Practical instructions for solving MWR forward and inverse problems

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Practical instructions for MWR forward and inverse problems

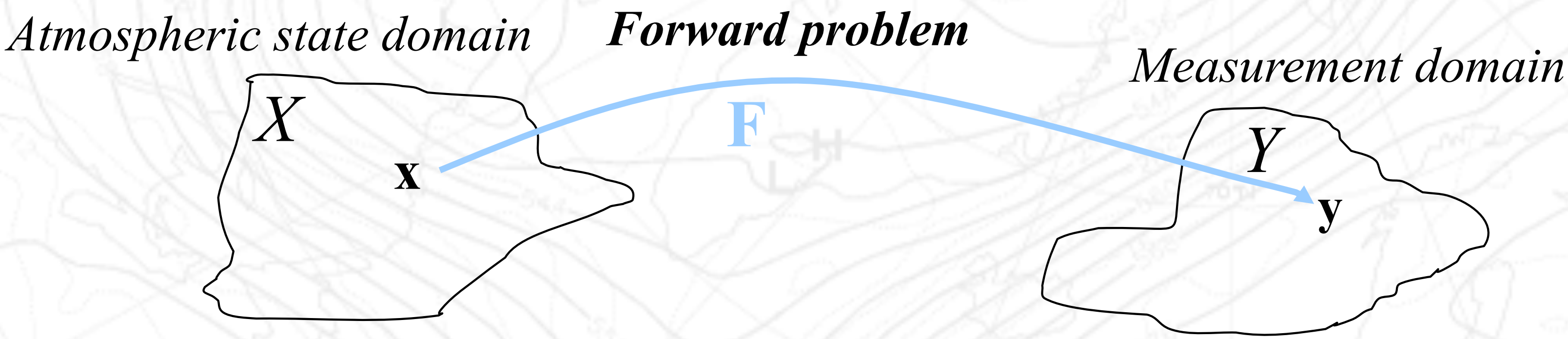
- Introduction
  - Forward and inverse problems

- Software tools
  - RTTOV-gb
  - 1DVAR
  - Net1D

- Summary and practical information

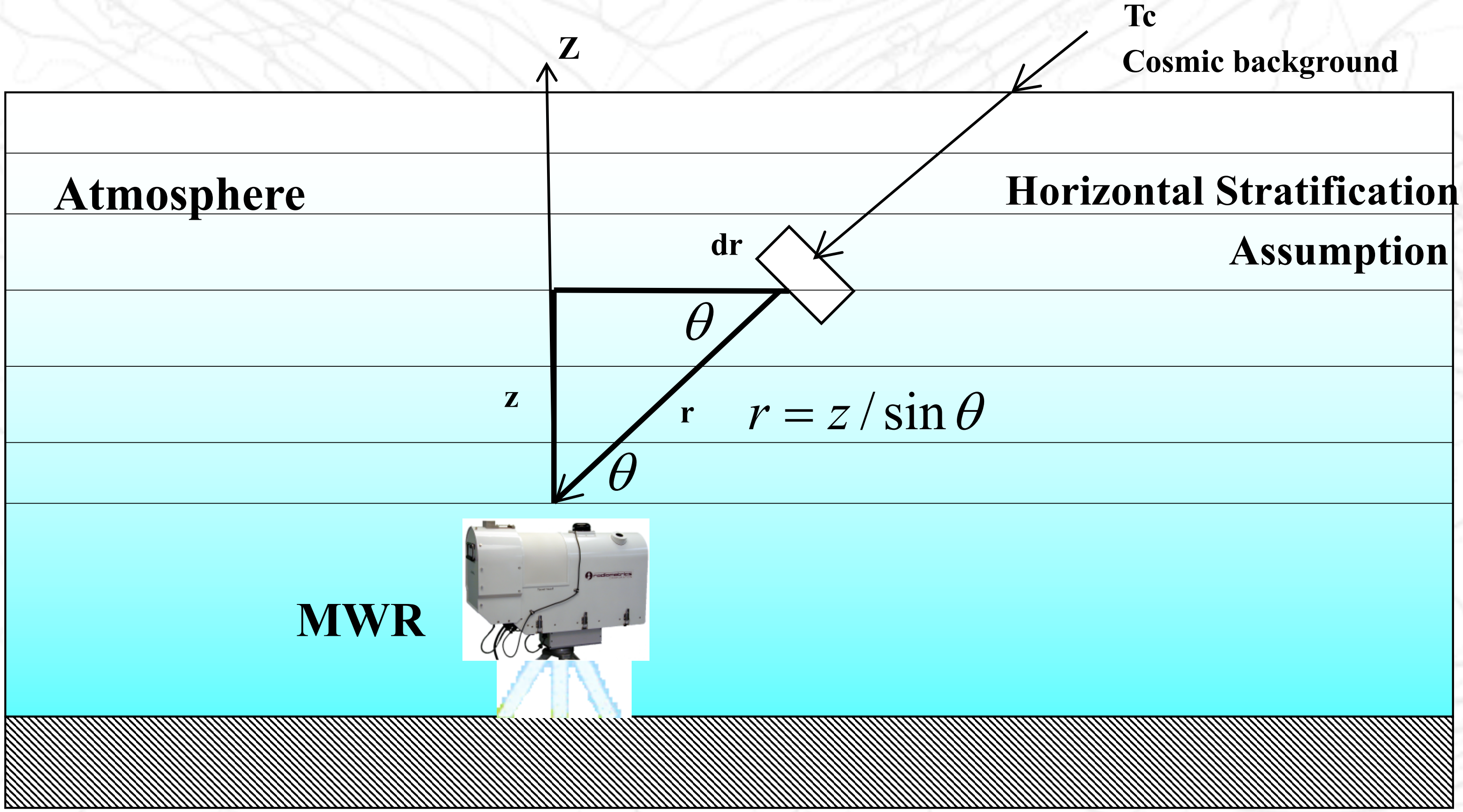
Introduction
Forward and inverse problems

- Going from to “atmospheric state → Tb” is called **Forward Problem**



Introduction
Forward and inverse problems

$$\underbrace{T_b}_{\text{Measured quantity}} = \underbrace{T_c \cdot e^{-\tau(0,\infty)}}_{\text{Cosmic background term (attenuated along the path)}} + \underbrace{\int_0^\infty K_E(r)\cdot T(r)\cdot e^{-\int_0^r K_E(r)dr'} \cdot dr}_{\text{Atmospheric term (emitted \& attenuated along the path)}}$$



Introduction
Forward and inverse problems

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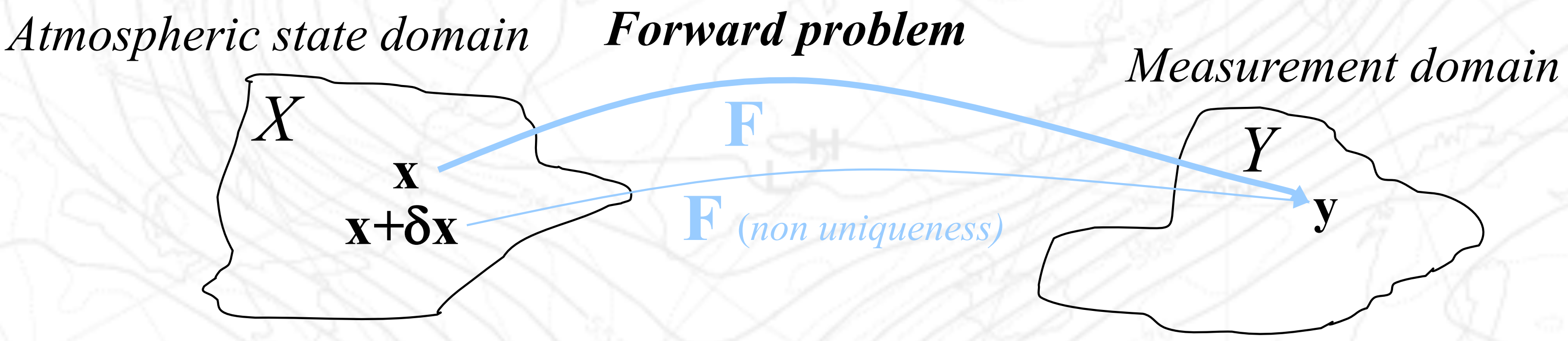
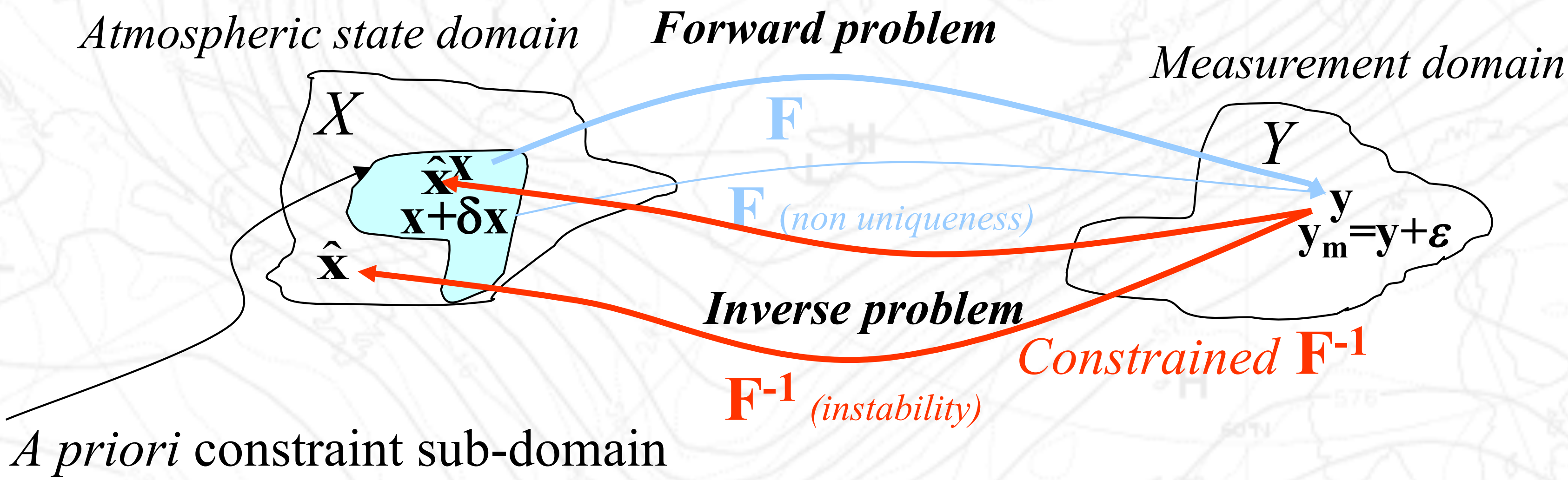


