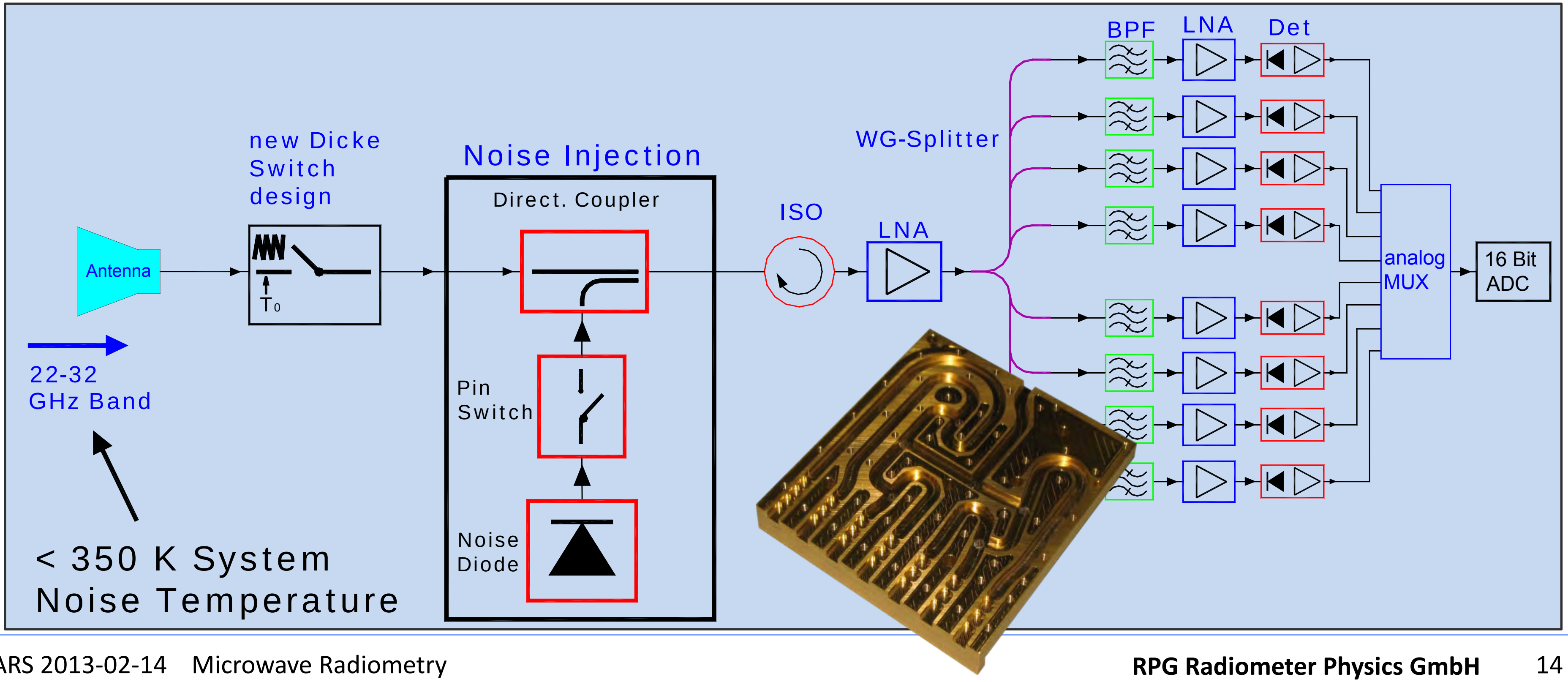
- Have a measurement device for microwave radiation
- Transform microwave measurements into atmospheric data

4. Radiometers: Hardware

Radiometer Technology (I): Layout

- Select **frequencies** for variables of interest (+ NEΔT, bandwidth, …)
- Select a receiver technology
  - Direct-Detection Filterbank: Amplify, split, filter, detect
  - Heterodyene: down-conversion to IF, the process the IF, or sequentially scan the LO over scpterum (slow, RFI problems)
- Select calibration mechanisms
- Engineer a robust infrastructure around the RF

