Water vapour profiling by microwave radiometers: absorption model uncertainty and recent advancements

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Introduction

Microwave Radiometer (MWR) provides:

- Low vertical resolution Temperature and Humidity profiles
- Integrated water vapor + liquid water path (IWV, LWP)
- high temporal resolution (~1min) and ~all weather

MWR applications require uncertainty characterization:

- Instrument
- Forward model (used for retrievals, validation, QC)
  - Radiative transfer
  - Atmospheric absorption model

WMO GRUAN (GCOS Reference Upper Air Network)

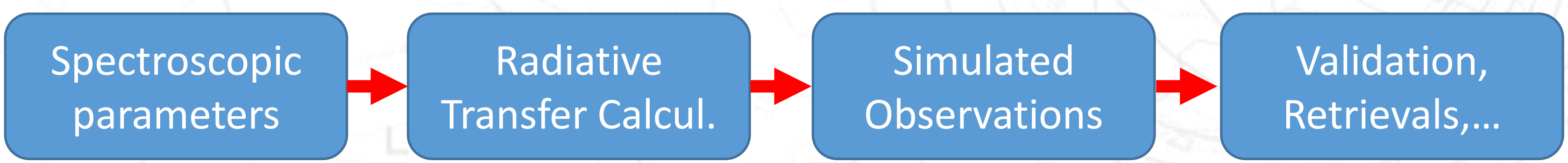
- Focus: characterizing the atmospheric absorption model uncertainty

Introduction

- Atmospheric absorption models
  - based on quantum mechanics theory
  - rely on parameterized equations using spectroscopic parameters

- Values of spectroscopic parameters are determined through
  - (i) theoretical calculations
  - (ii) laboratory experiments
  - (iii) field measurements

- Thus are inherently affected by uncertainty
  - Computational and/or experimental
  - Uncertainty propagates…



Approach

The analysis consists of four steps:

1. **Review state-of-the-art** of spectroscopic parameters and their uncertainties
2. Perform a **sensitivity study** to investigate the dominant uncertainty contribution to radiative transfer calculations
3. Estimate the full **uncertainty covariance matrix** for the dominant parameters
4. **Propagate the uncertainty** covariance matrix to estimate the uncertainty of simulated observations and atmospheric retrievals

1. Review state-of-the-art

- Take one RT model and absorption model
  - **Here**: RTE routines (NOAA) updated with Rosenkranz 2017*
  - But it could also be PAMTRA, ARTS, MonoRTM, AMSUTRAN,…
- List the used parameters (line & continuum absorption)
  - 21 for H_2O
  - 298 for O_2
- Uncertainties from 319 parameters were considered

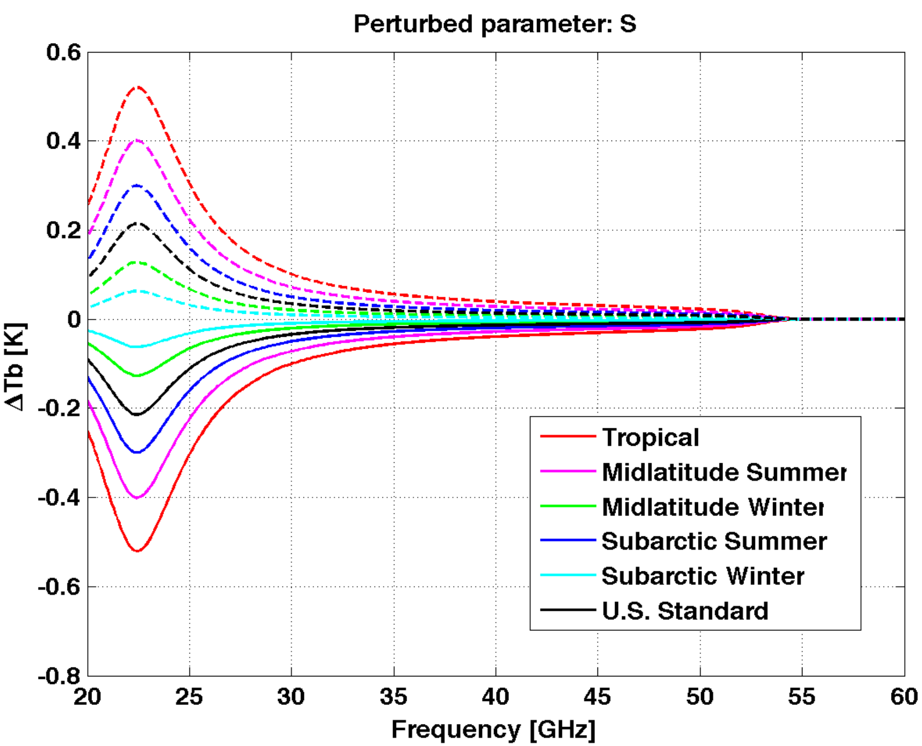
*https://doi.org/10.21982/M81013

2. Sensitivity to model parameter uncertainty

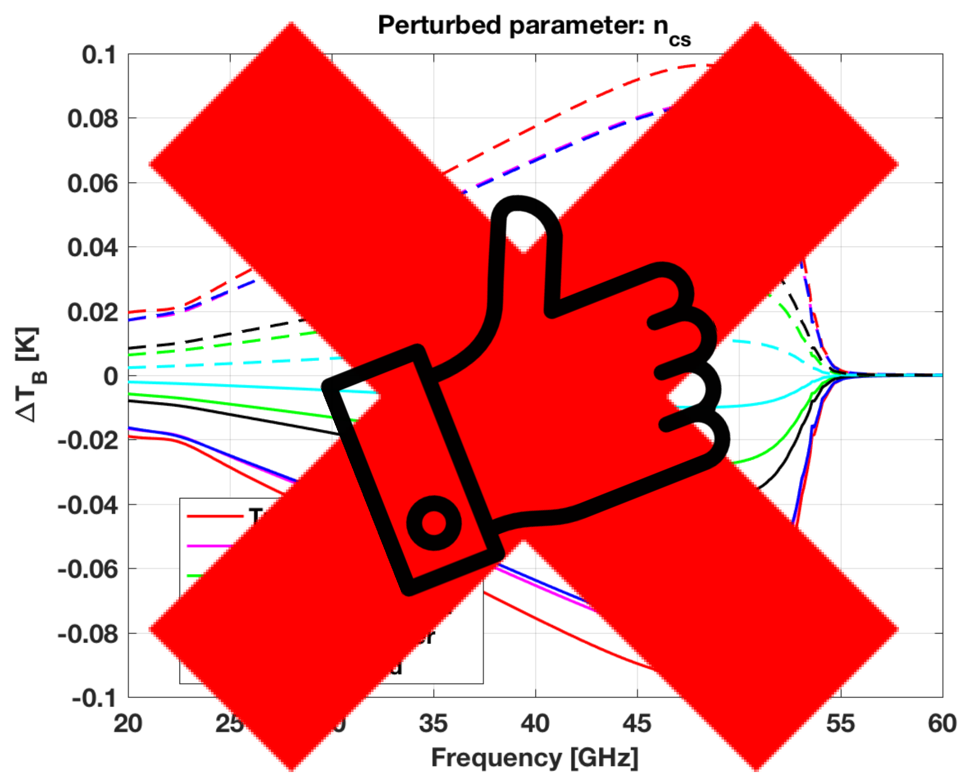
- Sensitivity to spectroscopic parameter uncertainty

$$\boldsymbol{T_B} = \boldsymbol{F}(\boldsymbol{p}) \qquad \Delta T_B = T_B(p_i) - T_B(p_i \pm \sigma_{pi})$$