Introduction
Forward and inverse problems

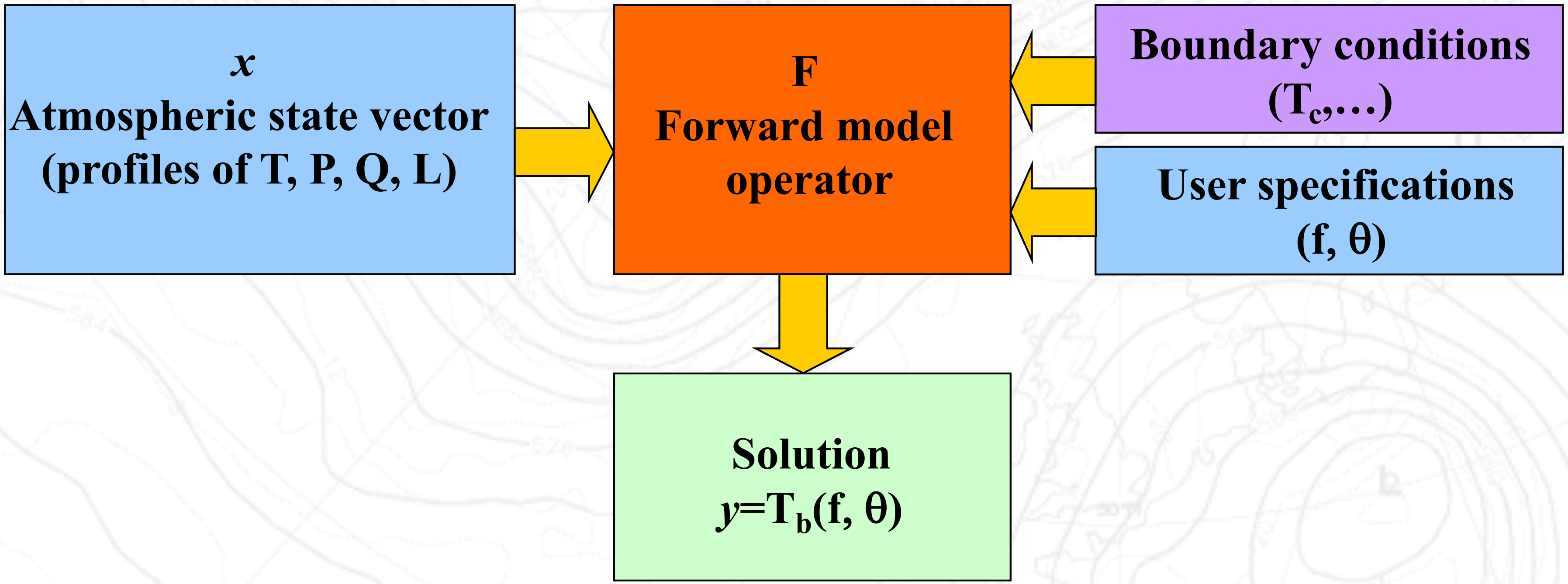
- Going from to “atmospheric state → Tb” is called **Forward Problem**



- Going from “Tb → Atmospheric state” is called **Inverse Problem**
  - Ill-posed problem
    - solution in not unique/stable
  - Need for a priori knowledge to constrain the solution

Introduction
Forward and inverse problems

- The Forward Problem can be modeled in a straightforward manner
- Forward model (FM) operator scheme



- Errors
  - Discretization errors
  - Absorption model uncertainties
  - Other assumptions (scattering, plane parallel,…)

Introduction
Forward and inverse problems

- The Inverse Problem may be very tricky
  - Tb are processed to estimate atmospheric variables
- Examples of inverse methods:
  - Multivariate regression
  - Neural-network methods
  - Optimal estimation method

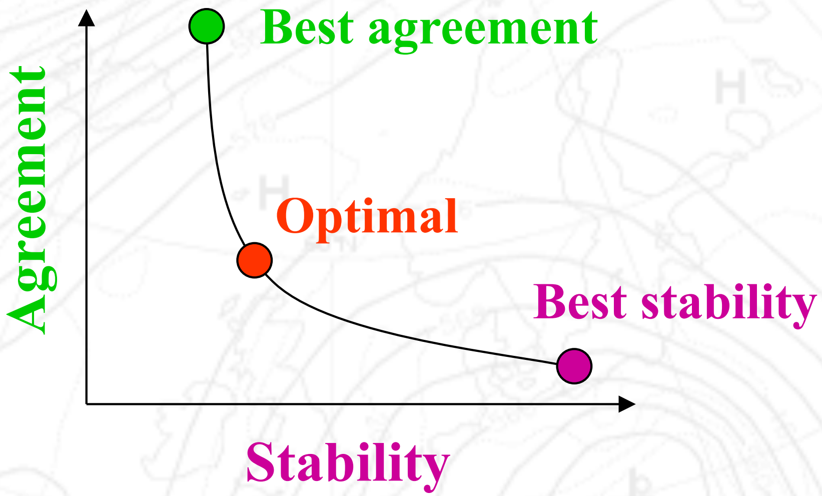
Multivariate regression and Neural-network methods: Provided by proprietary software of commercial MWR

Optimal estimation method: More research-oriented

Introduction
Forward and inverse problems

Optimal Estimation Method

- Method to optimally couple observations with a priori background knowledge (considering the uncertainty of both)



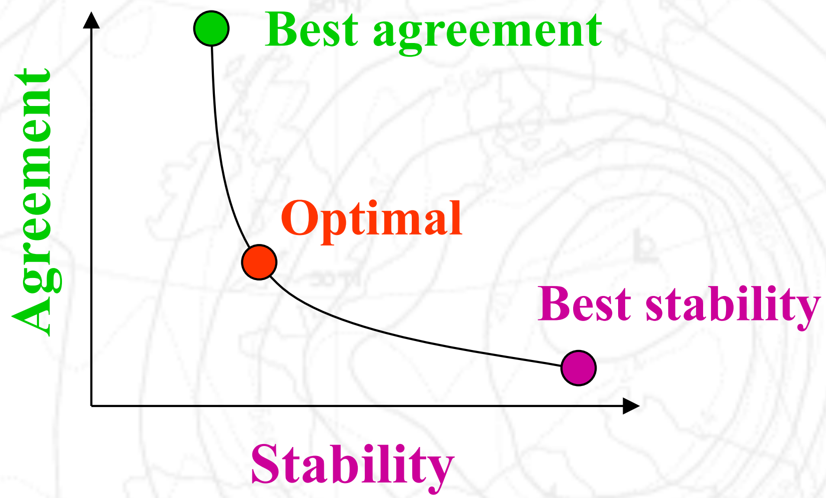
- Assumptions:
  - Moderately non-linear problem
  - Unbiased and Gaussian-distributed errors

Introduction
Forward and inverse problems

Minimization of a cost function *J*

$$J = [y - F(x)]^T R^{-1} [y - F(x)] + [x - x_b]^T B^{-1} [x - x_b]$$

Agreement (wrt the Obs) — **Stability (wrt the Bkg)**



- Where:
  - forward model F(x)
  - error covariance matrices of Bkg (B) and Obs (R)

Introduction
Forward and inverse problems

Iterative solution

Solution increment

$$\mathrm{x}_{\mathrm{i+1}} = \mathrm{x}_{\mathrm{i}} + \left(B^{-1} + K_i^{\mathrm{T}} R^{-1} K_i\right)^{-1} \left[K_i^{\mathrm{T}} R^{-1}\left(\mathrm{y} - F(\mathrm{x}_{\mathrm{i}})\right) - B^{-1}(\mathrm{x}_{\mathrm{i}} - \mathrm{x}_{\mathrm{b}})\right]$$

Updated solution

Solution at previous iteration

K^T transforms from *y* to *x* space

This pulls the solution towards obs; how strongly depends on R^{-1}

This pulls the solution towards *bkg*; how strongly depends on B^{-1}

y: Observation vector (T_B)
F: Forward Model (e.g. RTTOV-gb)
K: Jacobian ($\partial F/\partial x$)
x_b: a priori profile
R: Obs error covariance matrix
B: Bkg error covariance matrix
A: Solution error covariance matrix

The solution increment is weighted with the sum of obs and bkg uncertainty

$$\mathbf{A}_{i+1} = (\boldsymbol{B}^{-1} + \boldsymbol{K}_i^T \mathbf{R}^{-1} \boldsymbol{K}_i\ )^{-1}$$

If B and R are estimated correctly, the diagonal of A gives the expected random error at each height

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Software tools
RTTOV-gb

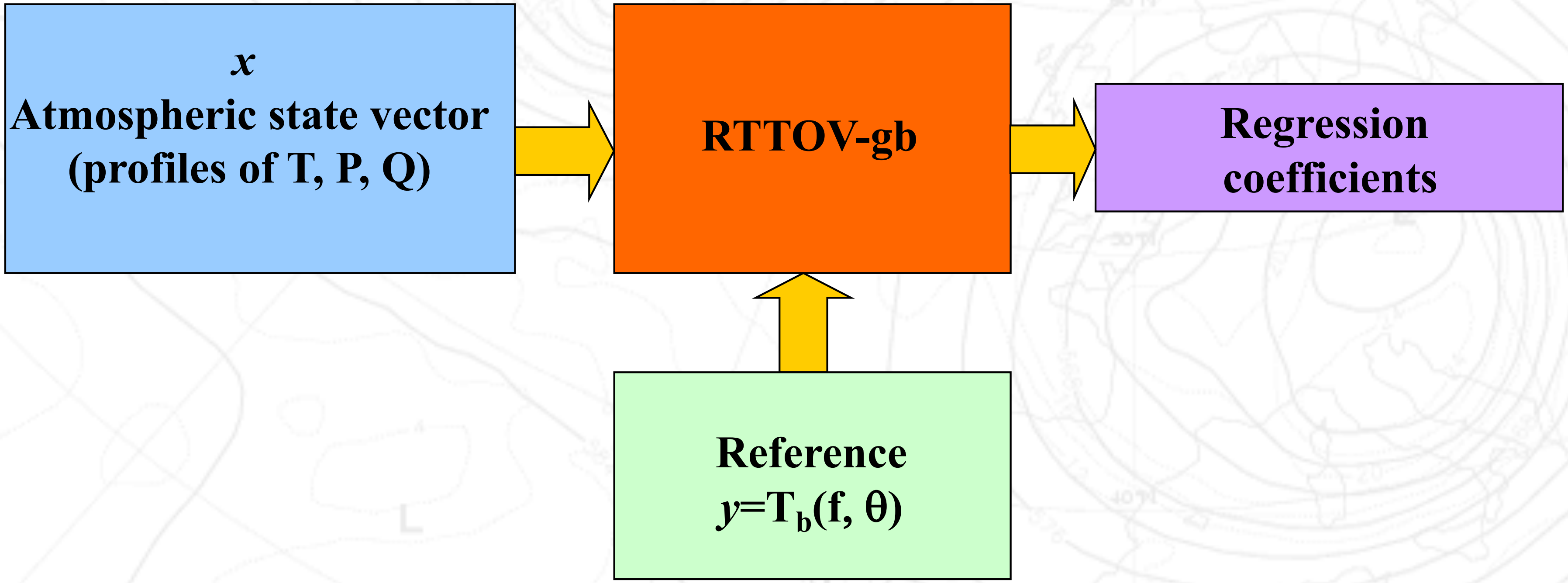
Forward model (FM)