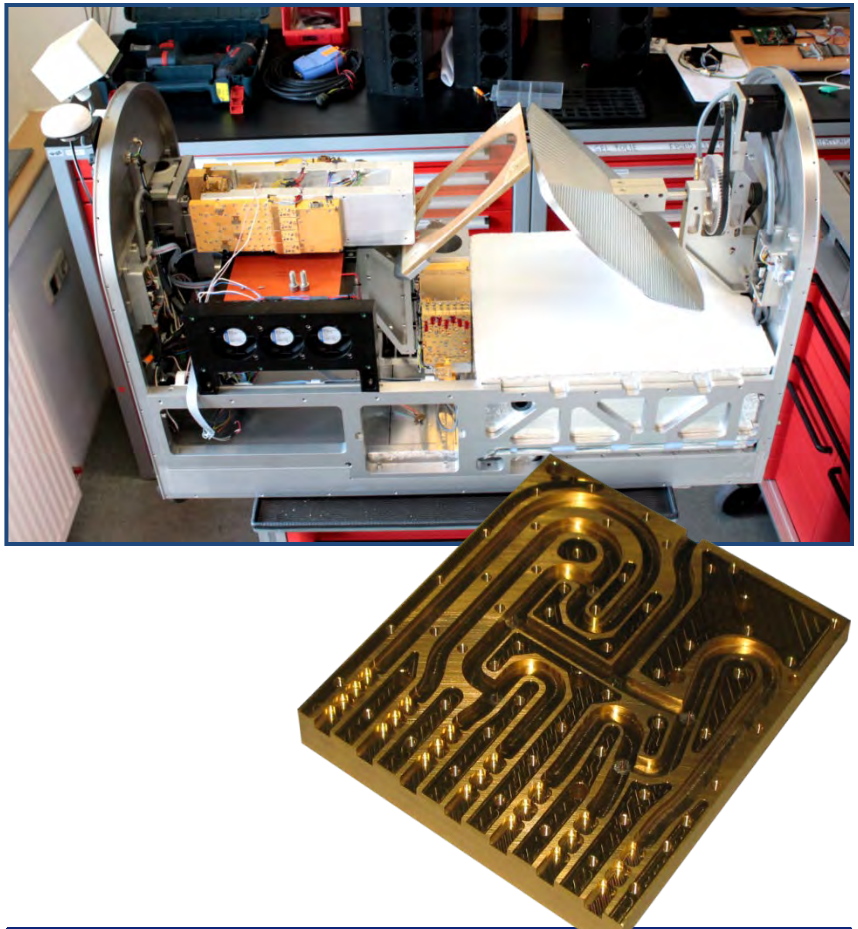




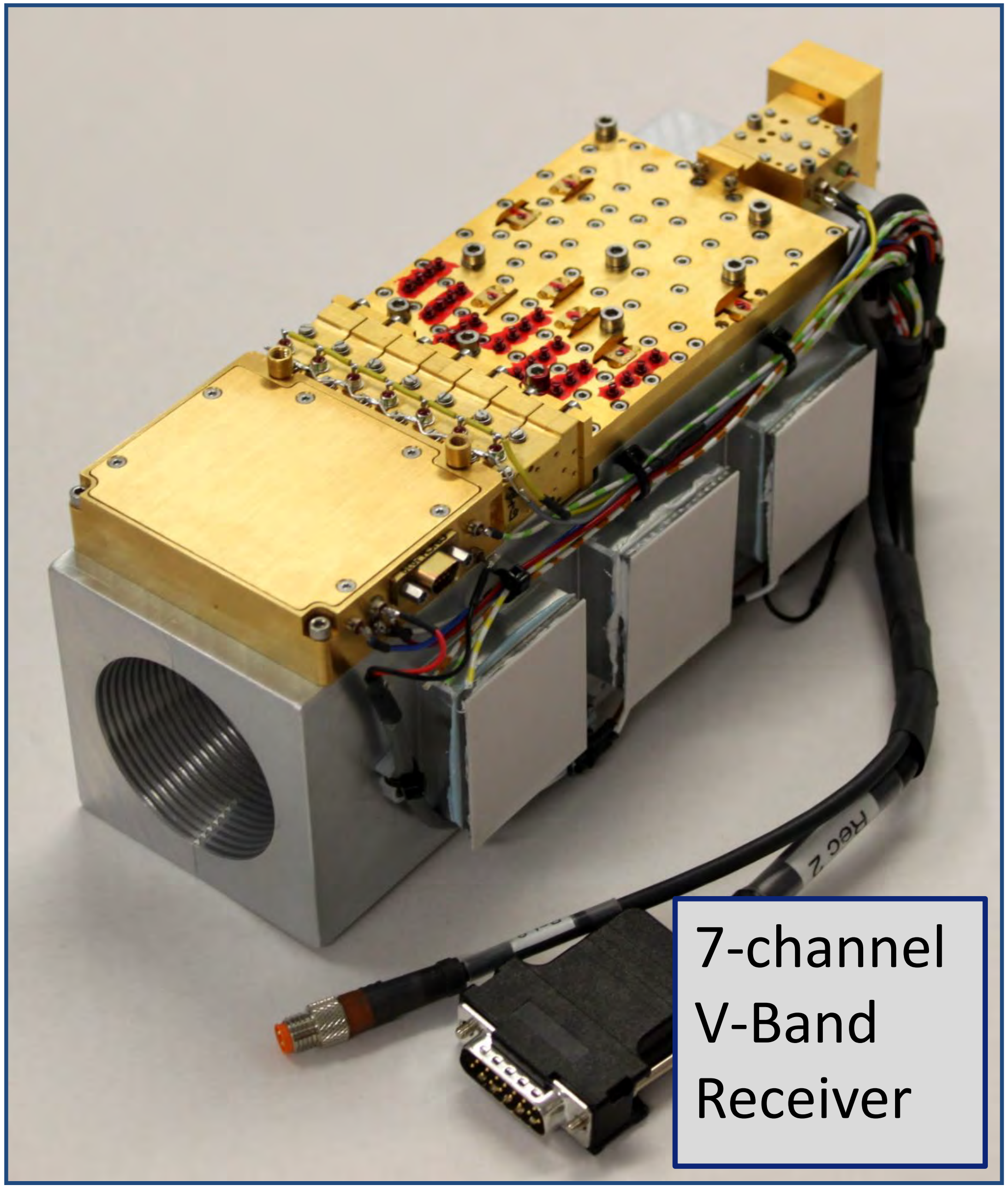
22-32 GHz Band

< 350 K System Noise Temperature

Hardware Example



HATPRO Direct Detection Filterbank Profiler
(parallel data aquisition 14 ch.)



7-channel V-Band Receiver

Frequencies, bandwith and # of channels

	K Band (22- 31)	V Band (50-60)
Channel 1	22.24 GHz / 200 MHz	51.26 GHz / 230 MHz
Channel 2	23.04 GHz / 200 MHz	52.28 GHz / 230 MHz
Channel 3	23.84 GHz / 200 MHz	53.86 GHz / 230 MHz
Channel 4	25.44 GHz / 200 MHz	54.94 GHz / 230 MHz
Channel 5	26.24 GHz / 200 MHz	56.66 GHz / 650 MHz
Channel 6	27.84 GHz / 200 MHz	57.30 GHz / 1000 MHz
Channel 7	31.40 GHz / 200 MHz	58.00 GHz / 2000 MHz
Tsys	< 350 K	< 600 K
Degrees of Freedom	2 to max. 3 uncorrelated informations	approx. 5 uncorrelated informations

Auto-Calibration Devices:

Noise Injection + Magnetically switched Isolators

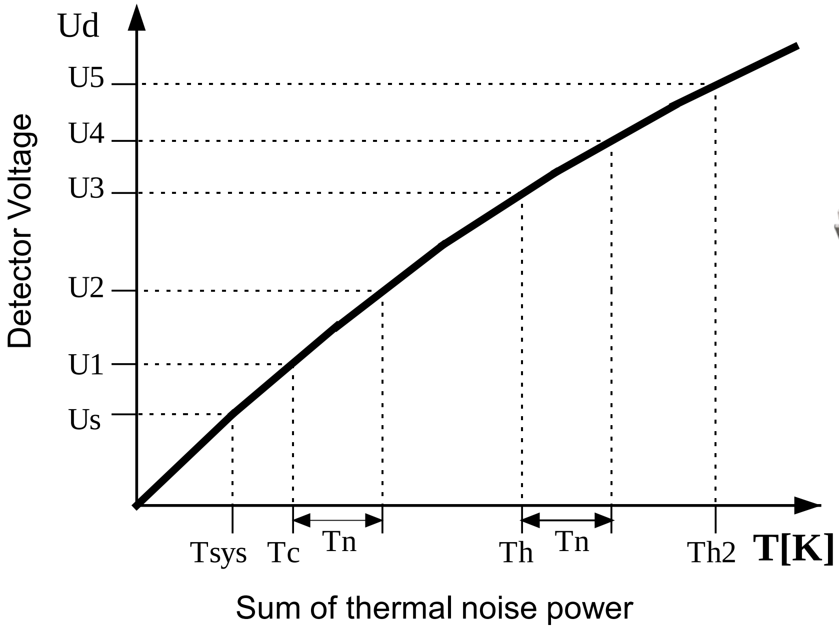
20 Hz Dicke-Switching, ultra-stable, **4000 s** Allan-Stability

Radiometer Technology (II): Calibration

$$\Delta T_B = \frac{T_{sys}}{\sqrt{\Delta\nu \cdot \tau_{int}}}$$

- Detector always „sees“ contributions from
  - system emission of lossy components,
  - plus scene (atmosphere signal),
  - plus additional calibration signals
- Voltage signal proportional to second moment of E-field (total power, no phase!)
- T_{sys} describes systems sensitivity limits by own emission:
  T_{sys}=3000 K, T_{sig}=300 K → SNR=0.1
- Gain (mV/K): frequently measure G by comparison of TB with black body (quasi-optical load or waveguide termination)

$$U_D = G(T_{sys} + T_{sig})^{\alpha} \quad , \quad \alpha \le 1$$



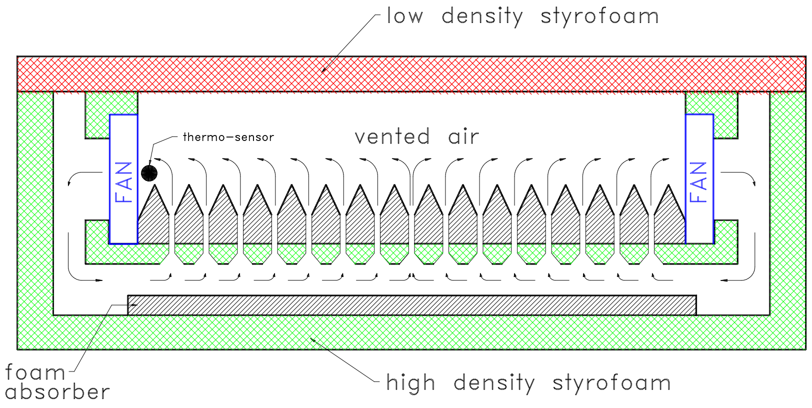
Initial 4-point Calibration:

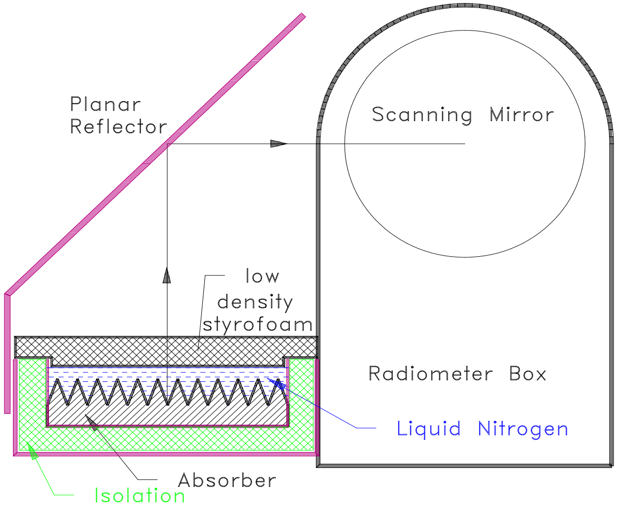
1) Cold load
2) Cold load + noise diode
3) Ambient load
4) Ambient load + noise diode

