Wrocław University of Environmental and Life Sciences

Real-time Precise Point Positioning supported with high-resolution troposphere models based on Numerical Weather Prediction

Tomasz Hadaś, Karina Wilgan, Paweł Hordyniec, Jarosław Bosy

IGS Workshop 2017, Paris (France), 3-7 July 2017

IGSWORKSHOP2017 PARIS
PATHWAYS TO IMPROVED PRECISION

MOTIVATION (1)

Zumberge J.F., et al. (1997). Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks. J.Geophys. Res., 102(B3), 5005-5017:

$$I_p = \frac{1}{f_1^2 - f_1^2}\left(f_1^2 P_1 - f_2^2 P_2\right) = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + \epsilon_p$$

$$I_\Phi = \left[\frac{1}{f_1^2 - f_1^2}\left(f_1^2 P_1 - f_2^2 P_2\right)\right]\lambda_{L3} = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + N\lambda_{L3} + \epsilon_\Phi$$

Drawbacks:

- troposphere is a major error source
- ZTD is highly correlated with U_r and δt_r
- long convergence time

Solution:

- introduce high-res tropo model
- U_r and δt_r are highly correlated
- shorter convergence time

Motivation (2)

Standard approach:

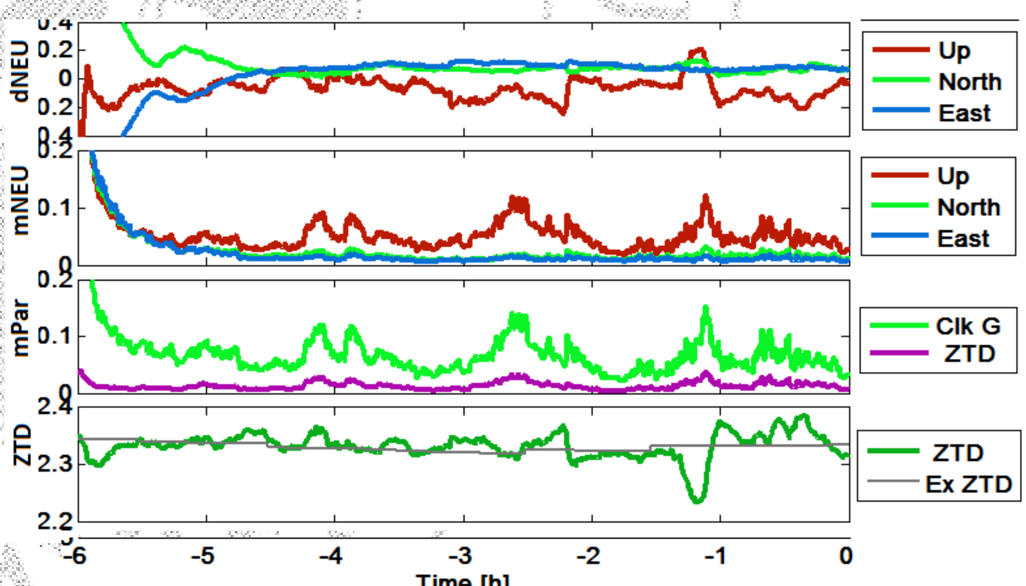
- ZHD from external model as fixed value
- ZWD estimated as random walk process

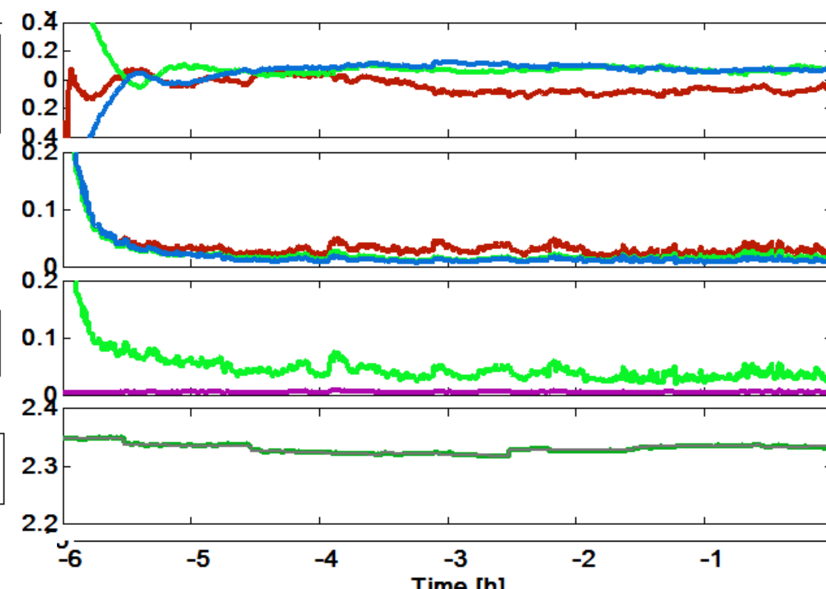
Troposphere constraining (post-proc):

- a priori ZTD from external model (first epoch)
- ZWD estimated as random walk process
- additional equation in functional model:

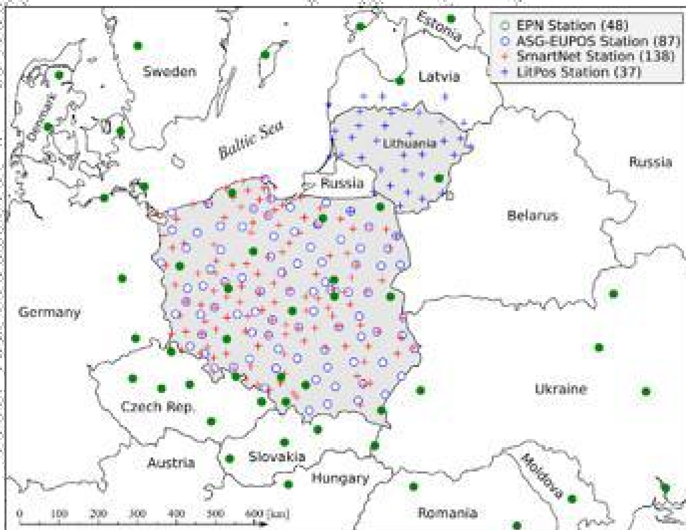
$$\delta ZTD = ZTD^{NRT} - ZTD'$$

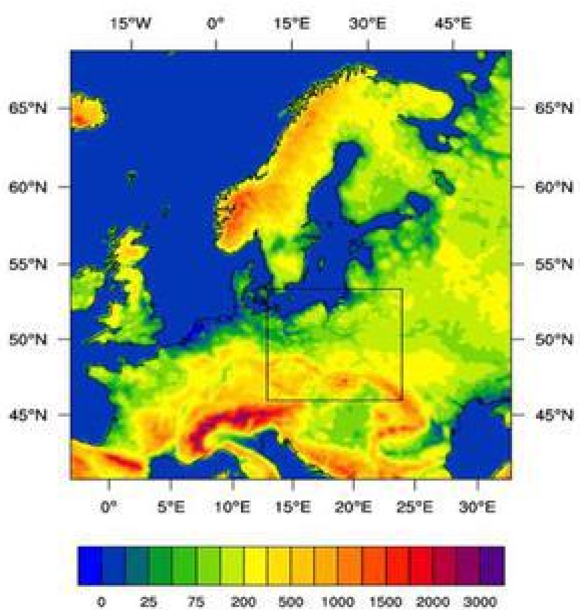
ZTD^{NRT} - the zenith troposphere delay from near real-time regional model
ZTD' - the a priori zenith troposphere delay value (from previous epoch)
δZTD - the correction to the a priori zenith troposphere delay value





DATA





NRT GNSS

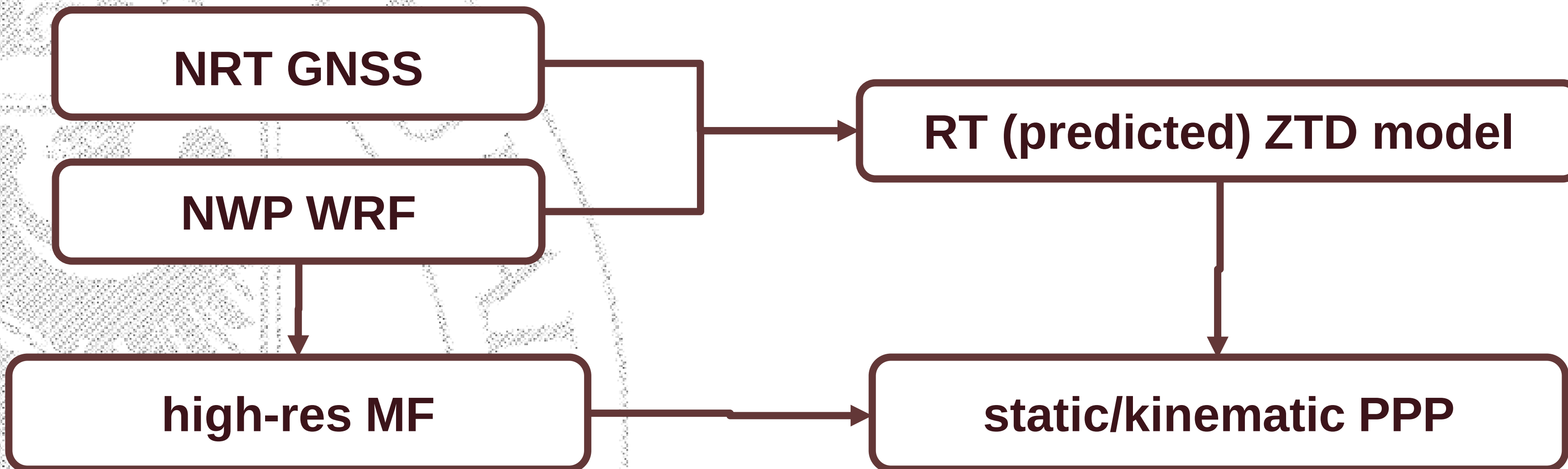
- near real-time ZTD and Hz gradients
- 272 stations from Poland and adjacent area
- ZTD with 1-h resolution
- ~6 mm accuracy

