Assimilation of wet refractivity field into WRF model

Natalia Hanna (TUW) & Estera Trzcina (WUELS)

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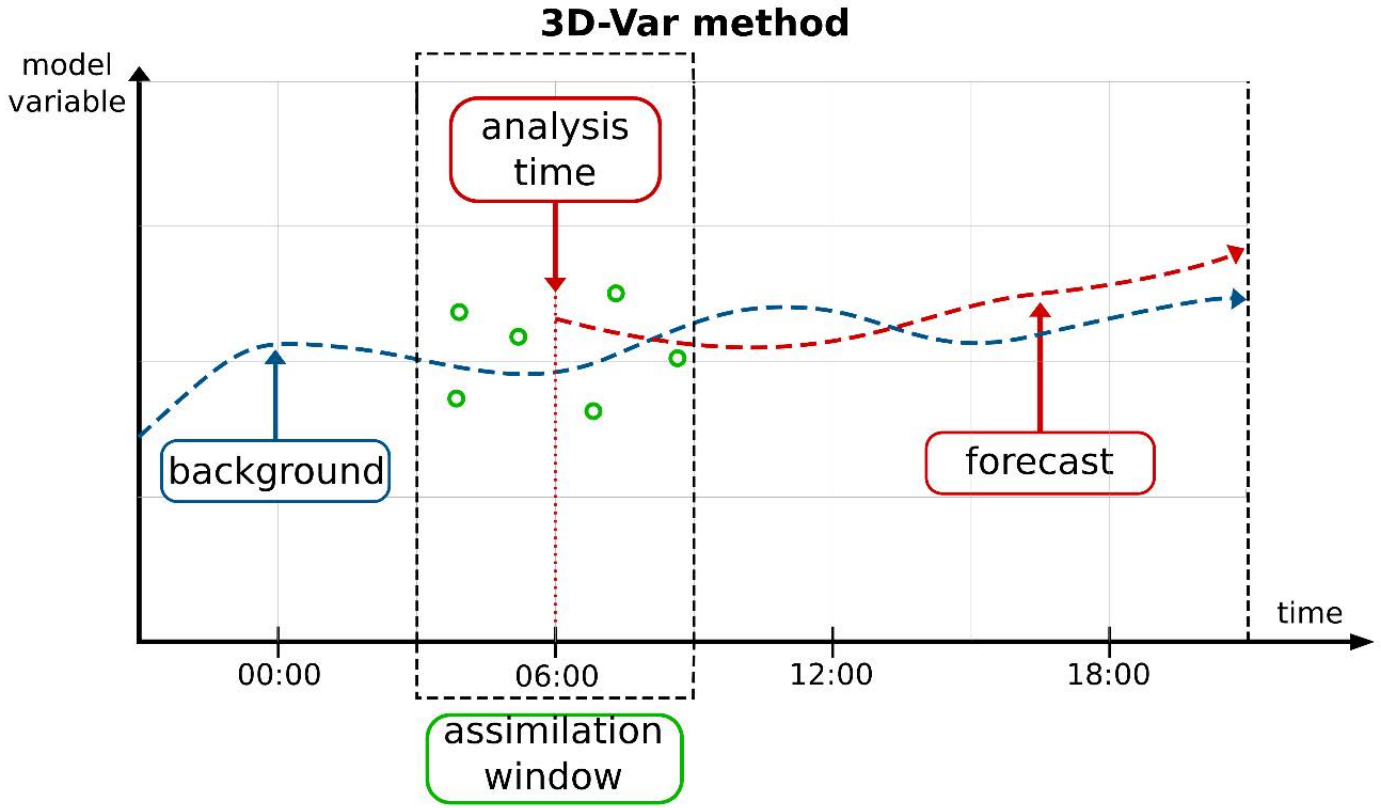
Data assimilation

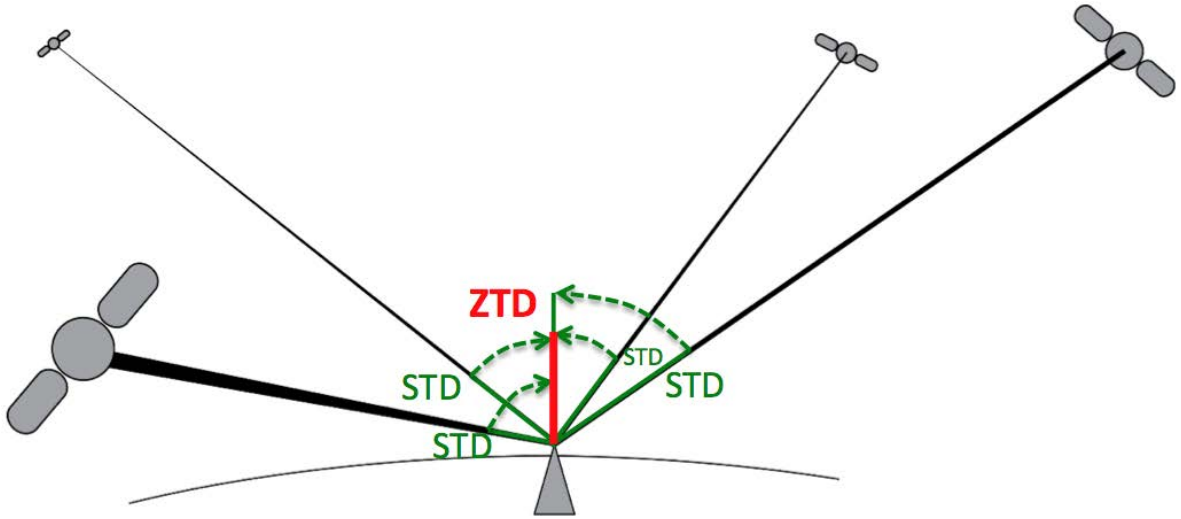
- Process by which optimal initial conditions for numerical forecasts are estimated.
- An **observation operator** is a function (or a set of functions), which provides the link between the analysis variables and the observations.
- Assimilation of a **new type** of observations requires development of a new operator.

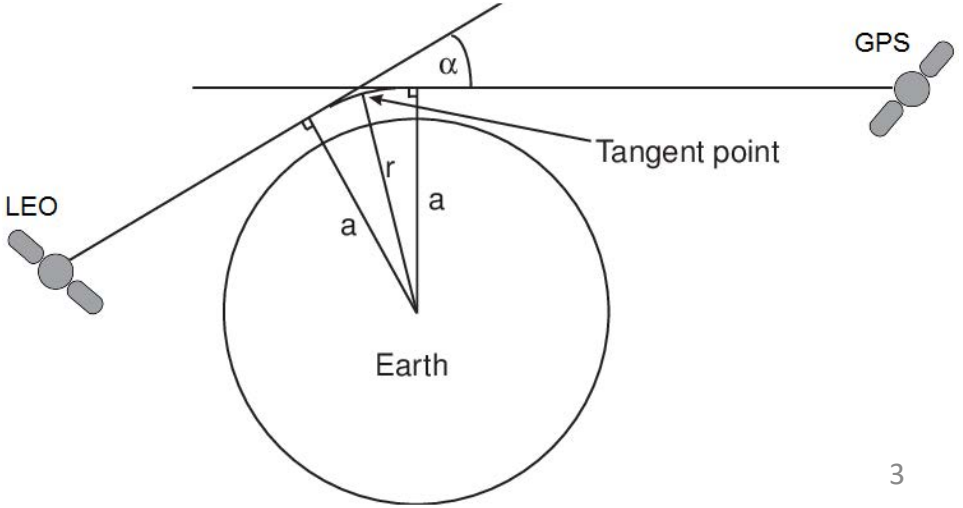


$$J(\mathbf{x}) = \underbrace{\frac{1}{2}\left(\mathbf{x}-\mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^b\right)}_{J_b} + \underbrace{\frac{1}{2}\left(\mathbf{y}-h(\mathbf{x})\right)^T \mathbf{R}^{-1}\left(\mathbf{y}-h(\mathbf{x})\right)}_{J_o}$$

GNSS Meteorology

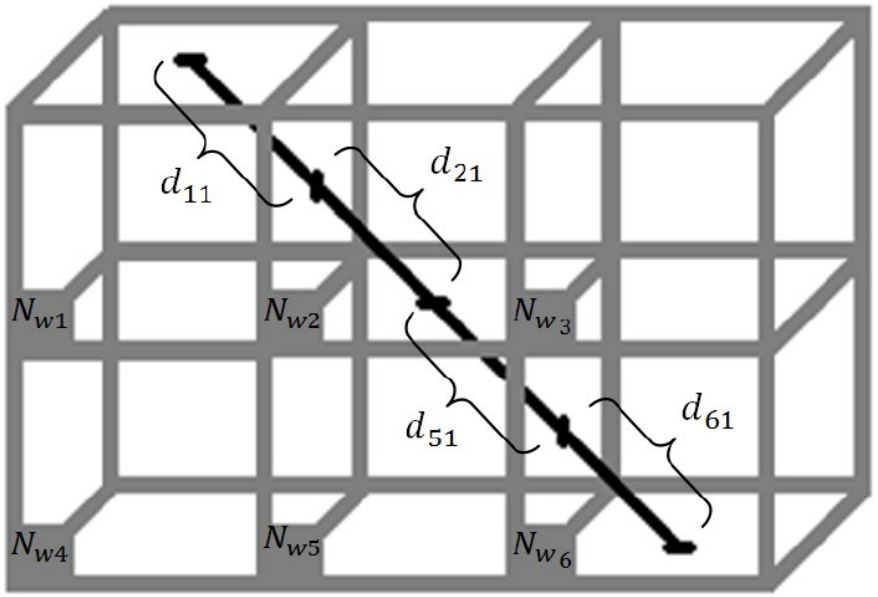
- **Zenith Total Delay (ZTD)** – integrated information about tropospheric delay in the column above the GNSS site
- **Integrated Water Vapor (IWV)** – intergrated information about water vapor content in the column above the GNSS site
- **Radio occultation profile (α, N)** – information about beding angle or total tropospheric refractivity
- **Slant Total Delay (STD)** – integrated information about tropospheric delay on the path between GNSS statelite and receiver