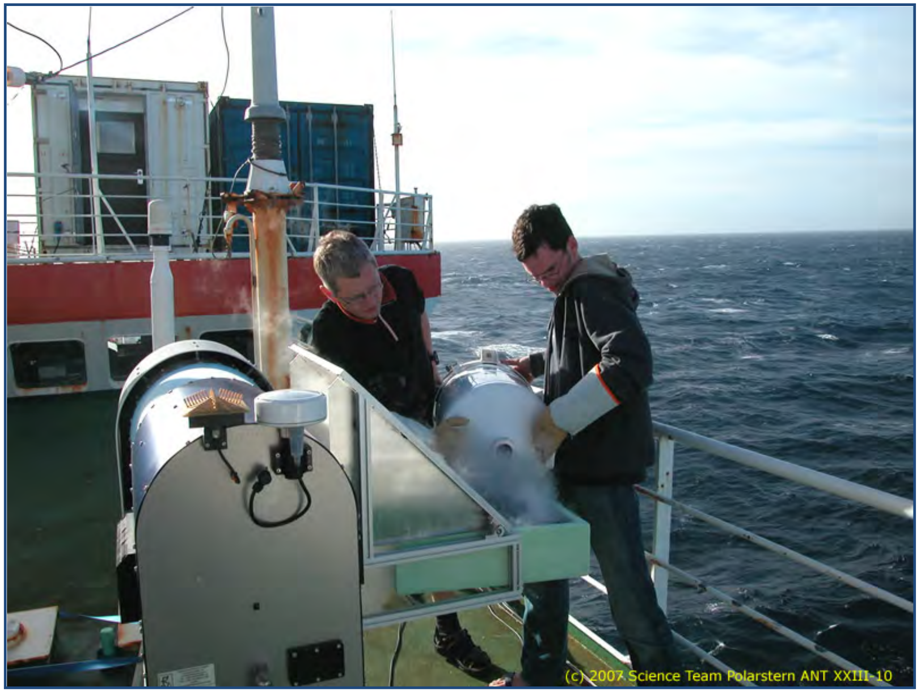
→ 4 Equations for 4 unknowns

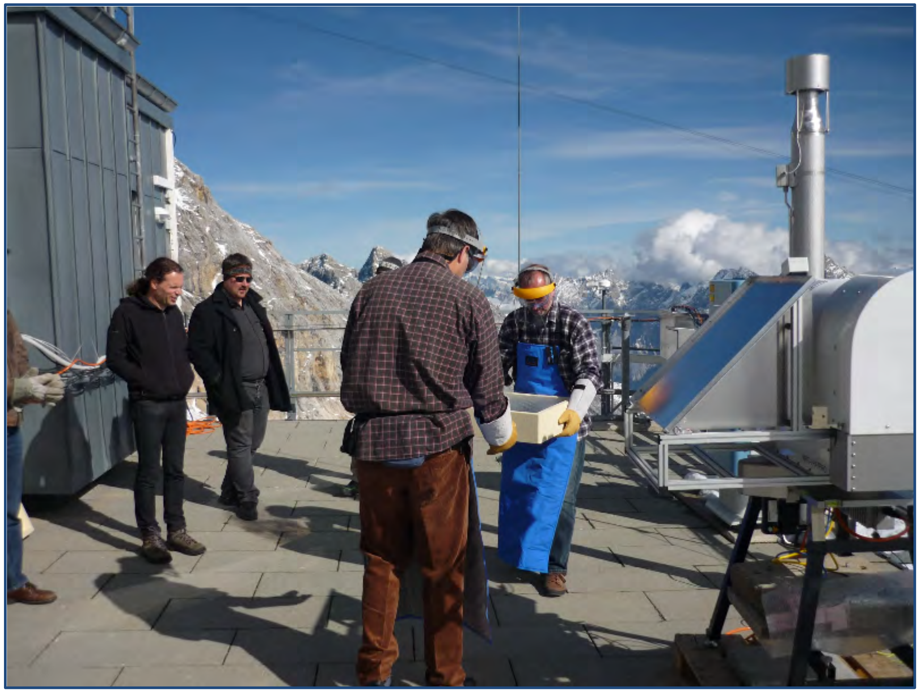
→ Derive G, T_{sys}, T_n, α

Radiometer Technology (III): Calibration examples



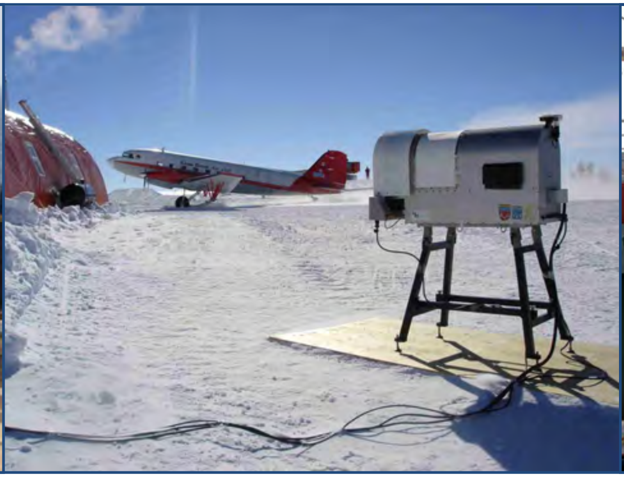



(c) 2007 Science Team Polarstern ANT XXIII-10

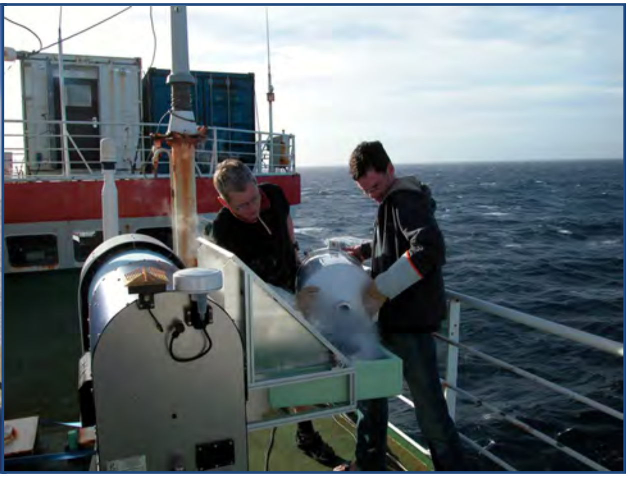


Challenge: Environment Conditions

Lampedusa, Italy
(humid, hot, salty)



Dome-C, Antarctica
(3.300m, -25 to -80 °C)



Research Vessel “Polarstern”
(Atlantic Ocean)

ALMA site, Chile
(5.500m above sea level)

Zugspitze, Germany
(2.800m, -35 °C, 250km/h wind)

AMMA campaign, Benin
(West-Africa, hot climate, dust)

