ACTRIS
CCRES

Microwave radiometry in ACTRIS

Bernhard Pospichal, Tobias Marke

CCRES/CLU Training school, Munich, 2-5 Sept. 2025

Microwave radiometry in ACTRIS

ACTRIS
CCRES

Outline

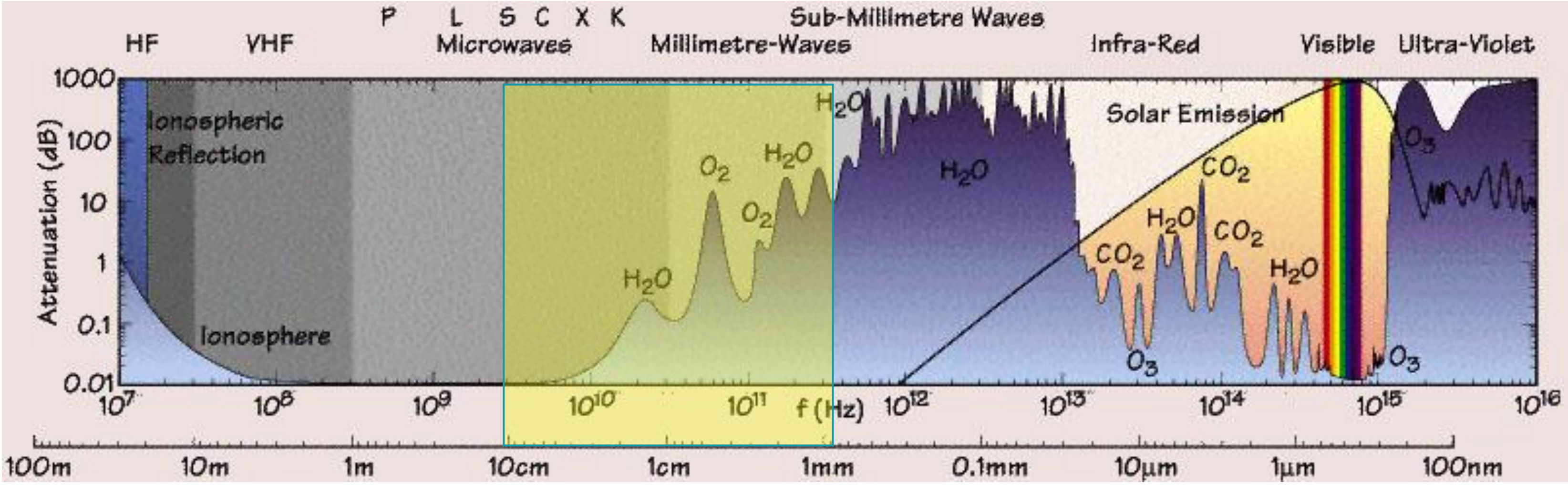
- Introduction to Microwave remote sensing
- Instruments
- Retrieval development
- Calibration

- MWR data processing in ACTRIS
- Recent developments

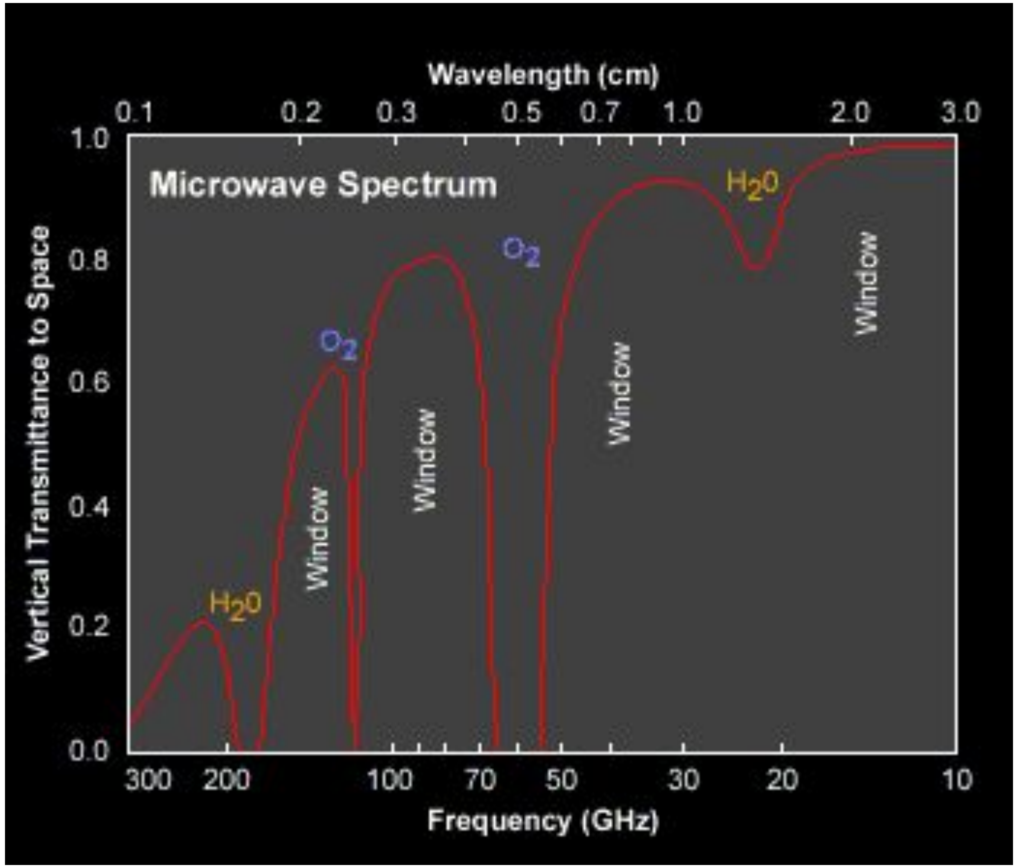
- Hands-on training

Microwaves in the atmosphere

- various definitions of microwaves, mostly 3 to 300 GHz (λ = 0.1-10 cm)
- sub-millimeter range between 300 GHz and 3 THz (1 mm to 100 µm)
- the lower the frequency, the higher the atmospheric transmission
- higher frequencies have more and more absorption characteristica of gases (absorption lines)



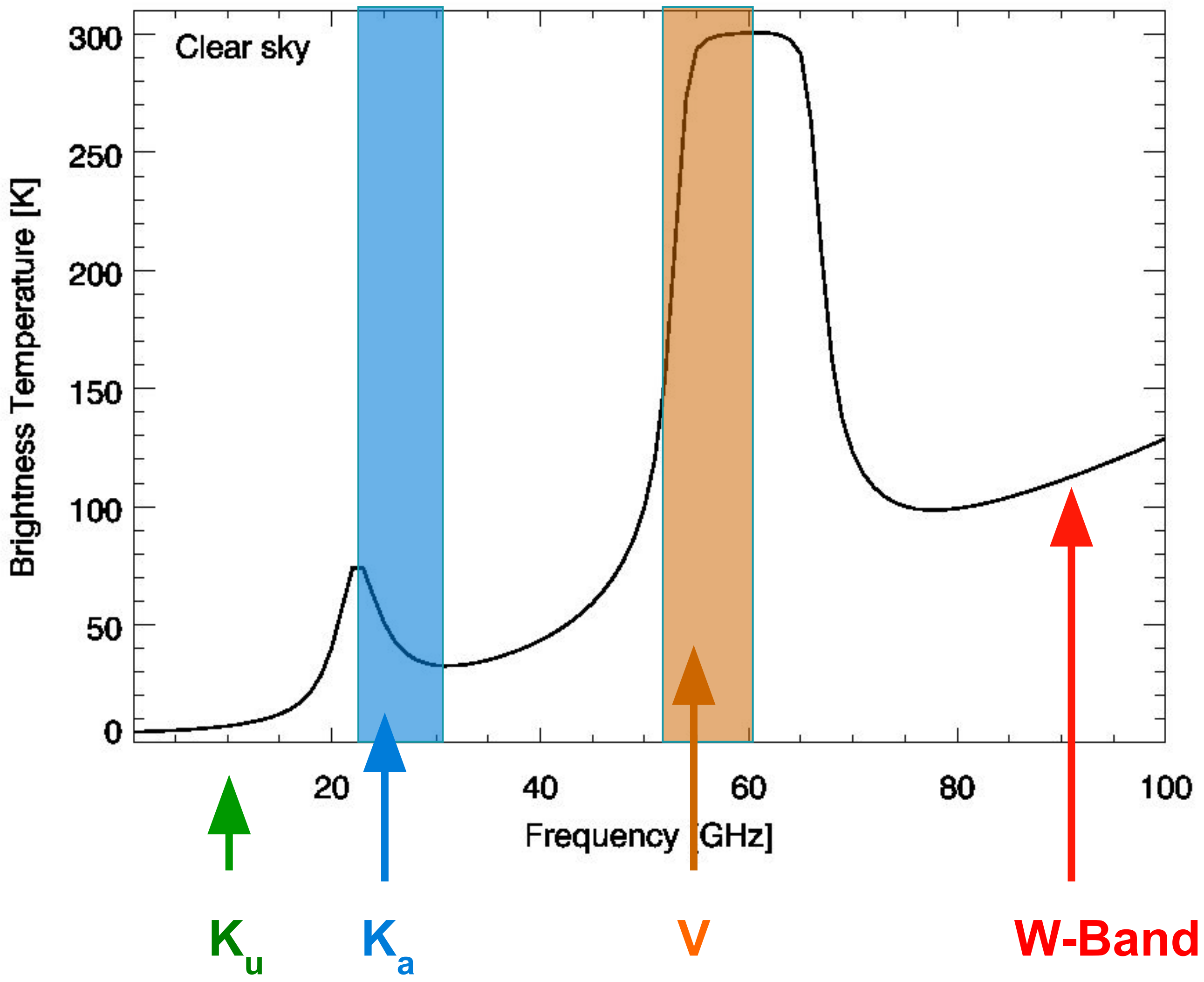
Microwaves in the atmosphere



- absorption lines of water vapor and oxygen (temperature profiles) used for remote sensing of the atmosphere
- window areas used for cloud remote sensing
- absorption of (liquid water) clouds increases with frequency
- absorption of ice only in higher frequencies (above ~100 GHz)
- Semi-transparency of clouds
  - therefore cloud observations possible (both active & passive)
  - profiles of temperature also when clouds are present

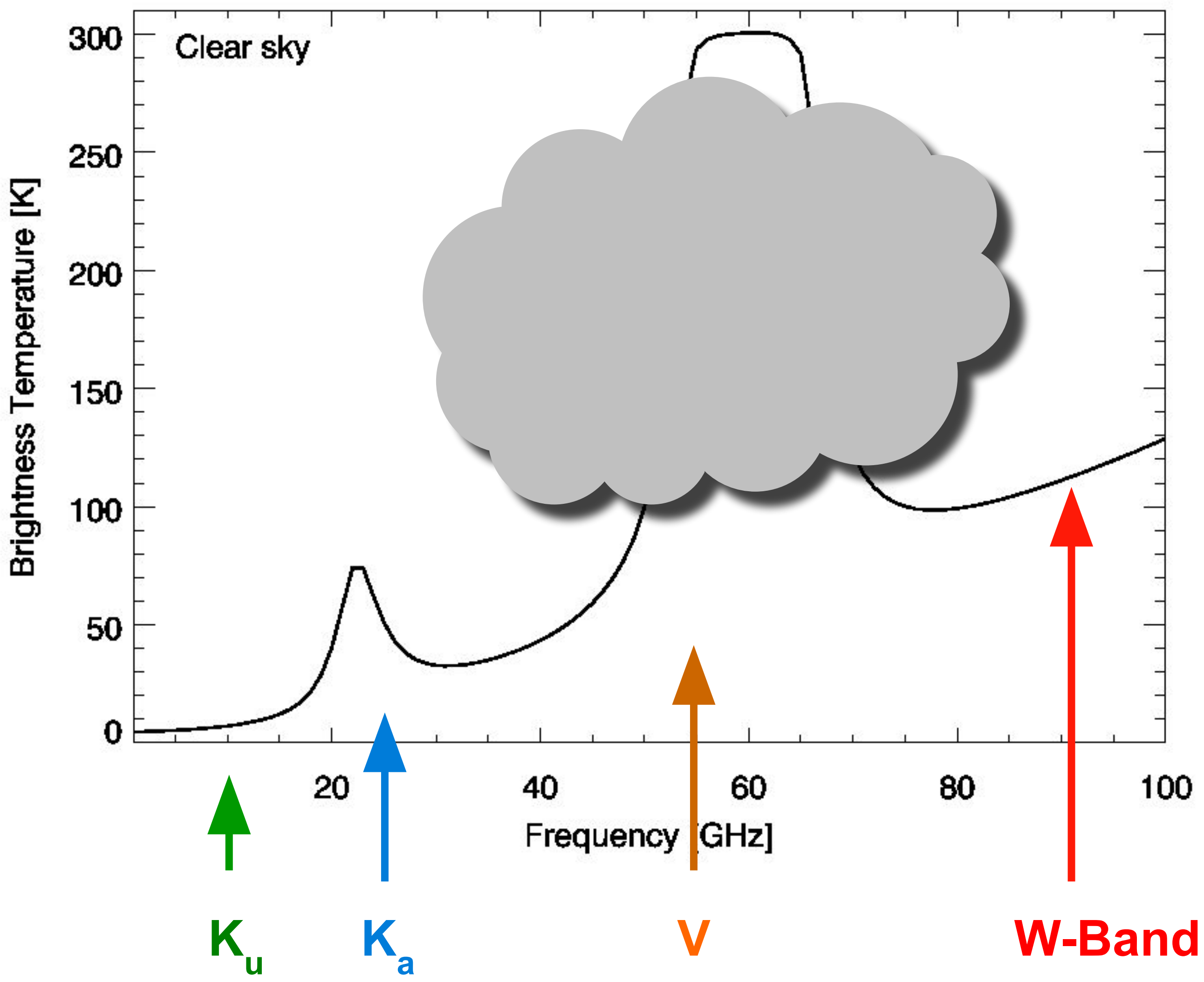
Frequency selection

- temperature profiles (V)
- humidity profiles and integrated water vapor content (IWV) (K_a)
- cloud liquid water path (LWP) (K_a+W)
- rain (K_u)



