Wrocław University of Environmental and Life Sciences

GNSS Meteorology – from near real time to real time troposphere delay estimation

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

International GNSS Seminar, May 13 2016, China University of Geosciences, Beijing, China

Presentation plan

1. Introduction
2. Motivation
3. Near Real Time service
4. Real Time service
5. Conclusion

Wrocław

WROCŁAW

is a dynamically functioning city with over **300 years of academic tradition**, 650 thousand residents, educating **130 thousand students**.

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

10 000
undergraduate and graduate students

227
PhD students

1 700
staff members

Faculties

Three university faculties have the status of **the National Center for Scientific Lead (KNOW)** in the field of agricultural sciences in Poland.

Environmental Engineering and Geodesy

Veterinary Medicine

Life Sciences and Technology

Biology and Animal Science

Food Science

The Faculty of Environmental Engineering and Geodesy

The Faculty of Environmental Engineering and Geodesy

11
laboratories

2
seminar rooms

4
computer rooms

3
workshop rooms

60
staff rooms

Institute of Geodesy and Geoinformatics

Structure of the Institute

Head of the Institute:
prof. Andrzej Borkowski

Department of Satellite Geodesy
GNSS Permanent Station "WROC" (http://www.igig.up.wroc.pl/spgnss)

Department of Geodesy and Geodynamics

Departament of Cartography, Photogrammetry and Geoinformatics
Laboratorium GISLab (http://www.gislab.up.wroc.pl)
Laboratory of Remote Sensing, LiDAR and 3D Modelling

Department of Geodesy Engineering and Land Surveying
Laboratory of Geodetic Technologies

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

Karina Wilgan
PhD student
GNSS and meteo integration

Dr. Jan Kaplon
GNSS and Meteo
NRT services

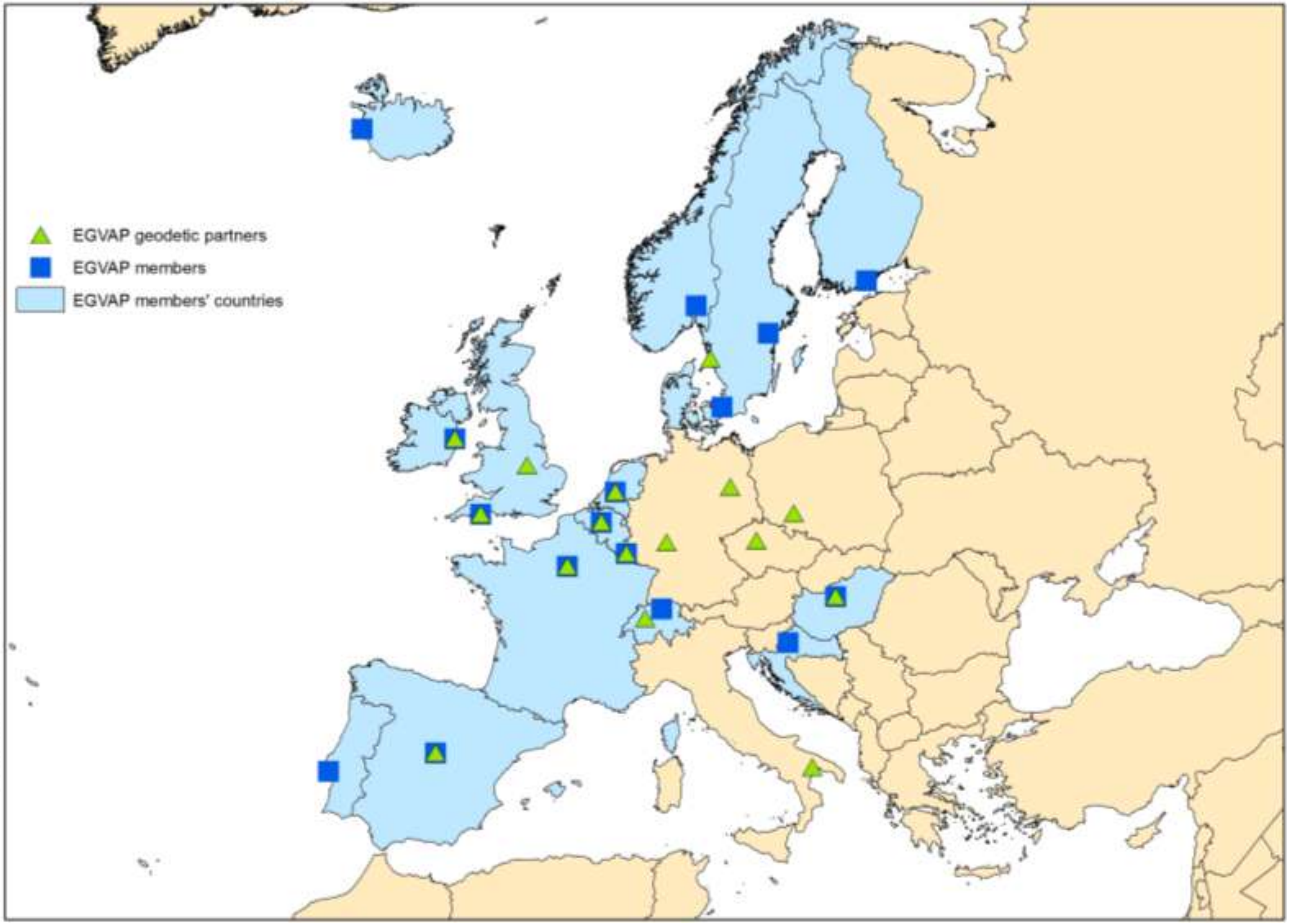
Jan Sierny
PhD student and IT support
GNSS and meteo data base

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

Kamil Kaźmierski
PhD student
Multi-GNSS

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



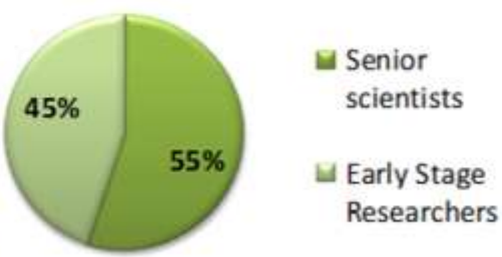
COST Action ES1206 - **GNSS4SWEC - Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate** *(http://gnss4swec.knmi.nl)*