Navigation

5. How to Retrieve Meteorological Data from TB data

Retrievals

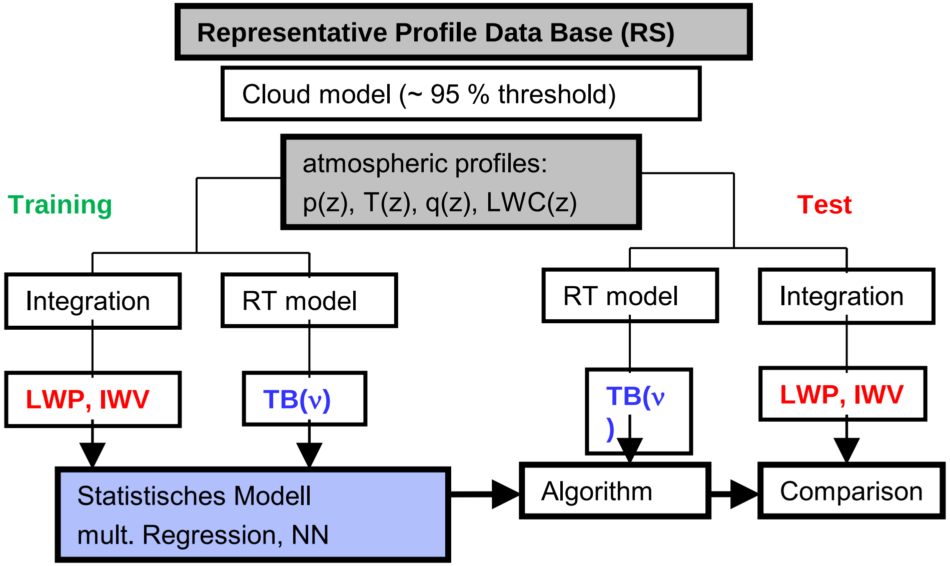
- Solving the „forward problem“ (radiative transfer for a given atmosphere)

$$TB = F(T(z), Q(z), P(z), LWC(z))$$

- Inversion of **F** is the „retrieval“, e.g.:

$$T(z) = F^{-1}(TB)$$

- Inversion problem is ill-posed
- Data set statistics important!



Representative Profile Data Base (RS)

Cloud model (~ 95 % threshold)

atmospheric profiles:
p(z), T(z), q(z), LWC(z)

Training

Integration

RT model

LWP, IWV

TB(ν)

Statistisches Modell
mult. Regression, NN

Test

RT model

Integration

TB(ν
)

LWP, IWV

Algorithm

Comparison

- Radiative Transfer Model simulates the instrument response to each atmospheric state („Forward Model“)
- Different choices for inversion scheme:
  - Regression retrievals derived by fitting mathematical function to explain atmospheric variables as a function of the TB-vector
  - Iterative („physical“) retrievals start with a first guess state and iteratively modify the profile to minimize the TB difference between simulated and mesured TB
    ➔ 1D-Var, 4D-Var

Building and Testing of a Statistical Retrieval

1. **Task:** Find equation that links IWV to brightness temperatures (TB):

   IWV = a0 + a1*TB1 + a2*TB2 + a3*TB3 + …

   (IWV = a0 + a1*TB1 + a2*$(TB1)^2$ + a3*TB2 + …)

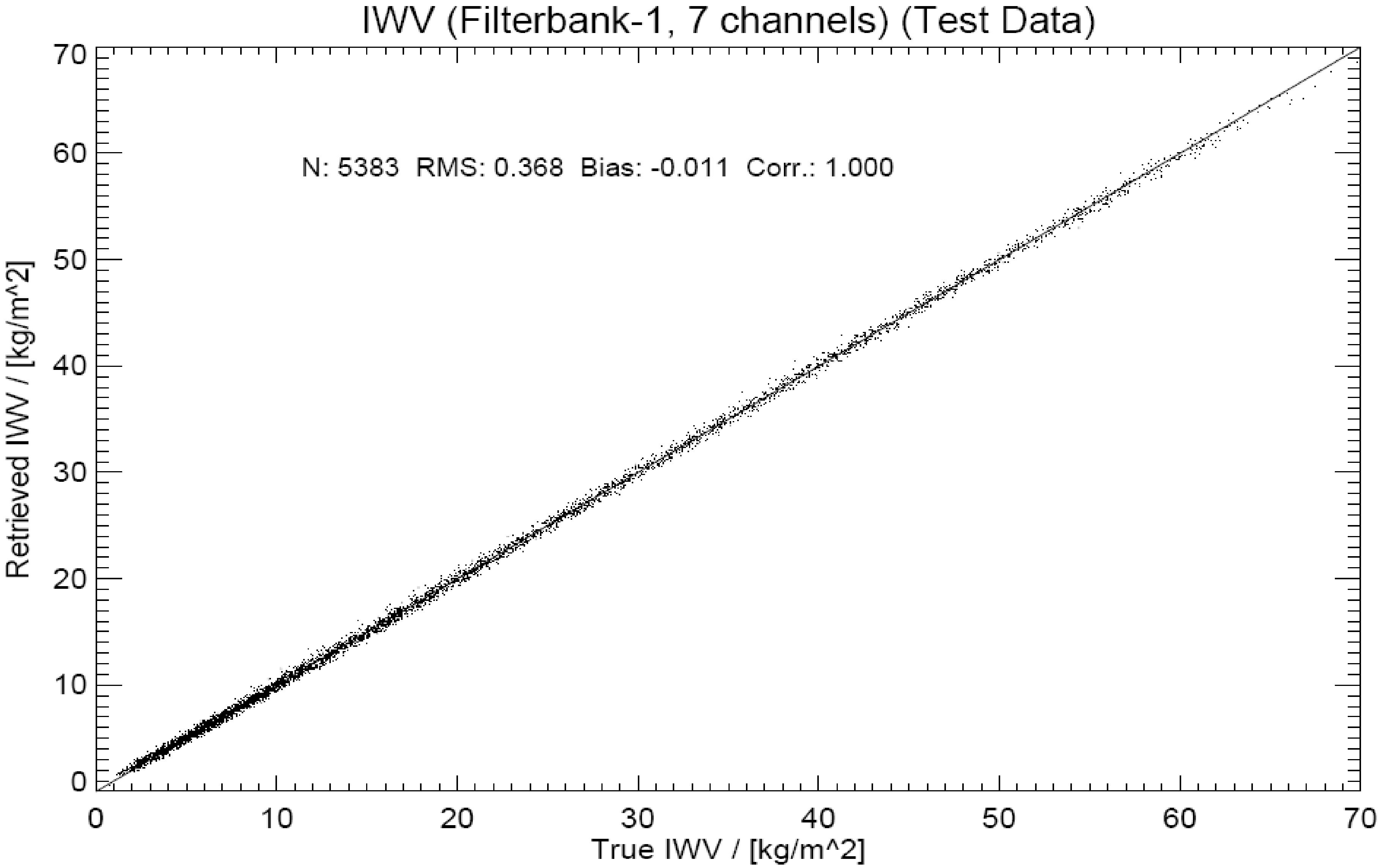
2. Use 10.000 Radio soundings to
   - → Calculate/Analyze real IWV from soundings
   - → Simulate TB1, TB2, TB3, …

3. Use 5.000 pairs of IWV and corresponding brightness temperature vectors (TB1, TB2, TB3, …) to derive coefficients a0, a1, a2, a3, …

4. Use remaining 5.000 pairs of real IWV and simulated TB to test the retrieval:
   - → For each set of simulated brightness temperatures, apply coefficients a0,a1,a2,.. to calculate (=retrieve) a simulated IWV (not real TB measurements, but simulated TB measurements used during retrieval)
   - → Compare “real IWV” to “simulated IWV” from application of retrieval
   - → For 5.000 cases, we have a difference of real IWV and retrieved IWV (and can calculate corellation, RMS, Bias)
   - → Real IWV is integral of RH-profile
   - → Simulated IWV is retrieved from simulated TB-vector, which is depending on the full atmospheric condition (different cloud situations, different T-profiles, etc…)

