Tomographic determination of the spatial distribution of Water Vapor using GNSS observations for real-time applications

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Workshop em Previsão Numérica – IPMA

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26 - 27 November 2018

Presentation structure

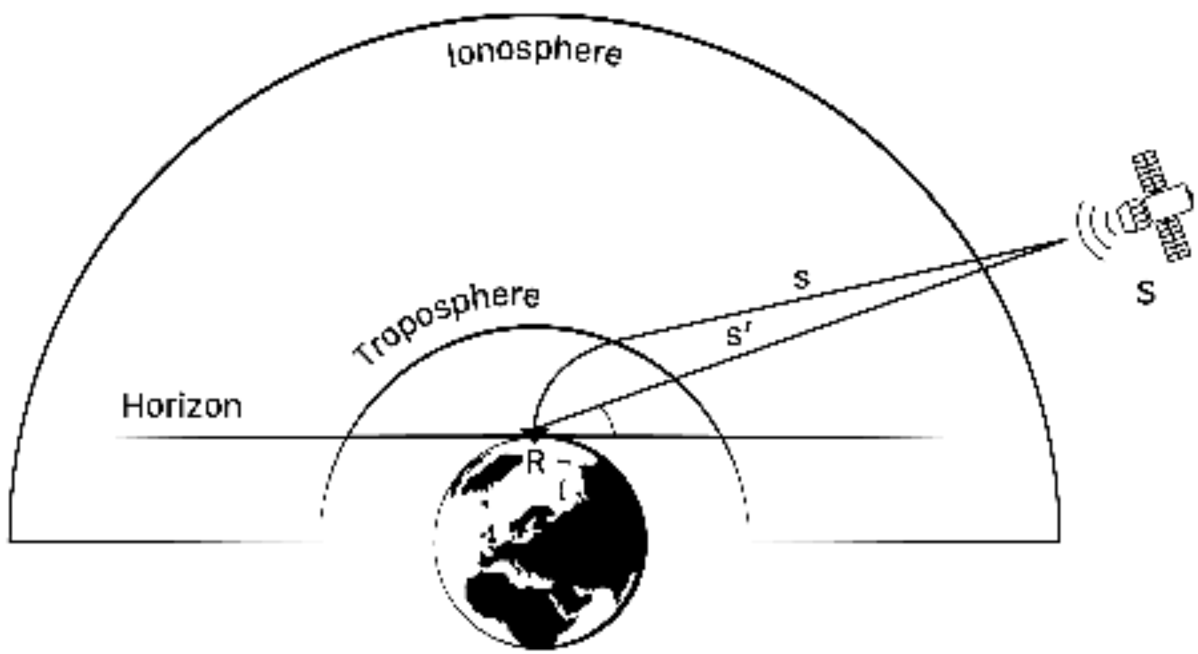
- Informative introduction
  - GNSS meteorology
    - Water vapor estimation
    - GNSS PWV
    - GNSS Tomography
- SWART tomographic system
- Case-studies
- Conclusions

Informative introduction

GNSS meteorology: Water vapor estimation

"You may delay, but time will not!" Benjamin Franklin

"Time, it's the physical parameter which we can measure with highest accuracy!" Gunnar Elgered



Informative introduction

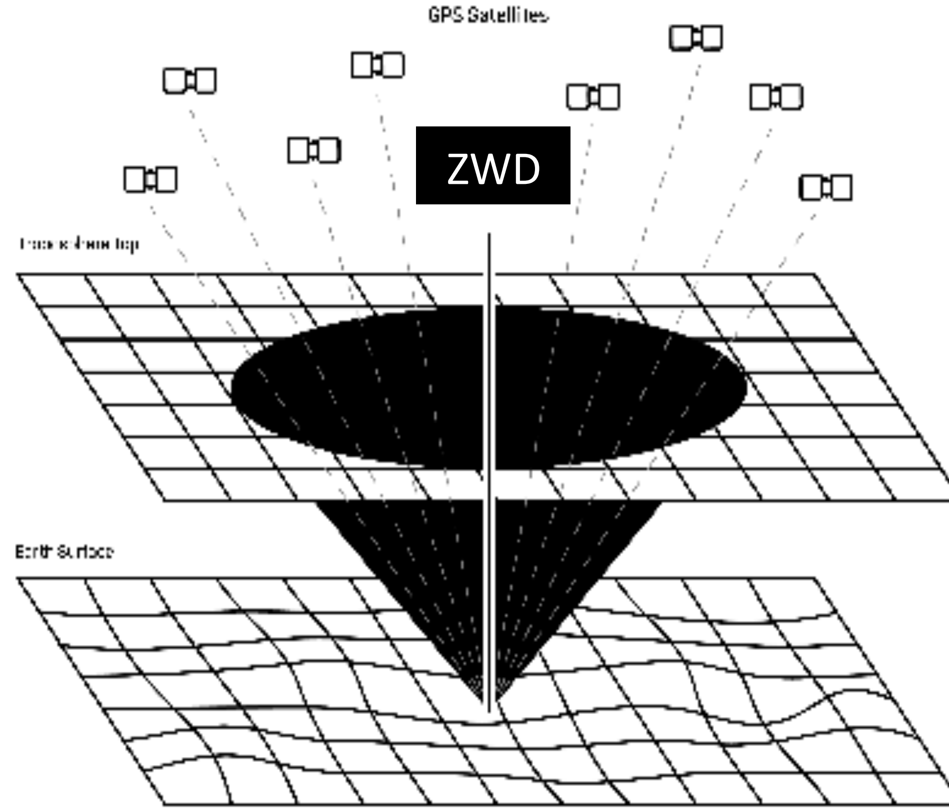
GNSS meteorology: Water vapor estimation

$$STD = mf_h(\varepsilon)ZHD + mf_w(\varepsilon)ZWD + S_w$$

$$ZTD = ZHD + ZWD$$

$$PWV = k * ZWD$$

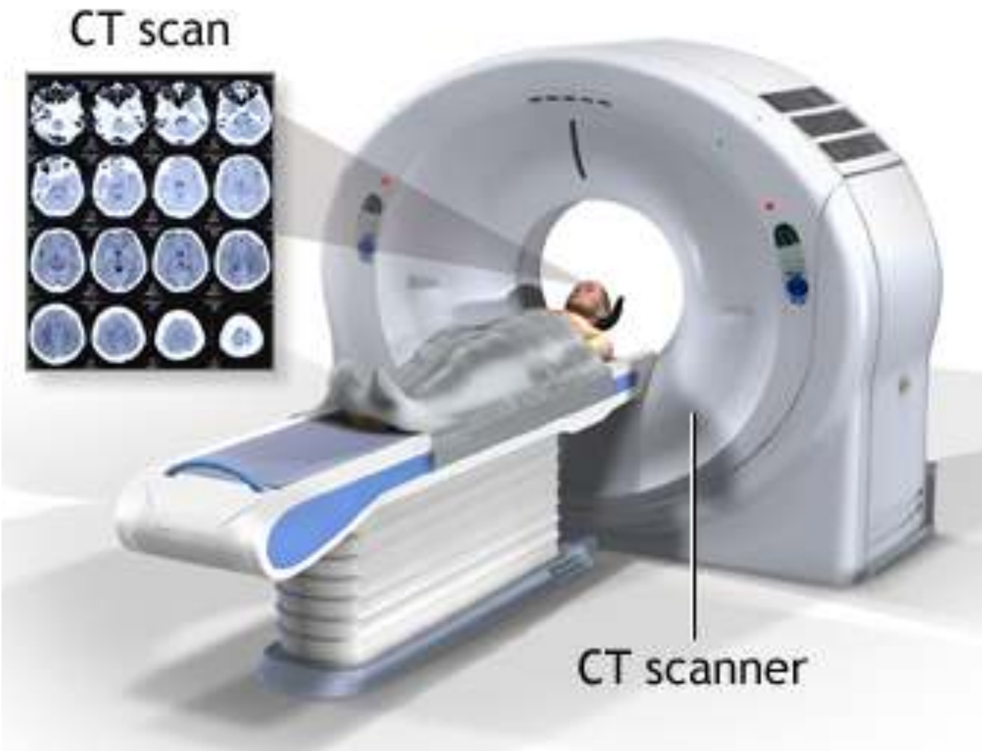
$$k = \frac{10^6}{\left(\frac{k_3}{T_m} + k'_2\right) R_v \rho}$$