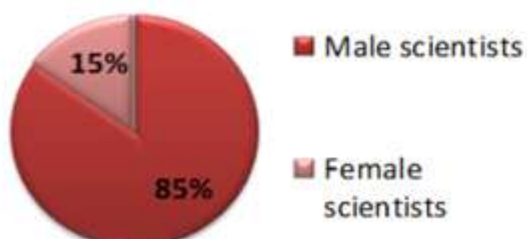
23 COST Countries

55 Participants

25 ESRs (45%)

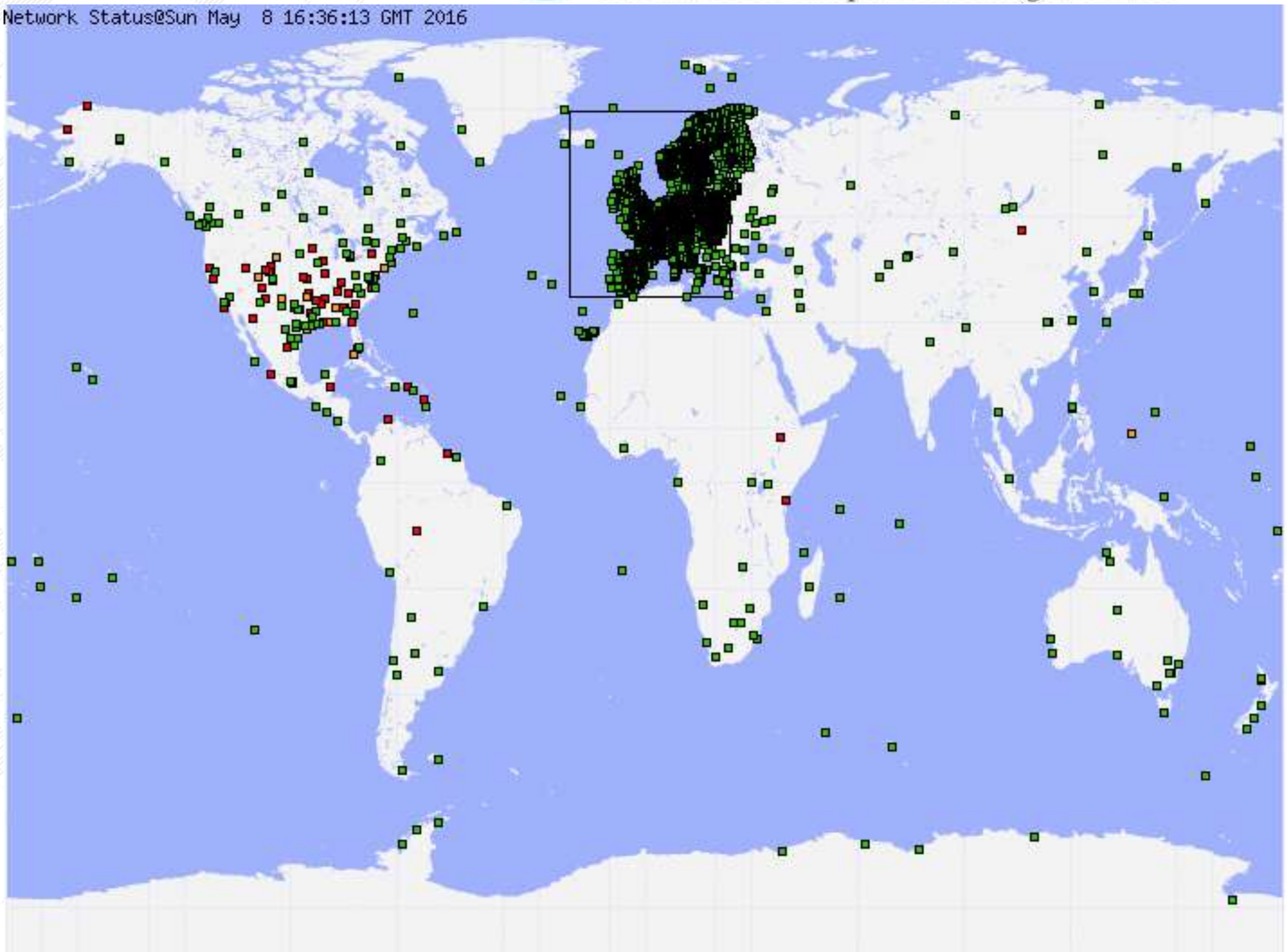
8 Female Scientists (15%)



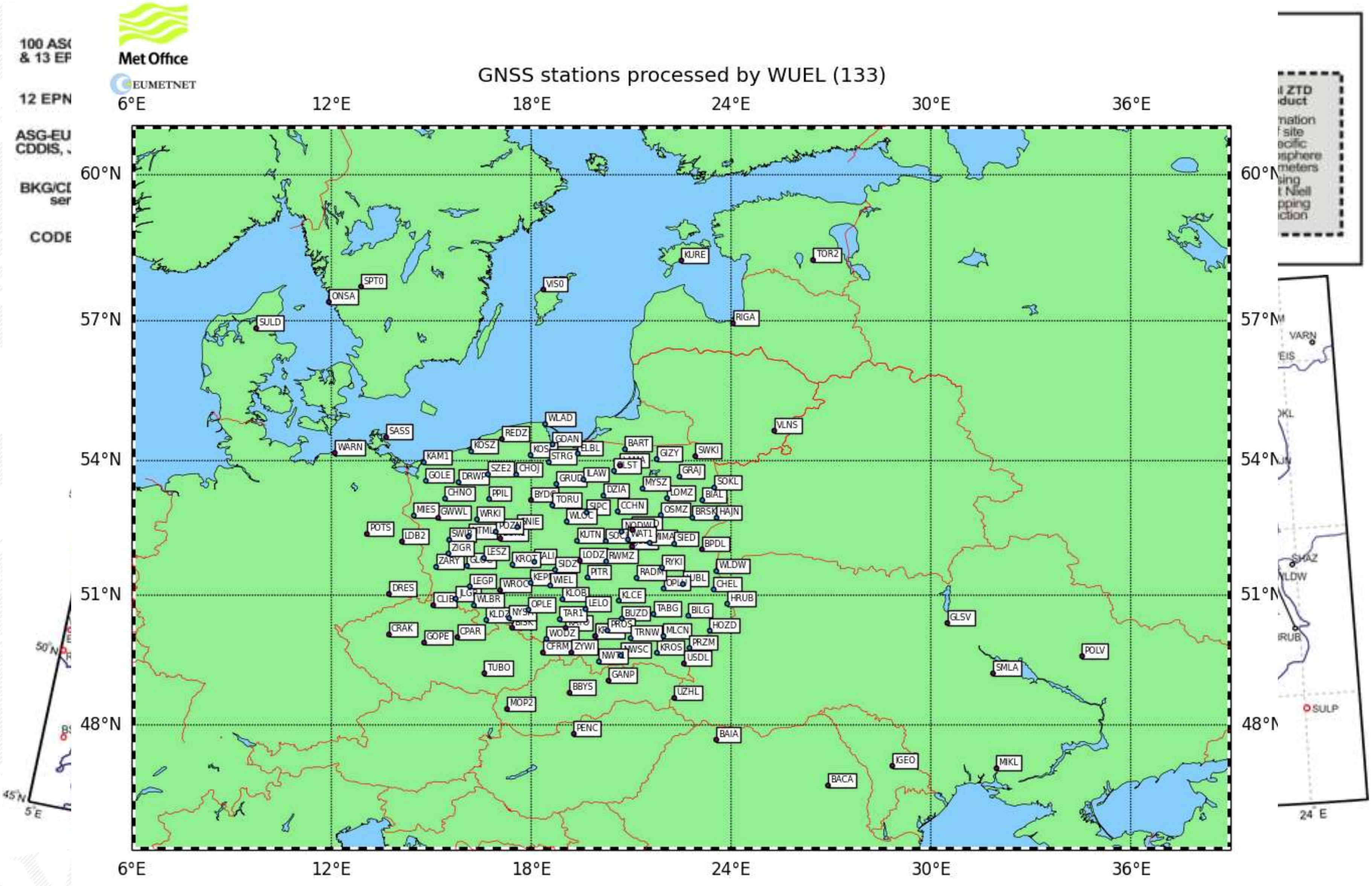


E-GVAP The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk)

