Wrocław University of Environmental and Life Sciences

Troposphere products for GNSS precise positioning and meteorology

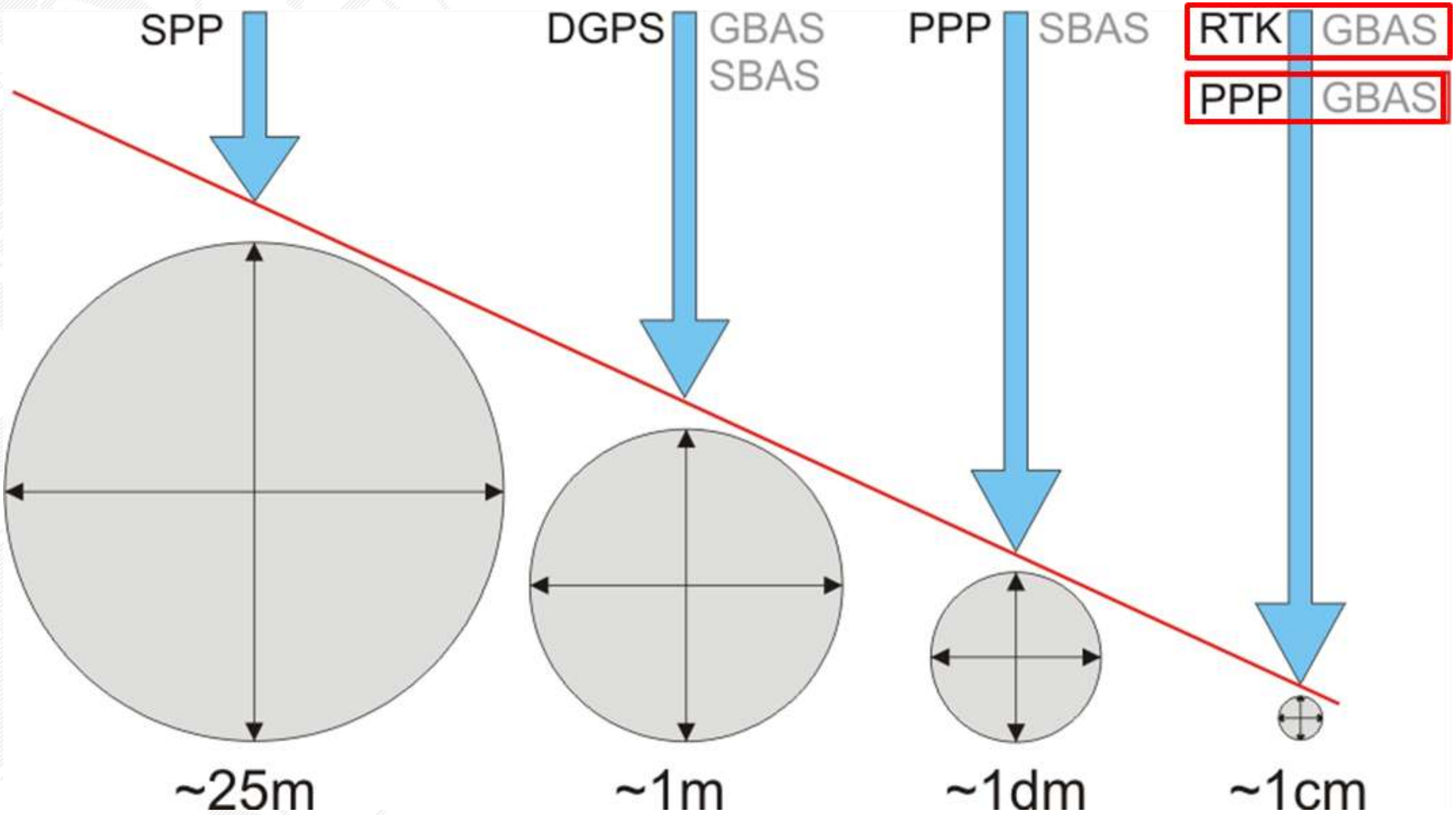
Jaroslaw Bosy, Witold Rohm, Jan Kaplon, Tomasz Hadas, Karina Wilgan, Pawel Hordyniec, Krzysztof Sosnica, Kamil Kazmierski, Jan Sierny

International Workshop on Precision Products for PPP: current status and future perspective
May 17 2016, Wuhan University, Wuhan, China

Presentation plan

1. Introduction
2. Near Real Time products
3. Real Time products
4. Conclusion

Motivation for GNSS positioning



GNSS and METEO comunity integration

euref

IGS

EUPOS®
European Position Determination System

GNSS

Meteorology

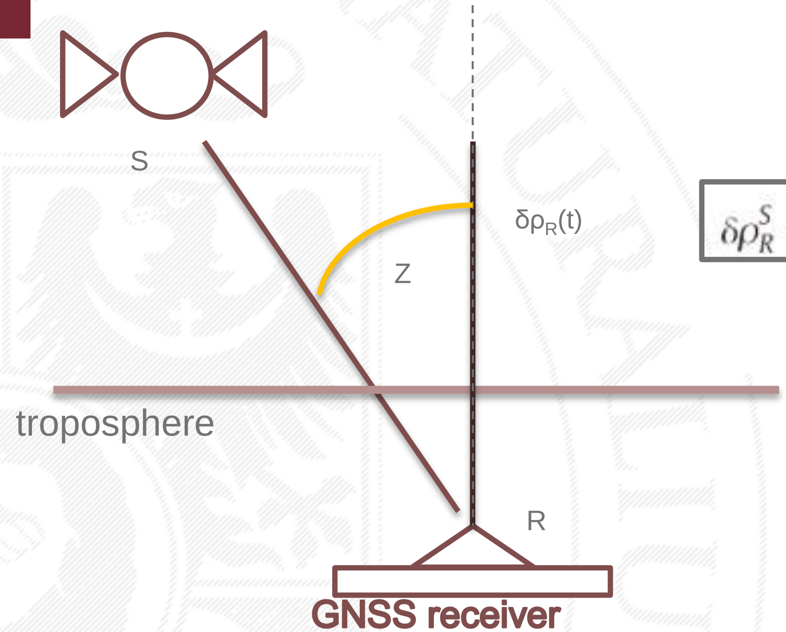
EUMETNET
The Network of European Meteorological Services

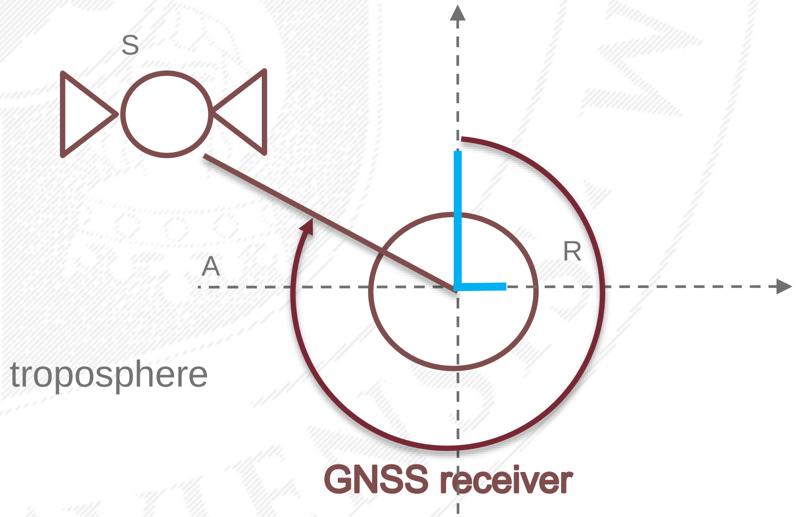
E-GVAP: The EUMETNET EIG GNSS water vapour programme

IAG
WG 4.3.2
WG 4.3.3

GNSS 4 SWEC

GNSS Troposphere delay





$$\boxed{\delta\rho_R^S} = \boxed{\delta\rho_{apr,R}\left(z_R^S\right)} + \boxed{\delta^h\rho_R(t)} \cdot map_N\left(z_R^S\right) + \boxed{\delta^n\rho_R(t)}\frac{\partial map_N}{\partial z}\cos A_R^S + \ldots\ldots + \boxed{\delta^e\rho_R(t)}\frac{\partial map_N}{\partial z}\sin A_R^S.$$

Apriori model of delay into the direction of satellite

Estimated parameter of delay into zenith direction (dZTD)

Gradients in North (n) and East (e) direction

STD is a sum of all estimated parameters

GNSS Troposphere delay

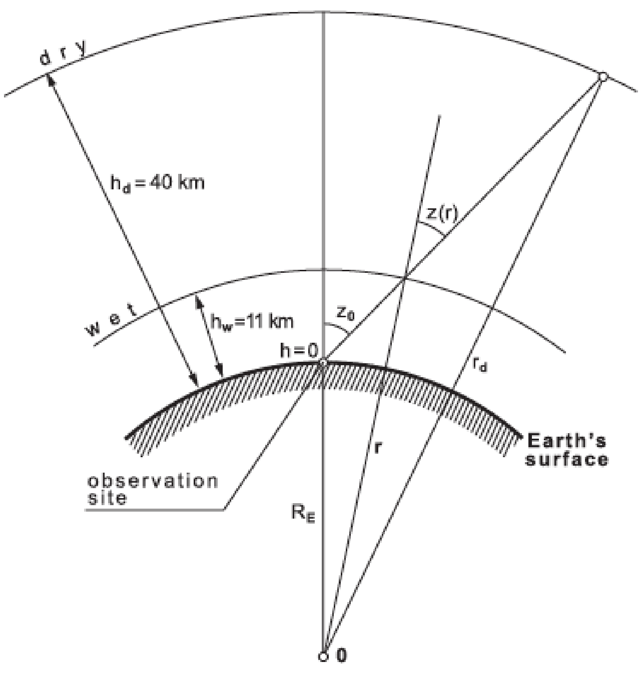
$$\delta T(z) = m_d(z) \cdot \delta T_{d,0} + m_w(z) \cdot \delta T_{w,0}$$

Saastamoinen (Saastamoinen, 1973)

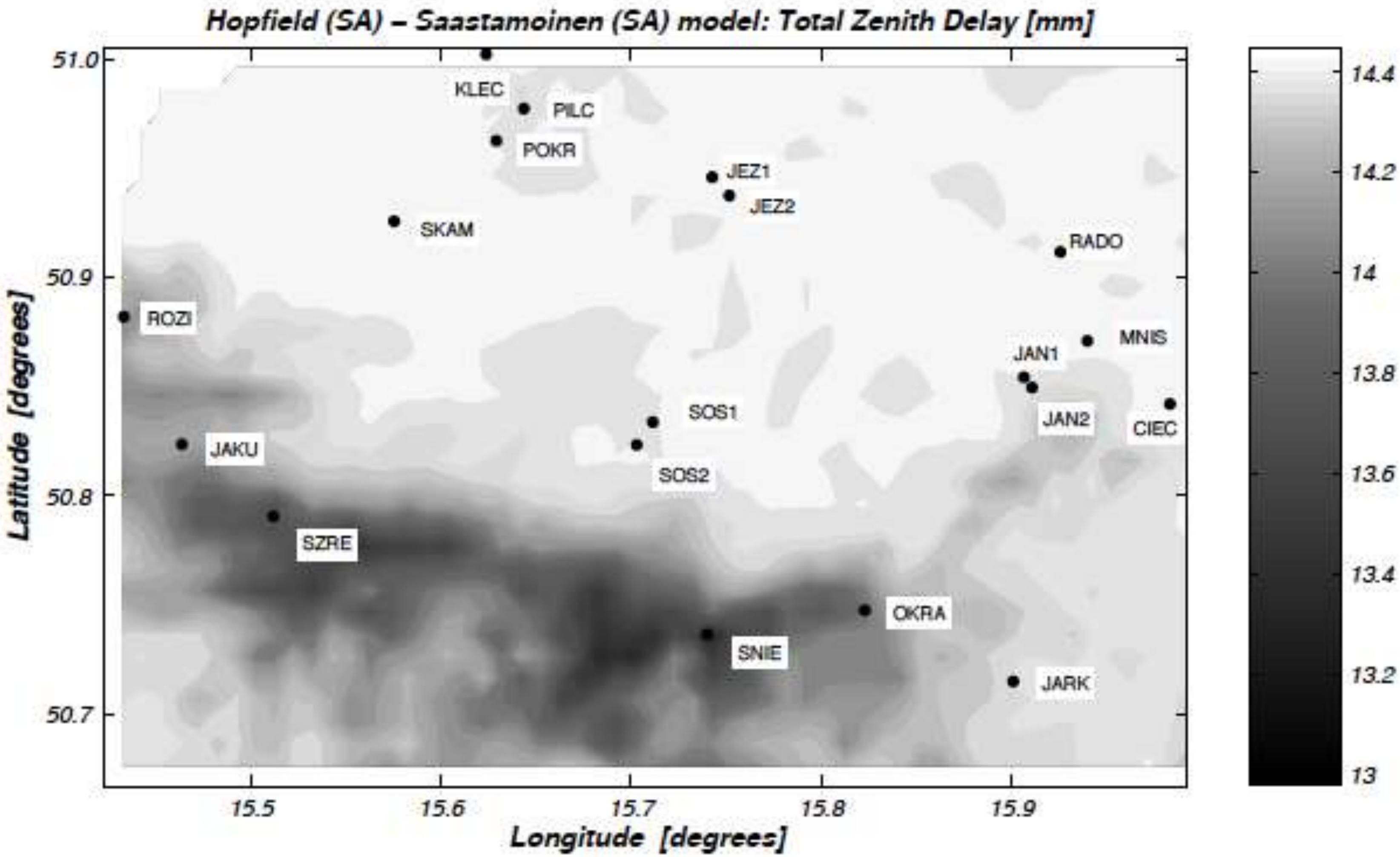
$$\delta T = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T_K} + 0.05\right)e - \mathrm{tg}^2 z\right]$$