NWP WRF

- WRF – Weather Research & Forecasting
- 4x4 km^2 grid
- 47 vertical levels
- forecasts at 0:00, 6:00, 12:00, 18:00 UTC
- total refractivity (N) from p, T, e with 1-h resolution (coefficients Rüeger `best average'):

$$N_{tot} = k_1 \frac{p-e}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

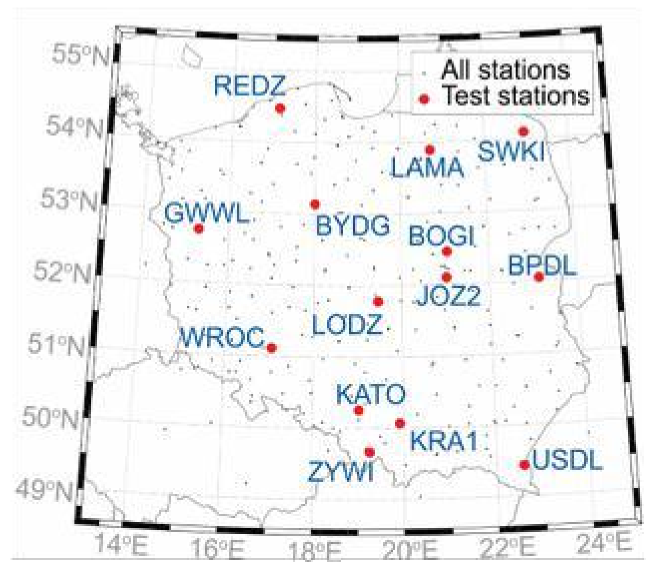
Methodology



3 test periods:

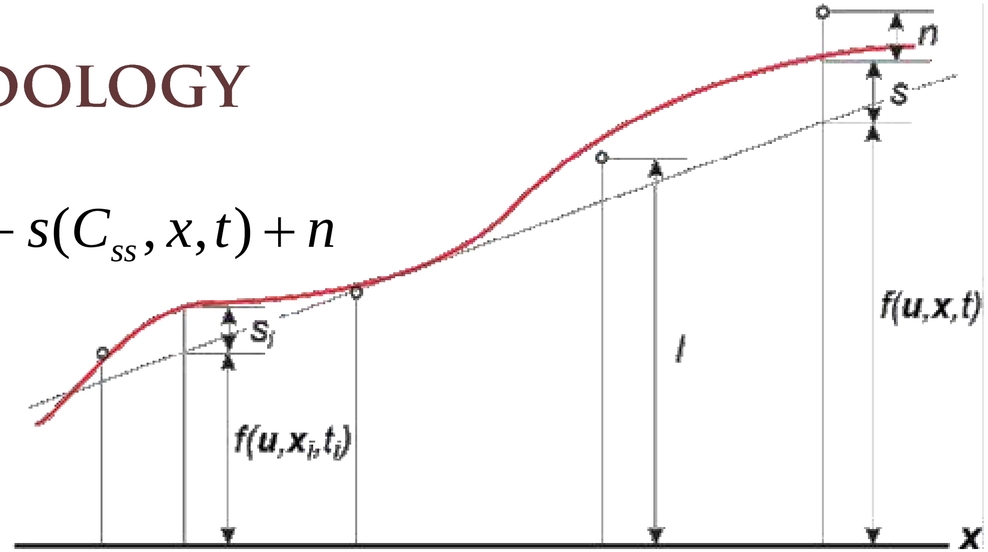
1. standard: Dec 2 – 8, 2015
2. calm: May 2 – 8, 2016
3. severe: Aug 28 – Sep 3, 2016

14 test stations (EPN) excluded from building the model



Real-time ZTD - methodology

$$l = f(u,x,t) + s(C_{ss},x,t) + n$$



Least-squares collocation using software COMEDIE developed at ETH Zürich

Zenith total delay (from NRT GNSS)

$$ZTD(x,y,z,t) = (ZTD_0 + a_{ZTD}(x-x_0) + b_{ZTD}(y-y_0) + c_{ZTD}(t-t_0)) \cdot e^{-\frac{z}{H_{ZTD}}}$$