WV line strength @ 22.2 GHz



WV self-continuum T exponent



Solid lines correspond to negative perturbation (value − uncertainty)
Dashed lines correspond to positive perturbation (value + uncertainty)

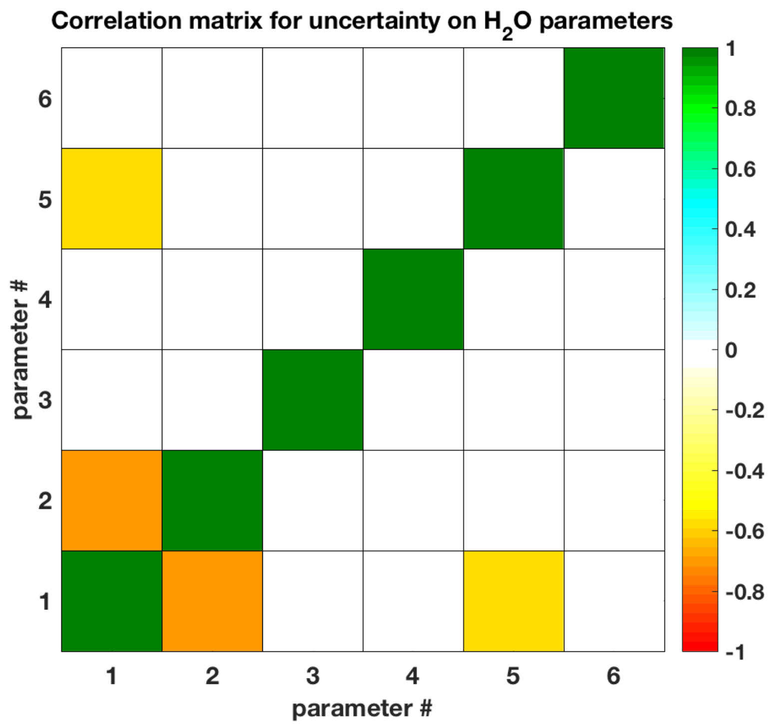
2. Sensitivity to model parameter uncertainty

- H_2O
  - Selected **6** dominating parameters (among **21**)
  - 3 for continuum (Cs, Cf, Xf)
  - 3 for lines (γ, S, shift-broad ratio)
- O_2
  - Selected **105** dominating parameters (among **298**)
  - 1 for continuum
  - 104 for lines (strength, broadening, mixing, mixing temp. dep.)

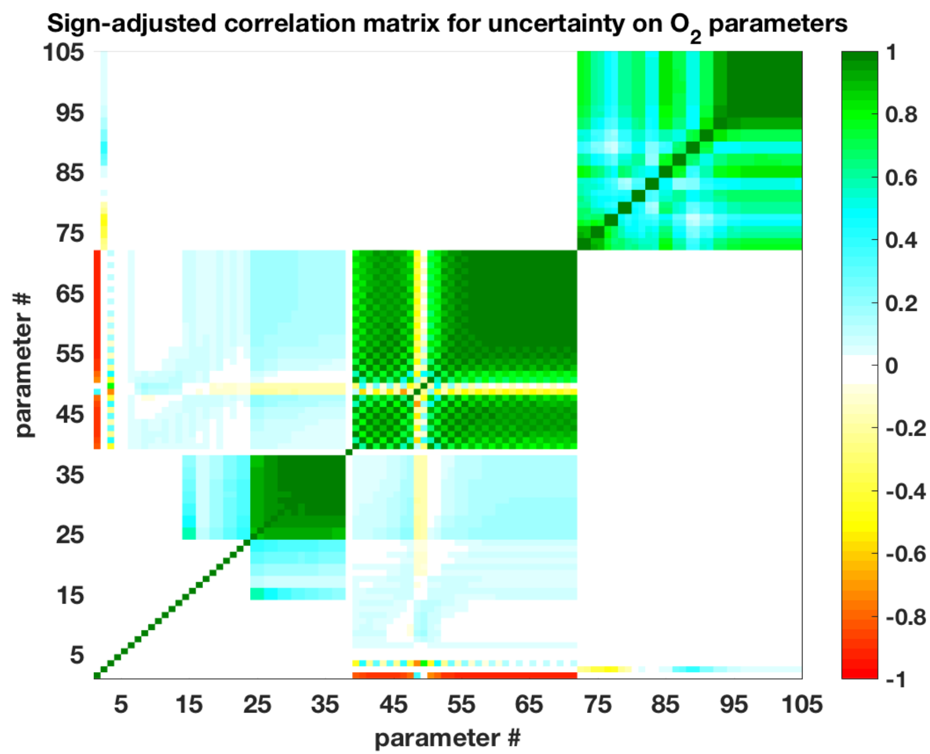
3. Uncertainty covariance matrix

- For the **111** dominant terms, we estimated the parameter uncertainty covariance **Cov**(*p*)

Water Vapor (6 parameters)



Oxygen (105 parameters)



