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Deutscher Wetterdienst
Wetter und Klima aus einer Hand

BMD-SEMINAR TALK:

WV-ENHANCE: SYNERGISTIC HUMIDITY DATA ASSIMILATION OF SCANNING MICROWAVE RADIOMETERS AND WV-LIDARS

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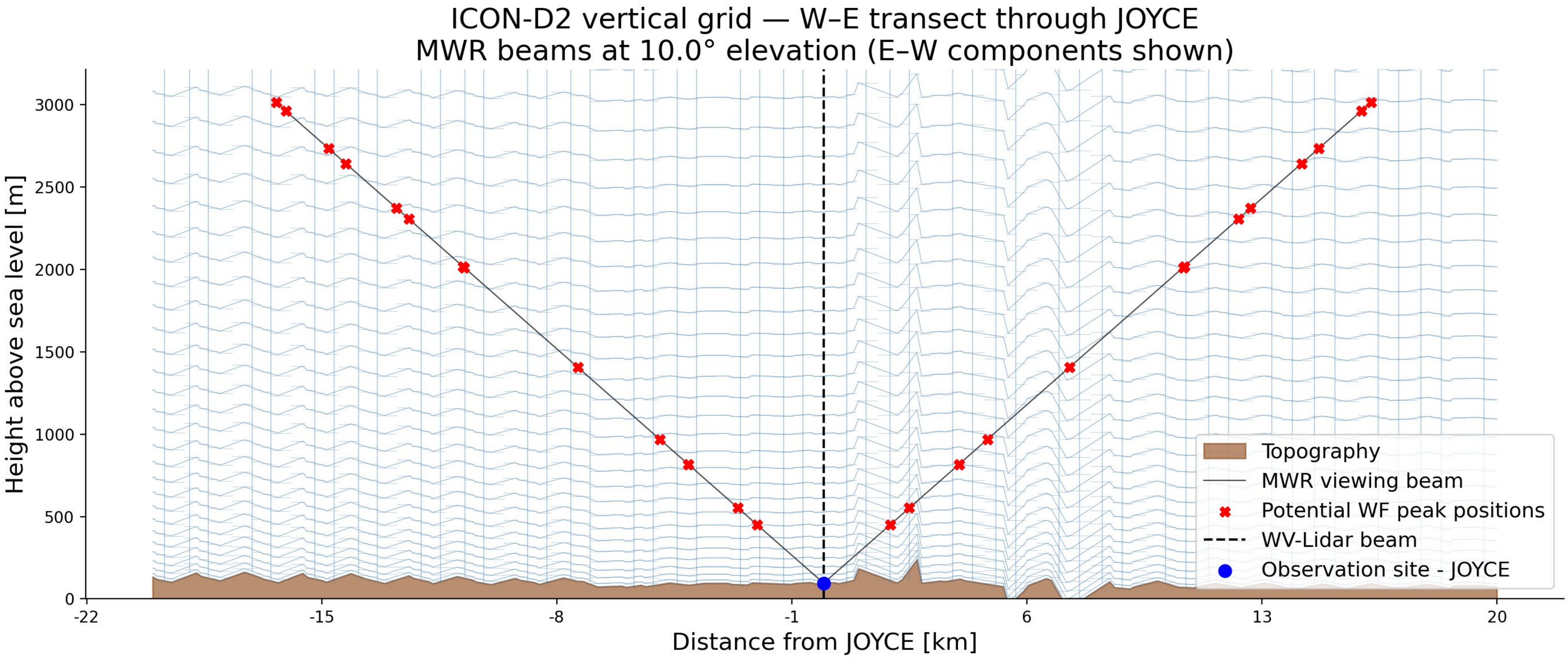
WV-Enhance

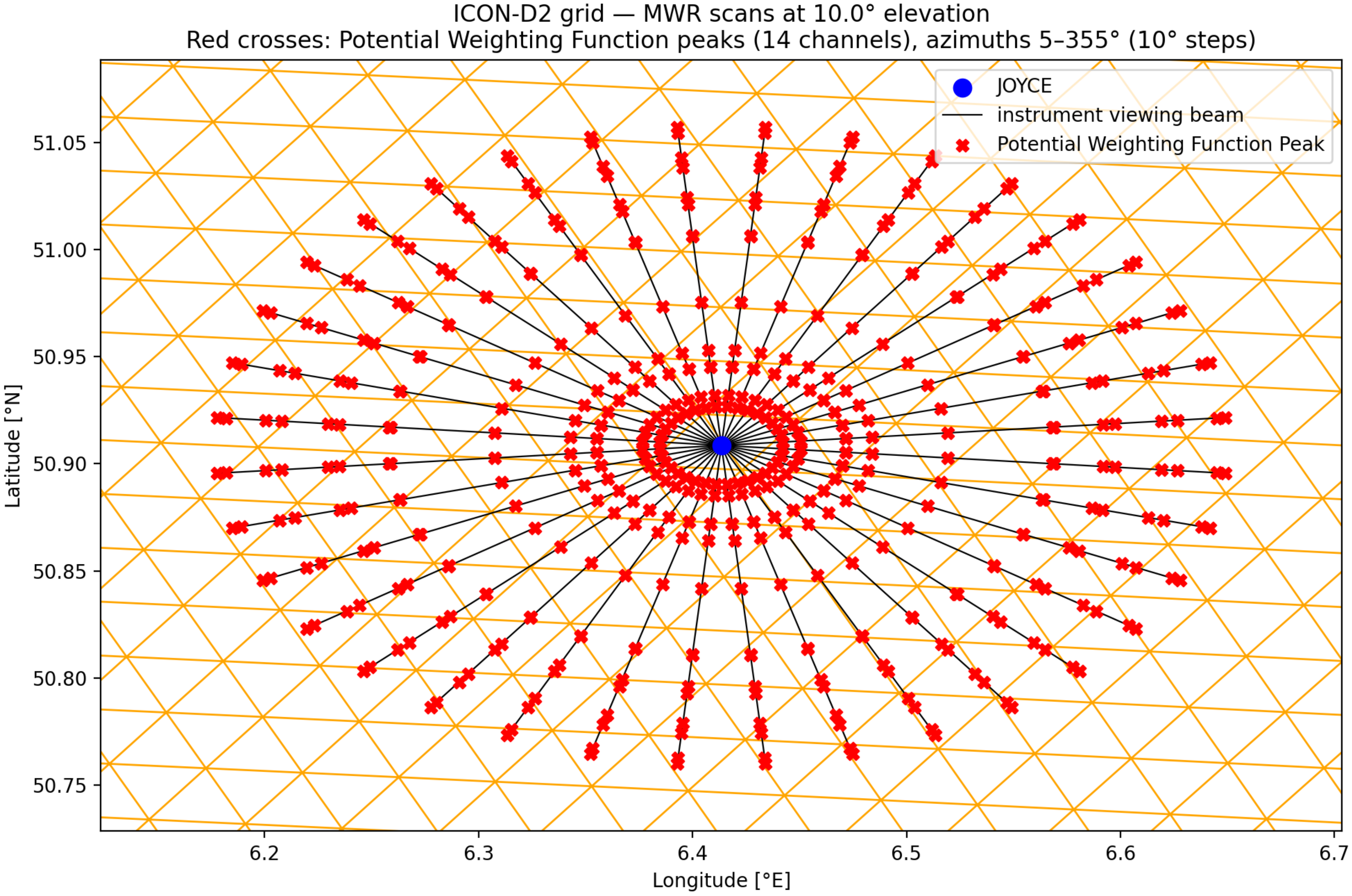
There is an observational gap within the BL!

- Satellite observations do have shortcomings:
  - VIS and IR do not penetrate clouds
  - Ground emissivity disturbs boundary layer (BL) observations even in clear sky
  - Vertical resolution small compared to active ground-based instruments.
- What can close the gap (Creeze et al. 2025)?
  - Radiosondes
  - Water Vapor DIfferential Absorption Lidar (WV-DIAL)
  - Water Vapor Raman Lidar (WV-RL)
  - MicroWave Radiometers (MWRs)
  - UAS (drones)


ICON-D2 vertical grid — W–E transect through JOYCE
MWR beams at 10.0° elevation (E–W components shown)
Height above sea level [m]
3000
2500
2000
1500
1000
500
0
-22
-15
-8
-1
6
13
20
Distance from JOYCE [km]
Topography
MWR viewing beam
Potential WF peak positions
WV-Lidar beam
Observation site - JOYCE

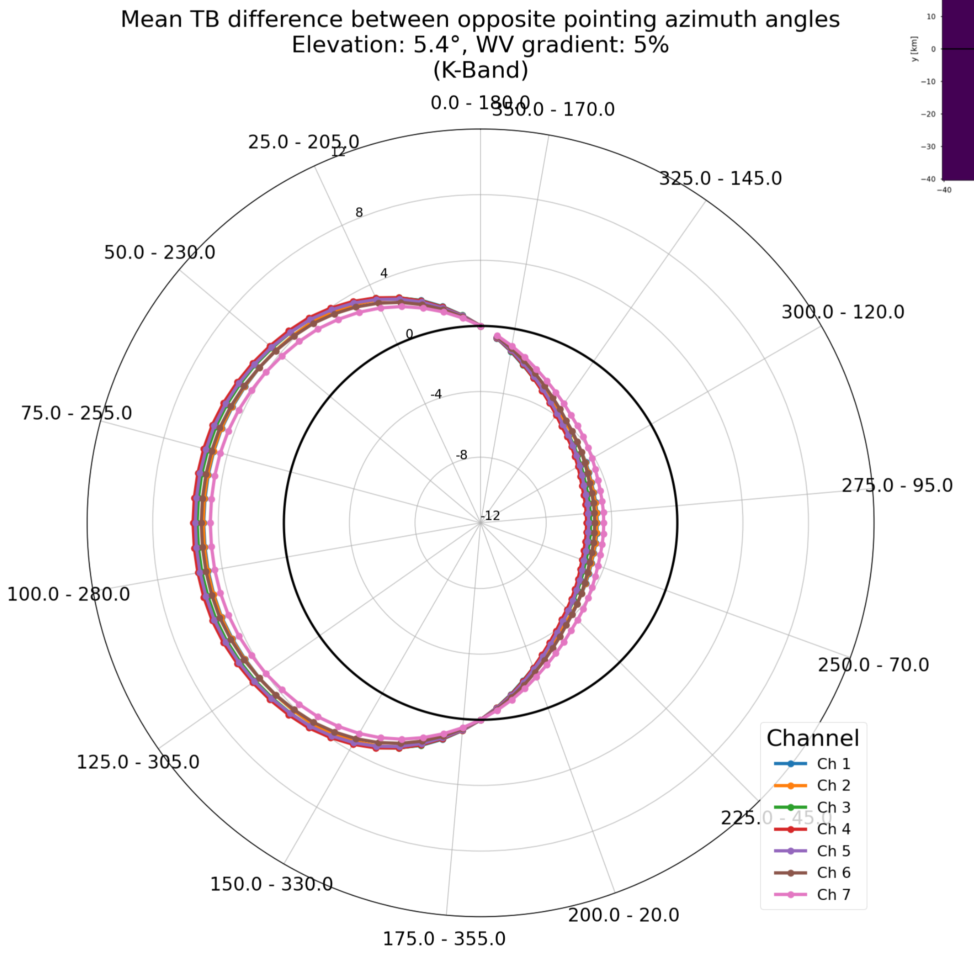
WV-Enhance:

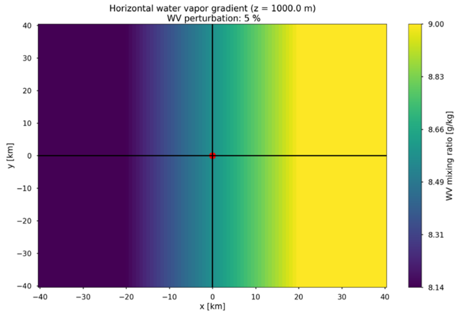
- Synergy of lidar and microwave radiometer (MWR) water vapor (WV) observations.