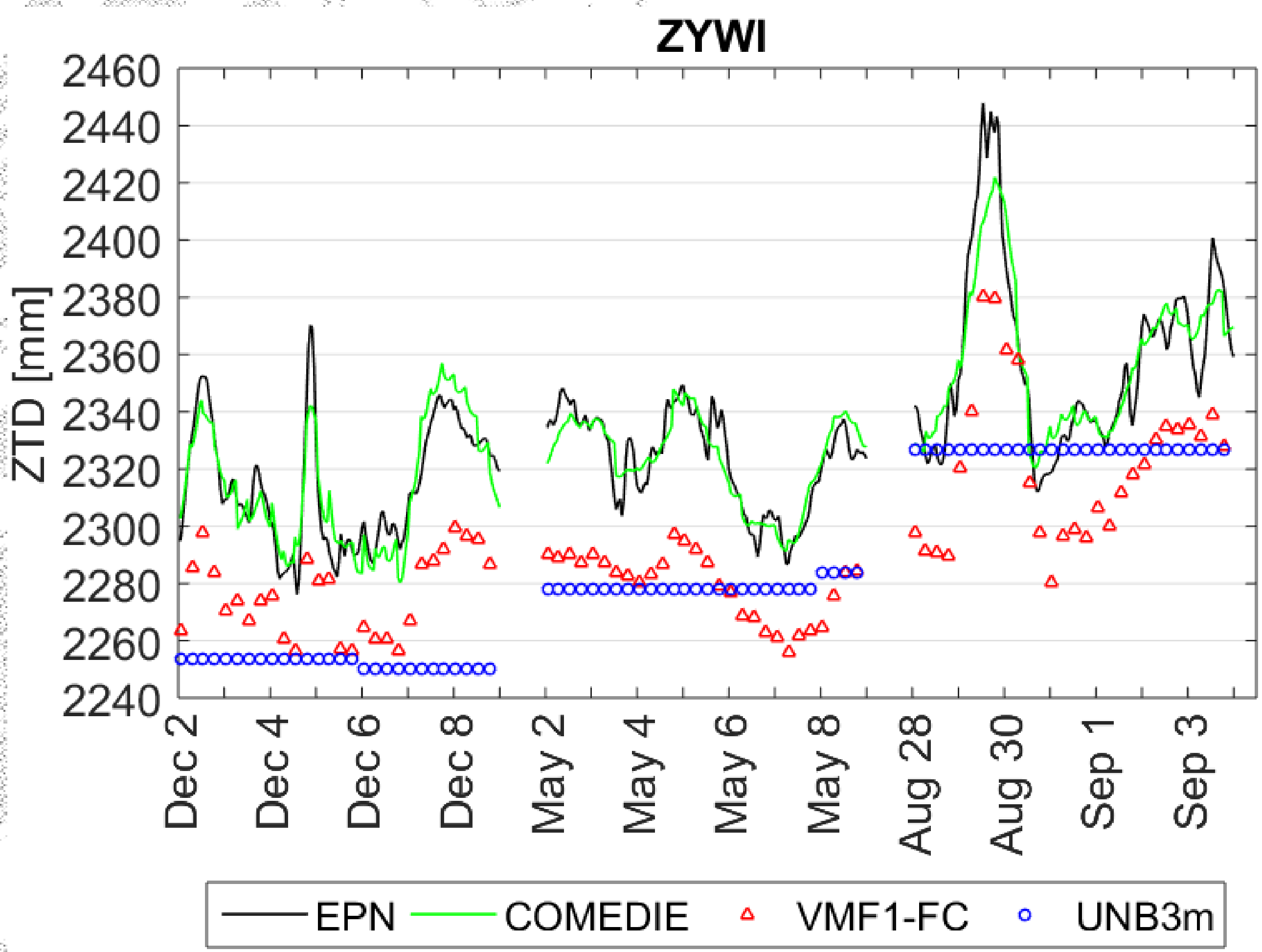
Total refractivity (from WRF)

$$N(x,y,z,t) = \frac{1}{H_{ZTD}}(ZTD_0 + a_{ZTD}(x-x_0) + b_{ZTD}(y-y_0) + c_{ZTD}(t-t_0)) \cdot e^{-\frac{z}{H_{ZTD}}}$$

More about a priori ZTD → Wilgan K, Hurter F, Geiger A, Rohm W, Bosy J (2017) *Tropospheric refractivity and zenith path delays from least-squares collocation of meteorological and GNSS data* J Geod 91(2): 117-134

REAL-TIME ZTD - RESULTS

Comparison of ZTDs obtained from 3 models (RT COMEDIE, VMF1-FC, UNB3m) w.r.t. EPN



σ=10mm (RT vs EPN)

Mapping function (WRFMF) - methodology

- the methodology based on VMF `fast' approach[1]
- hydrostatic b,c → from Isobaric Mapping Function:

  $b_h = 0.002905$

  $c_h = 0.0634 + 0.0014 \cdot \cos(2\varphi)$

$$MF(el) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{\sin(el) + \frac{a}{\sin(el) + \frac{b}{\sin(el) + c}}}$$

- wet b,c → from Niell Mapping Function:

  $b_w = 0.00146$

  $c_w = 0.04391$

- WRF ray-tracing (every 1 h) for *el*=3.3° → *SHD/SWD, ZHD/ZWD*

  $MF_h = (SHD + d_{geo})/ZHD$

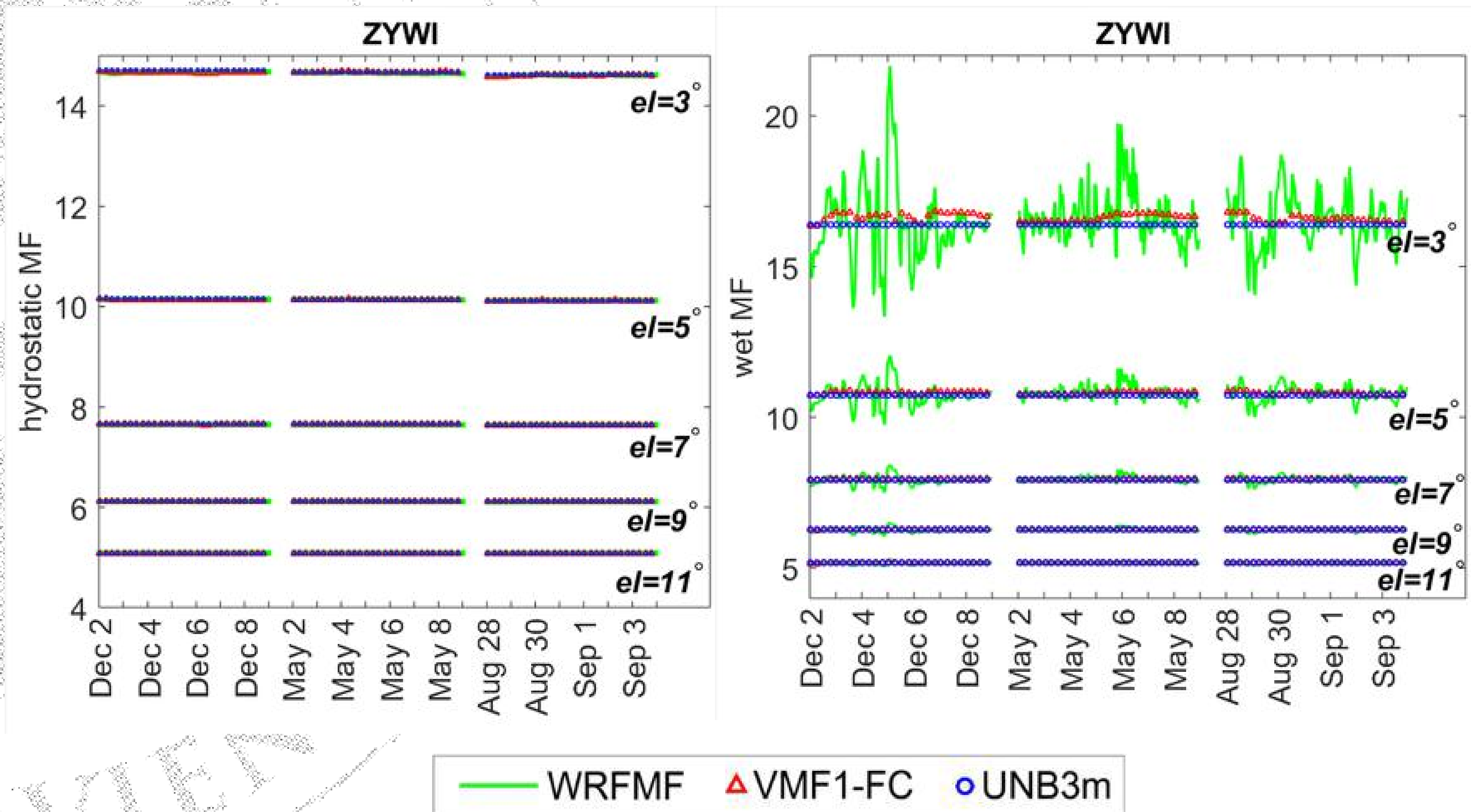
  $MF_w = SWD/ZWD$

- a-coefficients from inverting the continued fraction → WRFMF

[1] Boehm J, Schuh H (2004) Vienna mapping functions in VLBI analyses. Geophys Res Lett 31(1)

Mapping function (WRFMF) -results

Comparison of the hydrostatic and wet MFs from three models: WRFMF, VMF1-FC and UNB3m; station ZYWI; cut-off angle in processing 5°

