Microwave Radiometer Retrievals

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with contributions from Nico Cimini, Susanne Crewell, Harald Czekala, Thomas Rose,..

Ground-based profiling networks for improving weather forecasts
(COST ES1303 Training School)
EMS Workshop, 3 September 2017, Dublin

What "products" can we expect from MWR?

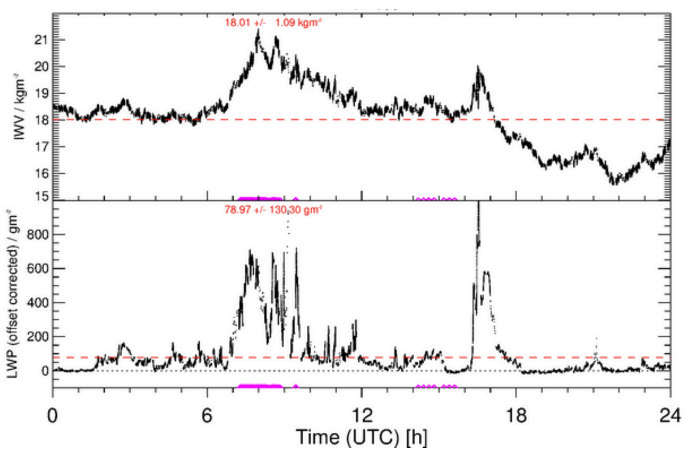
path-integrated **cloud liquid water**

(most reliable method overall)

continuous data in all-sky conditions: resolution of seconds to minutes

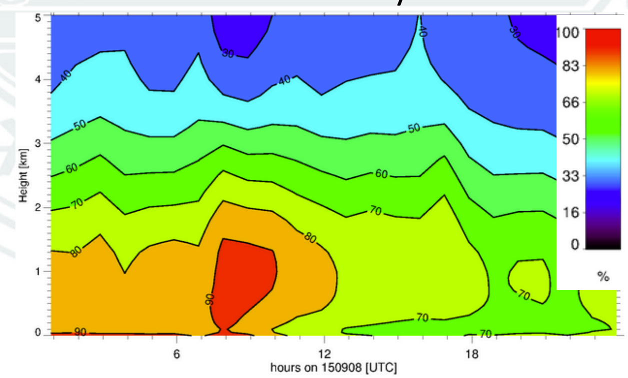
temperature (T) profile of the PBL, low resolution profile above

Measurement focus: PBL

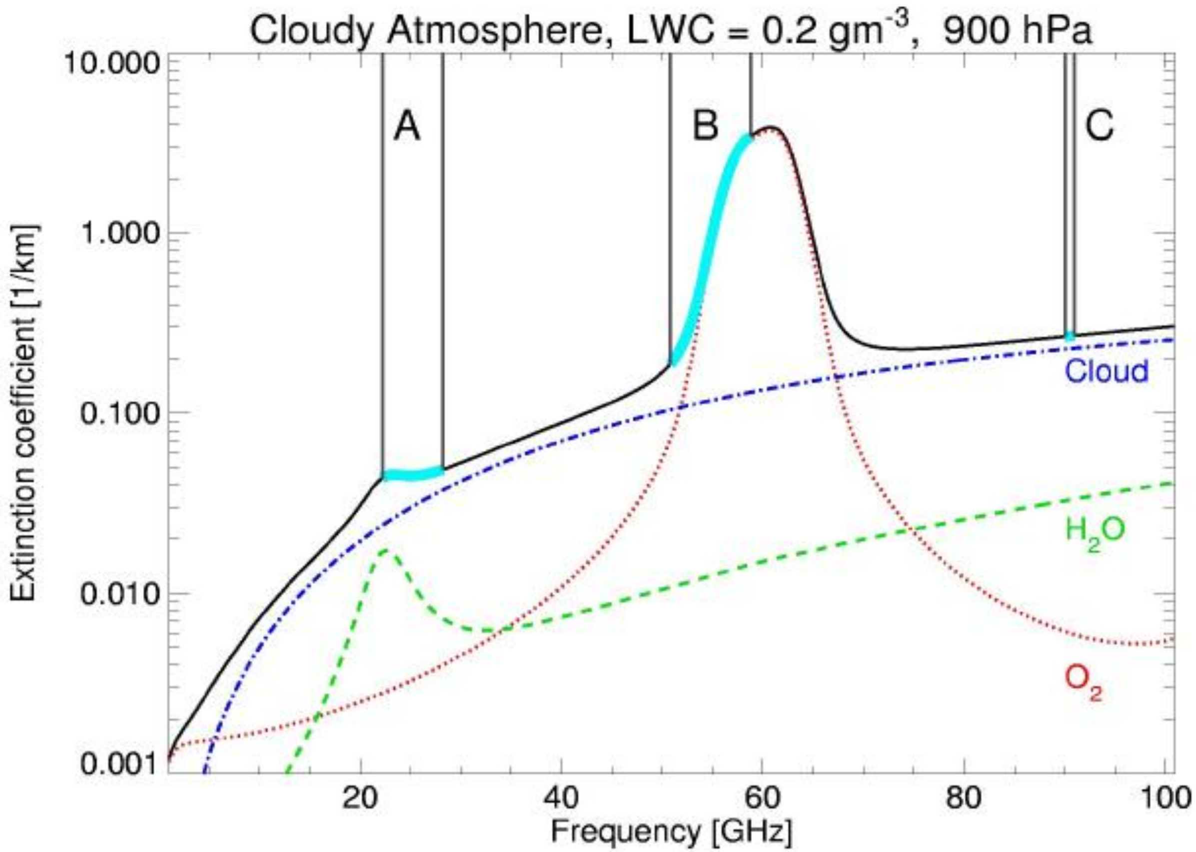


low resolution **water vapor (H) profile**, but excellent path-integrated values

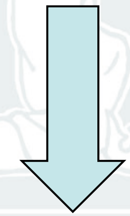
rel. humidity



Information from atmospheric thermal emission



Microwave region:
Extinction = Absorption

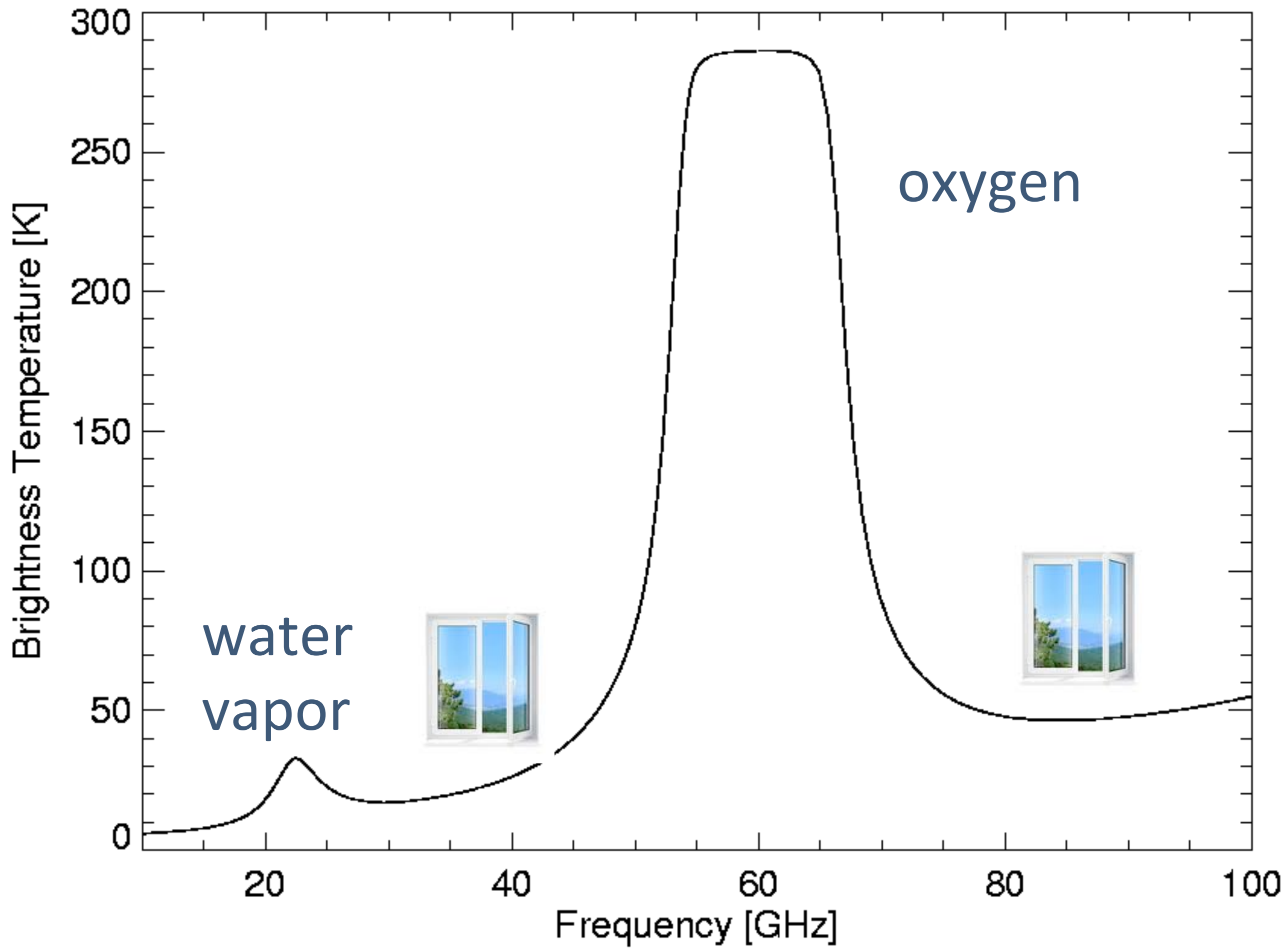


Kirchhoff's law: absorption is directly proportional to emission (LTE)