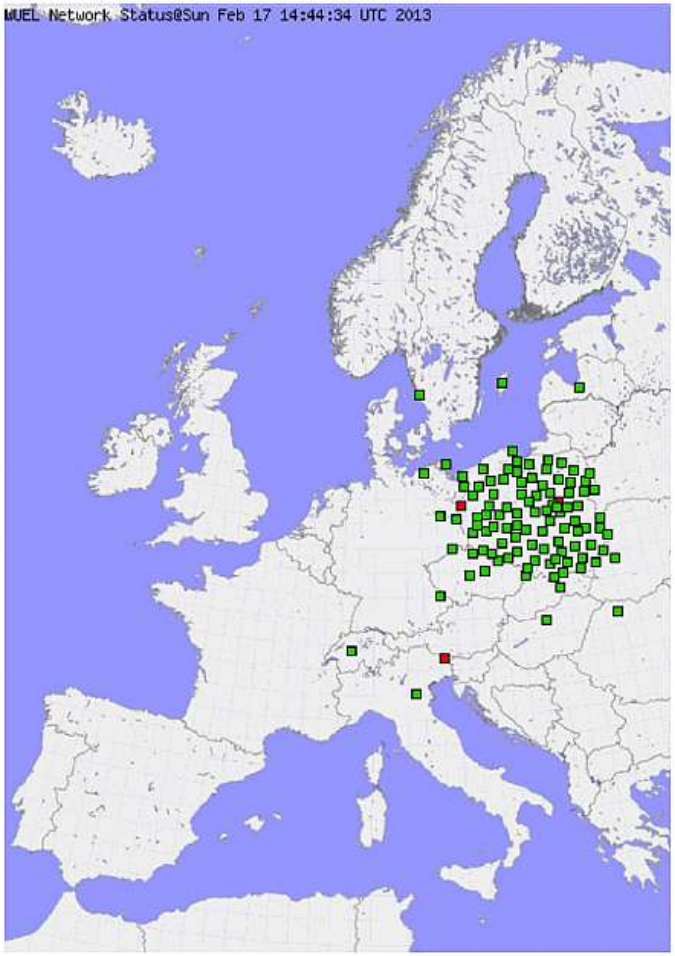
EUMETNET
The Network of European Meteorological Services



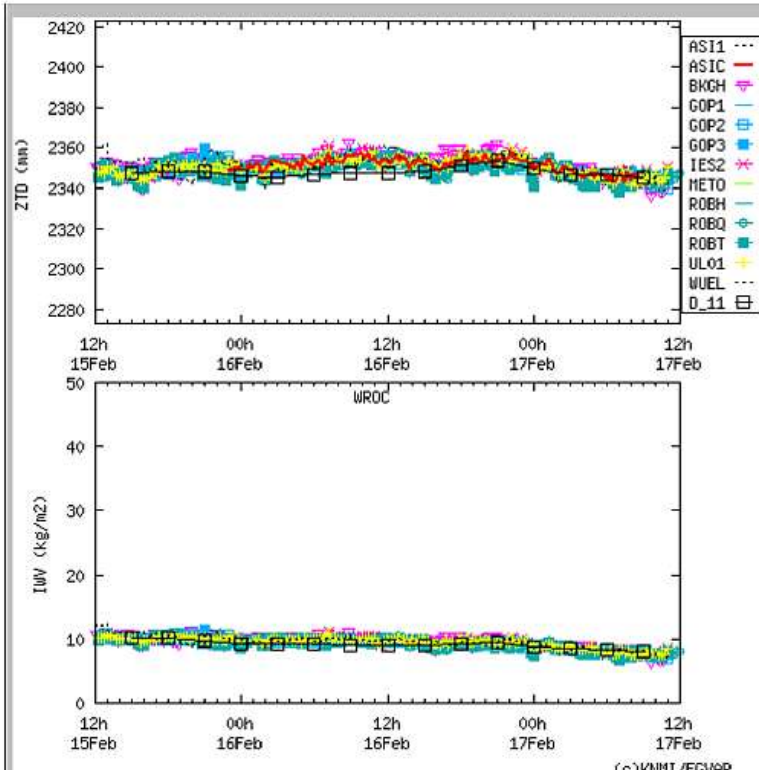
Former Bernese 5.0 estimation service for Poland



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

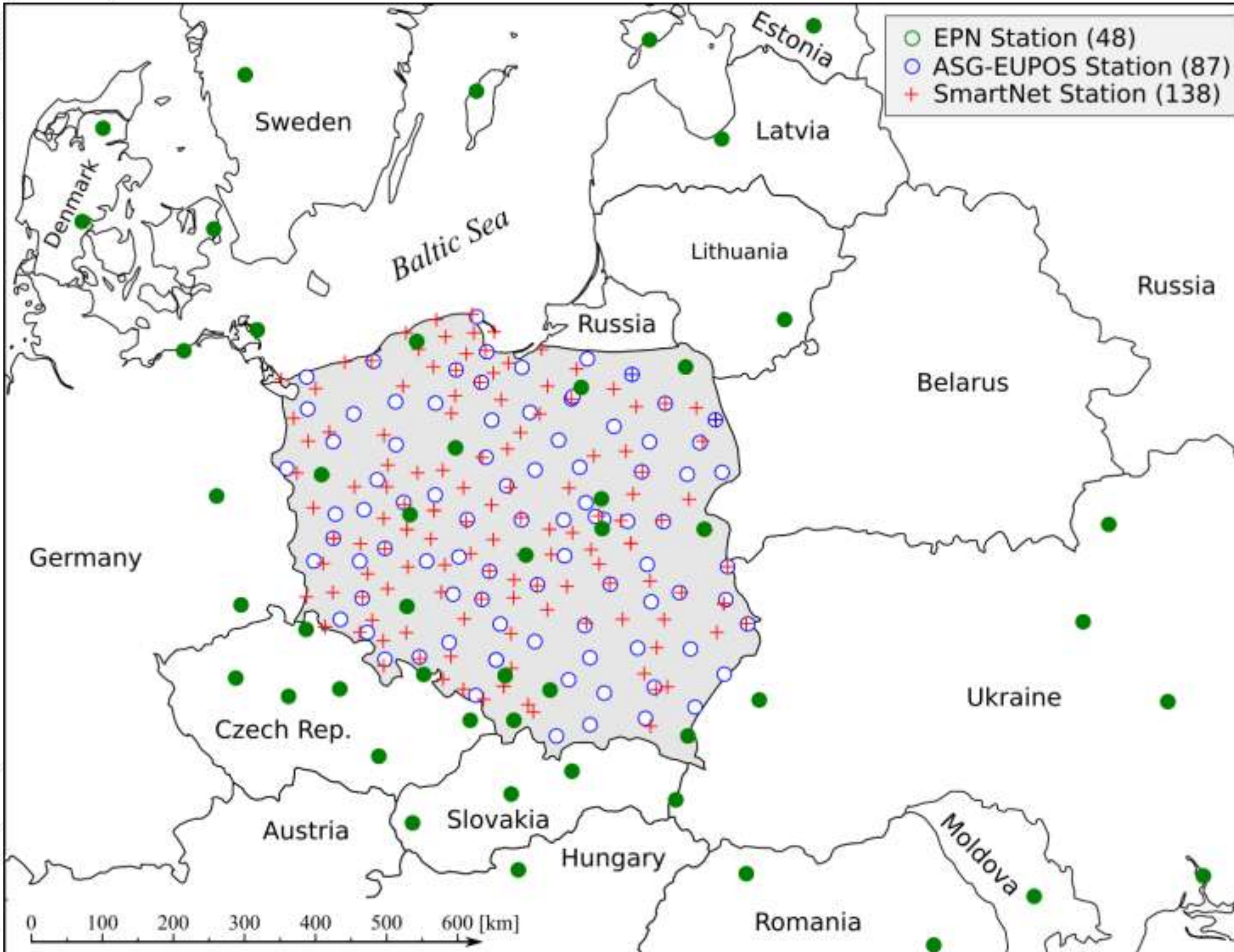
- Statistics are updated daily
- GPS ZTD are interpolated to NWP analysis time