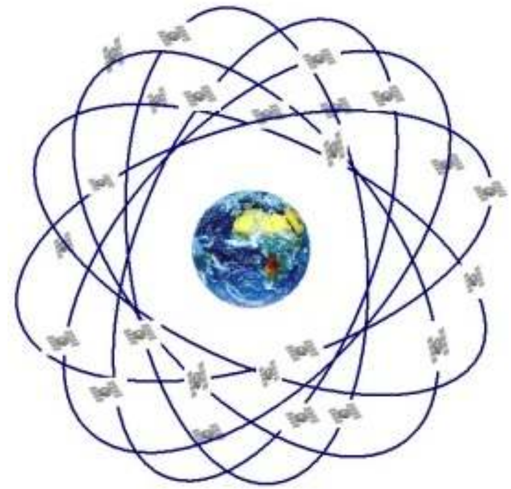


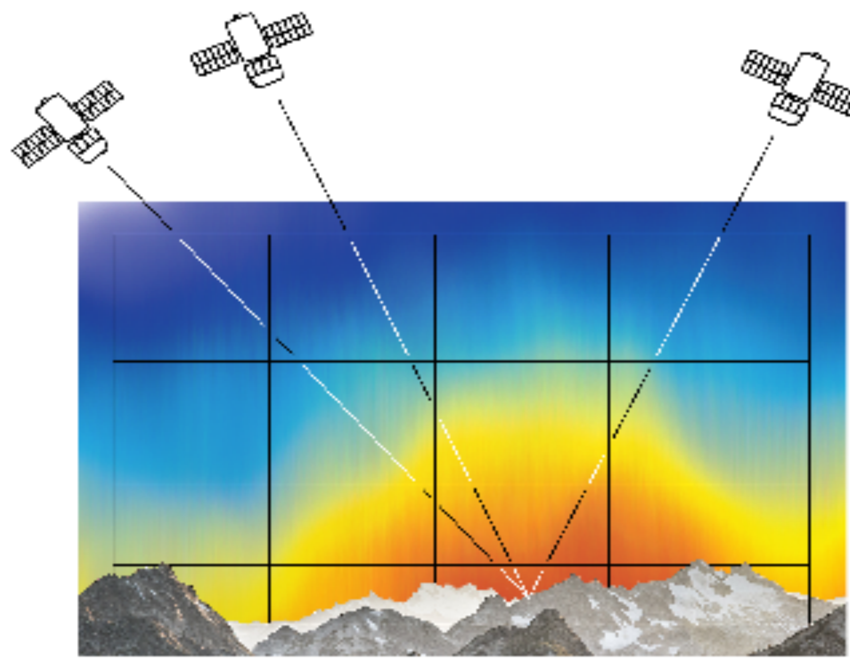
Constants related with water vapor: (k_3, k'_2, R_v, ρ)

Profile or integral of the mean temperature: (T_m)

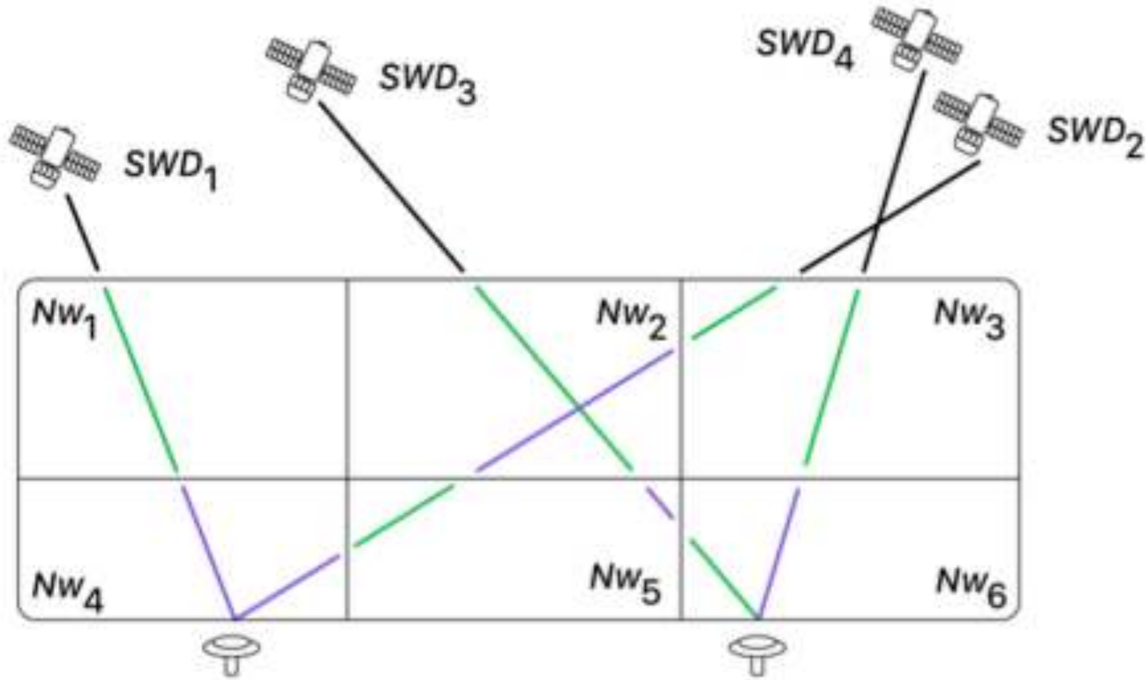
Informative introduction







Informative introduction



$$\begin{pmatrix} l_{11} & 0 & 0 & l_{14} & 0 & 0 \\ 0 & l_{22} & l_{23} & l_{24} & l_{25} & 0 \\ 0 & l_{32} & 0 & 0 & l_{35} & l_{36} \\ 0 & 0 & l_{33} & 0 & 0 & l_{46} \end{pmatrix} \cdot \begin{pmatrix} Nw_1 \\ Nw_2 \\ Nw_3 \\ Nw_4 \\ Nw_5 \\ Nw_6 \end{pmatrix} = \begin{pmatrix} SWD_1 \\ SWD_2 \\ SWD_3 \\ SWD_4 \end{pmatrix}$$