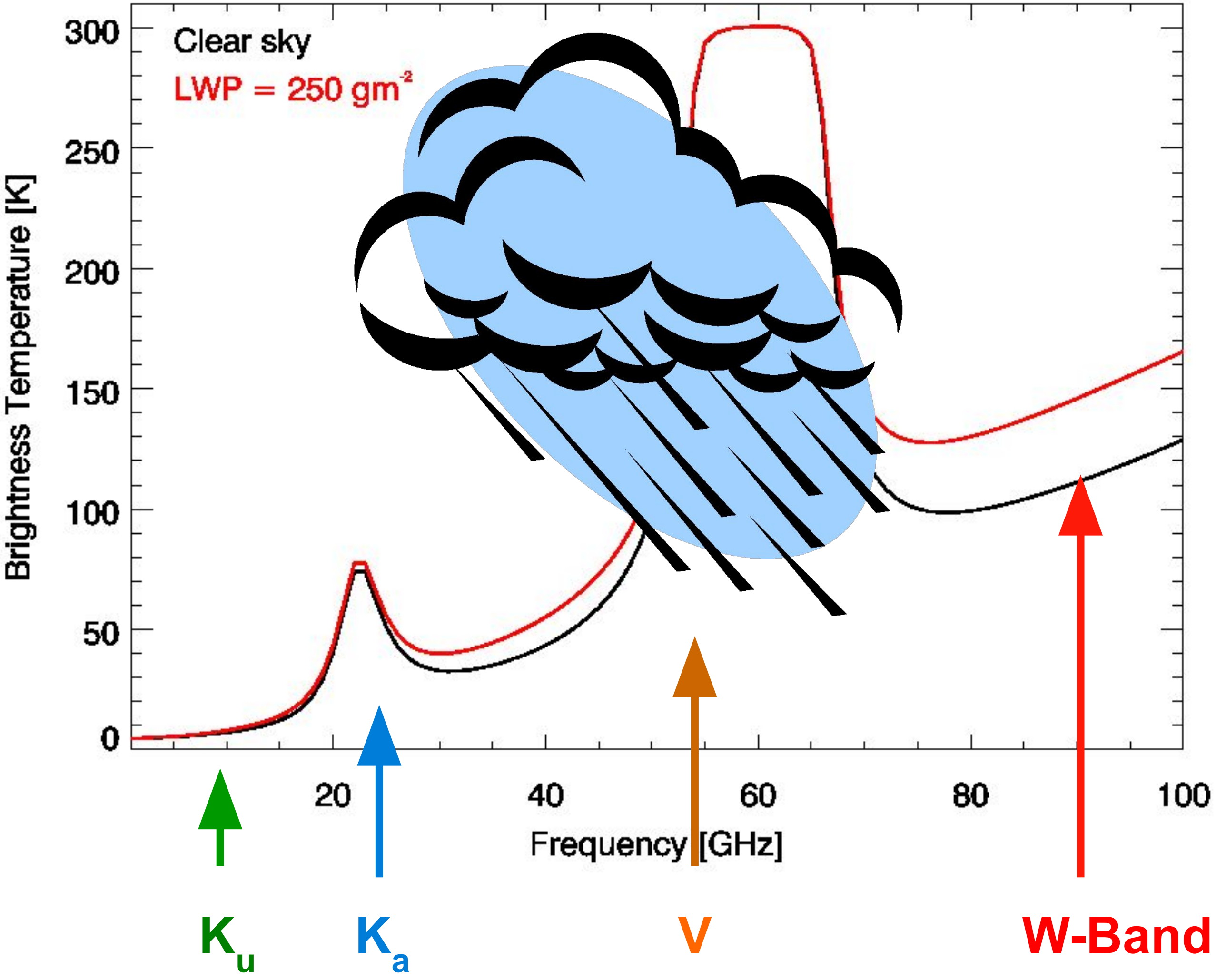
Frequency selection

- temperature profiles (V)
- humidity profiles and integrated water vapor content (IWV) (K_a)
- cloud liquid water path (LWP) (K_a+W)
- rain (K_u)



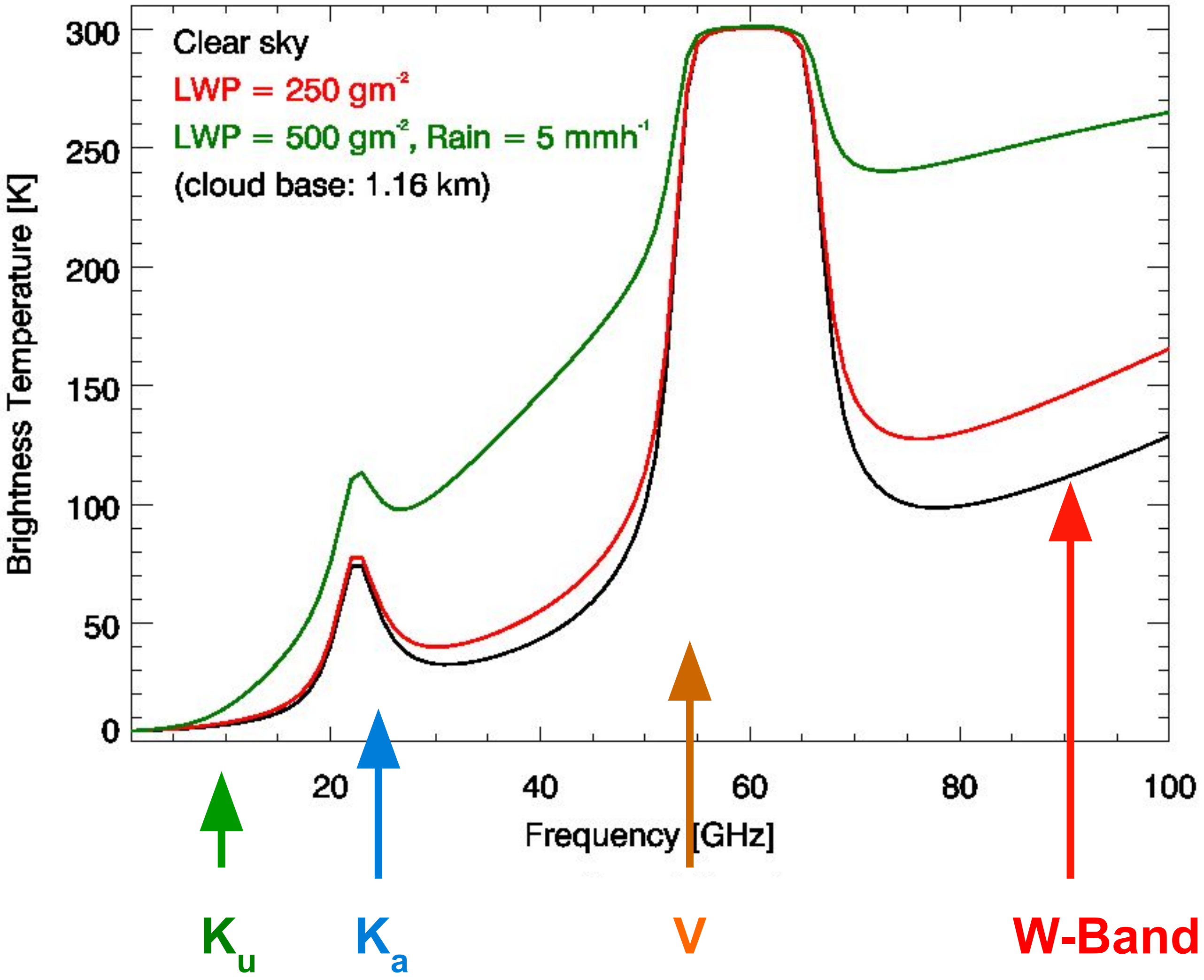
Frequency selection

- temperature profiles (V)
- humidity profiles and integrated water vapor content (IWV) (K_a)
- cloud liquid water path (LWP) (K_a+W)
- rain (K_u)



Frequency selection

- temperature profiles (V)
- humidity profiles and integrated water vapor content (IWV) (K_a)
- cloud liquid water path (LWP) (K_a+W)
- rain (K_u)



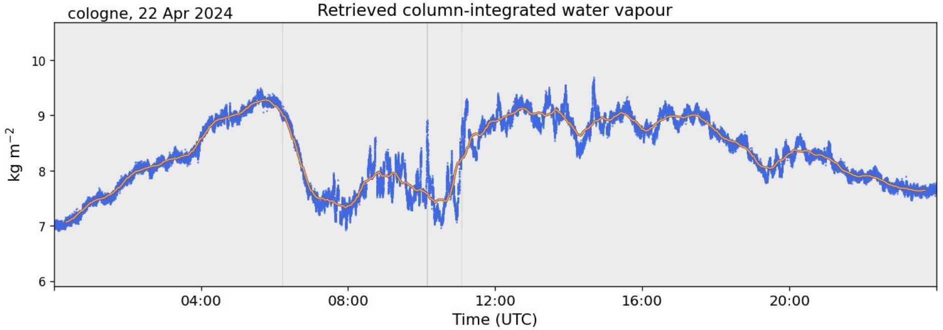
What do we want to see from MWR?

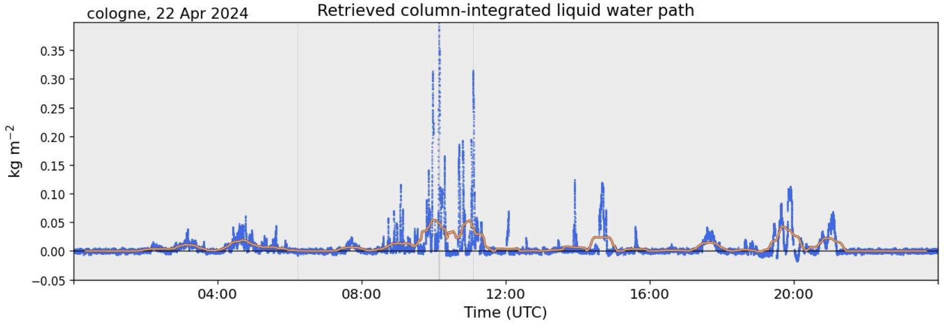
ACTRIS
CCRES

path-integrated **cloud liquid water (LWP)**

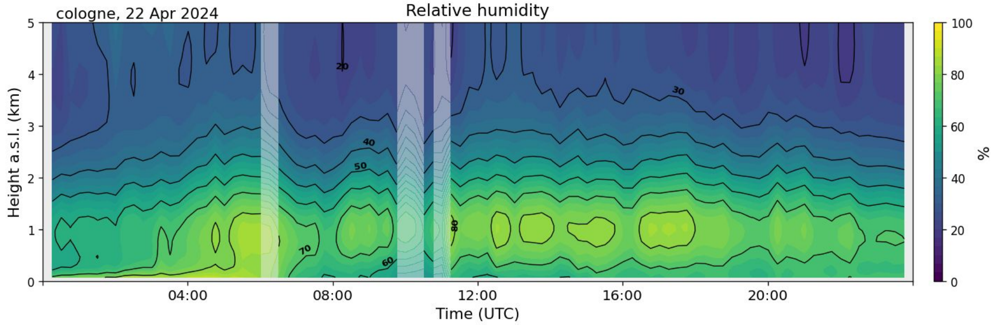
continuous data: resolution of seconds to minutes

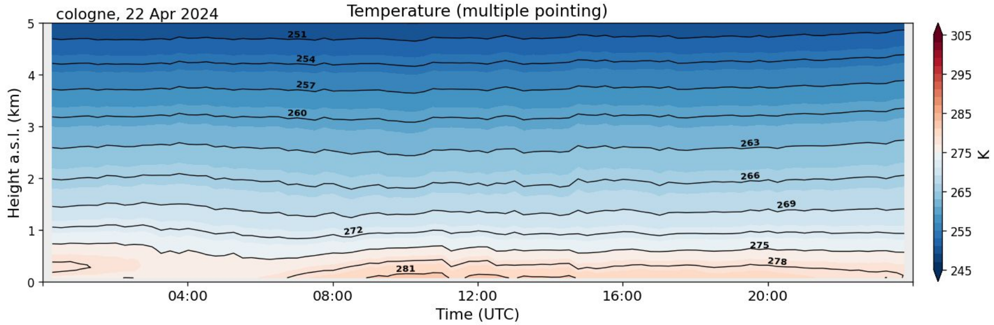
temperature profile of the PBL, low resolution profile above





low resolution **water vapor profile**, but excellent path-integrated values



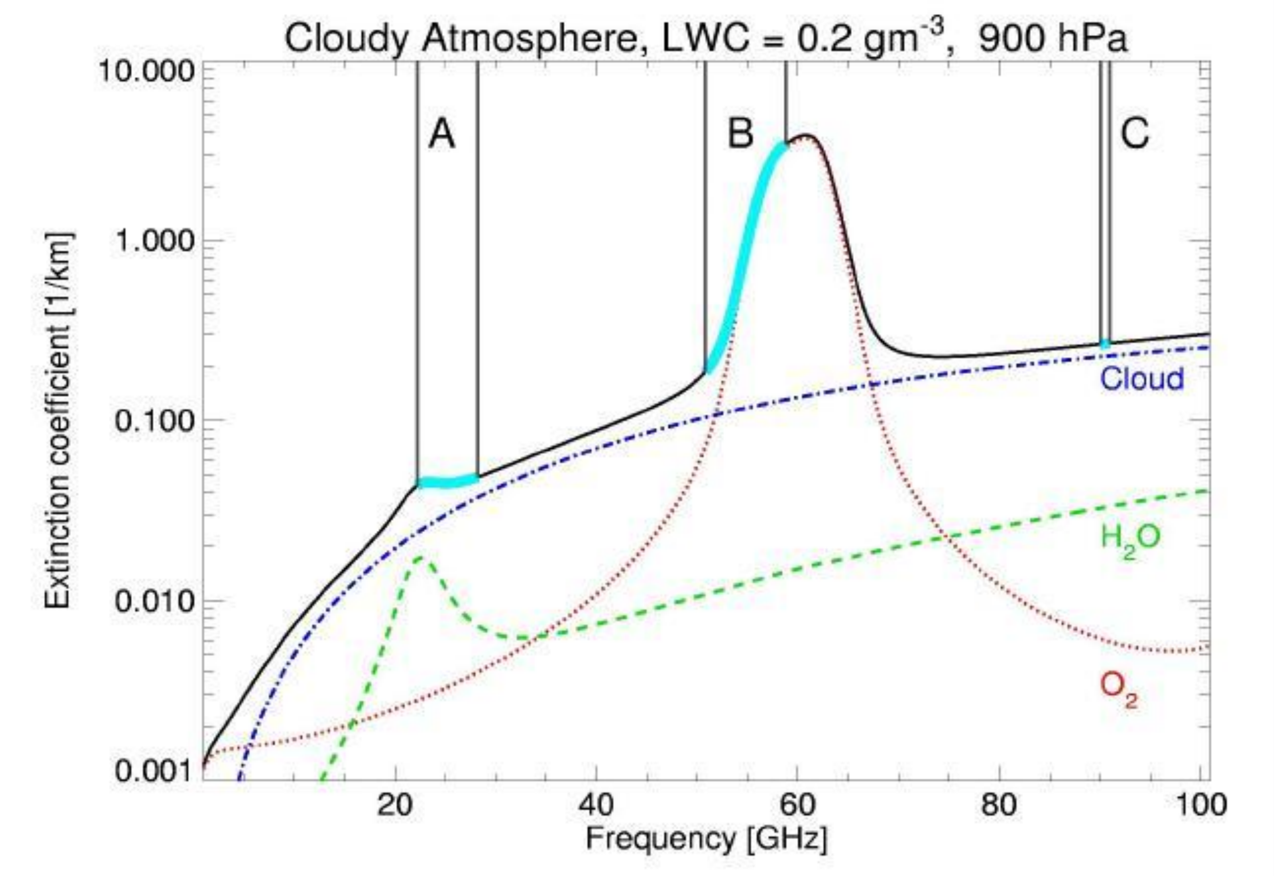


What does a MWR see?