Graphical location of the site

latitude	51.11330
longitude	17.06200
altitude	140.54

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

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



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

Products and models supporting NRT processing

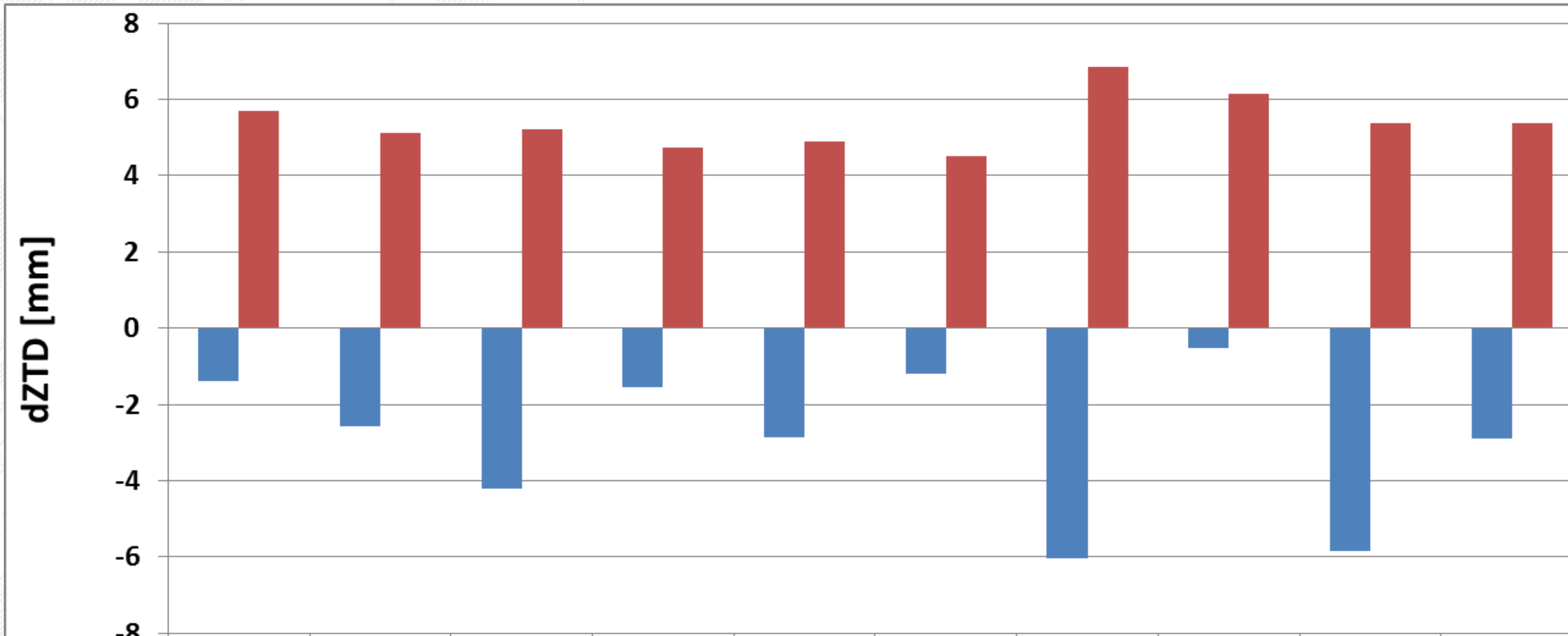
Product/Model	DD Solution
Reference frame	IGb08 (IGb08_R.CRD)
Orbits/ERPs	IGU
Satellite clocks	IGU
DCBs	P1C1 (CODE UR)
Antenna models	igs08.atx (the newest)
Planetary ephemeris	DE405 (JPL)
Nutation model	IAU2000R06.NUT
Sub-daily pole movement	IERS2010XY.SUB
Ocean tide model	OT_FES2004.TID
Frequency dependence of solid Earth tidal potential	TIDE2000.TPO
Atmosphere loading parameters	S1/S2 IERS2010
Ocean loading parameters	FES2004
Satellite health information	SAT_YYYY.CRX
Ionosphere information	~~CODE 2-day prediction (no UR product currently available)~~

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°
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.