Informative introduction

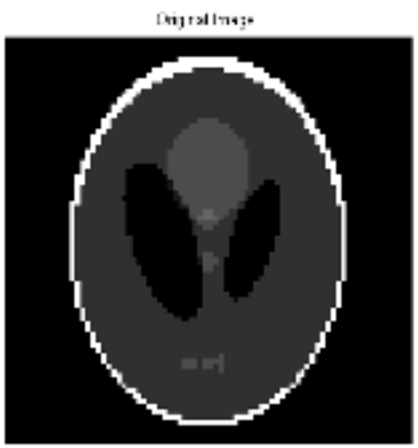
Standard techniques for solving linear inverse problems:

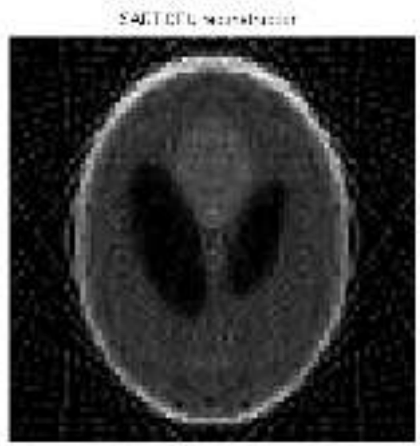
- Singular value decomposition
- Tikhonov-Regularization
- Conjugate gradient method
- Weighted least-squares solution
- Kalman-filter
- Algebraic reconstruction techniques

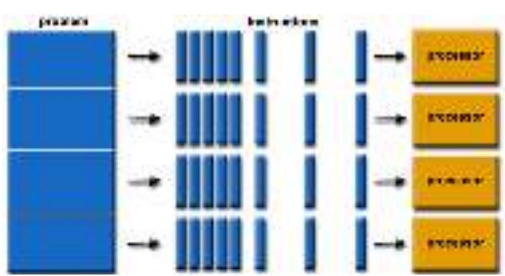
SWART tomographic system

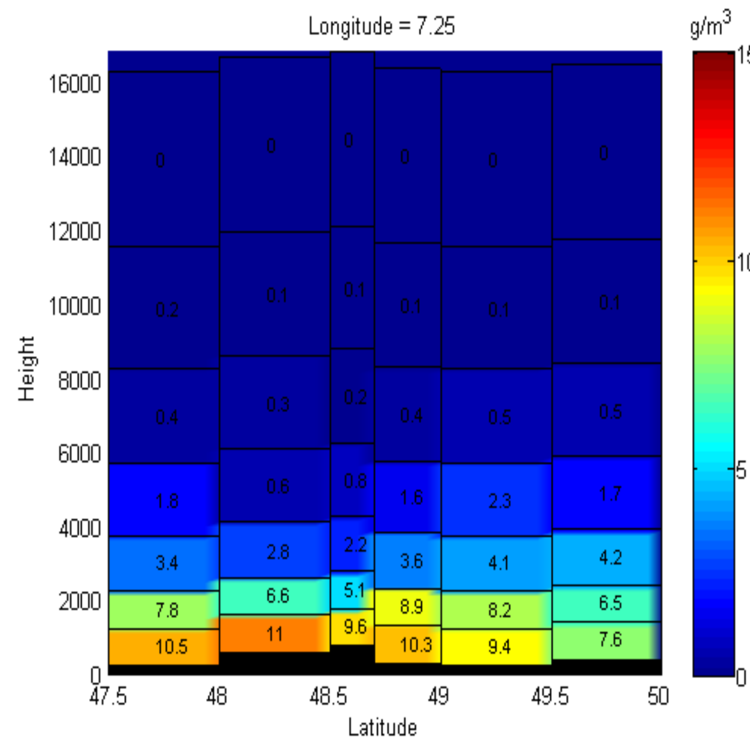
Tomographic system was developed that uses Algebraic Reconstruction Techniques (ART) for the tomographic water vapor (SEGAL GNSS Water Vapor Reconstruction Image Software – SWART);

Real-time processing capabilities through the parallelization of the ART.









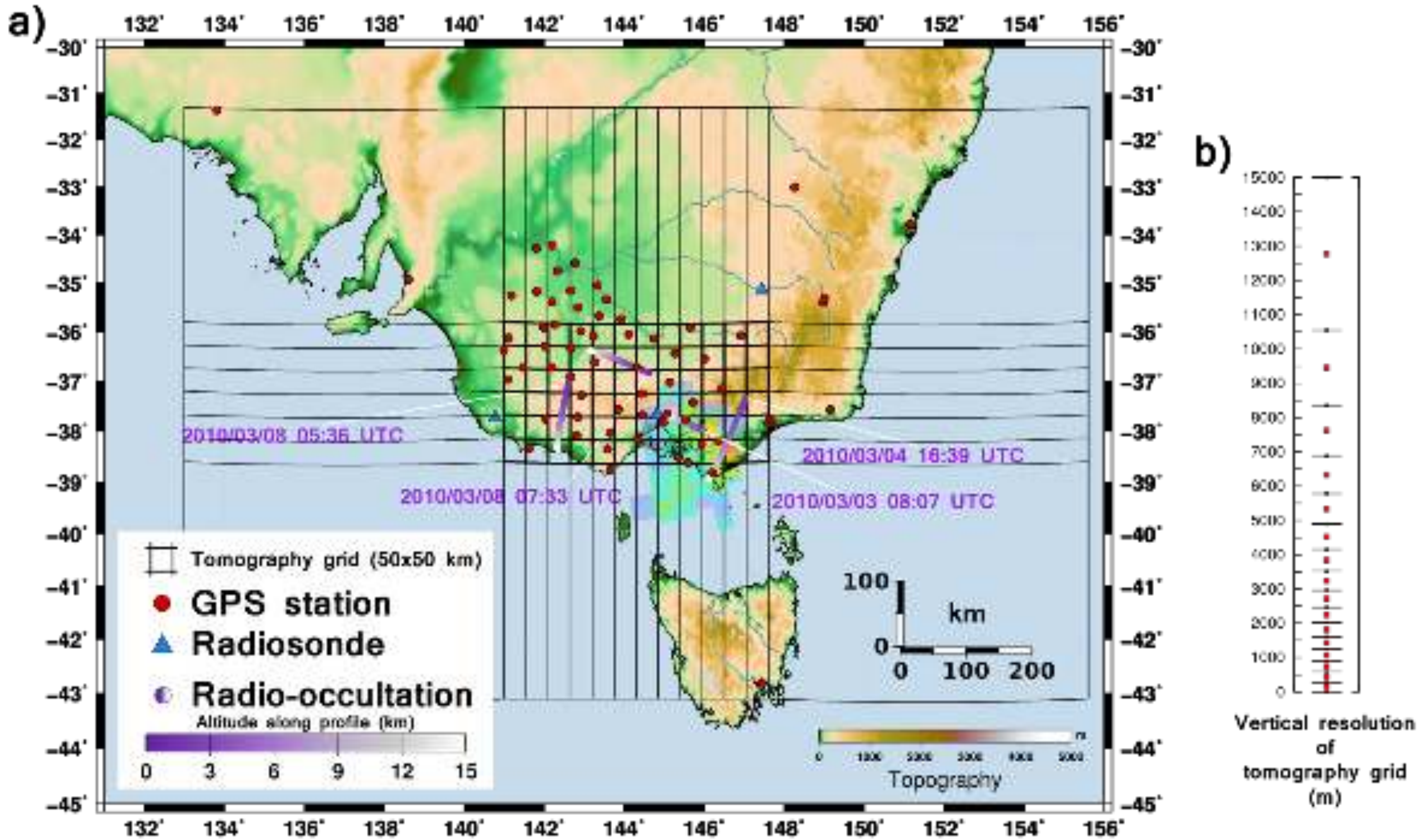
Case-studies

- Case Study I: Intercomparison multi-model tomography. The comparison of the SWART tomographic system results with other softwares.