Retrieval Test

- Retrieval self test estimates expected performance in terms of RMS



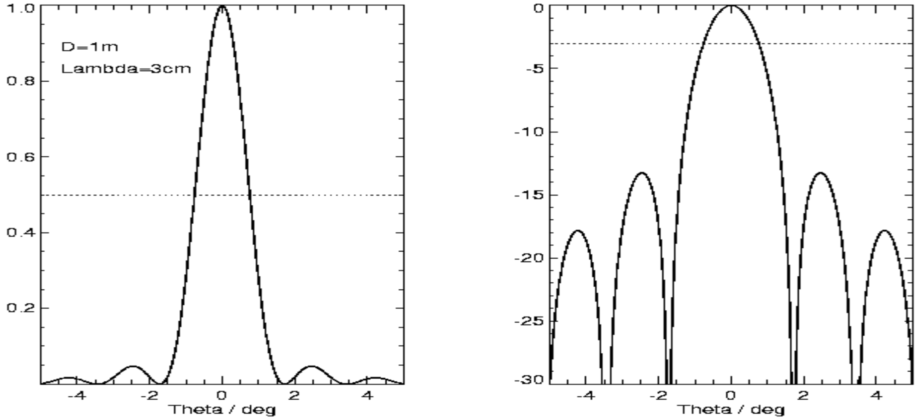
RTM Model

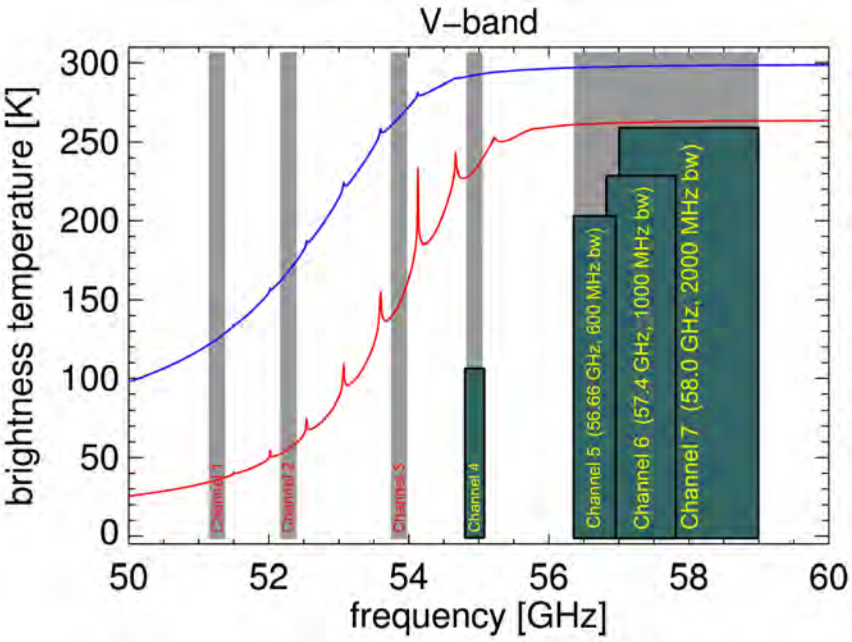
- RT model solves 1D or 3D radiative transfer equation
- Simple emission/absorption models
- Sophisticated (multiple) scattering codes
- Polarization (surface effects, non-spherical hydrometeors)

$$\frac{d\,\bar{\mathbf{I}}(z,\theta)}{\frac{1}{\mu}dz} = -\,\bar{\bar{\sigma}}_e(z,\theta)\,\bar{\mathbf{I}}(z,\theta) + \bar{\sigma}_a(z,\theta)\,B(T(z))$$

Before retrieval building:

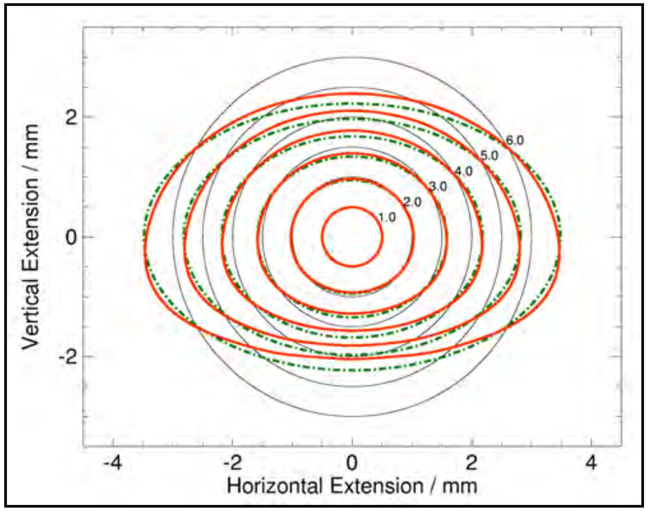
- Last processing layer needs to model the imperfections of the radiometer system, such as
  - RMS noise
  - Calibration uncertainties
  - Band width effects (no such thing as a centre frequency!)
  - Beam width (antenna patterns usually 1 to 10 degree)
  - Earth curvature (transparent channels)





RTM Model (continued)

- Simplified (non-scattering) RT model only good for non raining atmospheres
- Scattering more important at higher frequencies
- At low frequencies: Polarization effects by emission of non-spherical particles (rain at 10 GHz)
- Extension for rain or snow (graupel, ice, …):
  - Polarized RTE using the 4-component Stokes vector
  - 4 coupled Integro-Differential equations (with boundary conditions)



Differential change

Emission source

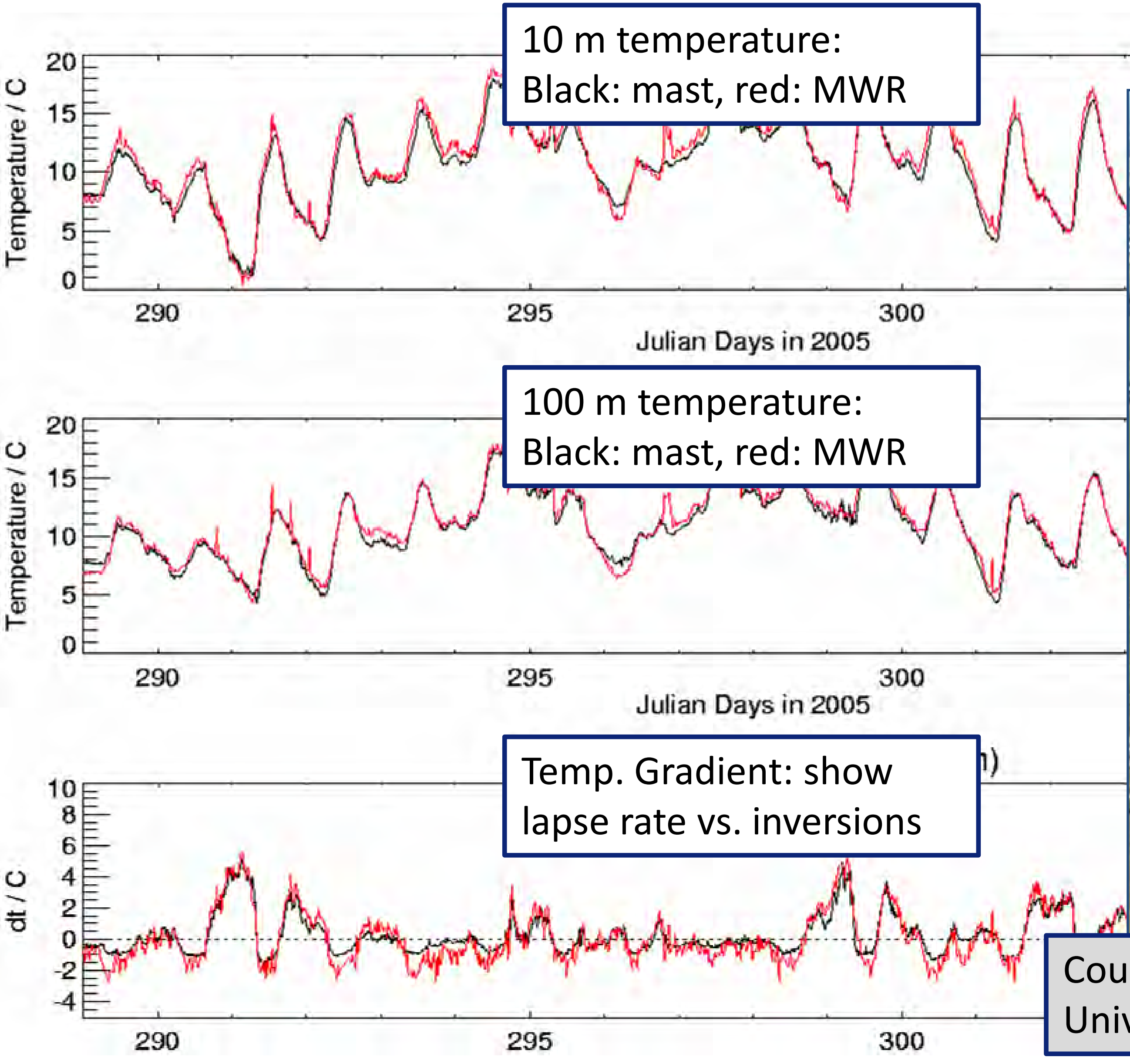
Scattering source (phase function)

$$\frac{d\bar{\mathbf{I}}(z,\theta)}{\frac{1}{\mu}dz} = -\,\bar{\bar{\sigma}}_e(z,\theta)\,\bar{\mathbf{I}}(z,\theta) + \bar{\sigma}_a(z,\theta)\,B(T(z)) + \int_0^{\pi} \bar{\bar{\mathbf{P}}}(z,\theta;\theta')\,\bar{\mathbf{I}}(z,\theta')\,\sin\theta' d\theta'$$

