6th Hans Liebe Lecture

Pushing ground-based microwave radiometry: from uncertainty to networking

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Foreword: "pushing" vs. "fostering"

Dictionary

Search for a word

pusher

/ˈpʊʃə/

noun

1. INFORMAL
   a person who sells illegal drugs.
   "an underworld of thugs, drug pushers, and thieves"
2. a person or thing that pushes something.
   "the checkout trolley pushers"

Translations, word origin, and more definitions

Foreword: Imposter syndrome

- Imposter feelings:
  - I can't do this
  - Who am I to be doing this?
  - I will be found out

- Imposter syndrome moments
  - Speaking in public (specially in front of world-class audience)

- A research on researchers found out that:
  - ~30% of the researchers are affected
  - ~70% of researchers have symptoms

- Severe attack of Imposter feelings when I got this invitation!

Foreword: Imposter syndrome

- Who am I to receive this honor and talk about radio science in front of this world-class audience?

- Tips to fight Imposter syndrome:
  1. Be brave and take action

- So I will do my best today to convince myself and (maybe) you that I'm not (totally) an imposter (in this particular occasion)…

Outline

- Intro: why ground-based microwave radiometry?
- Background
- Recent achievements towards operational exploitation, e.g. NWP
- Focus on uncertainty quantification
- Summary and conclusions

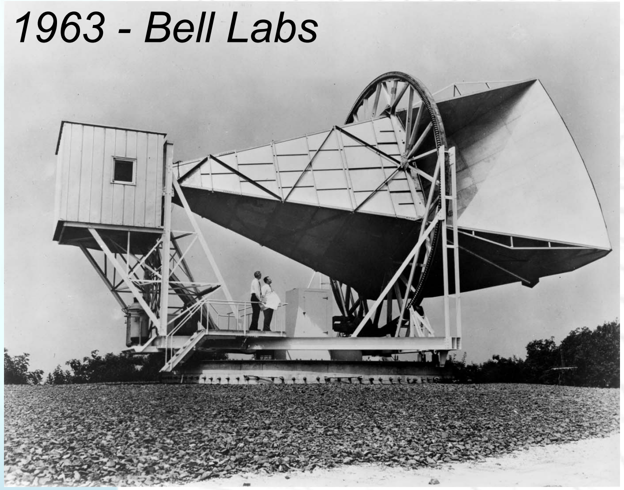
Intro: Why ground-based microwave radiometry?

- Passive technique: natural emission from the atmosphere (brightness temperature T_B)
- Microwave radiometers (MWR) are nowadays robust, (nearly) all-weather, unattended instruments
- Real-time continuous measurements of atmospheric essential variables
  - Temperature and humidity profiles
  - Total column water vapor and cloud liquid amounts

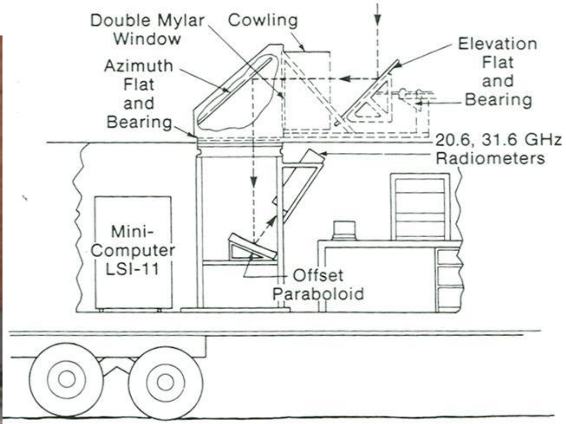
Intro: MWR history in 1-slide

- First experiments in 1960s

1963 - Bell Labs

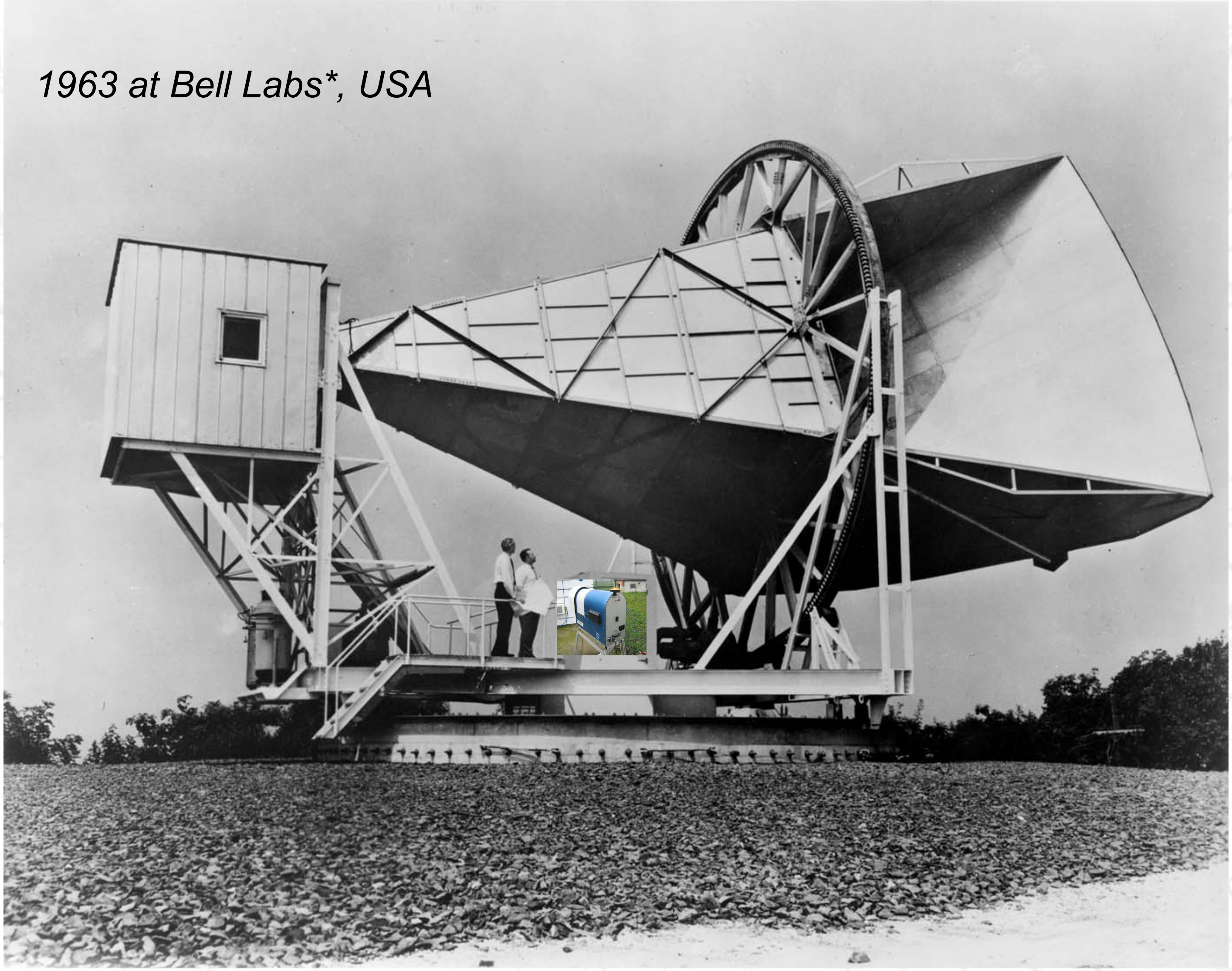


1978 - NOAA



- Commercial units in late 1980s

Intro: MWR history in 1-slide



*Penzias and Wilson: Nobel Prize in Physics 1978 for discovering the cosmic microwave background radiation

Background

MW atmospheric absorption models

- Theoretical models (+ code) that describe the absorption/emission (i.e. extinction coefficient) of MW wavelenghts by atmospheric gases
- Classic paper (H. Liebe 1989) introducing the Millimeter-wave Propagation Model (MPM)
  - a theoretical model (based on quantum mechanics)
  - relies on parametrized equations and spectroscopic parameters (valid between 0-1000 GHz)

$$\boldsymbol{A = f(p)} \qquad \boldsymbol{T_B = F(A) = F(f(p))}$$

- MPM is still widely used (with modified parameterization)
  - Different parameterization are continuously proposed/validated with laboratory and field experiment

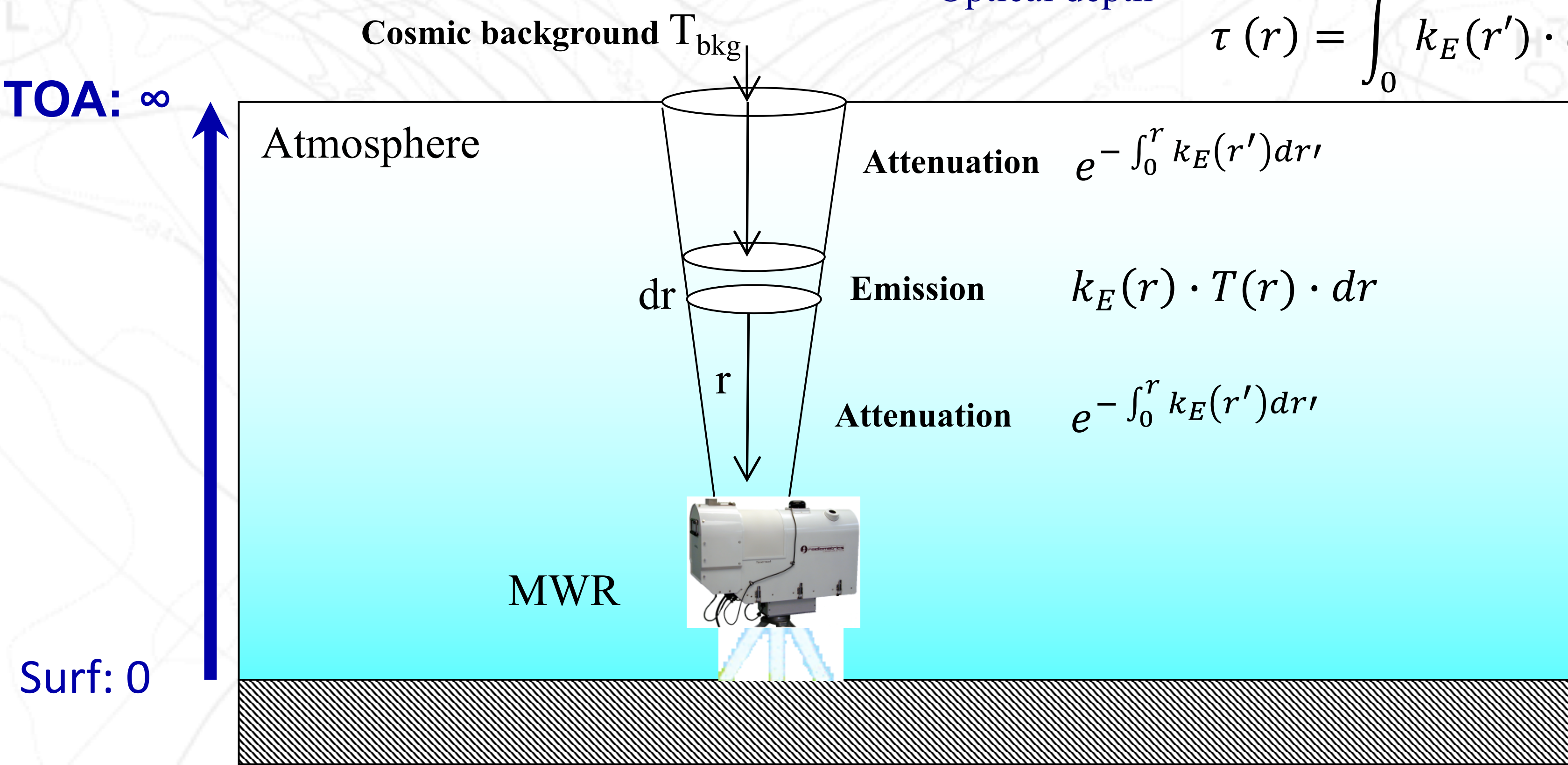
Background

$$\underbrace{T_B(0)}_{\text{Measured quantity}} = \underbrace{T_{bkg} \cdot e^{-\tau(TOA,0)}}_{\substack{\text{Cosmic background term} \\ \text{(attenuated along the path)}}} + \int_{TOA}^{0} \underbrace{k_E(r') \cdot T(r') \cdot e^{-\int_{r'}^{0} k_E(r')dr'} dr'}_{\substack{\text{Atmospheric term} \\ \text{(emitted \& attenuated along the path)}}}$$