Cross-validation of GPS tomography models and methodological improvements using CORS network, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2018-292, submitted. (Brenot et al., 2018)

- Case Study II: Evaluation of real-time applicability of the SWART tomographic system.

Case studies: case study I



GPS stations (red circles), Radiosonde sites (blue triangles), Radio-occultation profiles (white-purple lines), OMI cloud top altitude at 04:07 on 2010/03/06 (purple-blue-orange pattern; c.f. a) and the tomography grid (inner grid in thick black lines and outer grid in thin black lines); b) Red square represents altitudes above the sea level of the centres of each voxel of the tomography grid.

Case studies: case study I

Processing strategy:

- Double differenced Bernese 5.0
- ZTD + Gradients (30 min resolution)
- ZHD extracted from ACCESS-A
- Isotropic mapping function GMF
- Anisotropic mapping function Chen and Herring
- Gradient hydrostatic part was removed using ACCESS-A

$$L_{sym}^{wet}(\epsilon) = ZWD \cdot mf_{sym}^{wet}(\epsilon)$$

$$L_{az}^{wet}(\epsilon,\alpha) = mf_{az}^{wet}(\epsilon, C) \cdot (G_{NS}^{wet} \cdot \cos(\alpha) + G_{EW}^{wet} \cdot \sin(\alpha))$$

Used models:

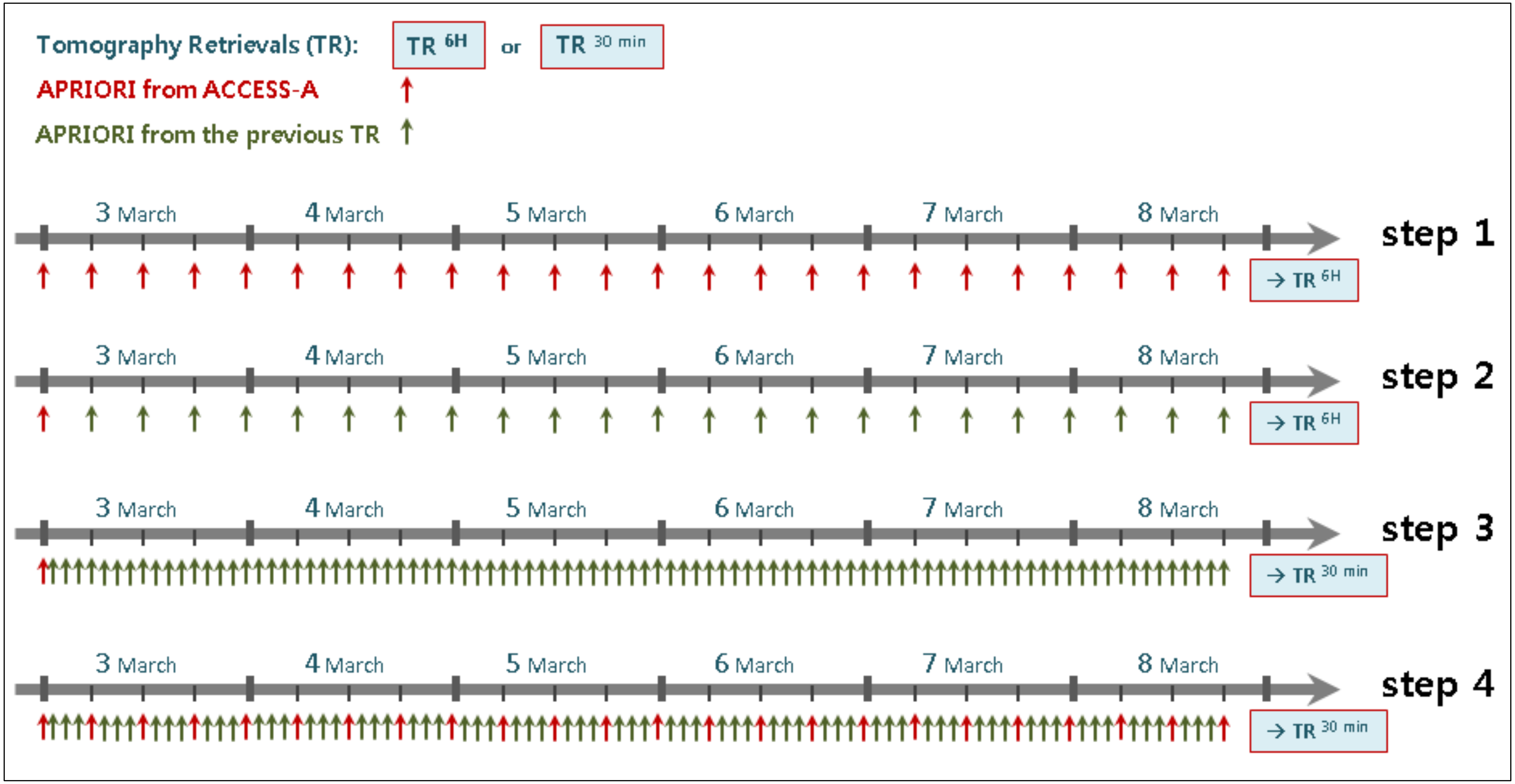
Tomography model	Inversion	Dim.	Retrievals
BIRA	SVD, weighted&damped LS adjustment	*3D*	*ρ wv , Nw*
TOMO2	Kalman filter with selective SVD	*3D*	*ρ wv , Nw*
SWART	SART	*3D*	*ρ wv , Nw*