→ Brightness temperature spectrum

Microwave TB spectrum

standard atmosphere



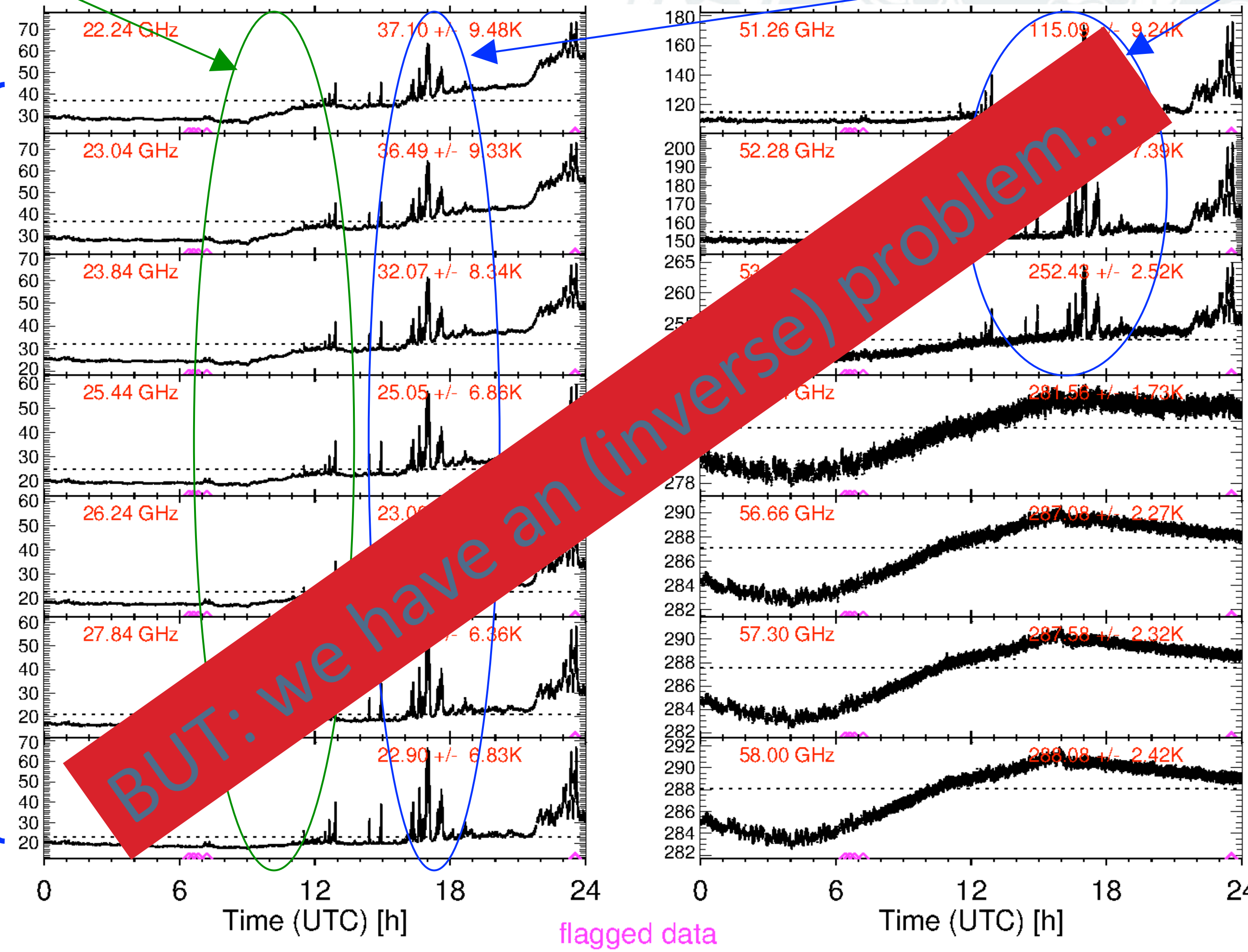
MWR Measurements at JOYCE

11 June 2013

water vapor signal is strongest at 22 GHz line center

cloud liquid signal increases strongly with frequency

TB@ 22 – 31 GHz



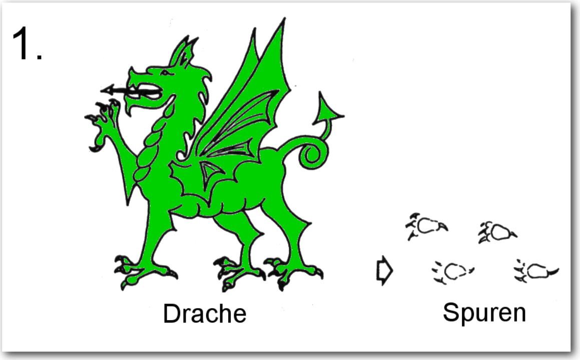
TB@ 51 – 58 GHz

strongly temperature dependent

Inverse Problem I

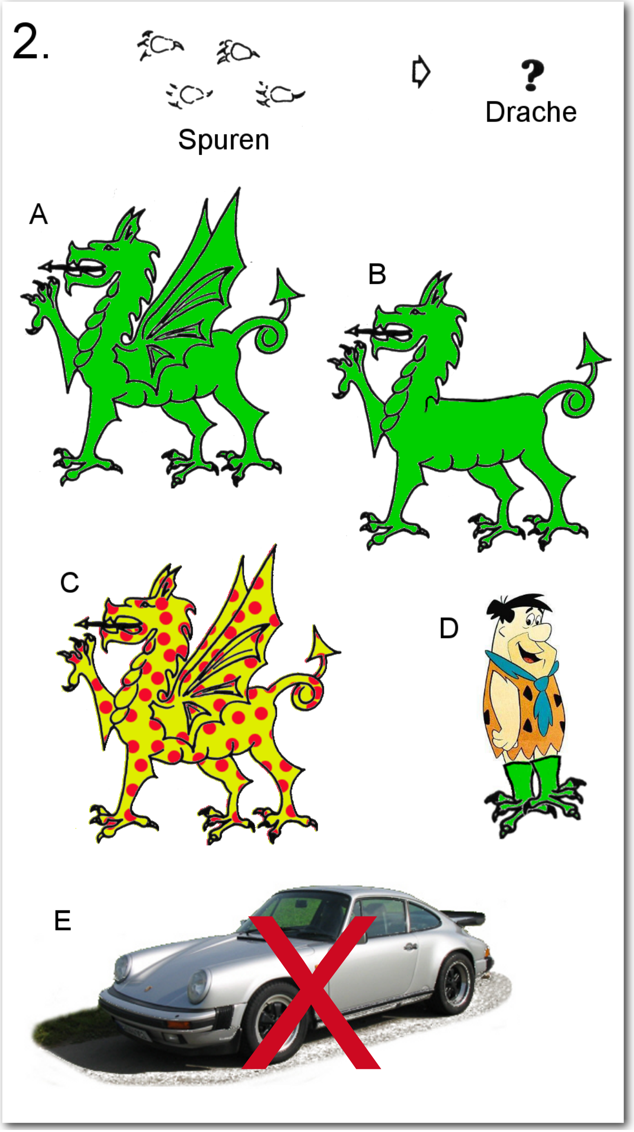
Forward problem

Describe dragon‘s track



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

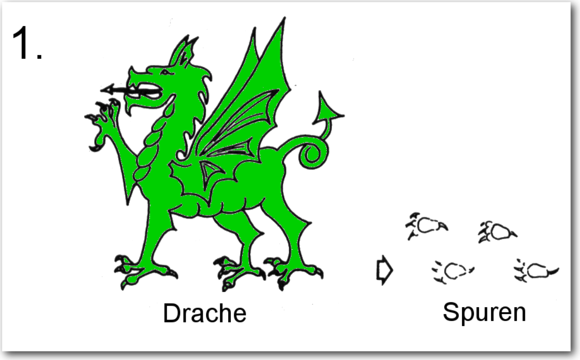
Ambiguous correct answers: A, B, C or D ??



Bernhard Mayer, LMU München

Inverse Problem II

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



Track = Brightness temperatures

Forward problem = Radiative transfer

Dragon = Atmosphere

Uncertainty of track measurement and F

So: what to do if the answers to our measurements are ambiguous?

Retrieve only a limited number of parameters

$$IWV = \int_{z=0}^{z=TOA} \rho_{WV}\, dz$$

Integrated Water Vapour (IWV)

$$LWP = \int_{z=0}^{z=TOA} \rho_{liquid}\, dz$$

Liquid Water Path (LWP)