- Measurement of downwelling radiation caused by emission of atmospheric gases (oxygen, water vapor) and hydrometeors

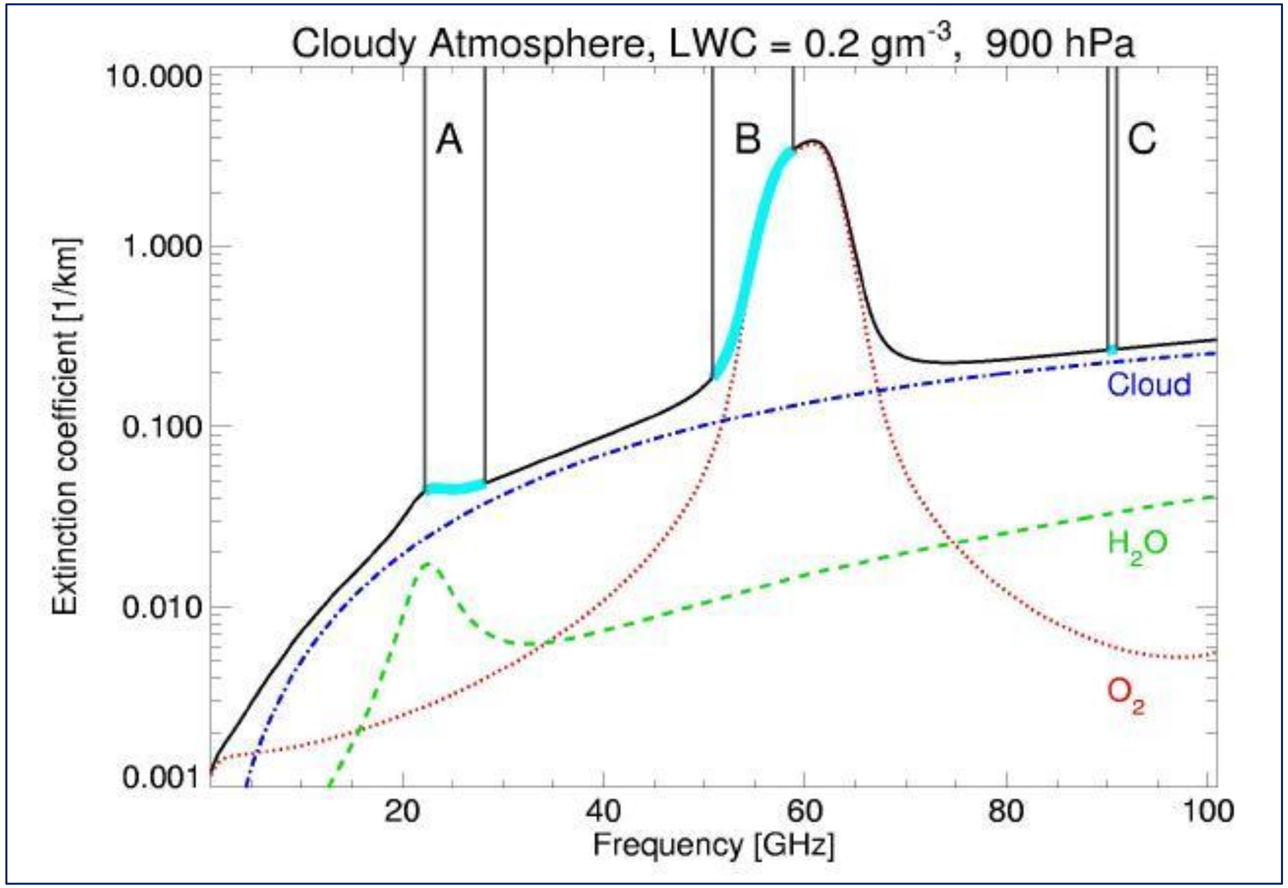
Microwave region: Extinction = Absorption

Kirchhoff's law: absorption is directly proportional to emission



What does a MWR see?

- Measurement of brightness temperatures usually in two frequency ranges (example valid for RPG-HATPRO)
- A: 22.235 –31.4 GHz, 7 channels on the upper wing of the water vapor line as well as window channels
- B: 51.26 – 58.0 GHz, 7 channels along the 60 GHz oxygen absorption complex
- Some radiometers have only one band, some measure also at higher frequencies (e.g. 90 or 183 GHz) for low-humidity conditions)



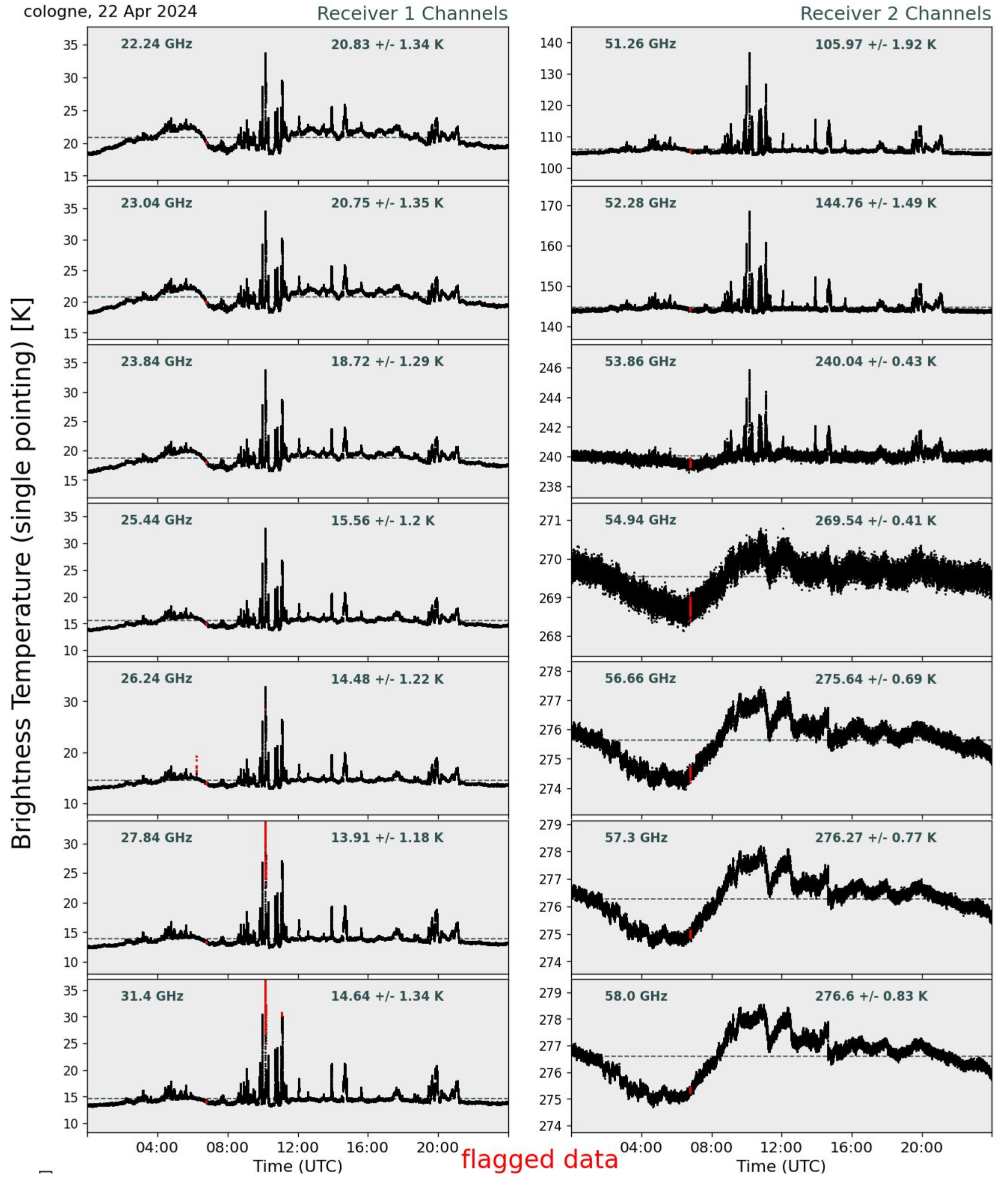
What does a MWR see?

ACTRIS CCRES

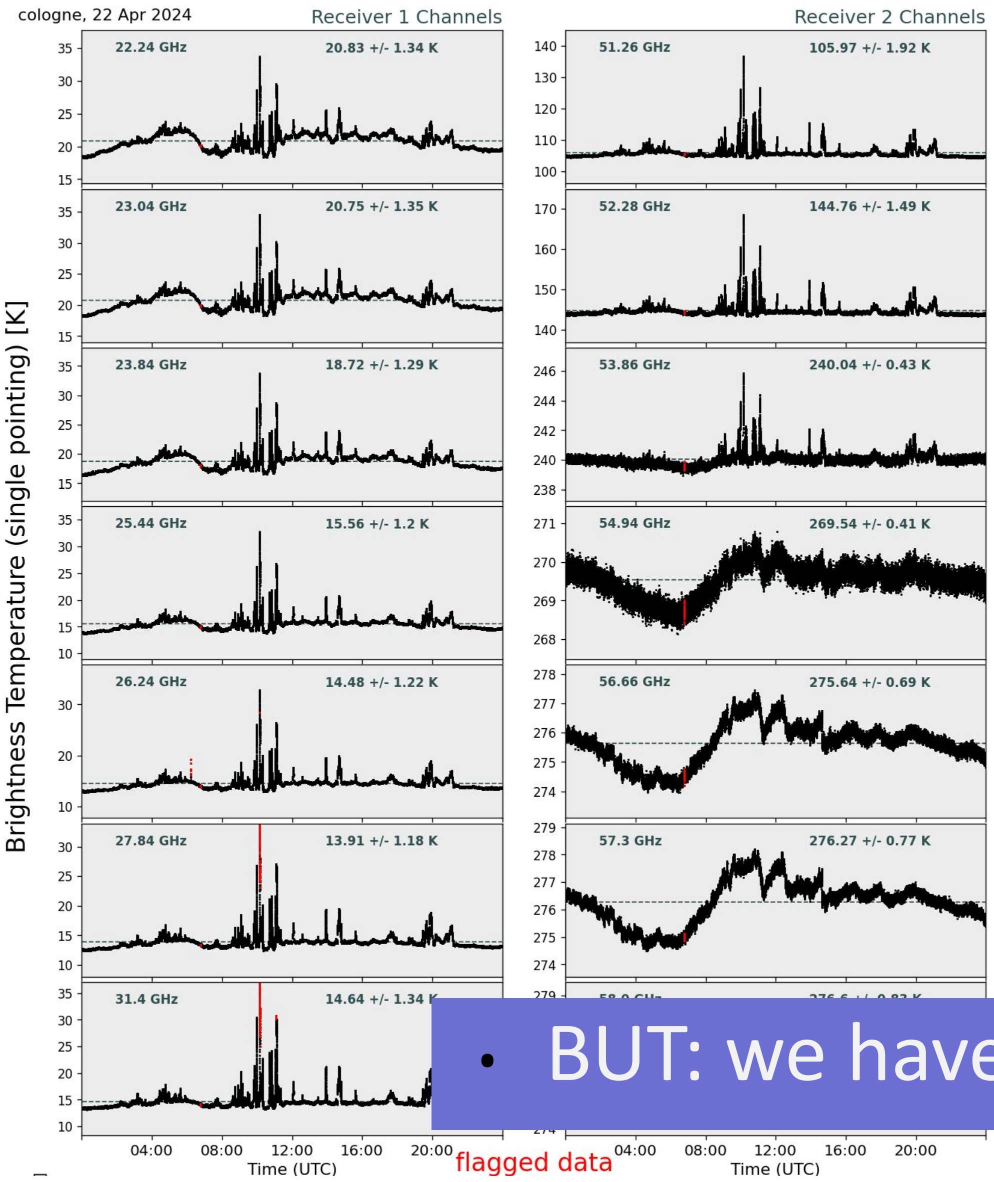
- Radiances in microwave radiometry are often expressed as brightness temperatures
- Radiometers measure Radiance **I** [W m^{-2} Hz^{-1} sr^{-1}] (***I* = *ε B***)
- Assuming an emissivity ε=1 we can formulate an equivalent blackbody temperature T_B, using the Rayleigh-Jeans approximation. This temperature is called **brightness temperature** (more precise: Planck-equivalent brightness temperature!)

$$T_B = \frac{\lambda^2}{2k_B} \cdot I_\nu$$

Rayleigh-Jeans approximation (simplified Planck equation)

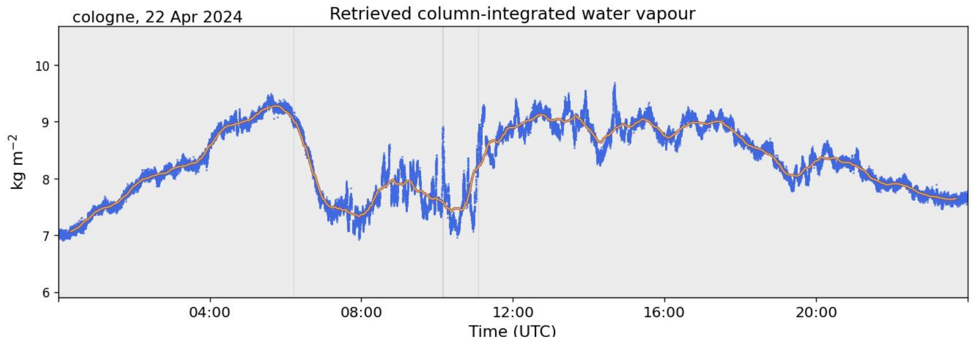


How to get to atmospheric quantities?