Broadening Mixing Mixing T dependence

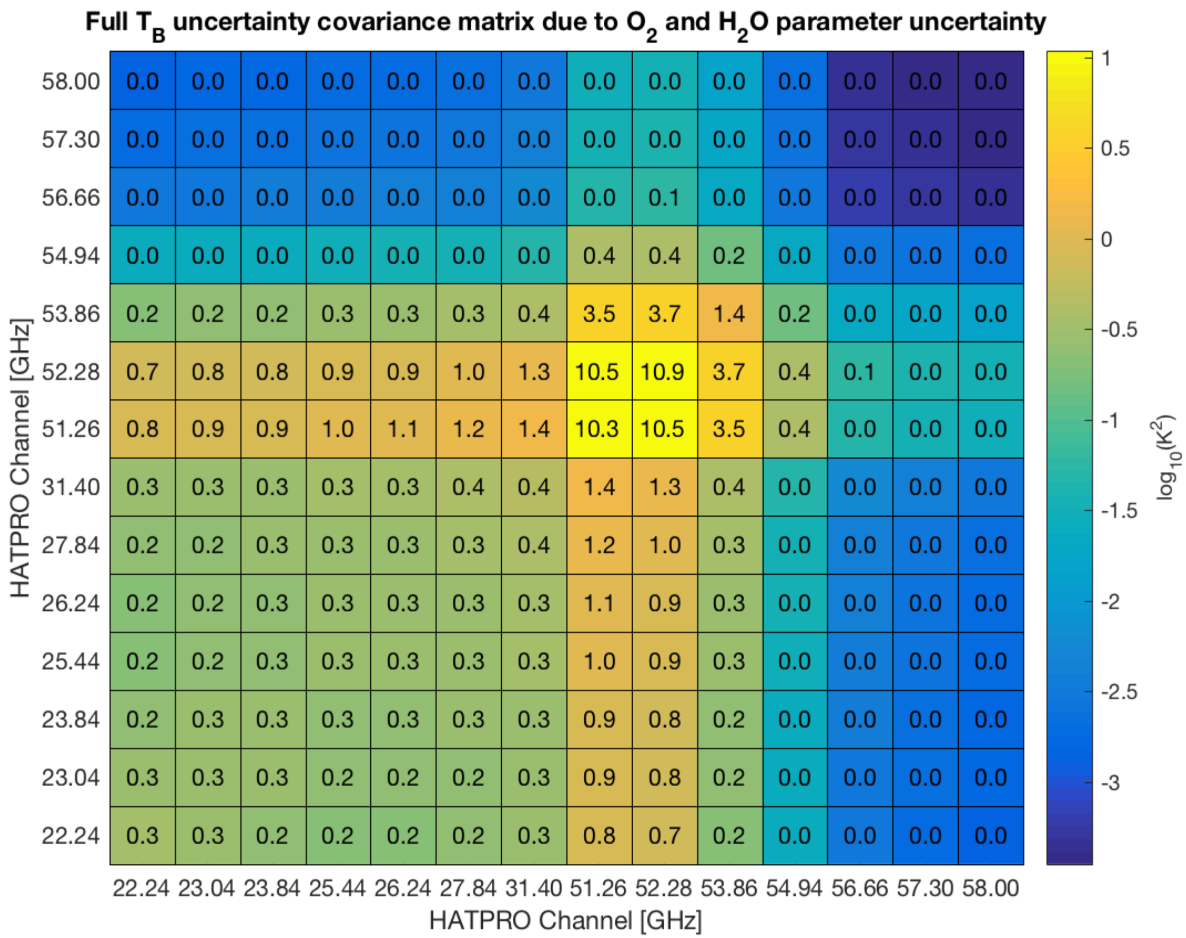
Cimini et al, ACP 2018

4. Uncertainty propagation

- Once **Cov**(*p*) is determined, we can map into **Cov**(T_B):

$$\mathbf{Cov}(\boldsymbol{T_B}) \cong \boldsymbol{K_p} * \mathbf{Cov}(\boldsymbol{p}) * \boldsymbol{K_p}^T$$

Total T_B uncertainty (full matrix)



HATPRO Channel [GHz]	22.24	23.04	23.84	25.44	26.24	27.84	31.40	51.26	52.28	53.86	54.94	56.66	57.30	58.00
58.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
56.66	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
54.94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.2	0.0	0.0	0.0	0.0
53.86	0.2	0.2	0.2	0.3	0.3	0.3	0.4	3.5	3.7	1.4	0.2	0.0	0.0	0.0
52.28	0.7	0.8	0.8	0.9	0.9	1.0	1.3	10.5	10.9	3.7	0.4	0.1	0.0	0.0
51.26	0.8	0.9	0.9	1.0	1.1	1.2	1.4	10.3	10.5	3.5	0.4	0.0	0.0	0.0
31.40	0.3	0.3	0.3	0.3	0.3	0.4	0.4	1.4	1.3	0.4	0.0	0.0	0.0	0.0
27.84	0.2	0.2	0.3	0.3	0.3	0.3	0.4	1.2	1.0	0.3	0.0	0.0	0.0	0.0
26.24	0.2	0.2	0.3	0.3	0.3	0.3	0.3	1.1	0.9	0.3	0.0	0.0	0.0	0.0
25.44	0.2	0.2	0.3	0.3	0.3	0.3	0.3	1.0	0.9	0.3	0.0	0.0	0.0	0.0
23.84	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.9	0.8	0.2	0.0	0.0	0.0	0.0
23.04	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.9	0.8	0.2	0.0	0.0	0.0	0.0
22.24	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.8	0.7	0.2	0.0	0.0	0.0	0.0

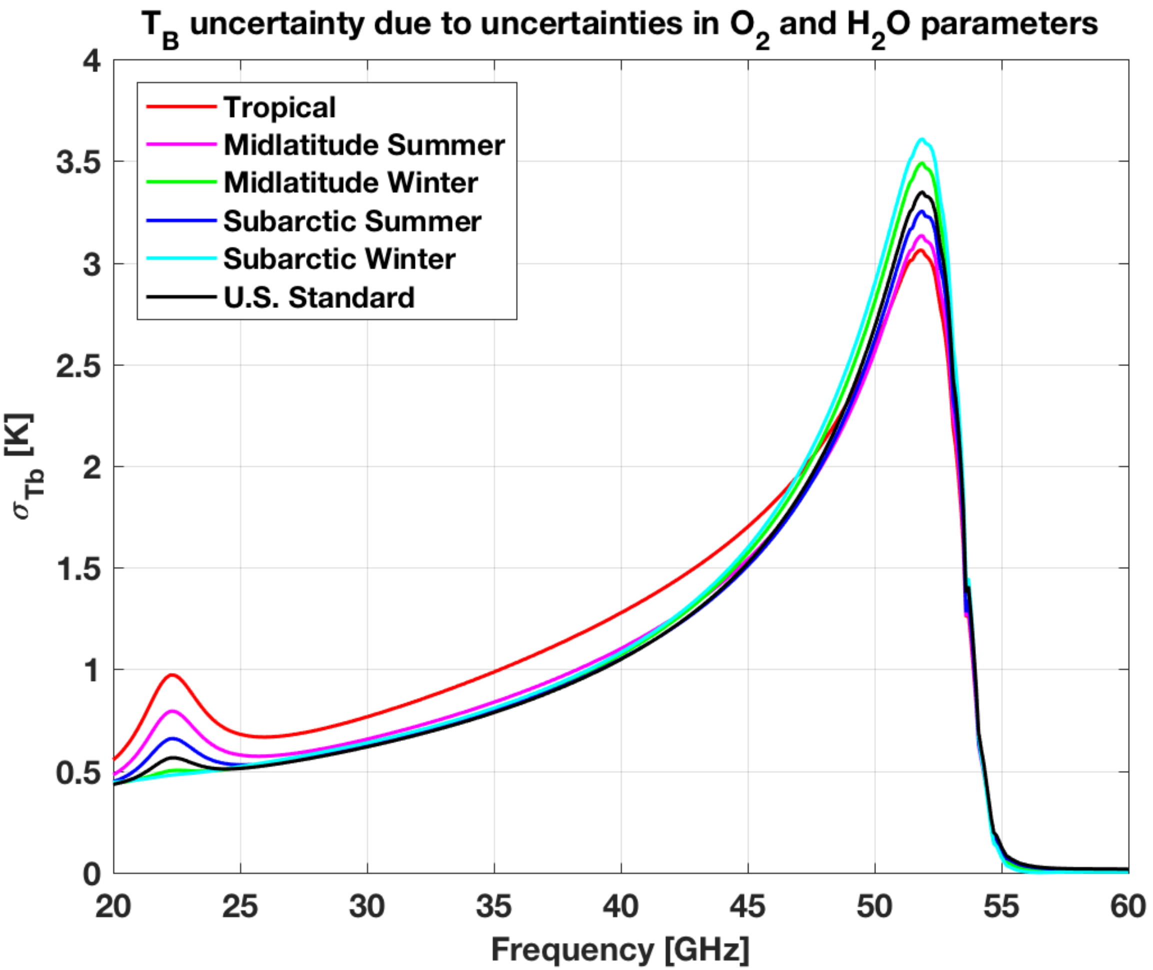
Cimini et al, ACP 2018

4. Uncertainty propagation

- Once **Cov**(p) is determined, **Cov**(T_B) can be easily computed:

$$\mathbf{Cov}(\boldsymbol{T_B}) \cong \boldsymbol{K_p} * \mathbf{Cov}(\boldsymbol{p}) * \boldsymbol{K_p}^T$$