GNSS Tomography

GNSS tomography provides the 3D information about wet refractivity distribution



$$SWD = 10^{-6} \int N_w ds$$

$$SWD = A * N_w$$

known estimated

$$A = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nm} \end{bmatrix}$$

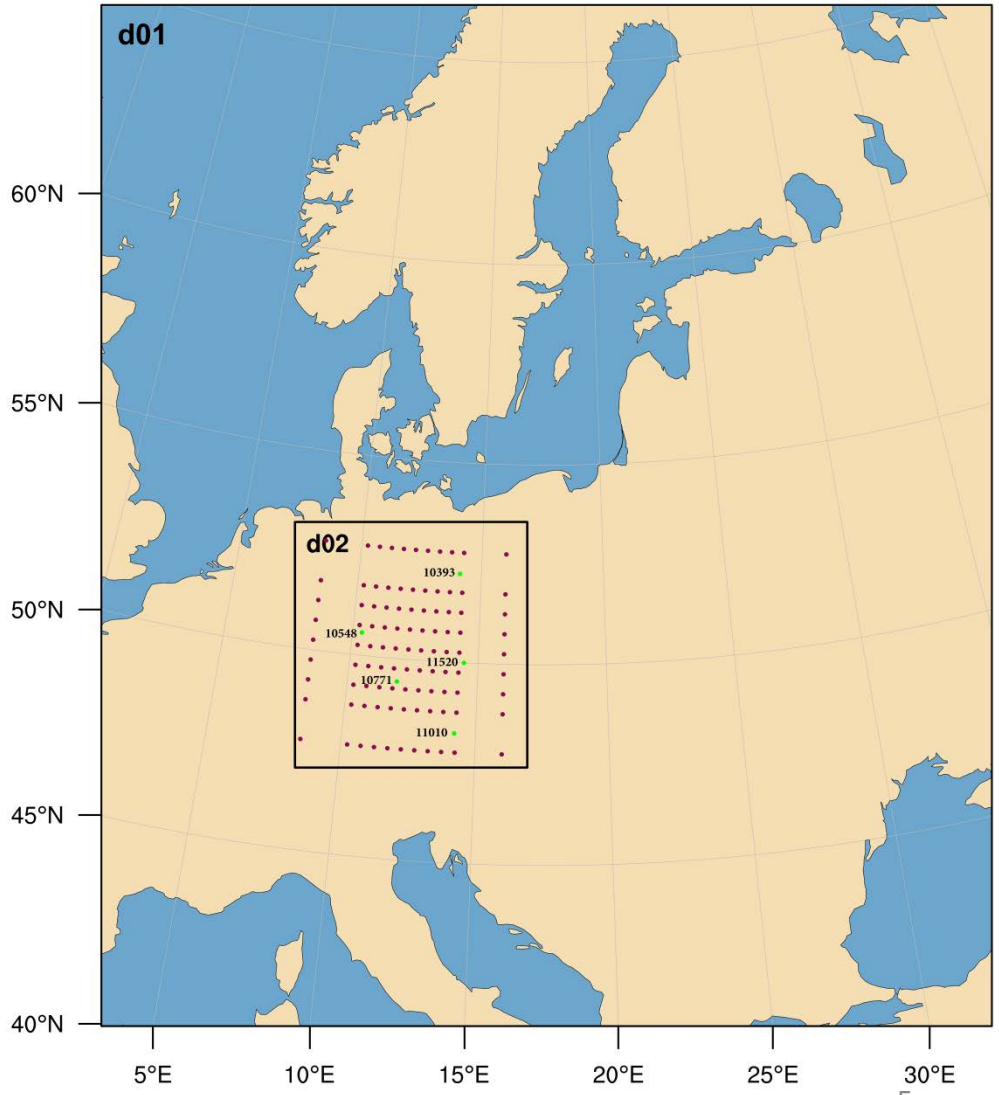
N_w assimilation using GPSREF

Total refractivity:

$$N_w + N_h = N$$

- N_w → tomography outputs
- N_h → ALADIN-CZ model
- N → assimilated

Hanna N., Trzcina E., Möller G., Rohm W., and Weber R. (2019). Assimilation of GNSS tomography products into WRF using radio occultation data assimilation operator. Atmospheric Measurement Techniques Discussions.



TOMOREF operator

Forward	Tangent Linear	Adjoint
p, q, T	$\delta p, \delta q, \delta T$	δN_w
↓	↓	↓
N_w	δN_w	$\delta p, \delta q, \delta T$

Forward operator

Forward
p, q, T
↓
N_w

Wet refractivity can be calculated as a function of model variables:

$$N_w = \mathcal{H}(p, q, T) = k_1 \frac{pq}{0.622\,T} + k_2 \frac{pq}{0.622\,T^2}$$

k_1, k_2 – empirical constants

p – atmospheric pressure

q – water vapor mixing ratio

T – temperature

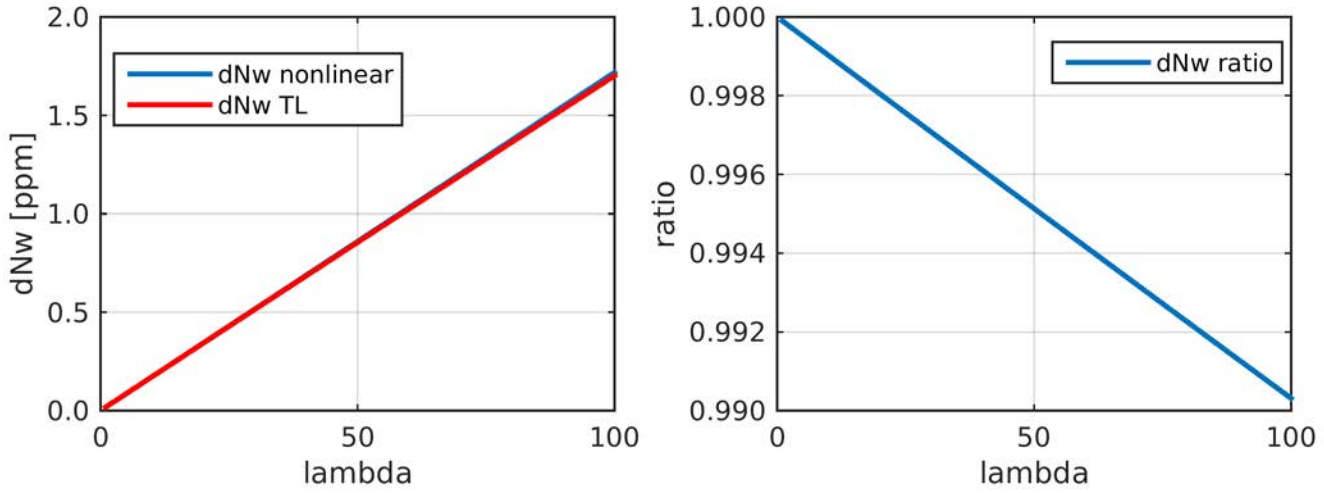
Forward operator is used to calculate the difference between the model and observations (innovation vector), to remove outliers.

Tangent Linear operator

TL
$\delta p, \delta q, \delta T$
$\downarrow$
δN_w

- H – Tangent Linear (TL) operator calculates the increments of wet refractivity based on the increments of model variables
- TL was tested as follows:

$$\lim_{\lambda \to 0} \frac{\mathcal{H}(x + \lambda \delta x) - \mathcal{H}(x)}{H(\lambda \delta x)} = 1$$



Adjoint operator

ADJ
δN_w
$\downarrow$
$\delta p, \delta q, \delta T$

- H^* – Adjoint (ADJ) operator is used to determine the impact of the wet refractivity increments on the model variables
- ADJ of the TL operator H was constructed as the linear operator H^* such that, for the inner product $\langle , \rangle$:

$$\forall x, \forall y \qquad \langle H(x), y \rangle = \langle x, H^*(y) \rangle$$

- Test results:

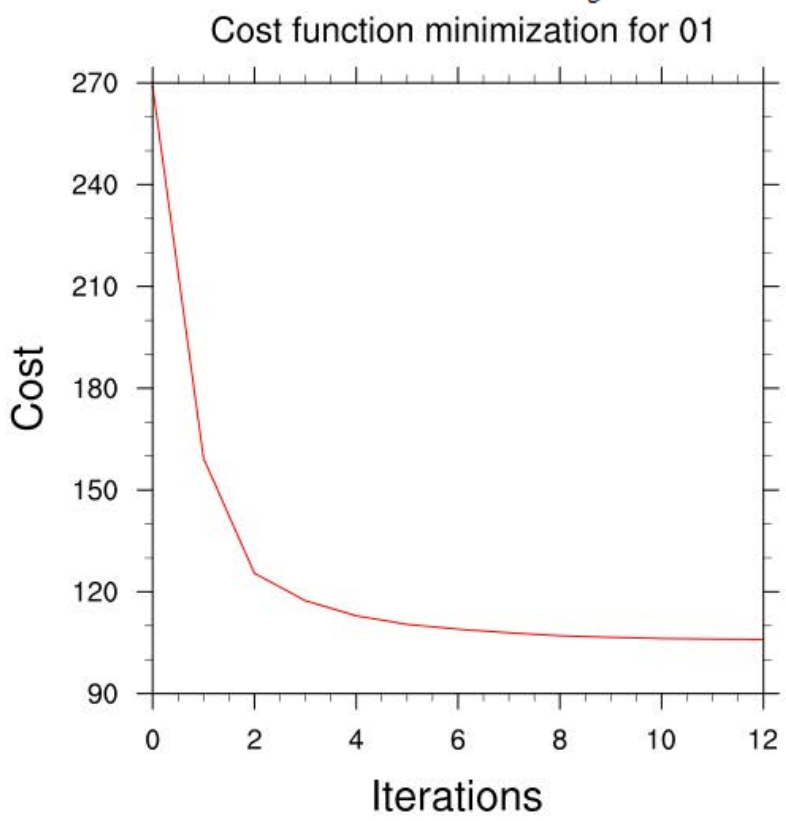
$$\langle H(x), y \rangle = -1.2346406187431304$$
$$\langle x, H^*(y) \rangle = -1.2346406187431326$$
$$Ratio\ of\ norms = 1.0000000000000002$$

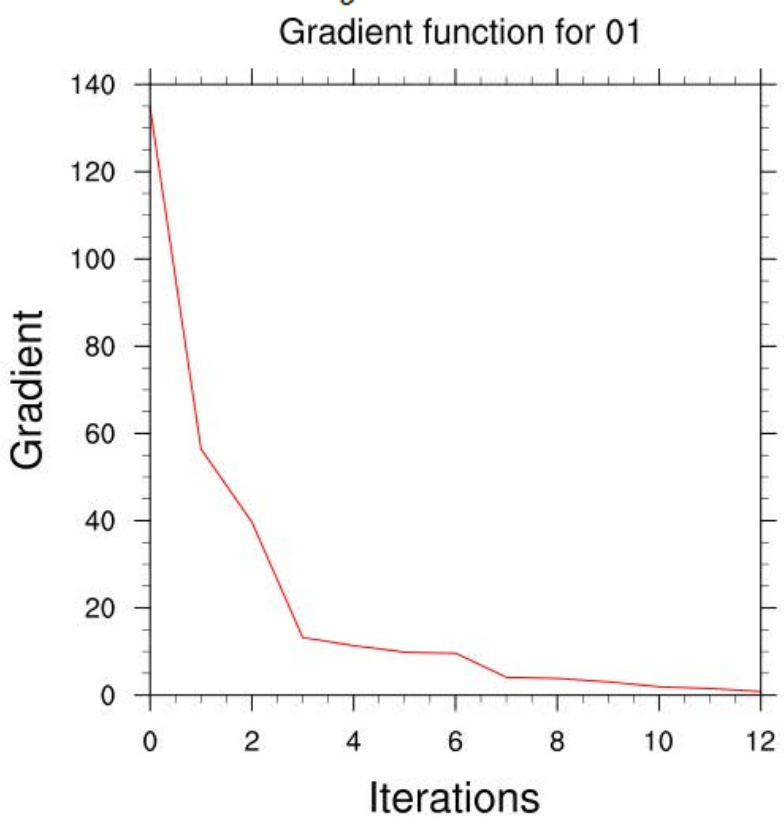
Cost function minimization

TOMOREF

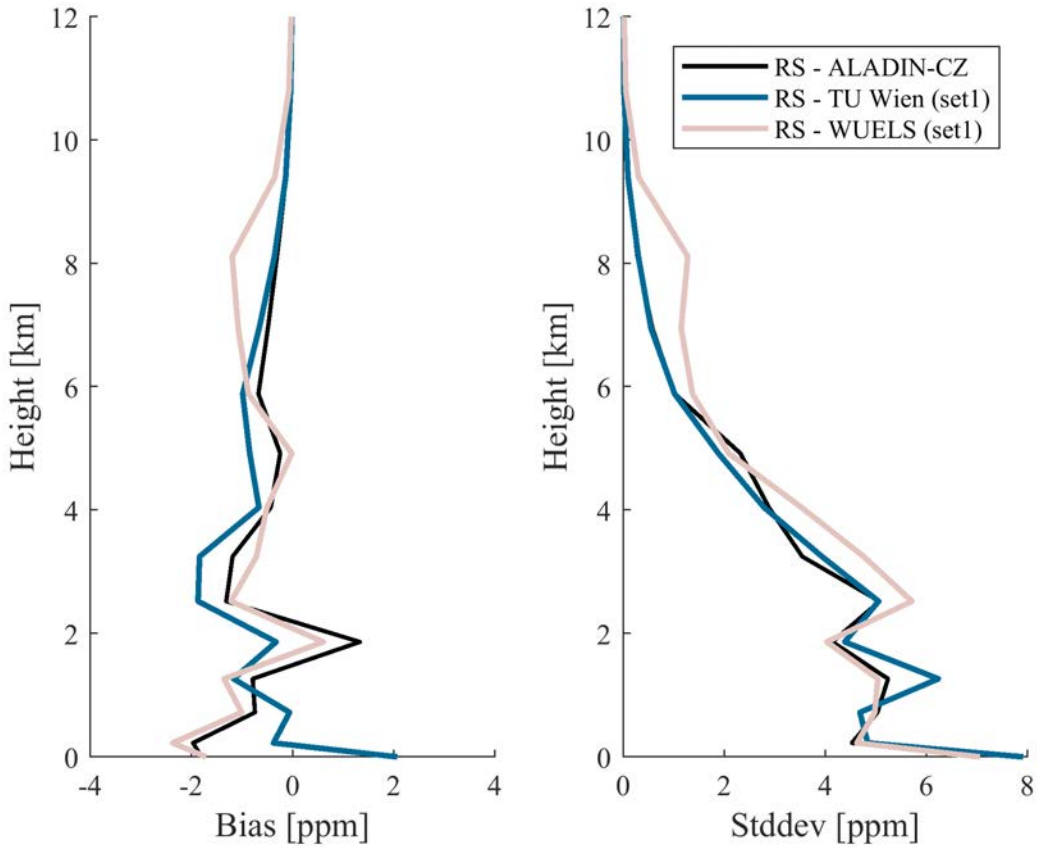
$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x}-\mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^b\right) + \frac{1}{2}\left(\mathbf{y}-h(\mathbf{x})\right)^T \mathbf{R}^{-1}\left(\mathbf{y}-h(\mathbf{x})\right)$$

J_b J_o





Observation error



Observations errors have been set based on the comparison of tomography results with radiosonde profiles (2 weeks period)

Height [km]	Nw error [ppm]
< 1.5	$0.1 \cdot N_w$
1.5 – 5.5	$0.2 \cdot N_w$
5.5 – 8.0	1.00
8.0 – 10.0	0.50
> 10.0	0.05