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

METHODOLOGY OF SLANT GNSS TROPOSPHERE DELAY ESTIMATION AT WUELS

The Slant Total Delay (STD) caused by refraction in neutral atmosphere may be divided to parts: hydrostatic (dry) and non-hydrostatic (wet). As an effect we obtain Hydrostatic Delay (HD) and Wet Delay (WD):

$$STD = \int (n-1)ds = 10^{-6}\int N_{dry}ds + 10^{-6}\int N_{wet}ds = SHD + SWD$$

where n is a refractivity index and N is refractivity (eg. Essen and Froome 1951)

$$STD(t,a,z) = ZTD_{apr}(t) * mf(z) + dZTD(t) * mf(z) + G_N(t) * \frac{\partial mf}{\partial z} cos(a) + G_E(t) * \frac{\partial mf}{\partial z} sin(a)$$

A priori model — *Estimated ZTD correction* — *Estimated Horizontal ZTD gradients*

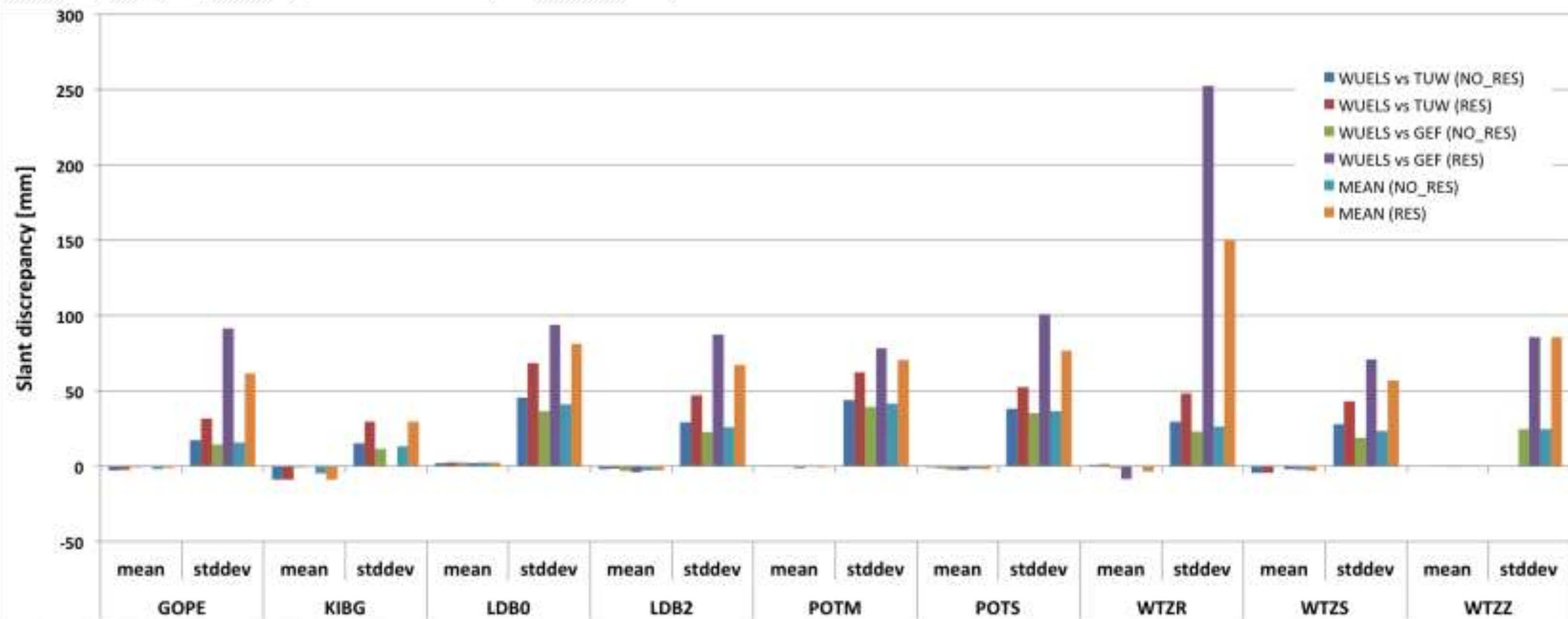
$$STD(t,a,z) = ZHD_{apr}(t) * mf_{Dry}(z) + ZWD_{est}(t) * mf_{Wet}(z) + G_N(t) * \frac{\partial mf}{\partial z} cos(a) + G_E(t) * \frac{\partial mf}{\partial z} sin(a)$$

SLANT GNSS TROPOSPHERE DELAY ESTIMATION AT WUELS

BENCHMARK CAMPAIGN CASE STUDY

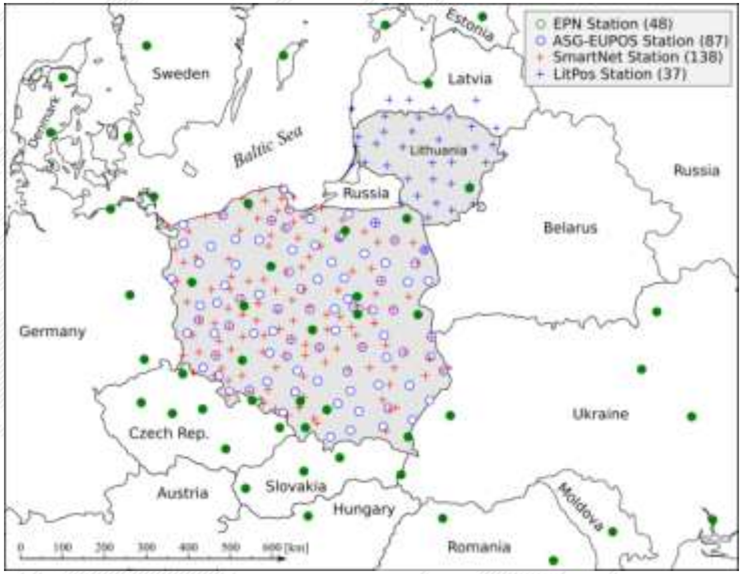
GNSS solutions used in comparison

Solution	Institution	Strategy	Software	GNSS	El. cut-off	Mapping function	Products	ZTD / gradients interval
WUELS	WUELS	PPP	Bernese 5.2	GPS	3 °	VMF1	CODE final	2.5 min/1h
GEF	ESGT	DD	GAMIT 10.6	GPS+GLO	3 °	VMF1	IGS final	2.5 min/1h
TUW	TU Wien	PPP	Napeos	GPS+GLO	3 °	GMF	ESA final	2.5 min/1h



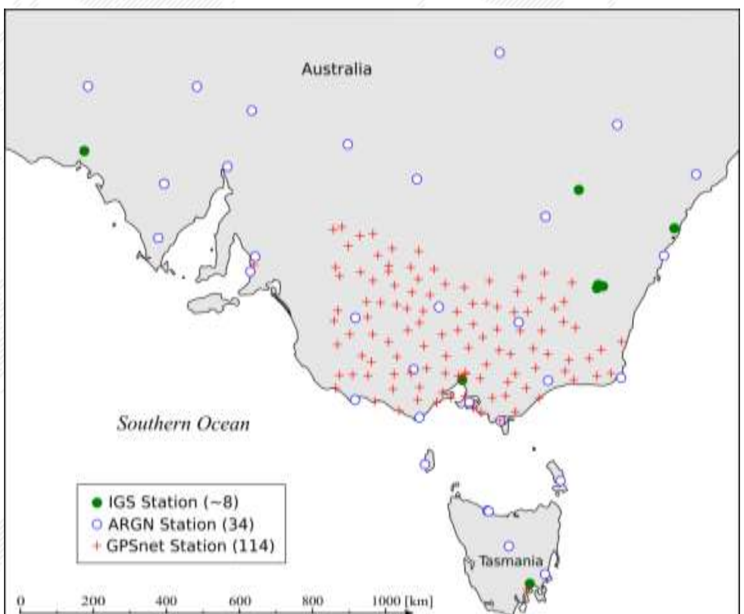
Bias (mean) and standard deviations (stdev) of all calculated slant total delay discrepancies