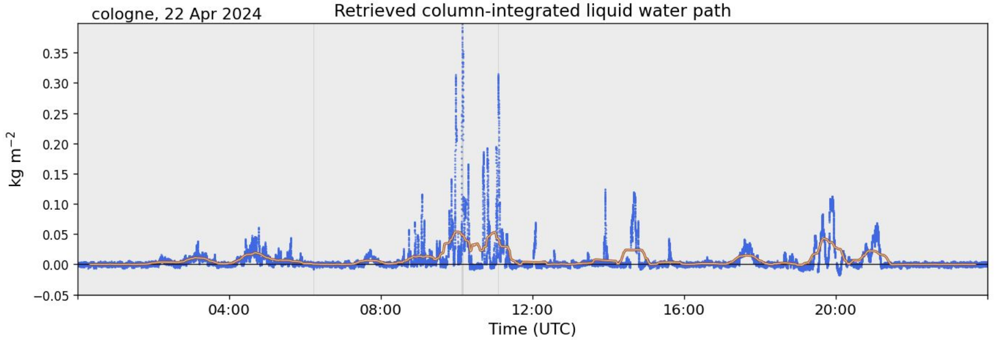
Level1 data : (brightness temperatures)

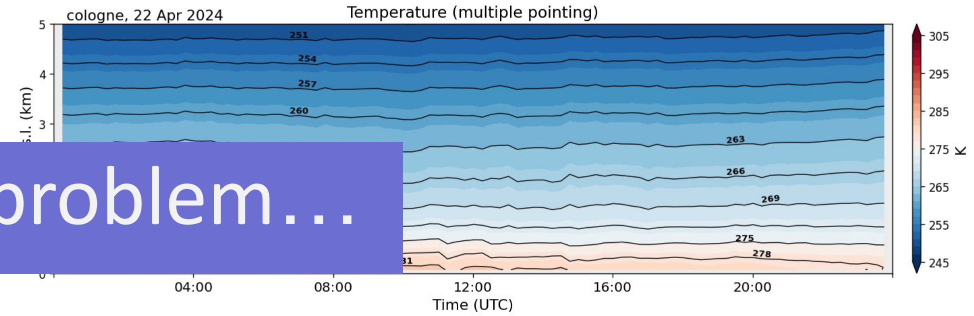
➡ calibration dependent



Level2 data : (atmospheric products)

➡ forward model and retrieval dependent

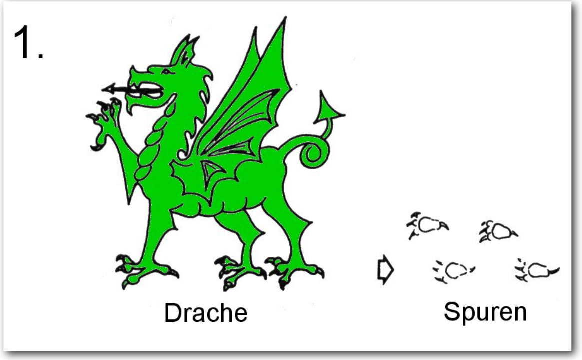




- BUT: we have an (inverse) problem…

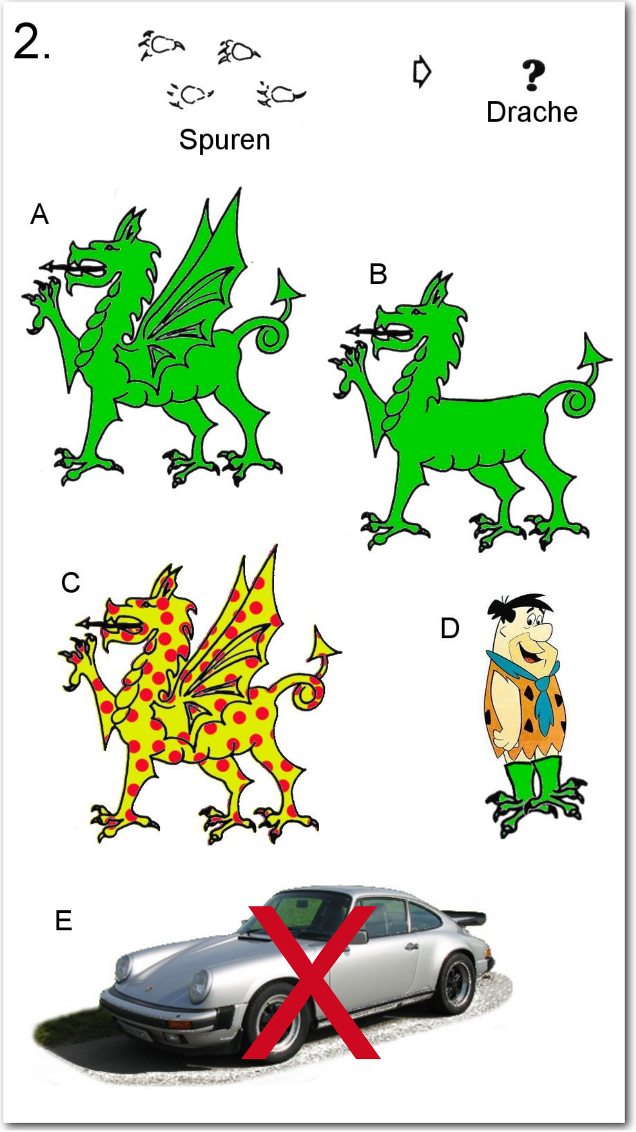
Inverse Problem

Forward problem
Describe dragon‘s track



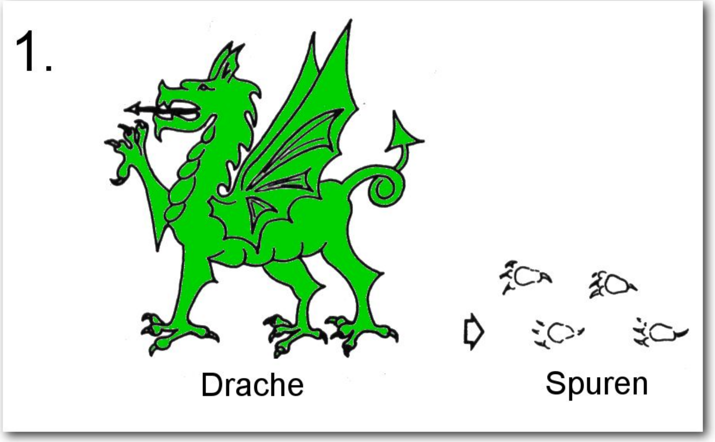
But now: what about the dragon when you only know the track?

Ambiguous correct answers: A, B, C or D ??



Inverse retrieval problem

- Ambiguous solutions to inverse problem



$$y = F(x) + \varepsilon$$

Track = Brightness temperatures

Forward problem = Radiative transfer

Dragon = Atmosphere

Uncertainty of track measurement and F

Retrieval of atmospheric quantities

Inverse modelling of atmosphere is under-determined problem > Recipe for statistical retrieval algorithm

1) Creation of a representative dataset of atmospheric states $\mathbf{x}_j^k$ with j parameters and k states (e.g. from radiosonde profiles)

2) Forward modelling for all states $\mathbf{y}_i = \mathbf{F}(\mathbf{x}_j)$
   → Simulation of **k** hypothetical measurements $\mathbf{y}_i^k$

3) Creation of a model **T*** with free parameters

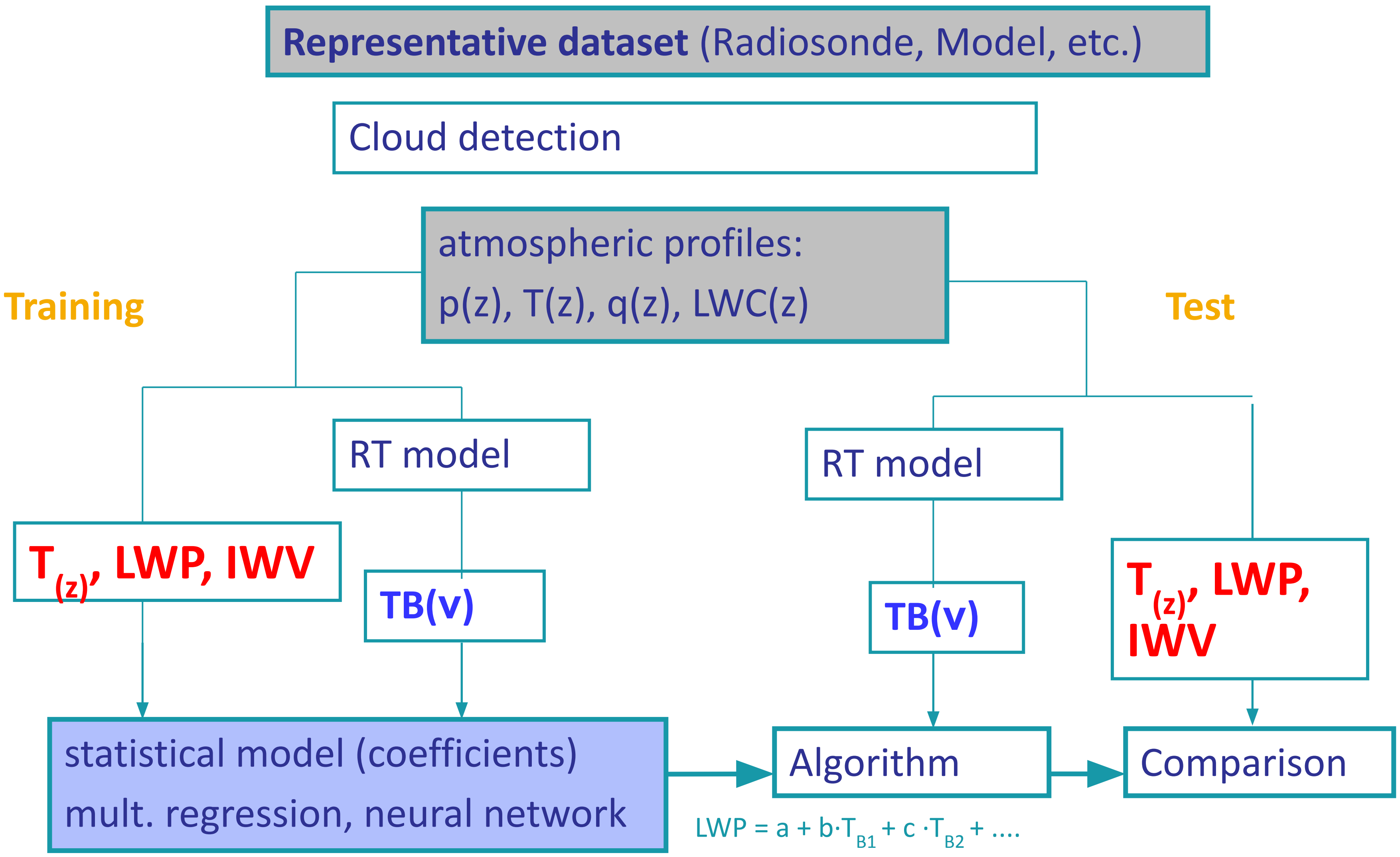
$$\hat{\mathbf{x}}_j = \mathbf{T}^*(\mathbf{y}_i,\ i=1,..,m) \quad j=1,..,n$$

4) Determination of free parameters T* so that

$$\sum_k \left(x_j - T^*(y_i, i=1,..,m)\right)^2 = \sum_k \left(x_j - \hat{x}_j\right)^2 \quad \text{minimal}$$

Truth (x_j) "Retrieval" ($\hat{x}_j$)