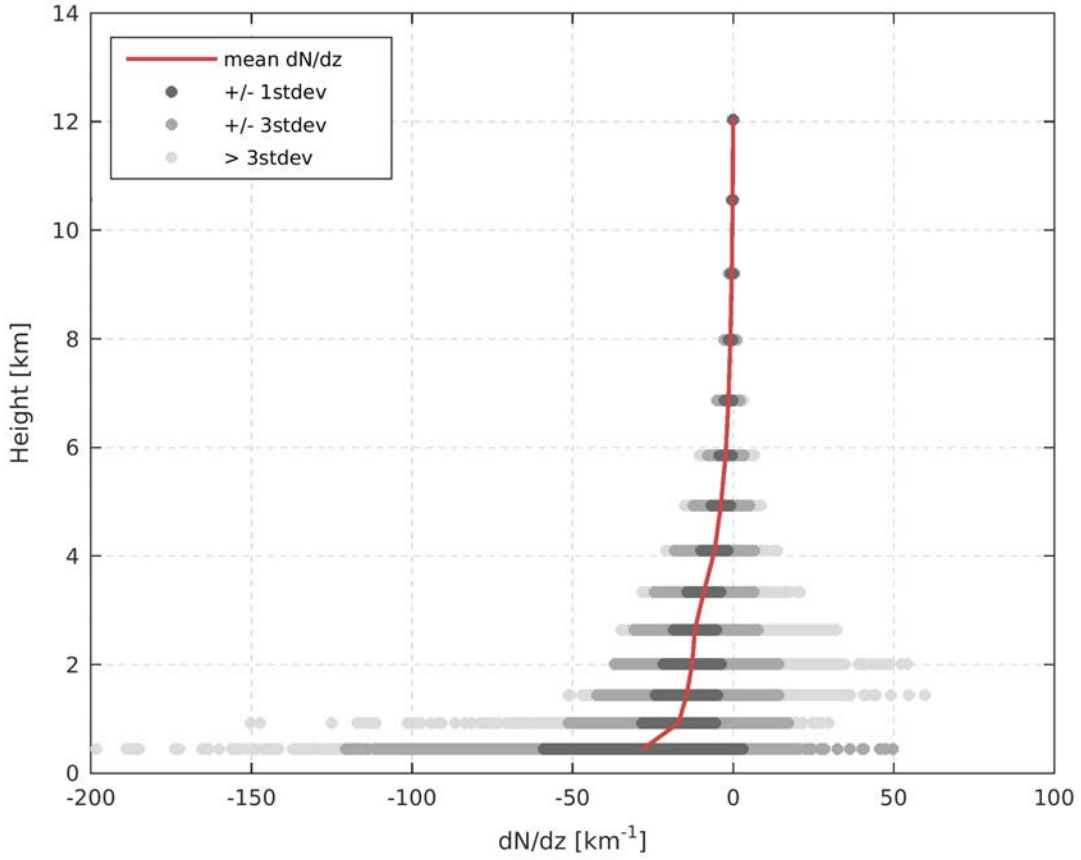
Quality Control

1) Based on the percent error

$$\left|\frac{O-B}{(O+B)/2}\right|$$

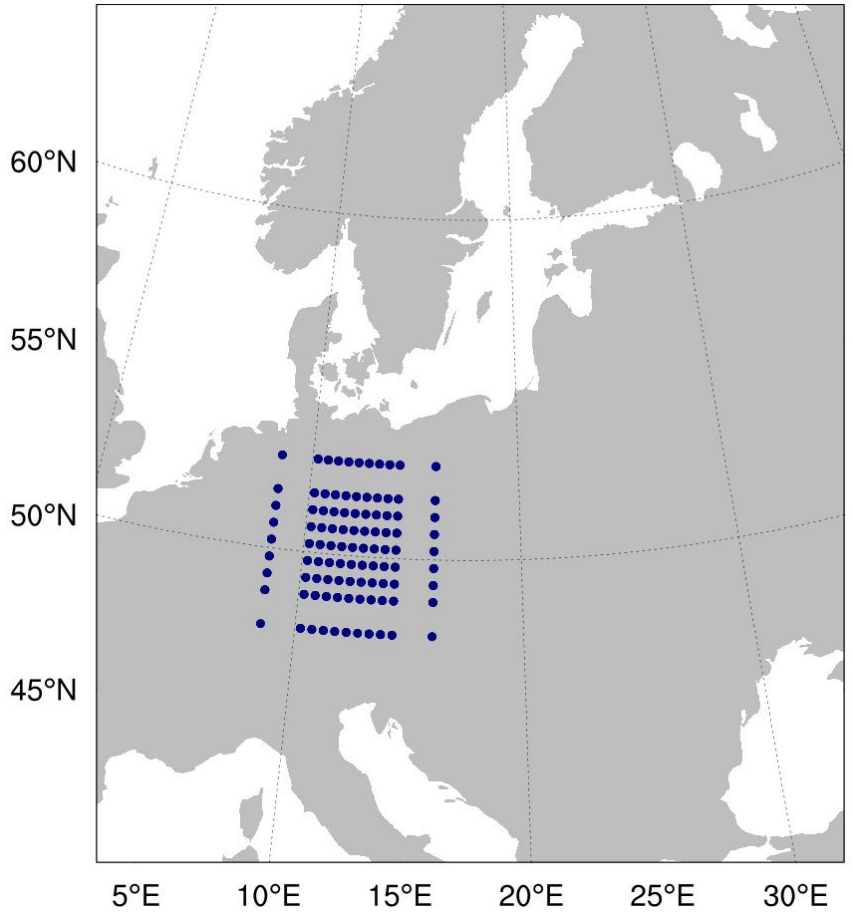
Height [km]	Max percent error	QC flag
< 2.5	0.15	-31
2.5 – 6.0	0.30	-32
> 6.0	0.40	-33

2) Based on the vertical gradient of N_w (QC flag -34)

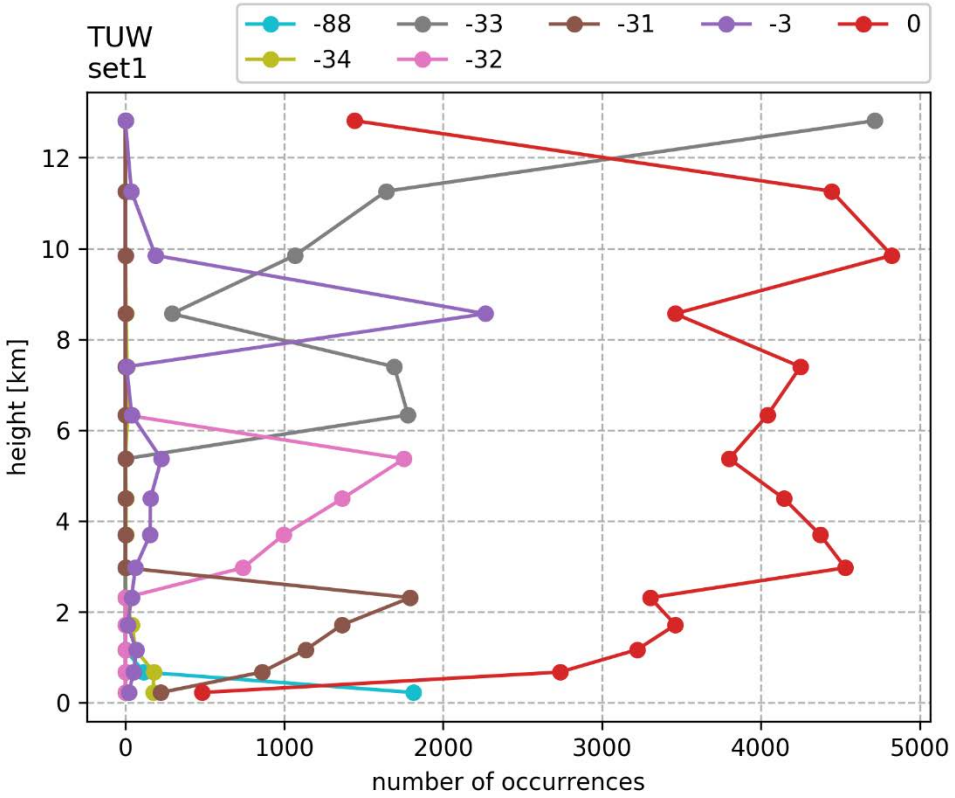


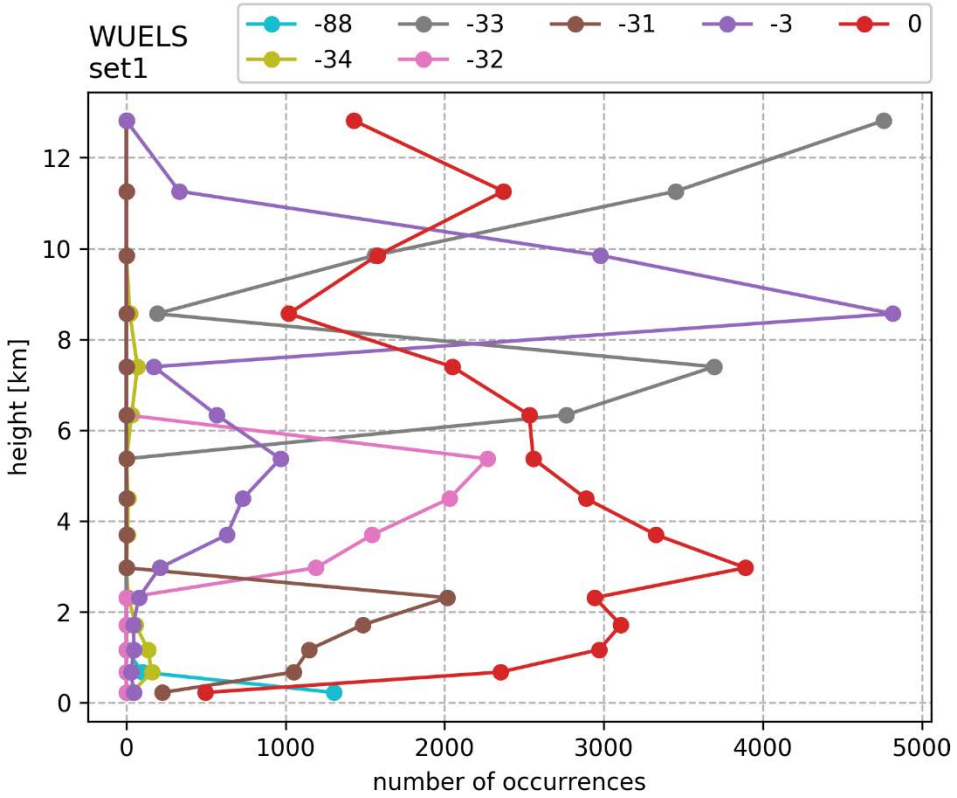
N_w assimilation

	Period of interest	29.05 – 14.06.2013
GNSS tomography	GNSS tomography models	TUW, WUELS
Assimilation	Horizontal resolution	12 km x 12 km
	Assimilation window	1 hour
	Time settings	every 6 hours (00, 06, 12, 18 UTC) (6 hours of model integration + 18 hours of forecast lead time)