WUELS networks under processing



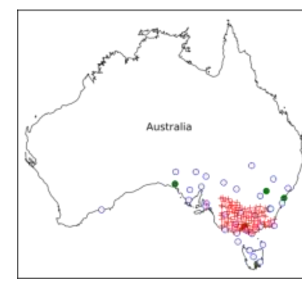
LitPos Network:

- total: 310 stations
- mean dist.: 40 km



VICNET Network:

- total: 156 stations
- mean dist.: 70 km



GNSS troposphere monitoring

PPP estimates: X,Y,Z, dt_{rec}, troposphere zenith delays (**ZTD**) and gradients

Integrated Water Vapour (IWV):

$$ZHD = [0.0022768 m/mbar] \cdot \frac{P_0}{f(\phi, h)}$$

$$f(\phi, h) = 1 - 0.00266 \cos(2\phi) - 0.00000028 h \approx 1$$

$$ZWD = ZTD - ZHD$$

$$IWV = \frac{ZWD}{10^{-6}(k_2' + k_3/T_m)R_v}$$

P_0 - surface air pressure [mbar]

h - point height [m]

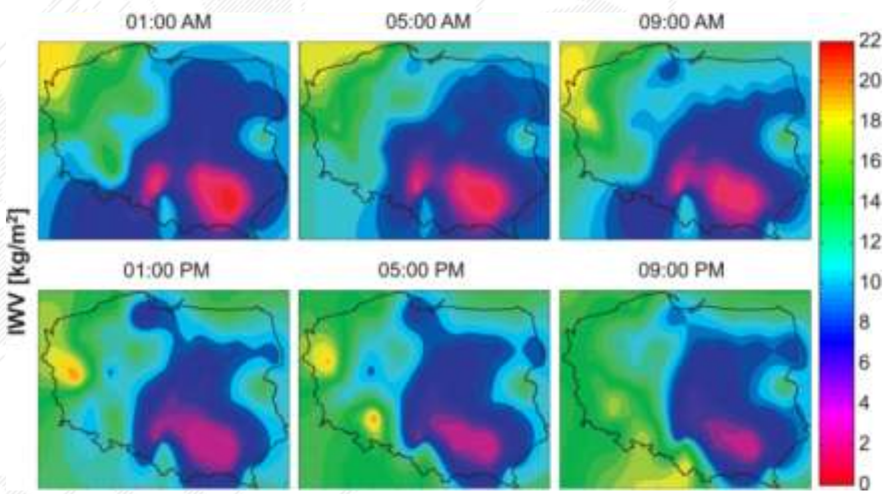
ϕ - point latitude [rad]

k_2', k_3 - empirical coefficients

T_m - $70.7 + 0.72 T_0$

T_0 - surface air temperature

R_v - 461.525 [J/(kg·K)]



Example of the Integrated Water Vapour (IWV) 2D distribution over the area of Poland calculated for November 7, 2012, shown as a time series with 4 hours interval

NWM requirements for tropopshere products

Running projects / actions:

- EIG EUMETNET, GNSS Water Vapour Programme (E-GVAP-II)
- Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)

Hourly ZTD	Treshold	Target	Optimal
Accuracy	15 mm	10 mm	5 mm
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N. America	Global
Horizontal Sampling	200 km	100 km	30 km

Sub-hourly ZTD	Treshold	Target	Optimal
Accuracy	15 mm	10 mm	5 mm
Timeliness	1 h	30 min	15 min
Spatial coverage	Europe	Europe to National	Regional to National
Horizontal Sampling	100 km	50 km	20 km

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

Governmental and Commercial RTK networks in Poland

ASG-EUPOS:

102 in Poland + 23 foreign:

- 125 GPS / 73 GLO / 39 GAL
- permanent service since 2009
- GPS RTN (+GLO regional)

Leica SmartNet:

now: 135 stationsin Poland

- GPS, GLO, GAL, BDS, QZSS
- operational + developments
- GNSS RTN

TPI Net PRO:

136 in Poland

- GPS, GLO, GAL
- operational
- GNSS RTN

Trimble VRS Net:

now: 56 in Poland

- GPS, GLO, GAL, 1 BDS
- under development?
- GNSS RTN

4 commercial RTK/RTN networks (2 still under developments) with > 370 stations

WUELS cooperates with ASG-EUPOS and Leica SmartNet:

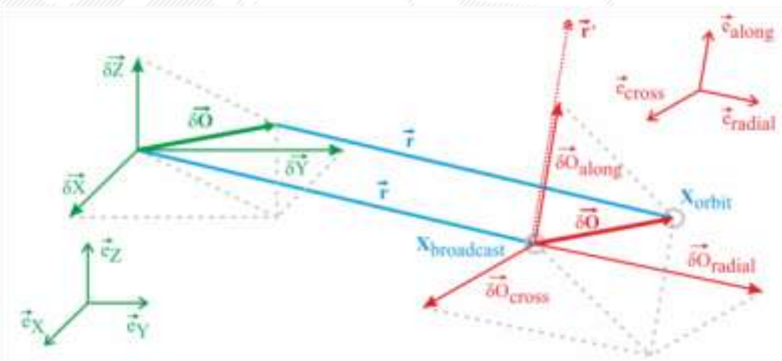
- hourly RINEX files from both network, including foreign stations
- 1Hz data streams from ~100 Leica SmartNet stations
- hopefully soon 1Hz data streams from ASG-EUPOS and +30 from Leica SmartNet

IGS Real-Time Service

IGS INTERNATIONAL GNSS SERVICE

IGS RTS - IGS Real Time Service

- real-time orbit and clock correction (SSR RTCM) + broadcast messages (RCTM)



$$\delta\boldsymbol{O} = \begin{bmatrix}\delta O_{radial}\\ \delta O_{along}\\ \delta O_{cross}\end{bmatrix} + \begin{bmatrix}\delta\dot{O}_{radial}\\ \delta\dot{O}_{along}\\ \delta\dot{O}_{cross}\end{bmatrix}(t-t_0)$$

$$e_{along} = \frac{\dot{r}}{|\dot{r}|} \quad e_{cross} = \frac{r\times\dot{r}}{|r\times\dot{r}|} \quad e_{radial} = e_{along}\times e_{cross}$$

$$\delta\boldsymbol{X} = [e_{radial} \quad e_{along} \quad e_{cross}]\delta\boldsymbol{O}$$