Process for developing retrieval algorithms



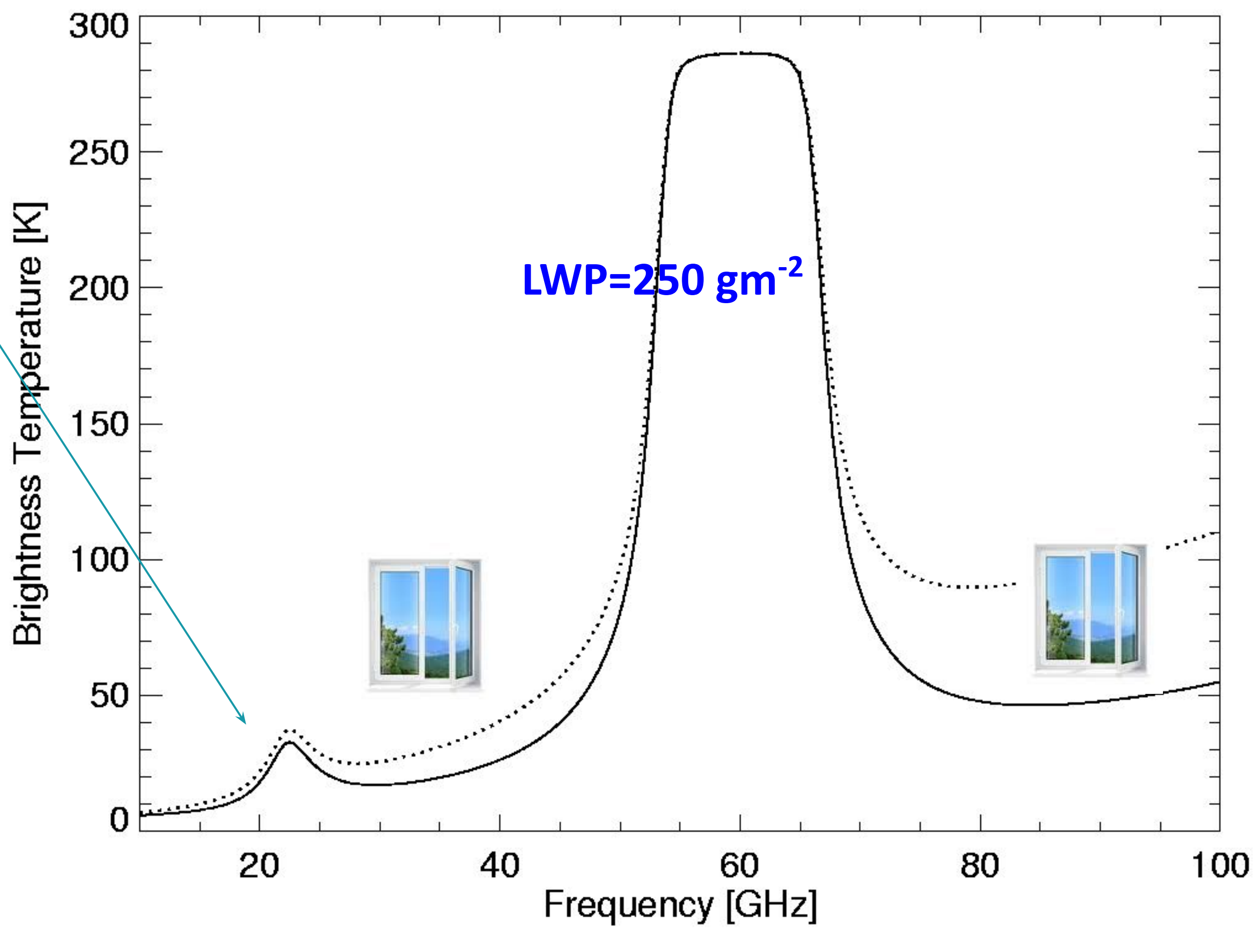
Retrieval of IWV / LWP

TB Amplitude of H_2O line is proportional to IWV

Water vapor leads to a TB increase *mainly* at H_2O line

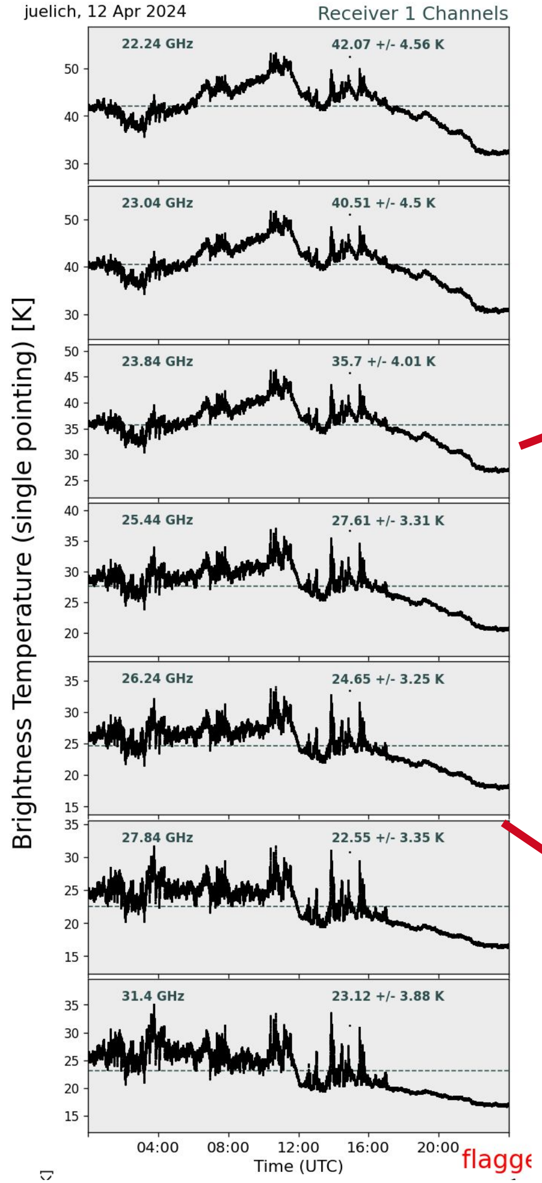
Clouds lead to a TB increase, *mainly* in window channels

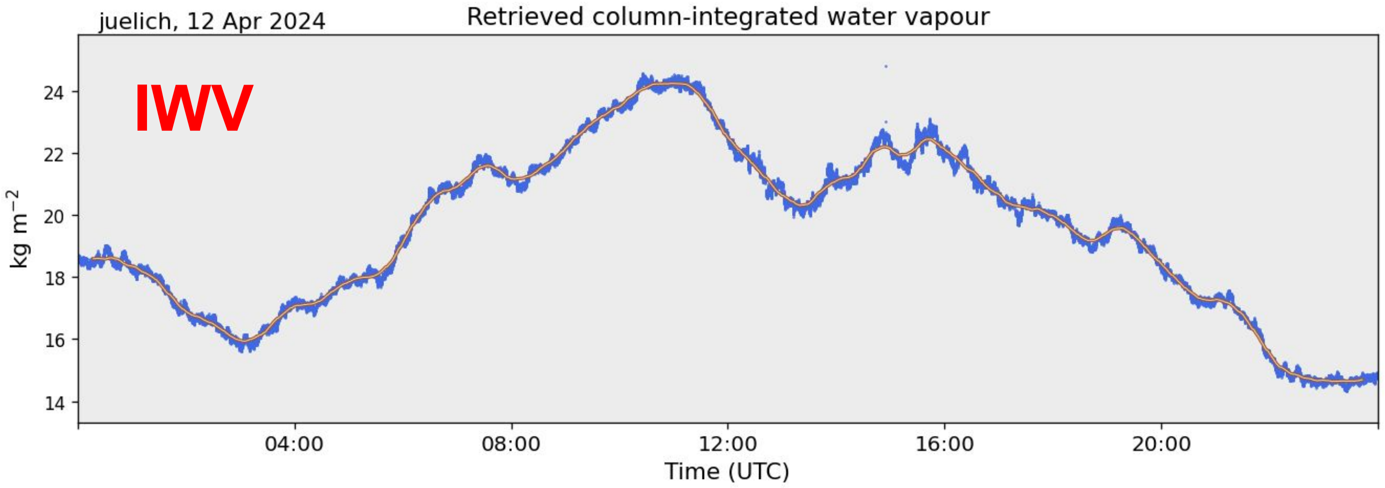
$$IWV = a_1 + b_1 * TB_{23} - c_1 * TB_{31}$$
$$LWP = a_2 - b_2 * TB_{23} + c_2 * TB_{31}$$

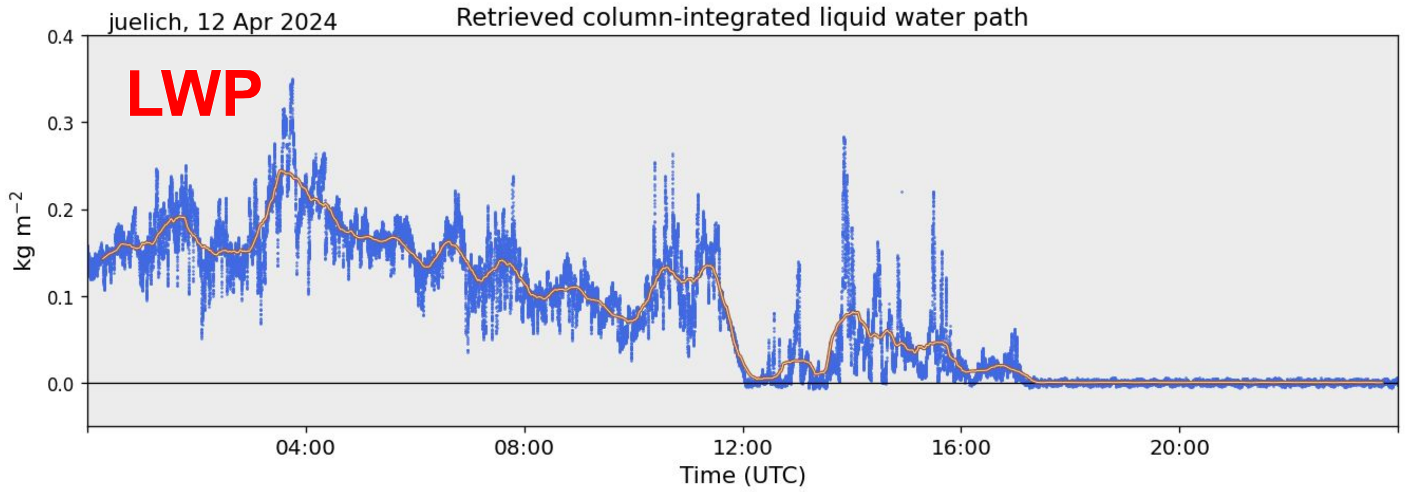


- Minimum 2 frequencies necessary. With 7 frequencies > only slight improvement.
- Adding 89 GHz improves LWP significantly (as well as low IWV)

Retrieval of IWV / LWP

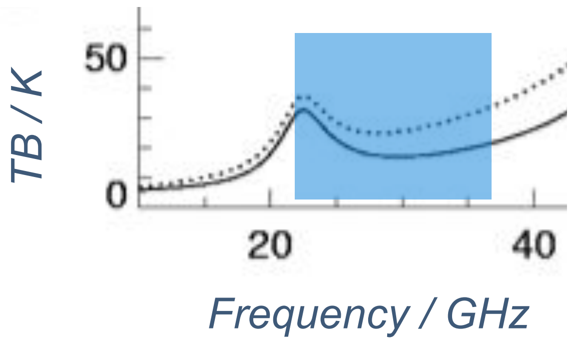


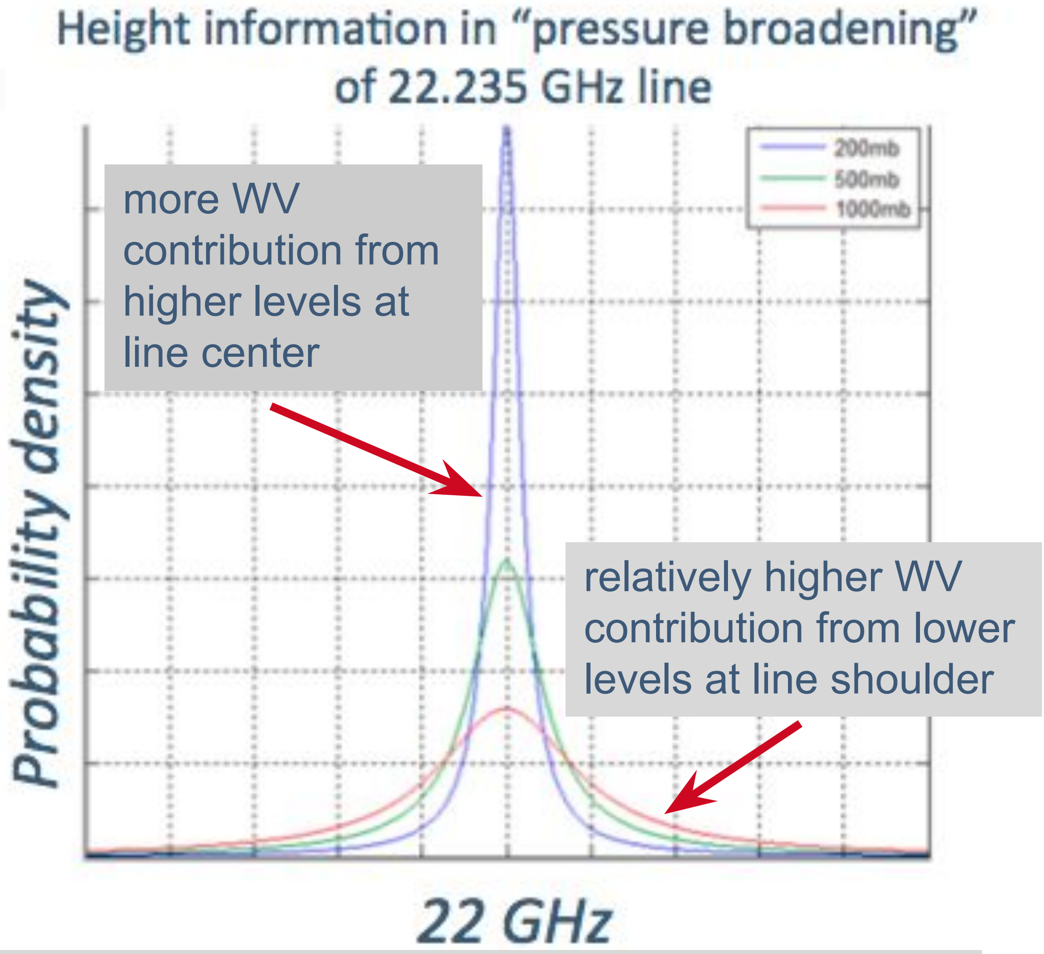




What about humidity profiles ?