Extinction loss (absorption + scattering)

6. Data Examples

Comparison with Mast data: 15 day time series



10 m temperature:
Black: mast, red: MWR

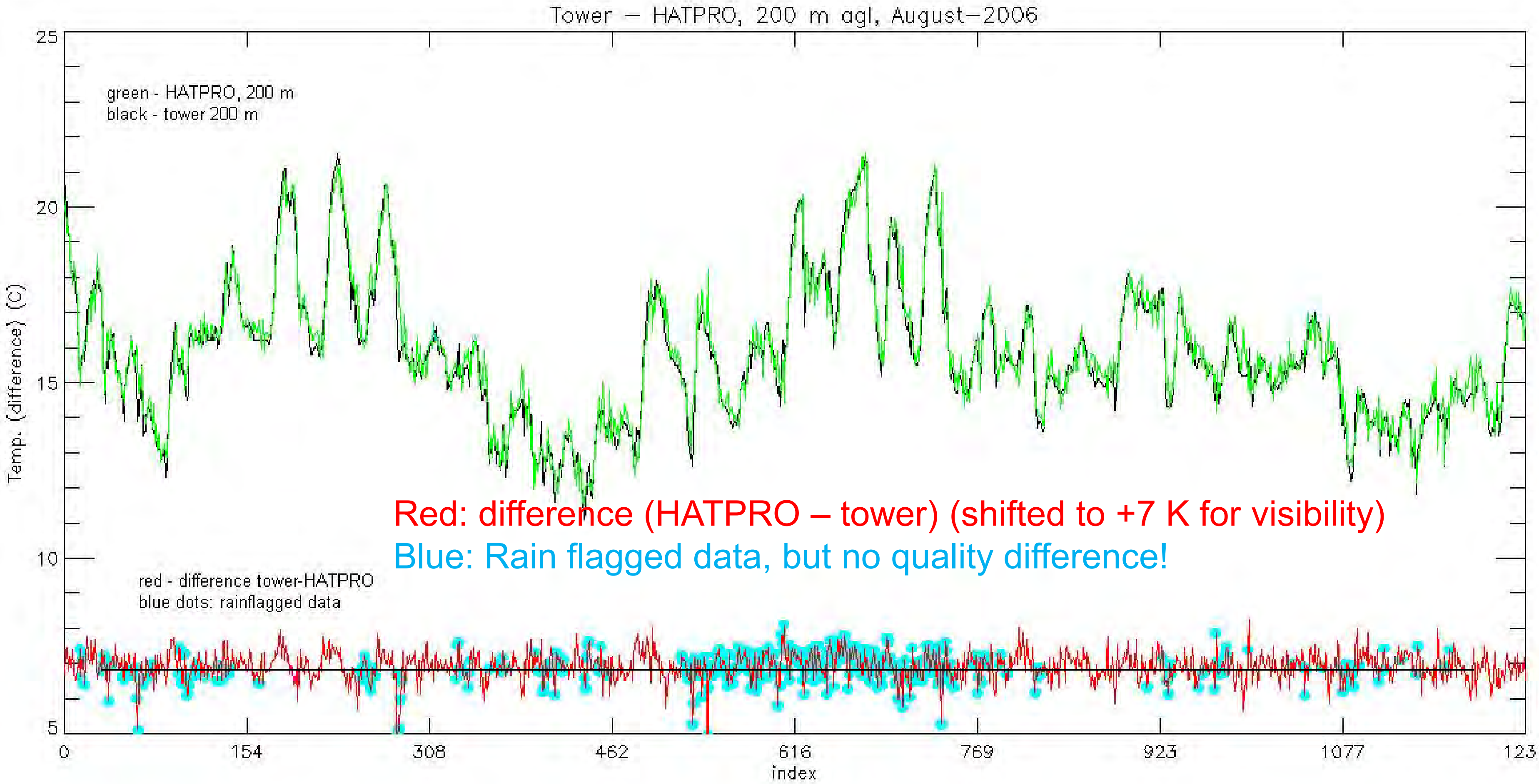
100 m temperature:
Black: mast, red: MWR

Temp. Gradient: show lapse rate vs. inversions

Courtesy of Susanne Crewell, University of Cologne, Germany

Measurements: 200m temperature at KNMI mast

- Comparison of HATPRO 200m temperature measurements with tower at 200m
- **RPG-Boundary-Layer-Mode**: elevation scans, optimized bandpass filters, small beam