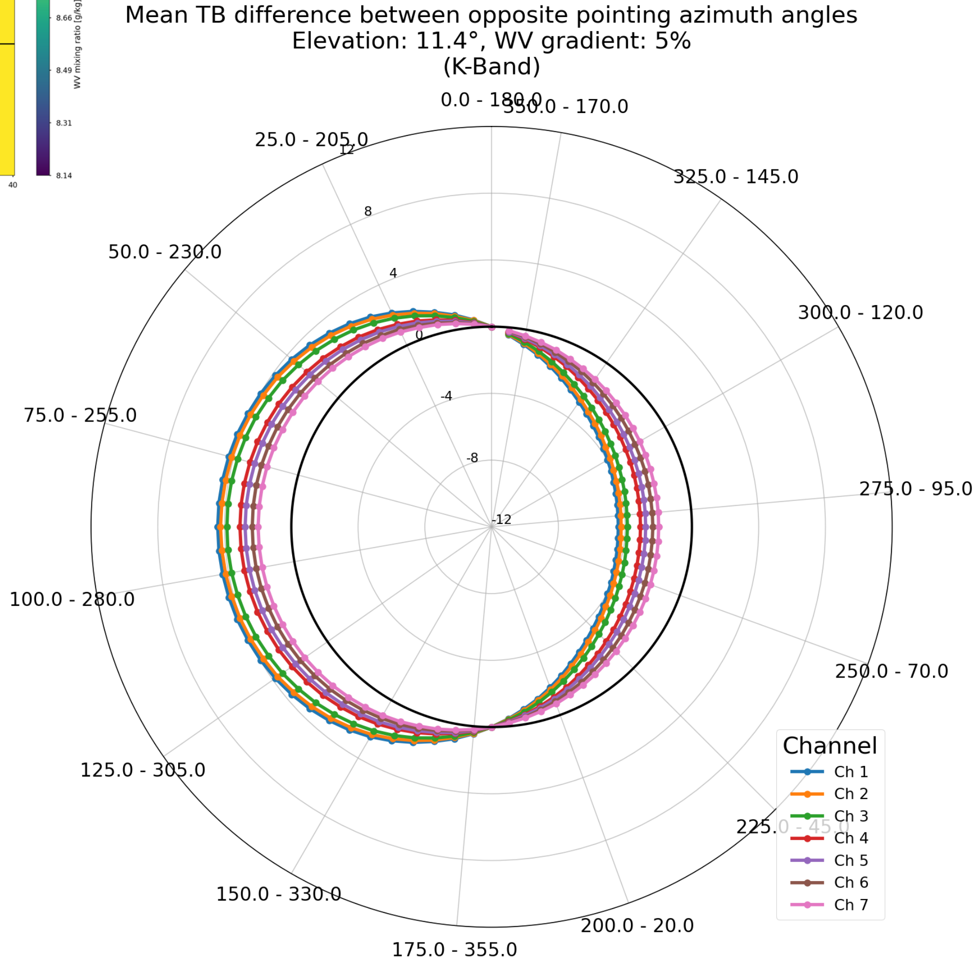
Horizontal gradient in scanning MWR

5.4° Elevation

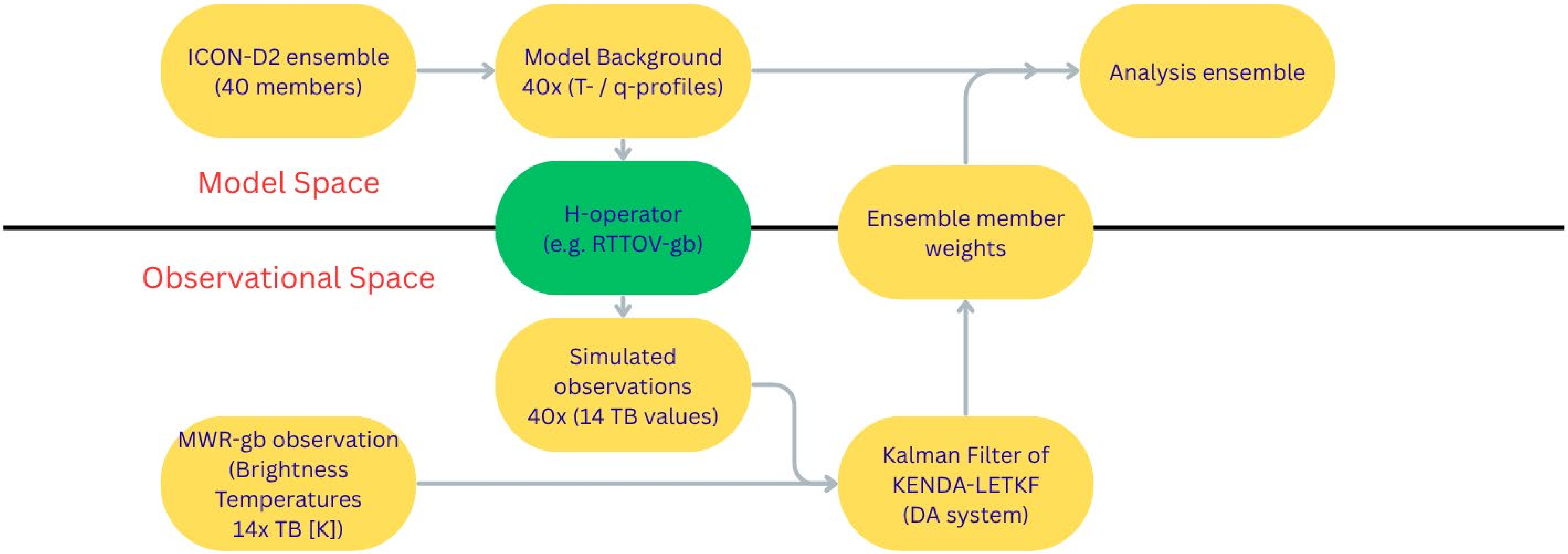




11.4° Elevation



MWR data assimilation into ICON-D2



How to estimate an error in data assimilation

- An observation error in data assimilation (DA) consists of measurement error and representation error:

$$\epsilon^{O} = \epsilon^{M} + \epsilon^{R}$$

- We know for MWRs $\boldsymbol{\epsilon^{M} \leq 0.5\ K}$ (Rose et al., 2005)
- The representation error itself consists of observation-operator-error (H), unresolved-scales-error (S) and preprocessing/QC-error (Janjic et al., 2018):

$$\epsilon^{R} = \epsilon^{S} + \epsilon^{\boldsymbol{H}} + \epsilon^{QC}$$

Paper-outline:

Towards Assimilation of Scanning Microwave Radiometer Observations into ICON-D2: An Elevation-Dependent Evaluation of RTTOV-gb and ARMS-gb

Introduction

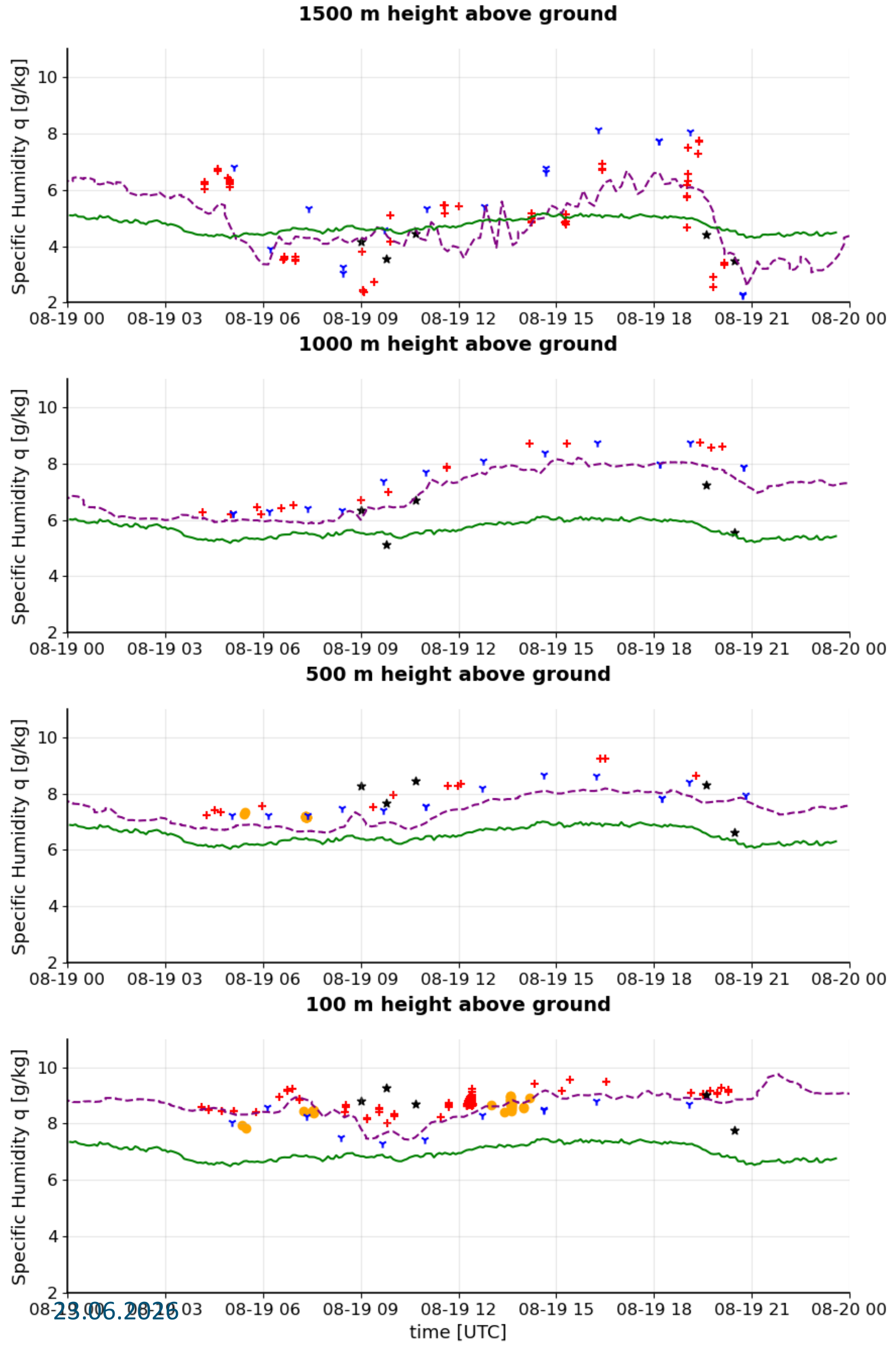
Introduction / background

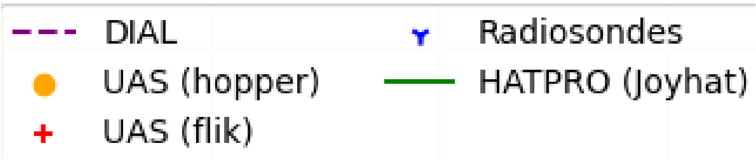
- Several studies have investigated ground-based microwave radiometer data assimilation:
  - ➢ Either indirect assimilation of thermodynamic profiles (Caumont et al. 2016, Thomas et al. 2024)
  - ➢ Or direct assimilation of brightness temperatures (Vural et al. 2023, Ikuta et al. 2025)
- Direct assimilation proved to yield better results (Cao et al. 2023)
- All of the studies so far focused on zenith-pointing observations and used slant path at most for corrections under assumed horizontal homogeneity in opaque channels (Martinet et al. 2017).
- Slant path so far yielded higher errors and additional challenges for quality control.