TB time series of multiple frequency channels on the right side of the 22 GHz line



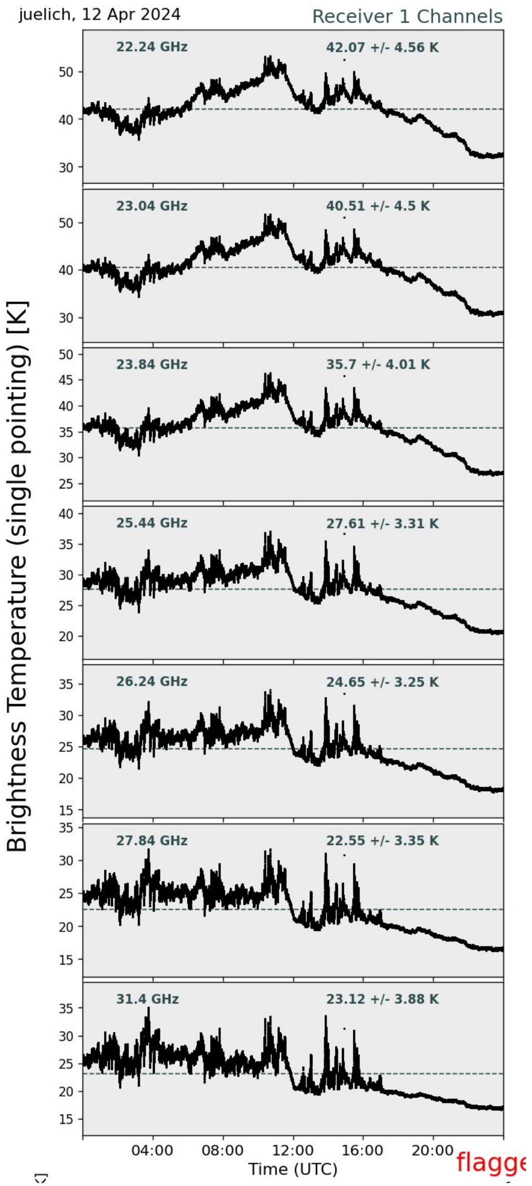


However: contributions in different channels highly correlated

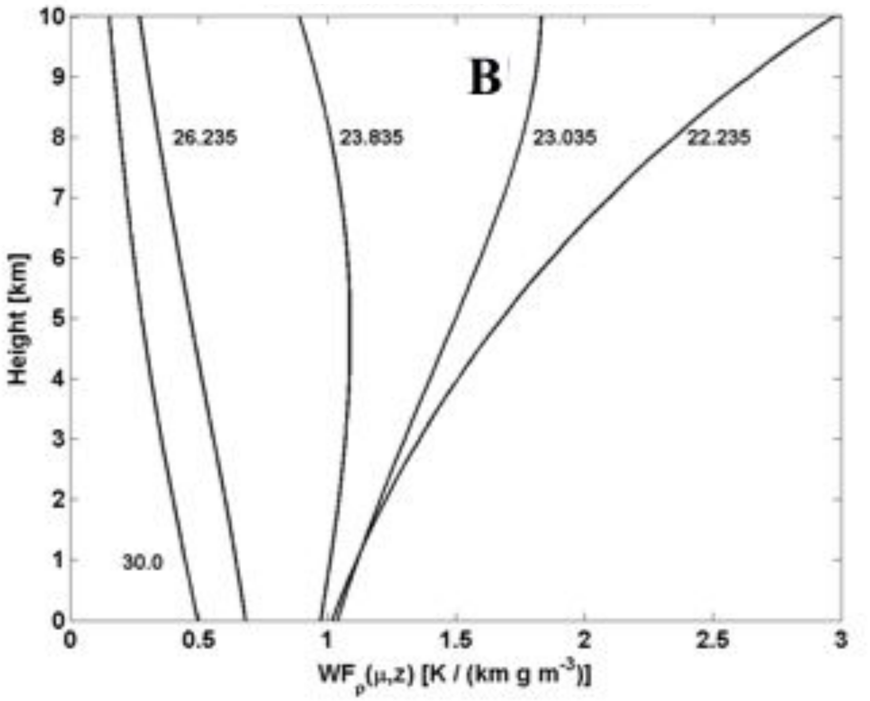
ACTRIS
CCRES

Humidity profiles

Typical: TB time series of 7 frequency channels on the right side of the 22 GHz line

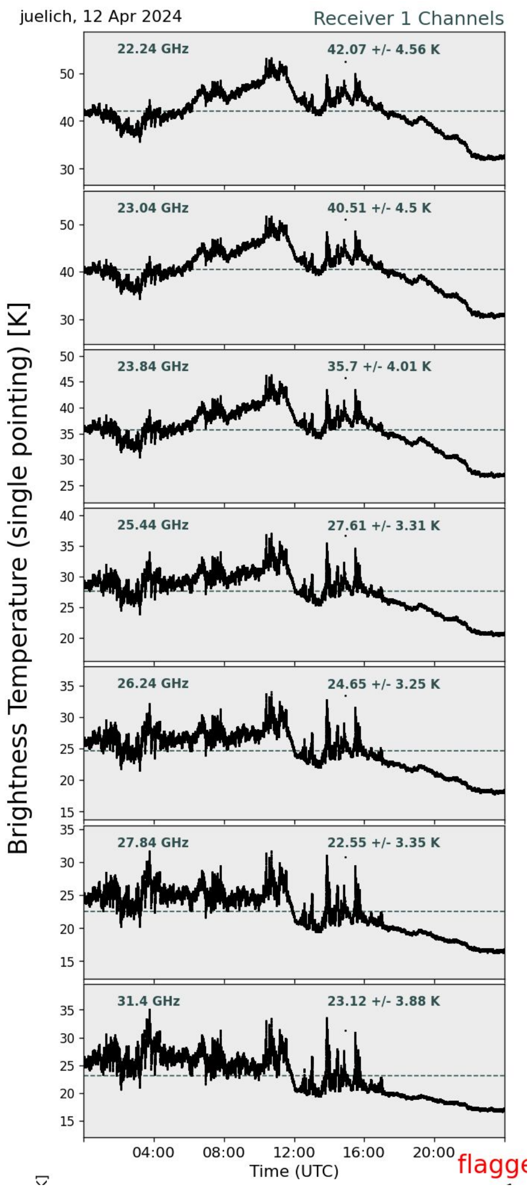


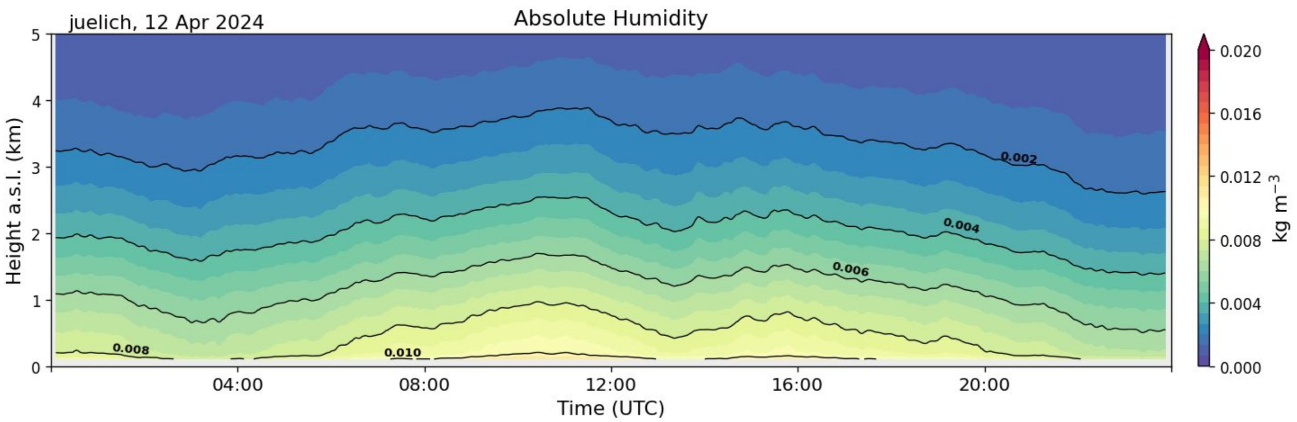
Water Vapor Weighting Functions

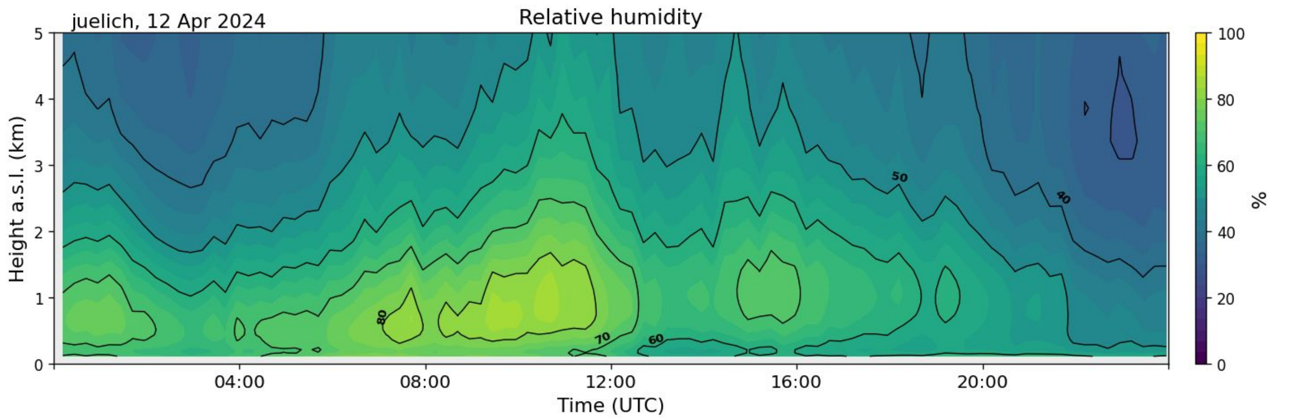


2-3 degrees of freedom for signal

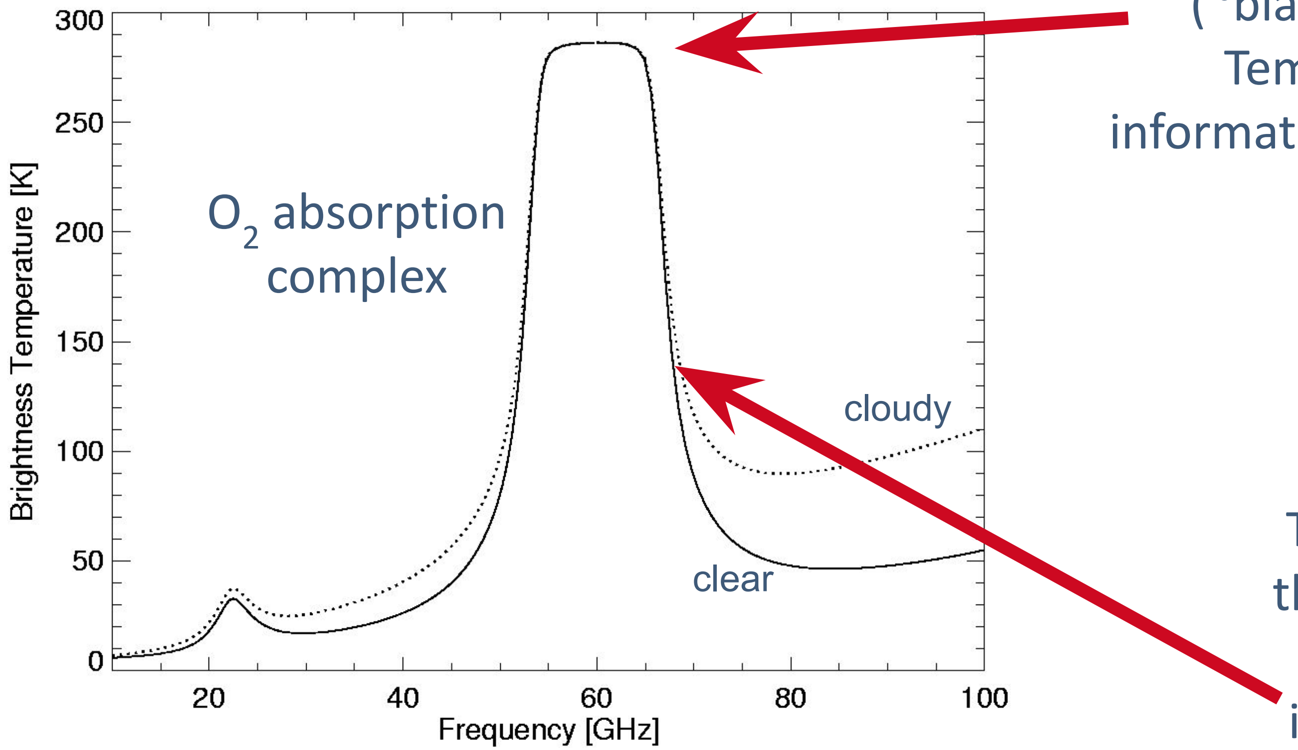
Humidity profiles







Temperature profile retrieval

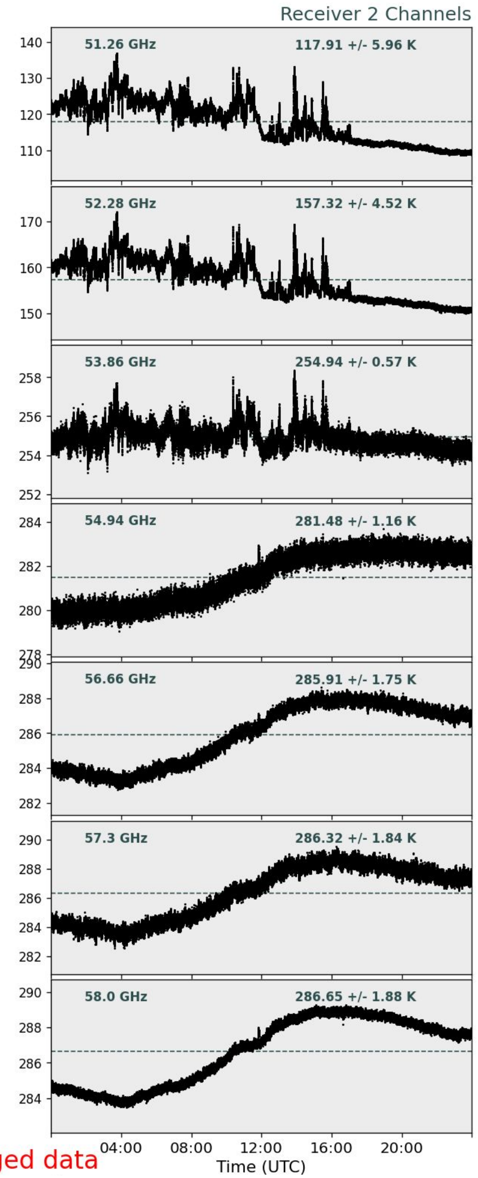


Atmosphere saturated (~black body) Temperature information from lower levels

The further away from the absorption complex center, the more information originates from higher levels in the atmosphere

O_2 has a constant mixing ratio with height TB only a function of temperature and pressure