→ both integrated column amounts

10 kg m^{-2} correspond to a liquid column of 1cm

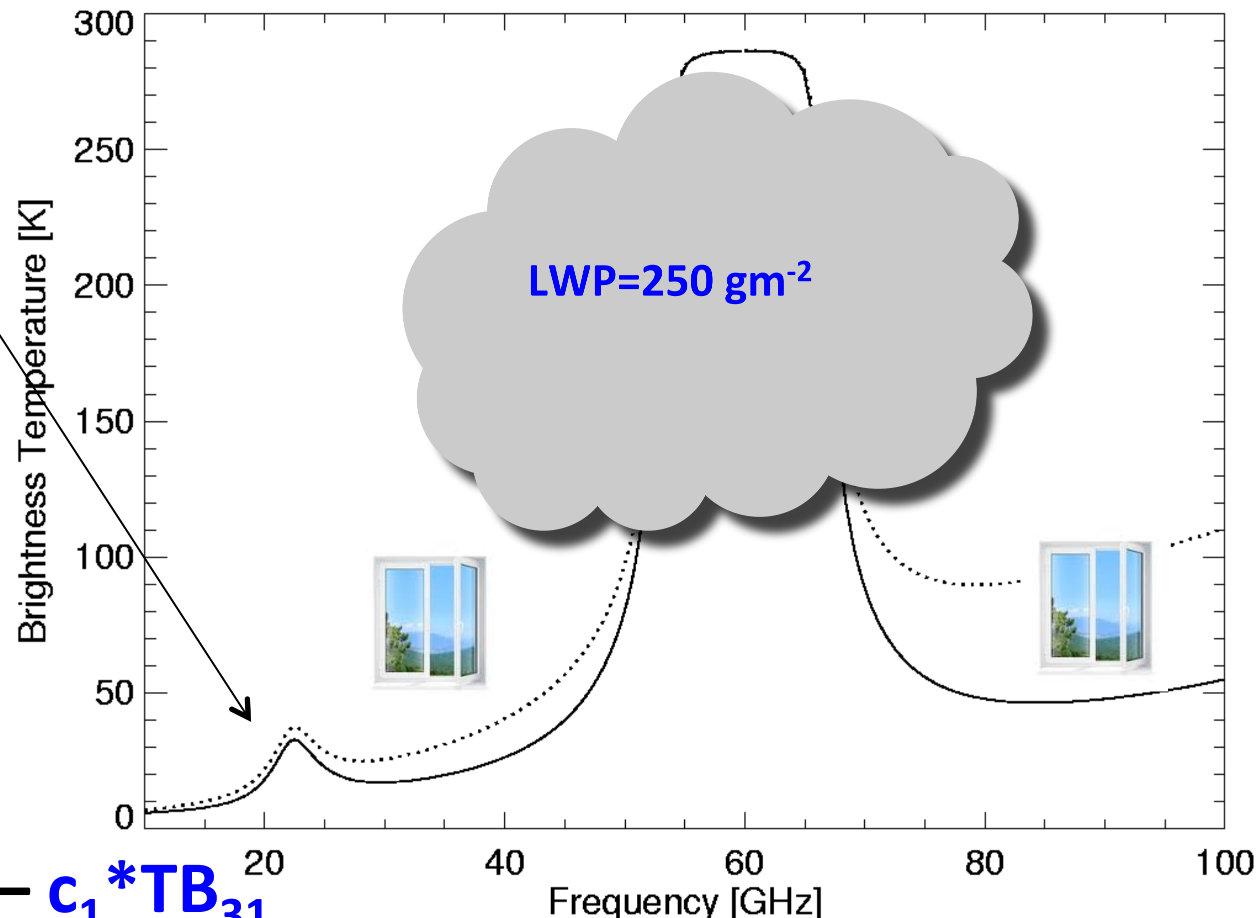
Retrieval of IWV and LWP

standard atmosphere

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



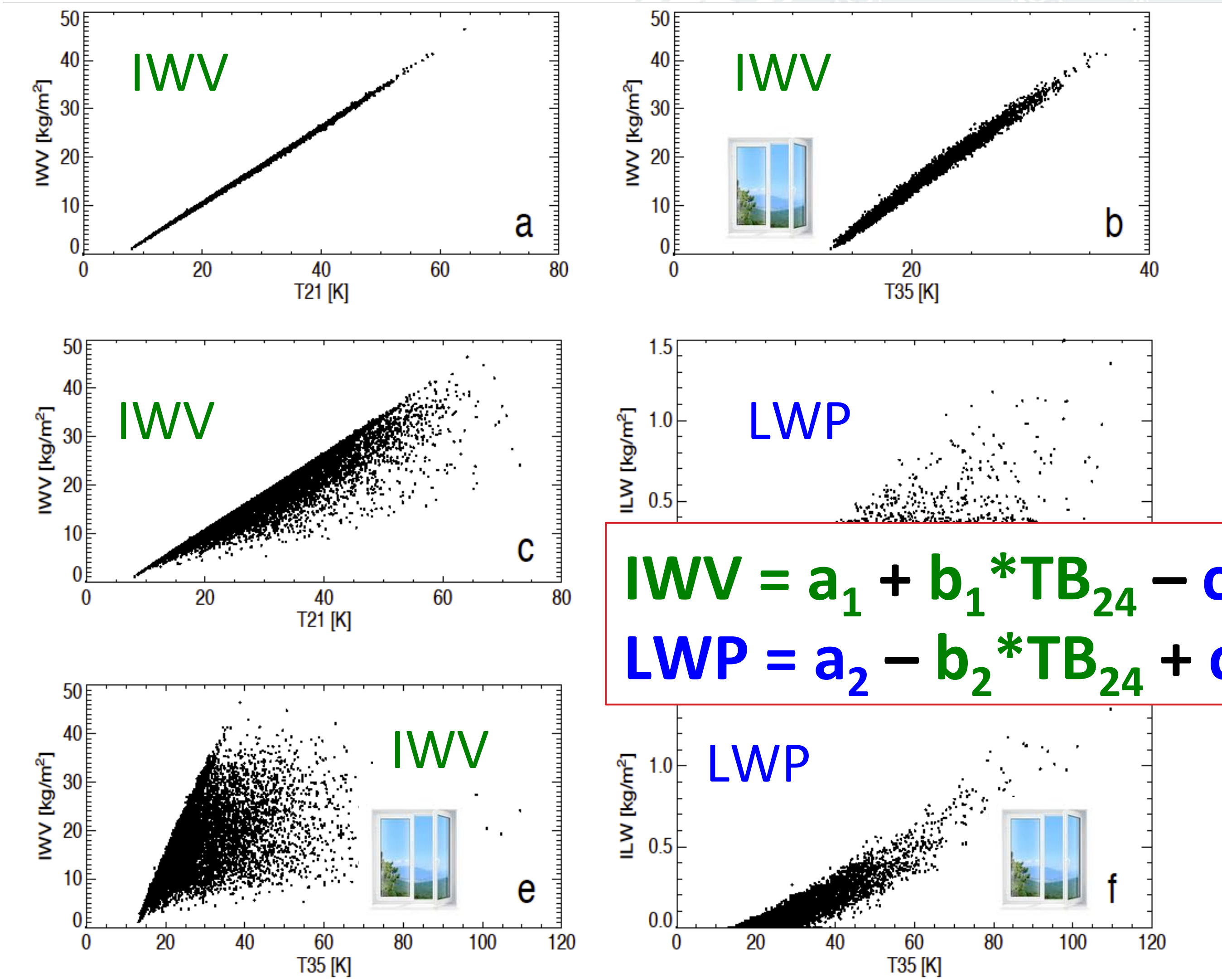
$$IWV = a_1 + b_1 * TB_{24} - c_1 * TB_{31}$$

$$LWP = a_2 - b_2 * TB_{24} + c_2 * TB_{31}$$

Statistical correlations TB vs. IWV/LWP

clear sky

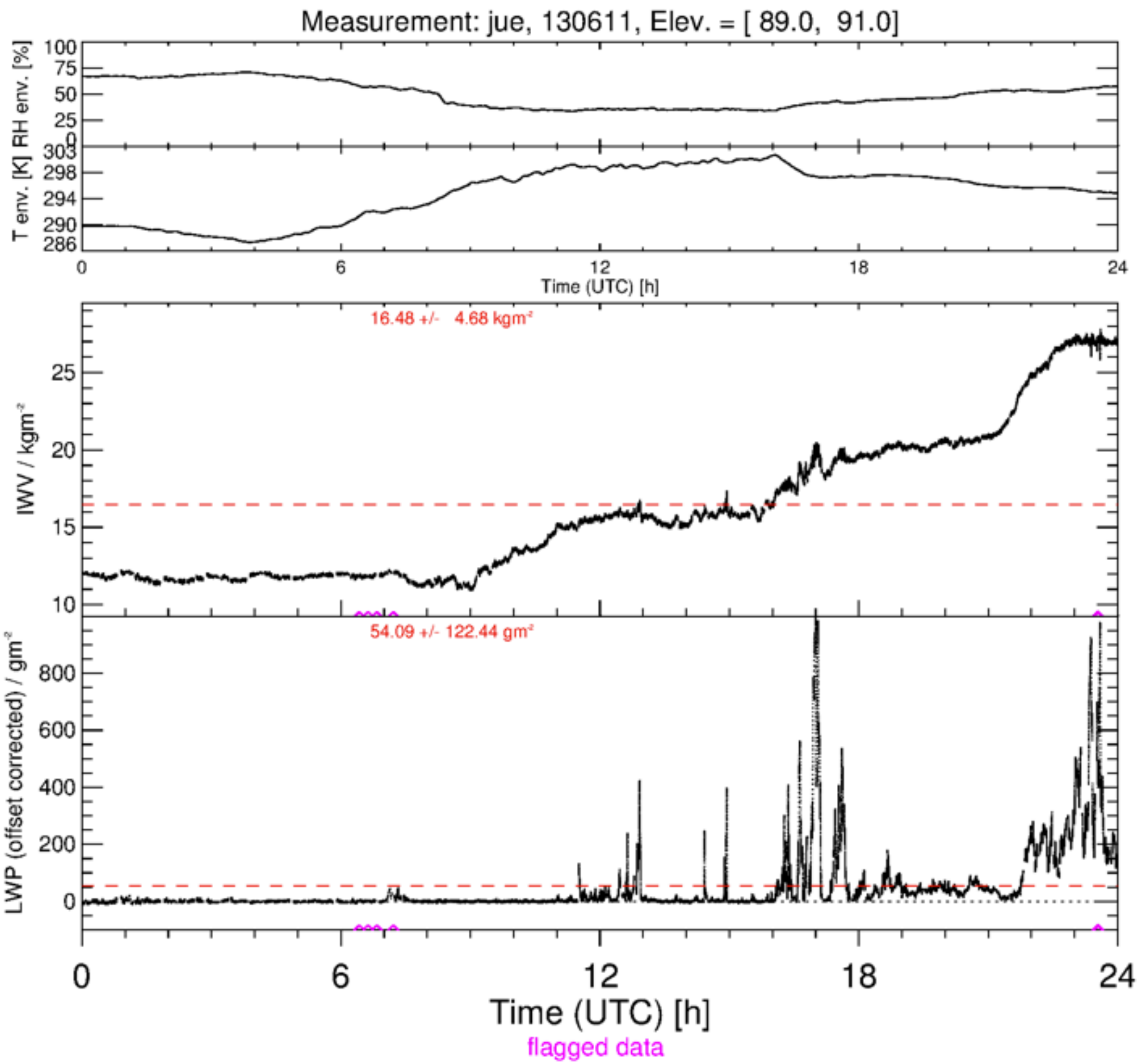
cloudy



$$\mathrm{IWV} = a_1 + b_1 {*} \mathrm{TB}_{24} - c_1 {*} \mathrm{TB}_{31}$$

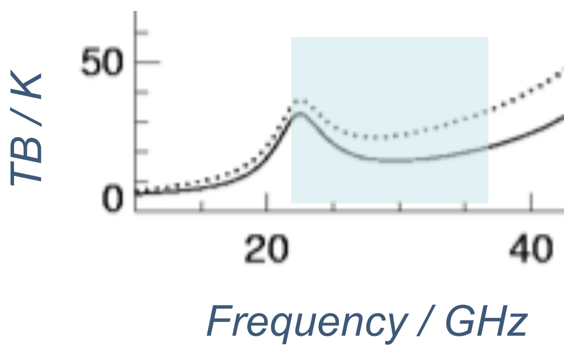
$$\mathrm{LWP} = a_2 - b_2 {*} \mathrm{TB}_{24} + c_2 {*} \mathrm{TB}_{31}$$