Optical depth

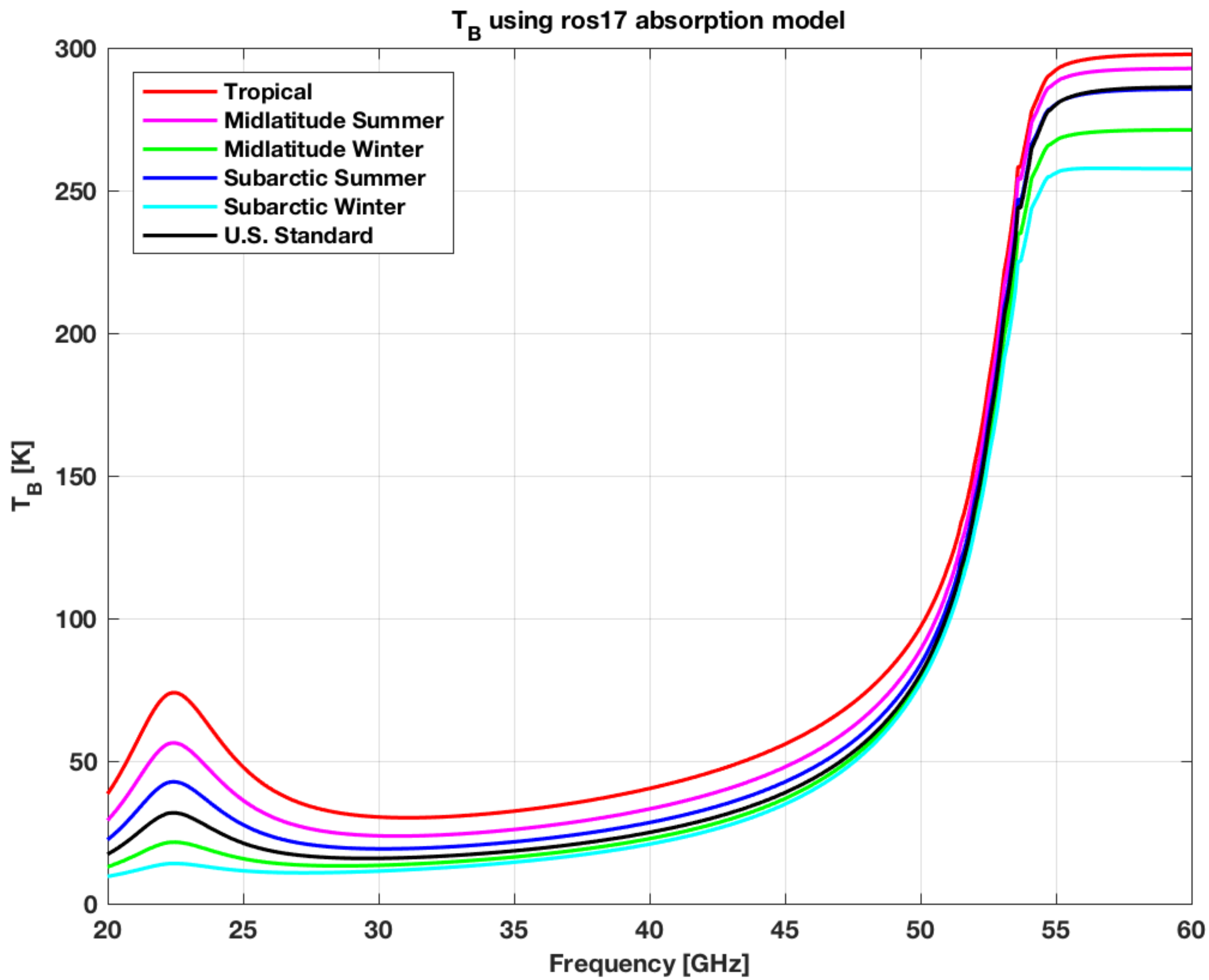
$$d\tau = k_E(r)dr$$

$$\tau\,(r) = \int_0^r k_E(r') \cdot dr'$$



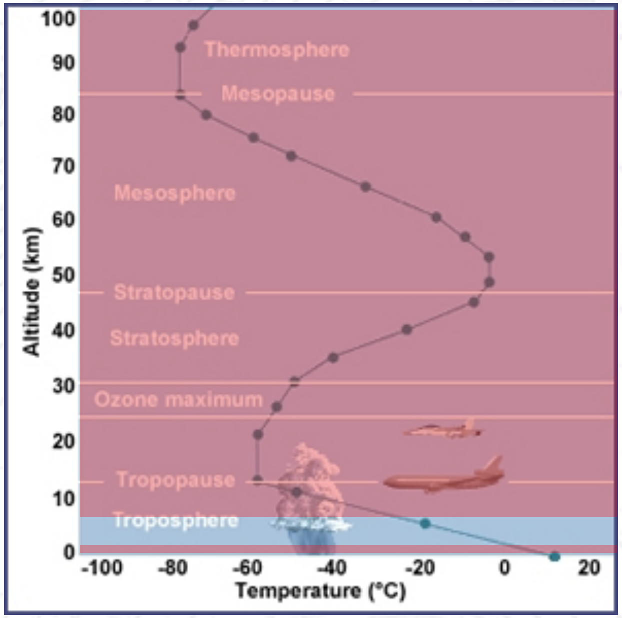
Background

- Typical T_B spectrum at 20-60 GHz



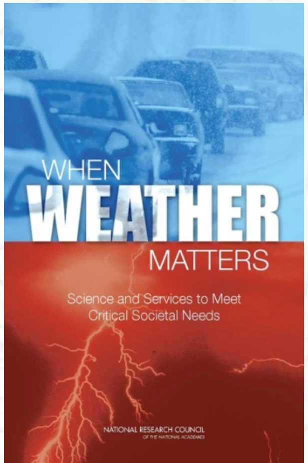
Motivations

- The planetary boundary layer (PBL) is the single most important under-sampled part of the atmosphere*



❑ Observation gap in the PBL, particularly important for forecasting:
  - air quality
  - severe weather initiation

<u>*U.S. National Research Council Reports:</u>
• **Observing Weather and Climate from the Ground Up;** A Nationwide Network of Networks (2009)
• **When Weather Matters:** Science and Service to Meet Critical Societal Needs (2010)



Motivations

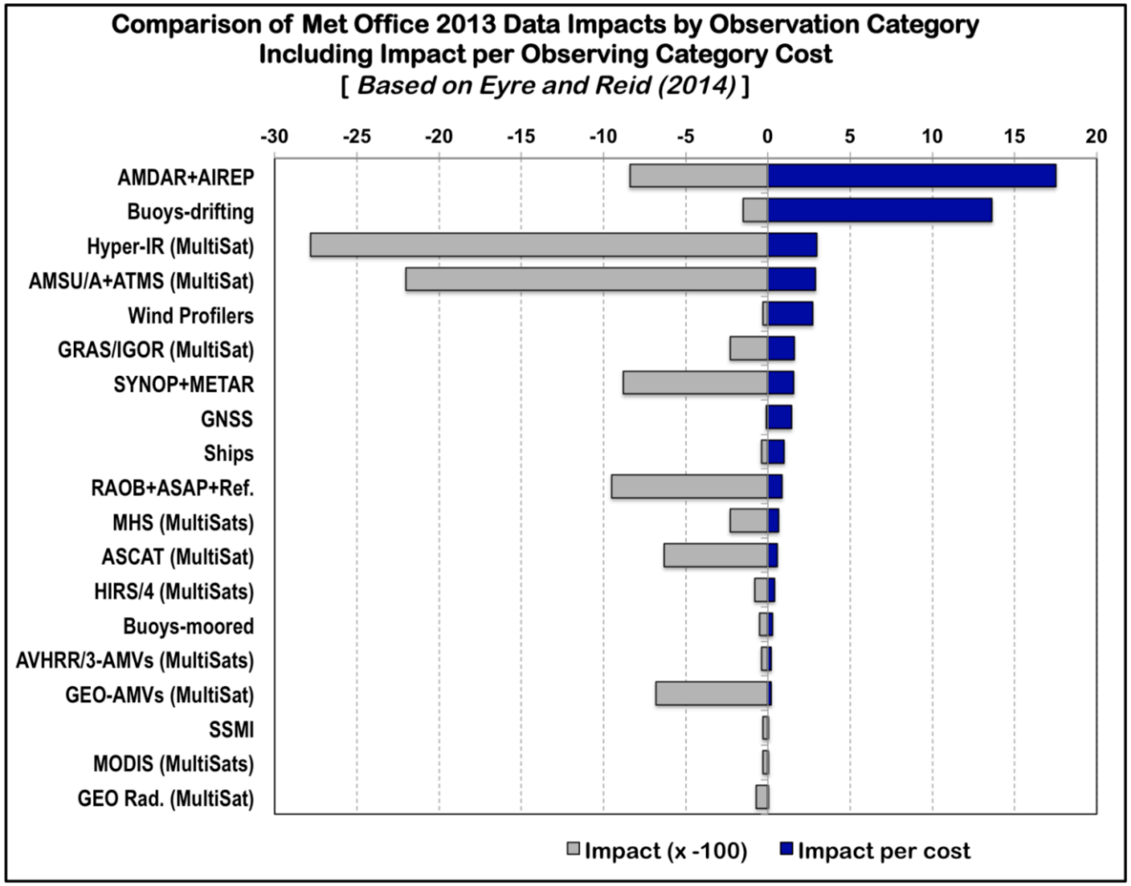
- **WMO***: For NWP the top-priority atmospheric variables not currently adequately measured
  - wind profiles
  - **temperature and humidity profiles (in cloudy areas)**
- T and H profiles can be obtained by ground-based MWR
- Yet MWR observations are not assimilated by any NWP system

*__WMO guidance on observations for NWP:__
https://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html

Motivations

Ground-based networks can have impact per cost comparable to satellite IR or MW obs

Observation impact on NWP



*Eyre and Reid, 2014

Previous MWR Data Assimilation experiments

Vandenberghe and Ware (2002)

- **Obs:** One single MWR
- **Period**: One case study (3-hour data assimilation)
  - winter fog event at Denver Airport (missed by NWP)

Otkin et al. (2011); Hartung et al. (2011)

- **Obs**: ~140 MWR (+other instr.)
  - OSSE: Observing System Simulation Experiment
- **Period**: One case study in continental U.S.
  - winter storm case

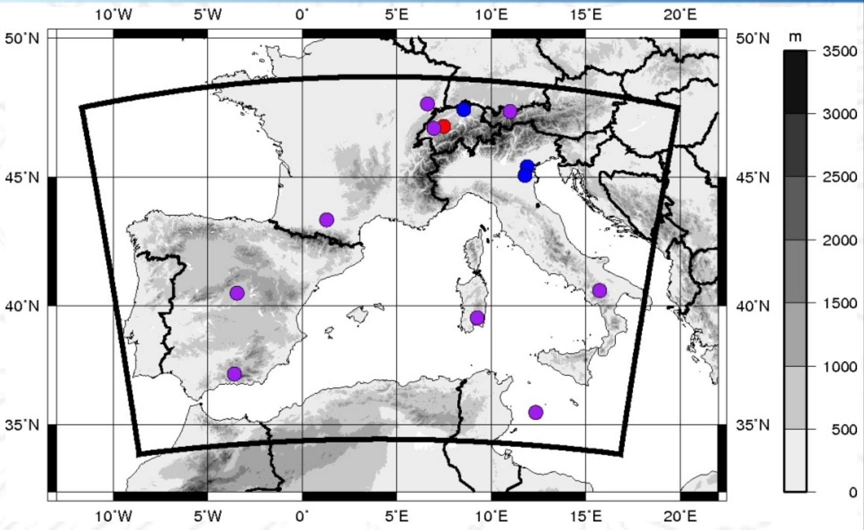
Caumont et al. (2016)

- **Obs**: 13 MWR
  - OSE: Observing System Experiment
- **Period**: ~2 months (Oct-Nov, 2011)
  - Western Mediterranean

First DA experiment of a real MWR network (retrievals)

MWR Data Assimilation Experiment

- Data set
  - ~2 months (Oct-Nov, 2011)
  - 13 MWR
    - H profilers (1)
    - T profilers (3)
    - T&H profilers (9)

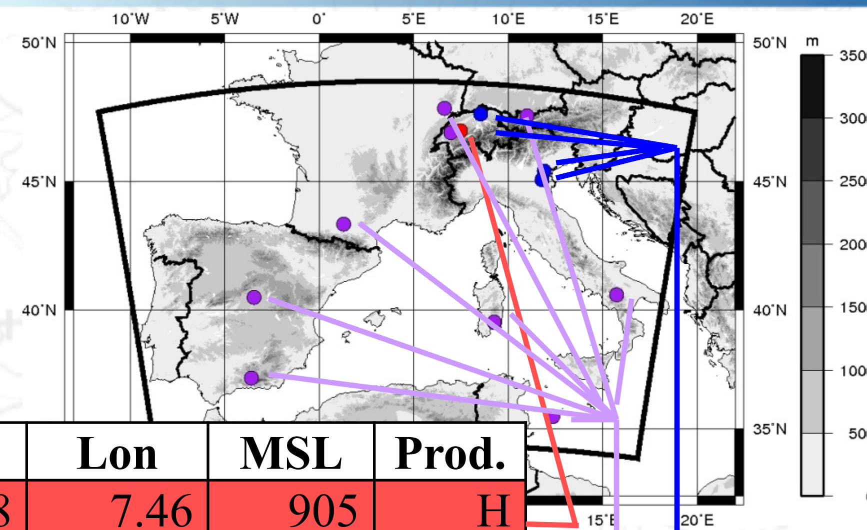


- Western Mediterranean (WMed) domain

- Arome-WMed NWP system (Météo-France)
  - 2.5 km horizontal resolution
  - 3DVAR assimilation every 3 h

MWR Data Assimilation Experiment

- Data set
  - ~2 months (Oct-Nov, 2011)
  - 13 MWR
    - H profilers (1)
    - T profilers (3)
    - T&H profilers (9)



Station	Institution	Lat	Lon	MSL	Prod.
Bern	IAP	46.88	7.46	905	H
Cagliari	INAF/OAC	39.5	9.24	623	T, H
Granada	CEAMA-UGR	37.16	-3.6	683	T, H
Kloten	MeteoSwiss	47.48	8.53	436	T
Lampedusa	ENEA	35.51	12.34	50	T, H
Madrid	UniLeon	40.49	-3.46	620	T, H
Padova	ARPAV	45.4	11.89	30	T
Payerne	MeteoSwiss	46.82	6.95	491	T, H
Potenza	IMAA/CNR	40.6	15.72	760	T, H
Rovigo	ARPAV	45.07	11.78	23	T
Schaffhausen	MeteoSwiss	47.68	8.62	437	T, H
Schneefernerhaus	UniCologne	47.42	10.98	2650	T, H
Toulouse	ONERA	43.38	1.29	144	T, H