- There are several forward model available for ground-based MWR (ARTS, MonoRTM, PAMTRA,…)
- But none was specifically designed for NWP Data Assimilation
  - Fast parameterized radiative transfer
- RTTOV is a fast forward model developed at EUMETSAT NWP SAF
  - Widely used in the NWP community for DA of satellite observations
  - But limited to satellite observing geometry
- RTTOV was modified within TOPROF to work for ground-based observations, hence RTTOV-gb
  - RTTOV-gb computes the forward + Jacobians (K) wrt to x
- RTTOV-gb currently only works for MW observations

Software tools
RTTOV-gb

How RTTOV-gb works? (similarly to the parent RTTOV)

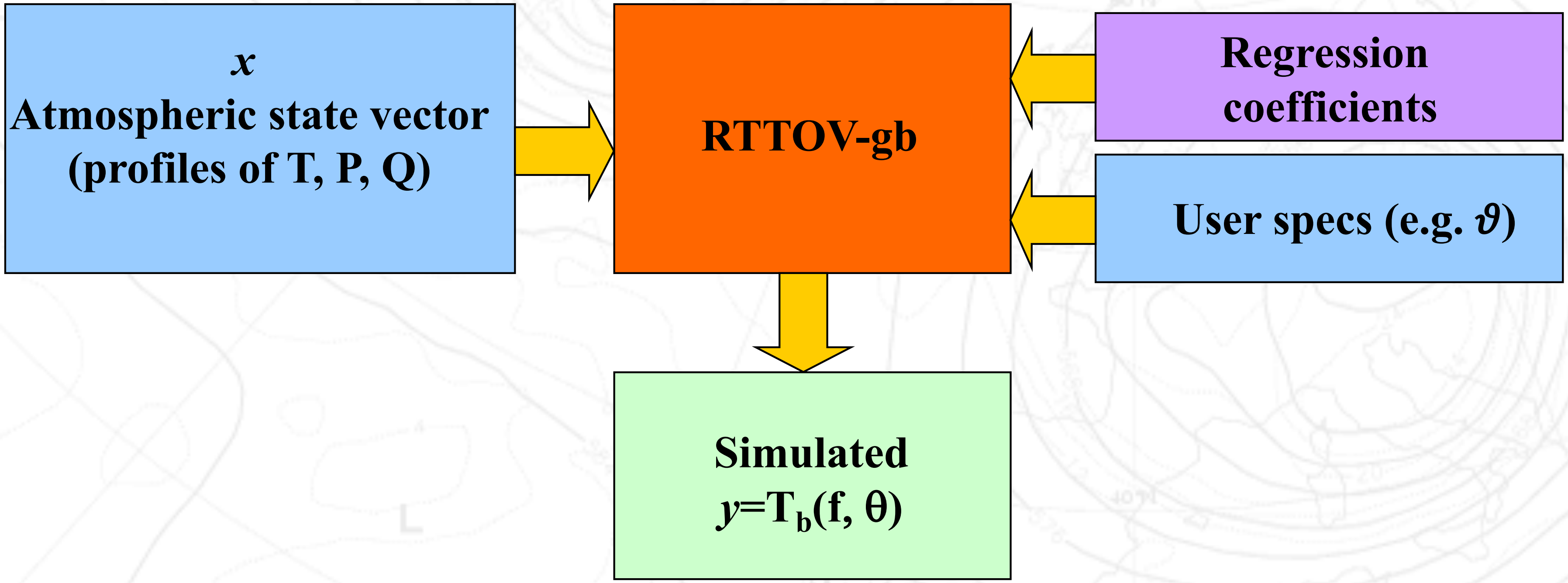
- **TRAINING**:
  - Input:
    - Climatological P,T, H profiles on N vertical levels;
    - Atmospheric transmittance calculated with a reference FM
  - Output: Regression coefficients



Software tools
RTTOV-gb

How RTTOV-gb works? (similarly to the parent RTTOV)

- **FORWARD COMPUTING**:
  - Input:
    - o P,T, H profiles on N vertical levels;
    - o Regression coefficients;
    - o User's specs (elevation angle, instrument)
  - Output: Simulated Tb



Software tools
RTTOV-gb

Statistical evaluation against reference model

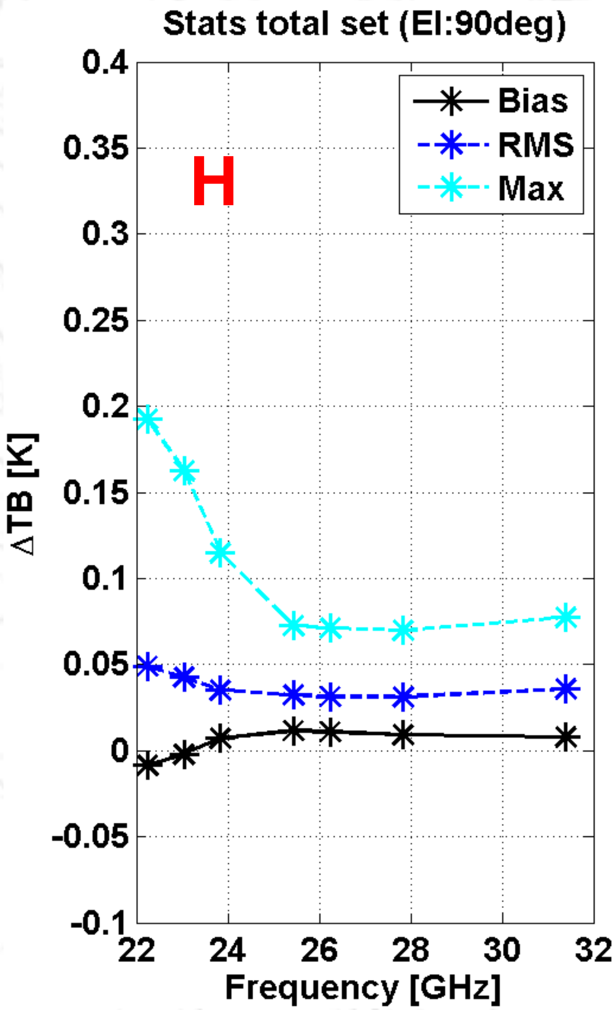
Specs:

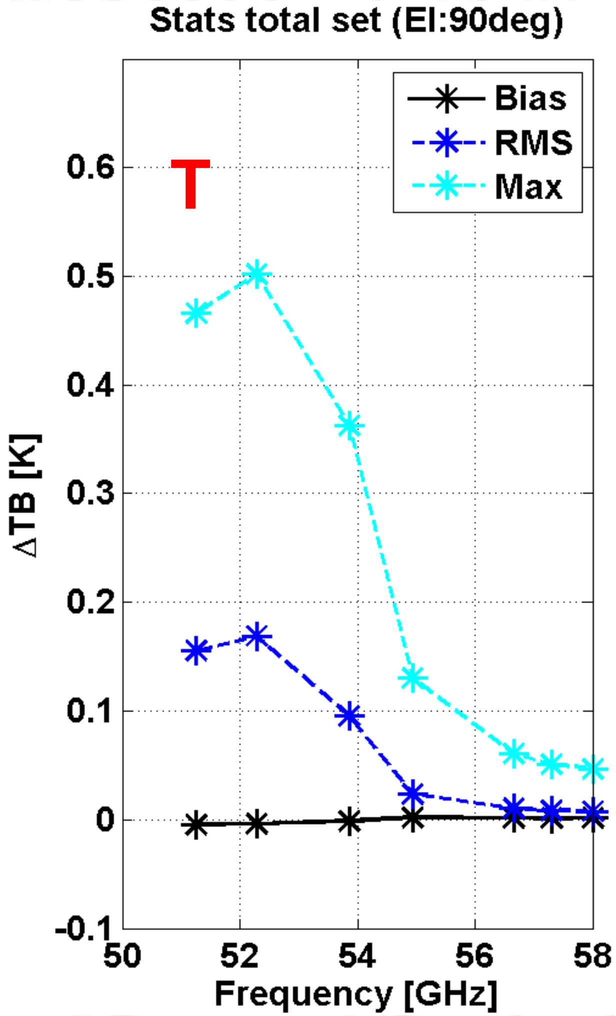
Training: LBL Rosenkranz 1998 (R98) model