Total T_B uncertainty (diagonal terms)

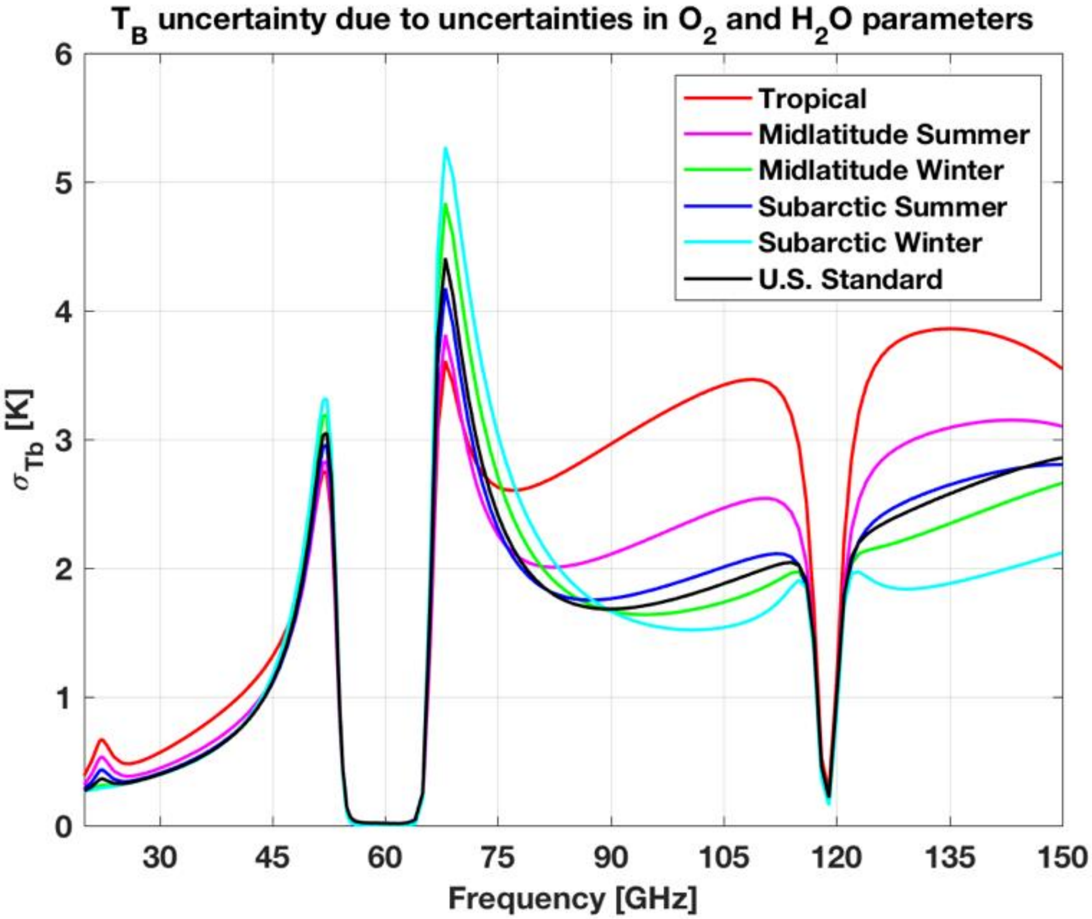


Cimini et al, ACP 2018

Extension to higher frequencies

- Extended to higher frequency (up to 150 GHz)
  - To include 90-150 GHz MWR used for low LWP retrievals
- New sensitivity study: 1 additional parameter to be considered

n_{Cs} (wv self continuum T dependence exponent) contributing 0.2-0.6 K to T_B uncertainty at 70-150 GHz



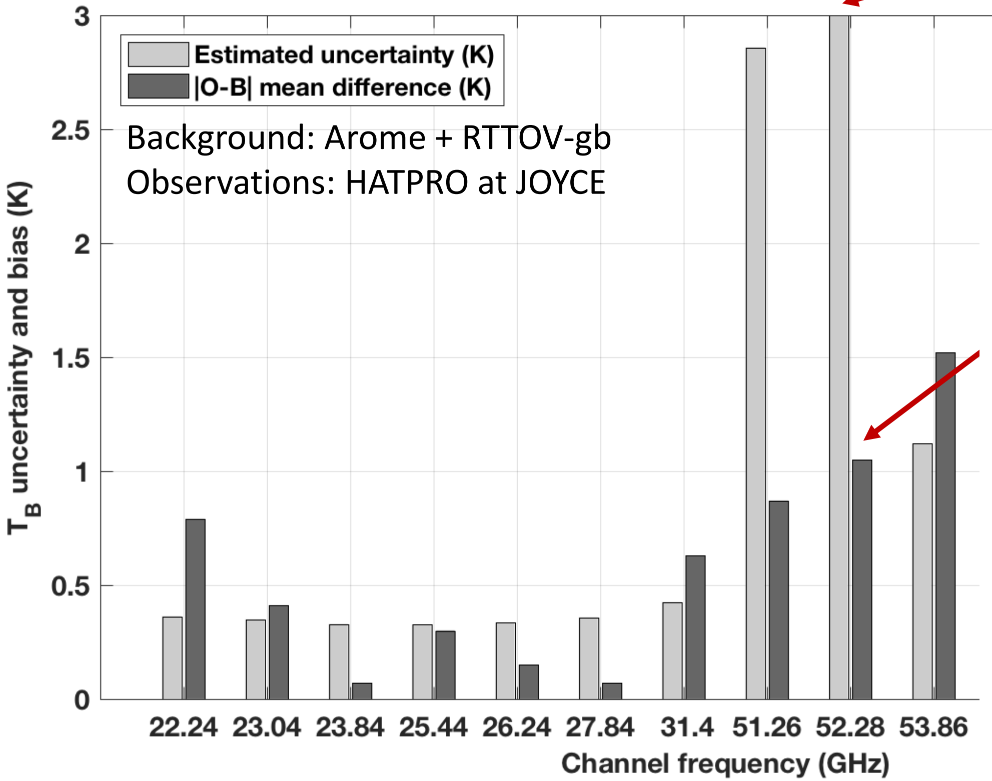
Cimini et al, GMD 2019

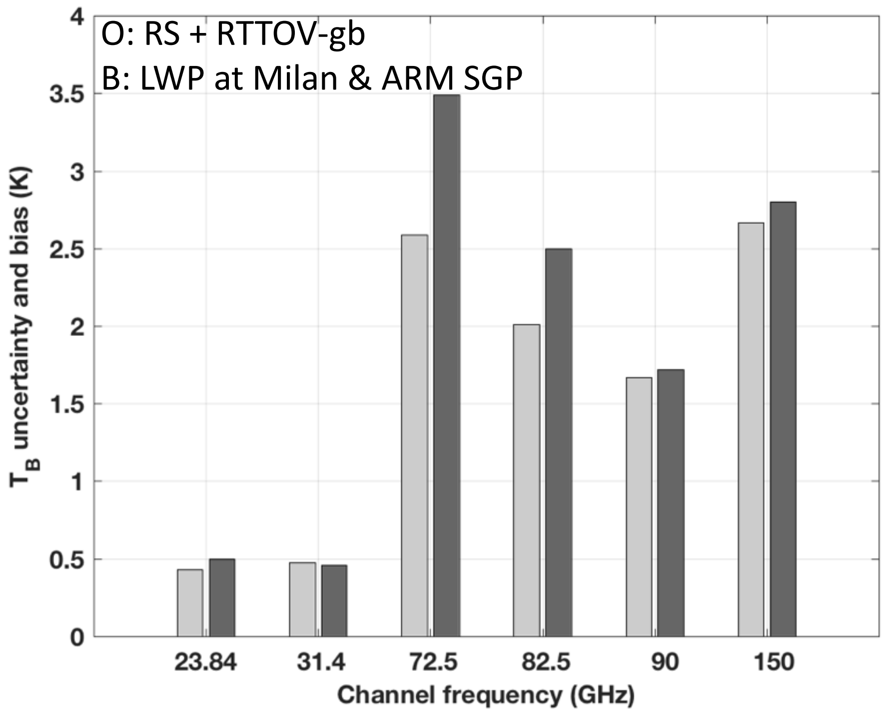
Absorption model uncertainty

- For a well maintained MWR, absorption model uncertainty explains most of the observation minus simulation (O-S) differences