MWR Data Assimilation Experiment

- Control (CTRL) run assimilate data from:
  - radiosondes
  - wind profilers
  - aircrafts
  - ships
  - buoys
  - automatic weather stations
  - satellite radiometers
  - weather radars
  - ground-based GPS
  - GPS radio-occultation

→ **….very little room to make an impact!**

Previous MWR DA experiments

Main conclusions from Caumont et al., 2016:

- Neutral-to-positive impact:
  - MWR data can be safely assimilated
  - MWR data provide useful information to NWP

- More positive impact expected from:
  - Denser network
  - Improved data quality control
  - Direct T_B assimilation (instead of T and Q retrievals)

* Caumont et al., QJRMS, 2016

Forward model development

- For direct T_B assimilation, a fast forward model (FM) is needed
  - Adapted RTTOV (developed for satellite DA) → RTTOV-gb
- Compared against reference model (MPM)
  - T_B differences less than typical MWR uncertainties
- RTTOV-gb well suited for variational data assimilation
  - now in experimental use at:
    - Universities: U. Köln (Germany), Ewha Univ. (South Korea)
    - National Weather Services: Meteo-France, DWD (Germany)
- RTTOV-gb is distributed by MetOffice similarly to RTTOV

De Angelis et al., Geosci. Model Develop., 2016

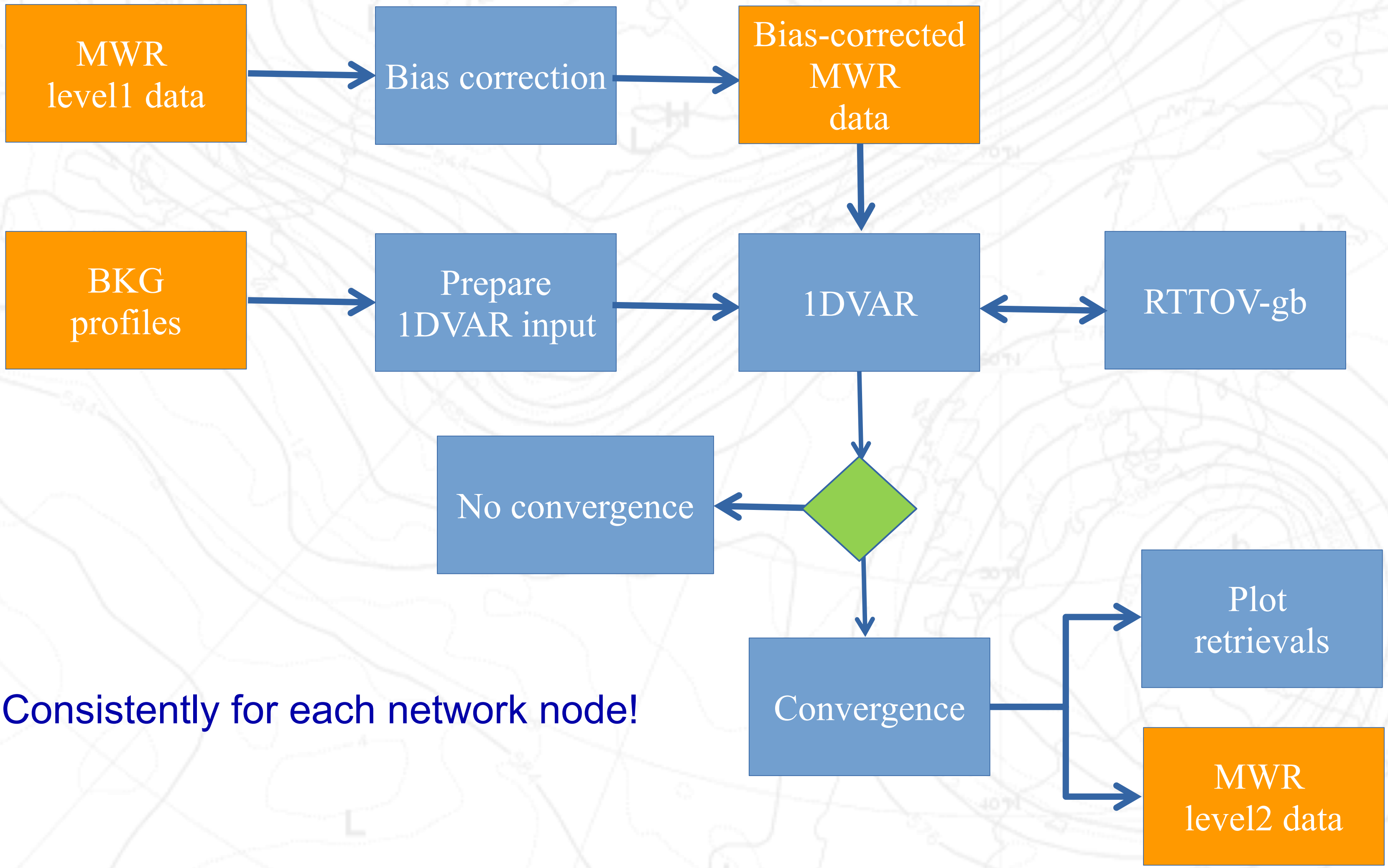
Inverse model development

- One-Dimentional Variational (1DVAR) retrieval coupled with RTTOV-gb

- Develop a flexible processing chain to perform 1DVAR retrievals on different instruments and configurations
    - **Net1D** (Network 1DVAR)

Inverse model development

Net1D processing chain

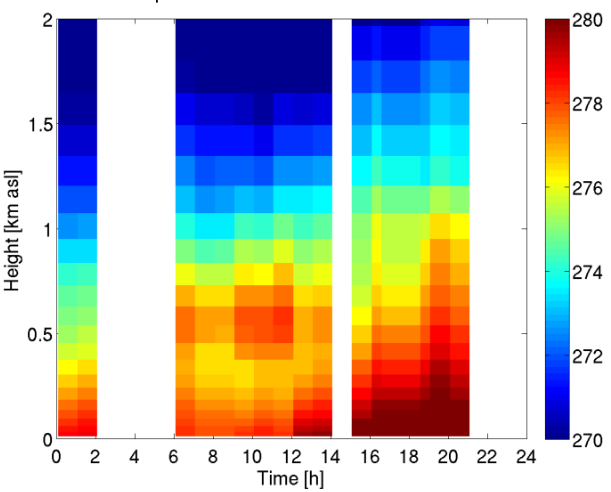


Consistently for each network node!