independent profiles

HATPRO Channels

90° elev. angle





Software tools
RTTOV-gb

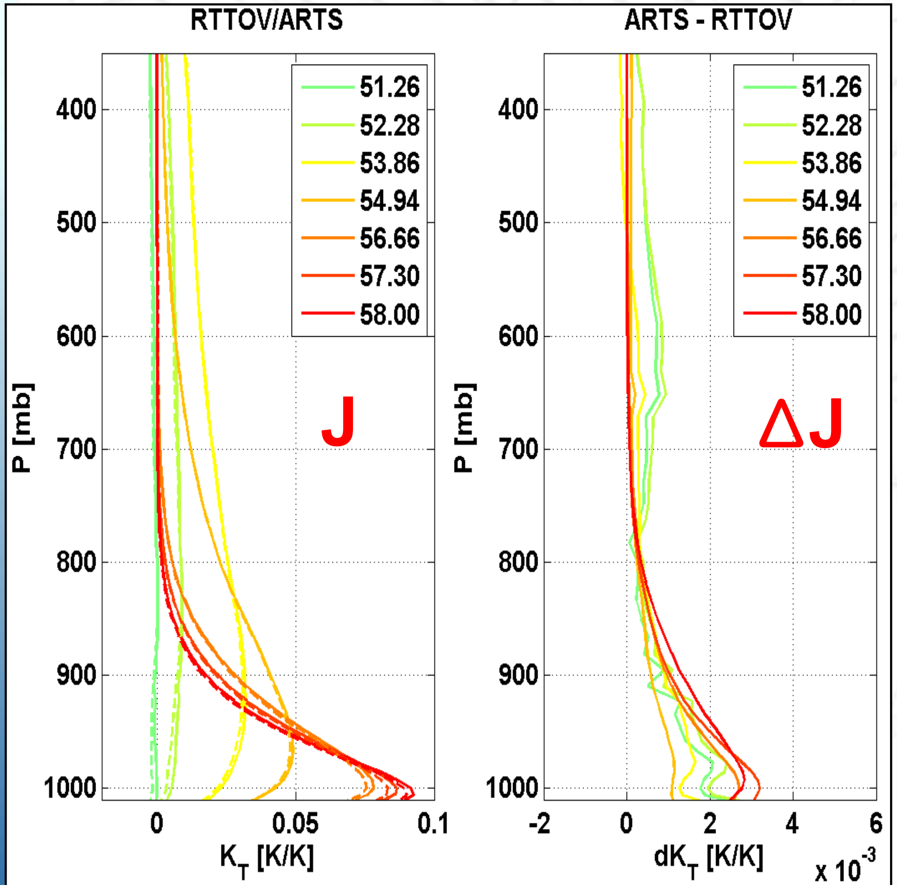
RTTOV and RTTOV-gb also copmpute the Jacobian K=∂F/∂x

Jacobian Evaluation (wih respect to reference model ARTS)

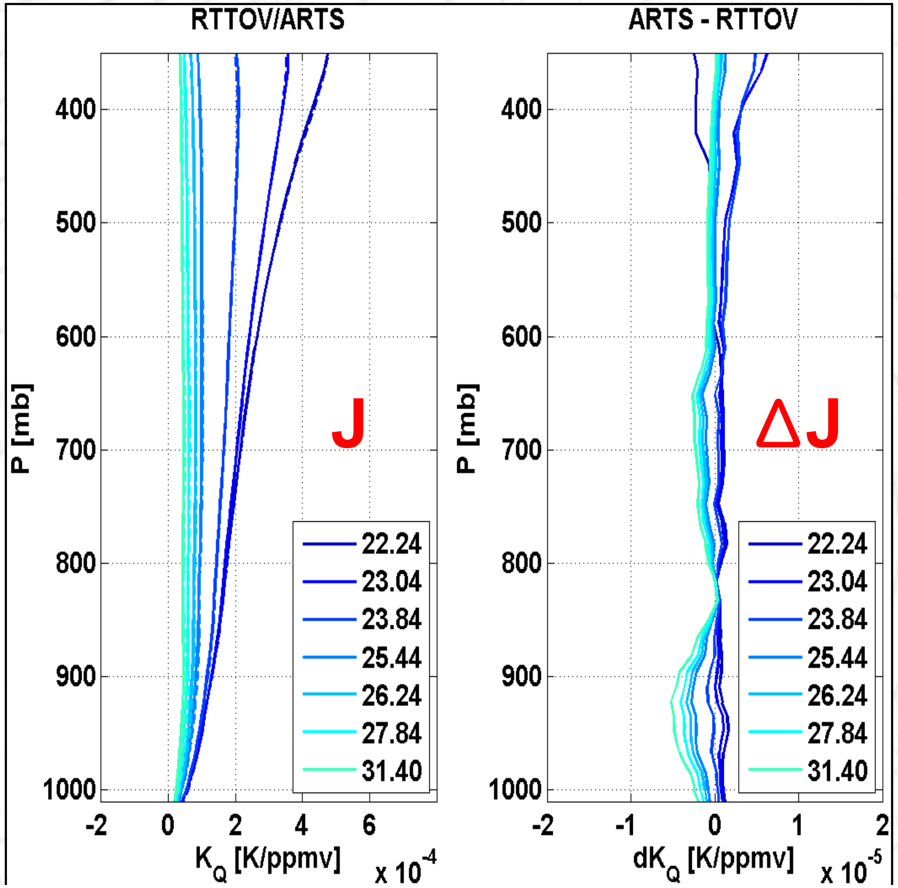
T Jacobian differences < 3%

Q Jacobian differences < 5%

TEMPERATURE



HUMIDITY



Software tools
RTTOV-gb

RTTOV-gb testing

- Comparison wrt reference model*
  - T_B differences less than typical MWR uncertainties
  - Jacobians nearly identical to reference model
  - RTTOV-gb faster than reference model

- RTTOV-gb well suited for serving as FM for the direct DA of MWR Tb observations.

- RTTOV-gb is now in experimental use at some European institutions:
  - University: Geophysics and Meteorology Inst. (Univ. Koln)
  - National Weather Services: Meteo France, DWD

* De Angelis et al., RTTOV-gb, Geosci. Model Develop., 2016

Software tools
RTTOV-gb

What do we need for network NWP Data Assimilation?

- Test the consistency NWP-FM-Obs → O-B analysis
- O-B: Observations minus Background
  - Observations are from the instruments
  - Background is from the NWP model
- O-B analysis is needed for
  - checking the consistency of the Obs with the Bkg
  - estimating the potential innovation in the Obs

Software tools
RTTOV-gb

MWR O-B analysis with RTTOV-gb

- **Period:** 1 year – Jan-Dec 2014
- **Format:** NetCDF, CF-compliant, after HD(CP)2
- **Observations:** 6 MWR (JOYCE, LACROS, CESAR, SIRTA, PAYERNE, RAO)
- **Background NWP model:**
  - AROME NWP system (3h-forecasts + Analyses)
- **Background Tb:**
  - Computed with RTTOV-gb from closest AROME profiles

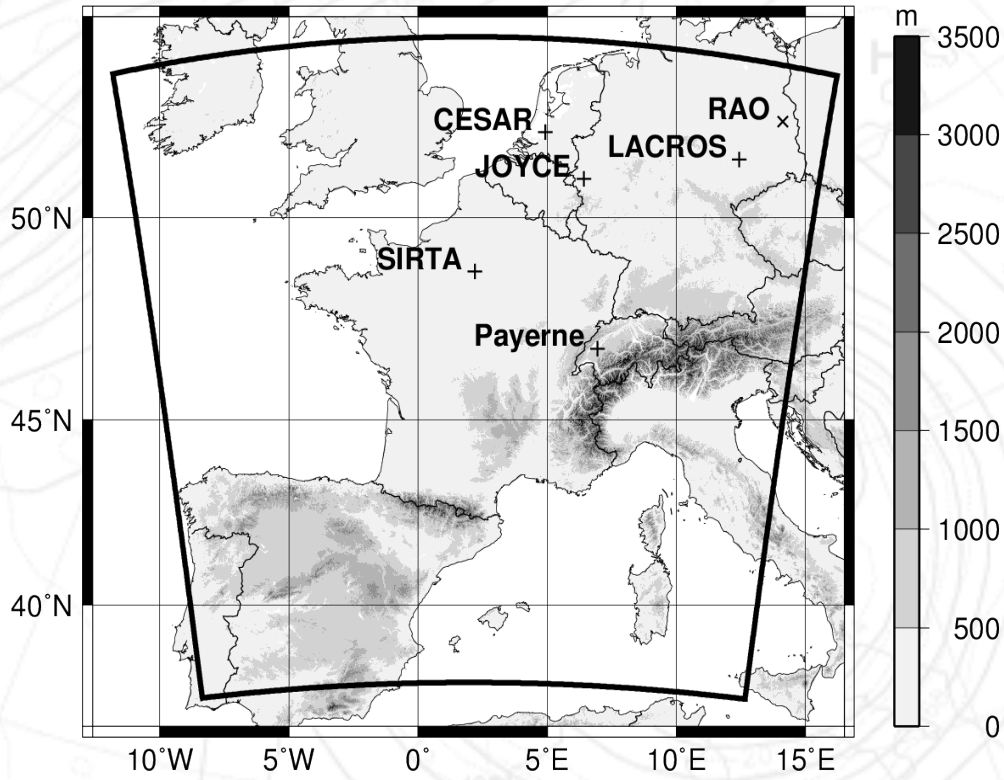
Software tools
RTTOV-gb

MWR O-B analysis with RTTOV-gb

- 6 stations
  - CESAR (NL) HATPRO
  - JOYCE (DE) HATPRO
  - LACROS (DE) HATPRO
  - Payerne (CH) HATPRO
  - RAO (DE) MP3000A
  - SIRTA (FR) HATPRO

HATPRO: 14 chans, 7 angles
MP3000A: 12 chans, 2 angles

- 1-year data set (2014)