Hopfield (Hopfield, 1969)

$$\delta T = \frac{10^{-6}}{5}\left[\frac{N_{d,0}^{trop} h_d}{\sin\sqrt{\varepsilon^2 + 6.25}} + \frac{N_{w,0}^{trop} h_w}{\sin\sqrt{\varepsilon^2 + 2.25}}\right]$$



GNSS Troposphere delay



GNSS Troposphere delay

Table 4.7: Input parameters for zenith troposphere dry delay models

Model	e	T	P	φ	h	β	κ	inne (other)
(Hopfield, 1969, 1971, 1972)		$\surd$	$\surd$					
(Goad and Goodman, 1974)		$\surd$	$\surd$					
(Saastamoinen, 1973)		$\surd$	$\surd$					
(Davis et al., 1985)			$\surd$	$\surd$	$\surd$			
(Baby et al., 1988)		$\surd$	$\surd$		$\surd$	$\surd$		g, R_e
(Elgered et al., 1991)			$\surd$	$\surd$	$\surd$			
(MOPS, 1998)		$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		DOY, g

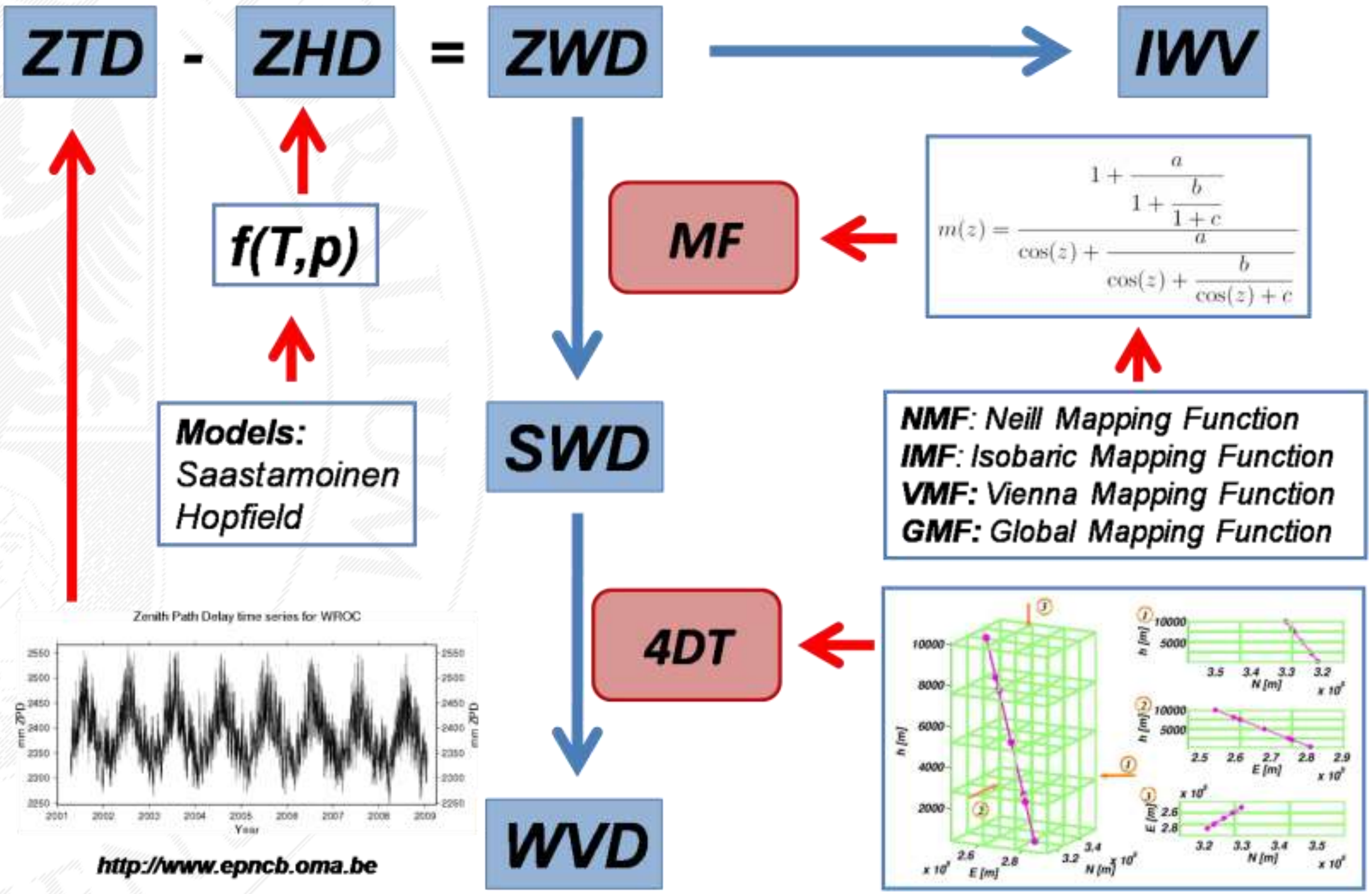
GNSS Troposphere delay – mapping functions

$$m(z) = \cfrac{1}{\cos z + \cfrac{a}{\cos z + \cfrac{b}{\cos z + \cfrac{c}{\cos z + \dots}}}}$$

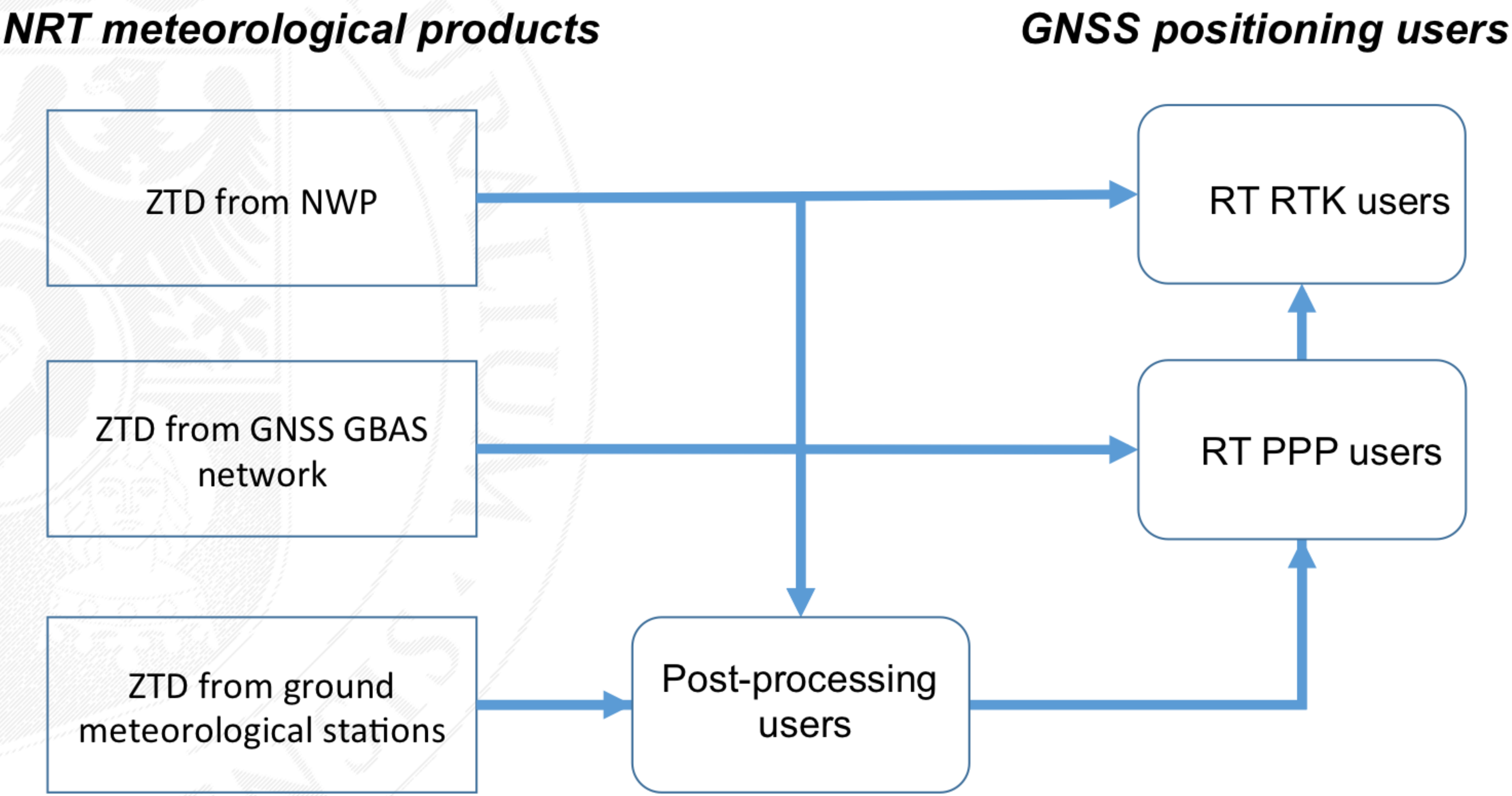
Table 4.11: Comparison of selected mapping functions

Funkcja (function)	P	T	e	β	h_T	h	φ	inne (other)	ε_{min}
(Baby et al., 1988)	√	√	√			√			10^o
(Black, 1978)		√							5^o
(Chao, 1972, 1974)									1^o
(Davis et al., 1985)	√	√	√	√	√				5^o
(Goad and Goodman, 1974)	√	√	√			√			n/a
(Herring, 1992)		√				√	√		3^o
(Hopfield, 1969)		√				√			n/a
(Ifadis, 1986)	√	√	√						2^o
(Marini and Murray, 1973)	√	√	√			√	√		10^o
(Niell, 1996)						√	√	*DOY*	3^o
(Saastamoinen, 1973)	√	√	√			√			10^o
(Yan and Ping, 1995)	√	√	√	√					2.5^o
(Guo and Langley, 2003)						√	√		2^o
(Foelsche and Kirchengast, 2001, 2002)									6^o