BIRA: BIRA – IASB

TOMO2: WUELS

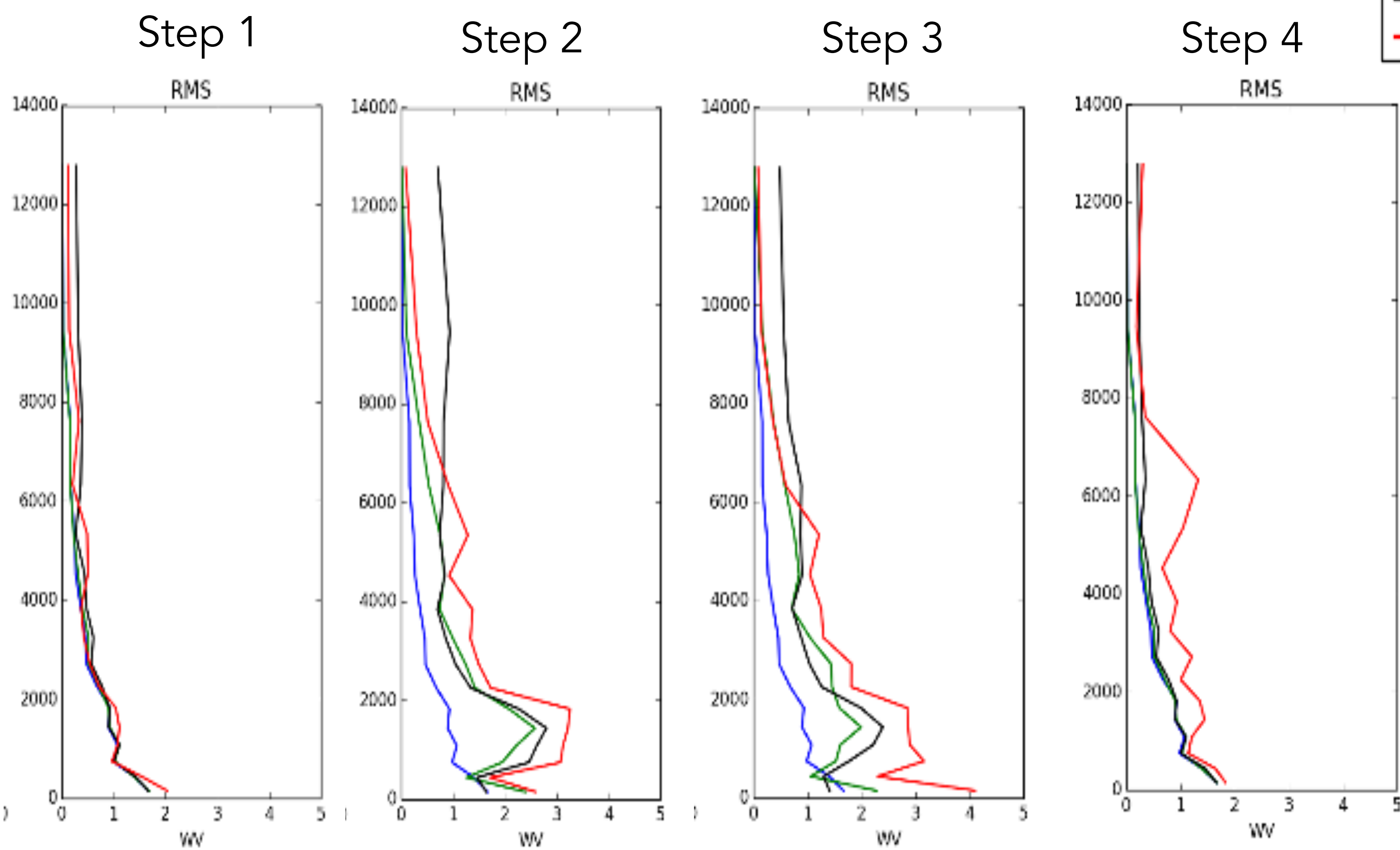
SWART: SEGAL – UBI

Case studies: case study I



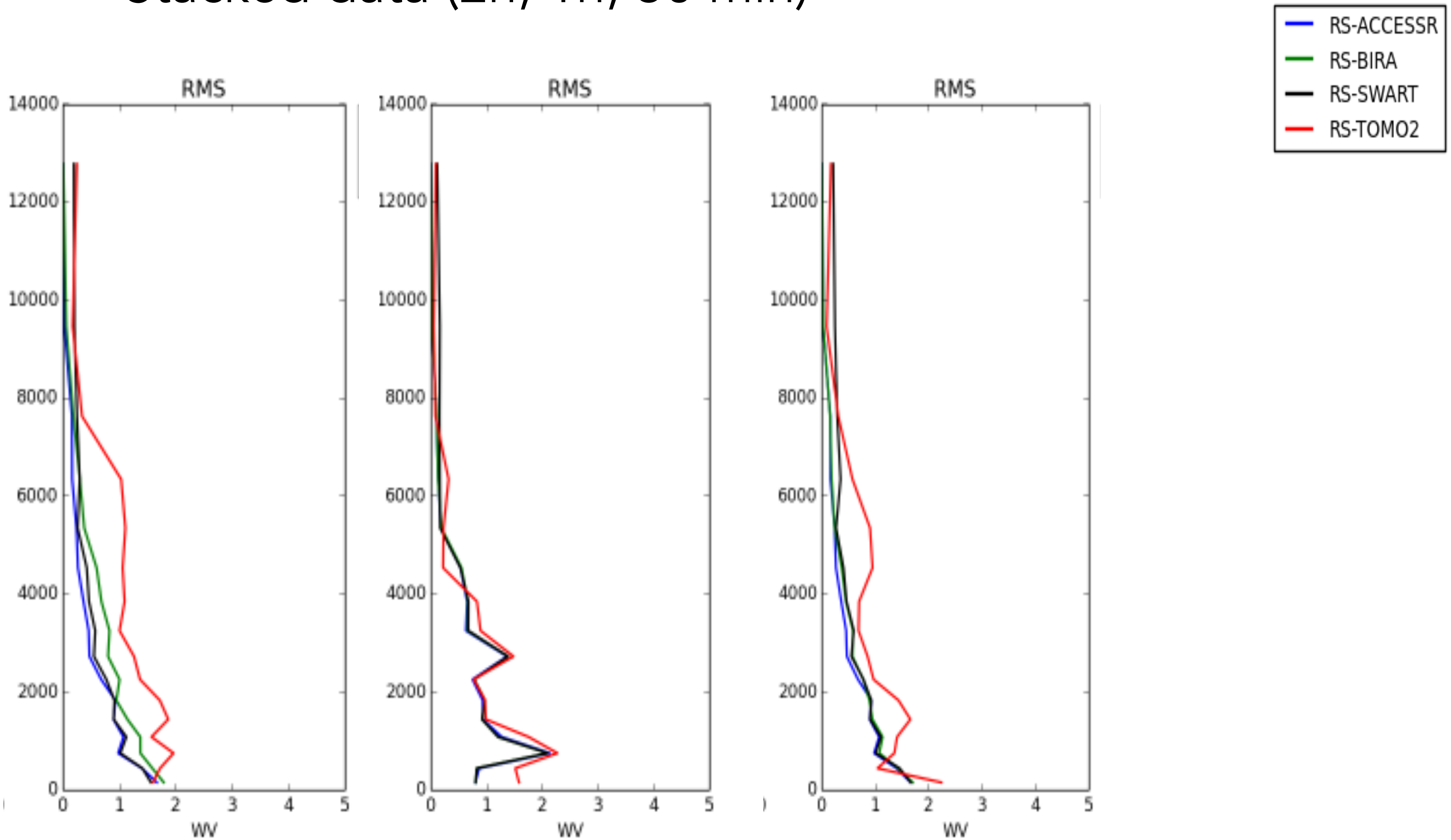
Case studies: case study I

- Initialization impact and time resolution