QC flags

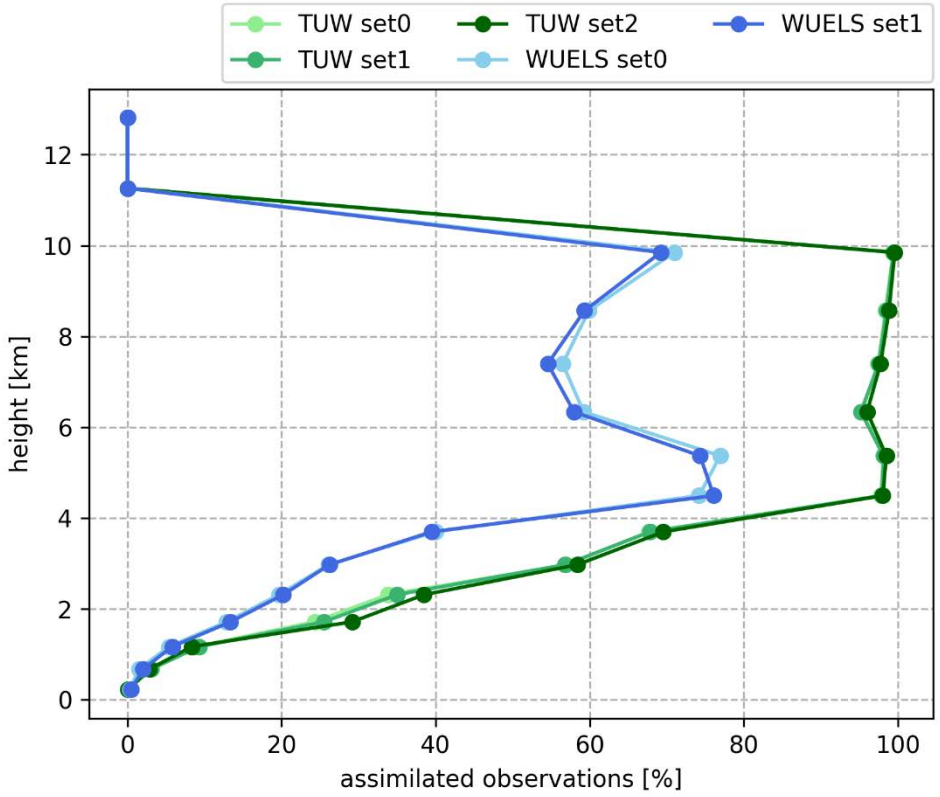




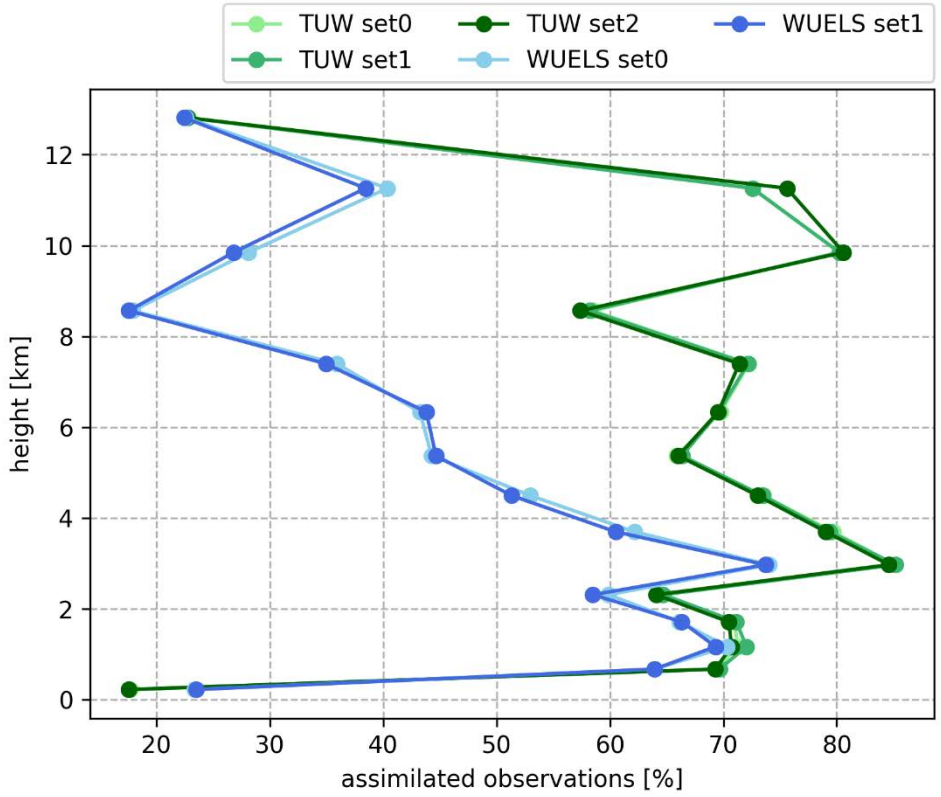
0	**-3**	**-31**	**-32**	**-33**	**-34**	**-88**
assimilated	maximum error check	percent error bottom levels	percent error middle levels	percent error top levels	vertical gradient	missing data

Assimilated observations

GPSREF



TOMOREF



Assimilated observations

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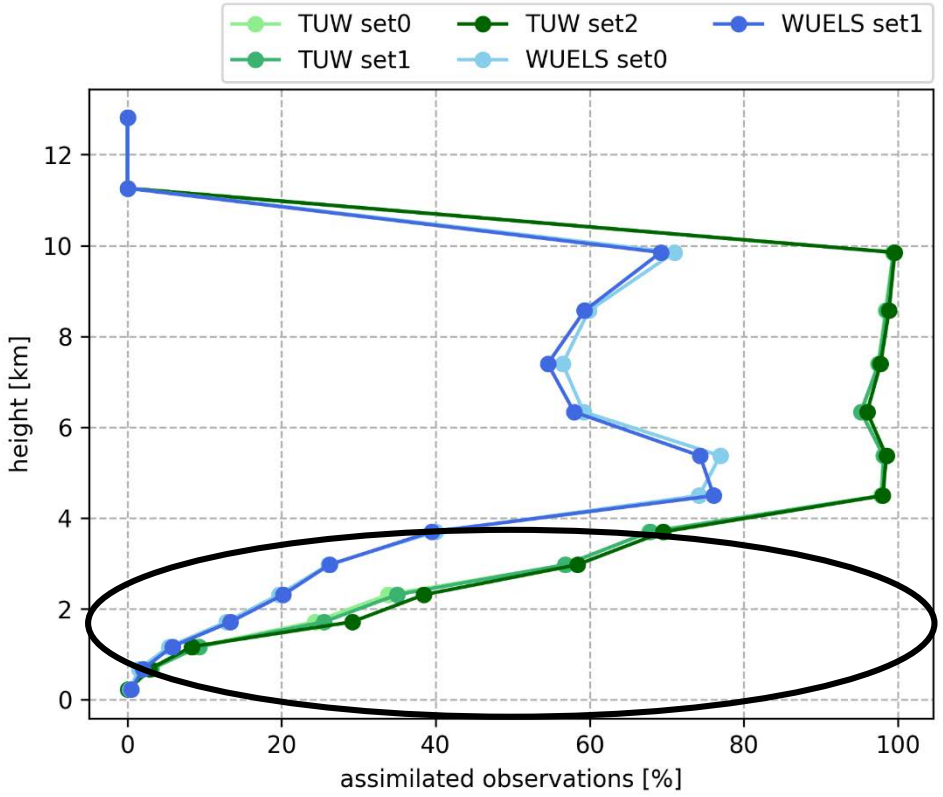

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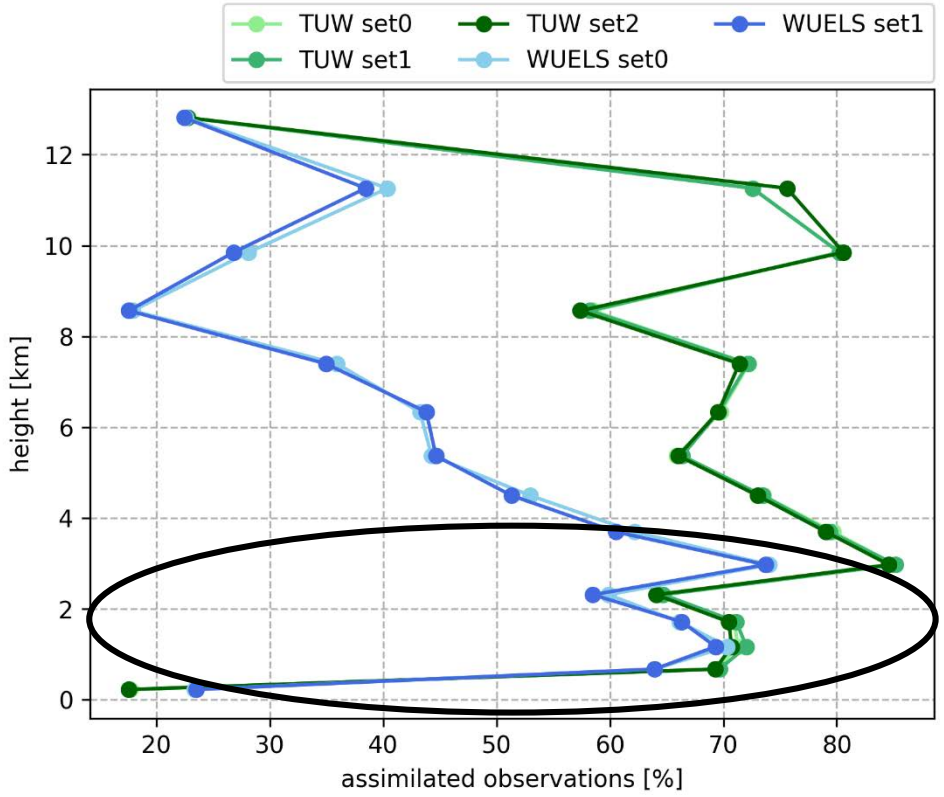