Abs. mod. uncertainty

O-S differences





Cimini et al, GMD 2019

Investigation of systematic uncertainty

- Are there sources of systematic uncertainty in current MW absorption models?
- Speed-dependence of line shapes is currently not considered
  - collision probability (i.e. cross-section) slightly depends on molecular speed
- Recent laboratory measurements provides speed-dependence parameters
  - for 22 and 118 GHz lines (Koshelev et al., 2017; 2018)
  - for 183 GHz lines (Tretyakov 2019, personal comm.)

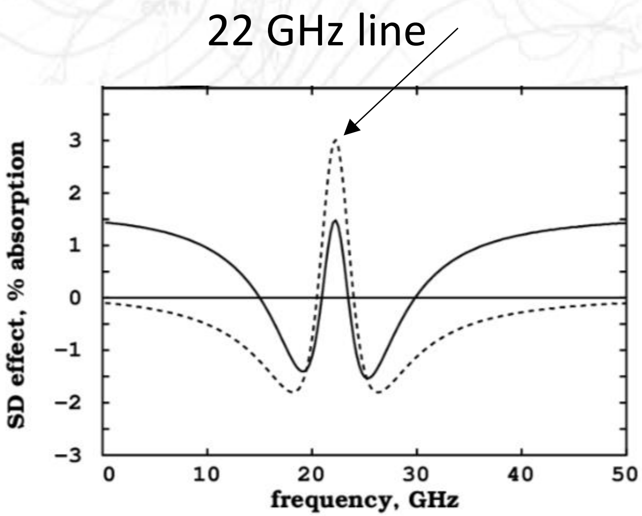
Investigation of systematic uncertainty

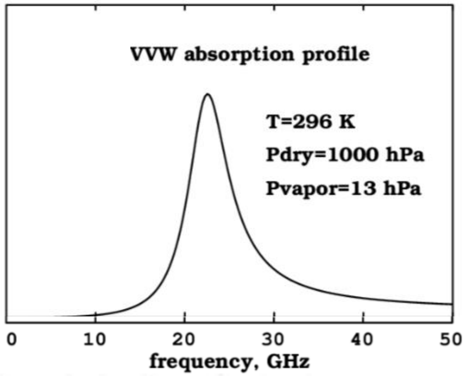
- Theory for MW speed-dependent line shape has been developed