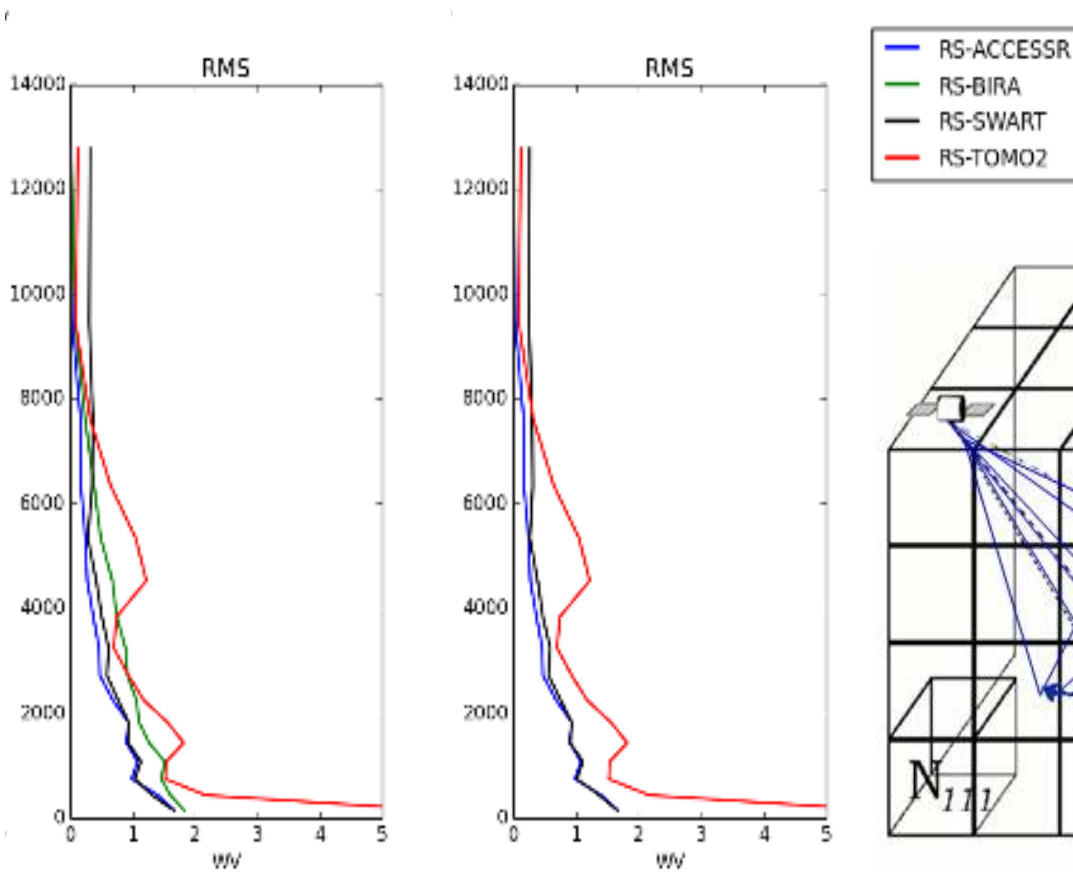
Case studies: case study I

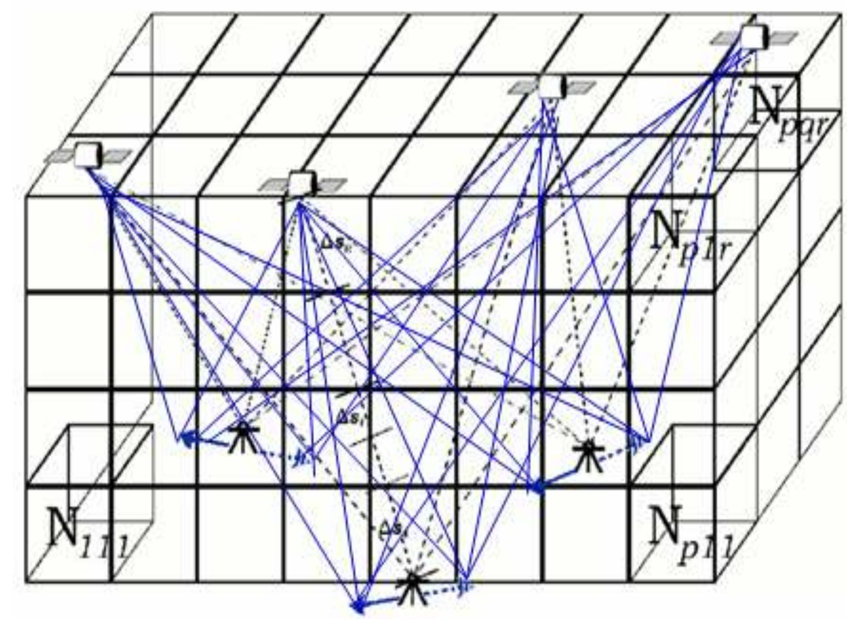
- Stacked data (2h; 1h; 30 min)



Case studies: case study I

- Add pseudo-observations (no stack; stacked data 30')