IWV & LWP Retrieval

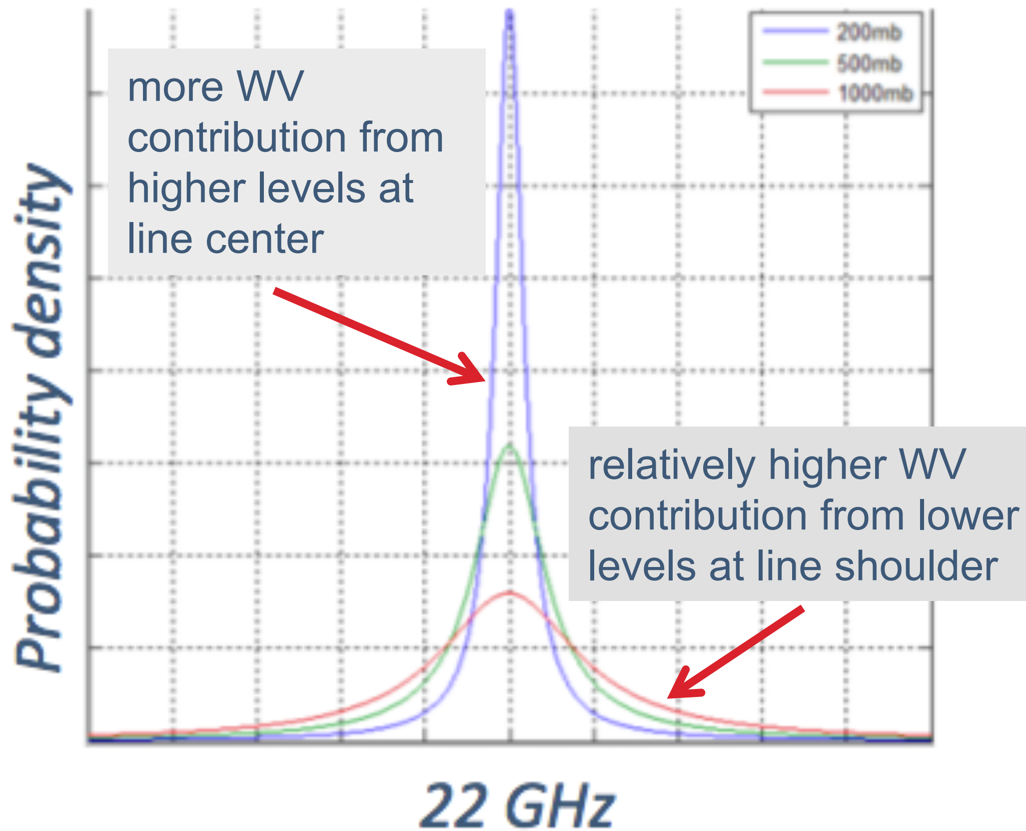


What about humidity profiles?

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



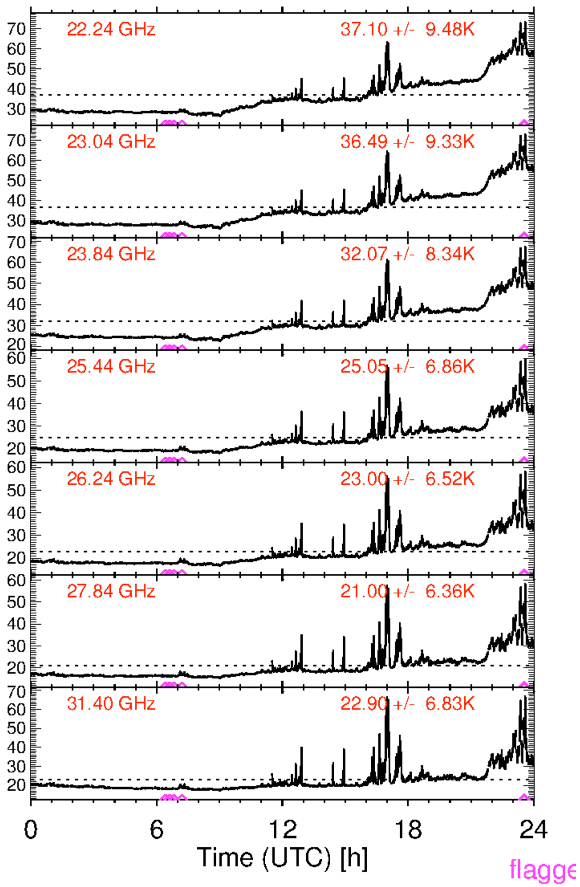
Height information in "pressure broadening" of 22.235 GHz line



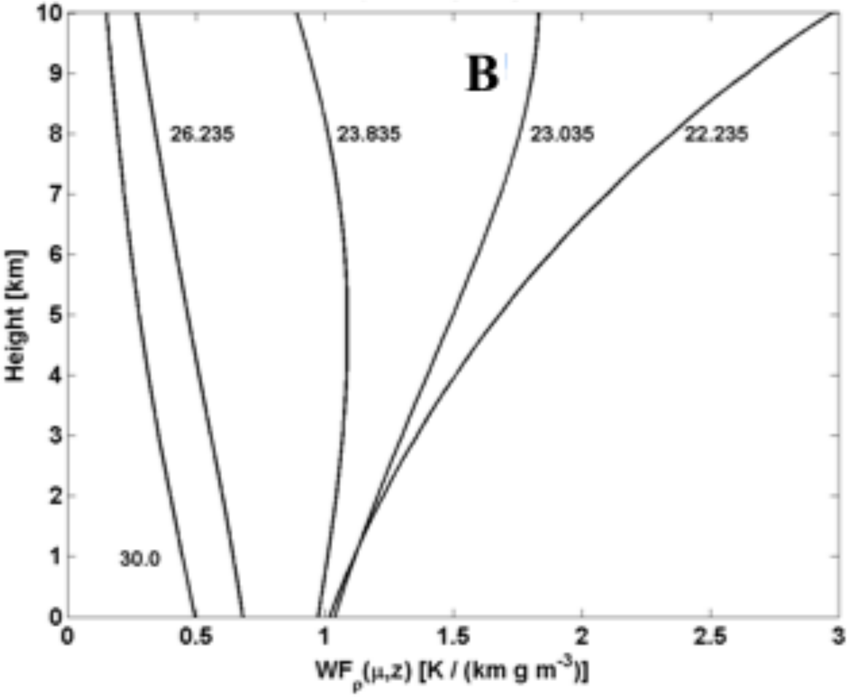
However: contributions in different channels highly correlated

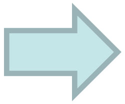
What about humidity profiles?