Data & Methods

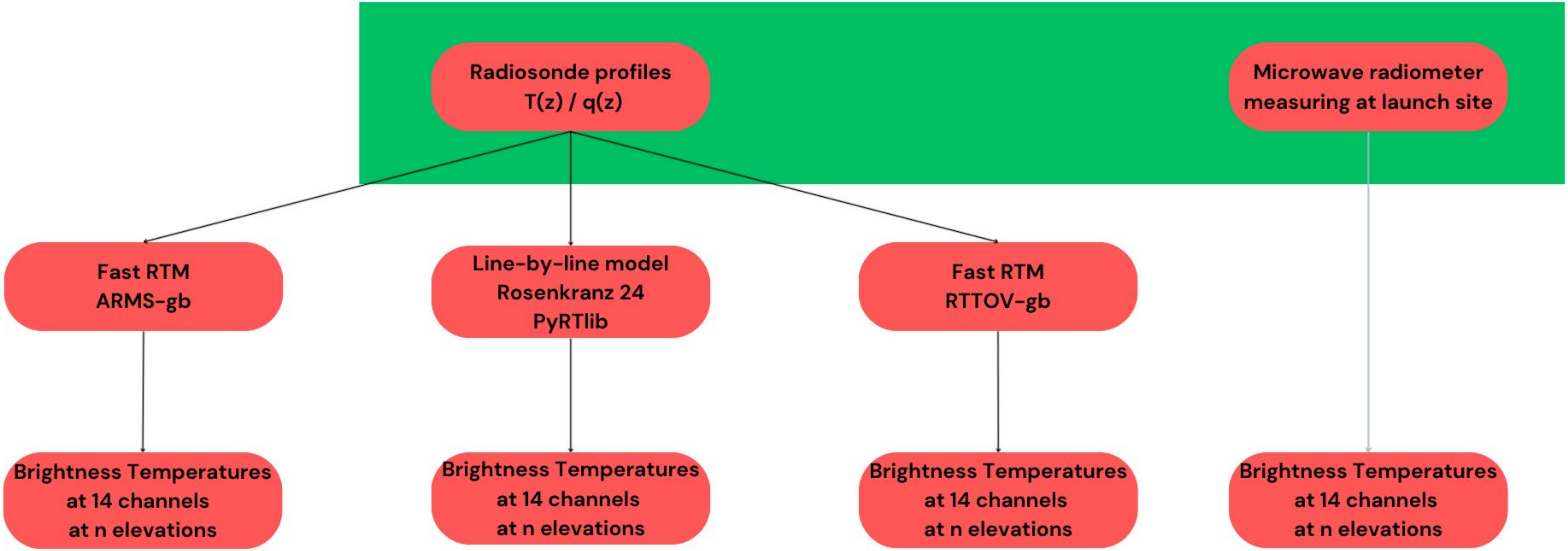
Datasets:

- FESSTVaL (May-August 2021 / Lindenberg, Germany):
  - Over 400 radiosonde launches and complementary MWR data
  - See: Hohenegger et al. 2023
- Vital I campaign (August 2024 / Jülich, Germany)
  - Investigated potential of novel observation strategies
  - Sensor synergy (e.g. satellite and MWR-gb combined retrievals)
  - 48 Radiosonde launches and complementary MWR data

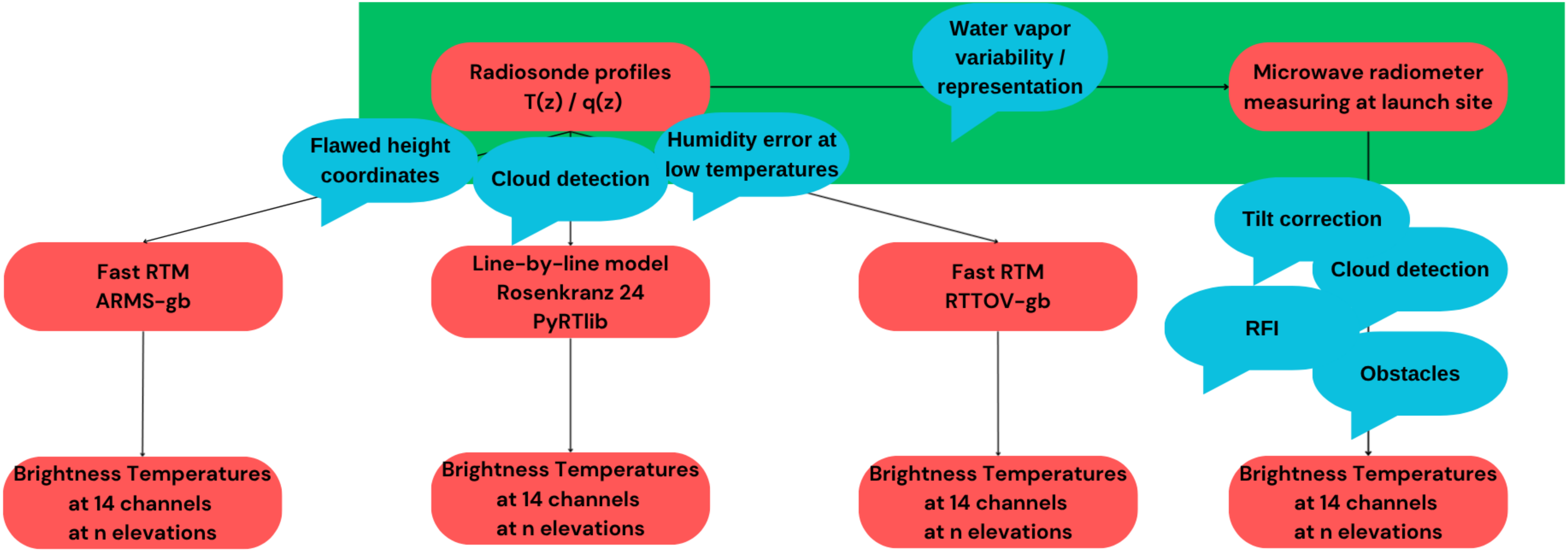




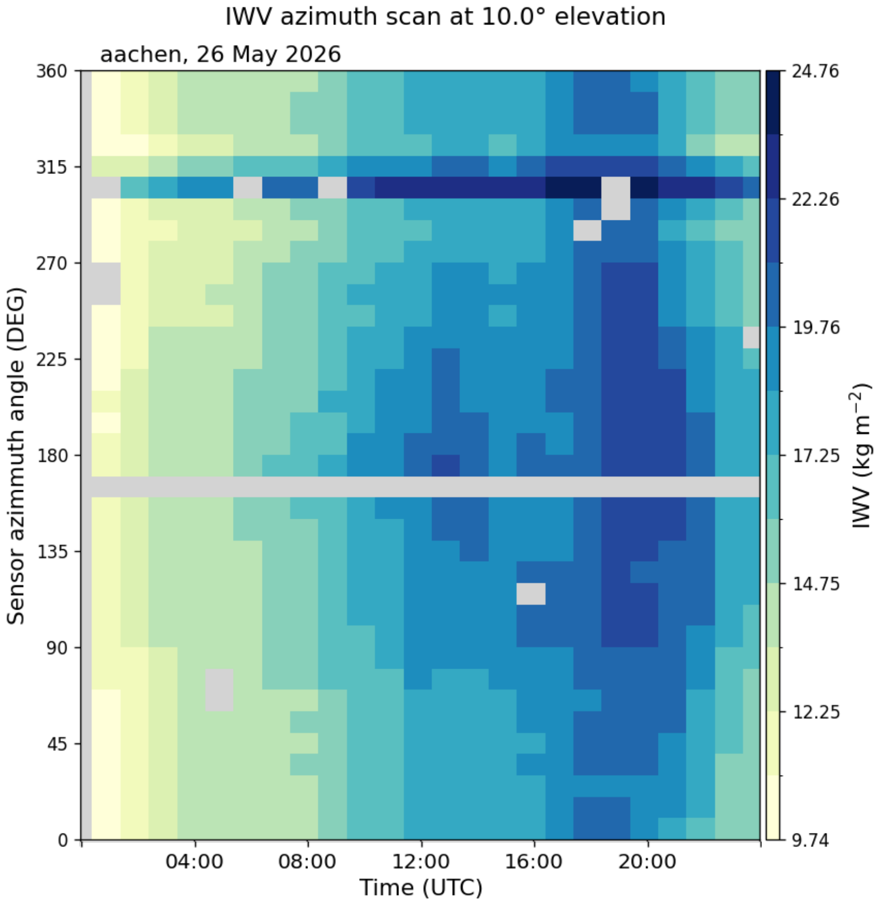
Methods

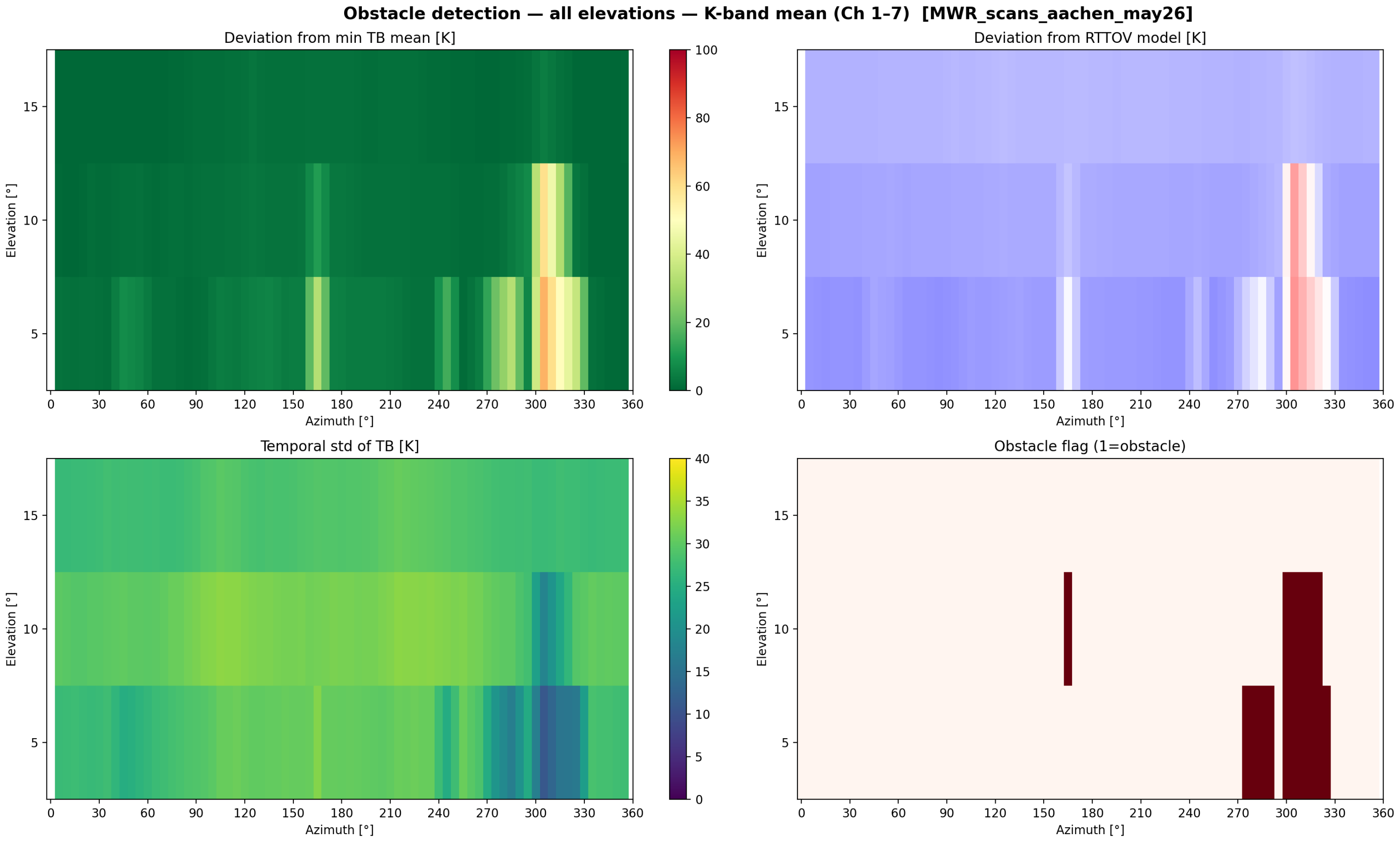

Radiosonde profiles
T(z) / q(z)
Microwave radiometer
measuring at launch site
Fast RTM
ARMS-gb
Line-by-line model
Rosenkranz 24
PyRTlib
Fast RTM
RTTOV-gb
Brightness Temperatures
at 14 channels
at n elevations
Brightness Temperatures
at 14 channels
at n elevations
Brightness Temperatures
at 14 channels
at n elevations
Brightness Temperatures
at 14 channels
at n elevations

Methods
=> How to distinguish between WV variability and error?