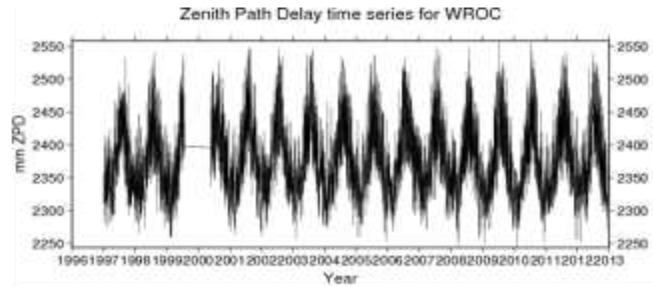
GNSS Troposphere delay for meteorology

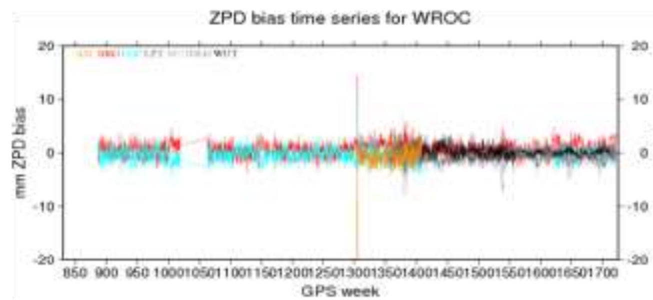


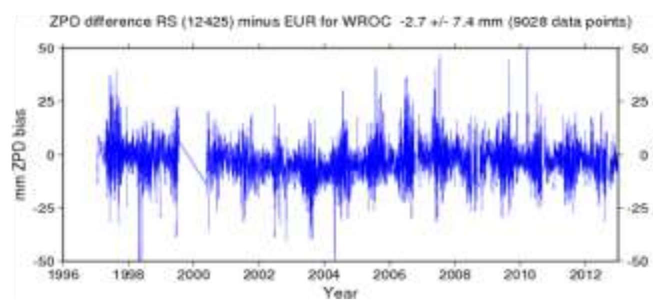
GNSS and METEO motivation



EUREF Permanent Network troposphere products







IGS Global Network troposphere products

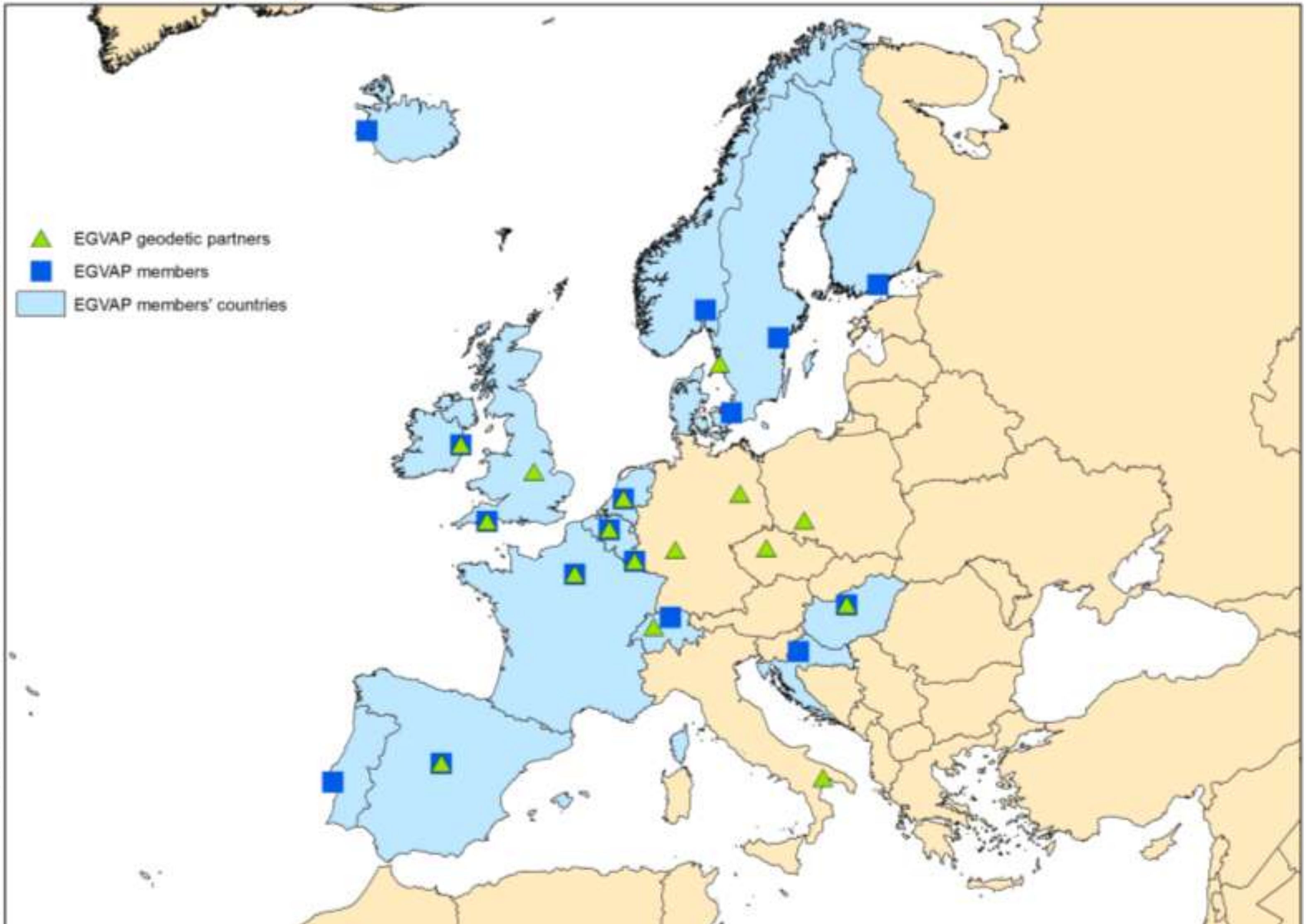
```
%=TRO 0.01 IGG 12:115:81494 ITR 12:115:68400 12:115:72000 P  MIX
*-------------------------------------------------------------------------------
+FILE/REFERENCE
*INFO_TYPE_________ INFO________________________________________________________
 DESCRIPTION        Wroclaw University of Environmental and Life Sciences/IGG
 OUTPUT             NRT Hourly SINEX and Troposphere SINEX
 CONTACT            Jan Kaplon (jan.kaplon@igig.up.wroc.pl)
 SOFTWARE           Bernese GPS Software Version 5.0
 HARDWARE           80 cores Intel(R) Xeon E7-4870 @ 2.4GHz, Debian 6.0.4
 INPUT              IGS/EPN/ASG-EUPOS GNSS tracking data
-FILE/REFERENCE
*-------------------------------------------------------------------------------
+TROP/DESCRIPTION
*_________KEYWORD_____________ __VALUE(S)_______________________________________
 ELEVATION CUTOFF ANGLE                           5
 SAMPLING INTERVAL                               30
 SAMPLING TROP                                 3600
 TROP MAPPING FUNCTION          WET NIELL
 SOLUTION_FIELDS_1              TROTOT STDDEV
-TROP/DESCRIPTION
*-------------------------------------------------------------------------------
+TROP/STA_COORDINATES
*SITE PT SOLN T __STA_X_____ __STA_Y_____ __STA_Z_____ SYSTEM REMRK
 BAIA  A    1 P  3945839.793  1720428.324  4691082.807 ITRF08 IGG
 ...              ...          ...          ...         ...    ...
 WROC  A    1 P  3835751.214  1177250.080  4941605.366 ITRF08 IGG
-TROP/STA_COORDINATES
*-------------------------------------------------------------------------------
+TROP/SOLUTION
*SITE ____EPOCH___ TROTOT STDDEV
 BAIA 12:115:70200 2348.6    1.4
 ...  ...           ...      ...
 WROC 12:115:70200 2337.8    1.0
-TROP/SOLUTION
%=ENDTRO
```

COST-716 Format

```
--------------------------------------------------------------------------------
COST-716 V2.0a          E-GVAPII
BIAL 12235M001          Bialystok (Poland)
TRIMBLE NETRS           TRM41249.00     TZGD
   53.132083   23.138750     191.393     163.157       0.000
21-NOV-2012 09:00:00    21-NOV-2012 10:39:30
IGIG                    BERN_V5.0               IGSULT                  NONE
   60    60 1440
00000065
-999
 09 00 00 fffffff 2345.4    1.5   -9.9   -9.9   -9.9   -9.9   -9.9 999.99 999.99   -9.99   -9.99 -9.999
   0
 09 59 00 fffffff 2349.5    2.7   -9.9   -9.9   -9.9   -9.9   -9.9 999.99 999.99   -9.99   -9.99 -9.999
   0
--------------------------------------------------------------------------------
```

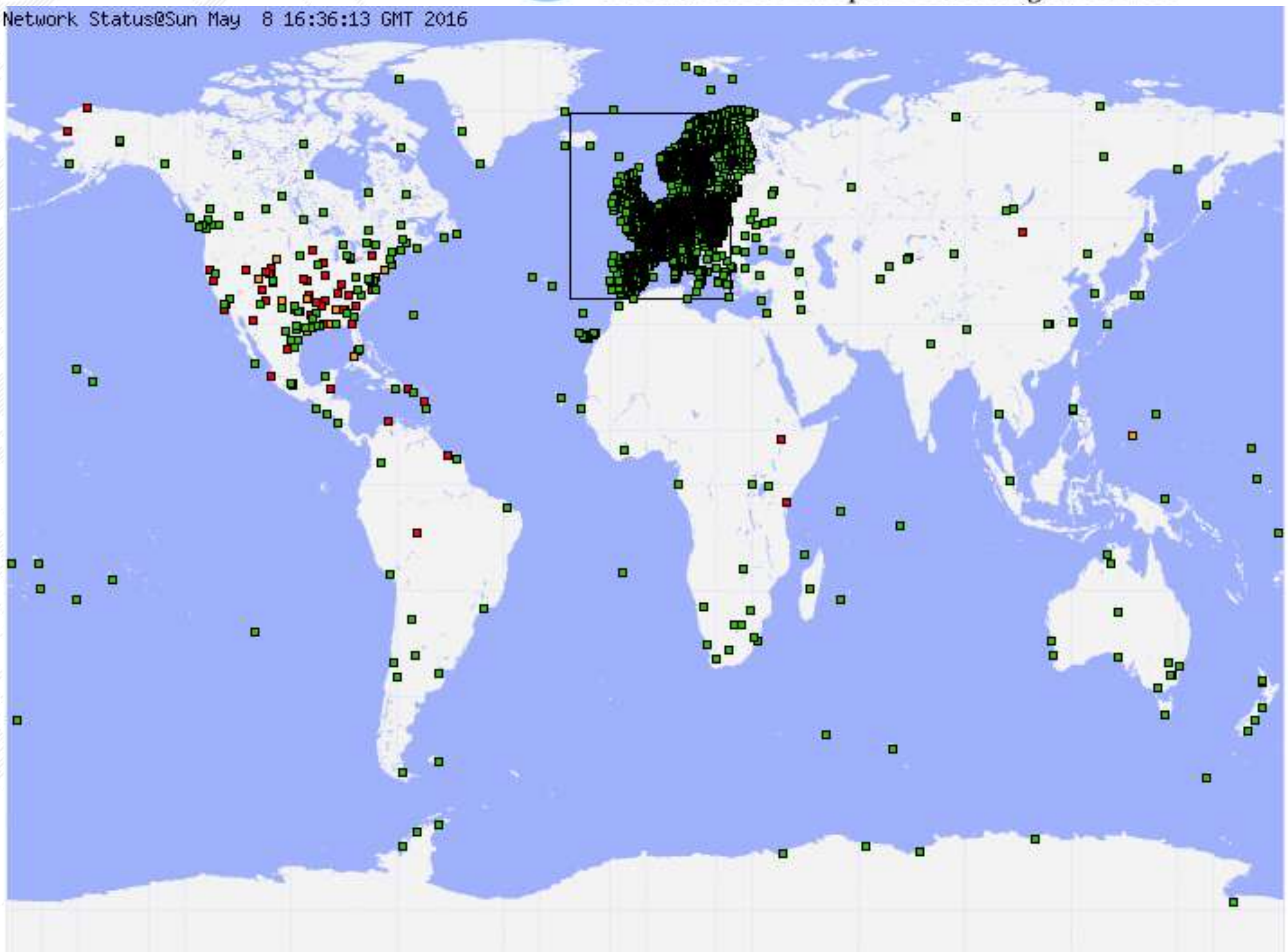
```
 ZTD    mZTD    ZWD    IWV     P      T     RH  ZTD Gradients  Grad. Errors   TEC
2345.4   1.5   -9.9   -9.9   -9.9   -9.9   -9.9 999.99 999.99 -9.99   -9.99 -9.999
```

E-GVAP The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk)