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



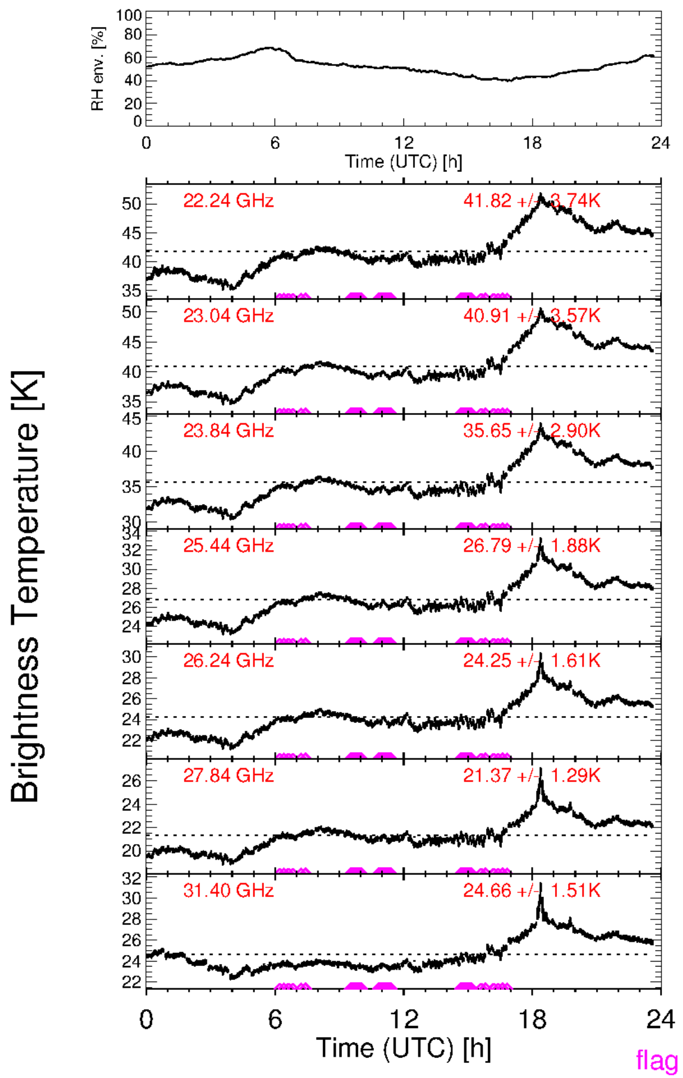
Water Vapor Weighting Functions

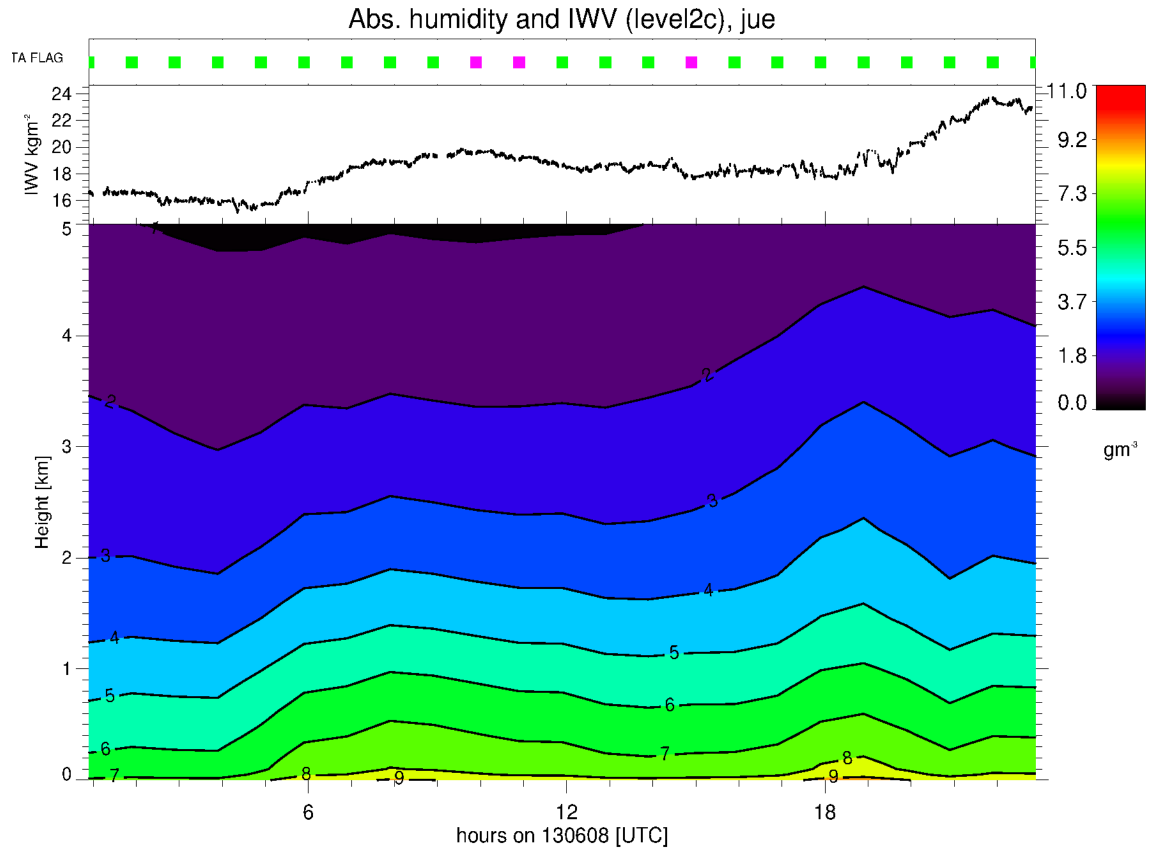




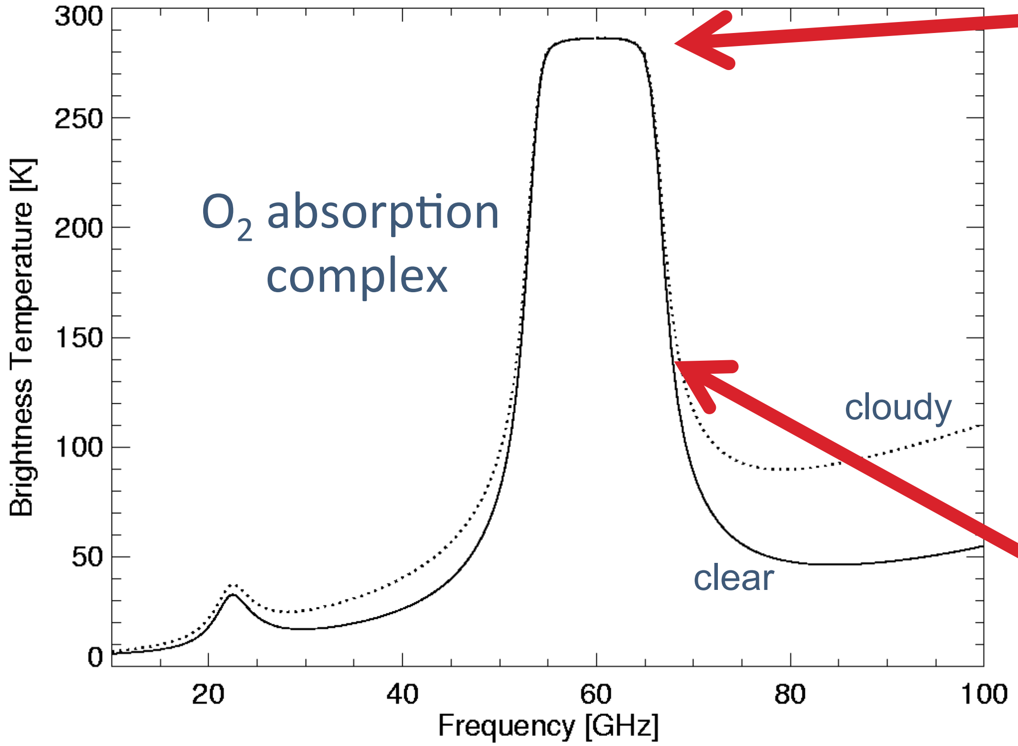
2-3 degrees of freedom for signal

Example Humidity Profile





Temperature Profile Retrieval

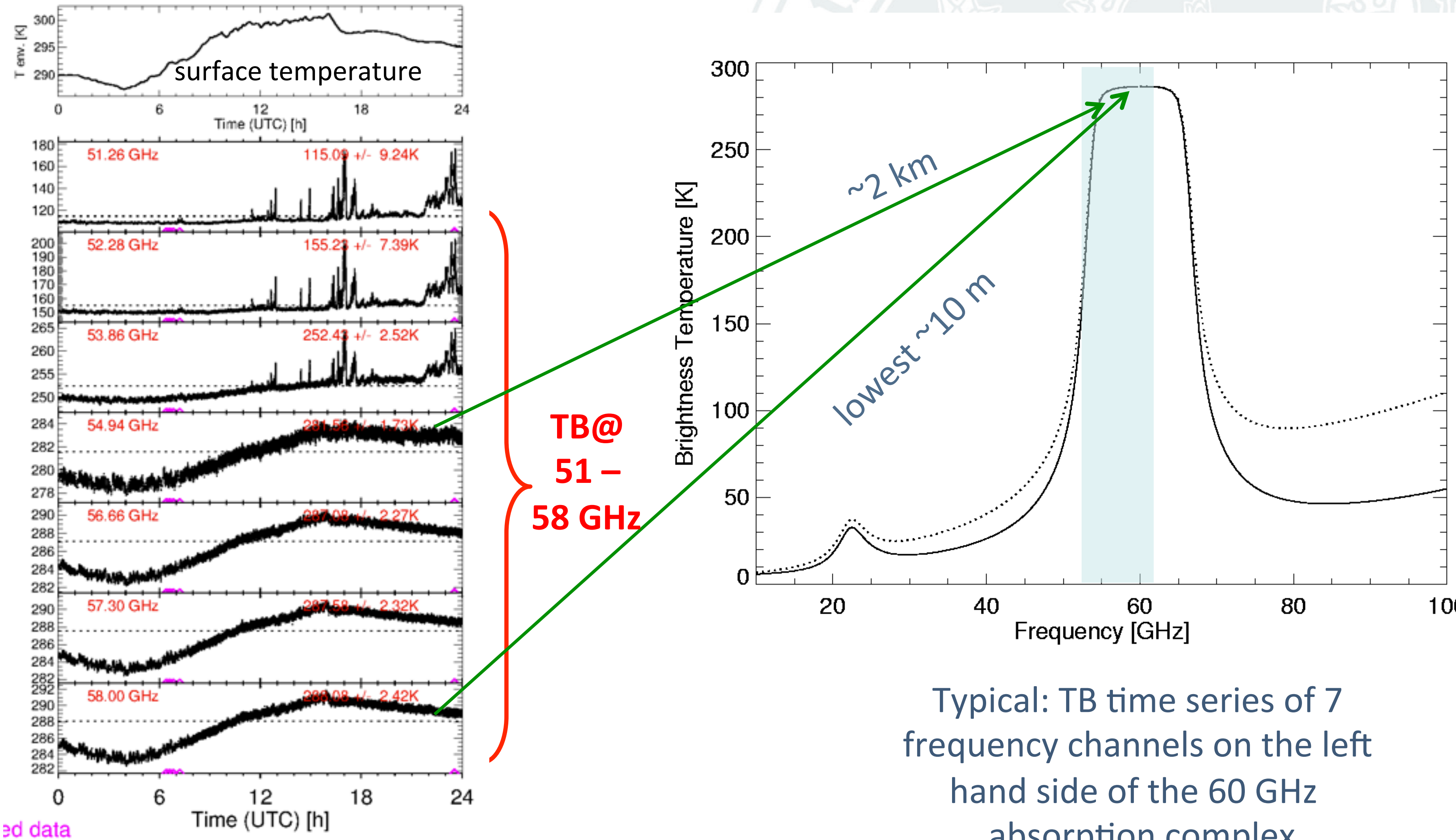


Atmosphere saturated (~black body) → Temperature information from lower levels

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