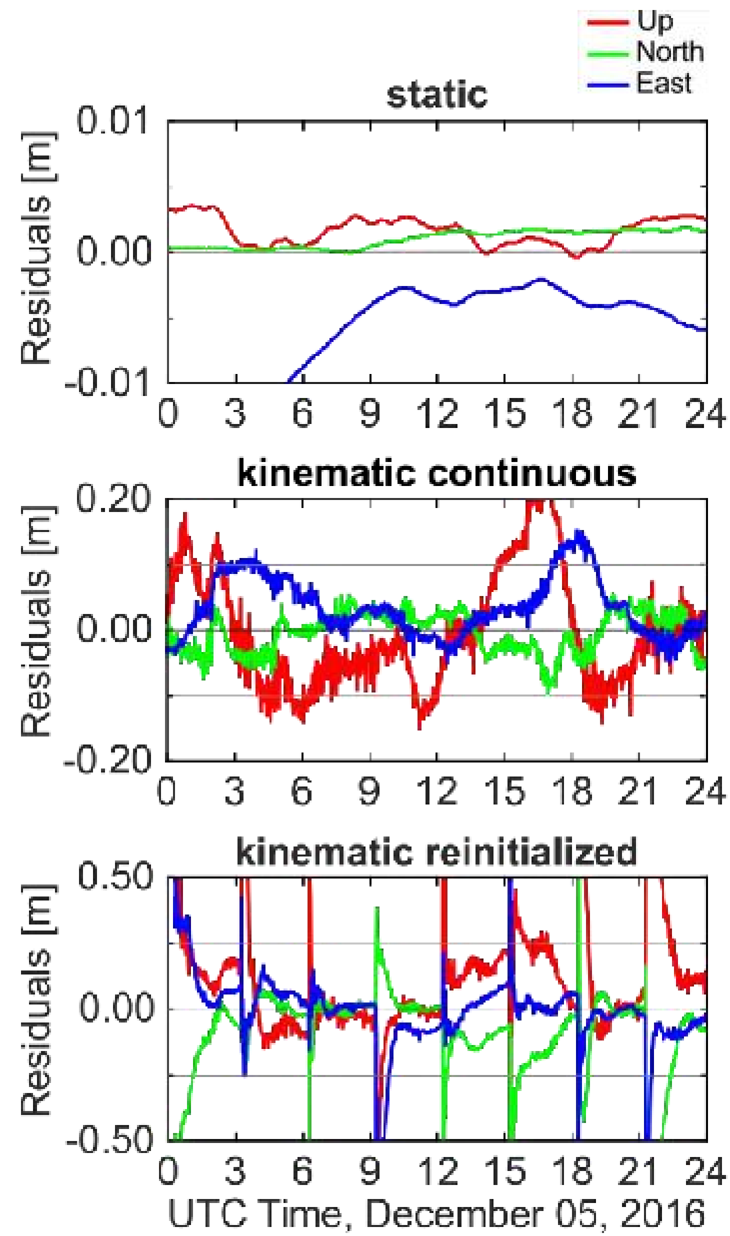


PPP Strategy

In house developed GNSS-WARP software:

- GPS PPP (L1/L2 iono-free)
- float ambiguities, IGS03 stream
- 3 types of coordinates (see Figure)
- 6 processing variants (see Table)

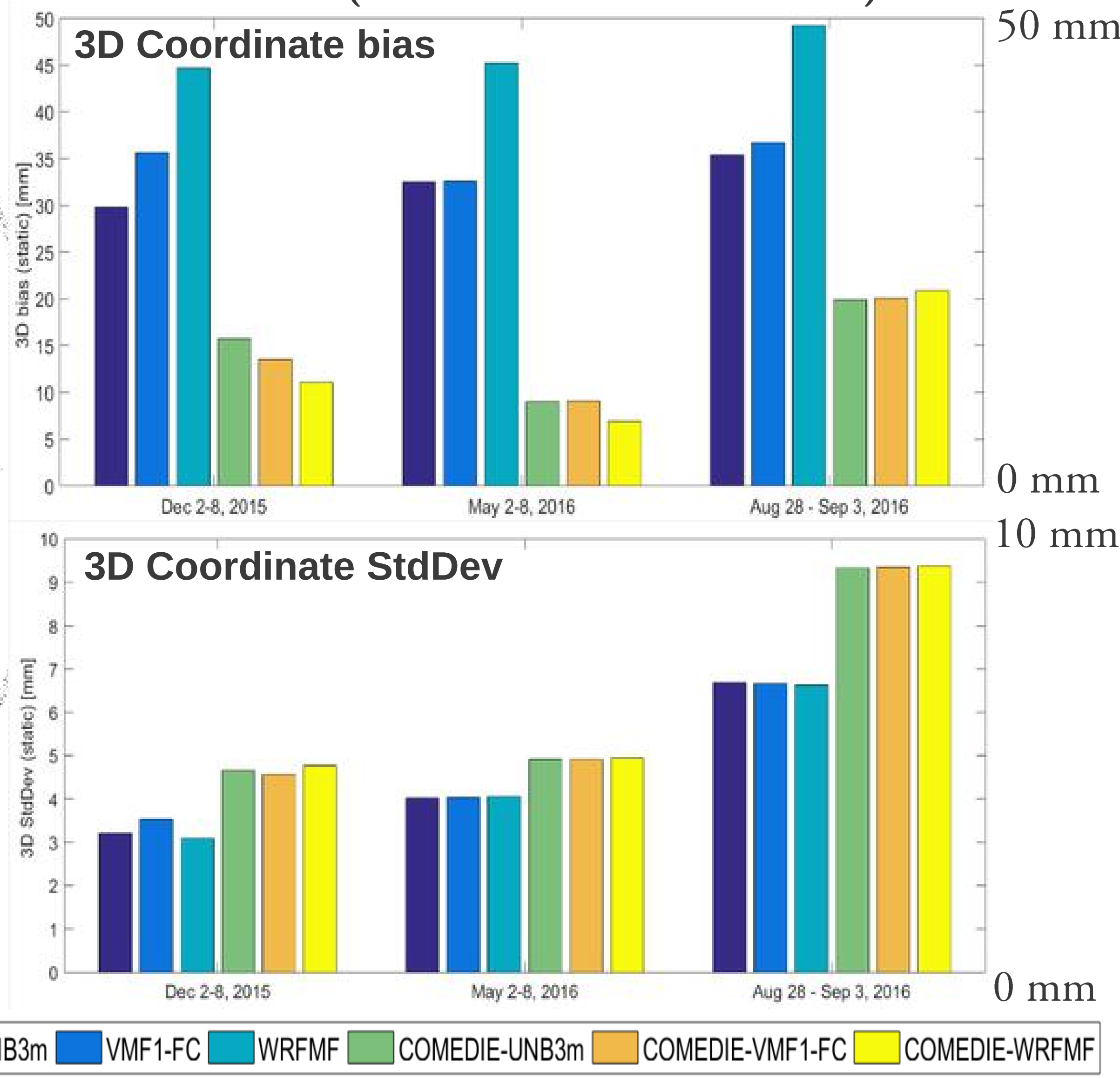
ZTD	Constr.	MF
UNB3m	None	UNB3m
VMF1-FC	None	VMF1-FC
WRF	None	WRFMF
COMEDIE	10 mm	UNB3m
COMEDIE	10 mm	VMF1-FC
COMEDIE	10 mm	WRFMF