Assimilated observations

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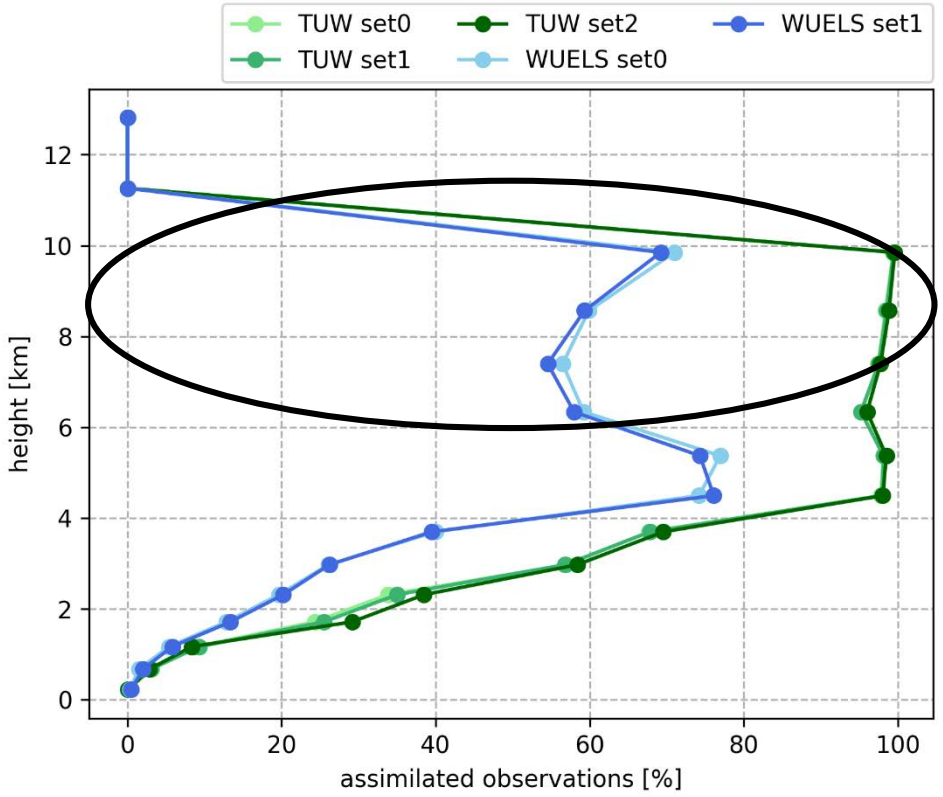

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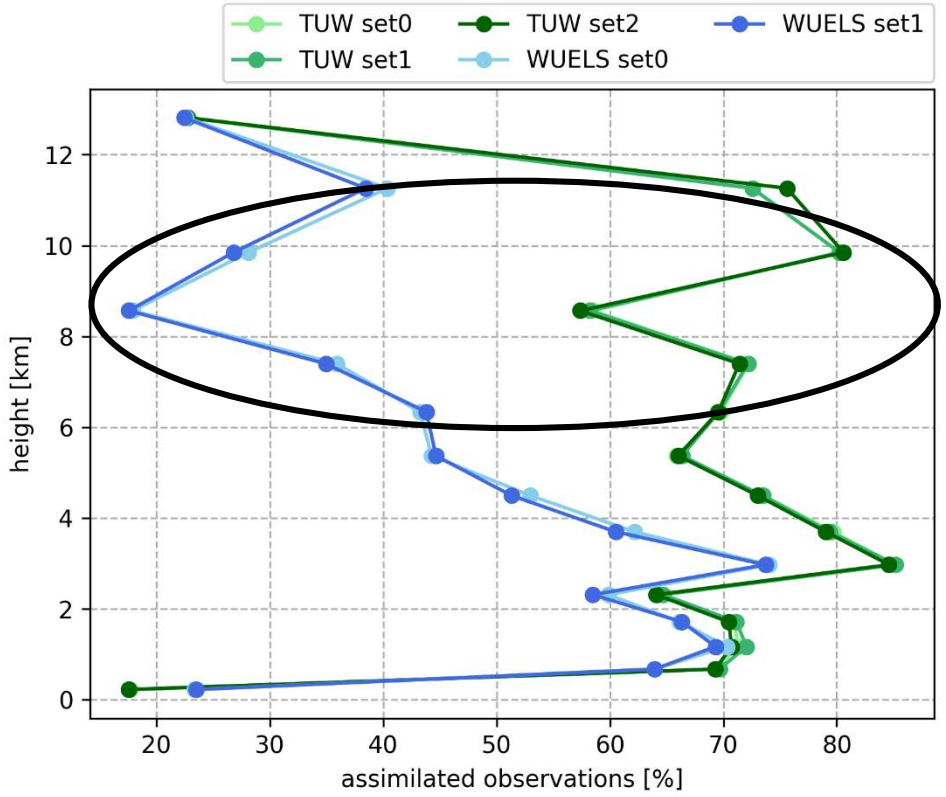
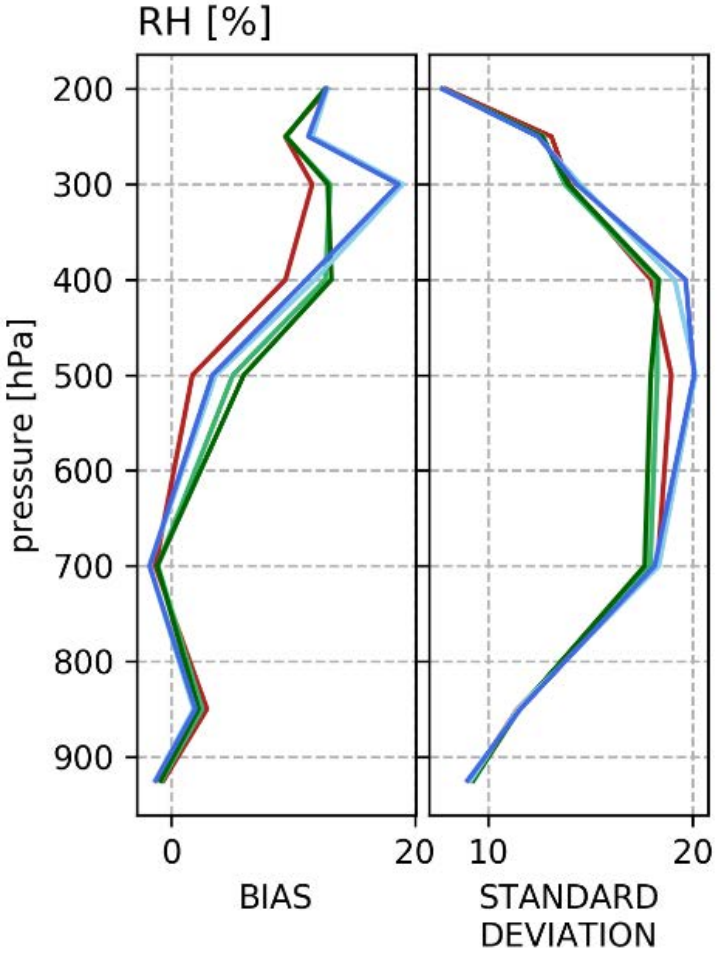


Radiosonde validation

GPSREF



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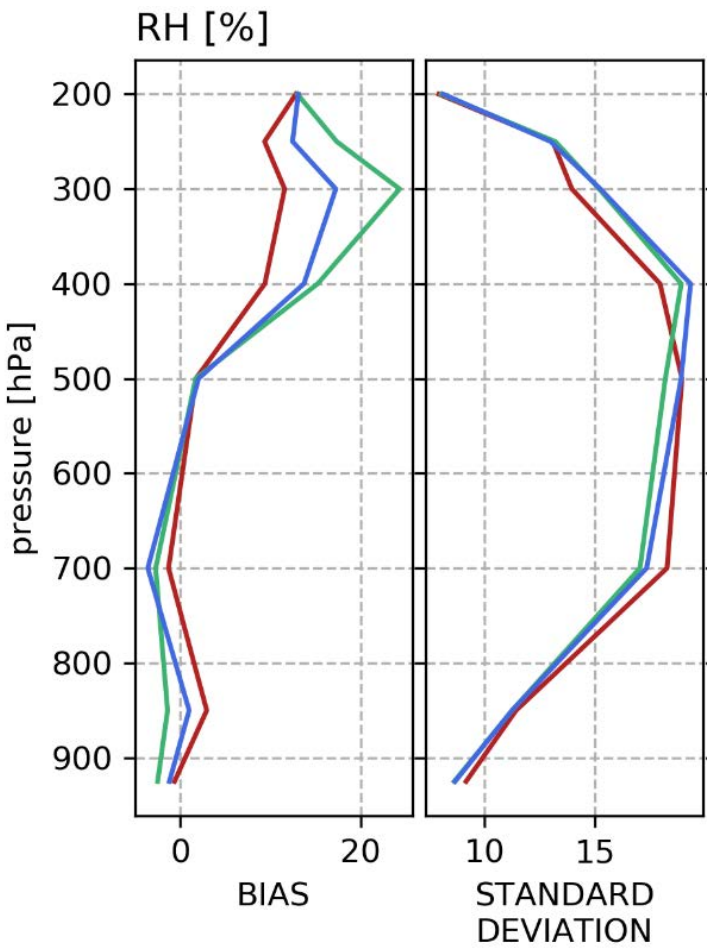
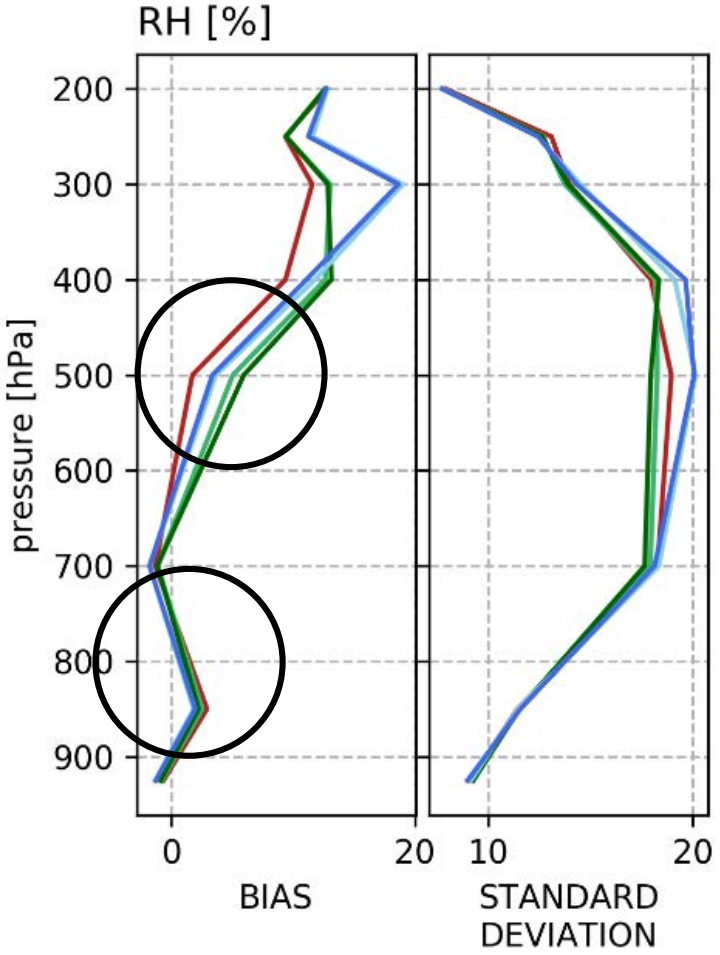