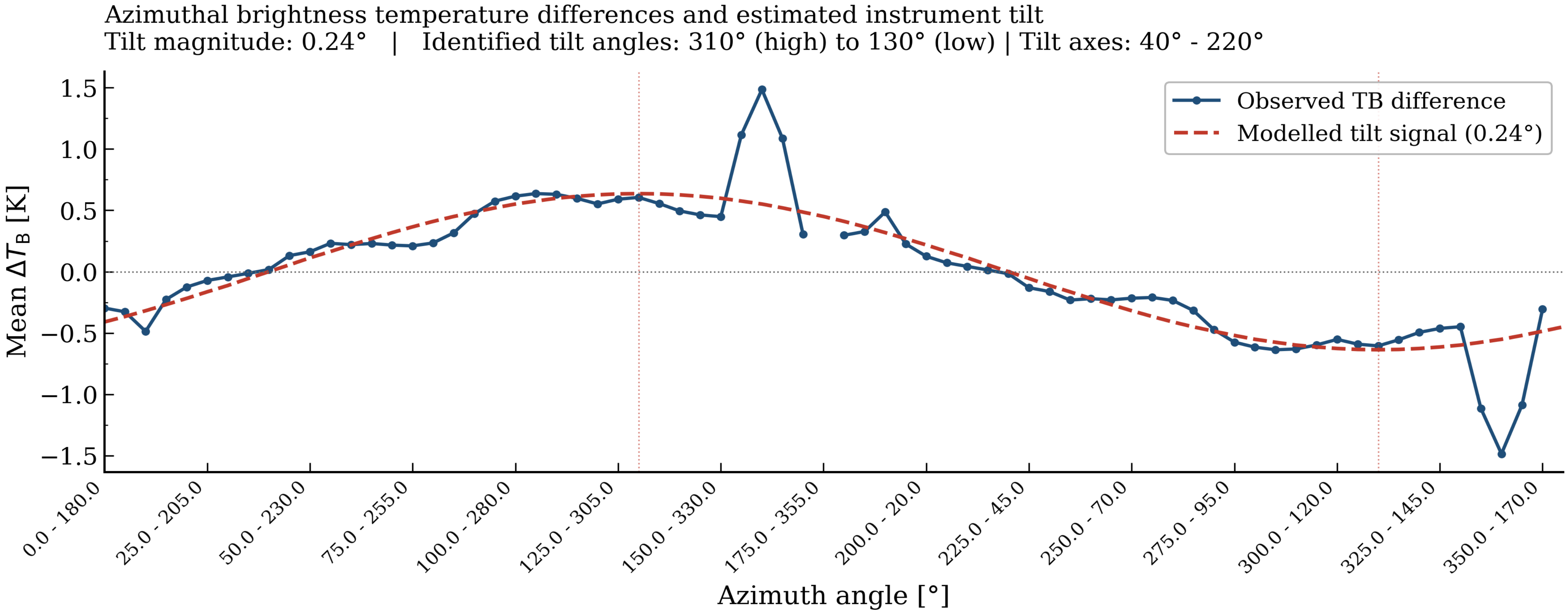


Obstacles need to be excluded



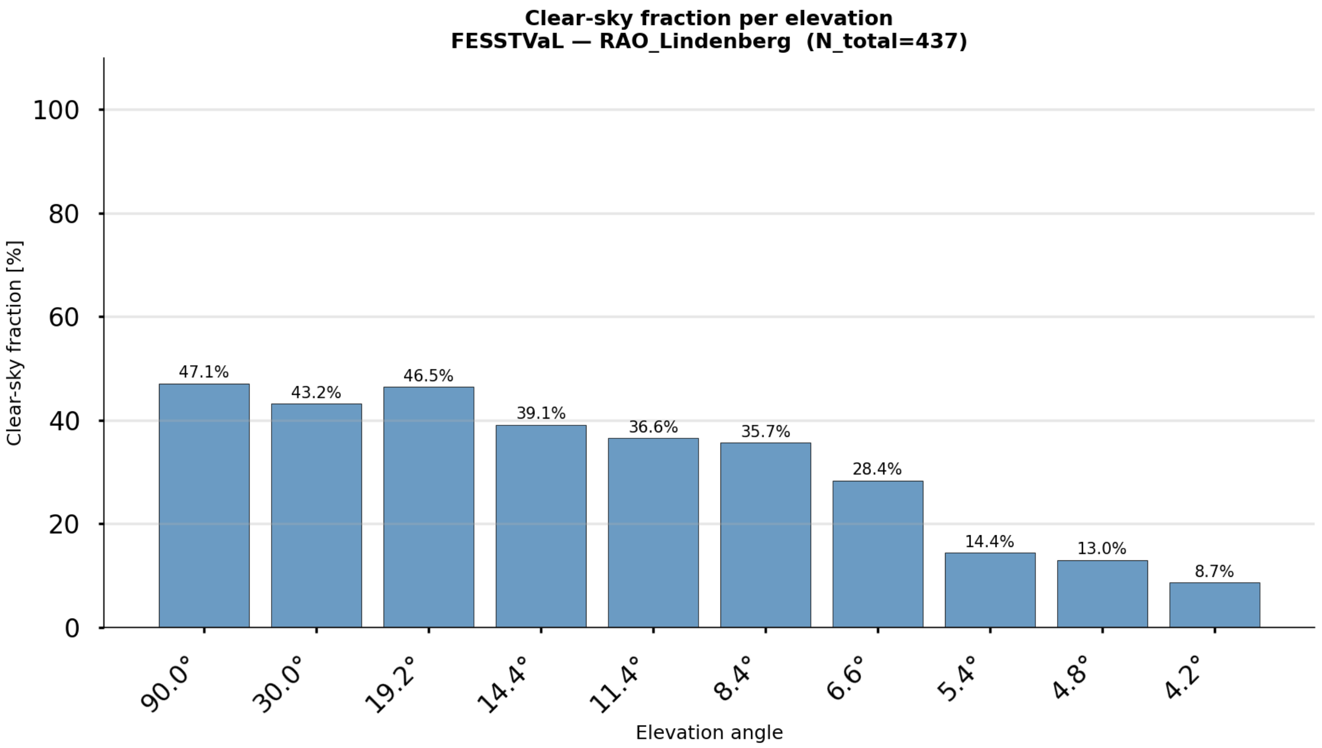


Instrument tilts can be determined and corrected (MWR during FESSTVaL)



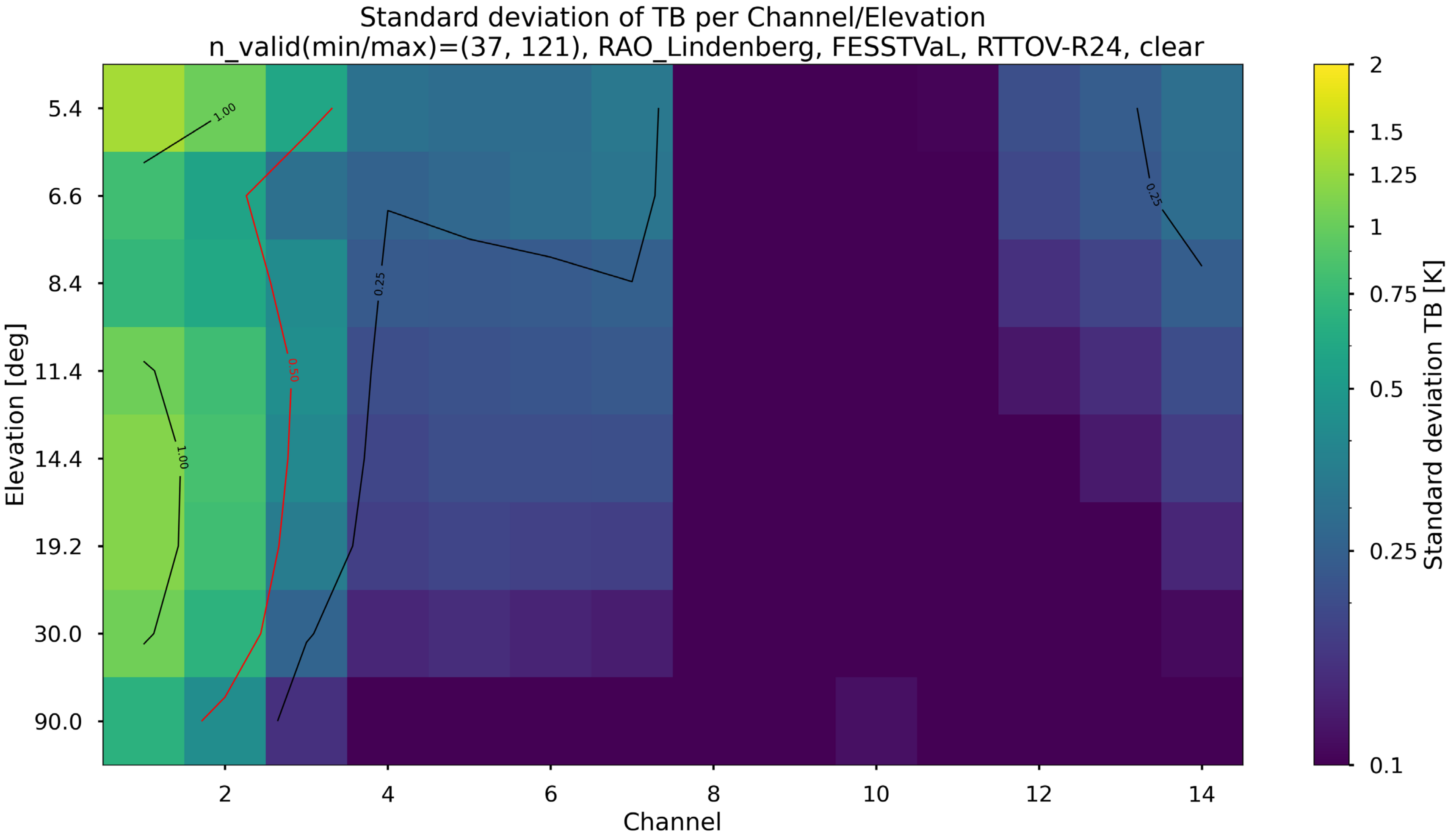
Cloudy observations need additional care

- Cloud flagging is required for assimilation with adaptive errors (Vural et al. 2023)
- Cloud flagging is far from trivial for slant path (not enough datapoints for standard deviations)
- A novel cloud flagging via Neural Network is used on FESSTVaL data (coming up for Vital I also)



Results

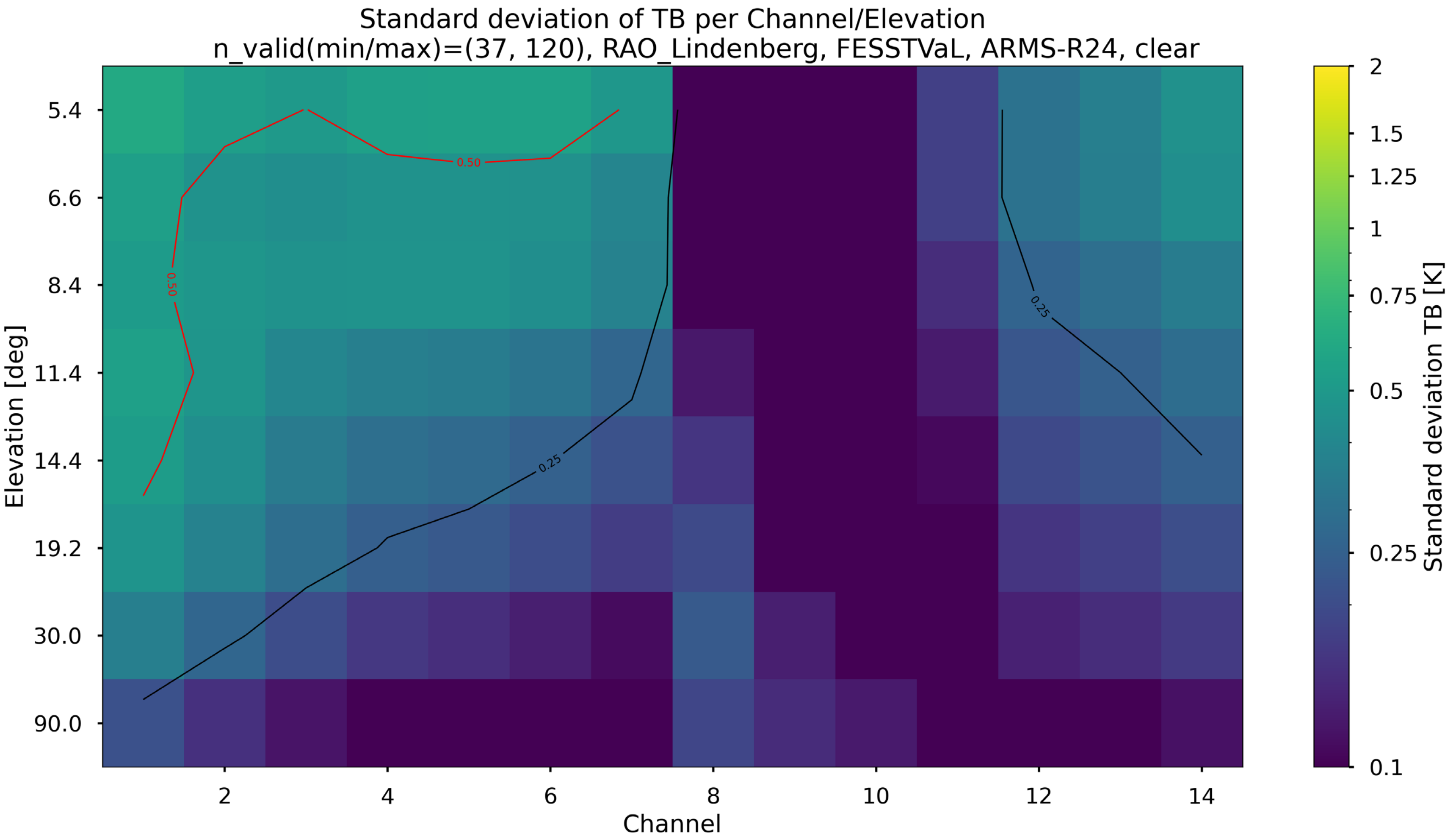
H-operator error by channel and elevation: RTTOV-gb