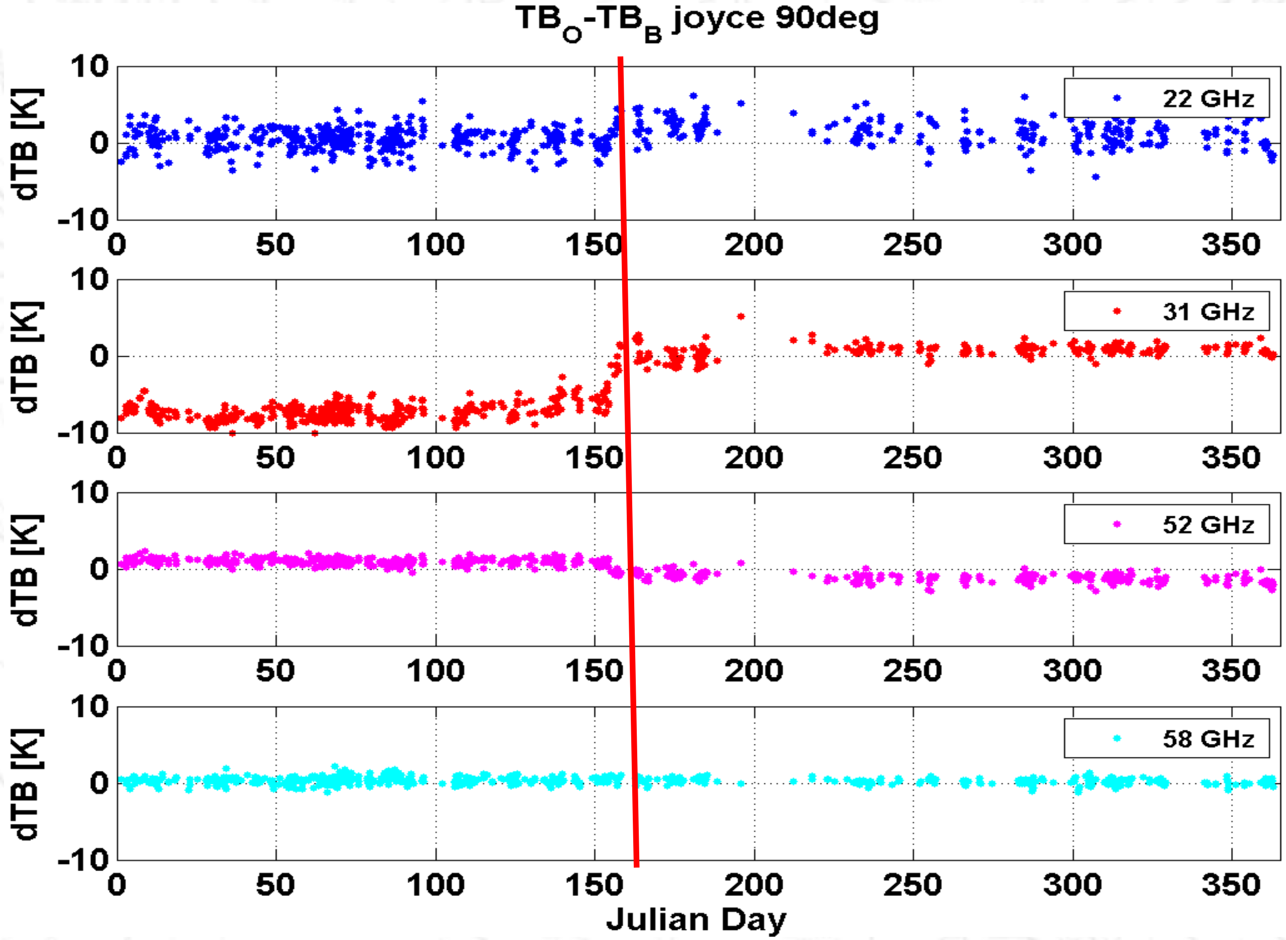


* De Angelis et al., Atm. Meas. Tech. Discuss., 2017

Software tools
RTTOV-gb

MWR O-B analysis: bias monitoring

Centralized remote monitoring

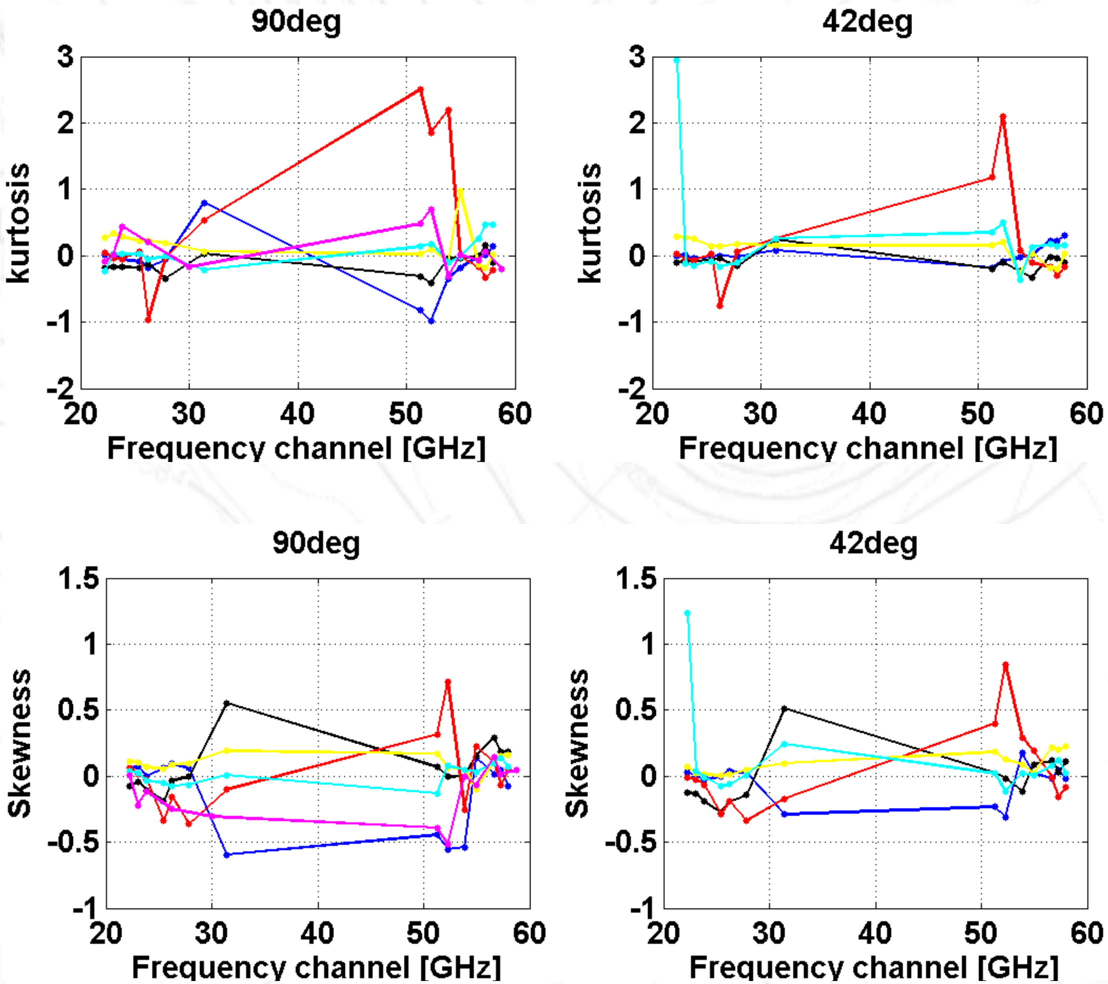


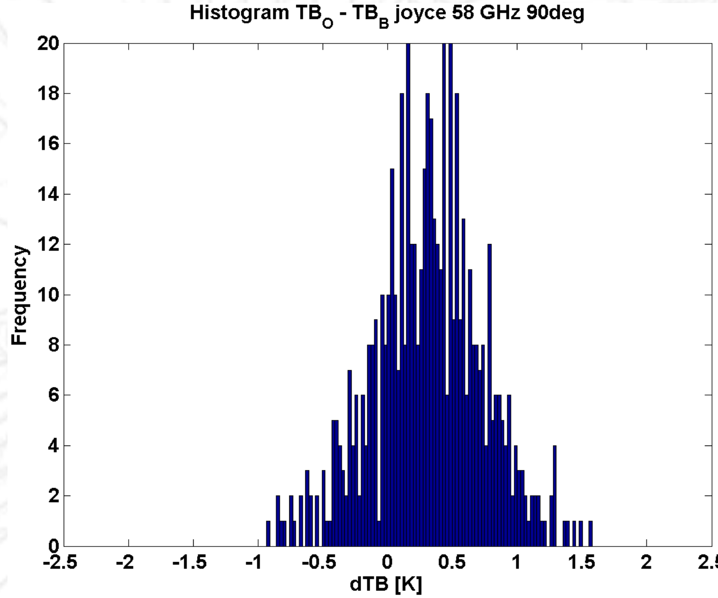
* De Angelis et al., Atm. Meas. Tech. Discuss., 2017

Software tools
RTTOV-gb

MWR O-B analysis: distribution monitoring

CESAR
JOYCE
LACROS
Payerne
RAO
SIRTA





95.8% excess kurtosis < 1
99.4% skewness < 0.5

Approximately Gaussian throughout the network

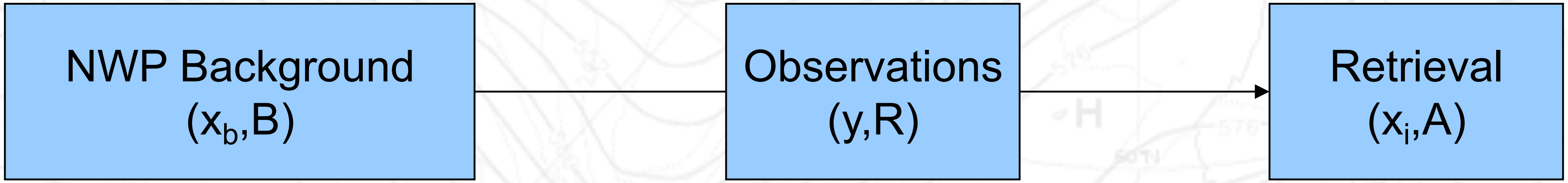
Obs and FM are consistent with NWP and can then be assimilated

* De Angelis et al., Atm. Meas. Tech. Discuss., 2017

Software tools
1DVAR

- Another step towards MWR data assimilation is the development of a one-dimensional variational retrieval (1DVAR)

- 1DVAR is a nonlinear retrieval technique based on Optimal Estimation Method with the a priori information taken from a NWP model output



Software tools
1DVAR

1DVAR development

- Start from the EUMETSAT NWP SAF 1DVAR package
  - Stand-alone system calling RTTOV (satellite applications)
- Modify to work with RTTOV-gb
  - NWPSAF 1DVAR v1.1 interfaced with RTTOV-gb v11.2
  - Modified the “composite instrument” option from “multiple instrument” to “same instrument with multiple elevation angles”
  - Added option to minimize humidity either in logarithm or in specific humidity
  - Extended quality check during the minimization (to avoid negative humidity and liquid water content values)
  - More flexibility in the LWP retrieval (background error defined by the user, minimization starting from the background value or a default value)