Radiosonde validation

BASE
TUW set0
TUW set1
TUW set2
WUELS set0
WUELS set1

GPSREF



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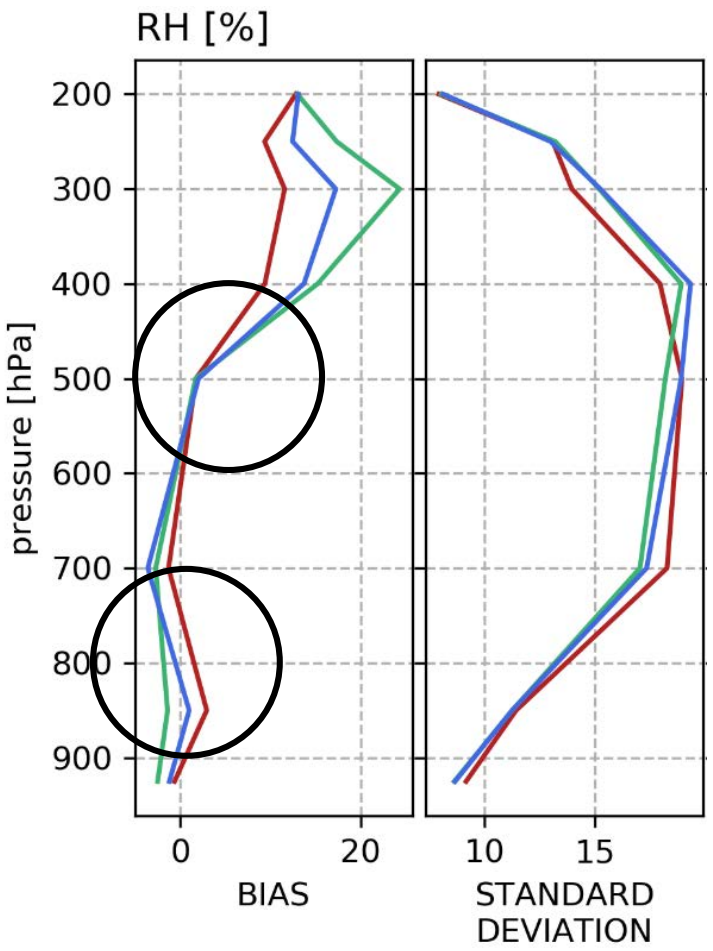

Radiosonde validation

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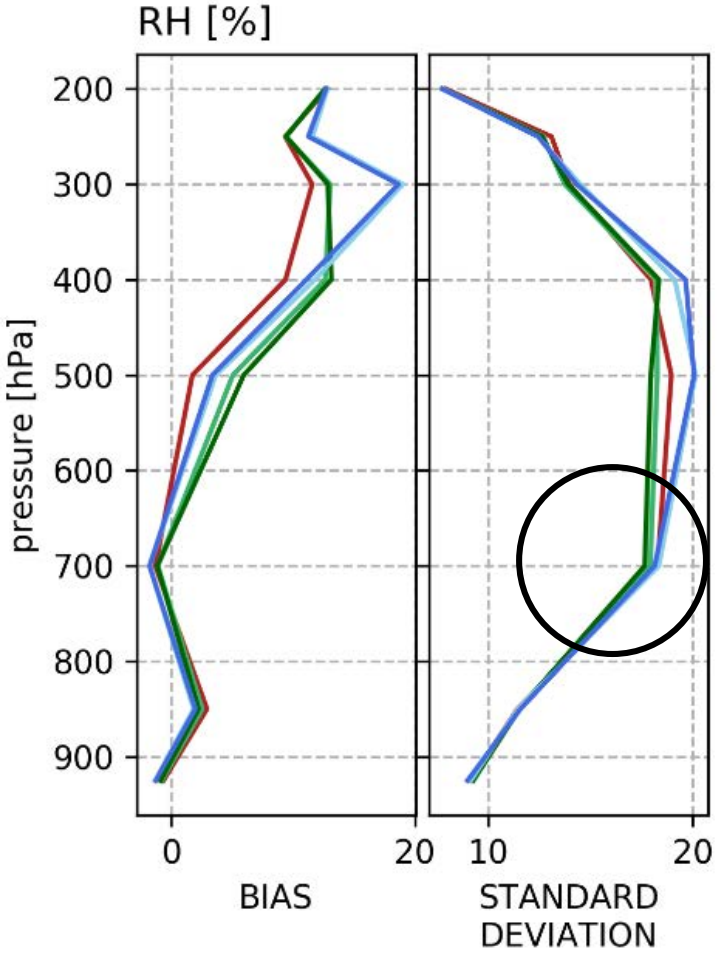

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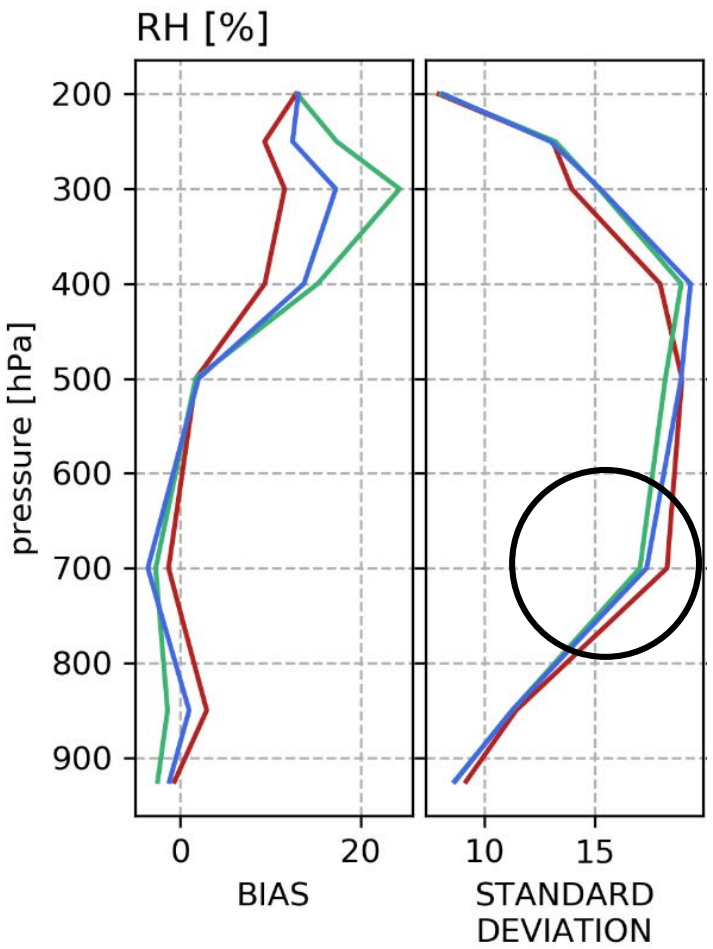
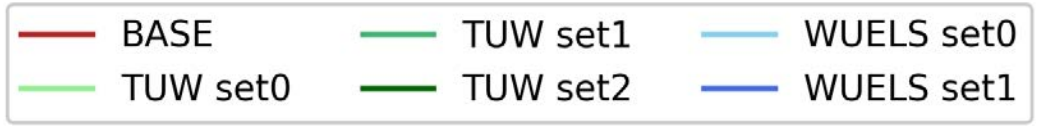