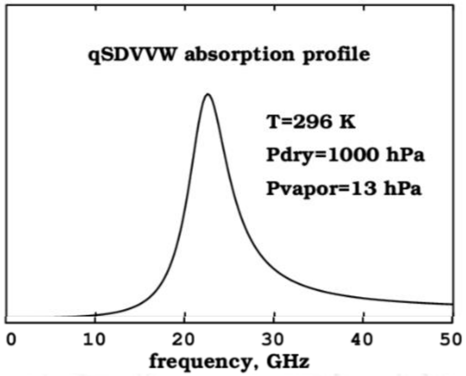
VVW → qSDVVW

Van Vleck-Weisskopf line shape

quadratic Speed-Dependent Van Vleck-Weisskopf line profile



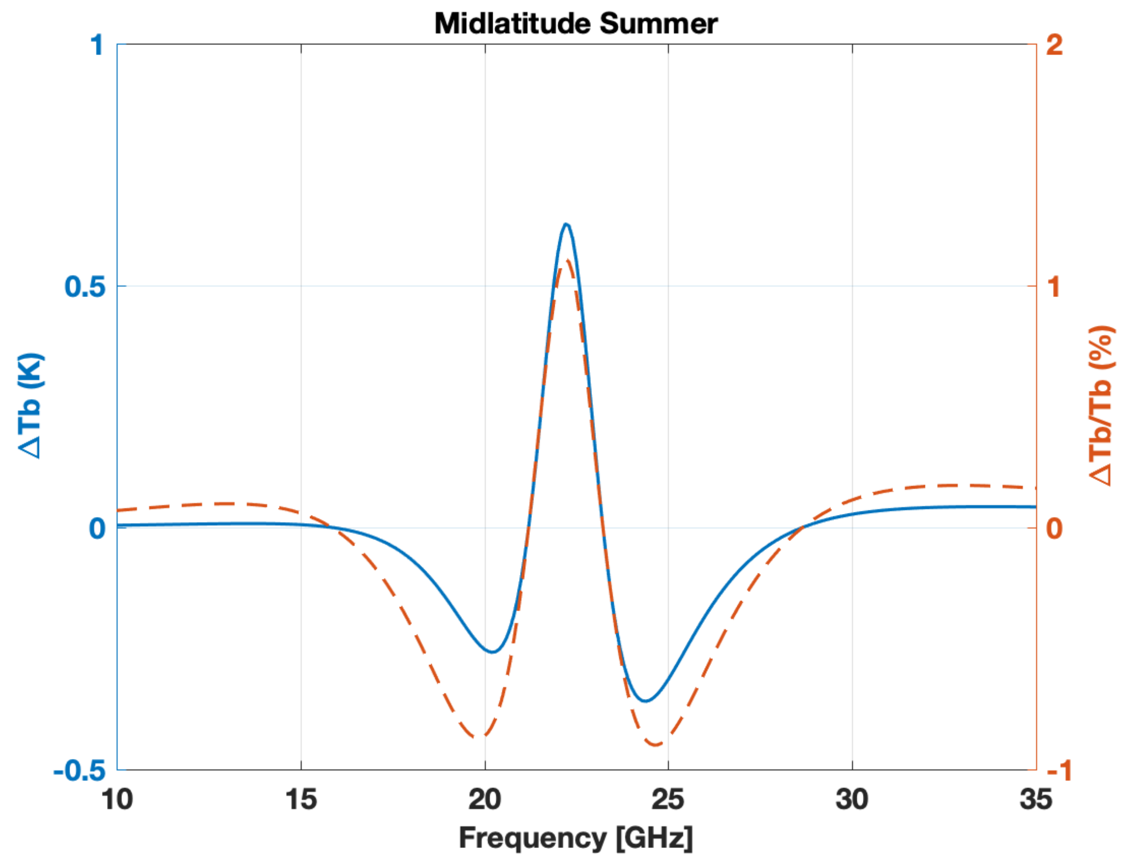




*Rosenkranz & Cimini, submitted to TGRS, in review, 2019

Investigation of systematic uncertainty

- Does it make a big impact on T_B? **Hopefully not!** 😃



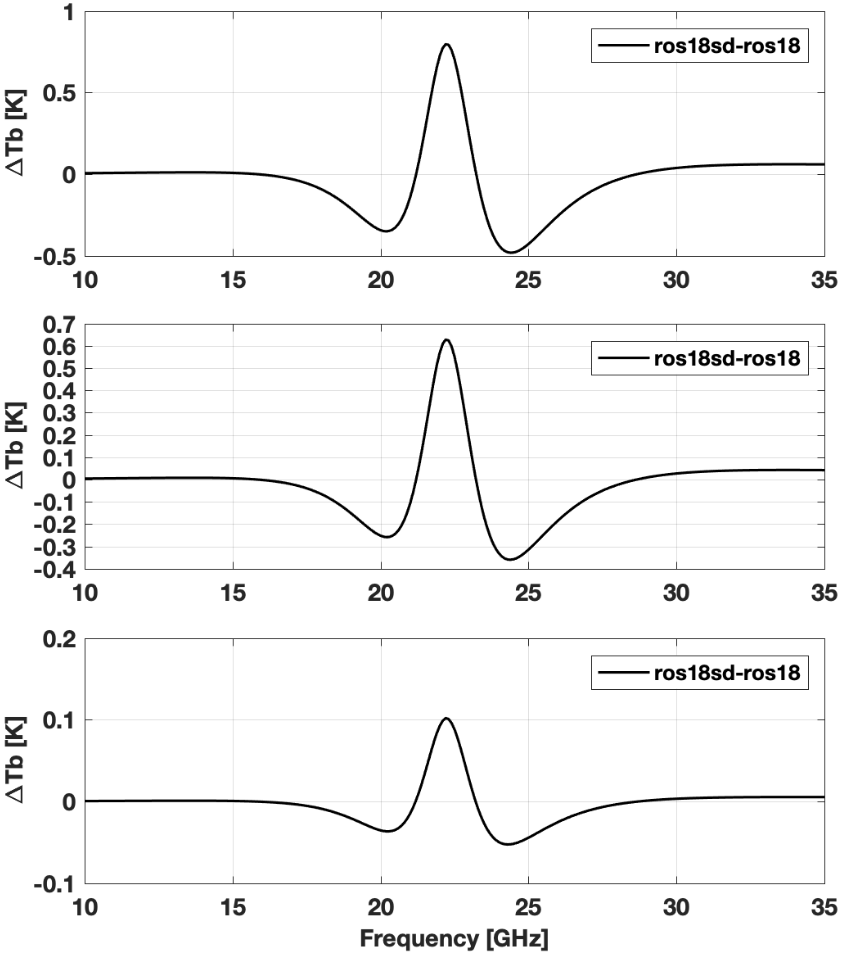
Investigation of systematic uncertainty

- Does it make a big impact on T_B? **Hopefully not!** 😃

Tropical
~ 2%

Mid-lat Summer
~ 1%

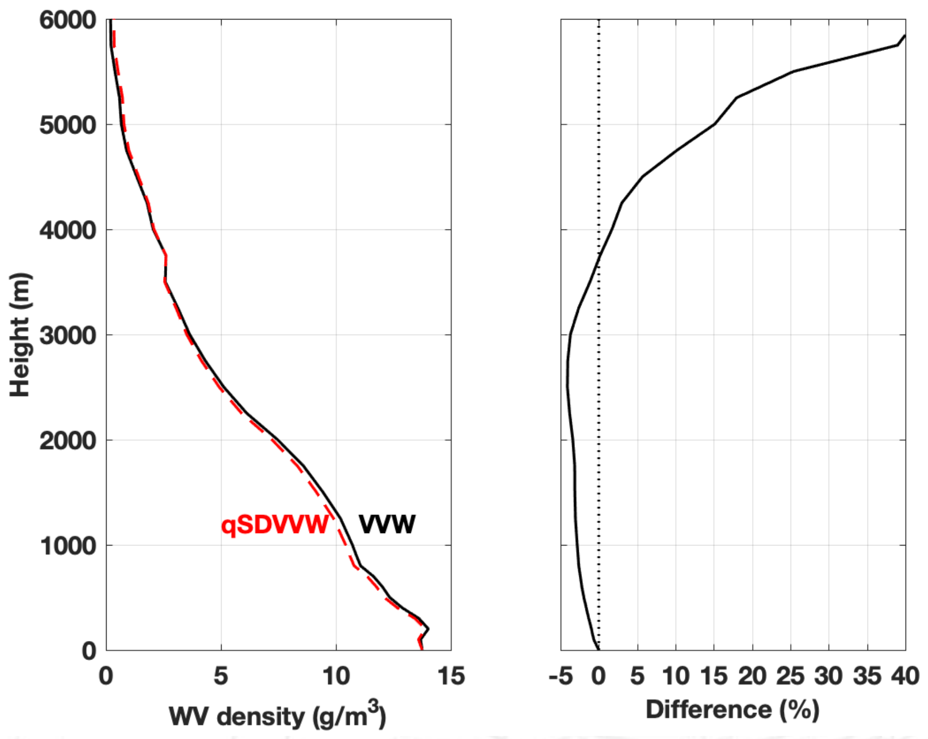
Sub Arctic Winter
~ 0.5%



Investigation of systematic uncertainty

- Impact on WV profile retrievals

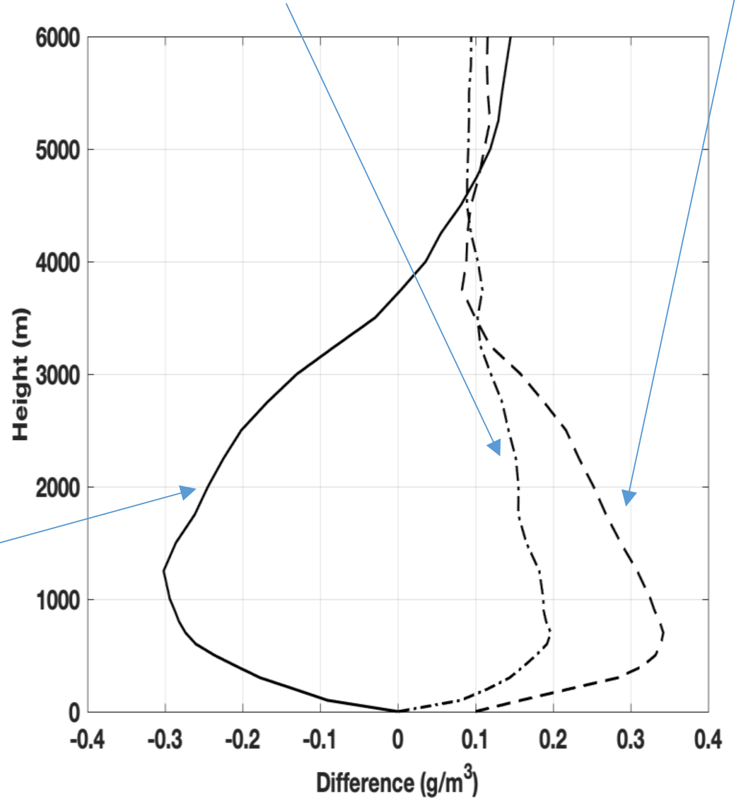
changes sign with height



*Rosenkranz & Cimini, submitted to TGRS, in review, 2019

Investigation of systematic uncertainty

- Impact on WV profile retrievals
- SD comparable to other uncertainty contributions
- But SD is systematic!
- e.g. it implies a (−1.1%) negative bias in ARM 2-channel IWV retrievals



Summary and future work

- Absorption model uncertainty for ground-based MW simulations has been quantified in the 20-150 GHz range
- A source of systematic uncertainty has been identified and quantified (Speed-Dependent line profile)
  - Impact comparable to other uncertainty contributions
  - Implies ~1% negative bias in IWV 2-channel retrievals
- Currently extending both analysis (spectroscopic uncertainty and speed-dependence) to satellite-based simulations (up to 700 GHz)

Thank you very much for your attention!