RT Static positioning

	3D Bias [mm]	3D StdDev [mm]
UNB3m	32.6	4.6
VMF1-FC	35.0	4.7
WRFMF	46.4	4.6
COMEDIE-UNB3m	14.9	6.3
COMEDIE-VMF1-FC	14.2	6.3
COMEDIE-WRFMF	12.9	6.4

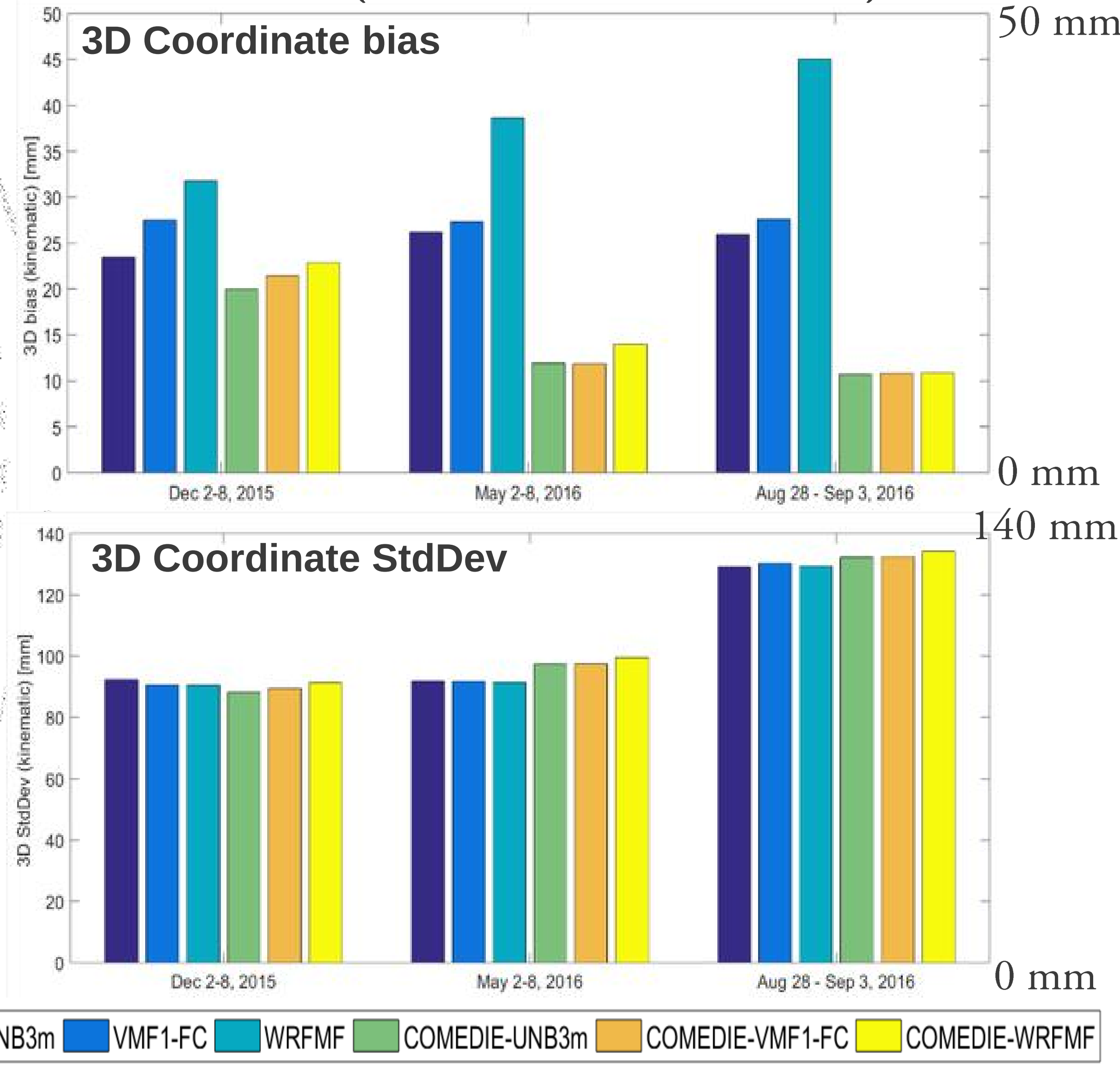
Residuals (estimated – EPN official)