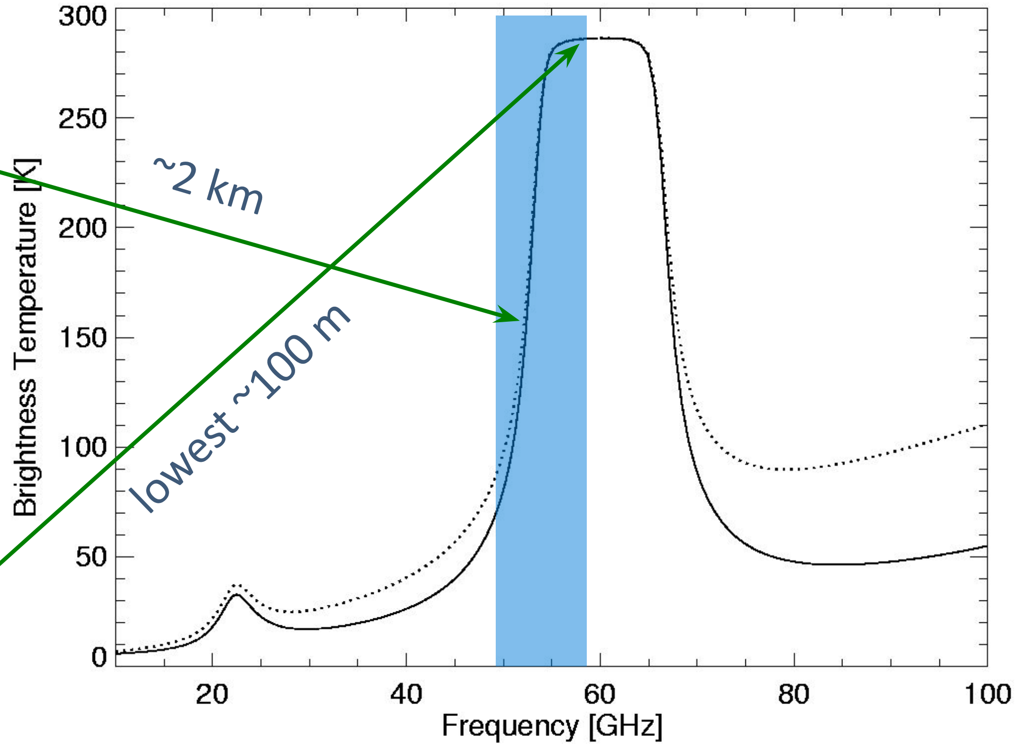
Temperature profile retrieval



TB@ 51 – 58 GHz

~2 km

lowest ~100 m

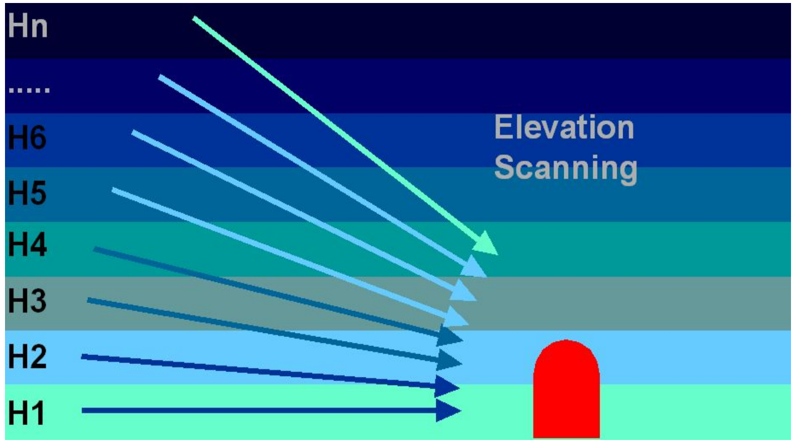


Typical: TB time series of 7 frequency channels on the left hand side of the 60 GHz absorption complex

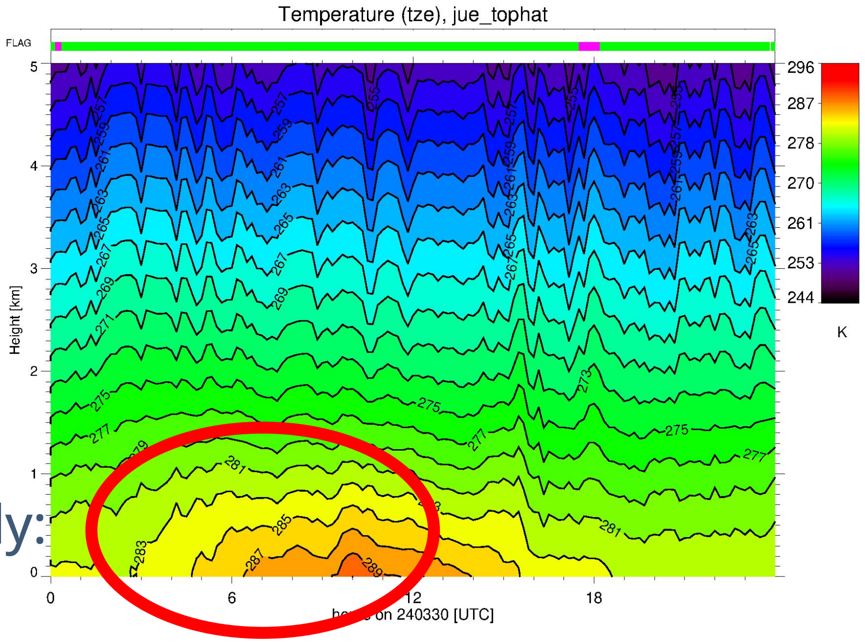
Temperature profile retrieval

additional temperature profile information in optically thick case

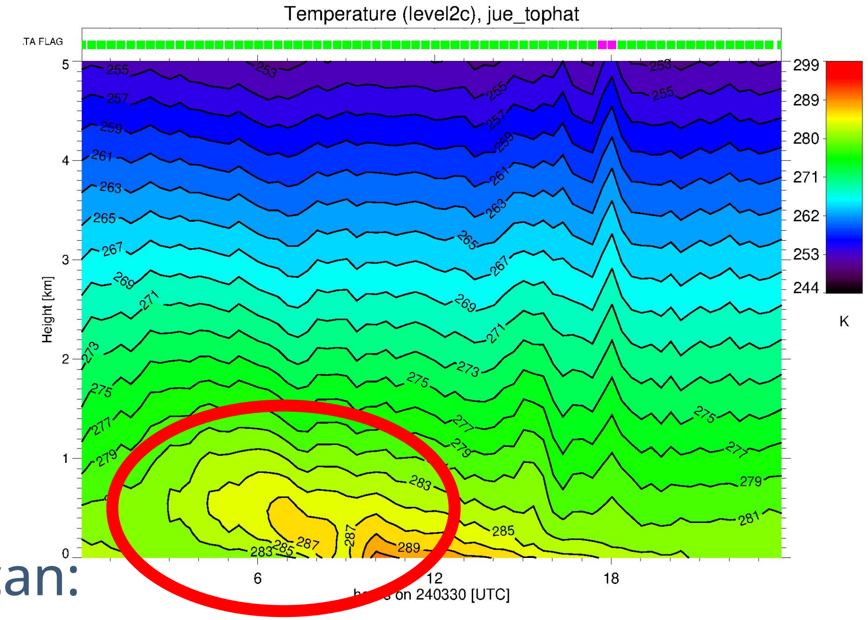
need to assume horizontal homogeneity



Zenith only:



Including elevation scan:

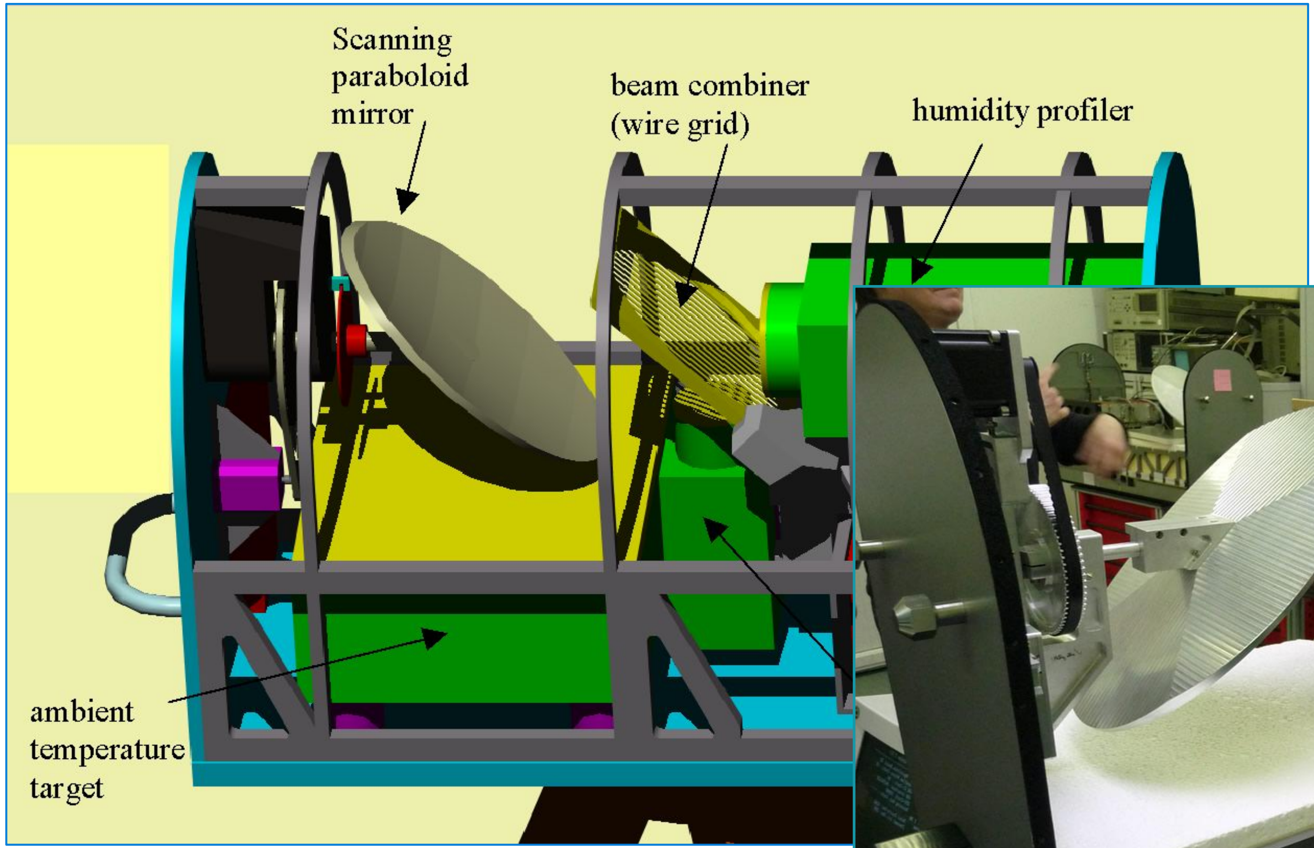


RPG-HATPRO Microwave Radiometer

- Most common instrument in ACTRIS network
- First built in 2004 (Generation 1), since 2016 G5 radiometers
- Main dimensions have not changed
- Technological advances since G1

- Instrument is equipped with
  - Weather station
  - GPS receiver
  - Infrared radiometer (optional)
  - Azimuth drive (optional)
  - Blower/Heater module

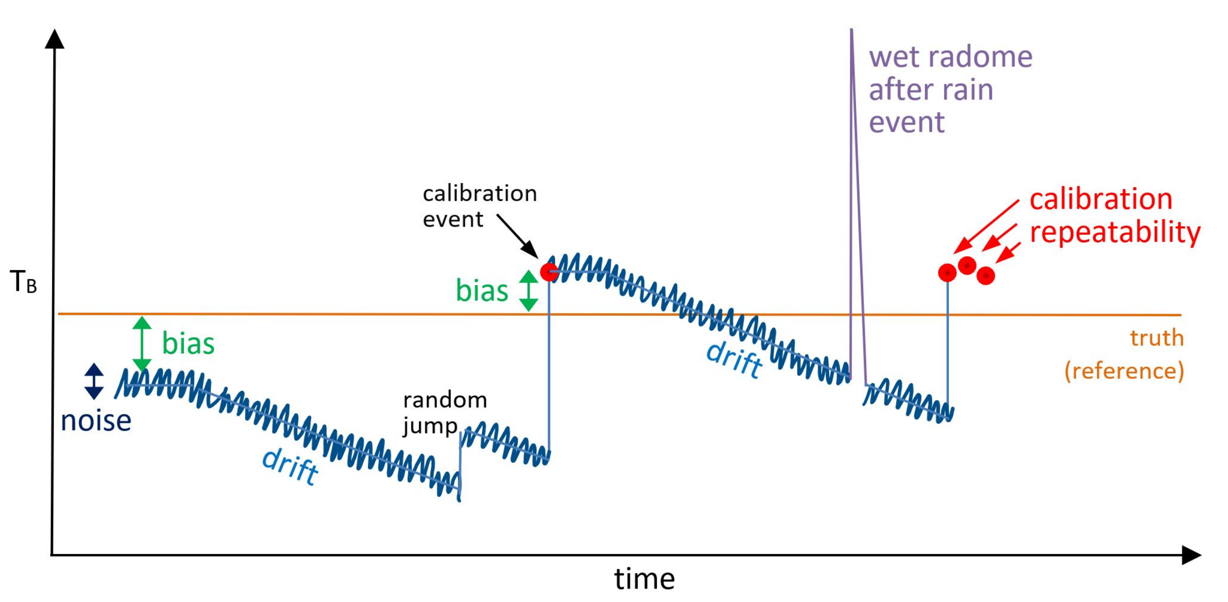
RPG-HATPRO Microwave Radiometer



MWR observation uncertainties

Sources for measurement uncertainties:

- **Random errors**
  - Instrument sensitivity (signal-noise ratio, detection limit)
- **Systematic errors**
  - Instrument stability (drifts in signals)
  - Absolute accuracy
- **Retrieval uncertainties**
  - Non-representative data for retrieval training
  - Measurement process not modelled correctly (noise levels, etc.)
  - Forward model uncertainties