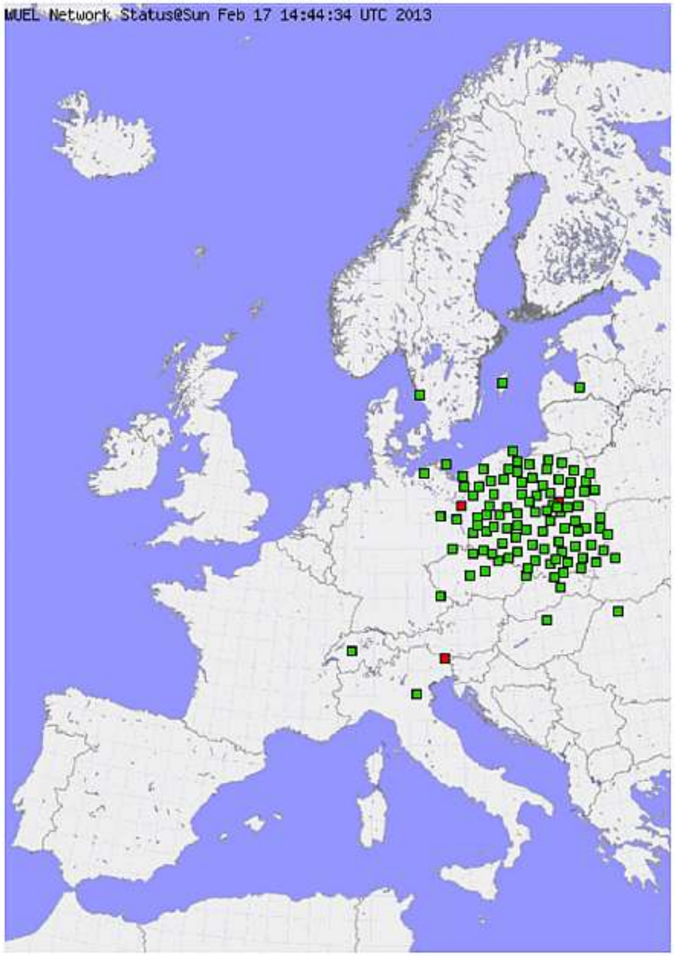


E-GVAP The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk)

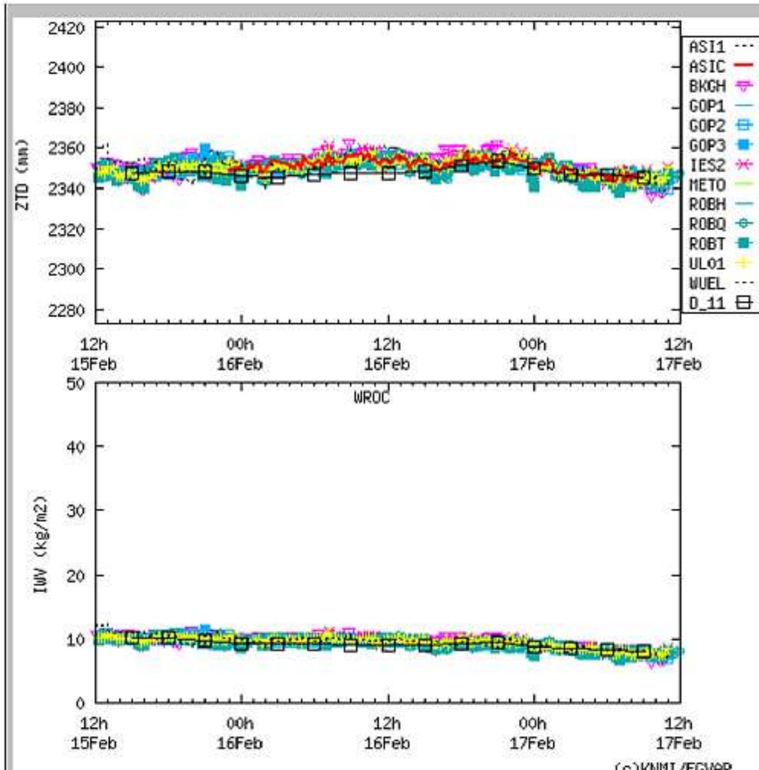
EUMETNET
The Network of European Meteorological Services



E-GVAP „WUEL” - The WUELS contribution



http://egvap.dmi.dk



HIRLAM(KNMI) AN - GPS ZTD
7day stat. 2013/02/09 - 2013/02/17

AC	num	bias	RMS	stddev
ASIC	56	2.0	3.9	3.3
GOP1	56	2.5	3.9	3.0
METO	56	2.6	4.4	3.5
ROBH	56	1.9	4.3	3.9
TEST				
ASI1	56	3.0	4.8	3.8
BKGH	55	5.7	6.6	3.5
GOP2	56	1.9	3.5	3.0
GOP3	55	3.1	4.8	3.7
IES2	56	2.6	4.4	3.5
ROBQ	56	2.0	4.6	4.1
ROBT	56	1.7	4.6	4.3
UL01	56	2.2	4.0	3.4
WUEL	56	4.3	5.7	3.7

Notes

- Statistics are updated daily
- GPS ZTD are interpolated to NWP analysis time

Graphical location of the site

latitude	51.11330
longitude	17.06200
altitude	140.54

Oct 15th, 2012 to Apr 11 2015 (BSW 5.0)

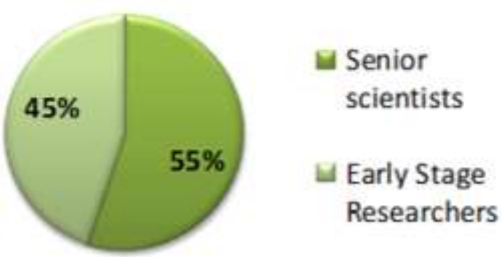
COST Action ES1206 - **GNSS4SWEC - Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate** *(http://gnss4swec.knmi.nl)*

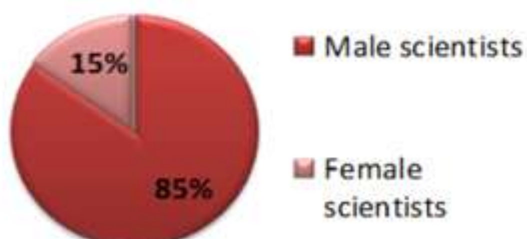
23 COST Countries

55 Participants

25 ESRs (45%)

8 Female Scientists (15%)





Met Office

COST Action ES1206 - **GNSS4SWEC - Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate** *(http://gnss4swec.knmi.nl)*

Action Chair: Jonathan Jones (esr)
Action co-chair: Guergana Guerova (f)

WG1 - Advanced GNSS Processing Techniques

Chair: Jan Dousa
Co-chair: Galina Dick (f)

WG2 - GNSS for Severe Weather Monitoring

Chair: Siebren de Haan (esr)
Co-chair: Eric Pottiaux (esr)

WG3 - GNSS for Climate Monitoring

Chair: Olivier Bock
Co-chair: Rosa Pacione (f)

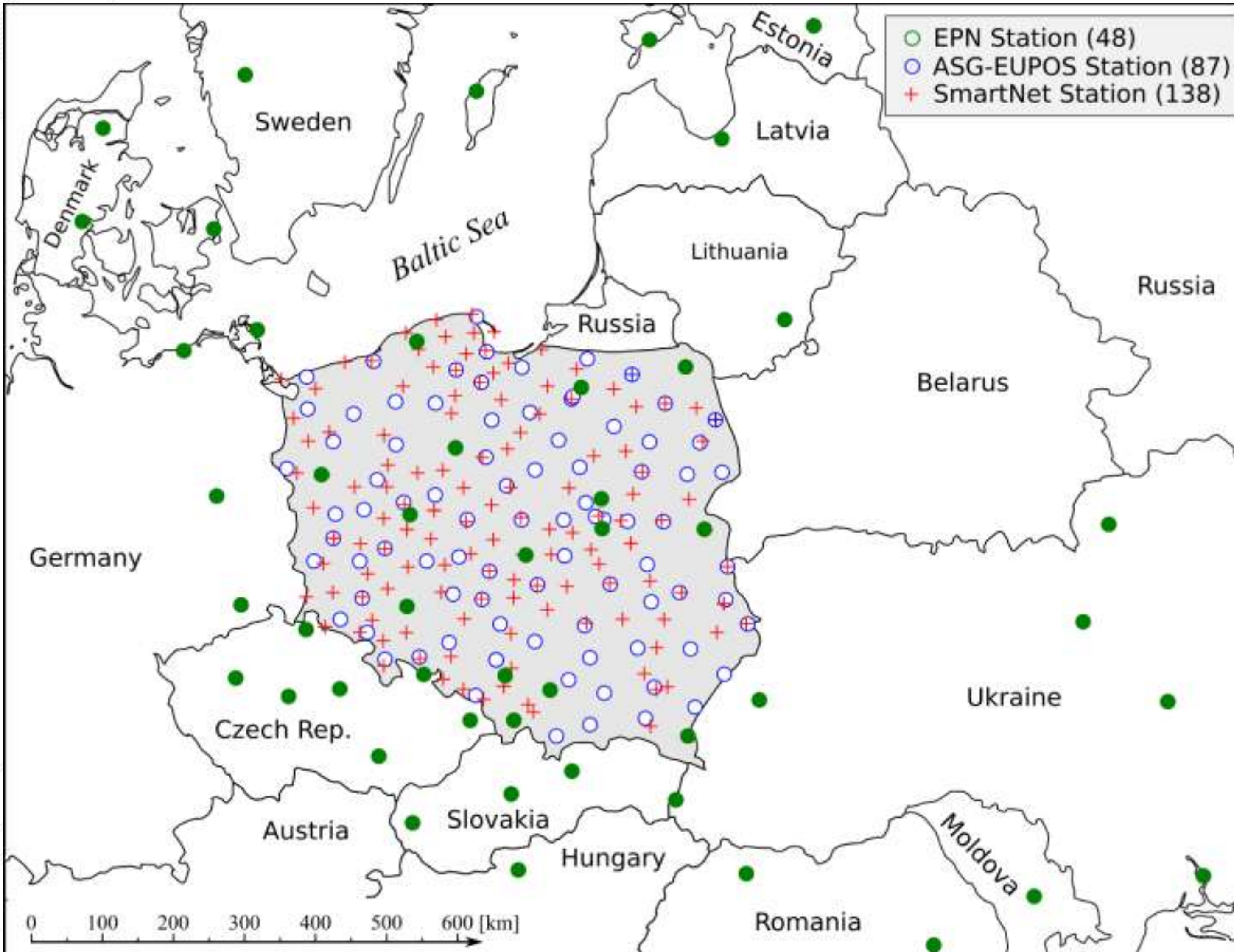
NRT DD processing details

Parameter	Value
Processing type	Post-processing (Double-differenced)
Satellite system considered	GPS only
Observation window	6 hours
Observation cut-off angle	5^o
Baseline forming strategy	OBS-MAX
Ambiguity resolution strategy	Baseline length dependent: a) < 20km: SIGMA on L1 and L2, b) 20km to 180km: SIGMA L5/L3 (wide-lane/narrow-lane), c) > 180km: QIF (quasi iono-free)
Ionosphere handling	Baseline length dependent: a) < 20km: Global model (CODE) for L1L2; b) 20km to 180km: Global model (CODE) for L5 and HOI L3; c) 180km to 1000km: Global model (CODE) + stochastic ionosphere parameters estimation (QIF)
Troposphere handling	**Phase observables screening stage:** a) A priori model DRY GMF, b) Site specific parameters WET GMF (ZTD spacing: 2h; no constraining), **Final solution stage:** a) A priori model: DRY GMF, b) Site specific parameters: WET GMF (ZTD spacing: 30min; no constraining; gradient model: CHENHER *Chen and Herring (1997)*, gradient spacing: 6h) **Product output:** Relative constraining over 1 hour (3mm for ZTD and 0.5 mm for gradients).
Reference frame for epoch solution	IGS and ARGN IGb08 coordinates and velocities
Method of referencing epoch solutions	Minimum constraining on all reference station positions.