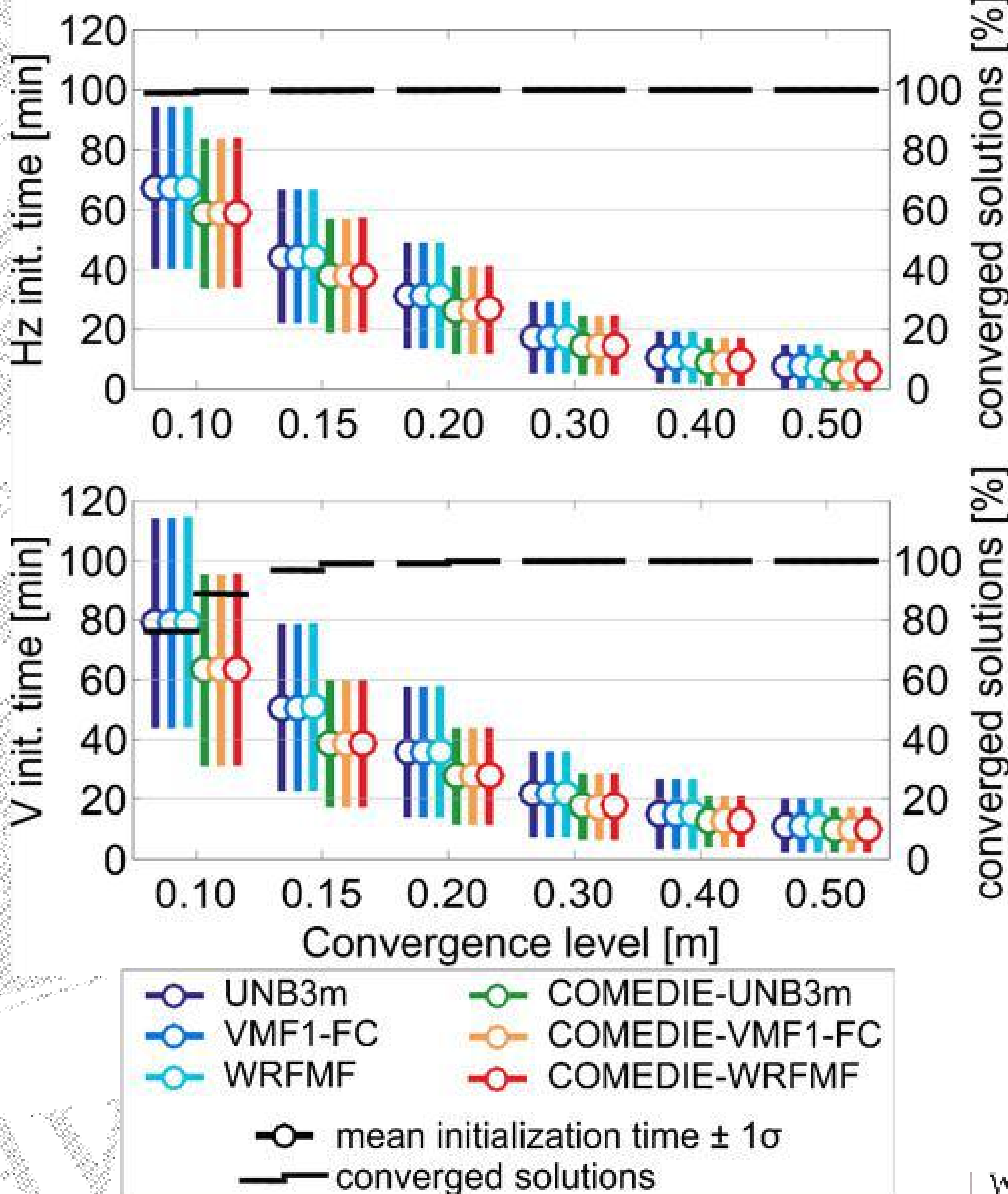
RT Kinematic positioning

	3D Bias [mm]	3D StdDev [mm]
UNB3m	25.2	104.4
VMF1-FC	27.5	104.2
WRFMF	38.5	103.8
COMEDIE-UNB3m	14.2	105.9
COMEDIE-VMF1-FC	14.7	106.4
COMEDIE-WRFMF	15.9	108.3

Residuals (estimated – EPN official)



Convergence time (3-h reinitialized kinematic)



Initialization time for **10 cm** level of convergence (based on formal error)

	UNB/VMF	COMEDIE
Hz (N/E)	67 min	58 min
V (Up)	79 min	63 min

Percentage of converged solutions during the 3-h reinitialization period for 10 cm level of convergence

	UNB/VMF	COMEDIE
Hz (N/E)	99%	100%
V (Up)	76%	88%

Summary

- RT PPP in 6 processing variants (different combinations of a priori ZTD and MFs), 3 time-periods
- 3 types of coordinates: static, continuous kinematic and reinitialized kinematic
- ZTD constraining with NWP:

- pros: **better accuracy** (< bias), **shorter convergence time**

- cons: slightly worse precision (> standard deviations)

Wilgan K., Hadaś T., Hordyniec P., Bosy J. (2017): Real-time precise point positioning augmented with high-resolution numerical weather prediction model. GPS Solutions 23(3), 1341-1353

Wrocław University of Environmental and Life Sciences

Thank you for your attention!

Questions?

tomasz.hadas@epwr.edu.pl (GNSS, PPP)
karina.wilgan@igig.up.wroc.pl (NWP, COMEDIE)
pawel.hordyniec@upwr.edu.pl (NWP, MF)

This work has been supported by COST Action ES1206 GNSS4SWEC (www.gnss4swec.knmi.nl) and Polish National Science Centre (Projects 2014/15/N/ST10/00824 and 2014/15/B/ST10/00084). COMEDIE software was originally developed at the Institute of Geodesy and Photogrammetry, ETH Zürich, Switzerland