$$\boldsymbol{X} = \boldsymbol{X}_{broadcast} - \delta\boldsymbol{X}$$

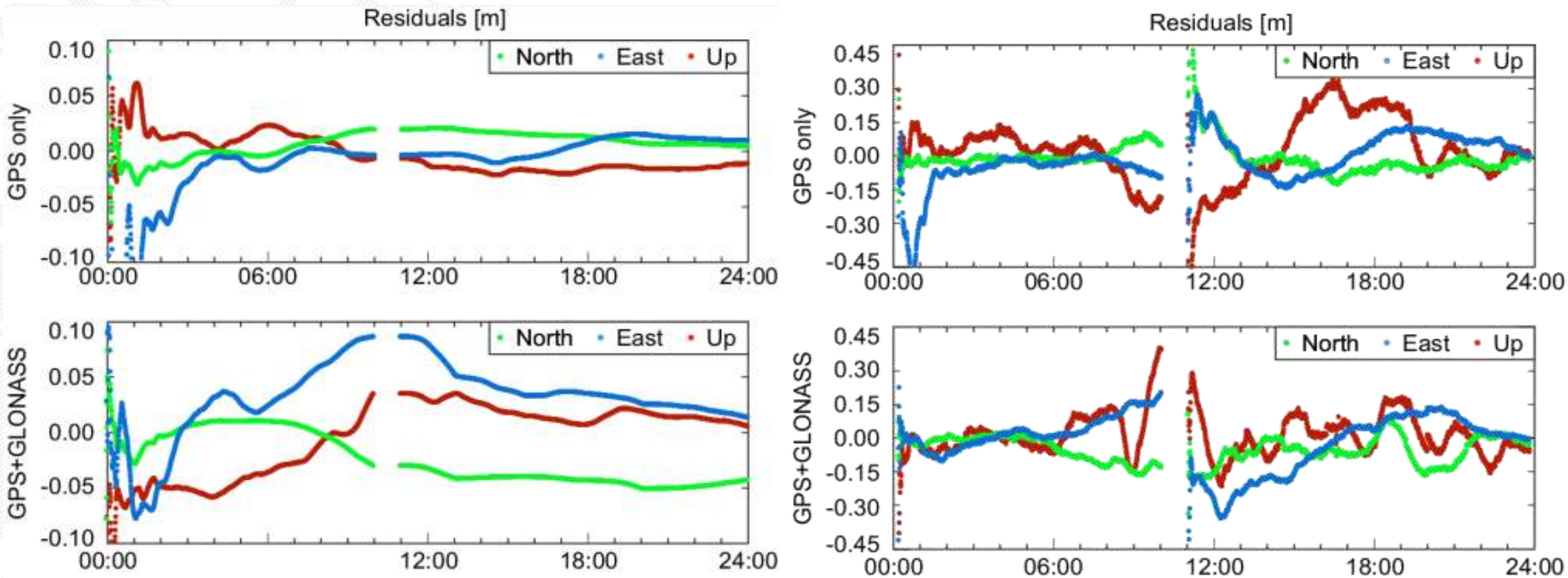
$$\delta C = C_0 + C_1(t-t_0) + C_2(t-t_0)^2$$

$$t^{sat} = t^{sat}_{broadcast} - \frac{\delta C}{c}$$

- official products for GPS: 5cm for orbits, 0.3ns (8.5cm) for clocks
- unofficial for GLONASS: 13cm for orbits, 0.8ns (24.5cm) for clocks
- availability >90%, latency ~30 sec.

Hadaś T., Bosy J.: ***IGS RTS precise orbits and clocks verification and quality degradation over time***, GPS Solutions, Vol. 19, 2015, pp. 93-105

Real-time PPP in static / kinematic mode

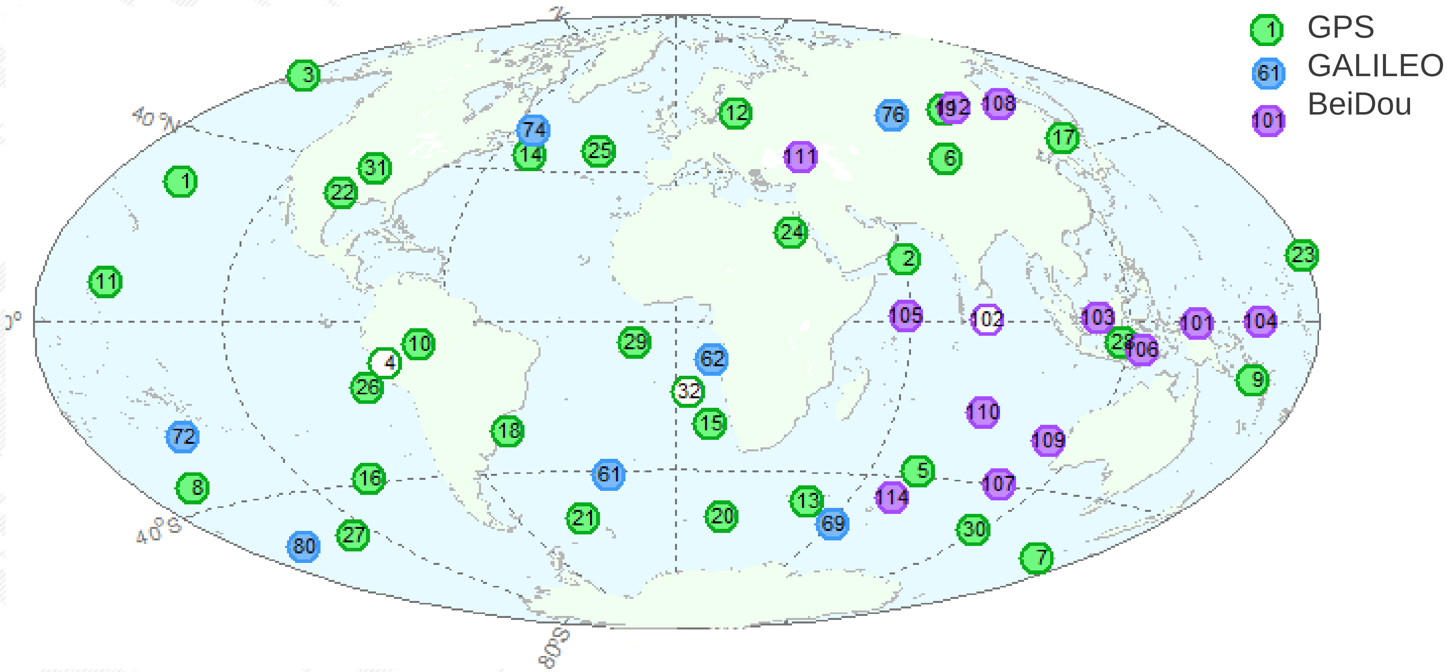


Time series of residuals for GPS only with IGS01 stream (top) and GPS+GLONASS with IGS03 stream (bottom) real-time positioning in static (left) and kinematic (right) mode for station WROC, DOY 114, 2014

	GPS only		GPS+GLO	
	Mean	Std.Dev.	Mean	Std.Dev.
North	0.005	0.002	**0.025**	**0.013**
East	0.007	0.006	**0.012**	**0.018**
Up	0.001	0.006	**-0.033**	**0.011**