NRT PPP processing details

Processing type	Post-processing (Zero-differenced)
Satellite system considered	GPS only
Observation window	12 hours
Observation cut-off angle	5º
Ambiguity resolution strategy	None
Ionosphere handling	Global model (CODE) for HOI L3;
Troposphere handling	**Phase observables screening stage:** a) A priori model DRY GMF, b) Site specific parameters WET GMF (ZTD spacing: 2h; no constraining), **Final solution stage:** a) A priori model: DRY GMF, b) Site specific parameters: WET GMF (ZTD spacing: 30min; no constraining; gradient model: CHENHER *(Chen and Herring (1997), Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data, Journal of Geophysical Research, 102(B9), pp. 20489-20502*) gradient spacing: 1h) **Product output:** Relative constraining over 1 hour (3mm for ZTD and 0.5 mm for gradients).
Reference frame for epoch solution	IGb08 coordinates of satellites
Method of referencing epoch solutions	Free solution

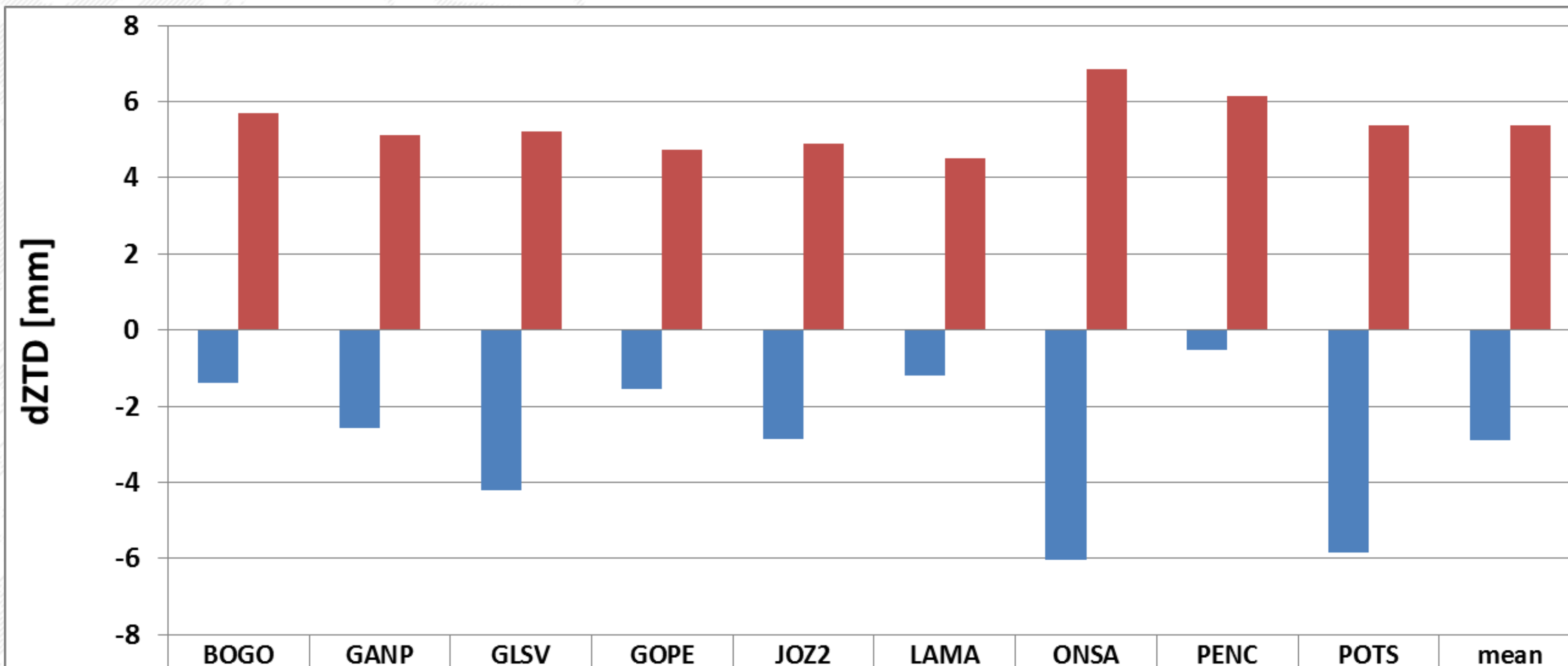
New „WUEL" network (ASG-EUPOS + SmartNet)



Since Aug 26, 2015
12:00 UTC (BSW 5.2)

Quality assesment of new NRT service

Comparison of ZTD estimates with CODE Rapid ZTDs on common IGS stations for the last three weeks of September 2015



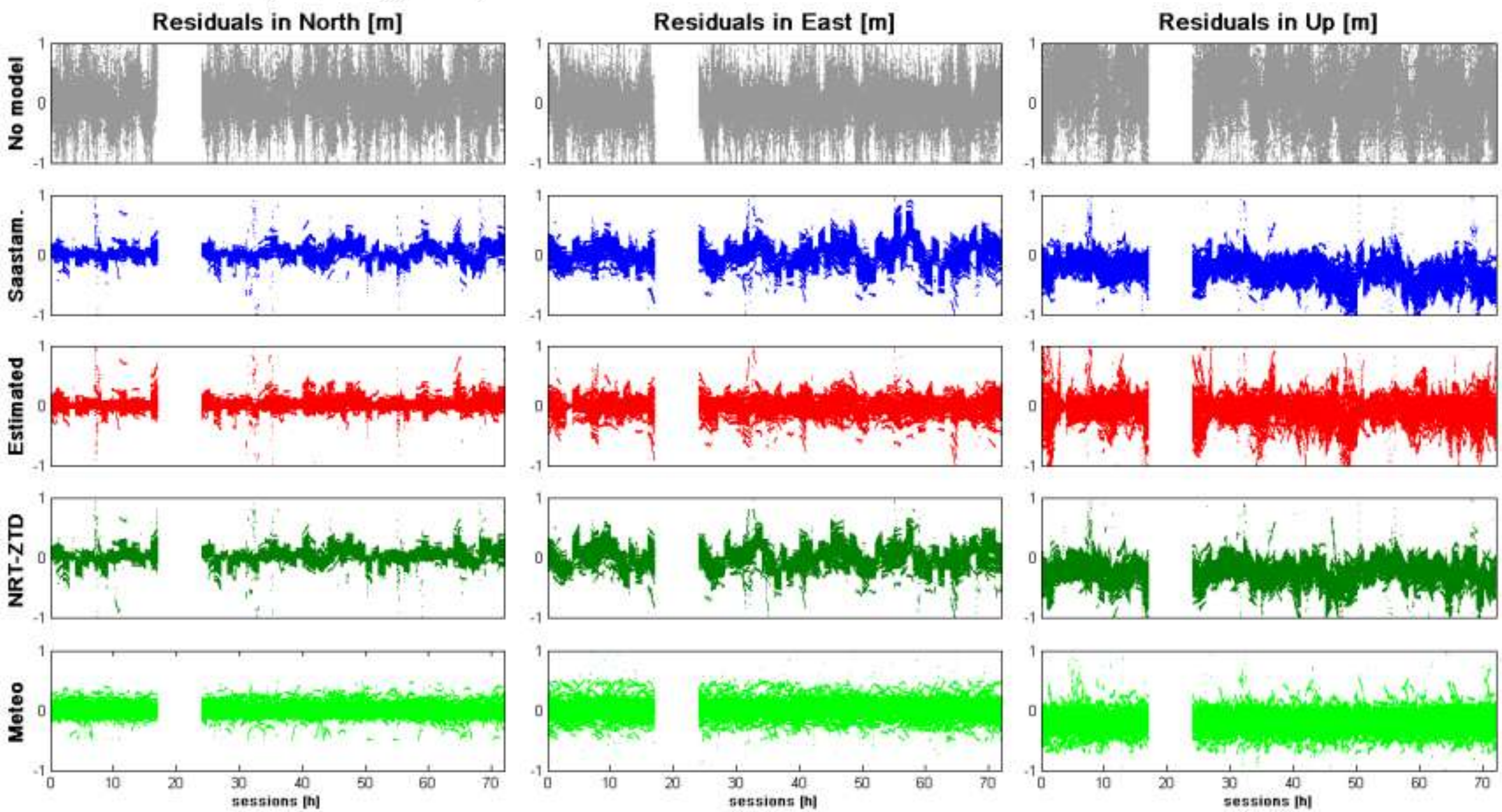
	BOGO	GANP	GLSV	GOPE	JOZ2	LAMA	ONSA	PENC	POTS	mean
bias	-1.39	-2.59	-4.21	-1.55	-2.86	-1.21	-6.03	-0.52	-5.84	-2.91
stdev	5.69	5.11	5.22	4.73	4.89	4.50	6.85	6.14	5.36	5.39

APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO PPP

Bernese GPS Software (postprocessing)

Solution	Model a-priori	Model ZTD	ZTD Est.	Resolution
No model	without	without	no	n/a
Saastamoinen	SA	Saastamoinen	no	30 s.
Estimation	SA	Saastamoinen	yes	30 s.
NRT-ZTD	without	NRT	no	1 h.
Meteo ZTD	meteo	Saastamoinen	no	1 h.

APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO PPP – comparison with IGS results



GNSS-WARP software

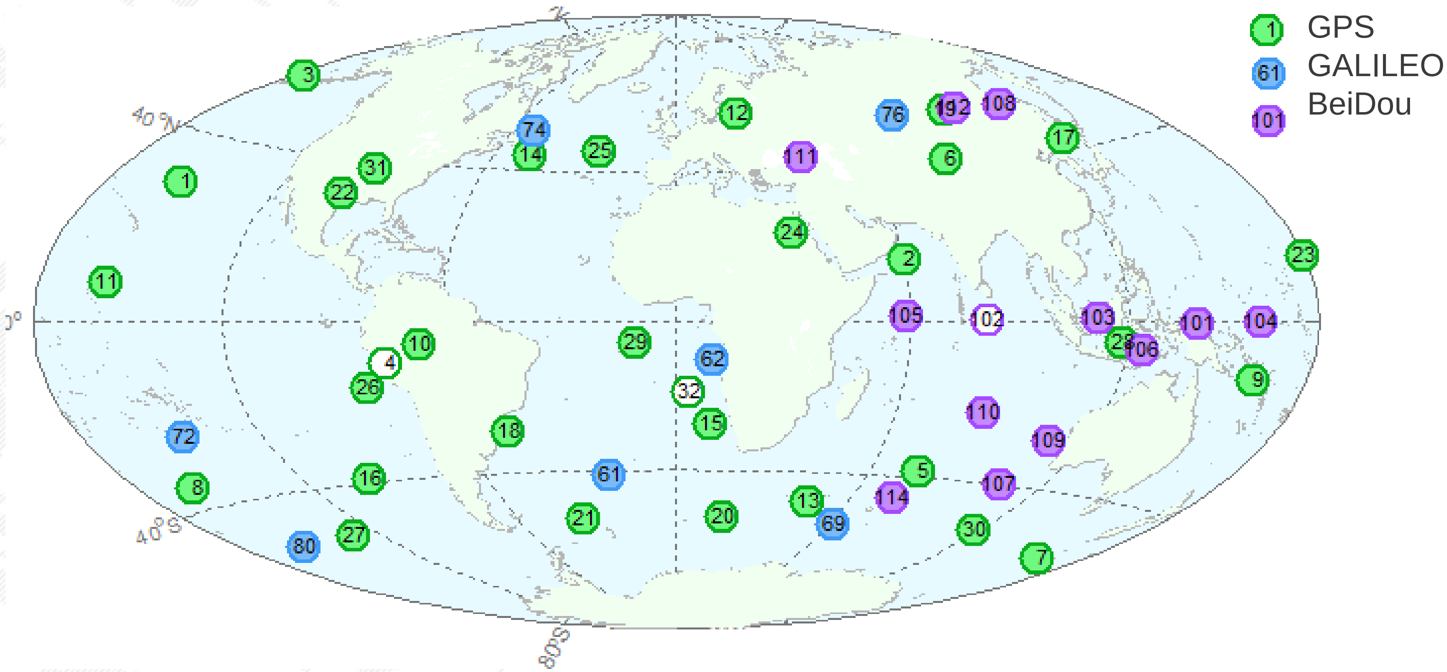
GNSS-WARP
Wroclaw **A**lgorithms for **R**eal-time **P**ositioning

- original, self-developed, state-of-the-art PPP software
- purpose: multi-GNSS RT-PPP & PPP-RTK algorithms development
- GNSS: GPS+GLO, GAL & BDS only with MGEX products, RT
- implemented in Matlab (2015a) + Instrument Control Toolbox
- BNC used as RTCM decoder of IGS RTS streams

RT-ZTD optimization (GNSS-WARP v2.1m):
- redeveloped and optimized for multi-station, continuous processing
- performance: >10stations / 1 second @1CPU
  (currently: >200 stations every 60 seconds)