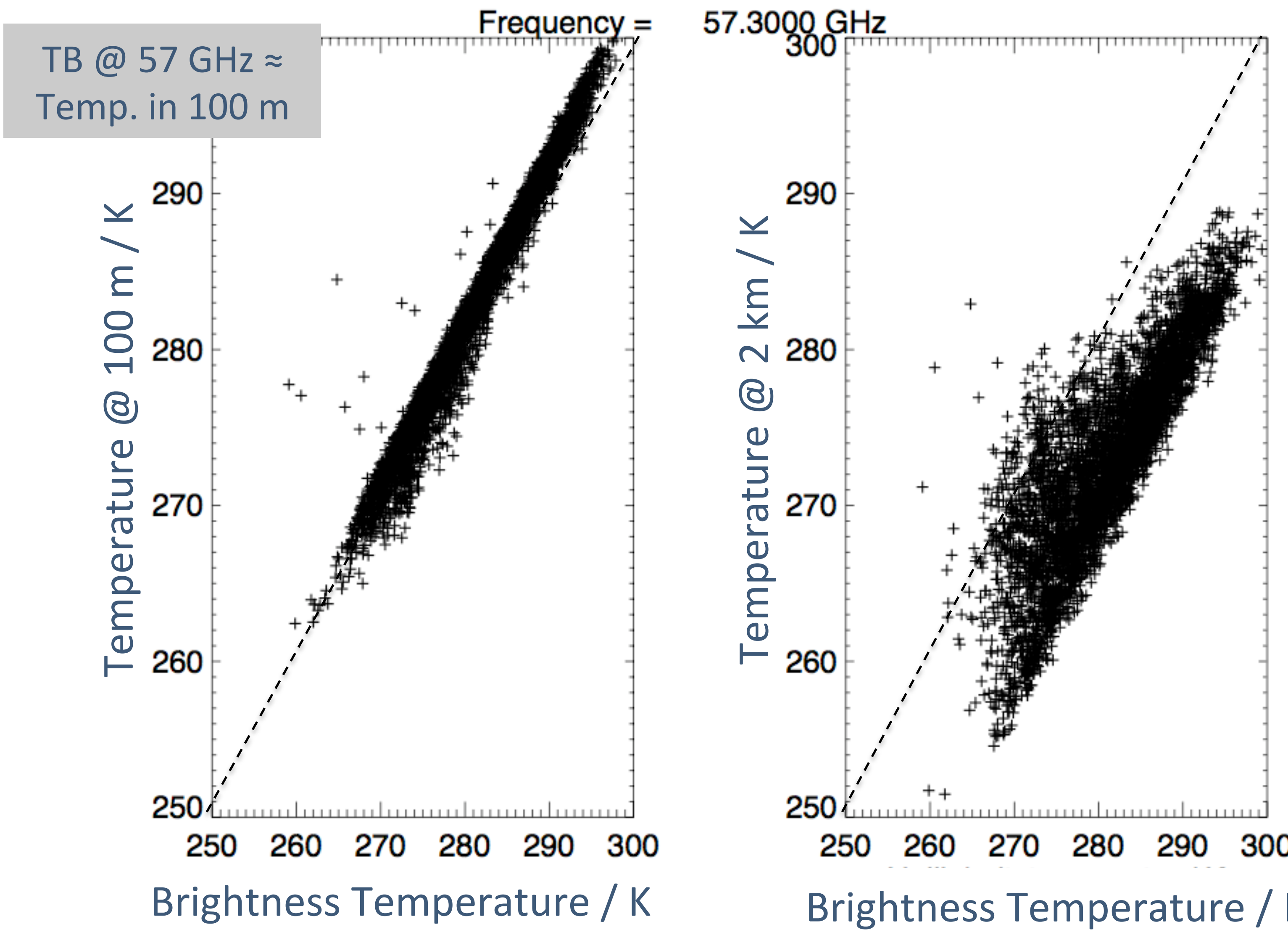
O$_2$ has a constant mixing ratio with height → TB only a function of temperature and pressure

Temperature Retrieval

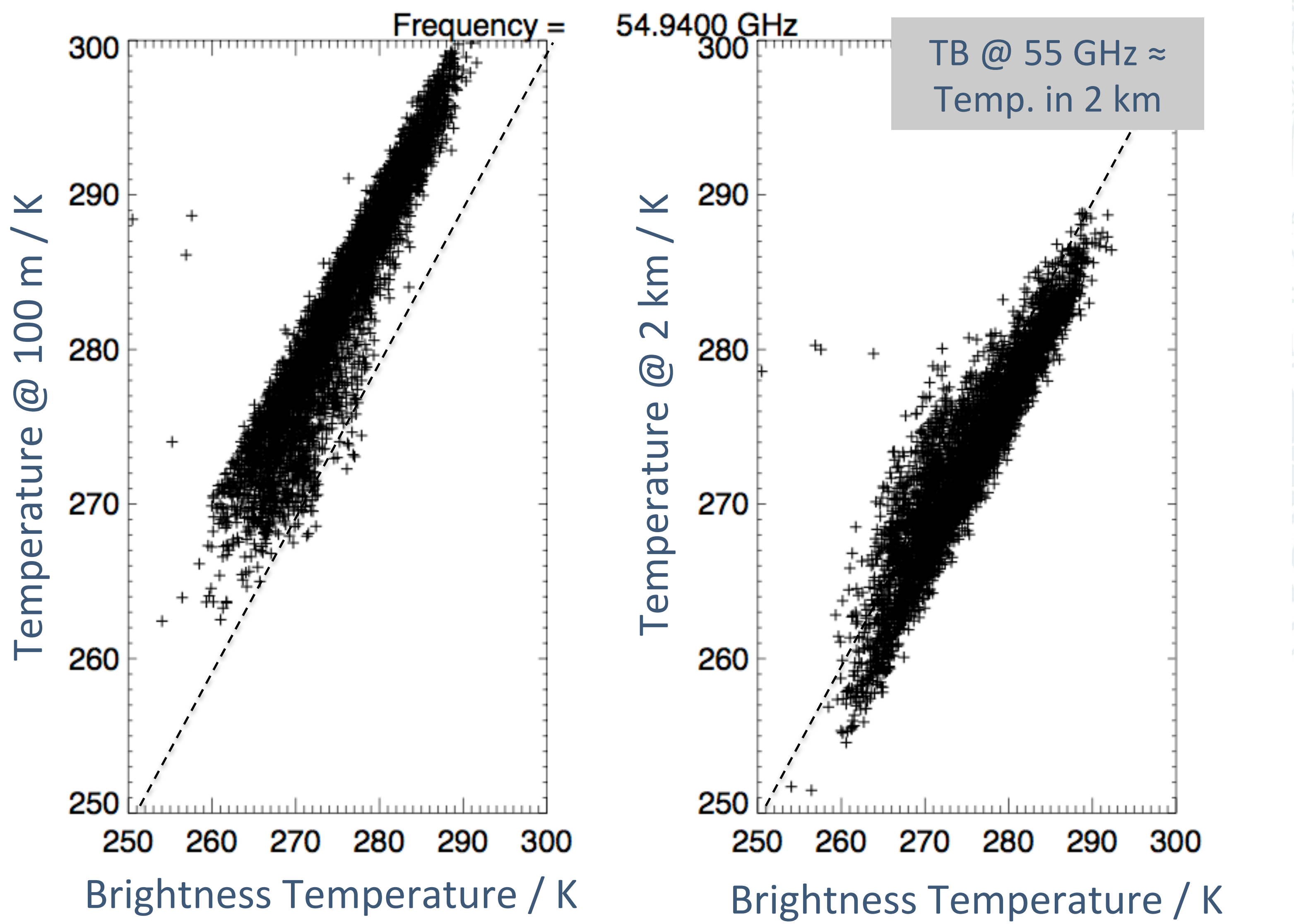


Typical: TB time series of 7 frequency channels on the left hand side of the 60 GHz absorption complex

Physical temperature – TB at 57.3 GHz correlation



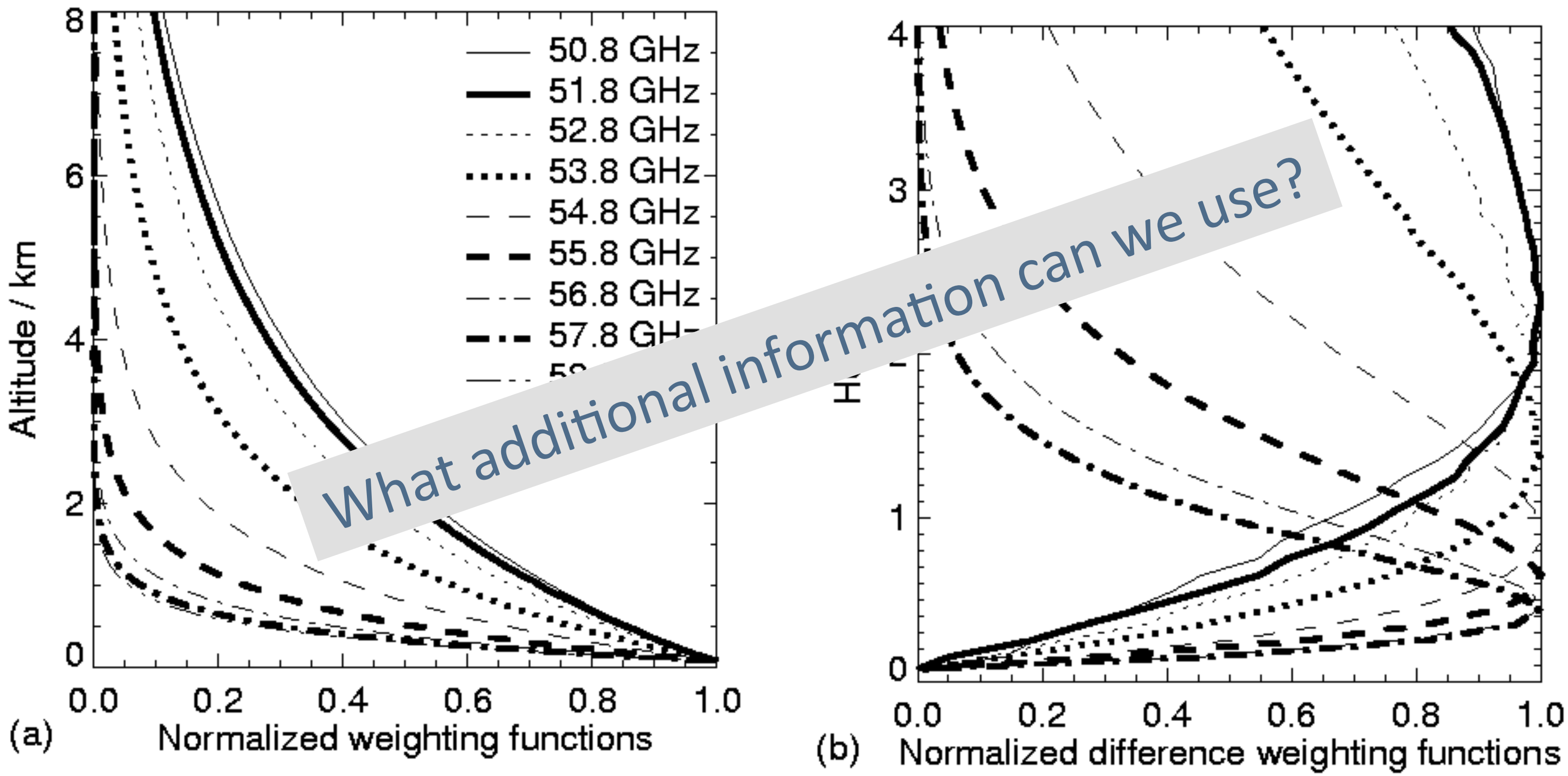
Physical temperature – TB at 55 GHz correlation