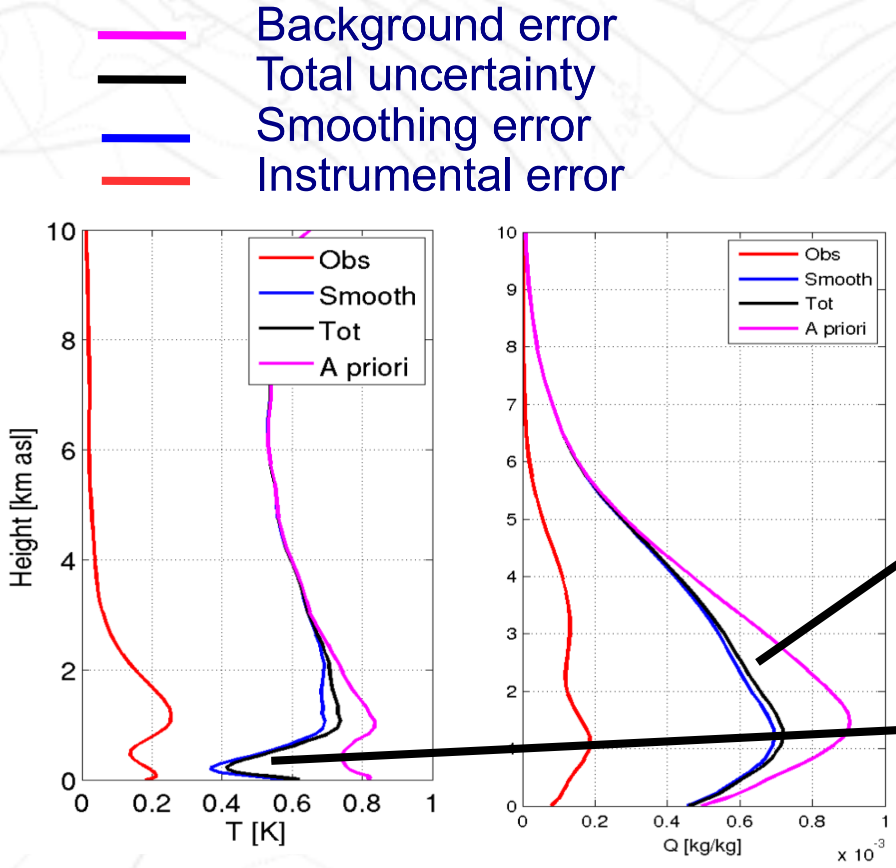
Software tools
1DVAR

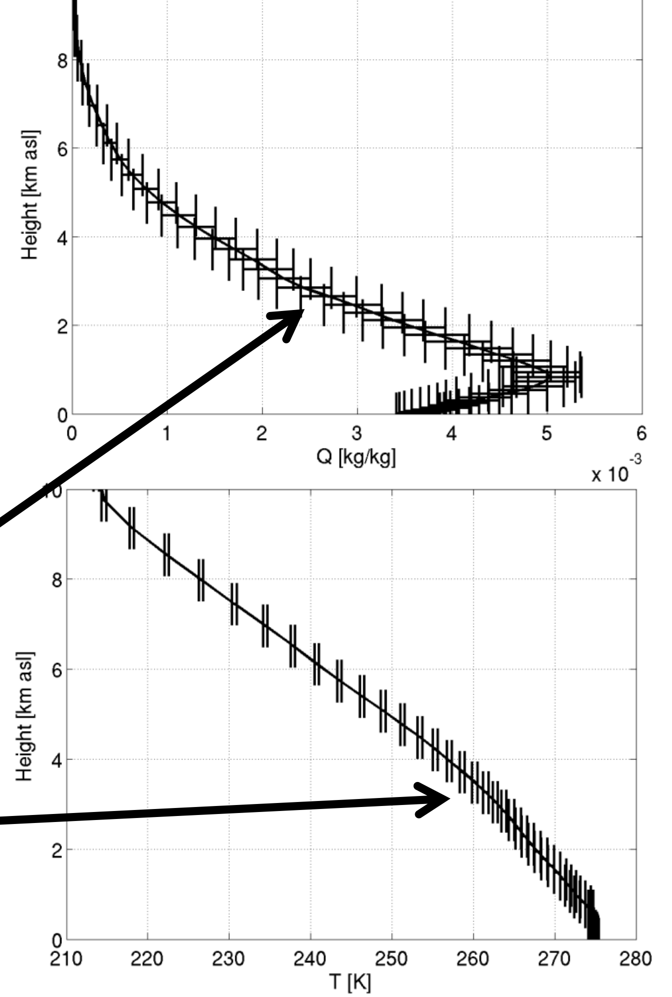
Error covariance

1DVAR results

$$A = \left(B^{-1} + K_i^T R^{-1} K_i\right)^{-1}$$

- T and Q profiles with estimated retrieval uncertainty
- Estimated uncertainties depends on the atmospheric situation (through Jacobians)





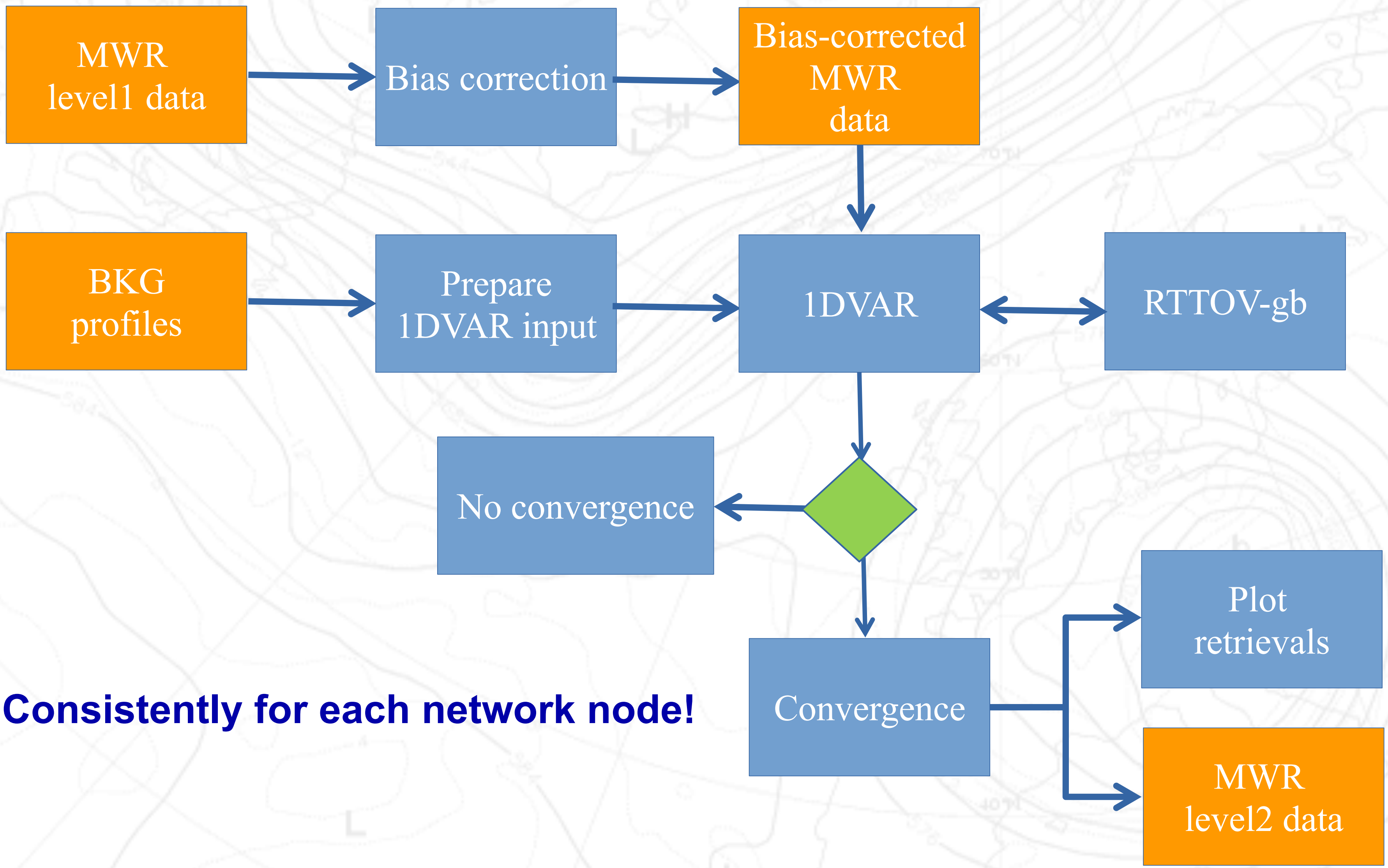
Software tools
Net1D

How can we test this for a MWR network?

- Consider a prototype-network
- Develop a flexible processing chain to perform 1DVAR retrievals on different sites with different instrument and configurations
- Evaluate retrieval accuracy and dominant sources of errors (uncertainty / systematic / drifts)

Software tools
Net1D

Net1D processing chain



Consistently for each network node!

Software tools
Net1D

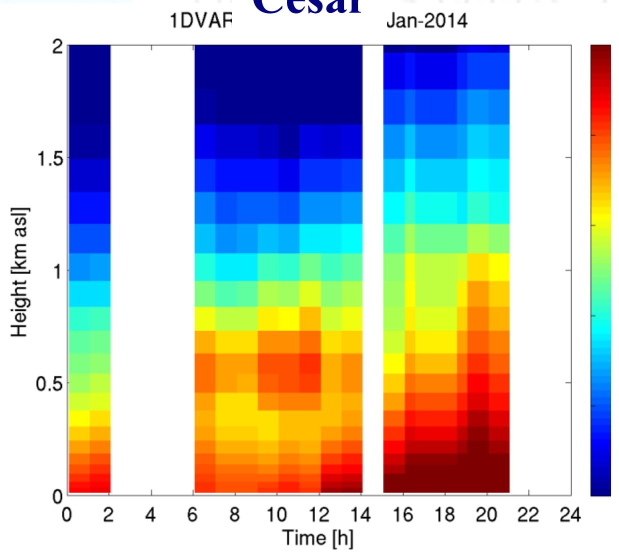
- The whole configuration is defined in one config file:
  - input data and paths
  - station (location, instrument)
  - period to process
  - sampling strategy
  - channels and elevation angles to be used
  - control variables
  - R and B matrix
  - cloud configuration
  - etc..