K-Band (channels 1-7) | V-Band (channels 8-14)

- Fast radiative transfer model RTTOV-gb compared to Rosenkranz24 accurate Line-by-line-model (LBL)
- For channels 3-14 and even at low elevations we find $\epsilon^{H} \leq \mathbf{0.5}\ \boldsymbol{K}$

H-operator error by channel and elevation: ARMS-gb



K-Band (channels 1-7) | V-Band (channels 8-14)

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Ê Ì ∑ª ‡Ů wa {‼»∞
±Ì Ê ˙ £″ª ∑Ůð Ì Ů
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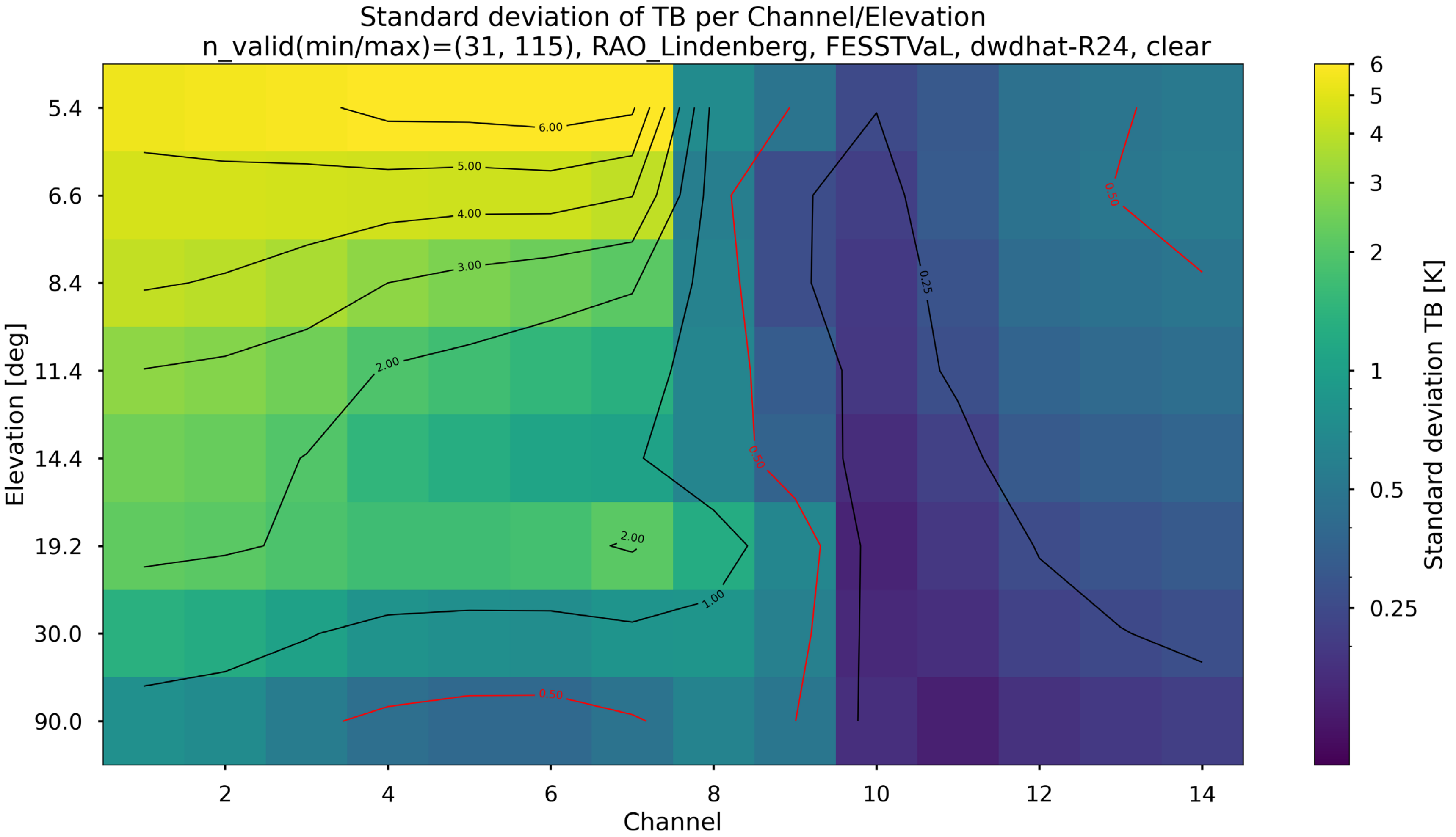
Line-by-line-model ⇸, [↓

CÌ ″Ů±œ£ÁÁª ‡ŮŃ‼łŇŮ£Á∑Ů
ª ğª ÁŮ£ðŮª ‡ª ğ£ðÌ Áł ŮŮ╗
İ ª Ůę Á∑Ů $\epsilon^{H} \leq 0.5\ K$

FESSTVaL: MWR against radiosonde



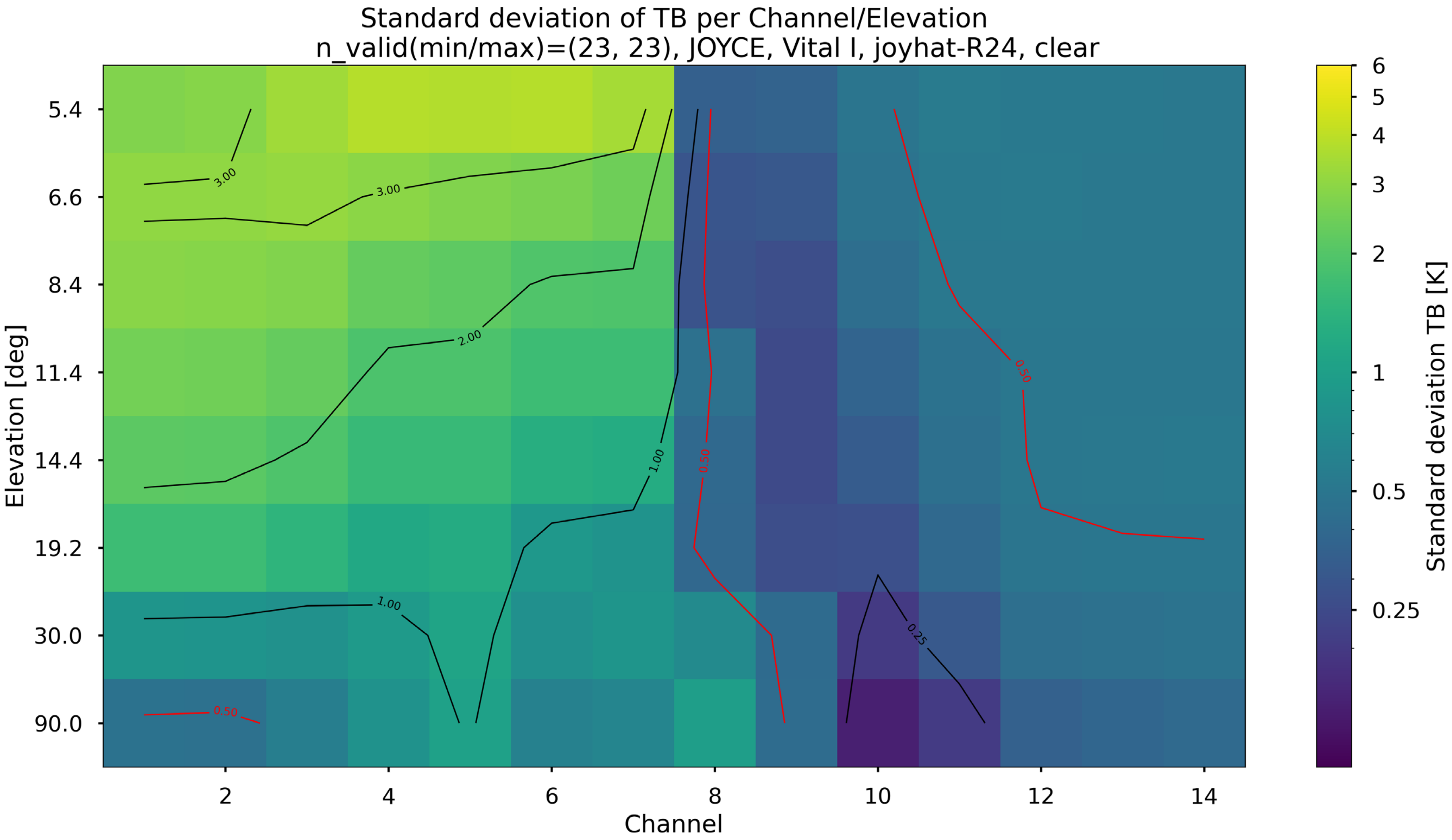
K-Band (channels 1-7) | V-Band (channels 8-14)

MWR compared to R24-LBL output of radiosondes (horizontal homogeneity assumed!)

These values contain:

- Quality control error: $\in^{QC}$
- Measurement error: $\in^{M} \leq 0.5$ K
- Operator error: $\in^{R24}$
- Water Vapor variability that we in fact want to observe

Vital I: MWR against radiosonde



K-Band (channels 1-7) | V-Band (channels 8-14)

MWR compared to R24-LBL output of radiosondes (horizontal homogeneity assumed!)

These values contain:

- Quality control error: $\in^{QC}$
- Measurement error: $\in^{\mathrm{M}} \leq 0.5$ K
- Operator error: $\in^{\mathrm{R24}}$
- Water Vapor variability that we in fact want to observe