Which Channel Contributes from which Heights?

→ Weighting Functions

- Strong redundancy in all channels
- How can the height information be made visible?

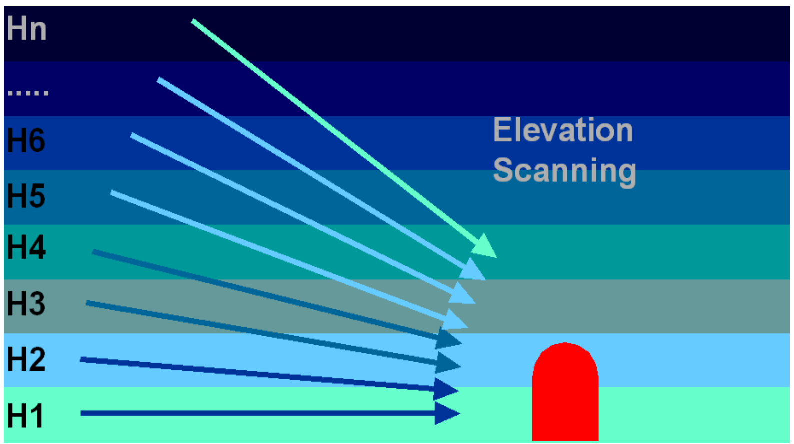


What additional information can we use?