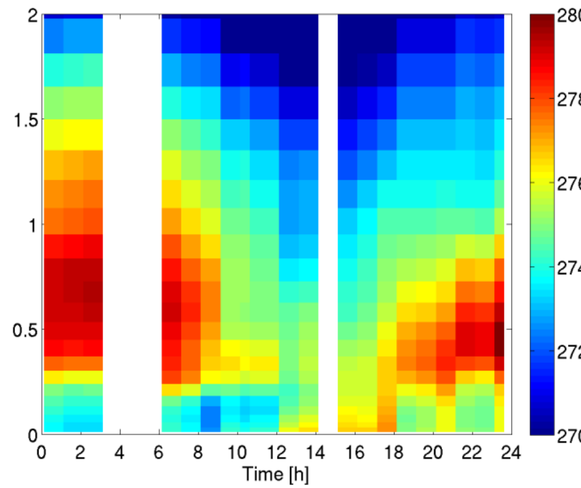
Network 1DVAR

Temperature (K) profile retrievals

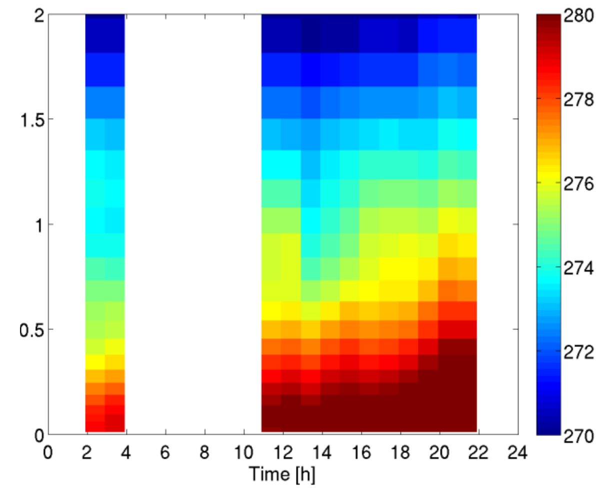
Cesar



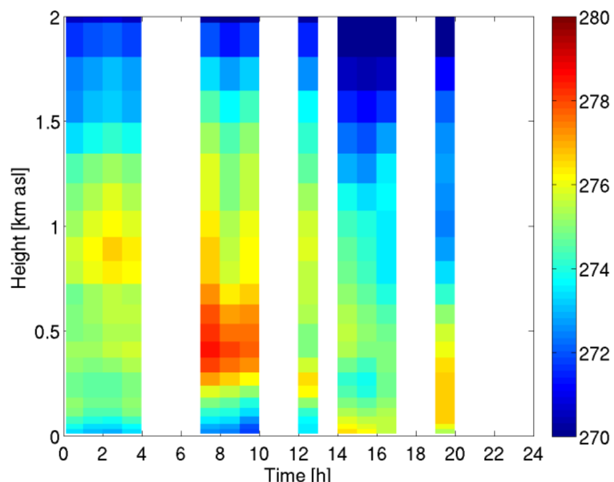
Lacros



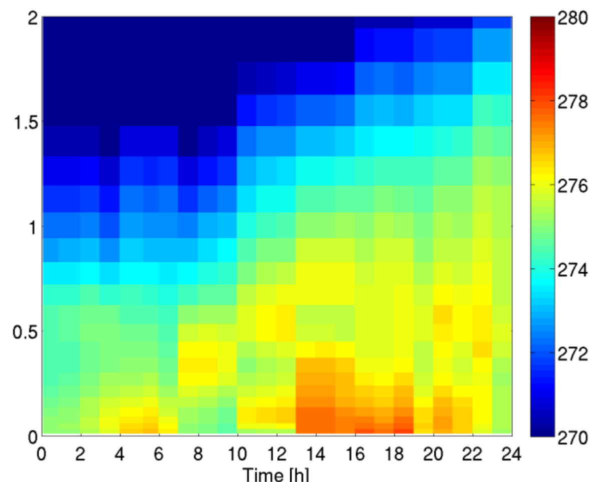
Joyce



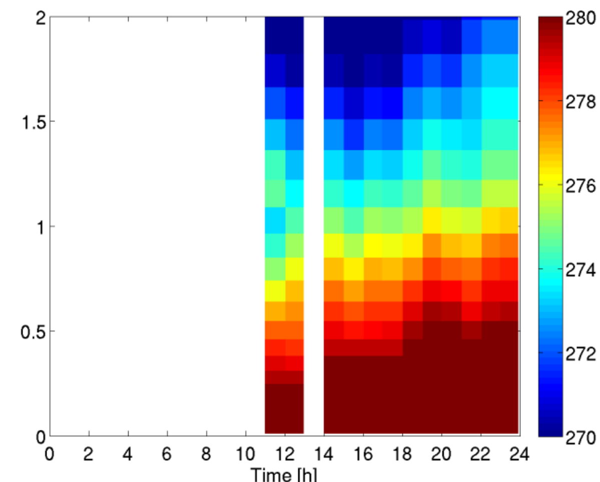
Lindenberg



Payerne

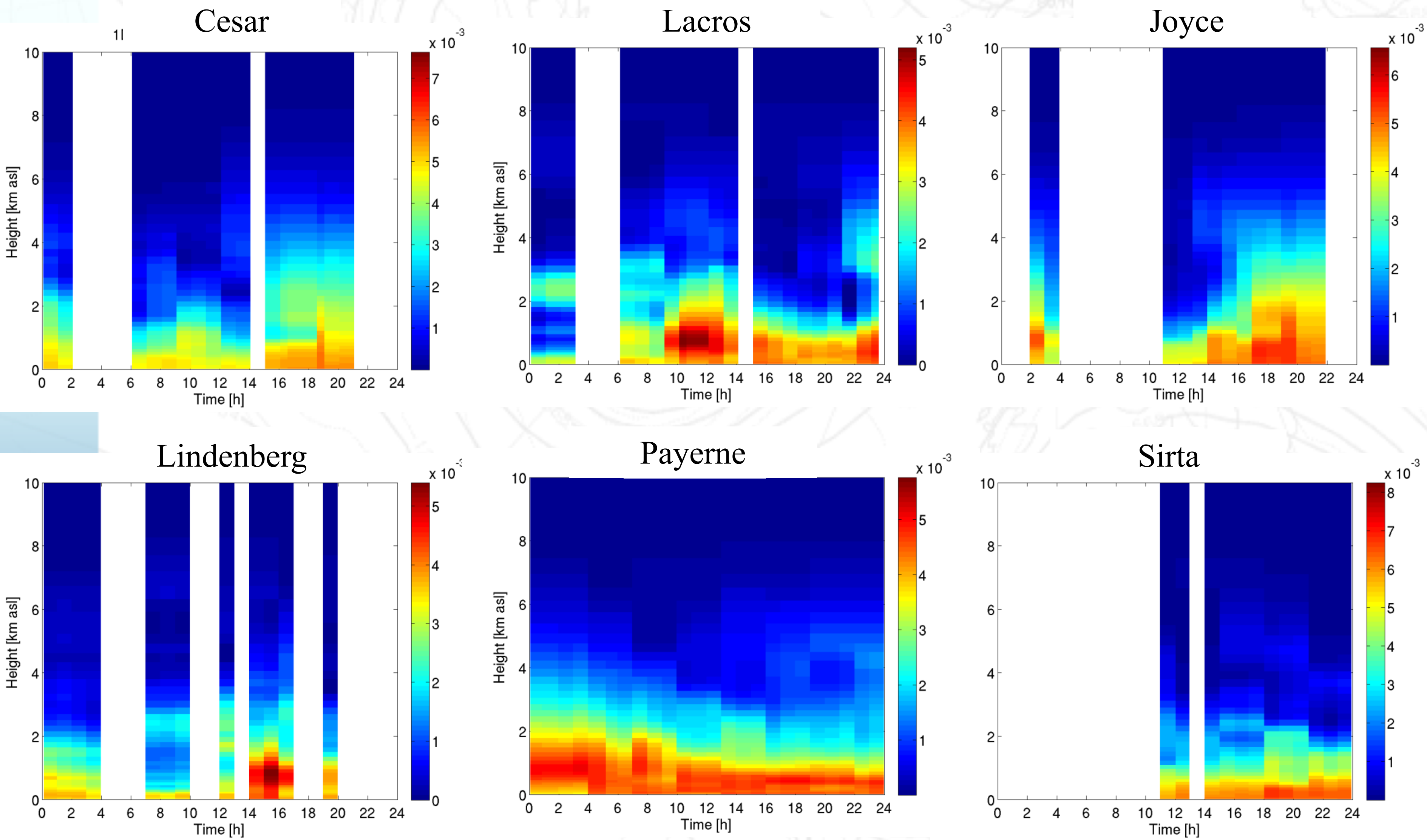


Sirta



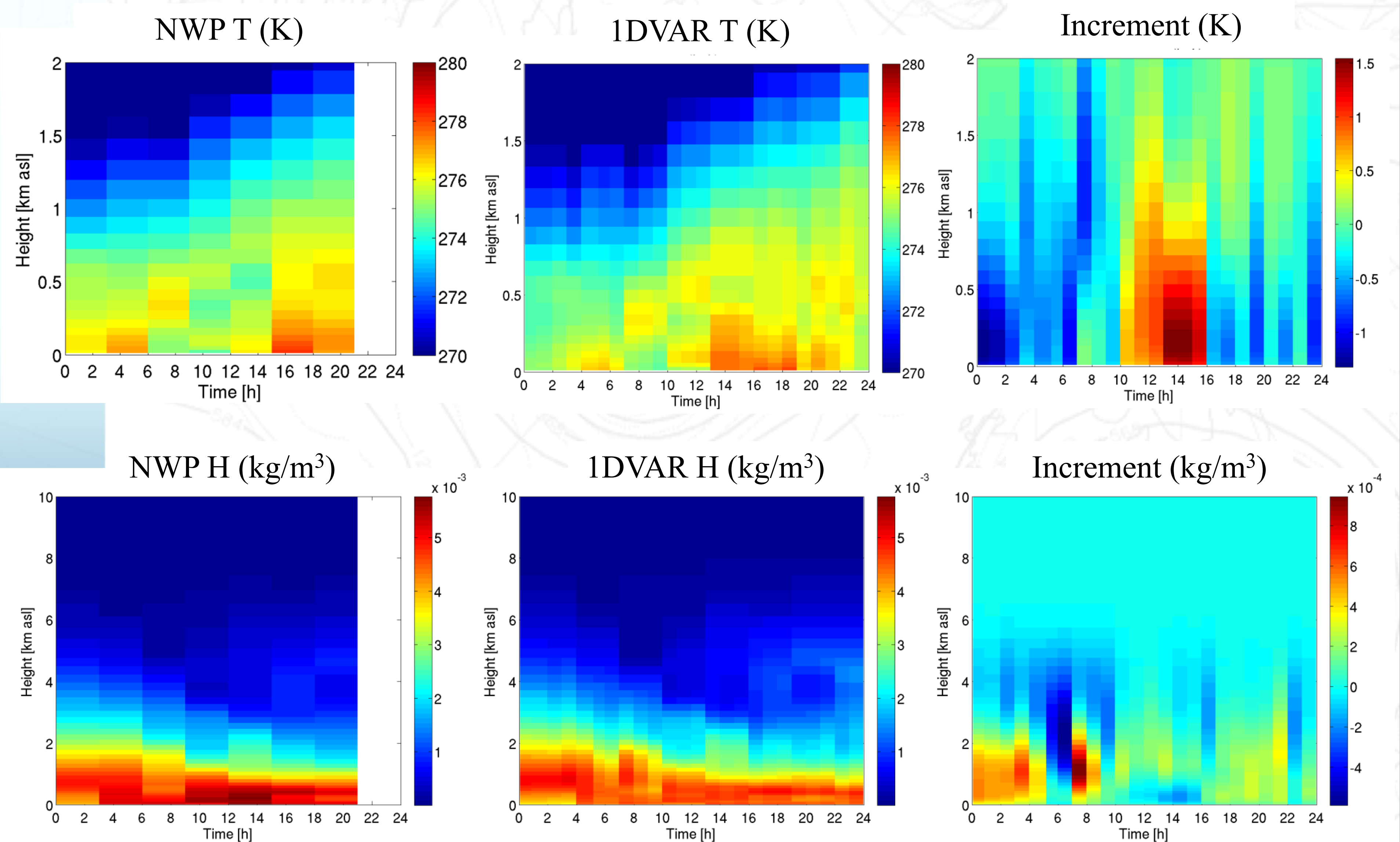
Network 1DVAR

Absolute humidity (kg/m³) profile retrievals



Network 1DVAR

Impact on the background

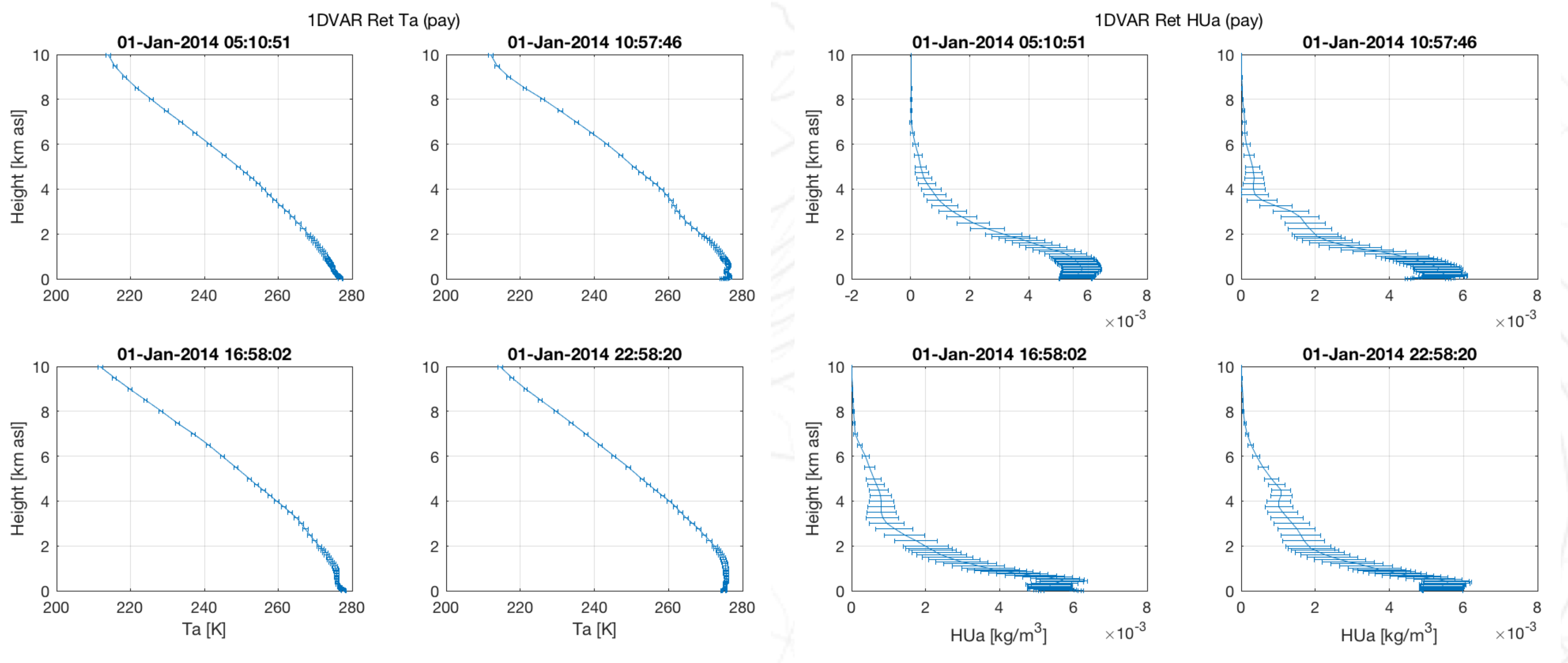


Network 1DVAR

Net1D output: profiles with uncertainty estimate

Temperature

Humidity



The importance of uncertainty

One common requirement of NWP and climate applications is the careful quantification of uncertainty

Le doute n'est pas une état bien agréable, mais l'assurance est un état ridicule (*)

Voltaire (François-Marie Arouet, 1694-1778)

Letter to Frederick William, Prince of Prussia (1770)

(*) Doubt is not a pleasant condition, but certainty is a ridiculous one

The importance of uncertainty

WMO-No. 8. Guide to Meteorological Instruments and Methods of Observation:

"All data are imperfect, but, if their **quality is known and demonstrable**(*), they can be used appropriately"

(*) i.e., if the uncertainty is quantifiable

Uncertainty of atmospheric absorption models

How can we quantify the uncertainty of atmospheric absorption models?

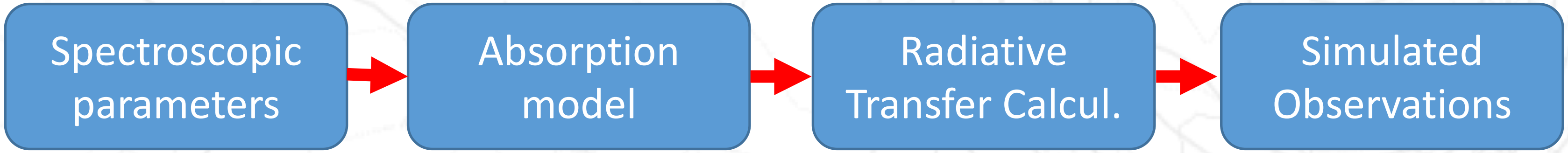
- Popular: evaluate different model and compute the difference
  - It provides only a relative estimate
- Rigorous: track uncertainty down to single contributions
  - i.e. spectroscopic parameters

Uncertainty of atmospheric absorption models

- Atmospheric absorption models rely on parameterized equations

- Parameterized equations are based on spectroscopic parameters
  - spectroscopic parameters' values are determined through
    - (i) theoretical calculations
    - (ii) laboratory experiments
    - (iii) field measurements
  - Thus are inherently affected by uncertainty
    - Computational and/or experimental

- Uncertainty propagates…



Uncertainty of atmospheric absorption models

- The spectroscopic literature provides uncertainty of individual parameters only (if you are lucky)
- Uncertainty affecting different parameters may be correlated
  - e.g., if values of two or more parameters are determined using the same laboratory experiment and settings, their uncertainty is correlated
- The full uncertainty covariance matrix should be estimated
- Lots of parameters, i.e. lots of work…

Uncertainty of atmospheric absorption models

Four-step approach:

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

1. Review state-of-the-art

- Take one absorption model
  - e.g., MPM, Rosenkranz 2017*
- List the used parameters
  - Focus on 20-60 GHz
  - H_2O and O_2
- Review relevant literature, searching for uncertainty

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

1. Review state-of-the-art

Water Vapor (Rosenkranz 2017)

Continuum

4 parameters

Parameter [units]	Meaning	Value	Uncertainty	Reference
Cf [km^{-1} mb^{-2} GHz^{-2}]	Foreign-broadened water vapor continuum coefficient	$5.43e^{-10}$	$5.56e^{-11}$	Rosenkranz 1998; Turner et al., 2009
Cs [km^{-1} mb^{-2} GHz^{-2}]	Self-broadened water vapor continuum coefficient	$1.8e^{-8}$	$3.245e^{-9}$	Rosenkranz 1998; Turner et al., 2009
n_{Cf} [unitless]	Foreign-broadened temperature dependence coefficient	3.0	0.6	Tretyakov, 2016
n_{Cs} [unitless]	Self-broadened temperature dependence coefficient	7.5	0.6	Tretyakov, 2016

1. Review state-of-the-art

Water Vapor (Rosenkranz 2017)

21 parameters in total

Lines

15 water vapor absorption lines:
22 GHz
183 GHz
13 in sub-mm range (321–916 GHz)

Parameter [units]	Meaning	Value @22GHz	Uncertainty @22GHz	Value @183GHz	Uncertainty @183GHz	Reference
ν_0 [kHz]	Line frequency	22235079.85	0.05	183310087	1	Tretyakov, 2016
γ_a [MHz/mb]	Air-broadening parameter	2.7227	0.1050	2.9447	0.0150	Tretyakov, 2016
γ_w [MHz/mb]	Water-broadening parameter	13.2011	0.3750	14.7762	0.3750	Tretyakov, 2016
n_a [unitless]	Temperature-exponent of air-broadening	0.70	0.05	0.74	0.03	Tretyakov, 2016
n_w [unitless]	Temperature-exponent of water-broadening	1.20	0.05	0.78	0.08	Tretyakov, 2016
S [Hz/cm^2]	Line strength	$1.3161e^{-14}$	$1.2891e^{-16}$	$2.3222e^{-12}$	$2.3084e^{-14}$	Tretyakov, 2016
r_{s2w} [unitless]	Shift to width ratio	$2.7548e^{-4}$	0.0275	-0.0245	0.0026	Tretyakov, 2016
E_{low} [cm^{-1}]	Resonant line lower-state energy	446.5106590	4×10−8 %	136.163927	7×10−7 %	Tennyson et al. (2013)