- First evaluation of Net1D chain on one day and six stations

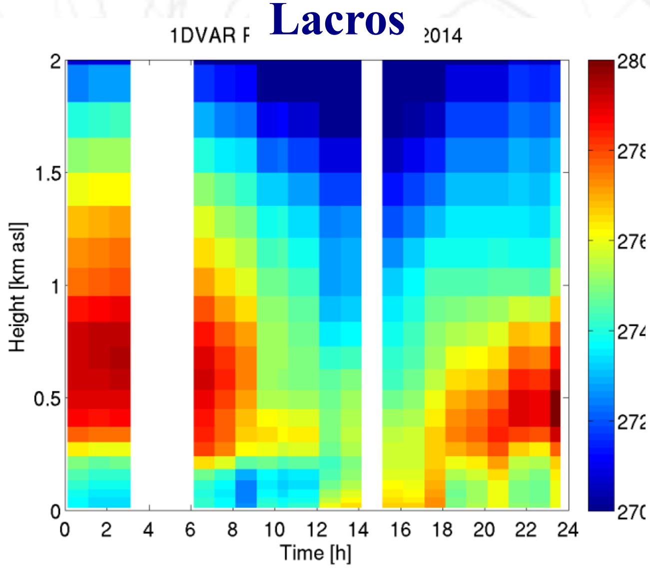
Software tools
Net1D

Temperature profile retrievals

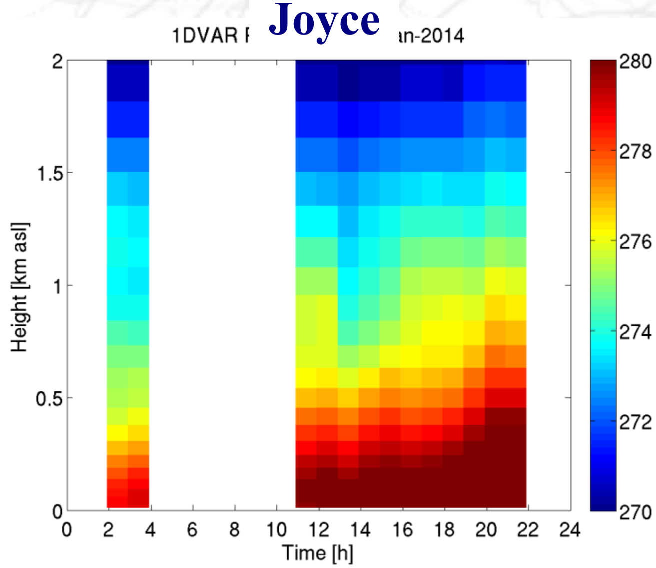
Cesar



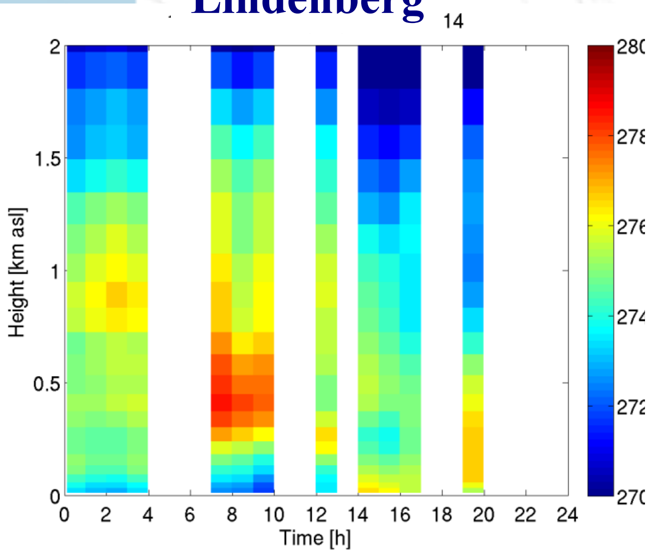
Lacros



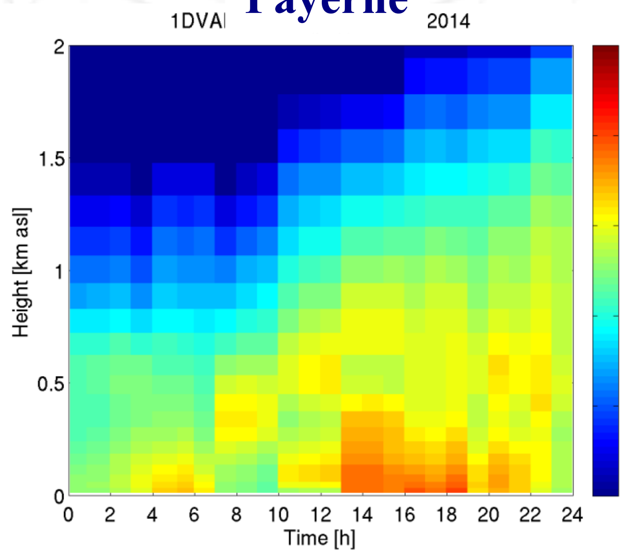
Joyce



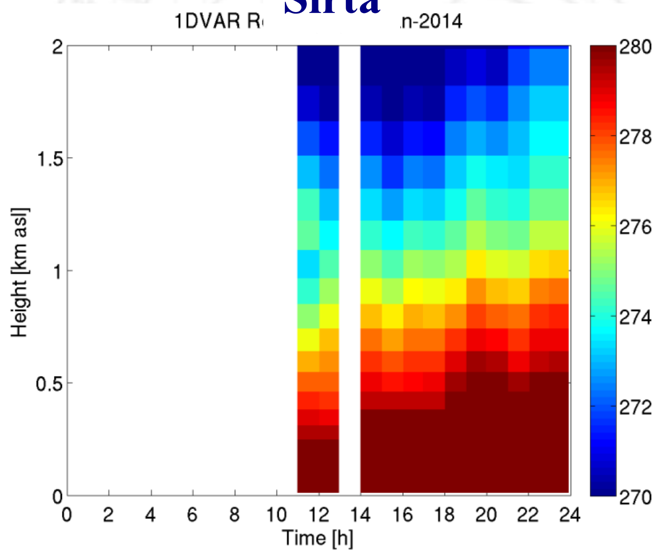
Lindenberg



Payerne

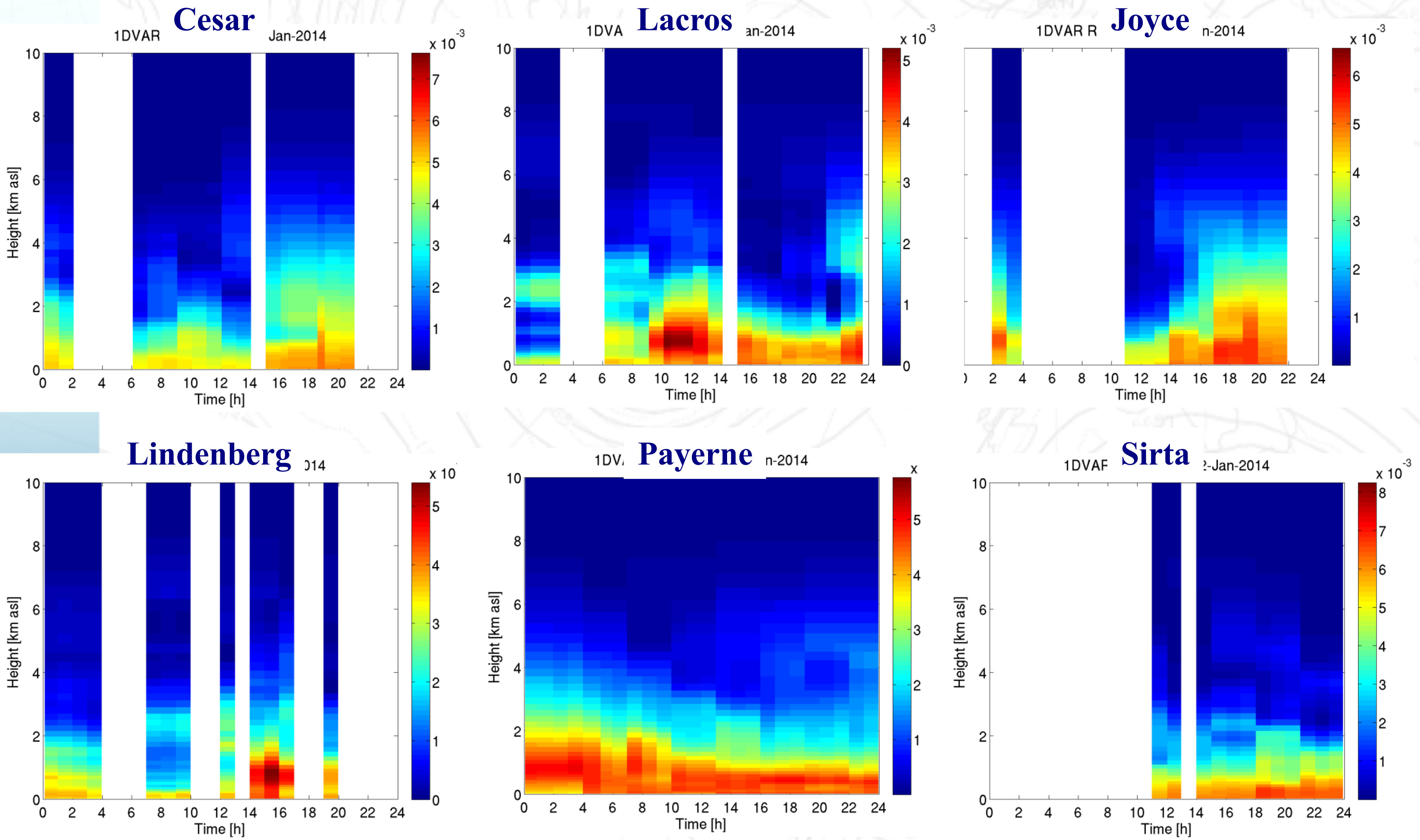


Sirta



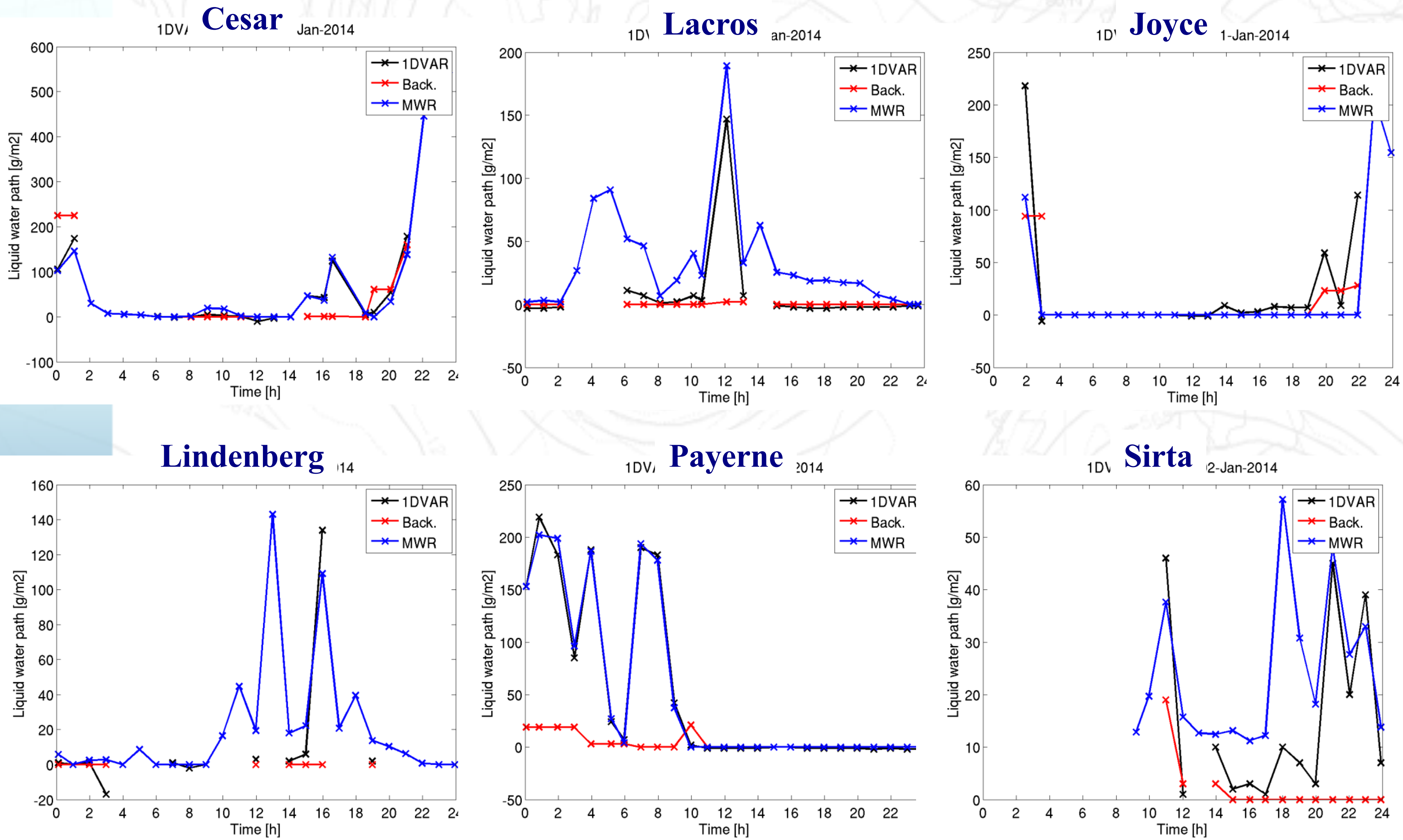
Software tools
Net1D

Humidity profile retrievals



Software tools
Net1D

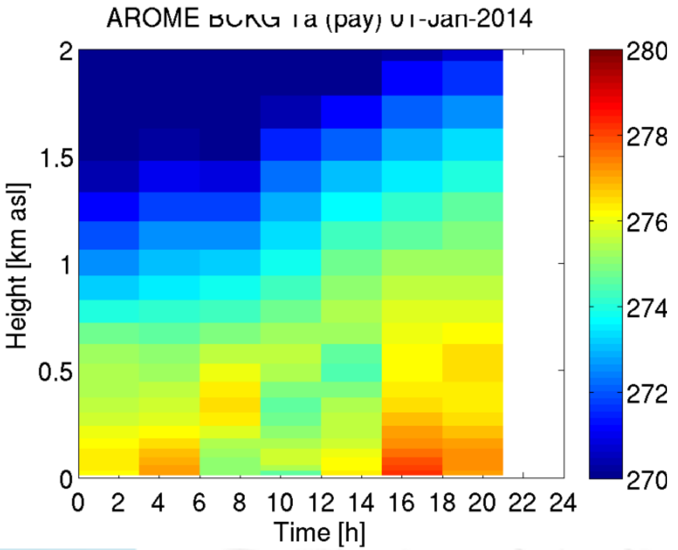
Liquid water path retrievals



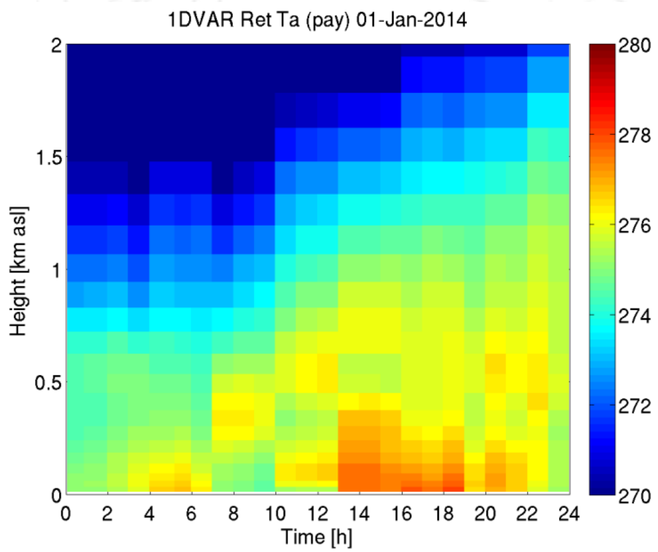
Software tools
Net1D

Impact on the background

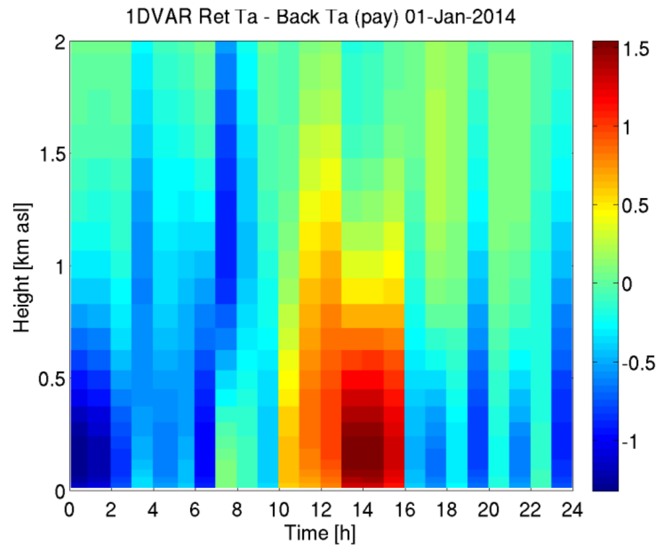
T AROME



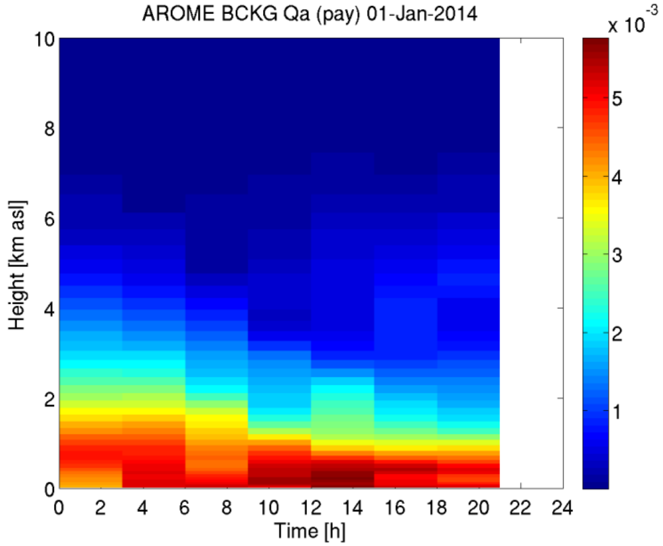
T 1DVAR



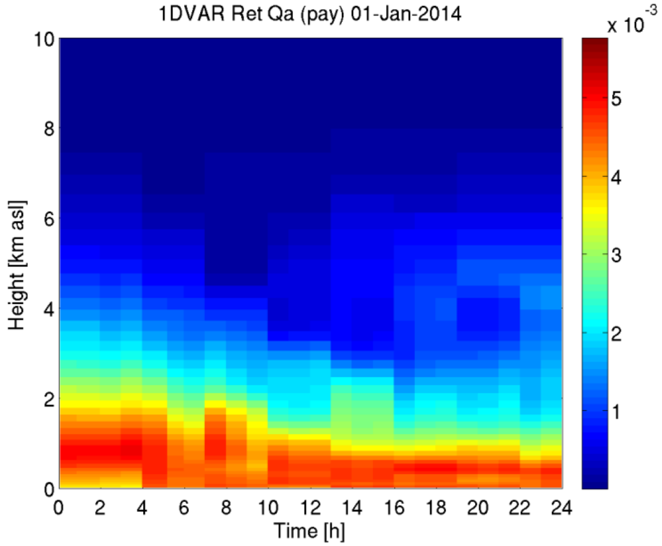
Increment



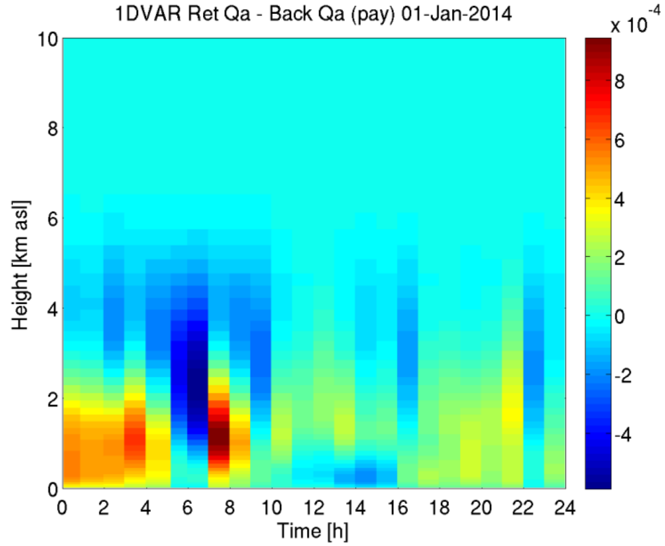
Q AROME



Q 1DVAR



Increment



Software tools
Net1D

- Next steps:
  - perform one year of retrievals
  - validation against radiosondes where available

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Summary and practical information

Software tools:

- **RTTOV-gb**
  - fast FM for ground-based MWR
  - Ingests atmospheric profiles
  - Computes Tb and Jacobians
- **1DVAR**
  - fast 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 (curr. 6 nodes)
  - Computes 1DVAR retrievals consistent throughout the network

Summary and practical information

Availability:

- **RTTOV-gb**
  - will be available through NWP SAF
  - needs a free RTTOV licence
- **1DVAR**
  - available through P. Martinet (Météo France)
  - needs RTTOV-gb
- **Net1D**
  - currently available on GitHub (Matlab code)
  - plans for translating to python
  - needs RTTOV-gb and 1DVAR