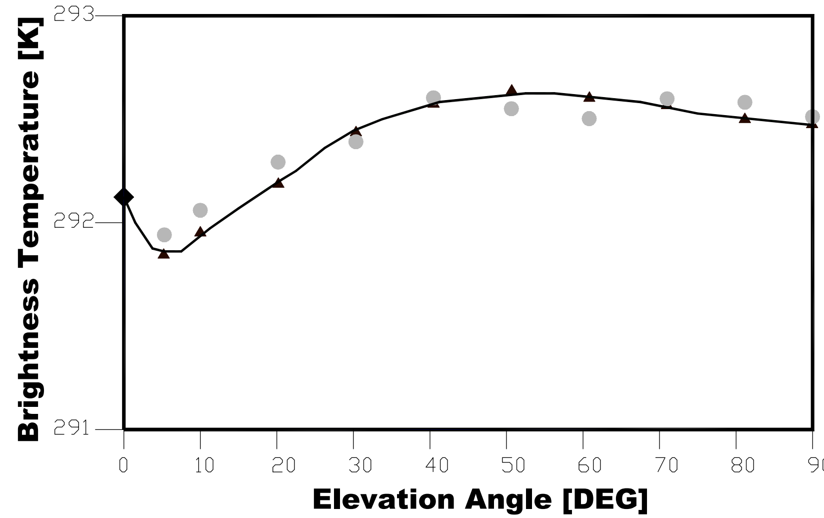
~3 degrees of freedom for signal

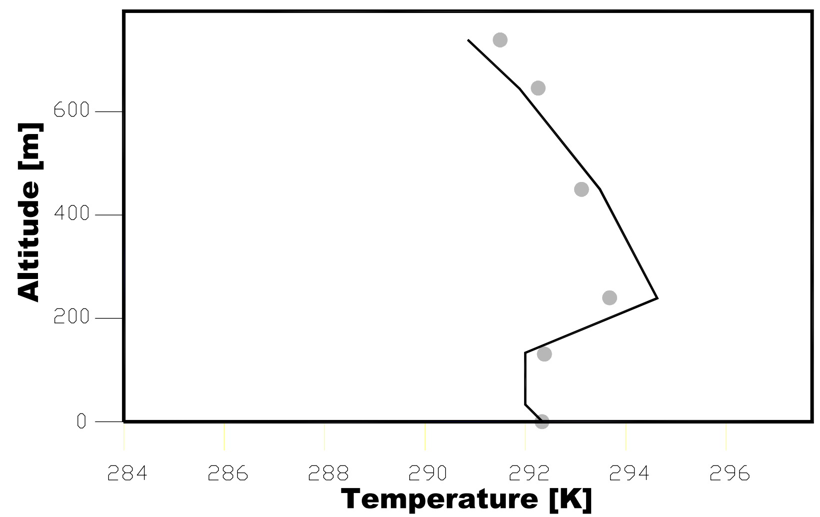
Microwave radiometer elevation scanning

additional temperature profile information in optically thick case

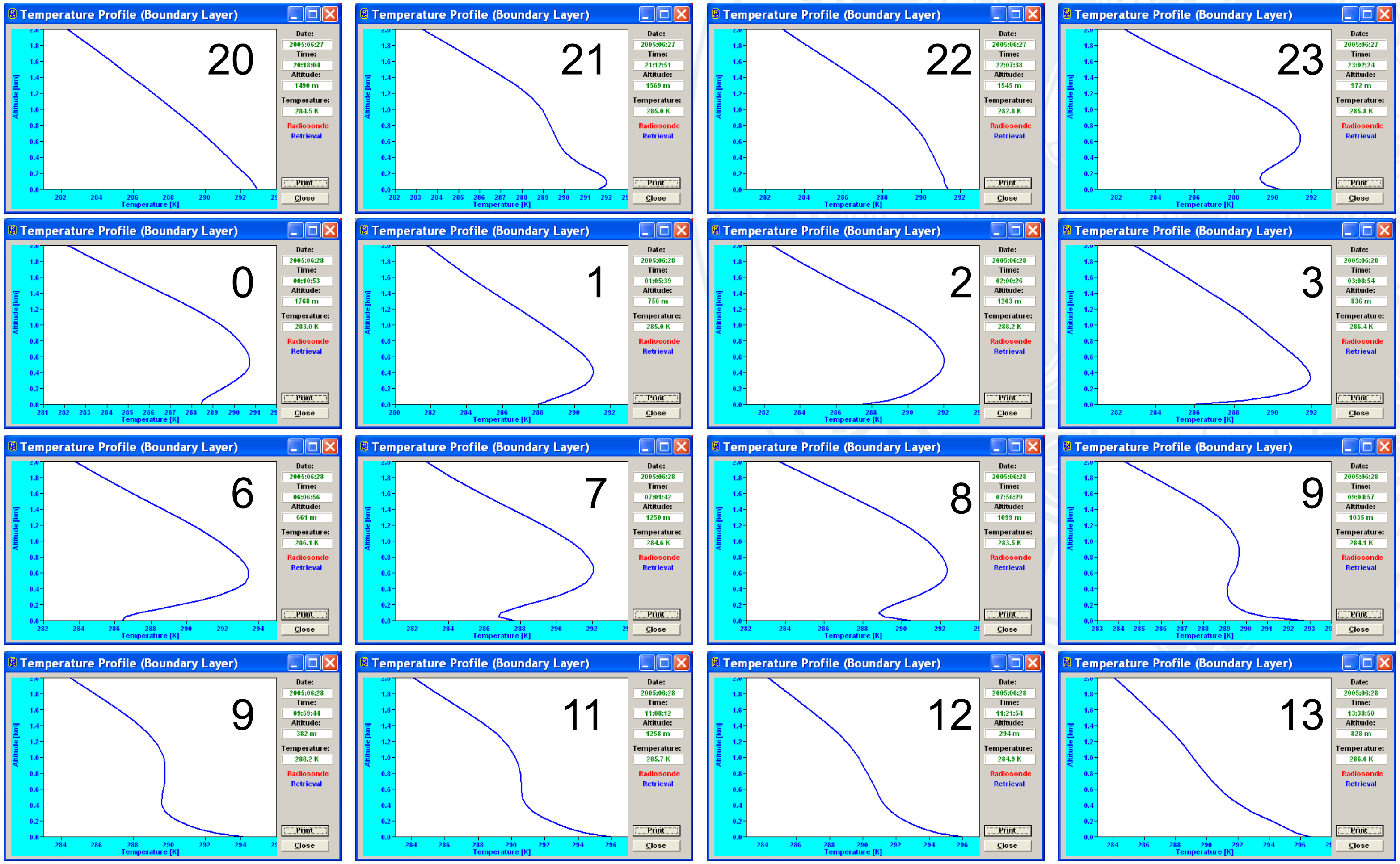


need to assume horizontal homogeneity

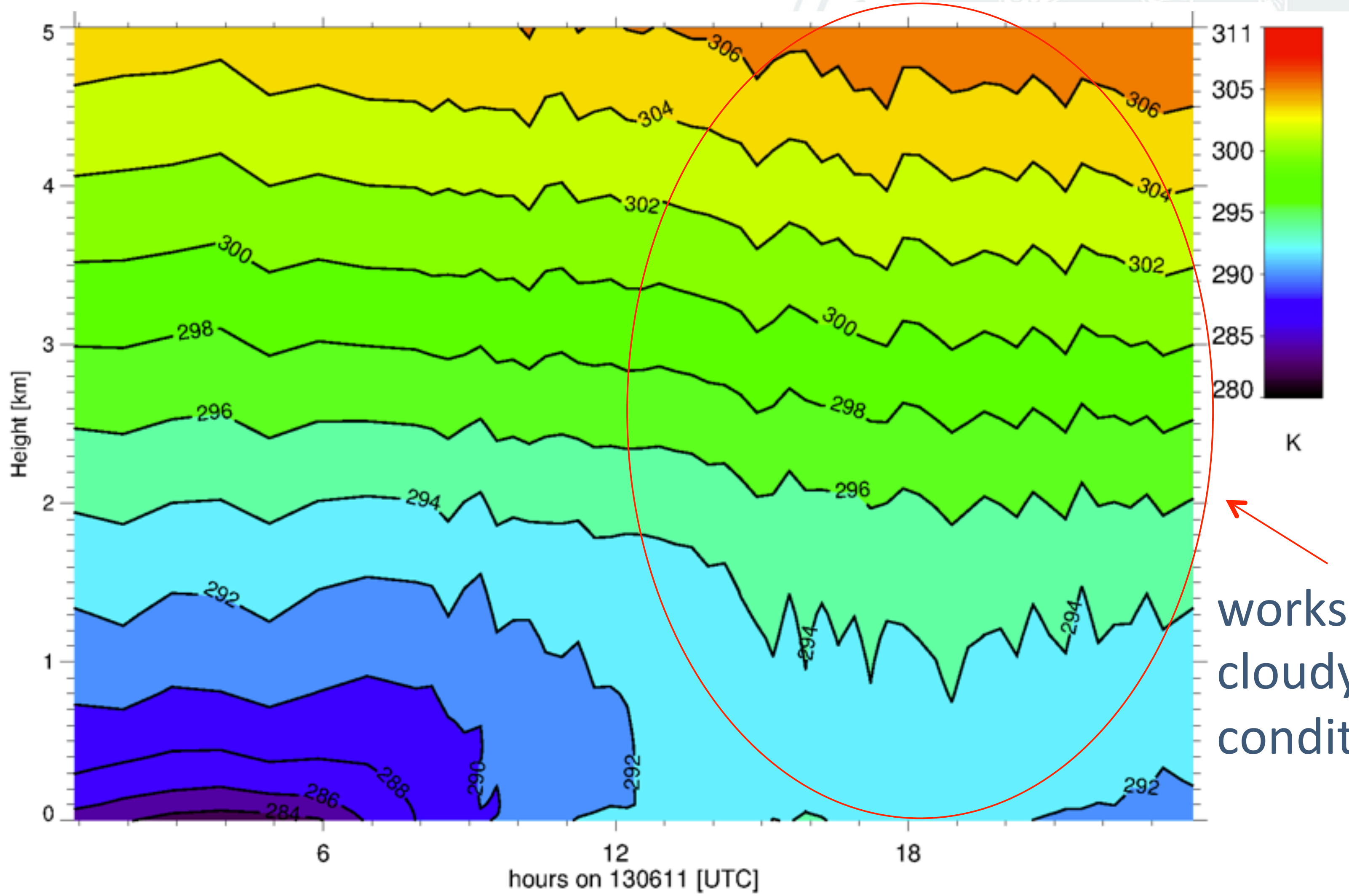




ABL Development

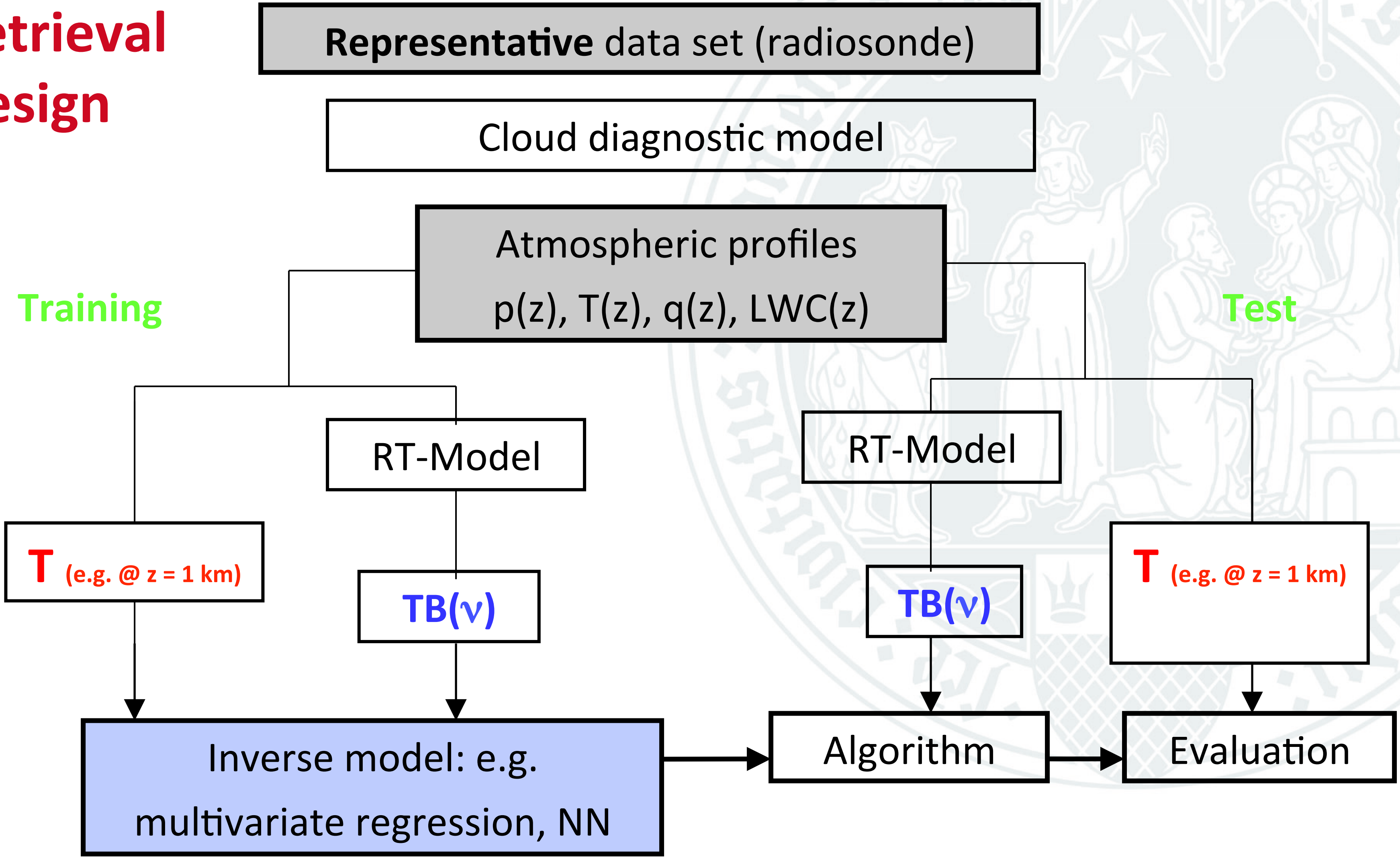


Potential temperature retrieval



works also in cloudy conditions

Retrieval Design



$$T(z{=}1\text{km}) = a(z) + b(z)\cdot T_{B1} + c\,(z)\cdot T_{B1}^{\,2} + d(z)\cdot T_{B2} + e(\,z)\cdot T_{B2}^{\,2} + \,..$$

Advanced Variational Approaches

Need to be given: Correlated(!) uncertainties of **TB** and **a priori profile**

Observations:
Brightness temperature
TB from HATPRO

+

a priori atmospheric profile:
climatology or model
forecast

“Optimal Estimation”

Optimized atmospheric profile

Is atmospheric profile consistent with the observations?

Repeat **iteratively** until **convergence criterion** is met

Optimal Estimation Equations

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \underbrace{\left(\mathbf{S}_a^{-1} + \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \mathbf{K}_i\right)^{-1} \left[\mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \left(\mathbf{y} - F(\mathbf{x}_i)\right) - \mathbf{S}_a^{-1}(\mathbf{x}_i - \mathbf{x}_a)\right]}_{\text{Solution increment, if} \rightarrow 0 \text{ convergence is reached}}$$

Profile of the previous iteration

Updated profile

Makes solution physically consistent with observation; how strongly is determined through weighting with $\mathbf{S}_e^{-1}$, $\mathbf{K}^T$ transforms from *y* to *x* space

„Pulls" solution towards *a priori* profile; how strongly is determined through weighting with $\mathbf{S}_a^{-1}$

Weighting of the whole solution update by weighting with the sum of observation and a priori uncertainty

- **y**: Observation vector ($\mathbf{T}_B$)
- F: Forward model (radiative transfer operator)
- **K**: Jacobian ($\partial\mathbf{F}/\partial\mathbf{x}$)
- $\mathbf{x}_a$: a priori profile
- $\mathbf{S}_\varepsilon$: Error covariance matrix
- $\mathbf{S}_a$: a priori covariance matrix
- **S** : Error covariance solution

If the errors of observation and a priori are estimated correctly, the diagonal components of **S** will give the expected random error at each height

$$\mathbf{S}^{-1} = \left(\mathbf{S}_a^{-1} + \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \mathbf{K}_i\right)$$

To what would you invert this K-band signal?