Parameter [units]	Meaning	Value	Uncertainty	Reference
n_S	Resonant line intensity temperature-dependence exponent	2.5	0.5%	Gamache et al. (2017)

1. Review state-of-the-art

Oxygen (Rosenkranz 2017)

298 parameters in total

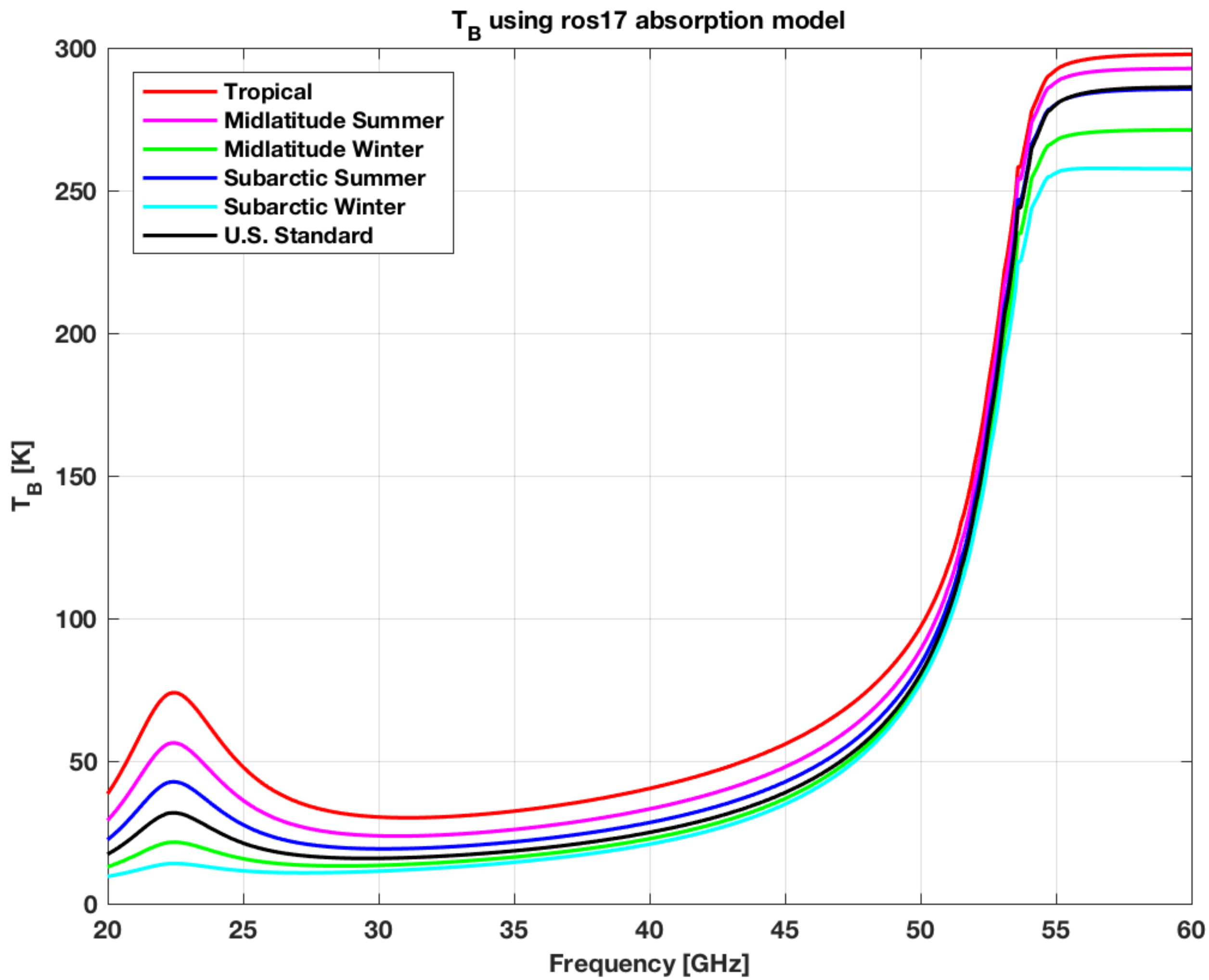
49 oxygen absorption lines

37 at 60 GHz
1 at 118 GHz
11 in mm sub-mm (233–895 GHz)

Par [units]	Meaning	Value	Uncertainty	Reference
S_i [Hz/cm^2]	Line strength	HITRAN, 2012	1%	Tretyakov, Pers. Comm. 2016
ν_i [kHz]	Line frequency	Table 1	Table 1	Tretyakov et al., 2005
n_a [unitless]	Temperature dependence of broadening coefficient for O_2 lines	0.80*	0.05*	Tretyakov et al., 2005
n_S [unitless]	Resonant line intensity temperature- dependence exponent	2.0	0.1%	Gamache et al. (2017)
r_{w2a} [unitless]	Water-to-air broadening ratio	1.20	0.05	Koshelev et al. 2015
E_{low} [cm-1]	Resonant line lower-state energy	HITRAN 2004	0.25%	
B_e [unitless]	Temperature-exponent for strength	HITRAN, 2012	<1%	Tretyakov, Pers. Comm. 2016
γ_i [MHz/mb]	Pressure-broadening parameter	Table 5	Table 1 + calculations	Tretyakov et al., 2005 Rosenkranz, 2017 Pers. Comm.
γ_0 [MHz/mb]	Non-resonant pressure broadening width	Table 5	15%	Rosenkranz, 2017 Pers. Comm.
y [1/bar]	Mixing coefficients	Table	Table	Rosenkranz, 2017 Pers. Comm.
V [1/bar]	Mixing coefficients temperature dependence	Table 5 (last column)	20%	Rosenkranz, 2017 Pers. Comm.

1. Review state-of-the-art

- Typical T_B spectrum at 20-60 GHz

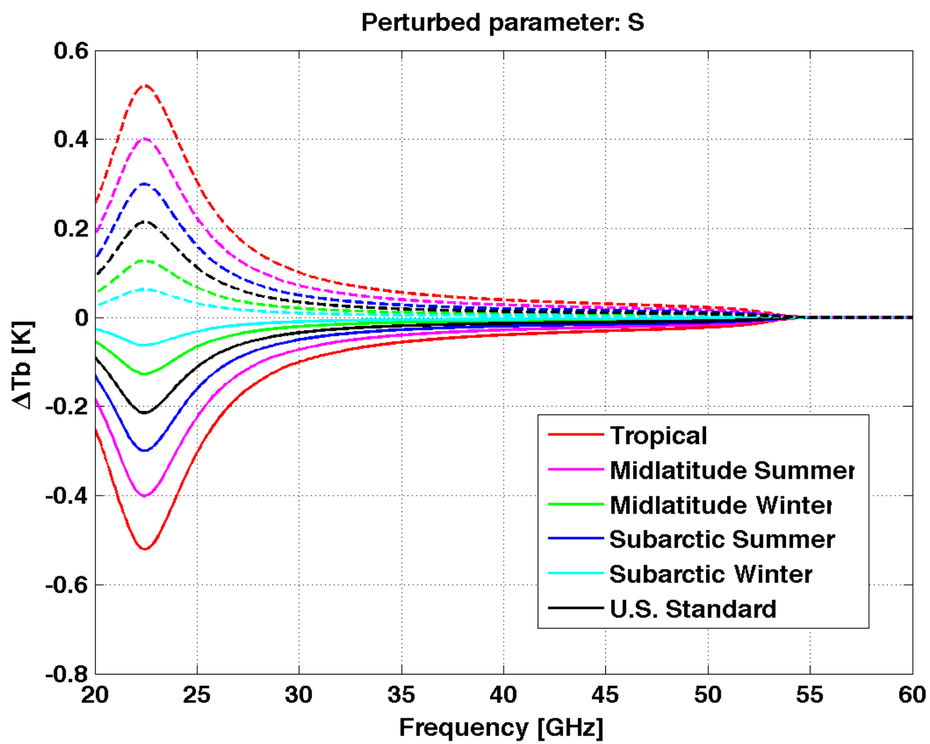


2. Sensitivity to model parameter uncertainty

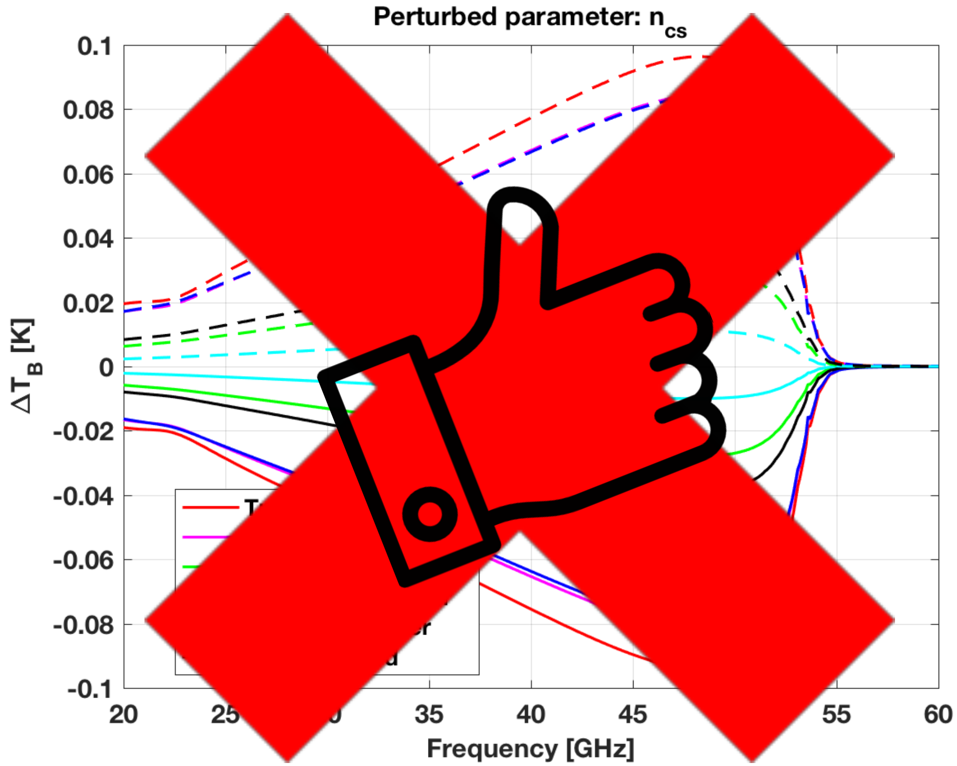
- Sensitivity to spectroscopic parameter uncertainty