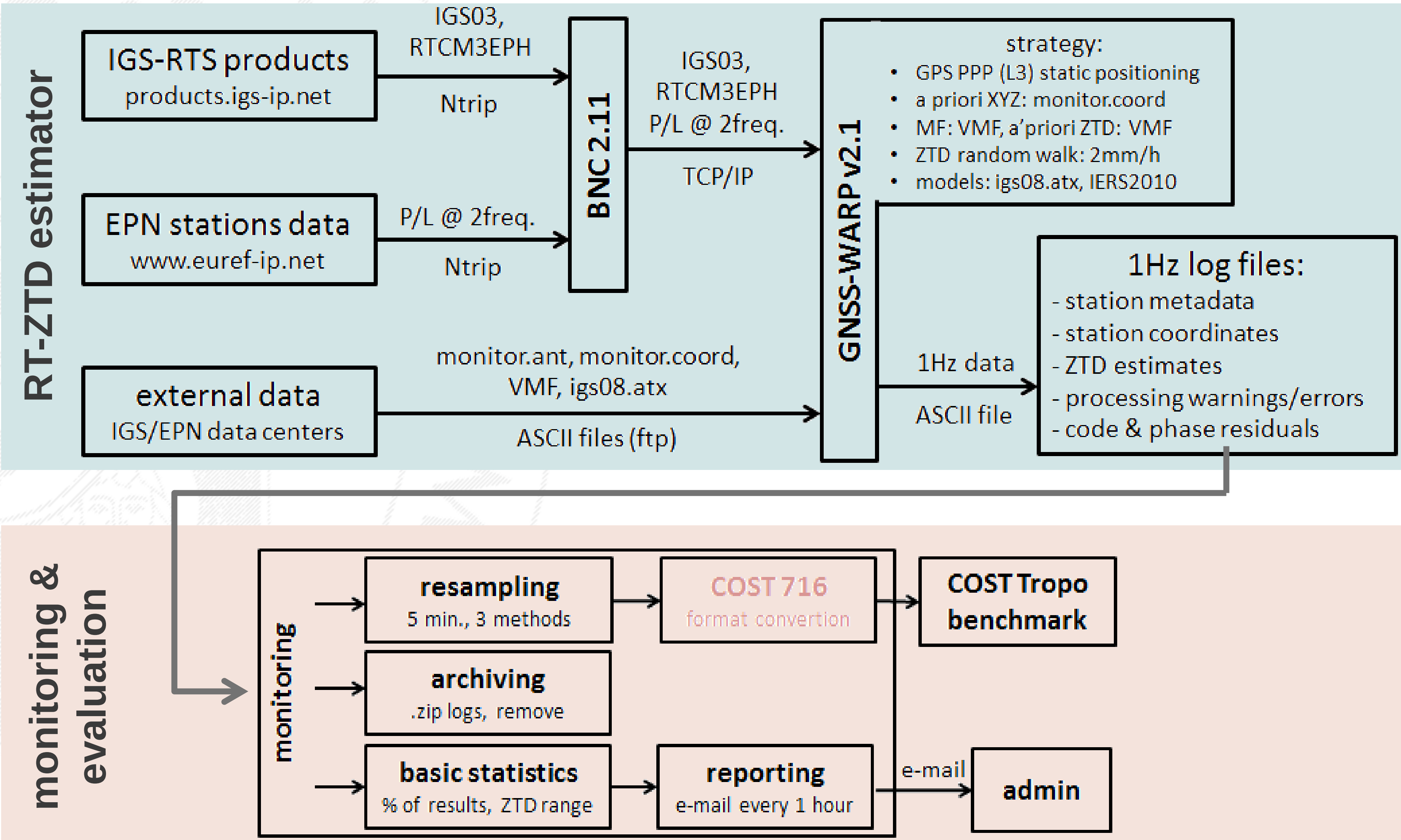
Strategy:
- PPP, static positioning, VMF, IGS03, IERS 2010 models

GNSS-WARP status

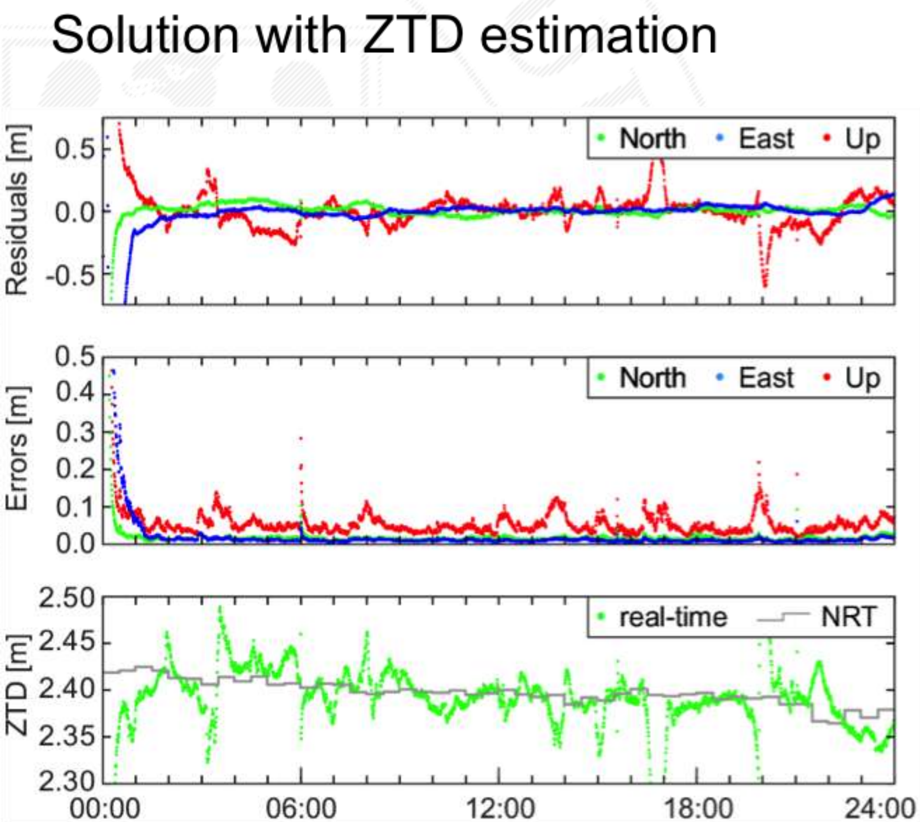


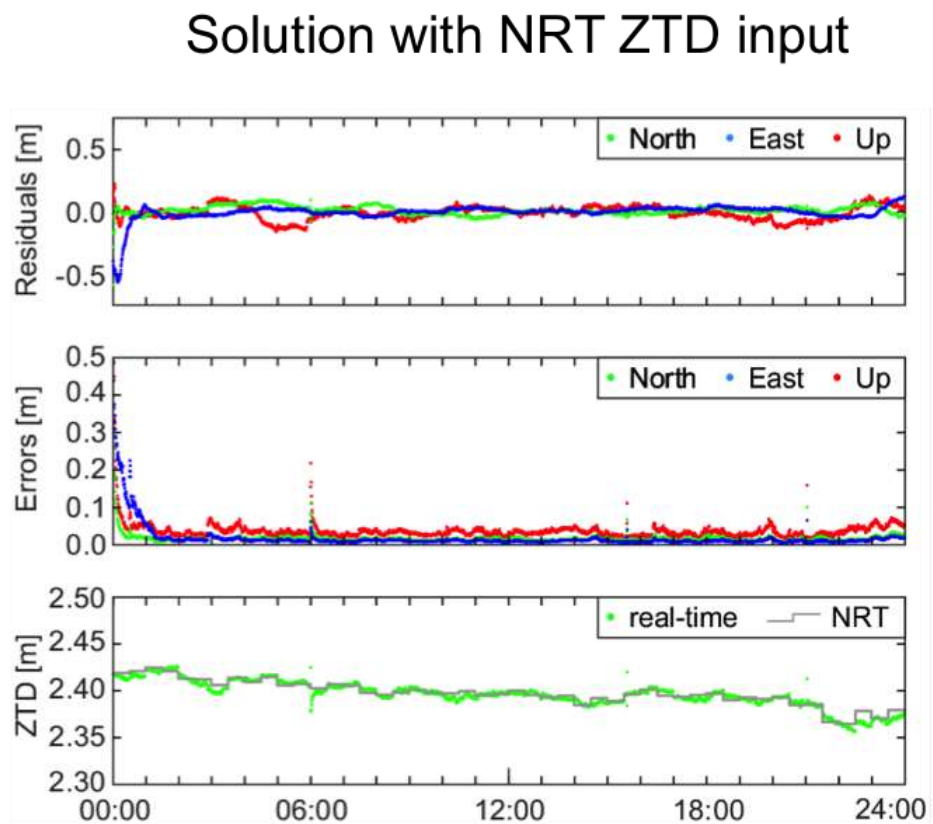
	GPS	GLONASS	Galileo	BeiDou
SP3+CLK	operational	operational	operational	test phase
broadcast	operational	operational	operational	tracked
real-time	operational	IOD problems	test phase	not available