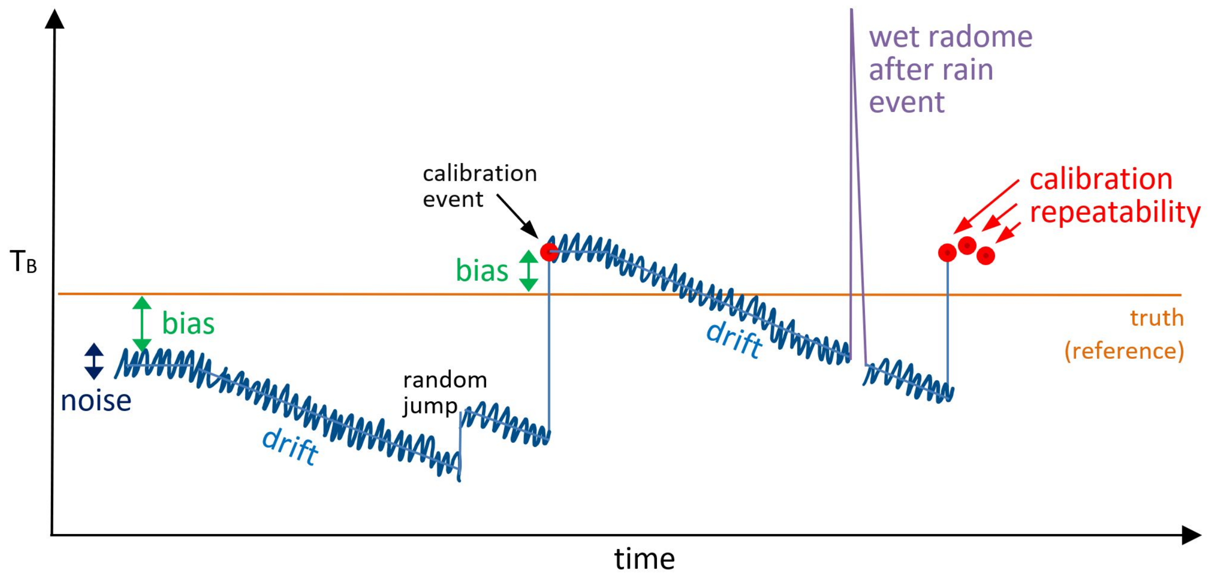


Böck et al., 2025

MWR observation uncertainties

Sources for measurement uncertainties:

- **Random errors**
  - Instrument sensitivity (signal-noise ratio, detection limit)
- **Systematic errors**
  - Instrument stability (drifts in signals)
  - Absolute accuracy
- **Retrieval uncertainties**
  - Non-representative data for retrieval training
  - Measurement process not modelled correctly (noise levels, etc.)
  - Forward model uncertainties



Böck et al., 2025

MWR calibration

- Regular calibration is vital for any microwave radiometer
- Uncalibrated radiometers do not produce any meaningful data
- MWR have several calibration options
  - absolute (using external blackbodies with well-defined temperatures)
  - relative (using secondary standards, such as noise diodes)

- Detected receiver voltage has to be „translated“ into a brightness temperature.
- Relationship has to be determined with a calibration.

$$U_D = G \cdot T_{sys}{}^{\alpha} = G(T_R + T_A)^{\alpha}$$

U_D Detector voltage
T_{sys} System “noise“ temperature
T_R Receiver noise temperature (all instrumental noise sources combined)
T_A antenna temperature (atmospheric source, calibration blackbody)
G Gain [V/K] (proportionality factor)
α Non-linearity factor

Radiometer calibration

- Determination of receiver noise temperature (T_R):

- Challenge: Very small power has to be detected (example: 50 K brightness temperature, 800 MHz bandwidth: power of 10^{-13} W.

- Sensitivity of receiver needs to be high. However, the noise of all receiver components (thermal noise) is considerably high and must not be neglected.

- The sensitivity limit ΔT_B depends directly on T_{sys} (plus bandwidth and integration time)

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

- To reduce noise we use longer integration times at calibrations

- Separation of $T_{sys} = T_R + T_A$ (receiver noise / antenna signal) is not straightforward. The measured voltage is always a combination of both contributions.

Radiometer formula / automatic calibration

$$U_D = G \cdot T_{sys}{}^{\alpha} = G(T_R + T_A)^{\alpha}$$

Unknowns: G (Gain factor),
T_R (system noise = contribution to signal by components),
α (non-linearity factor)

G, and T_{sys} have to be regularly calibrated (minutes to seconds)
For most radiometers, G is updated by looking at a blackbody at ambient temperature or using a noise diode signal (T_N). For HATPRO G5, a stable noise diode is used that switches with a frequency of 50 Hz.

T_{sys} is updated by looking at blackbody targets at ambient temperature (every 5-10 minutes)
The frequency and integration time for automatic calibrations can be determined when defining a measurement (part of MWR SOPs in ACTRIS)

α, and T_N are stable over long-term (months) and are only updated during absolute calibrations

Absolute calibration

- To determine all calibration parameters, two different well-known temperatures (T_C, T_H) are used (Hot/cold method).

- A microwave blackbody on this well-known temperatures needs to fill the whole antenna field of view.
- Due to Planck's law, the blackbody physical temperature and the brightness temperature will be the same.

- The cold calibration point is usually reached by an absorber target filled with liquid nitrogen, the hot target is located in the interior of the instrument.

- For a linear receiver we can write:

$$U_C = (T_C + T_R) \cdot G$$

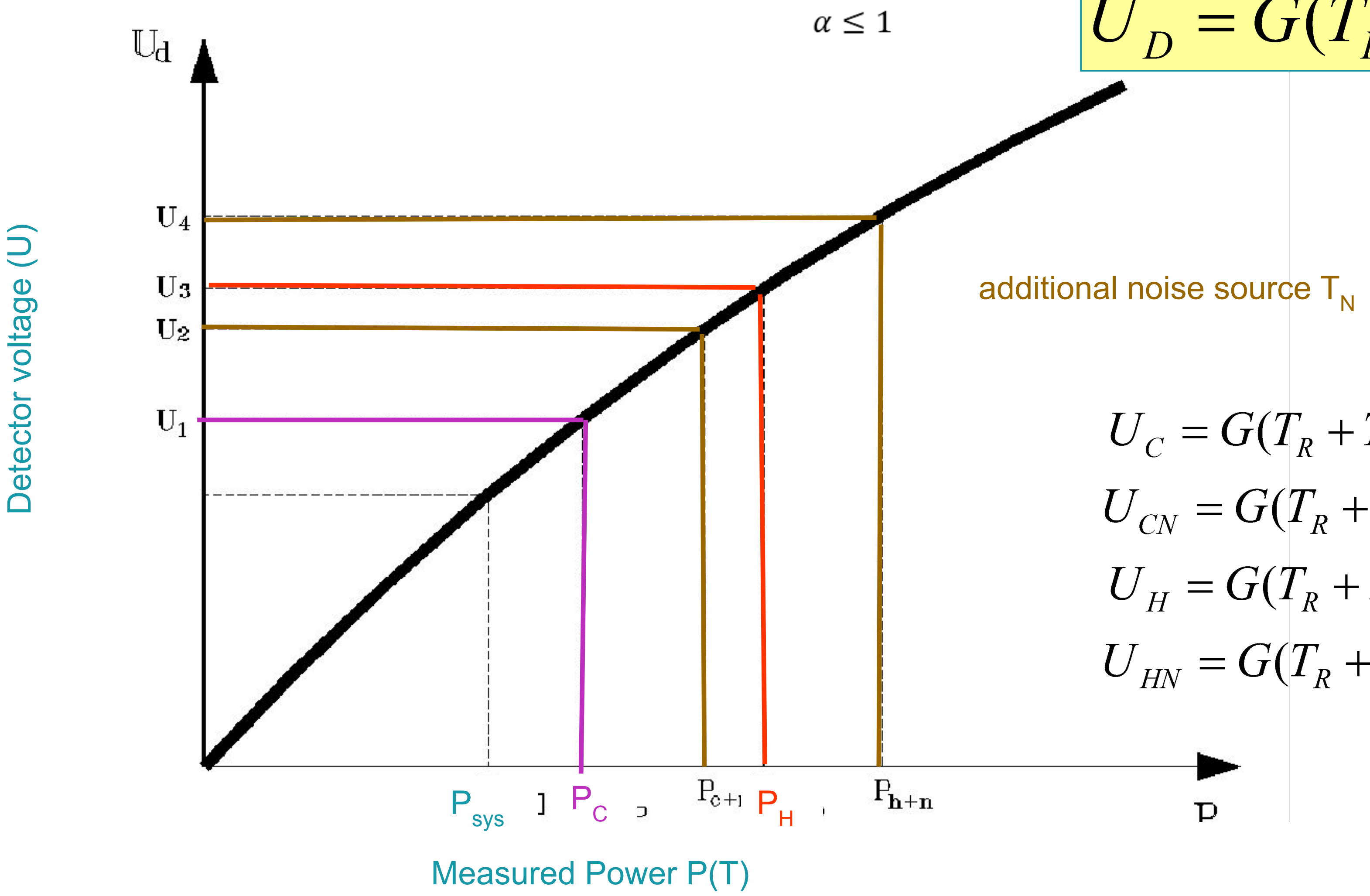
$$U_H = (T_H + T_R) \cdot G$$

Absolute calibration

ACTRIS
CCRES

Reality: Non-linear receiver

$$U_D = G(T_R + T_A)^{\alpha}$$



$$U_C = G(T_R + T_C)^{\alpha}$$

$$U_{CN} = G(T_R + T_C + T_N)^{\alpha}$$

$$U_H = G(T_R + T_H)^{\alpha}$$

$$U_{HN} = G(T_R + T_H + T_N)^{\alpha}$$

Performing absolute calibration

- Absolute calibrations using liquid nitrogen (LN_2) have to be performed every 6 months or after relocation of the instrument
- If possible, perform calibrations at low relative humidity conditions (RH < 70%) to reduce the likelyhood of condensation
- Before and after a calibration take a short measurement sample at cold load in order to estimate the drift/offset since the last calibration
- Do not refill liquid nitrogen too often, in order to avoid oxygen to be mixed into LN_2 > causes change in boiling temperature and a wrong calibration. Same is valid for using non-pure LN_2

ACTRIS CCRES

HATPRO calibration strategy in ACTRIS

- Common standards for automatic calibration depending on instrument type and generation (MWR SOPs)
- Absolute calibration to be performed every 6 months
- Continuous performance monitoring at ACTRIS data centre
  - housekeeping parameters
  - calibration log-files
  - O-B statistics with model
  - spectral consistency checks

may determine and change calibration intervals

- HATPRO software provides with covariances and log-files for calibration and performance monitoring
- Current generation of calibration targets for HATPRO (since 2016) allows much more accurate calibration than before > new further developments at RPG
- PT-V2 target (since 2021) facilitates calibration handling (less LN2 needed, no turning of target necessary)
- Tipping-curve calibration is currently not considered in ACTRIS

HATPRO observation and calibration SOPs

ACTRIS CCRES

- SOP (Standard Operation Procedure) document for MWR includes mandatory and suggested measurement and calibration cycles
  - Standard mode: performing zenith observations interrupted by elevation scans for T-profiles every 15-30 min
  - Optional azimuth scans
  - At least 50% vertical observations for all CCRES instruments necessary
  - Automatic calibration settings
  - Datasets to store

- Special document on performing LN2 calibrations is available

- Documents and calibration guidelines can be found at the ACTRIS website: https://actris.eu/topical-centre/ccres/operation-support-ccres-nf-and-users

Practical exercises on LN2 calibration

HATPRO-G5 instrument

- Radome change (1st slot)
- Calibration
- Use of radiosondes of Munich-Oberschleissheim (DWD) for comparison

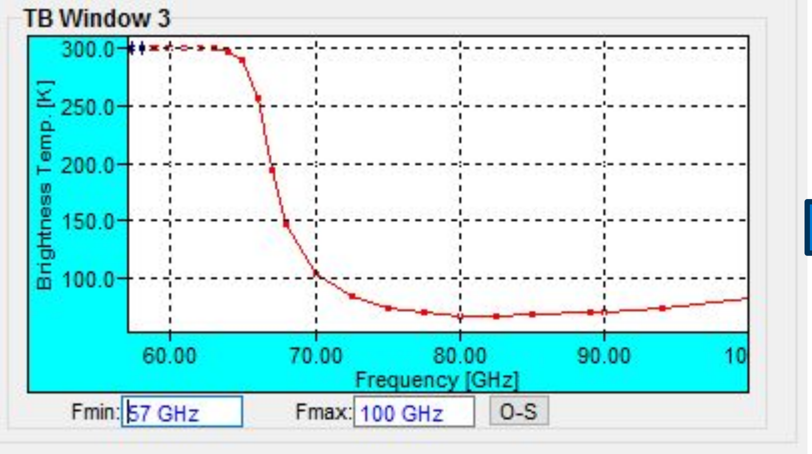
- Calibration transfer to RPG cloud radar (2nd slot)

Evaluation:

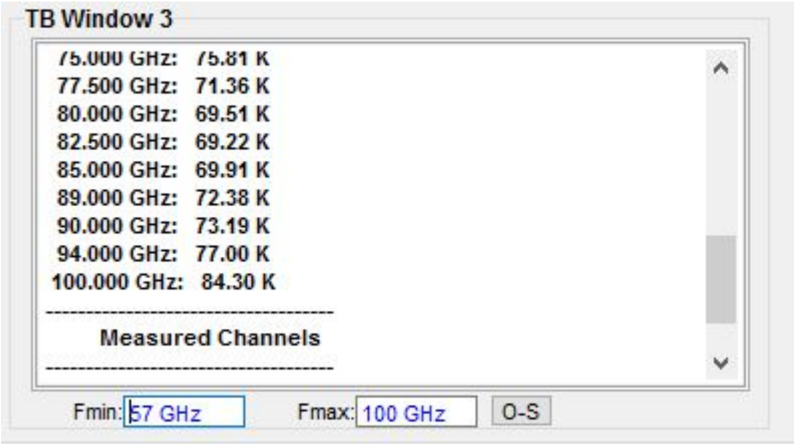
- Comparison of brightness temperatures before and after calibration on LN2
- Forward modelling of radiosonde > comparison with observations

Calibration of RPG cloud radar

- Passive channel (=receiver) of RPG cloud radars (W/Ka) can be calibrated using HATPRO brightness temperatures as cold target in case of clear sky conditions
- Warm target: Absorber covers the antenna
- Spectral retrieval (SPC) provides extrapolated brightness temperatures from HATPRO observations
- Best performed directly after HATPRO absolute calibration
- Ka-Band passive channel = 31.4 GHz (same as Channel 7 for HATPRO)
- W-Band passive channel = 89 GHz (extrapolation from spectral observations)



Double click on TB spectrum provides channel values



ACTRIS CCRES

Thank you !