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

WV line strength @ 22.2 GHz



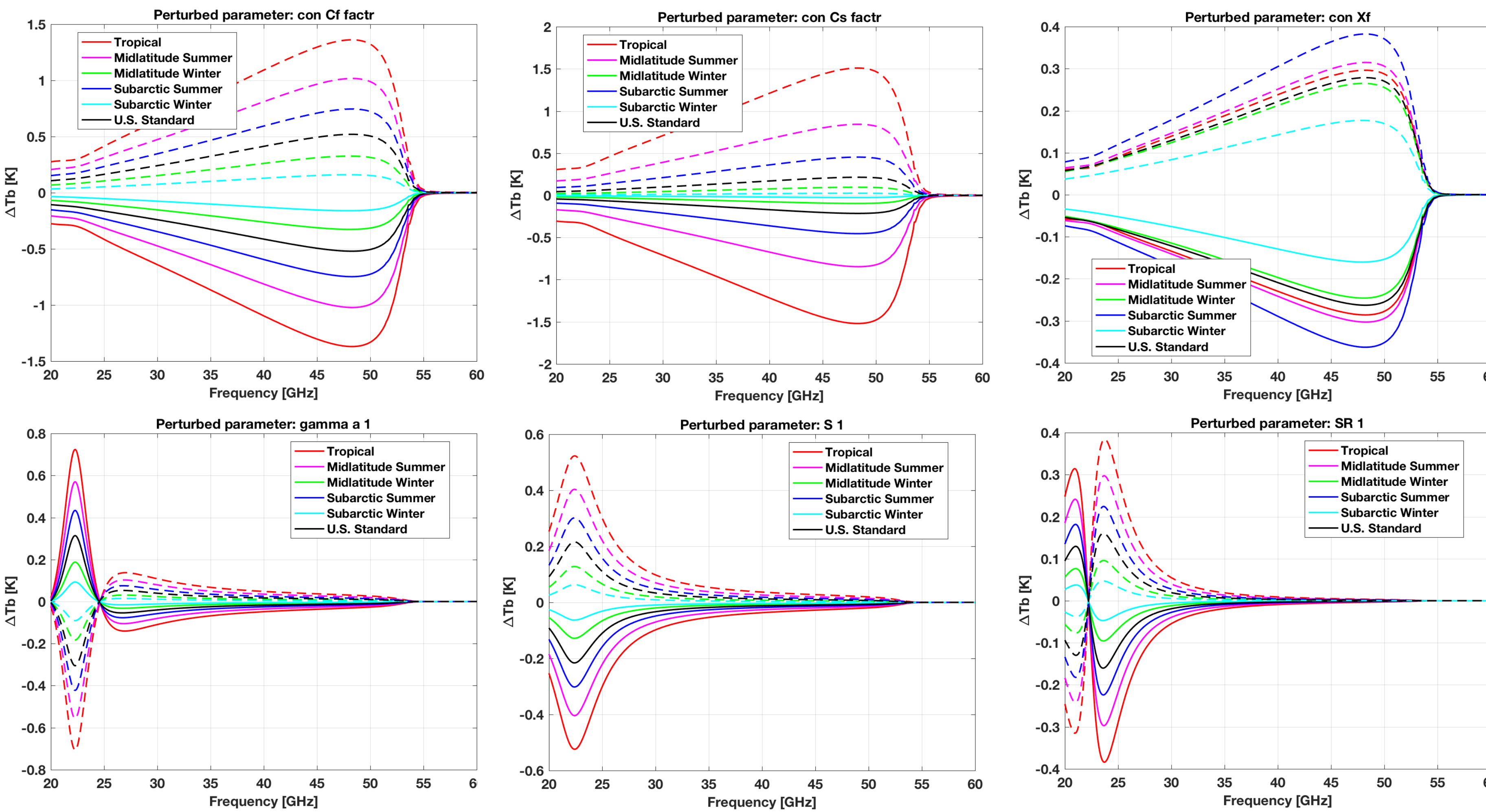
WV self-continuum T exponent



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

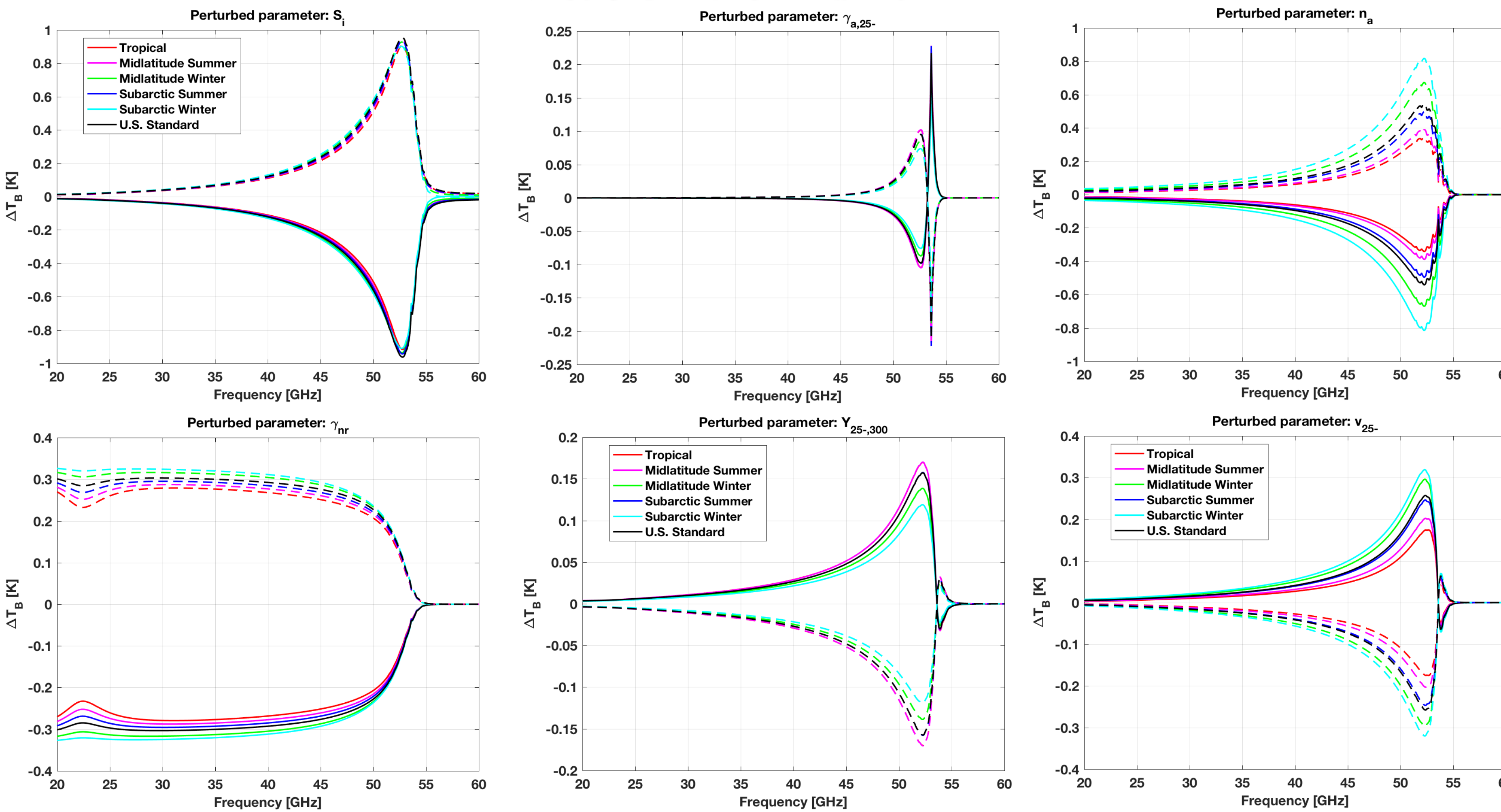
2. Sensitivity to model parameter uncertainty

- H_2O: Among **21** parameters, **6** are found to be dominating



2. Sensitivity to model parameter uncertainty

- O_2: Among **298** parameters, **105** are found to be dominating



3. Uncertainty covariance matrix

- Once the dominant terms are determined (**111**), the associated uncertainty shall be calculated

$$\boldsymbol{T_B} = \boldsymbol{F}(\boldsymbol{p})$$ where T_B and p are vectors

$$\boldsymbol{T_B} \cong \boldsymbol{K}_p(\boldsymbol{p} - \boldsymbol{p}_0) + \boldsymbol{F}(\boldsymbol{p}_0)$$

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

$\boldsymbol{K}_p$	Jacobian of the measurement with respect to spectroscopic parameters
$\mathbf{Cov}(\boldsymbol{T_B})$	Simulated measurement uncertainty covariance matrix due to p
$\mathbf{Cov}(\boldsymbol{p})$	Uncertainty covariance matrix of spectroscopic parameters p

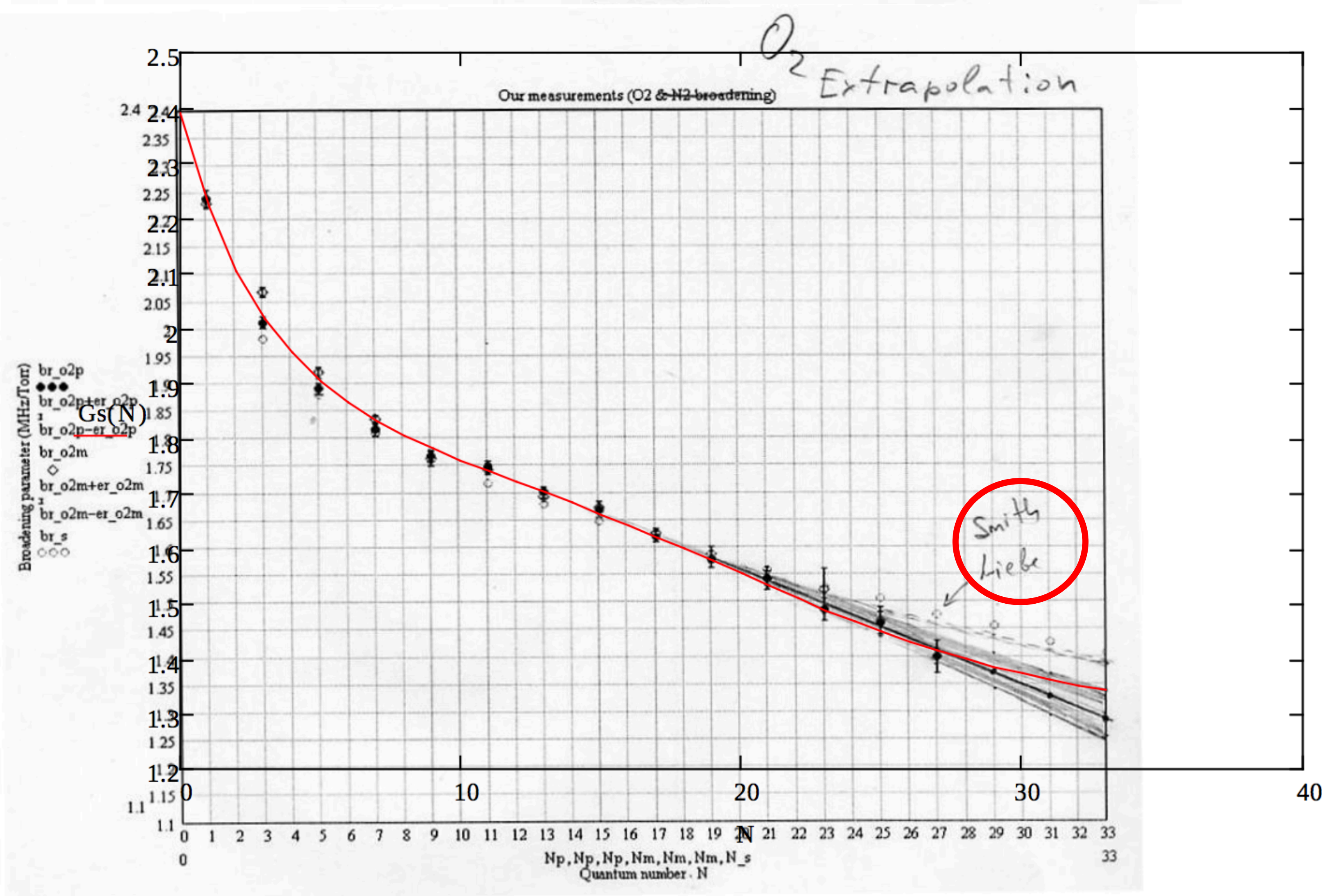
- Off-diagonal terms of ***Cov(p)*** need to be estimated
  - Lot of efforts, but… is it worth?

3. Uncertainty covariance matrix

- Major contribution from:
  - Phil Rosenkranz (MIT, USA)
  - Mikhail Tretyakov and Maksim Koshelev (IAP, RAS, RU)

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

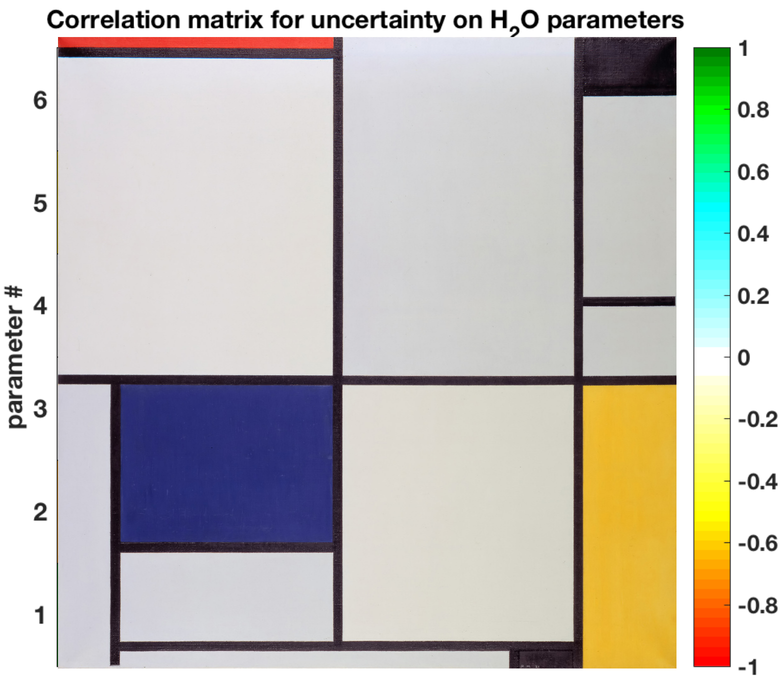
3. Uncertainty covariance matrix



3. Uncertainty covariance matrix

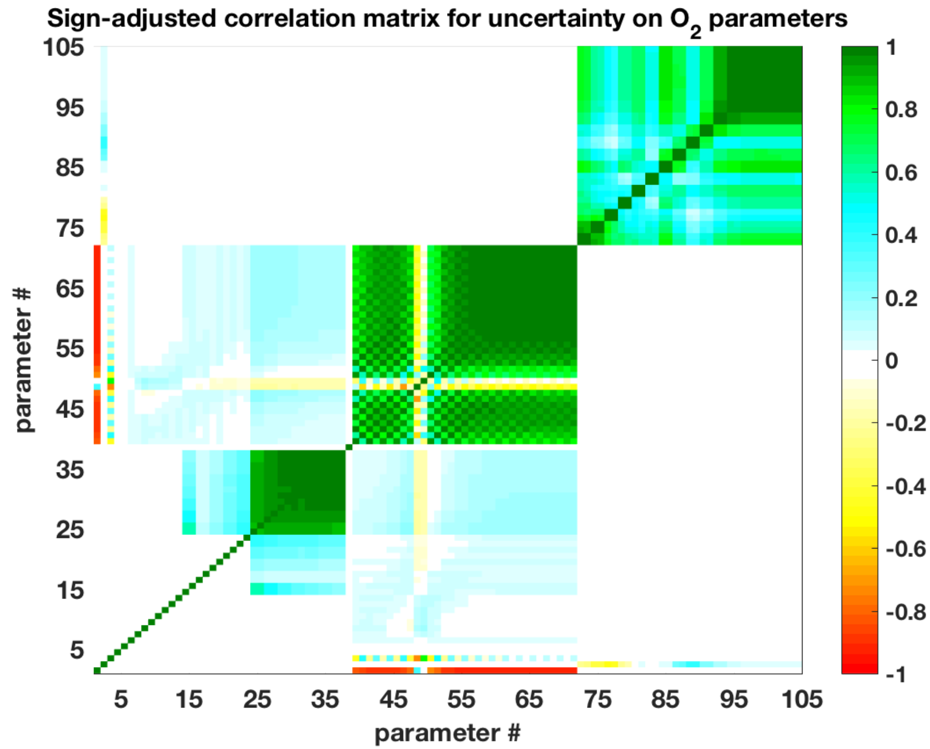
- Parameter uncertainty covariance **Cov**(*p*)