GNSS-WARP software – real-time troposphere service

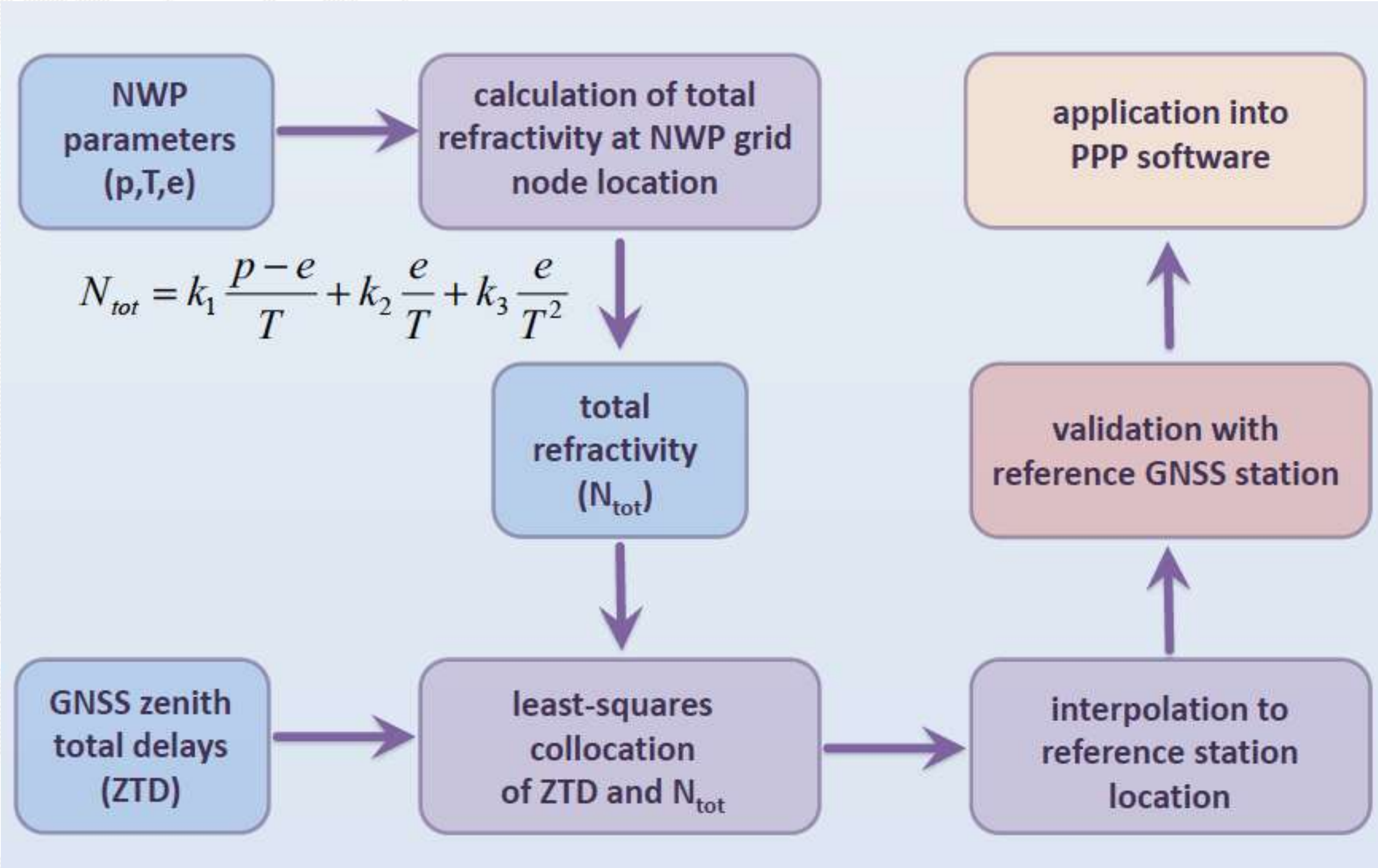


APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO RT PPP



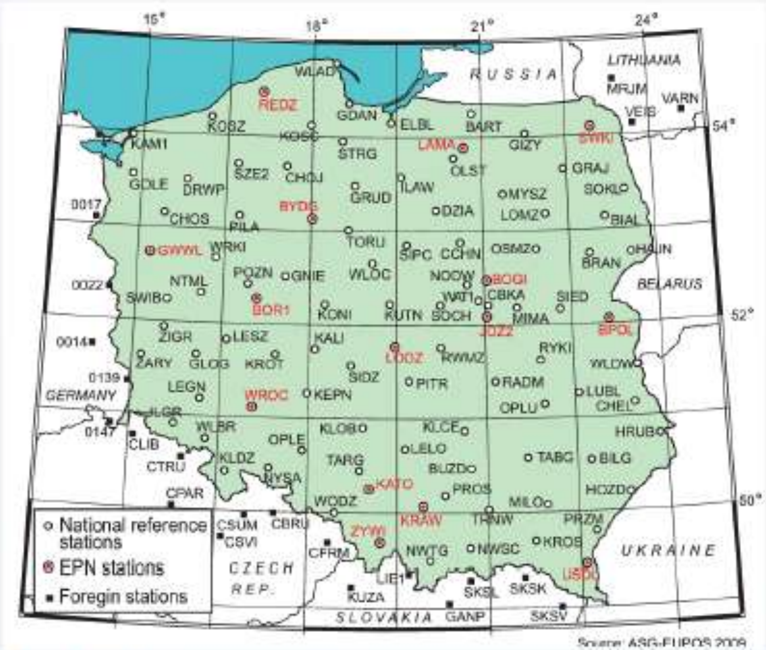


APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP - Methodology



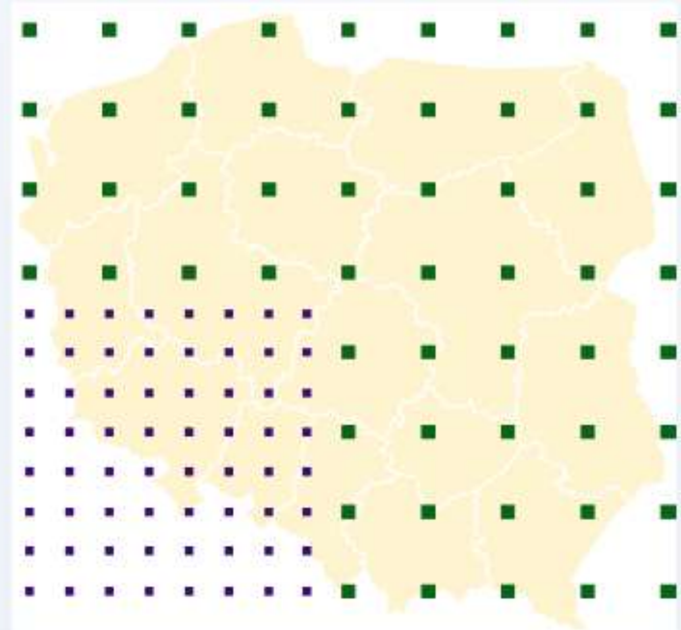
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP - Data

GNSS



- 277 Polish stations
- near-real time
- ZTD with 1 h resolution
- product of Bernese software v5.2
- post-processing
- double-differenced

NWP WRF



- WRF – Weather Research and Forecasting
- 219x237 horizontal nodes
- 4x4 km² grid
- 47 vertical levels
- 24-hour forecasts at 0:00 UTC
- p, T, e with 1 h resolution

APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – Collocation - ZTD results

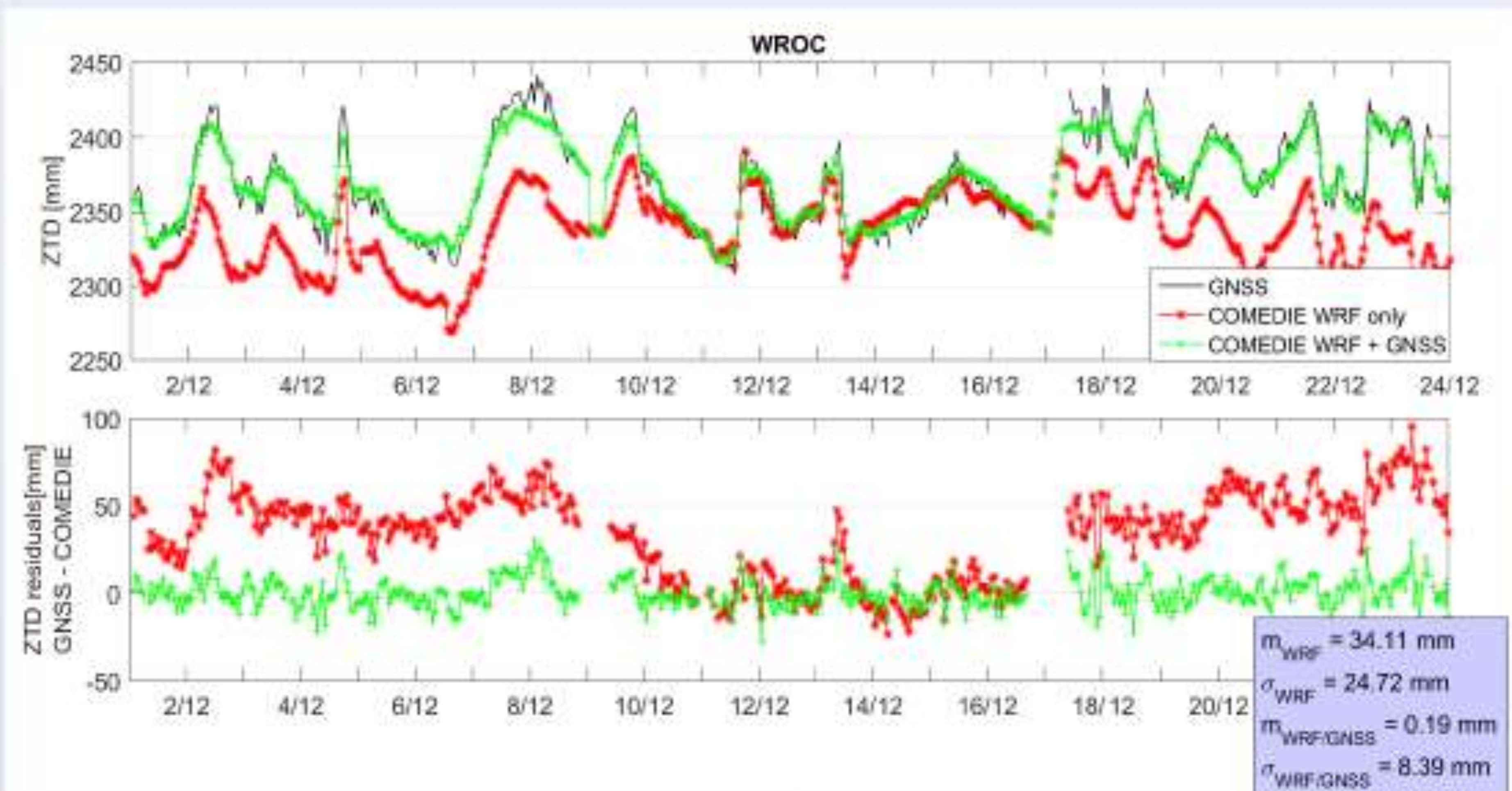


Fig.1. Comparison of COMEDIE models w.r.t. reference GNSS data

APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – troposphere constrainig (1)

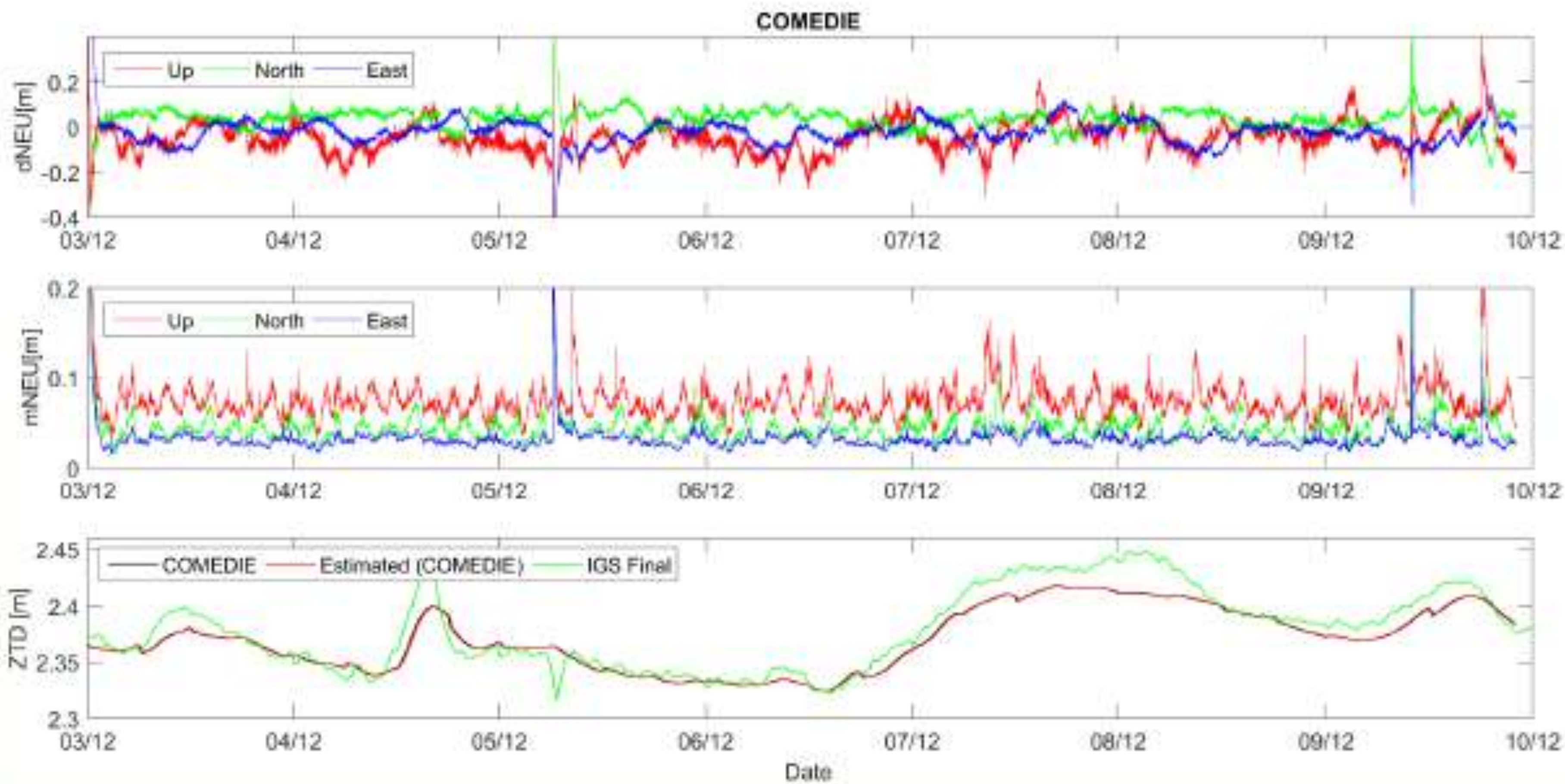


Fig. 3. Results of real-time kinematic PPP with ZTD constrained to COMEDIE model, station WROC, DoY 337-343, 2015

APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – troposphere constrainig (2)