GRUAN

- GRUAN: GCOS (Global Climate Observing System) Reference Upper Air Network
- GRUAN delivers reference-quality measurement of essential climate variables (ECVs), for which the uncertainty contributions are carefully evaluated
  - Radiosonde observations (Dirksen et al., 2014)
  - Plans for ground-based MWR profilers
- MWR adds value to GRUAN by providing redundant measurements with respect to radiosondes, but covering the complete diurnal cycle at high (e.g., 1 min)
- Uncertainty for MWR retrievals have been reviewed
  - GRUAN-related GAIA-CLIM project
  - Spectroscopic parameter uncertainty was found to be the least investigated among all

3. Uncertainty covariance matrix

Just one example:

- Oxygen line-broadening parameters
  - Coefficients with $N > N_*$ are determined through linear extrapolation of measured coefficients ($N < N_*$)

$$\gamma_N = \gamma_* + (N - N_*)\mu$$

pivot values: γ_*, N_*

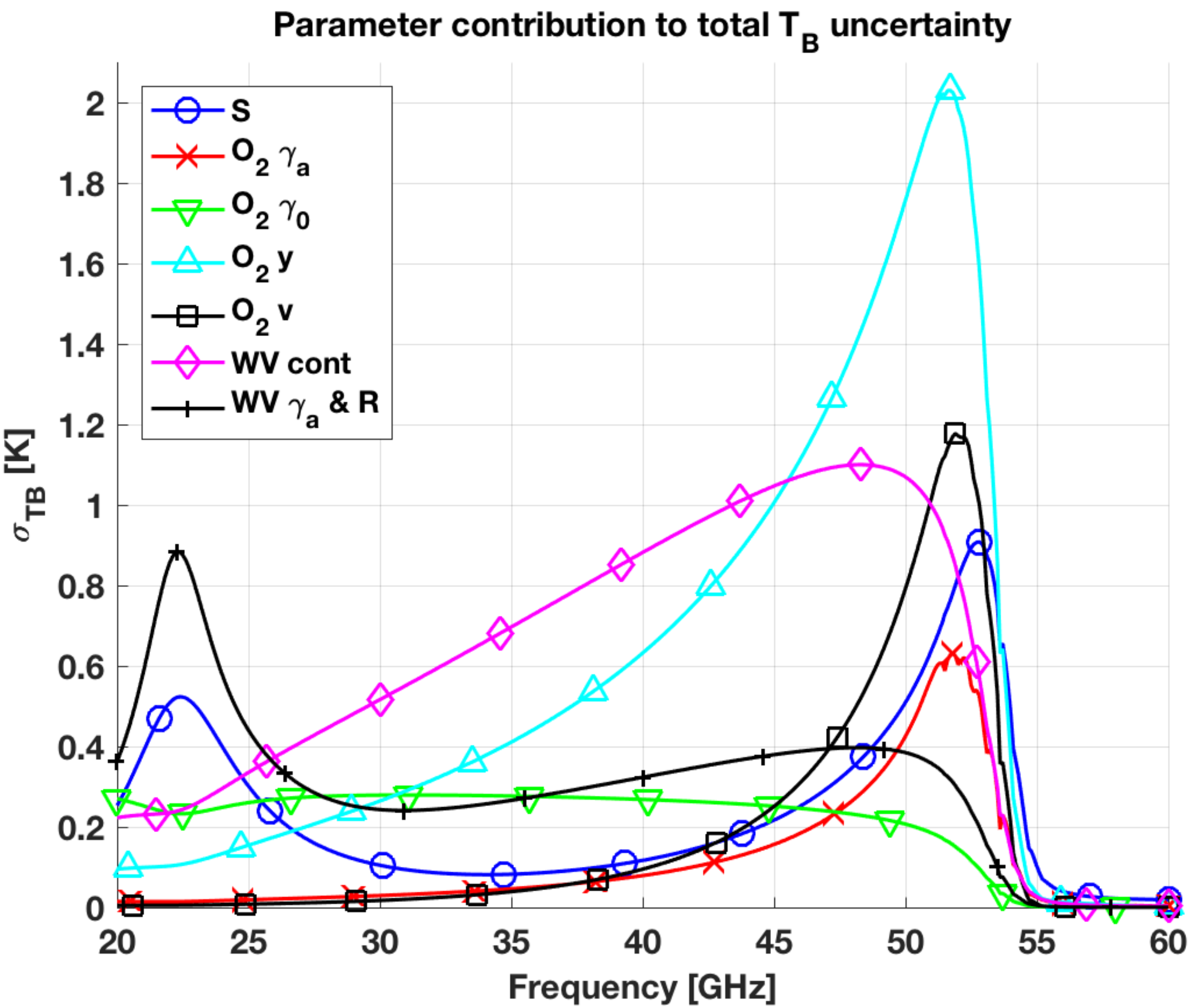
N is the O_2 rotational quantum numb

  - The extrapolation introduces correlations among the coefficients

4. Uncertainty propagation

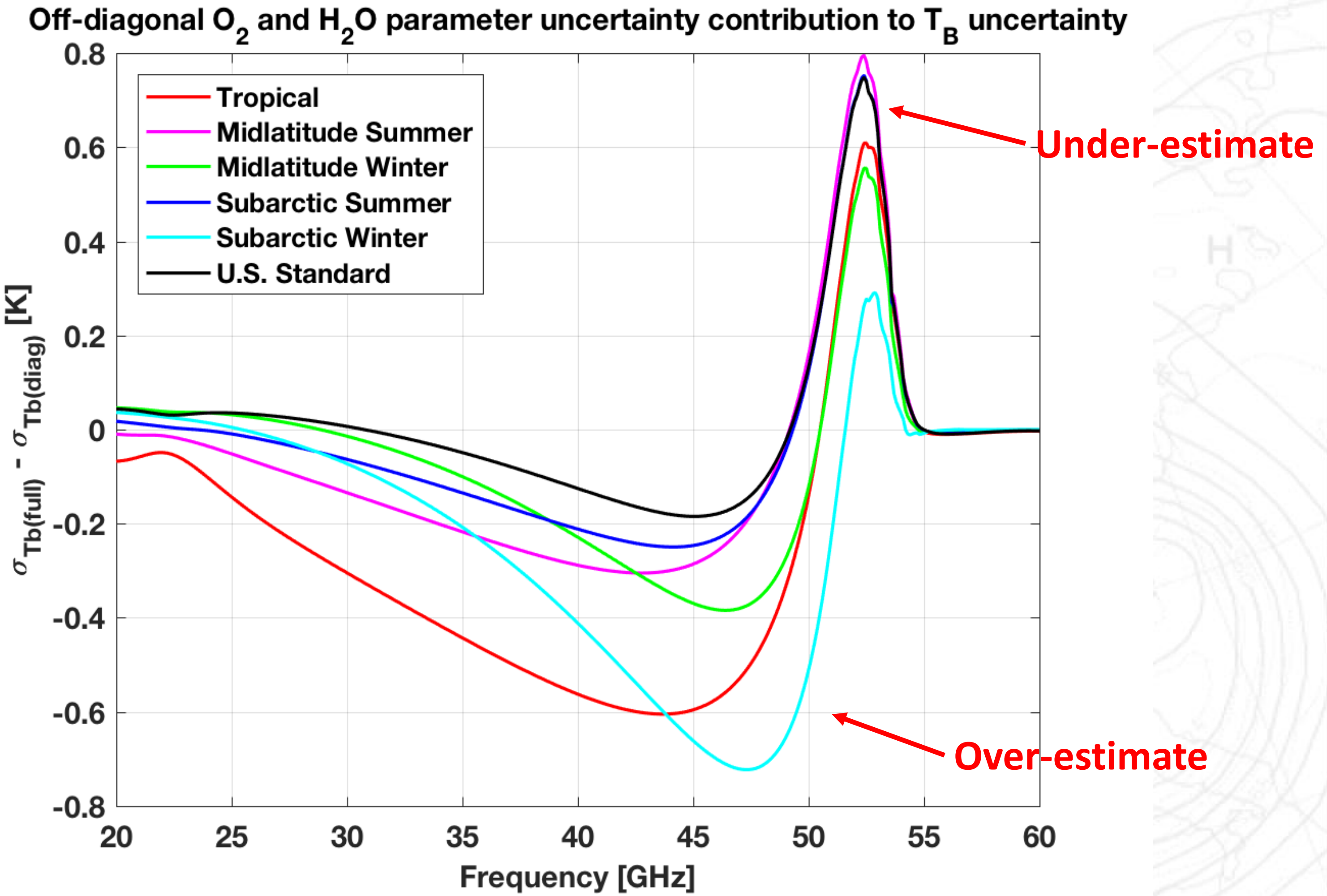
- Contributions T_B uncertainty

Tropical atmosphere



4. Uncertainty propagation