Water Vapor (6 parameters)



Piet Mondrian, Tableau I (1921)

Oxygen (105 parameters)



Broadening **Mixing** **Mixing T dependence**

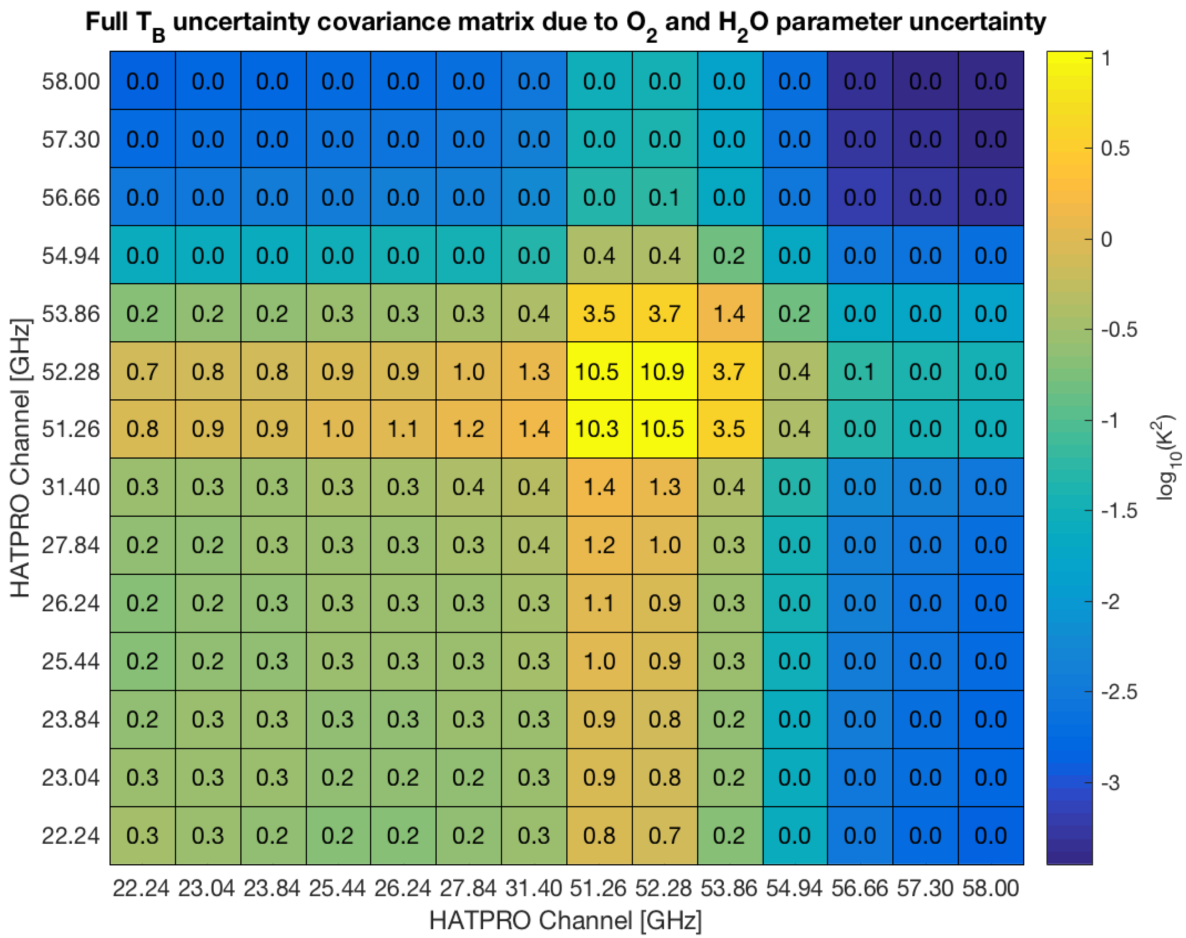
Cimini et al, ACP 2018

4. Uncertainty propagation

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

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

Full T_B covariance 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

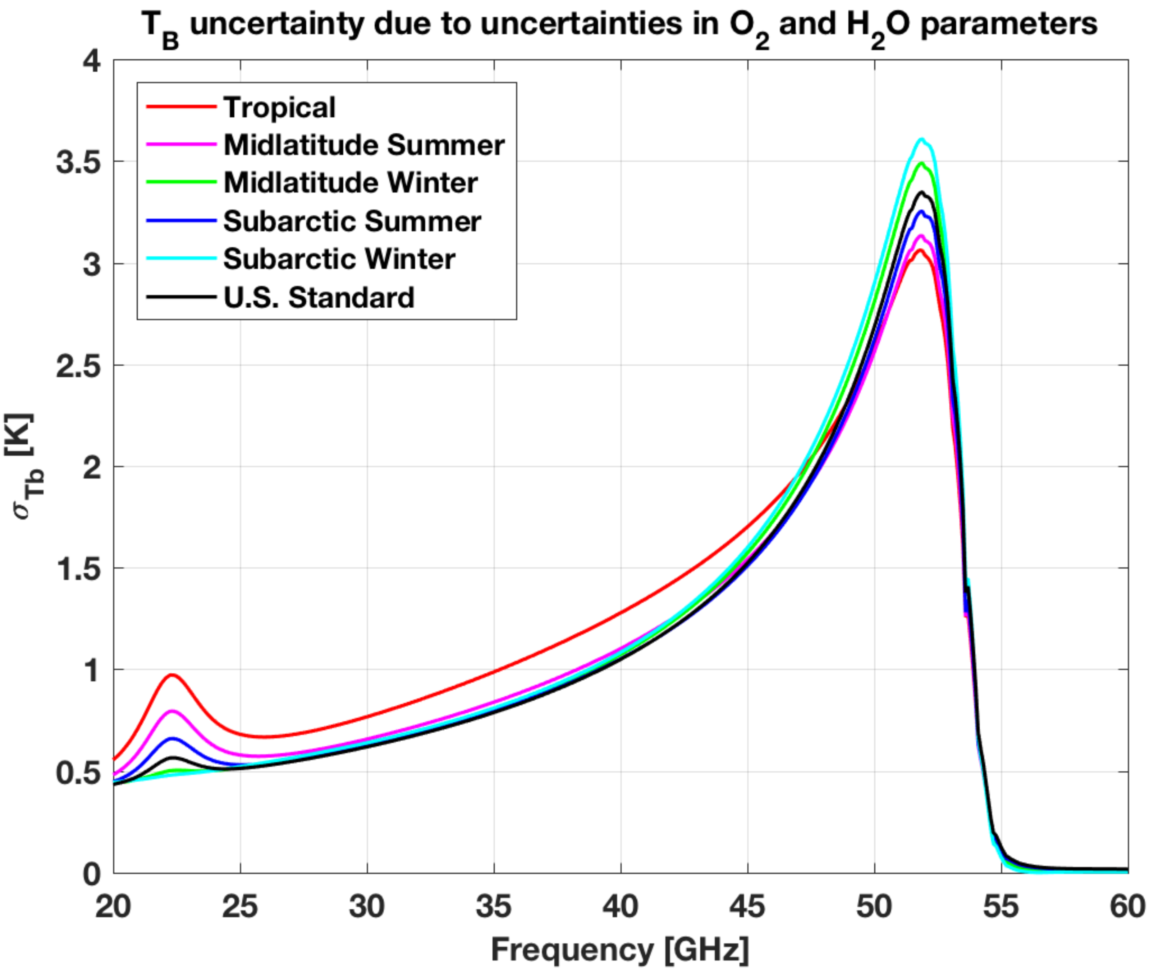
Cimini et al, ACP 2018

4. Uncertainty propagation

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

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

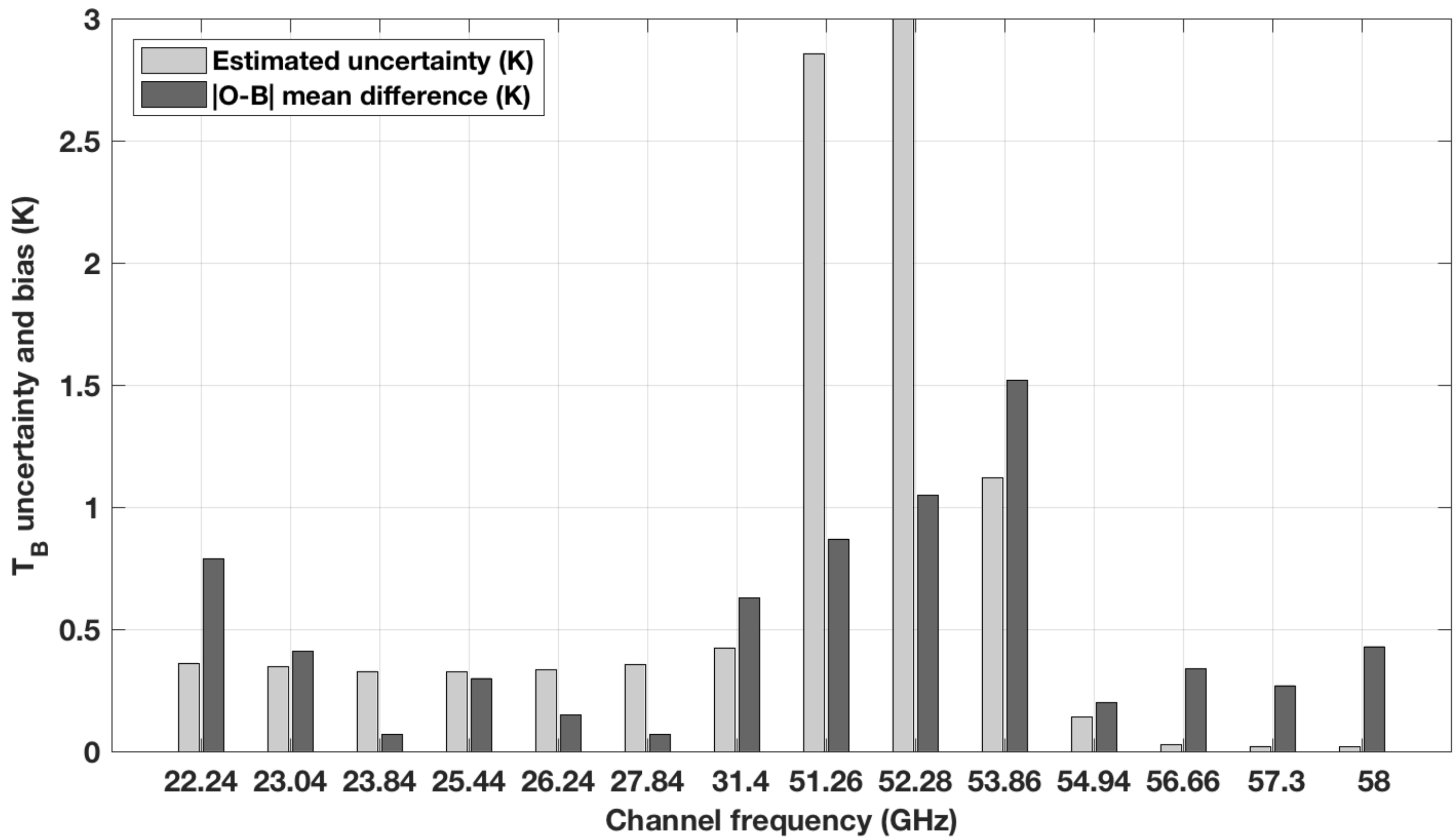
Total T_B uncertainty (diagonal terms)



Cimini et al, ACP 2018

4. Uncertainty propagation

- O-B stats vs FM uncertainty
  - Background: Arome West-Med + RTTOV-gb
  - Observations: HATPRO at JOYCE