Discussion & Outlook

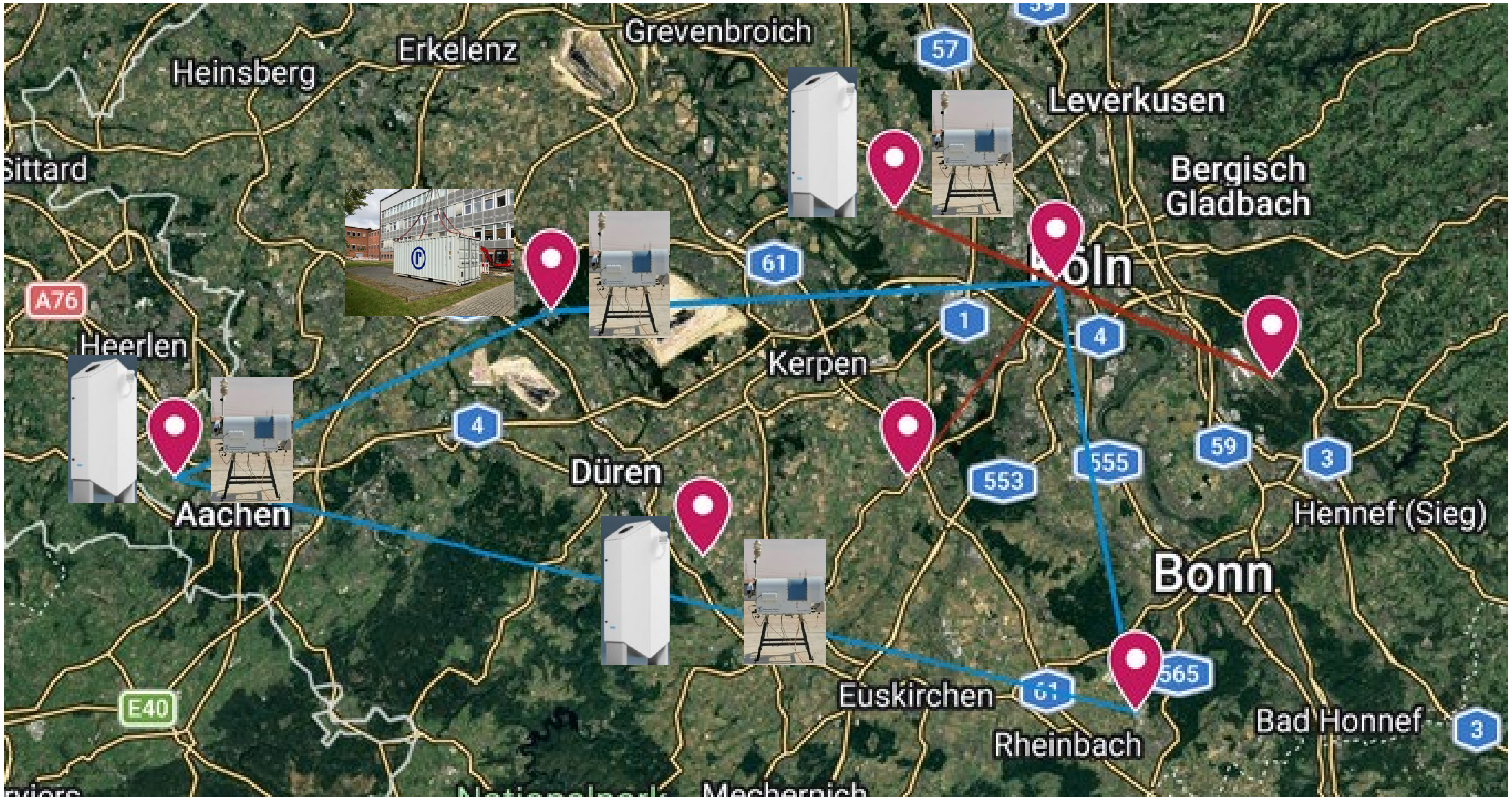
Summary

- Which channels to use for slant path MWR-gb data assimilation?
  - ➢Hopefully all (depending on non-diagonal R-matrix becoming available in KENDA-LETKF soonish)
  - ➢But also assimilation of 2 channels would yield some information (Ikuta et al. 2025, Vural et al. 2023)– e.g. ch 7 + ch 10 (based on operator errors).
- Which elevation angles to use for slant path MWR-gb data assimilation?
  - ➢10° elevation probably offers a better compromise between coverage and errors than 5°.
- But once proper data assimilation is performed O-B-statistics have to be considered.

Vital II campaign (June-August 2026)

VITAL Campaigns

Vertical profiling of the troposphere:
Innovation, optimization and application



Outlook

- How to exclude water vapor variability for radiosonde and MWR comparison?
    - ➢Determining gradient of regression between water vapor standard deviation and TB deviation between MWR and simulated TBs from radiosonde. Subtracting WV variability x gradient of deviation by WV.
- Applying Neural Network for cloud detection to all parts of my dataset
- Working further on good quality control: (1) tilt correction, (2) RFI filtering, (3) exclusion of obstacles.
- Possibly also including Vital II data in autumn.
- Going through with proper Vital II data assimilation for WV-lidars and scanning MWRs in winter.

The End

- Thank you very much for your attention!

Acknowledgements

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DWD

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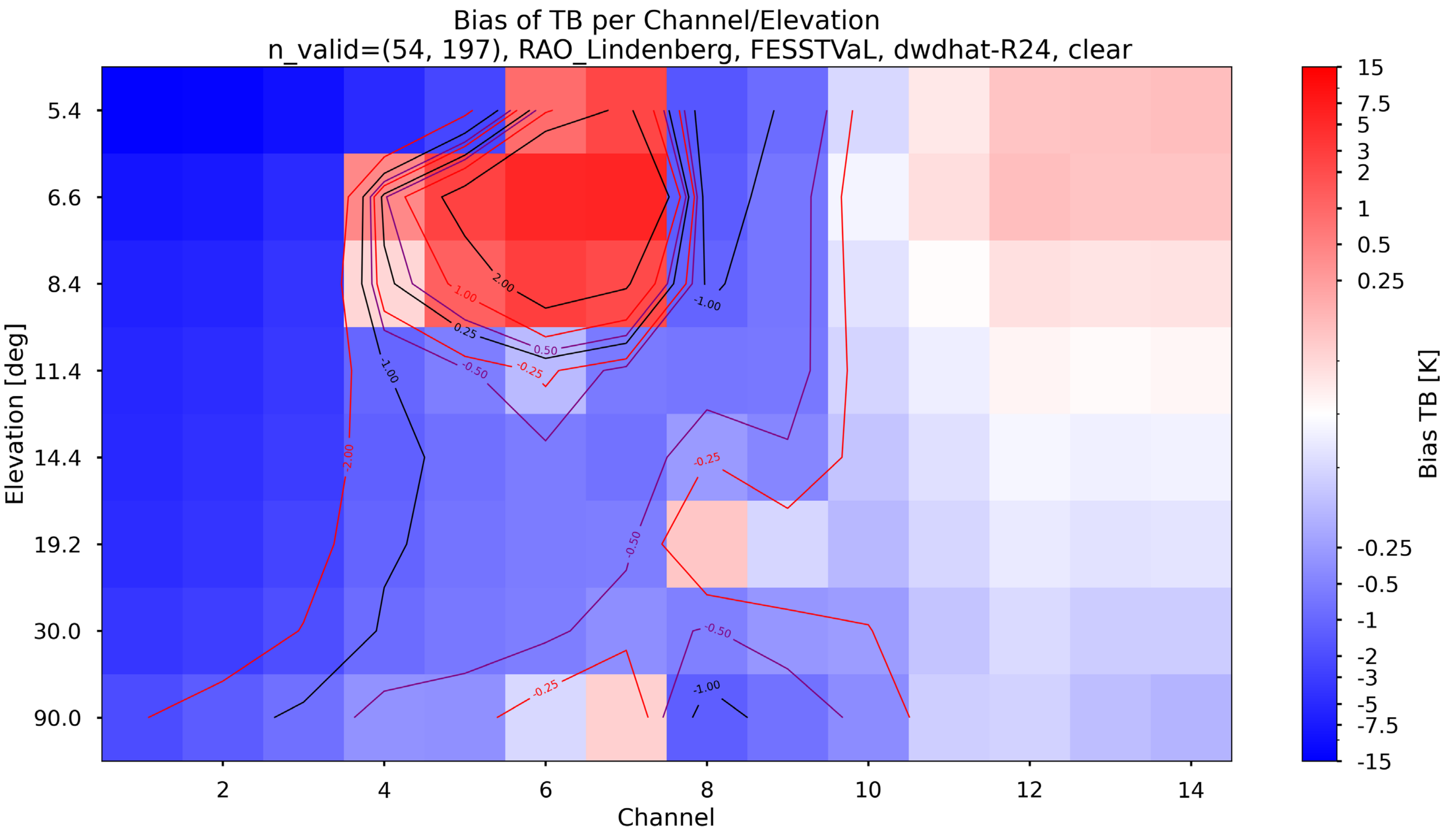
- The authors gratefully acknowledge the provision of observational data from the FESSTVaL 2021 campaign (PI: C. Hohenegger, MPI-M Hamburg)and the Vital I 2024 campaign (PI: U. Löhnert, University of Cologne). This work will further benefit from the upcoming Vital II campaign.
- The PhD project underlying this work is supervised by U. Löhnert, M. Toporov, and A. Schomburg, whose guidance is gratefully acknowledged.

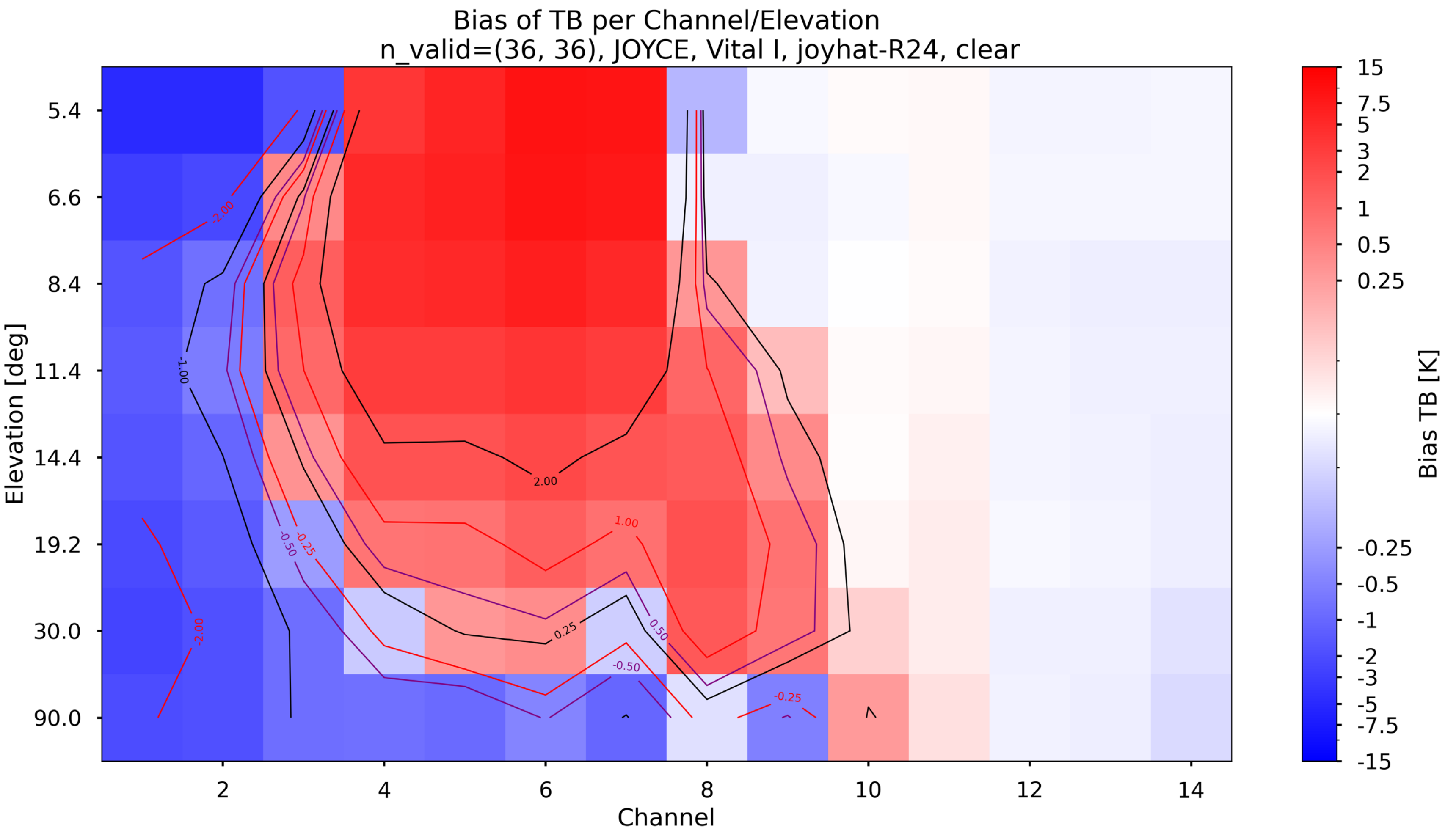
FESSTVaL: MWR against radiosonde (Bias)



MWR compared to R24-LBL output of radiosondes (horizontal homogeneity assumed!)

K-Band (channels 1-7) | V-Band (channels 8-14)

Vital I: MWR against radiosonde (Bias)



MWR compared to R24-LBL output of radiosondes (horizontal homogeneity assumed!)