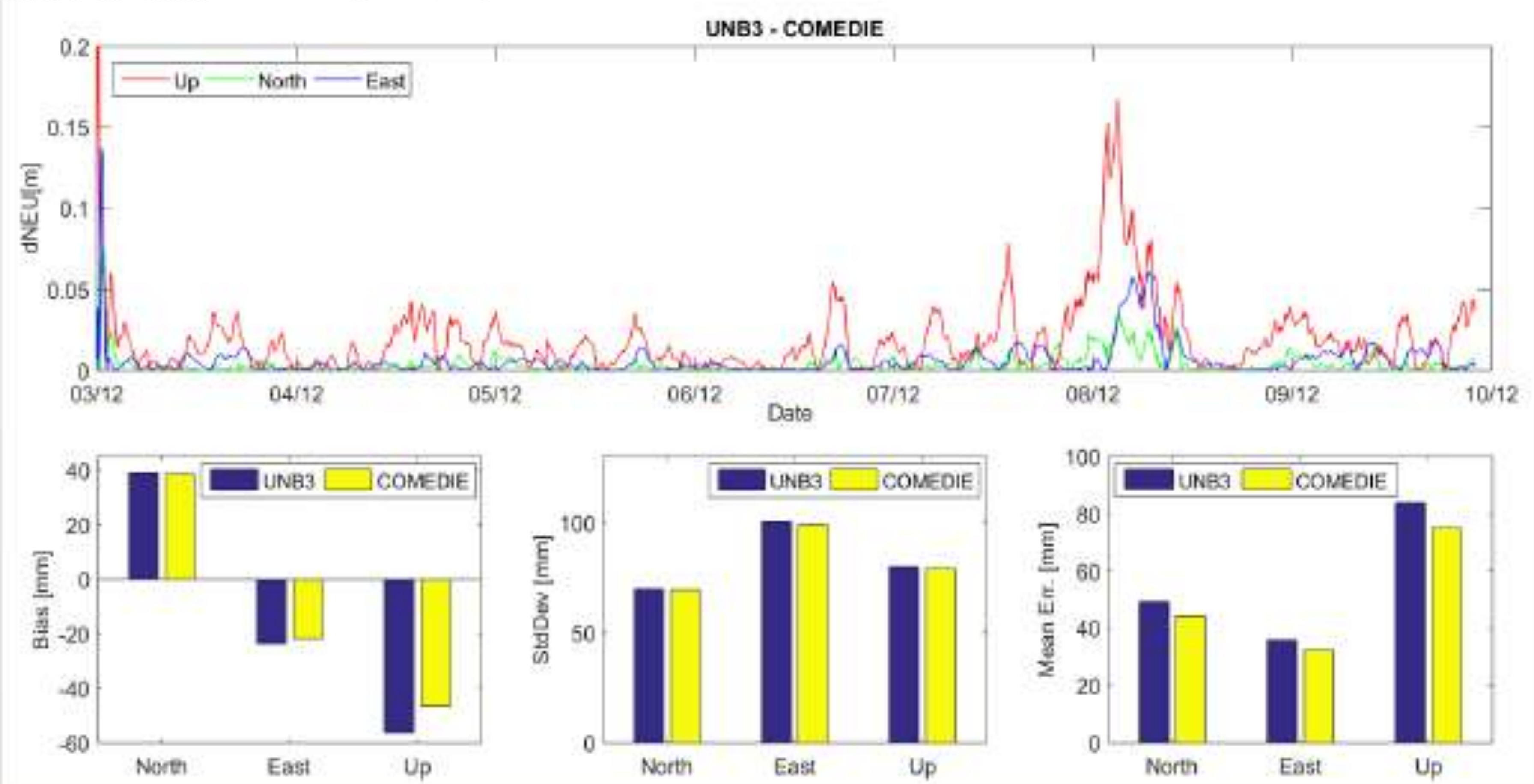


Fig.6. Comparison of unconstrained and COMEDIE-constrained solutions (top - absolute differences in coordinates, bottom - general statistics for solutions w.r.t. static weekly PPP solution)

APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – troposphere constrainig (3)

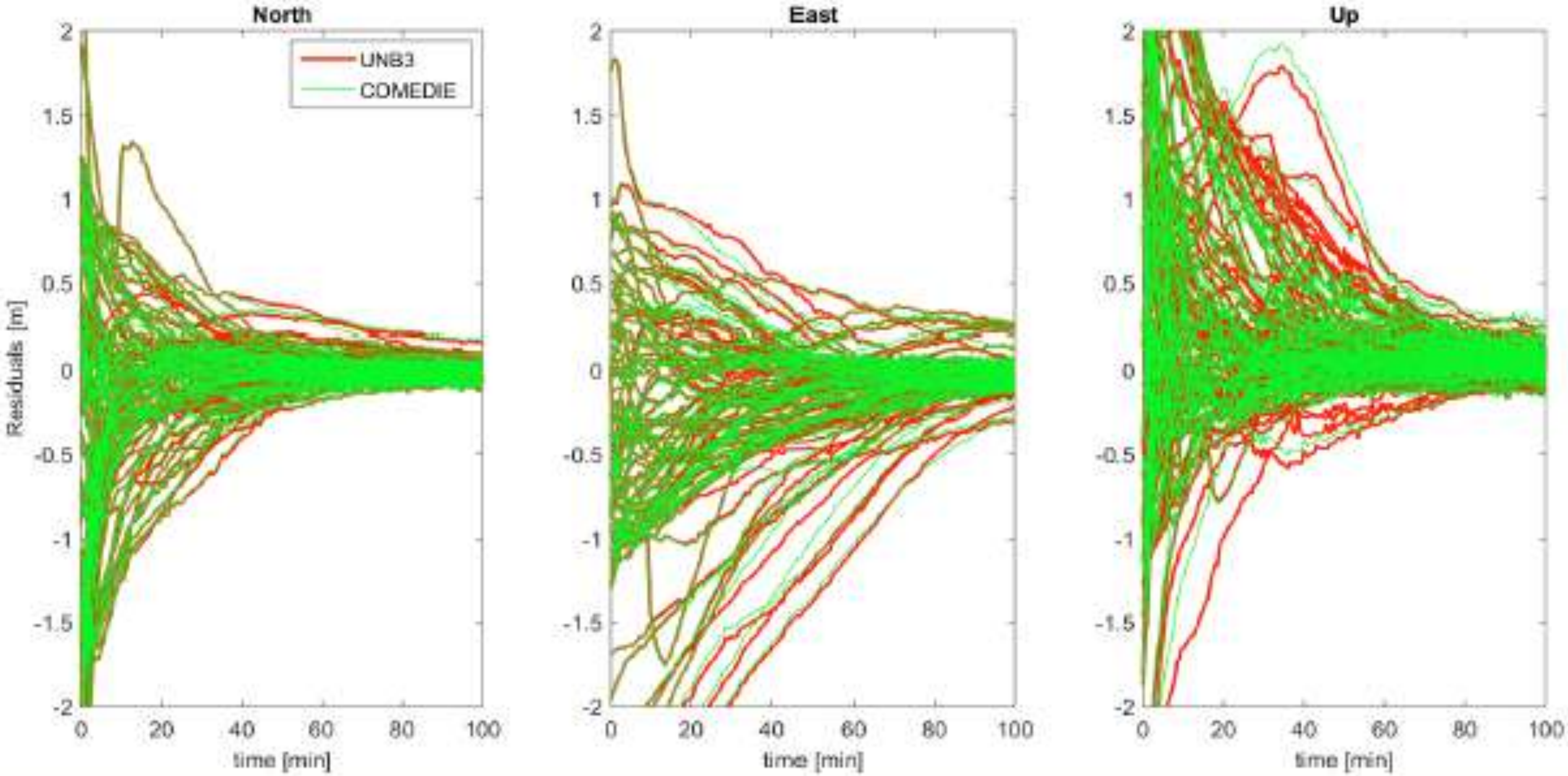


Fig.7. Coordinate residuals w.r.t. static weekly PPP solution from unconstrained (red) and COMEDIE-constrained (green) solutions, imposed re-initialization every 2 hour, 2-hour period overlaid, station WROC, DoY 337-343, 2015

CONCLUSIONS

1. **NRT ZTD future developments:**
   - to reduce the latency to 5 minutes (from 20 minutes)
   - to increase the processing interval to 15 minutes (from 1 hour)
   - to support Multi-GNSS data (currently GPS and GLONASS solution)
   - improvements in PPP solution
   - development of optimal ZTD and gradient constraining strategy to obtain consistency with NWP models
   - NRT estimation of Slant Tropospheric Delays

2. **Real-Time future developments:**
   - continuous processing (without re-initializations)
   - full GNSS constellation
   - ambiguity fixing
   - estimation of Slant Tropospheric Delays
   - Mapping functions development

GNSS&Meteo WUELS working group

Prof. Jarosław Bosy
Chair of WG
Vice-Chair of IAG Sub-Commission 4.3:
Atmosphere Remote Sensing

Dr. Witold Rohm
Chair of Meteo section
Chair of IAG WG 4.3.6
Troposphere Tomography

GNSS meteorology

Positioning

SLR&GNSS

Pawel Hordyniec
PhD student
ROWUELS software

Dr. Jan Kaplon
GNSS and Meteo
NRT services

Dr. Tomasz Hadas
GNSS-WARP software
Chair of IAG WG 4.3.4
Ionosphere and Troposphere
Impact on GNSS Positioning

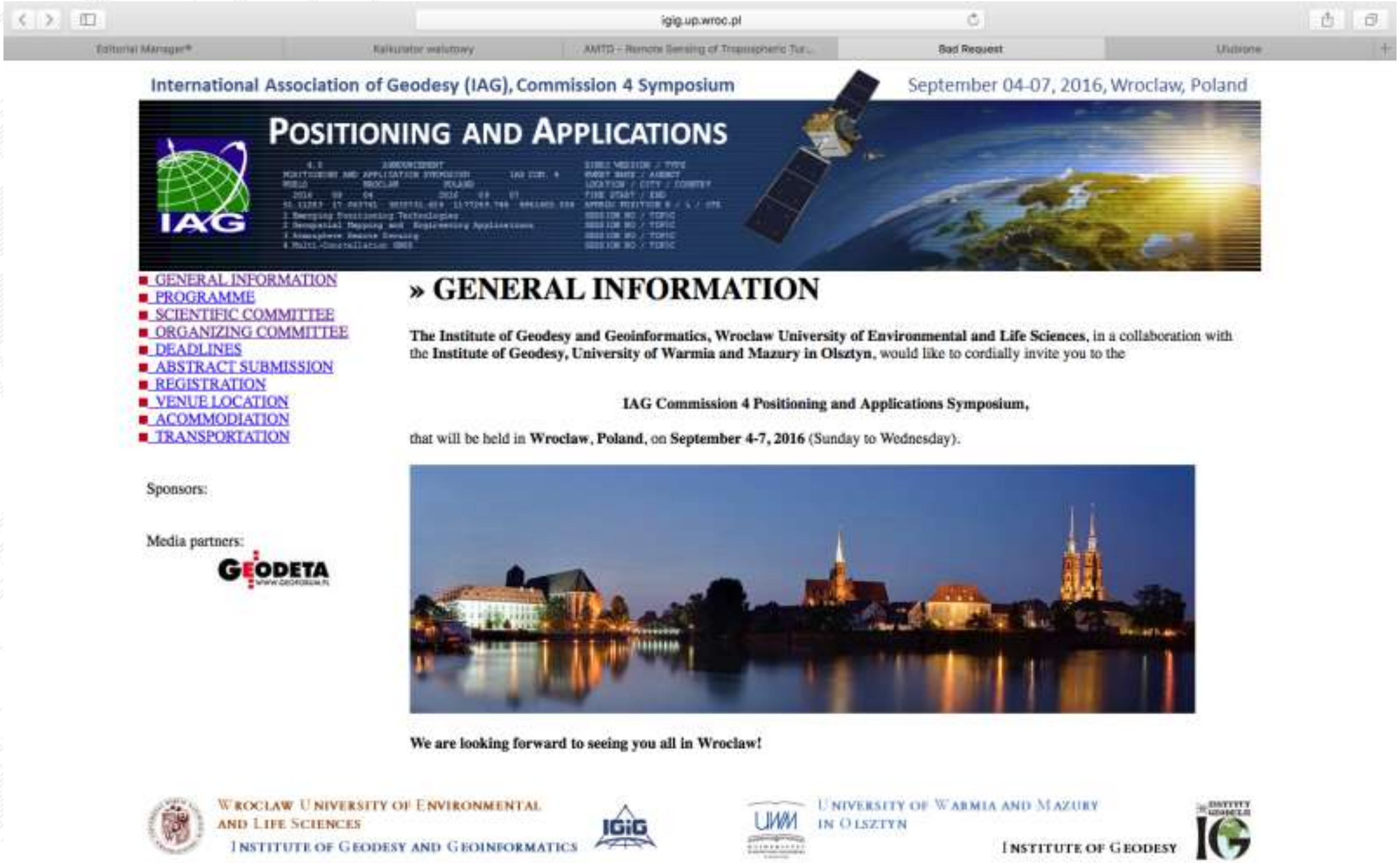
Dr. Krzysztof Sosnica
Chair of IAG JSG0.21:
Fusion of multi-technique
satellite geodetic data

Karina Wilgan
PhD student
GNSS and meteo integration

Jan Sierny
PhD student and IT support
GNSS and meteo data base

Kamil Kaźmierski
PhD student
Multi-GNSS

IAG Commission 4 Positioning and Applications Symposium Wroclaw Poland, September 4-7, 2016



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Wrocław University of Environmental and Life Sciences

Thank You!

jaroslaw.bosy@up.wroc.pl

Presenting author:
Professor Jaroslaw Bosy
Institute of Geodesy and Geoinformatics
Wroclaw University of Environmental and Life Sciences

Coresponding authors:

- meteo: witold.rohm@up.wroc.pl
- real-time: tomasz.hadas@up.wroc.pl
- near real-time: jan.kaplon@up.wroc.pl
- multi-GNSS: kamil.kazmierski@up.wroc.pl

www.up.wroc.pl