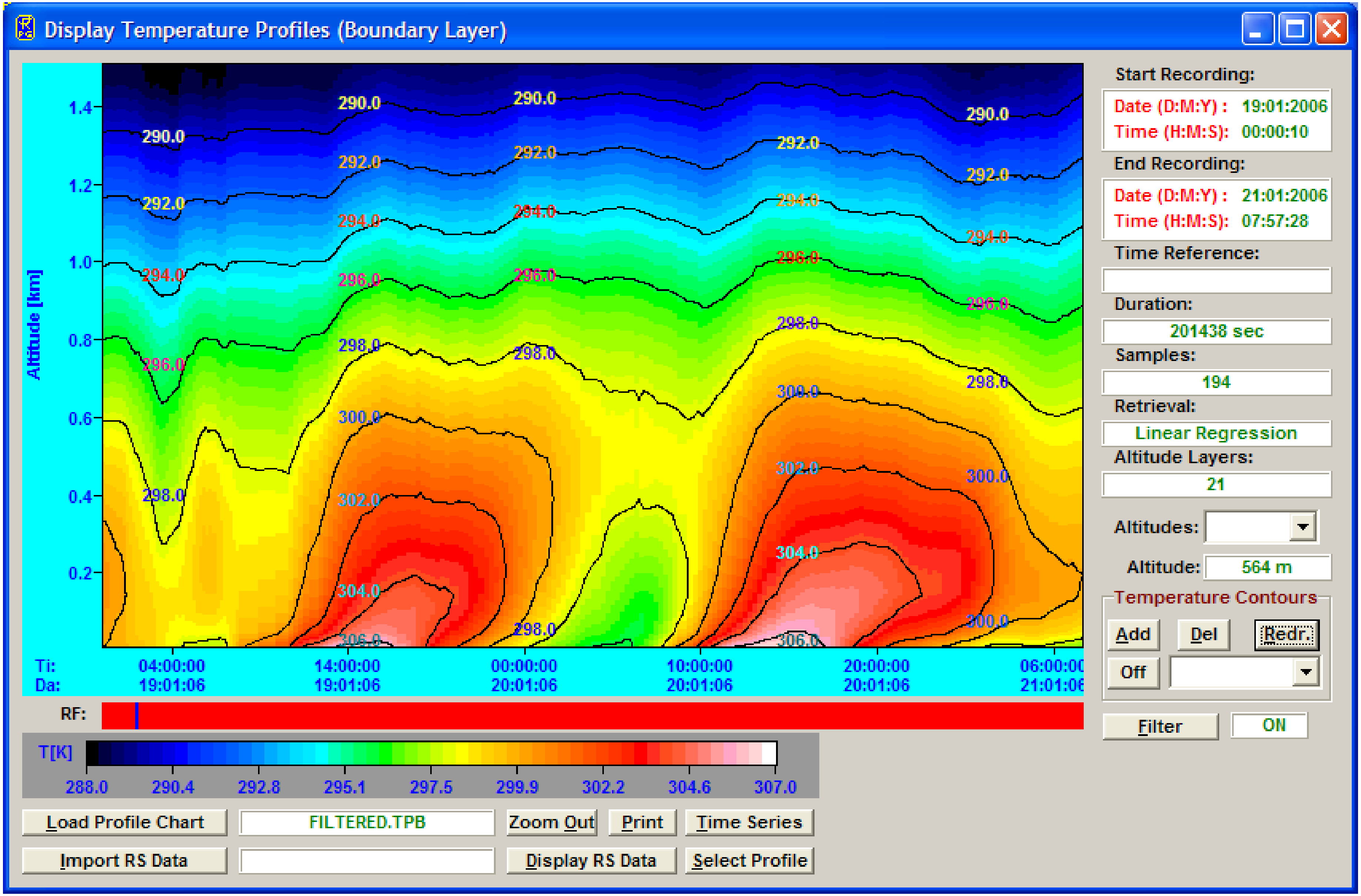


Red: difference (HATPRO – tower) (shifted to +7 K for visibility)

Blue: Rain flagged data, but no quality difference!

Courtesy of Henk Klein-Baltink, KNMI, Neatherlands

Boundary Layer temperature profile



Start Recording:
Date (D:M:Y) : 19:01:2006
Time (H:M:S): 00:00:10

End Recording:
Date (D:M:Y) : 21:01:2006
Time (H:M:S): 07:57:28

Time Reference:

Duration: 201438 sec

Samples: 194

Retrieval: Linear Regression

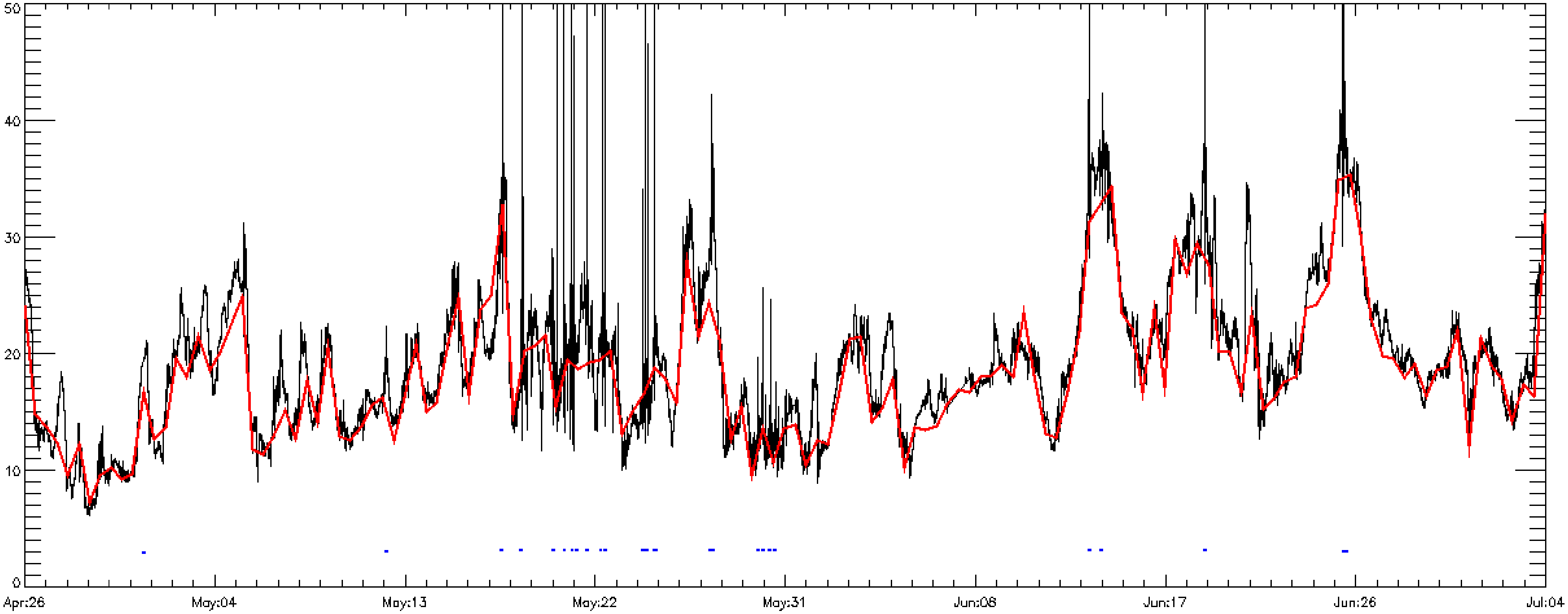
Altitude Layers: 21

Altitude: 564 m

Filter: ON

FILTERED.TPB

IWV at Cabauw, KNMI



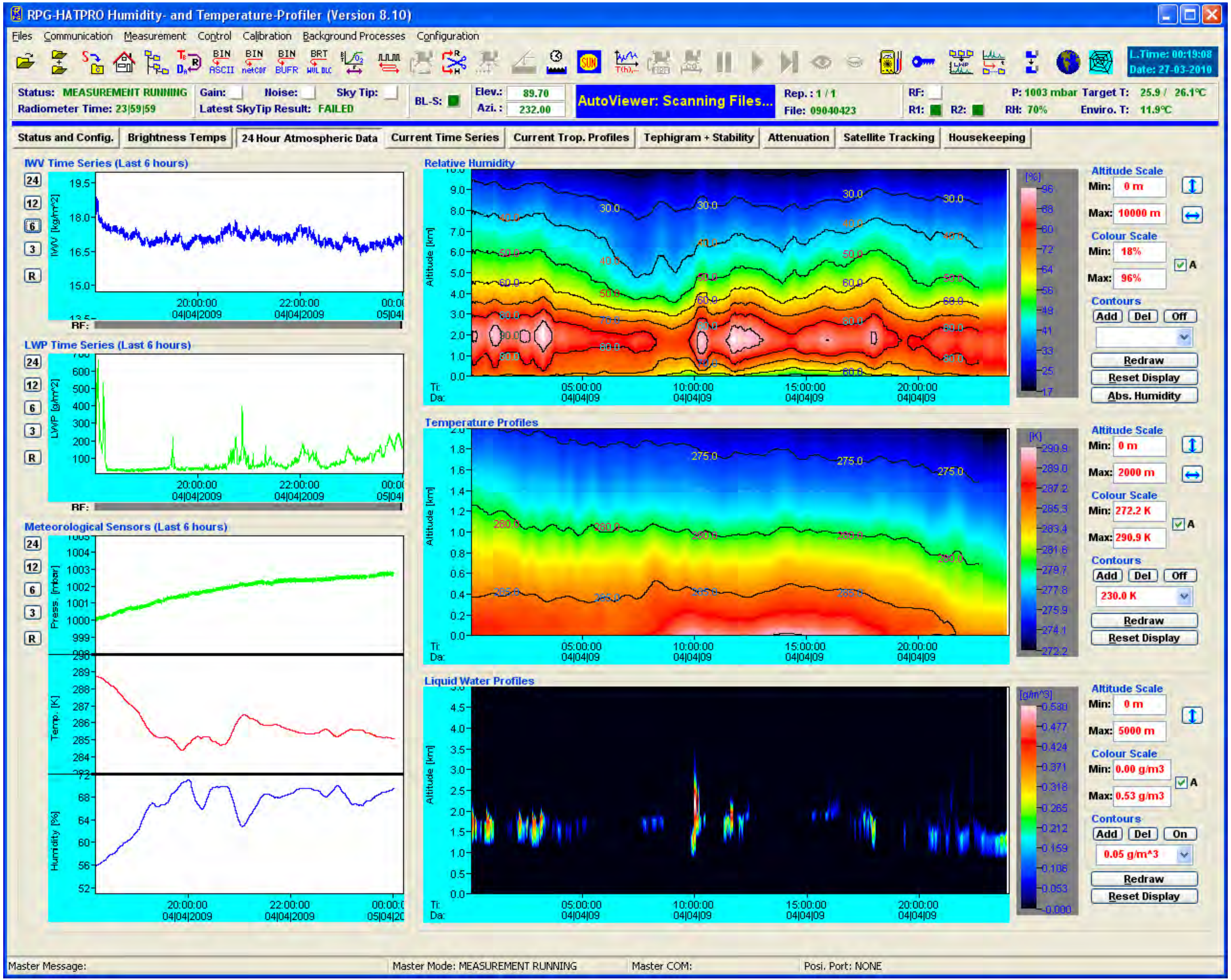
IWV time series over one month (KNMI, May 2006).