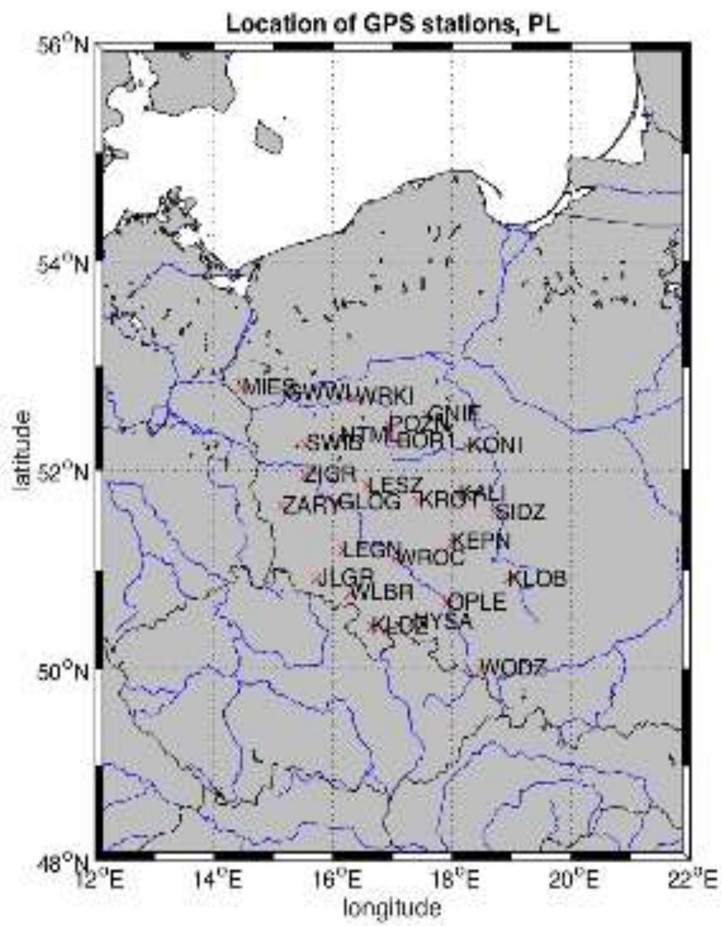


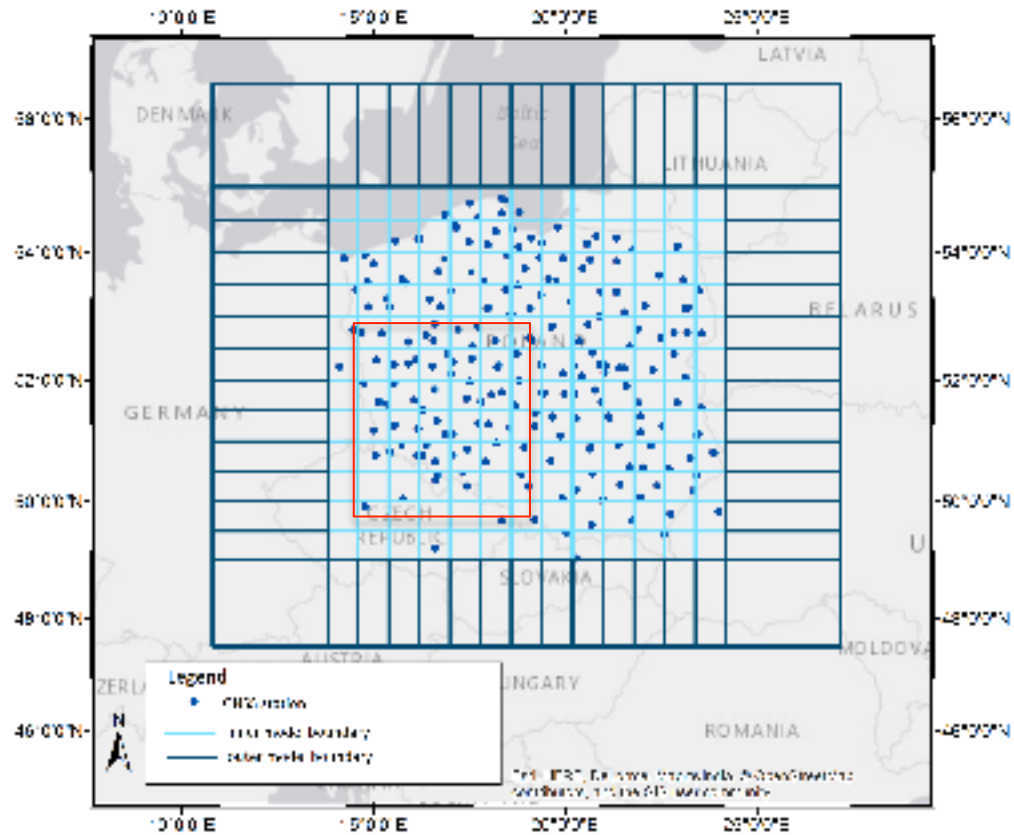
Case studies: case study I

- Processing Time

Number of slants	1826	3151	6094	15756
Matrix size	1826*1792	3151*1792	6094*1792	15756*1792
SWART (seconds)	15.81	21.70	34.15	114.51
BIRA (seconds)	120 (2 min)	480 (8 min)	7800 (130 min)	Not computed

Case studies: case study II





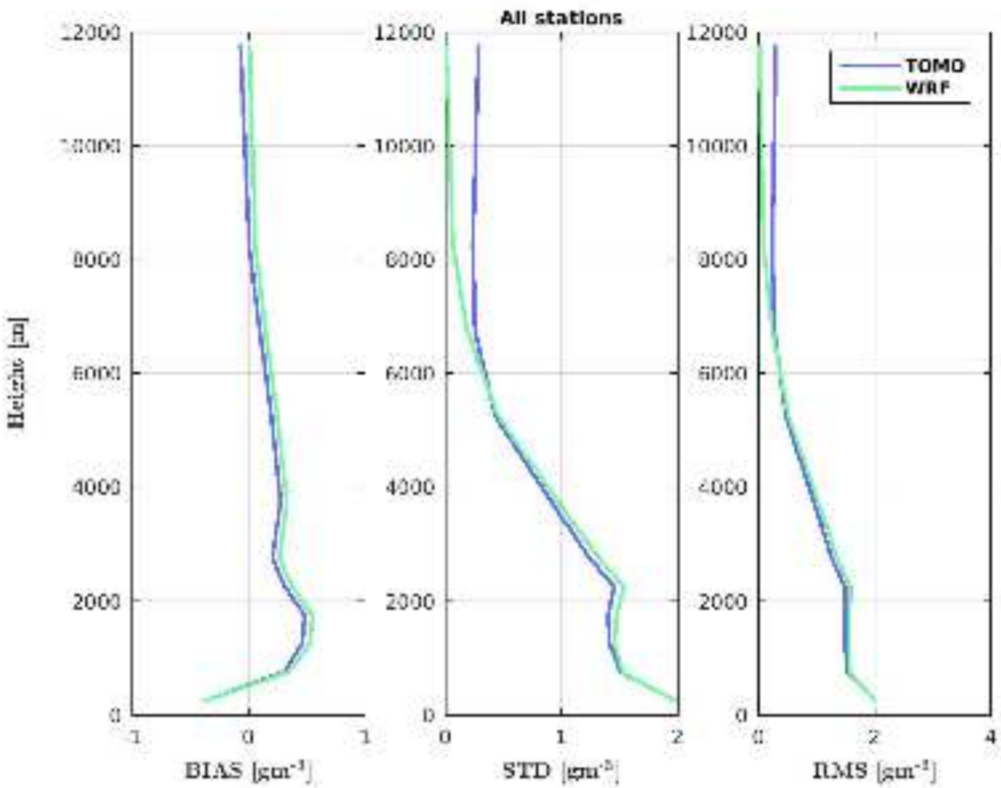
Performed over the territory of Poland using data from a period of 56 days (from 05-05-2013 to 29-06-2013). 26 GNSS stations were used with an average distance of 50 km.

Case studies: case study II

- The goal of this case study was to understand the performance quality of the SWART tomographic model using simulated real-time data. For this purpose, the post-processed 15-min data were interpolated into a 5-min solution to simulate real-time conditions. Following Schenewerk (2003) a 9-term trigonometric interpolater was implemented.