K-Band (channels 1-7) | V-Band (channels 8-14)

Why MWRs and DIALs are made for each other

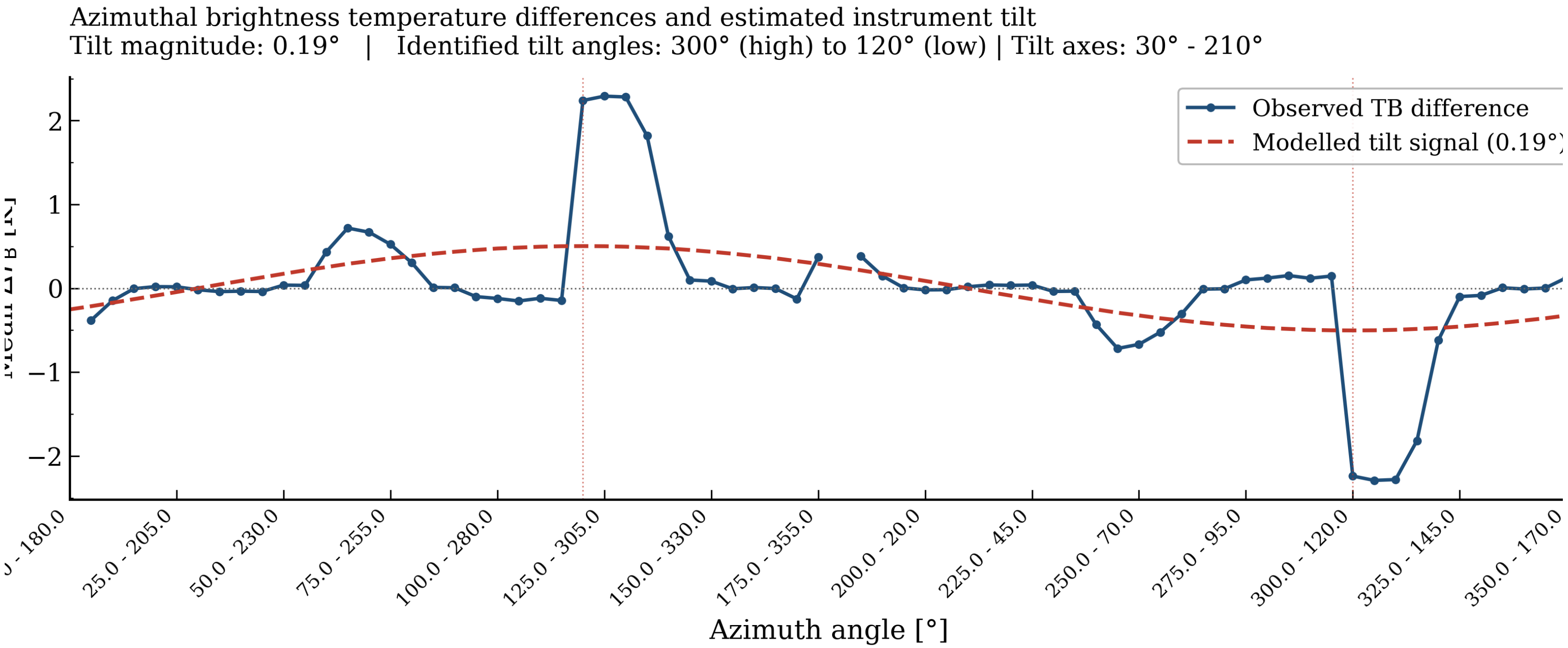
MWR

- Cloud penetrating
- Accurate Liquid Water Path (LWP)
- Temperature profiles
- Not aerosol dependent

WV-DIAL

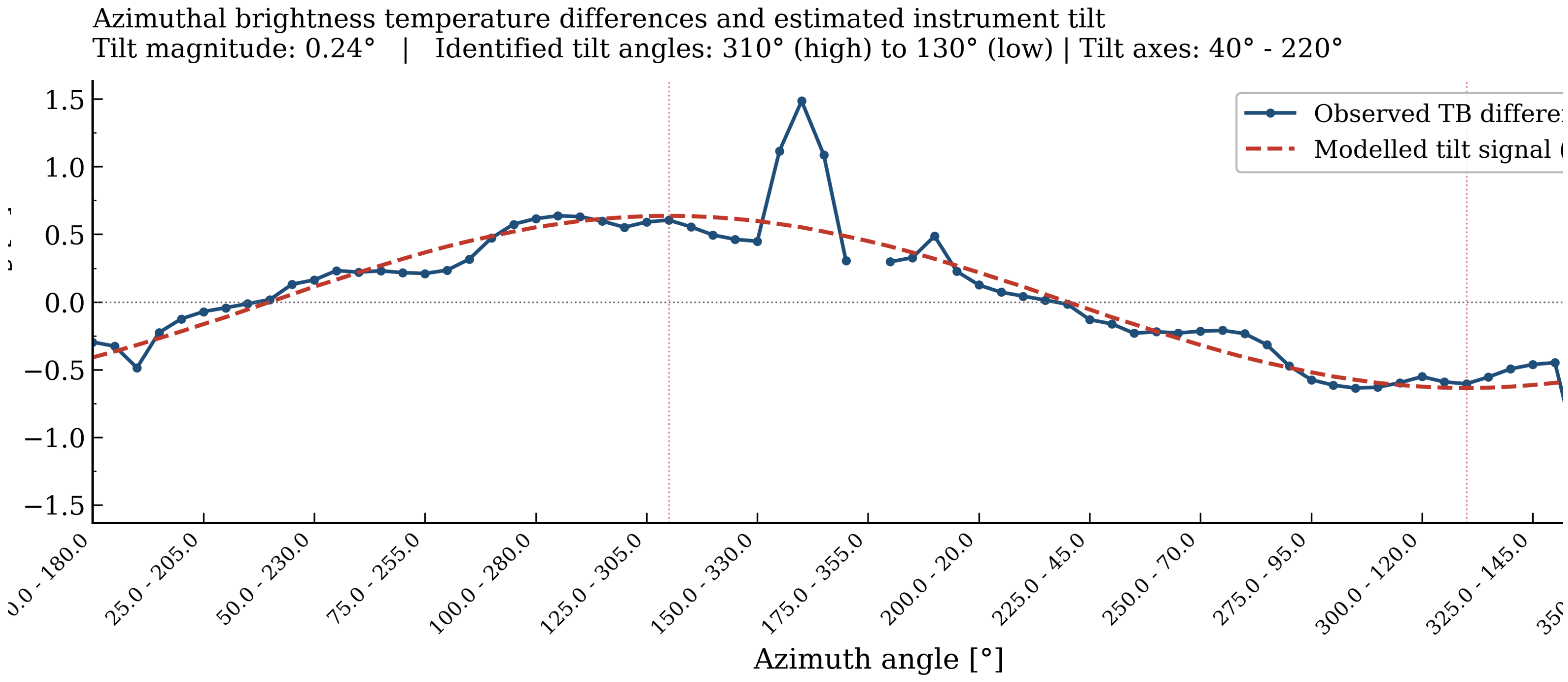
- Non-cloud penetrating
- High vertical resolution
- No temperature profiles
- Aerosol dependency limits to BL

Instrument tilt



Joyhat
(upper; Vital I
June-September 2024)

Foghat
(lower FESSTVaL
May-Aug 2021)



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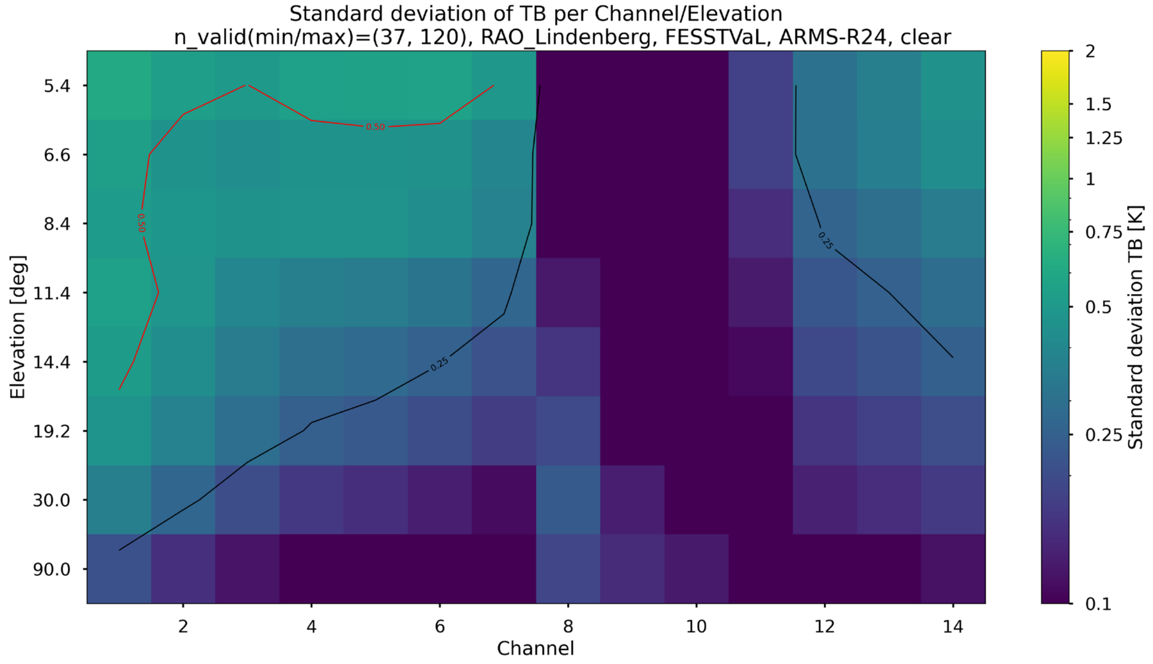
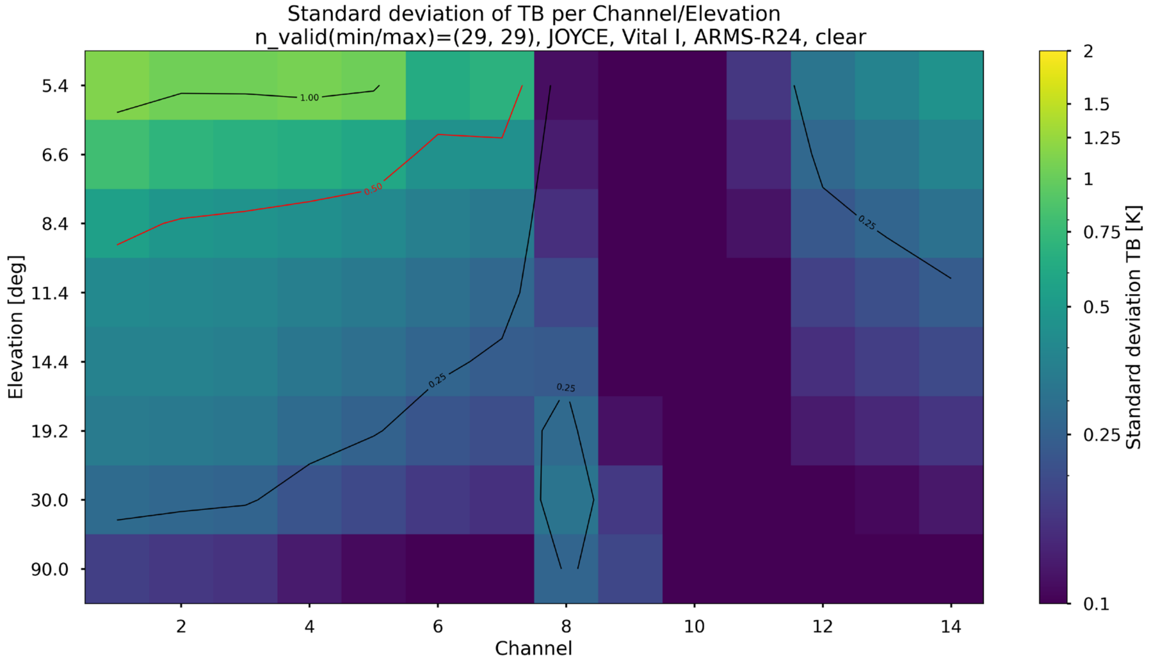
Same for ARMS-gb (Shi et al. 2025)