140 radio soundings (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

Software – 24-hour readings of OWV, LWP, Cloud, Met-sensors



RPG-HATPRO Humidity- and Temperature-Profiler (Version 8.10)

L.Time: 00:19:08
Date: 27-03-2010

Status: MEASUREMENT RUNNING
Radiometer Time: 23|59|59
Gain: ☐ **Noise:** ☐ **Sky Tip:** ☐
Latest SkyTip Result: FAILED
BL-S: 🟩
Elev.: 89.70
Azi.: 232.00
AutoViewer: Scanning Files...
Rep.: 1 / 1
File: 09040423
RF: ☐
R1: 🟩 **R2:** 🟩
P: 1003 mbar **Target T:** 25.9 / 26.1°C
RH: 70% **Enviro. T:** 11.9°C

Relative Humidity

Altitude Scale
Min: 0 m
Max: 10000 m
Colour Scale
Min: 18%
Max: 96%
☑ A
Contours

Temperature Profiles

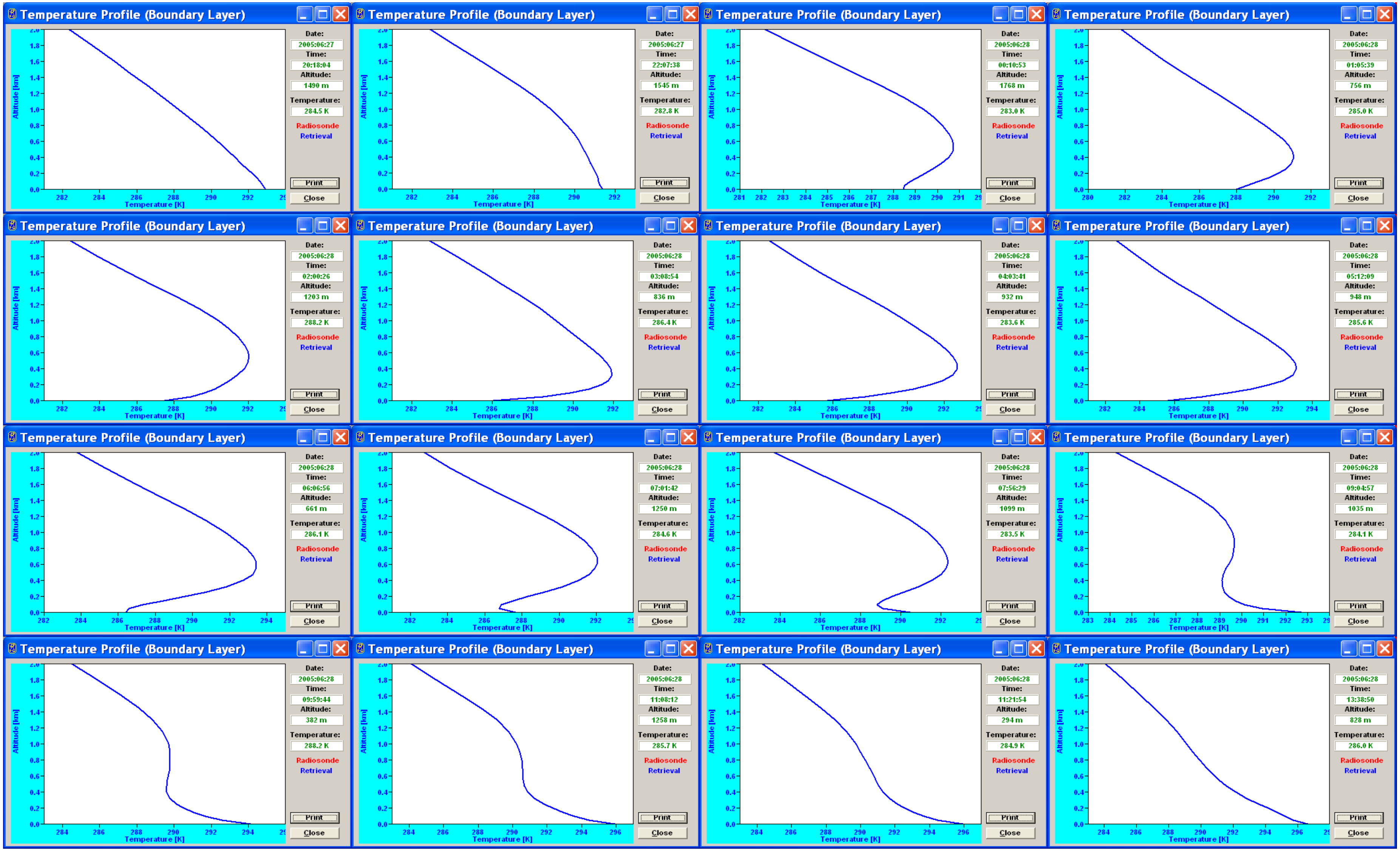
Altitude Scale
Min: 0 m
Max: 2000 m
Colour Scale
Min: 272.2 K
Max: 290.9 K
☑ A
Contours
230.0 K

Liquid Water Profiles

Altitude Scale
Min: 0 m
Max: 5000 m
Colour Scale
Min: 0.00 g/m3
Max: 0.53 g/m3
☑ A
Contours
0.05 g/m^3

Master Message:
Master Mode: MEASUREMENT RUNNING
Master COM:
Posi. Port: NONE

Time series of temperature inversion



Date: 2005:06:27 Time: 20:18:04 Altitude: 1490 m Temperature: 284.5 K

Date: 2005:06:27 Time: 22:07:38 Altitude: 1545 m Temperature: 282.8 K

Date: 2005:06:28 Time: 00:10:53 Altitude: 1768 m Temperature: 283.0 K

Date: 2005:06:28 Time: 01:05:39 Altitude: 756 m Temperature: 285.0 K

Date: 2005:06:28 Time: 02:00:26 Altitude: 1203 m Temperature: 288.2 K

Date: 2005:06:28 Time: 03:08:54 Altitude: 836 m Temperature: 286.4 K

Date: 2005:06:28 Time: 04:03:41 Altitude: 932 m Temperature: 283.6 K

Date: 2005:06:28 Time: 05:12:09 Altitude: 948 m Temperature: 285.6 K

Date: 2005:06:28 Time: 06:06:56 Altitude: 661 m Temperature: 286.1 K

Date: 2005:06:28 Time: 07:01:42 Altitude: 1250 m Temperature: 284.6 K

Date: 2005:06:28 Time: 07:56:29 Altitude: 1099 m Temperature: 283.5 K

Date: 2005:06:28 Time: 09:04:57 Altitude: 1035 m Temperature: 284.1 K

Date: 2005:06:28 Time: 09:59:44 Altitude: 382 m Temperature: 288.2 K

Date: 2005:06:28 Time: 11:08:12 Altitude: 1258 m Temperature: 285.7 K

Date: 2005:06:28 Time: 11:21:54 Altitude: 294 m Temperature: 284.9 K

Date: 2005:06:28 Time: 13:38:50 Altitude: 828 m Temperature: 286.0 K

Thank you!

`czekala@radiometer-physics.de`