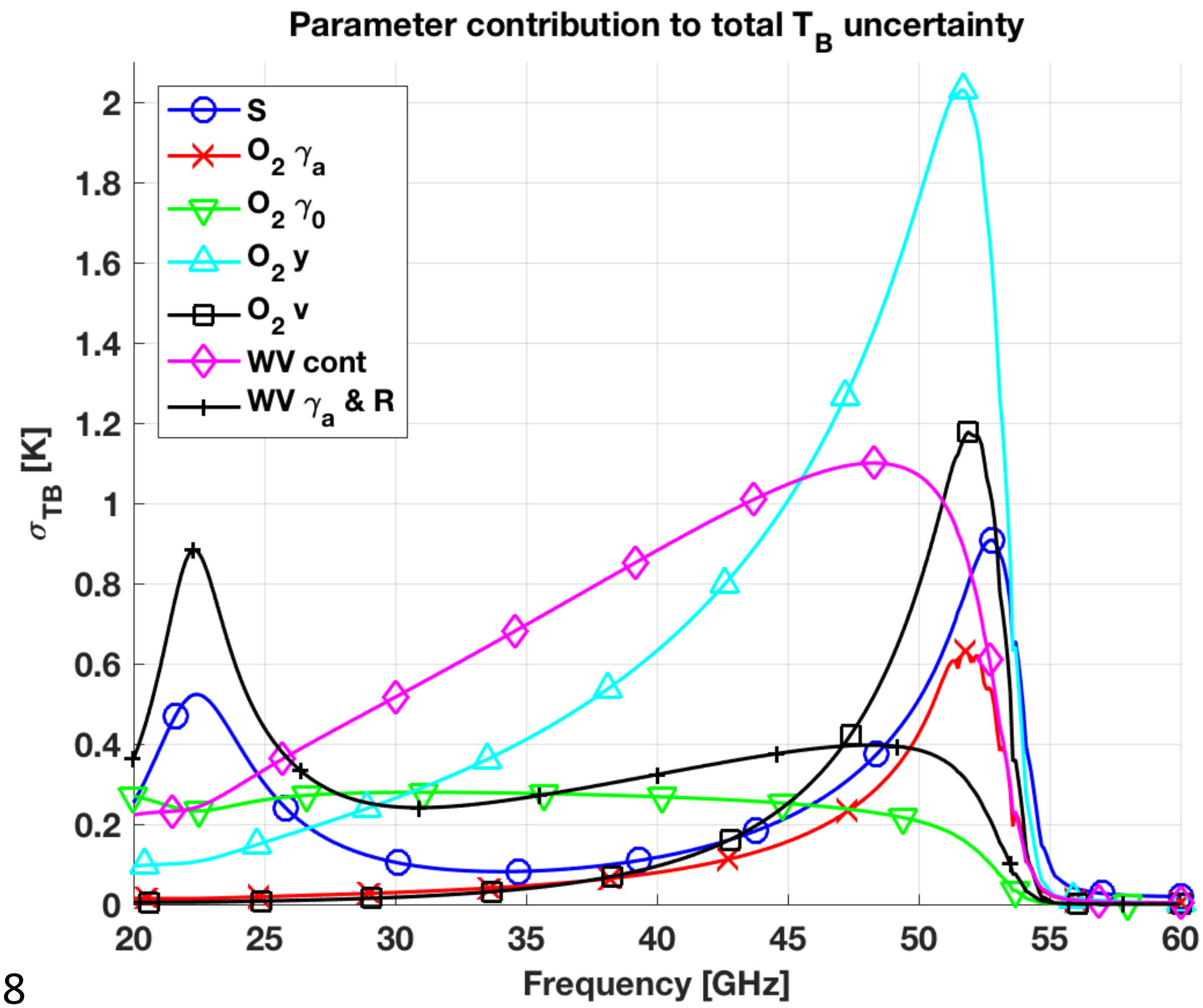


4. Uncertainty propagation

- Contributions T_B uncertainty

Tropical atmosphere

"Anatomy" of T_B uncertainty



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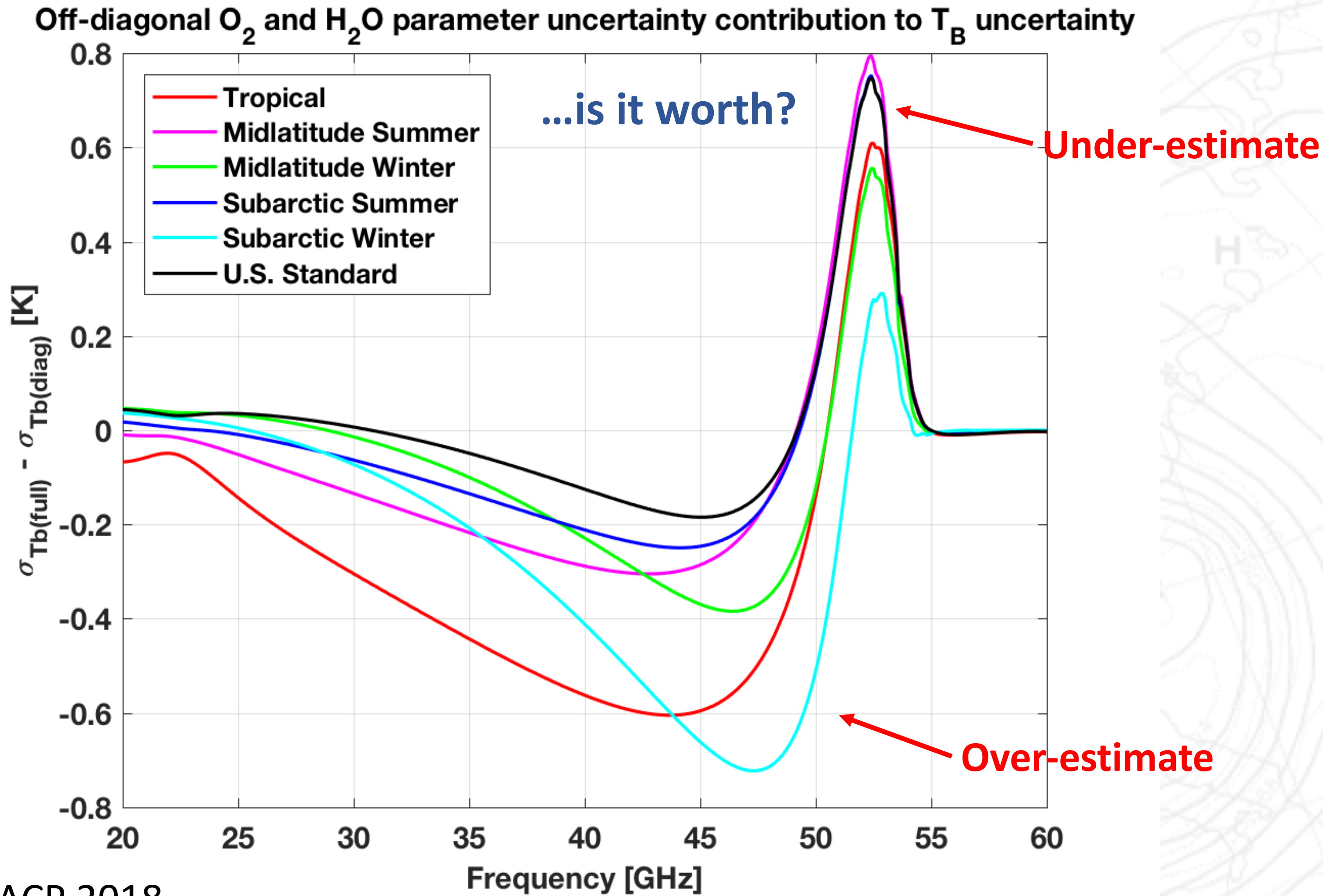
4. Uncertainty propagation

- Off-diagonal terms contributions to T_B uncertainty



Cimini et al, ACP 2018

Summary of developed tools

Towards operational use of ground-based MWR for improving NWP

- **RTTOV-gb**
  - fast FM for ground-based MWR
  - ingests atmospheric profiles
  - computes T_B and Jacobians
- **1DVAR**
  - inversion scheme
  - ingests ground-based MWR obs
  - computes retrievals of T and H profiles and LWP
- **Net1D**
  - network 1DVAR retrievals
  - ingests ground-based MWR obs from a network
  - computes 1DVAR retrievals consistent throughout the network

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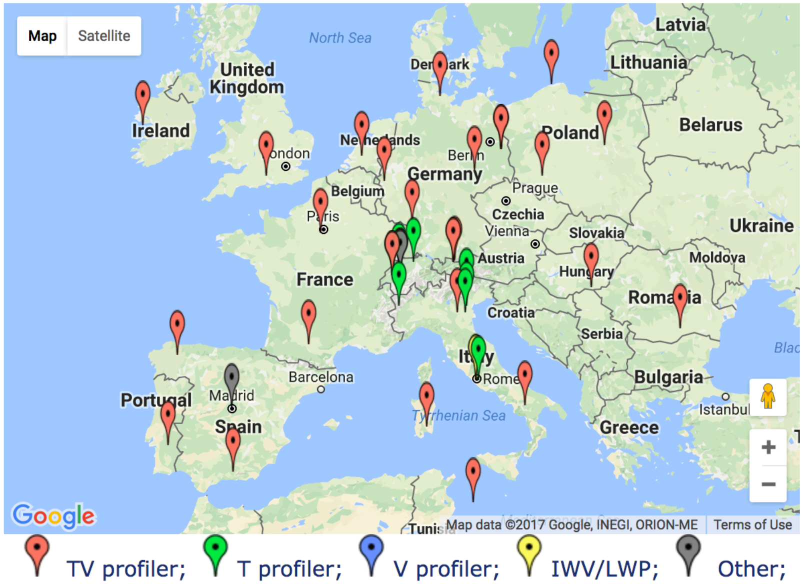
Towards operational NWP service

- EUMETNET (Network of 31 EU Nati
- EUMETNET Profiling Programme vertical profiles of wind, aerosols a
  - wind profilers
  - ceilometer/Lidar

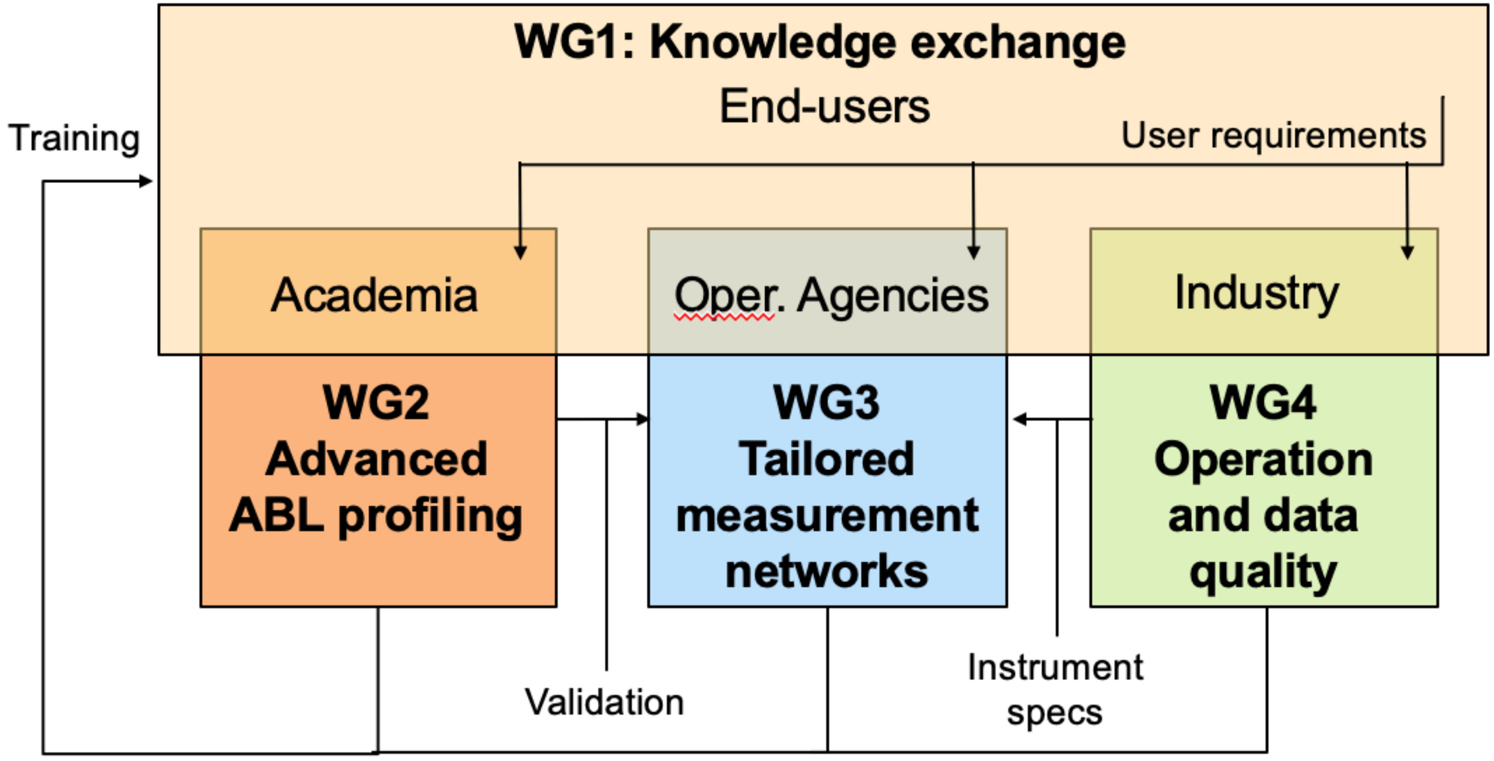


- Proposal to EUMETNET:
  - Addition of MWR to E-PROFILE for profiling BL T and H
  - Task-team to complete a business case within E-PROFILE 2nd phase (2019-2023)

PROBE

PROfiling the atmospheric **B**oundary layer on the **E**uropean scale

- A new COST Action (approved 5/6/2019): Oct 2019 – Oct 2023



Summary and conclusions

Recent achievements in ground-based microwave radiometry:

- NWP DA demonstration of a real network of MWR First time ever!
- Development of software tools:
  - RTTOV-gb Fast forward model
  - 1DVAR Inverse model
  - Net1D Network 1DVAR retrievals
- Uncertainty characterization
  - Absorption model uncertainty
- Towards operational exploitation
  - NWP
  - Climate

Epilogue: Imposter syndrome

- Tips to fight Imposter syndrome:
  1. Be brave and take action
  2. In case of a recognition, don't discount your achievements: just say "Thank you"

Thank you very much for this honor and your kind attention!

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