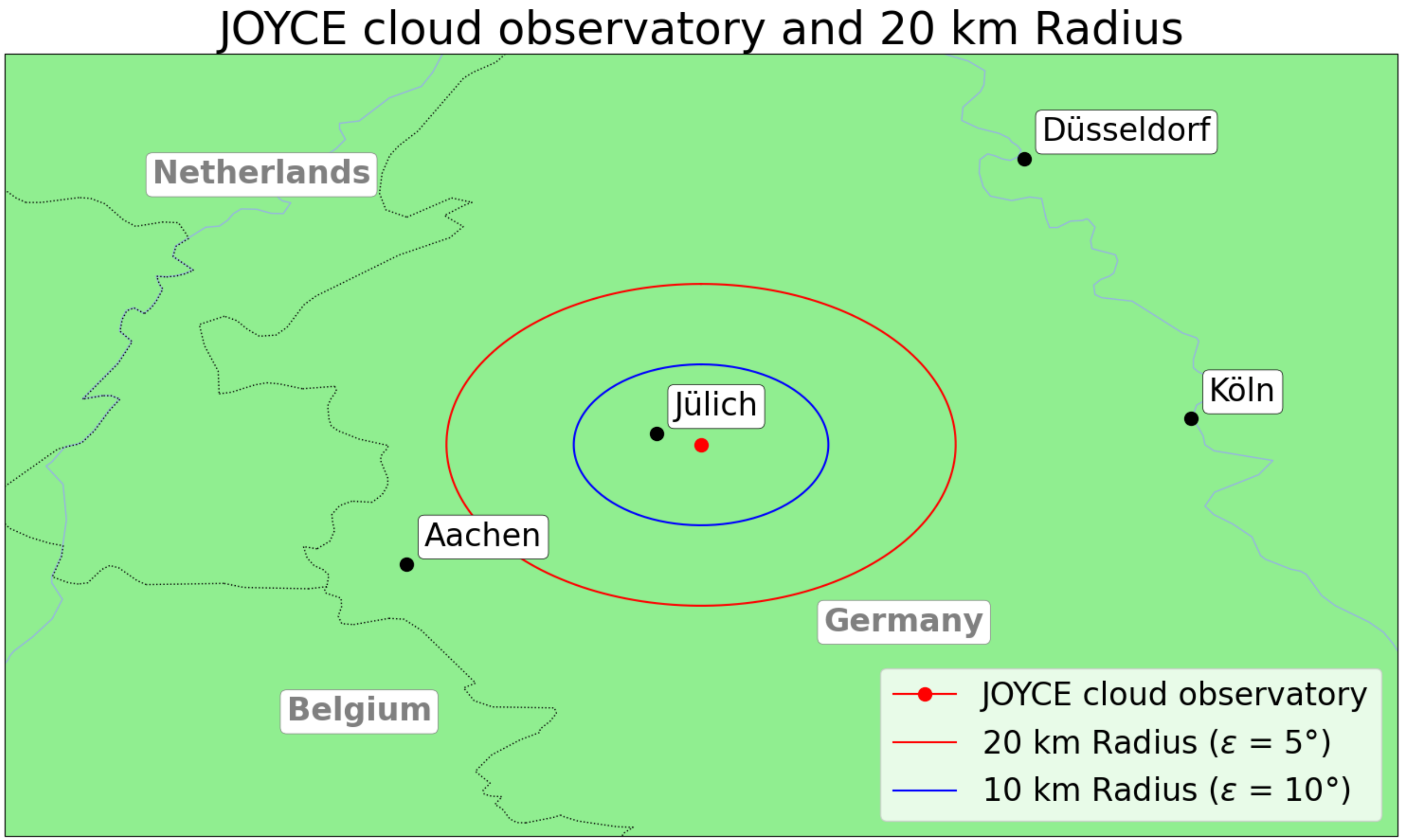
Direct assimilation of MWR brightness temperatures yields better results (Cao et al., 2023)…

…but it needs an H-operator.





Synergistic setup of DIAL and scanning MWR for DA



- Circles show radius within 2 km deep BL

DIALs are a great candidate to fill part of the gap

- DWD already works on an operational network of 13 instruments

=> Check out talks by Nina Raabe and Jens Pruschke

Questions

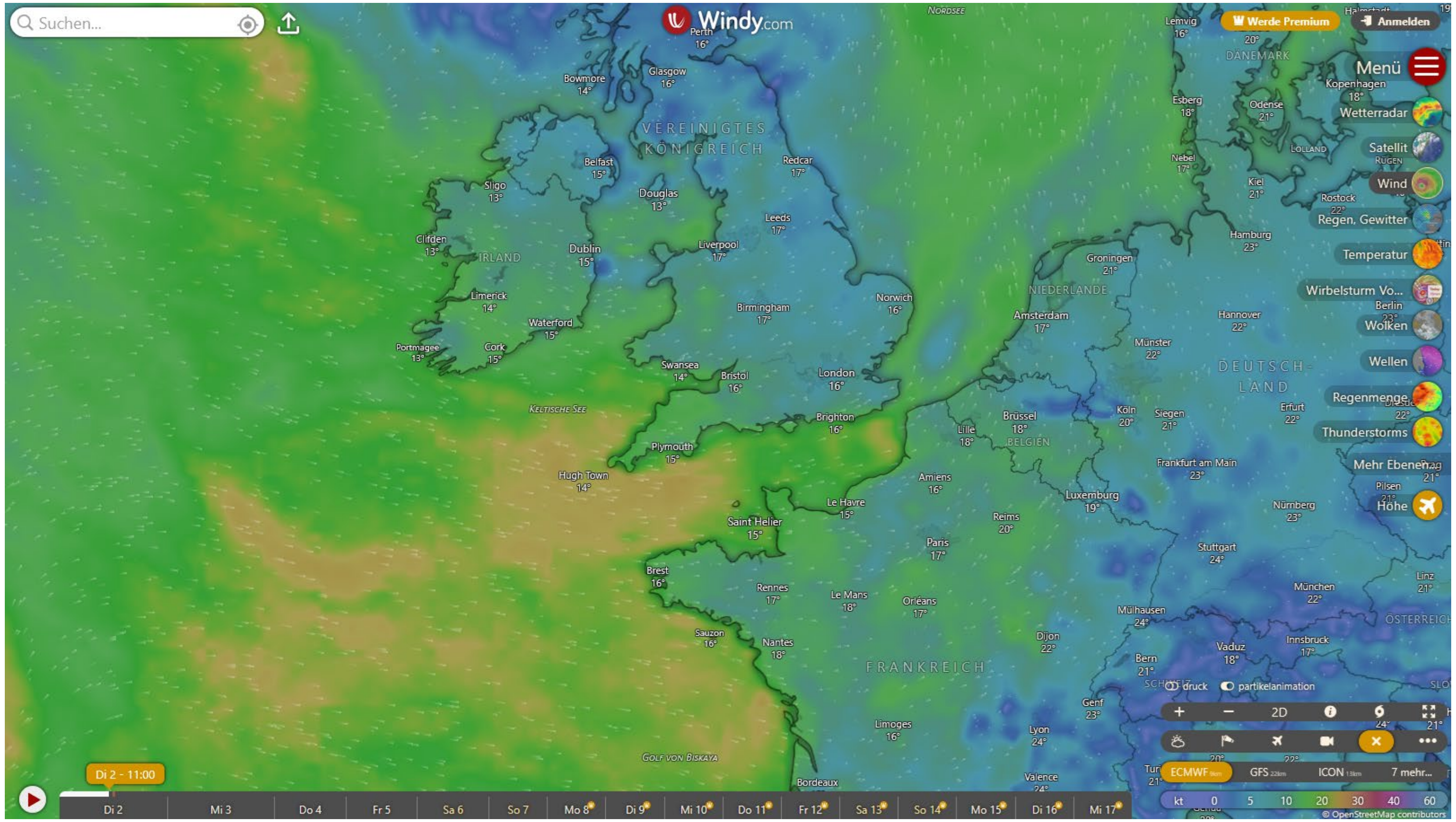
- How to identify WV variability in standard deviations of elevations. If I derive WV variability from 360° Azimuthscans and subtract them from the calculated std, I basically treat the whole measurement as measurement without error…
- How much of my measurements will be thinned out by the current KENDA-LETKF DA-system anyways, because of the relative closeness of these observation points?
- Who needs to be named as an author? How about Bernhard and Tobias?

Numerical weather prediction works like a PC game

1. We determine the state of the atmosphere
2. With the laws of physics we calculate further movement of air parcels and thermodynamic processes within them stepwise

Determining the state of the atmosphere is far from trivial:

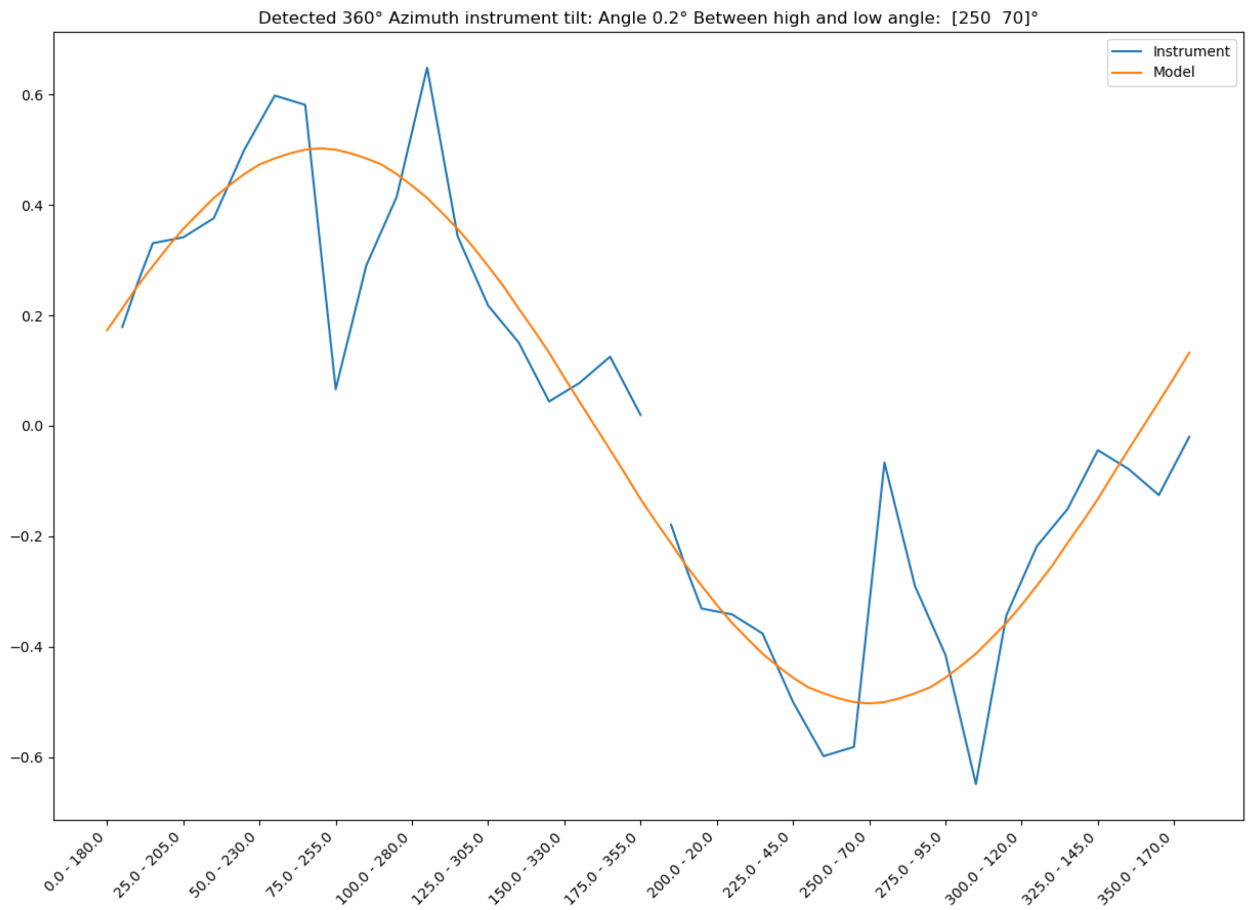
A former forecast (background) is corrected with current observations under consideration of the forecasts and the observations respective errors (Data Assimilation).



Source: Windy.com

Other error sources

- Instrument tilt:



Next steps

- Derive Jacobians / Weighting functions of MWRs (PyRTlib and RTTOV-gb)
- How to quantify horizontal WV-variability vs. random error?
- How to determine obstacles in Azimuth scans in data? (Important for Vital II !)
- How to apply Moritz‘ NN for cloud detection to Vital I data?
- Work on timeseries of Tilt error and correction of it.
- Correlations between angles and channels…(?).

Dataset and Methods so far

- Campaigns: FESSTVaL, Socles and Vital I
- Atmospheric profiles from 521 radiosondes
- Collocated HATPRO MWR TBs (max dt=15 min from radiosonde start)
- Vertical profiles standardized to 180 levels up to at least 10 km and referenced to height above sea level
- Thinned and smoothed radiosonde profiles with enhanced resolution below 3 km and climatological extension above 10 hPa
- Following results are from clear sky (LWP < 5 g m-2)

Planned Data Assimilation work flow

Vital II campaign
=> 5 HATPROs
(5° / 10°azimuth scans)
(BL scans: 4 azimuths / many elevations)
=> 4 WVLidars
(June-August 2026)

Preprocessing
=> Bias correction
=> Tilt correction (Böck et al. 2024)
=> Other corrections (Meunier et al. 2012)
=> Error determination (Desrozier 2005)
(October '26 -March '27)

Datool forMWR slant fofs:
=> With VarQC and non-diagonal R
(Ikuta et al. 2025)
=> Development based on Module by Vural
and Radar Module Emvorado
(October '26 -March '27)

DA experiment
=> June 2026 used for O-B statistics
=> July and August 2027 used for assimilation
(March '27 - September '27)

Evaluation
=> Verification data: Radiosondes and UAS
=> PAI method (Diefenbach et al. 2022)
=> Other methods for Forecast evaluation
(October '27 - December '27)