Case studies: case study II

Comparison between SWART WV (initialization each hour) and WRF



Stats Tomography

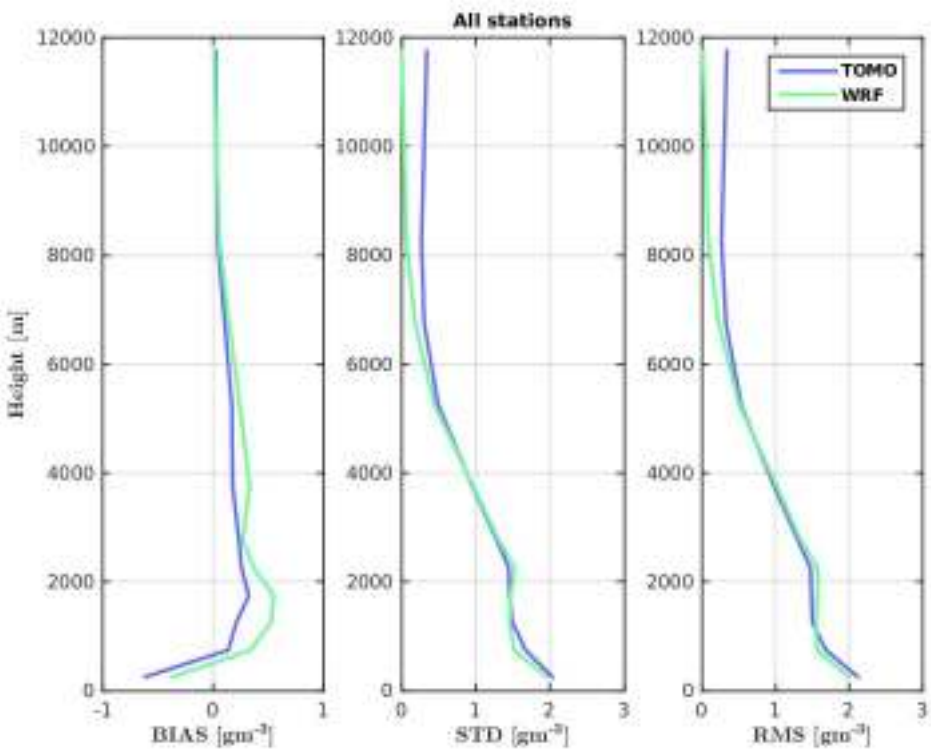
Height	BIAS	STD	RMS
250	-0.3760	1.9665	2.0021
750	0.3043	1.5046	1.5351
1250	0.4584	1.4085	1.4812
1750	0.4788	1.3964	1.4762
2250	0.3087	1.4485	1.4810
2750	0.2019	1.2385	1.2549
3750	0.2722	0.9050	0.9451
5250	0.1926	0.4253	0.4669
6750	0.0921	0.2521	0.2684
8250	0.0014	0.2341	0.2341
11750	-0.0721	0.2822	0.2913

Stats WRF

Height	BIAS	STD	RMS
250	-0.3721	1.9678	2.0026
750	0.3363	1.5210	1.5578
1250	0.5255	1.4524	1.5445
1750	0.5486	1.4684	1.5675
2250	0.3714	1.5334	1.5778
2750	0.2630	1.3184	1.3443
3750	0.3267	0.9645	1.0183
5250	0.2420	0.4513	0.5121
6750	0.1433	0.1854	0.2343
8250	0.0547	0.0620	0.0827
11750	0.0065	0.0039	0.0076

Case studies: case study II

Comparison between SWART (initialization each 24h) and WRF



Stats Tomography

stats_TOMO_WV.txt

Height	BIAS	STD	RMS
250	-0.6121	2.0306	2.1208
750	0.1346	1.6741	1.6795
1250	0.2064	1.4911	1.5053
1750	0.3190	1.4558	1.4903
2250	0.2588	1.4519	1.4748
2750	0.2323	1.2884	1.3092
3750	0.1764	0.9589	0.9749
5250	0.1673	0.5039	0.5309
6750	0.1032	0.3046	0.3216
8250	0.0401	0.2641	0.2671
11750	0.0202	0.3387	0.3393

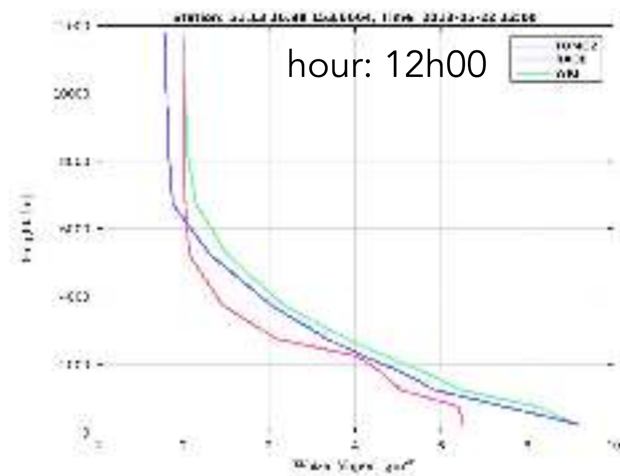
Stats WRF

stats_WRF_WV.txt

Height	BIAS	STD	RMS
250	-0.3721	1.9678	2.0026
750	0.3363	1.5210	1.5578
1250	0.5255	1.4524	1.5445
1750	0.5486	1.4684	1.5675
2250	0.3714	1.5334	1.5778
2750	0.2630	1.3184	1.3443
3750	0.3267	0.9645	1.0183
5250	0.2420	0.4513	0.5121
6750	0.1433	0.1854	0.2343
8250	0.0547	0.0620	0.0827
11750	0.0065	0.0039	0.0076

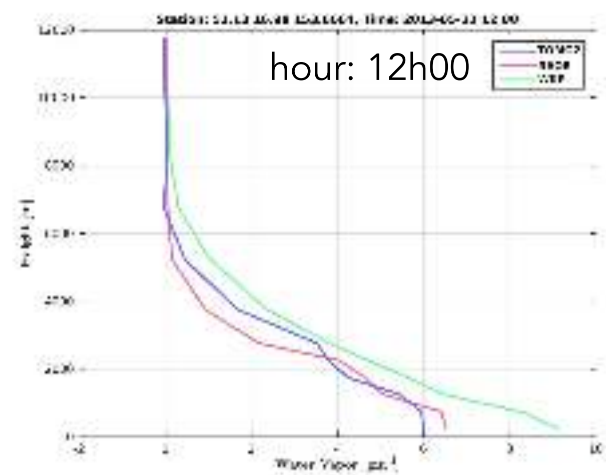
Case studies: case study II

Initialization every 1h



Date: 2013-05-22

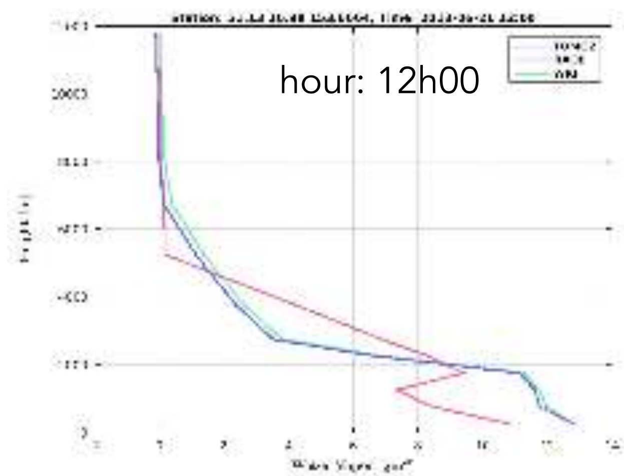
Initialization each 24h



Case studies: case study II

Date: 2013-06-21

Initialization every 1h



Initialization each 24h

Conclusions

- Implementation and validation of a GNSS tomographic system was successfully tested;
- The results of the tests and studies performed in comparison to other tomography systems revealed SWART as a reliable tomography technique to estimate water vapor in the atmosphere;
- The various tests conducted emphasize the importance of a priory data for initialization of tomography with high impacts in the retrieved solution. SWART presents better results with the increase of the amount of the data.
- When sharp variability is observed in the RS profiles, and not detected by the WRF, the SWART is only able to reproduce such variations when WRF a priori initialization data is used only at the first epoch.
- Concerning the real-time capabilities this issue was addressed by using ART algorithms parallelized. The SWART processing time SWART 34.15" - BIRA 30 min.

End!

Thanks for your attention!