- Off-diagonal terms contributions to T_B uncertainty



2. Missing MW absorption model uncertainty

Retrieval impact

$$\boldsymbol{S} = \boldsymbol{M} + \boldsymbol{N} + \boldsymbol{P}$$

Total retrieval error covariance matrix (considering model parameter contribution)

$$\boldsymbol{M} = \boldsymbol{D}_y \boldsymbol{S}_\epsilon \boldsymbol{D}_y^T$$

Retrieval measurements error covariance matrix

$$\boldsymbol{N} = (\boldsymbol{A} - \boldsymbol{I})\boldsymbol{S}_a(\boldsymbol{A} - \boldsymbol{I})^T$$

Smoothing error covariance matrix

$$\boldsymbol{P} = (\boldsymbol{D}_y \boldsymbol{K}_b)\boldsymbol{S}_p\left(\boldsymbol{D}_y \boldsymbol{K}_b\right)^T$$

Model parameter error covariance matrix

$$\boldsymbol{D}_y = \partial \boldsymbol{I}(\boldsymbol{y})/\partial \boldsymbol{y}$$

Contribution function matrix (i.e. Jacobian of the inverse model with respect to the measurement)

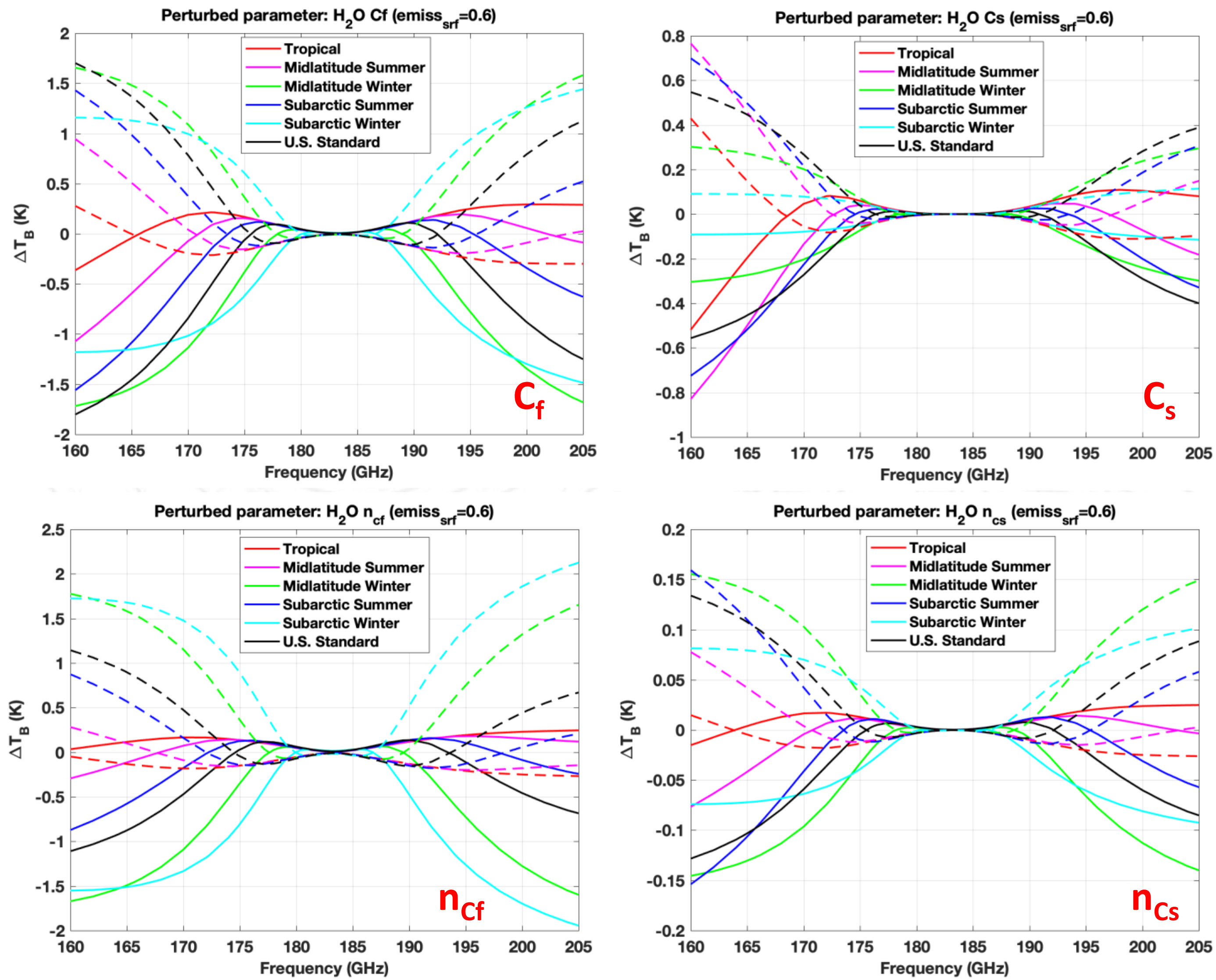
$$\boldsymbol{A} = \boldsymbol{D}_y \boldsymbol{K}_x$$

Averaging kernel matrix

Extending to higher frequency + satellite

- WV continuum coeff. & T expon.

Surface emissivity = 0.6



Extending to higher frequency + satellite

- WV continuum coeff. & T expon.

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