Radiosonde validation



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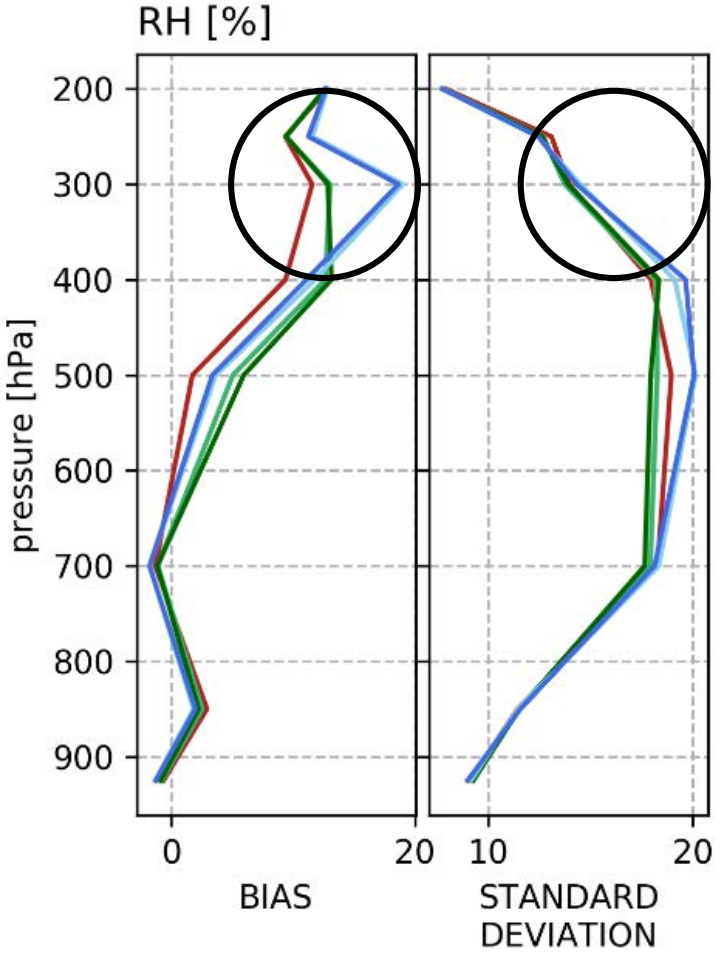

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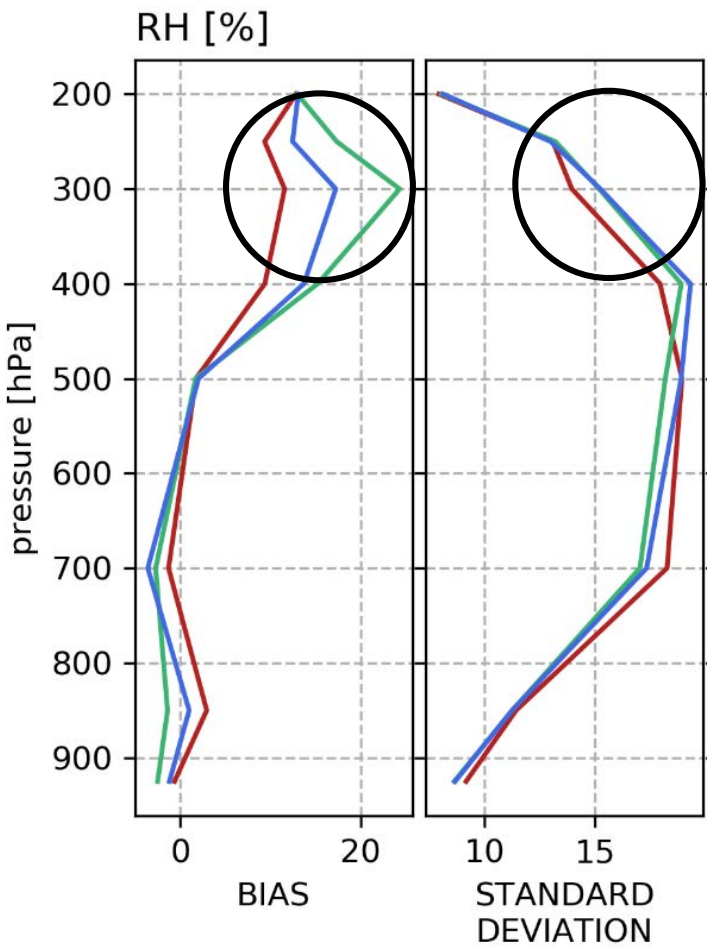


Conclusions

Why to assimilate wet refractivity field from GNSS tomography using TOMOREF operator?

- No need for using of external data for N_h calculations
- Appropriate observations errors assignment
- Adjusted quality control process

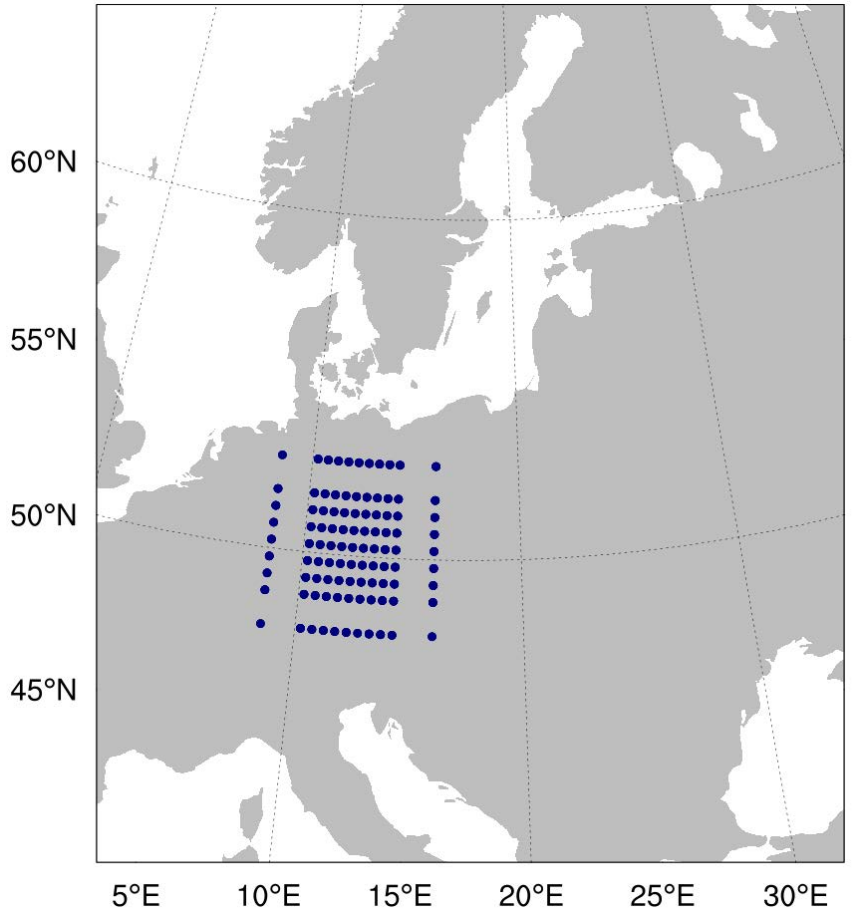
Near future plan

- Improvement of the quality control process for upper layers
- Comparison with ZTD assimilation

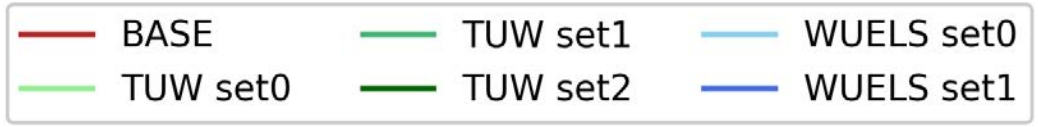
Thank you for your attention!

N_w assimilation

	Period of interest	29.05 – 14.06.2013
GNSS tomography	GNSS tomography models	TUW, WUELS
	A priori data	ALADIN-CZ 6 hour forecast
	Time settings	every 6 hours (00, 06, 12, 18 UTC)
Assimilation	Horizontal resolution	parent domain 36 km nested domain 12 km
	Assimilation window	1 hour
	Time settings	every 6 hours (00, 06, 12, 18 UTC) (6 hours of model integration + 18 hours of forecast lead time)



Radiosonde validation



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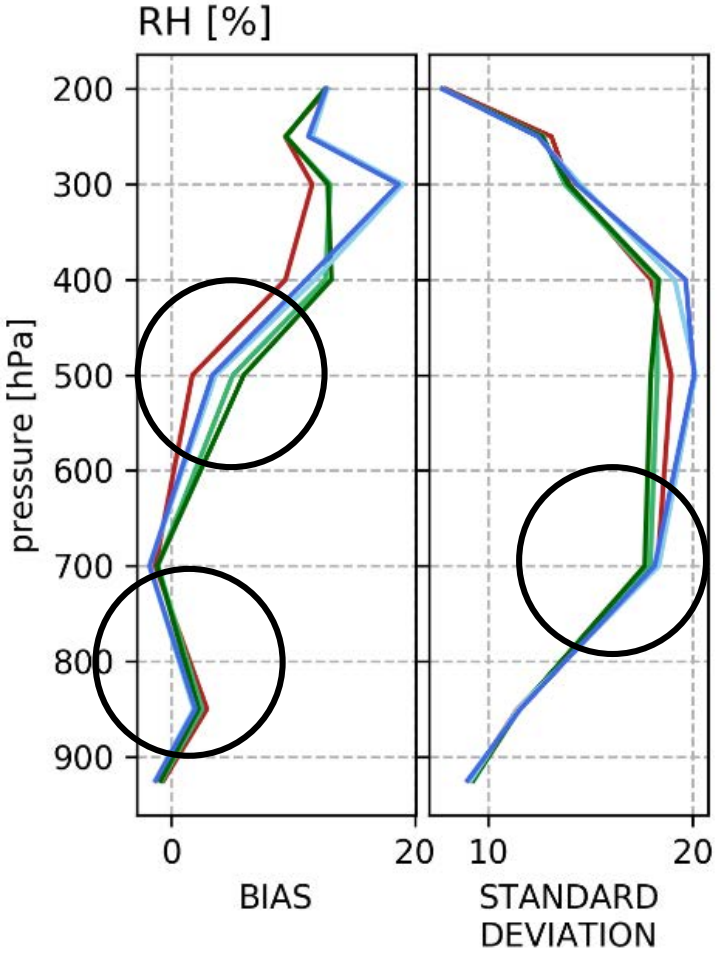

TOMOREF