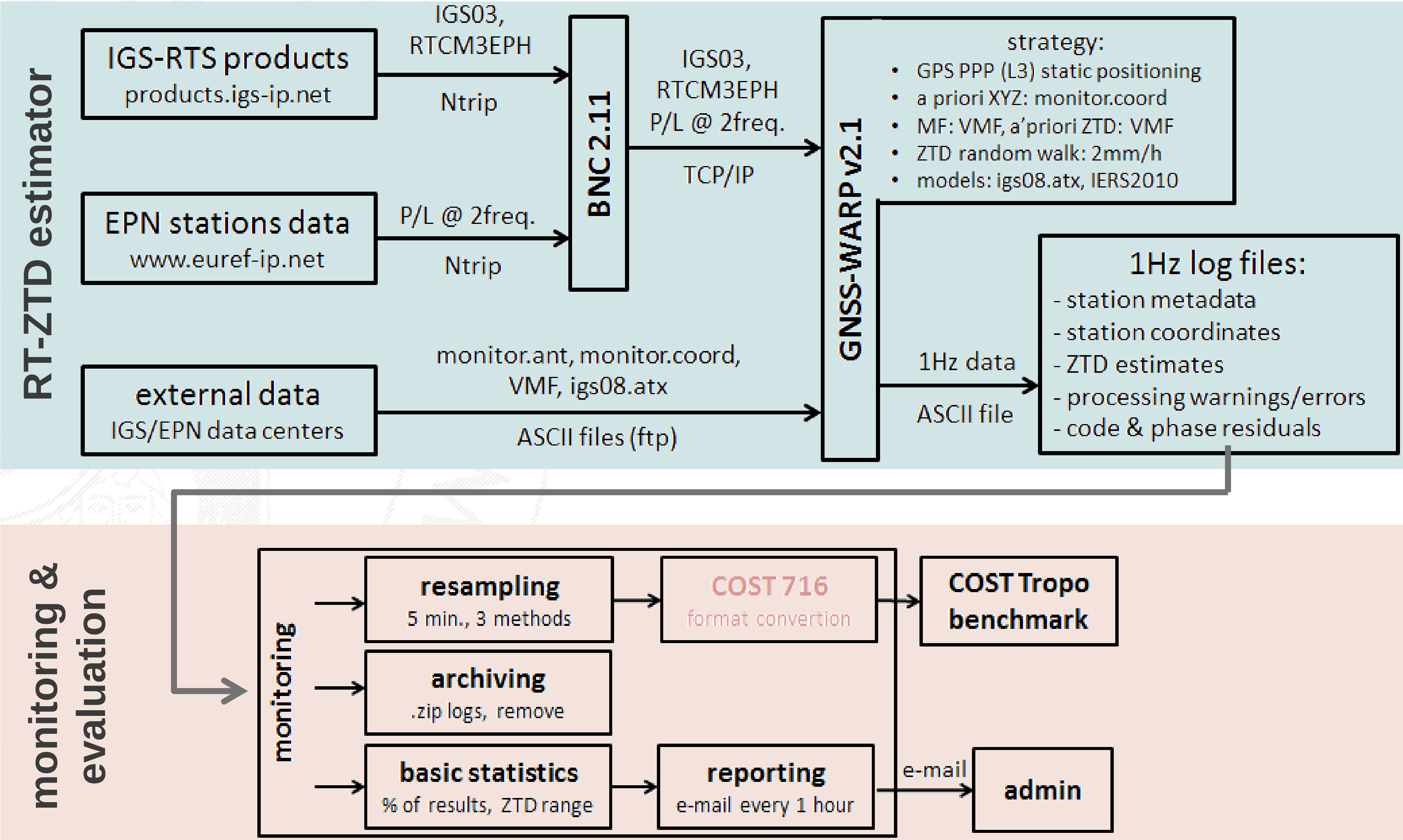
	GPS only		GPS+GLO	
	Mean	Std.Dev.	Mean	Std.Dev.
North	0.007	0.03	0.015	0.035
East	0.004	0.027	0.004	0.032
Up	0.057	0.12	**-0.031**	**0.092**

GNSS-WARP status



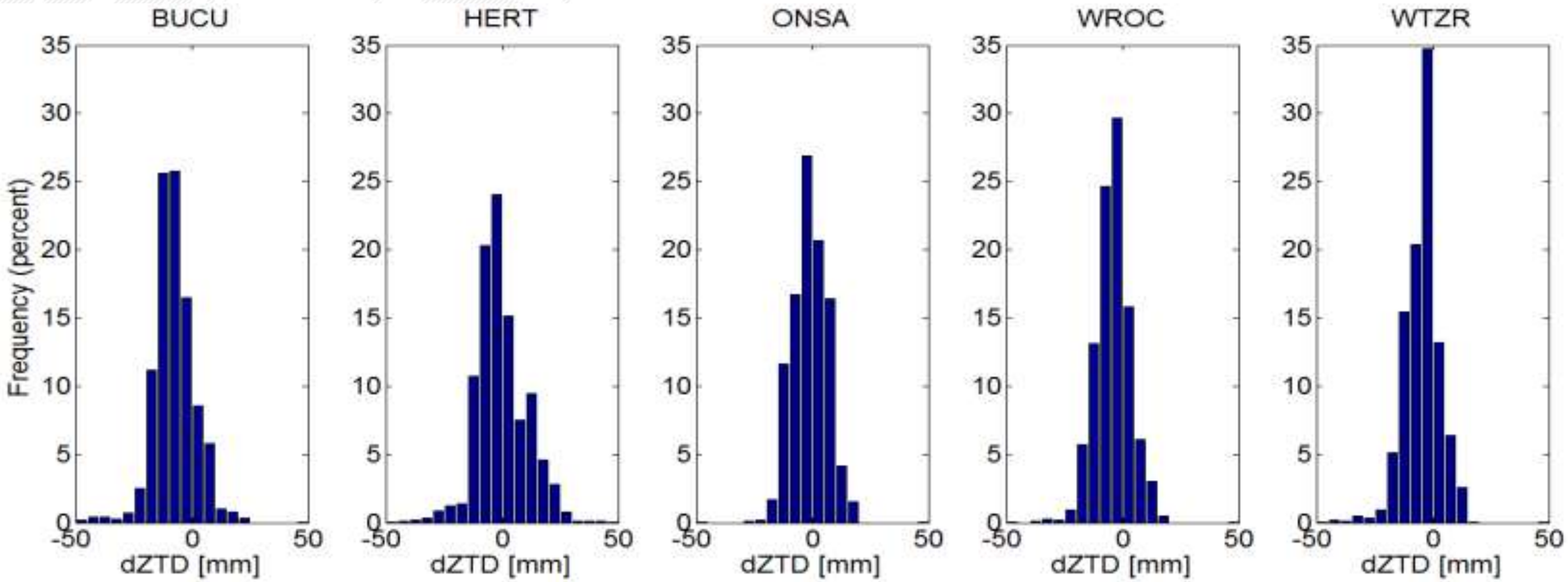
	GPS	GLONASS	Galileo	BeiDou
SP3+CLK	operational	operational	operational	test phase
broadcast	operational	operational	operational	tracked
real-time	operational	IOD problems	test phase	not available

GNSS-WARP software – real-time troposphere service



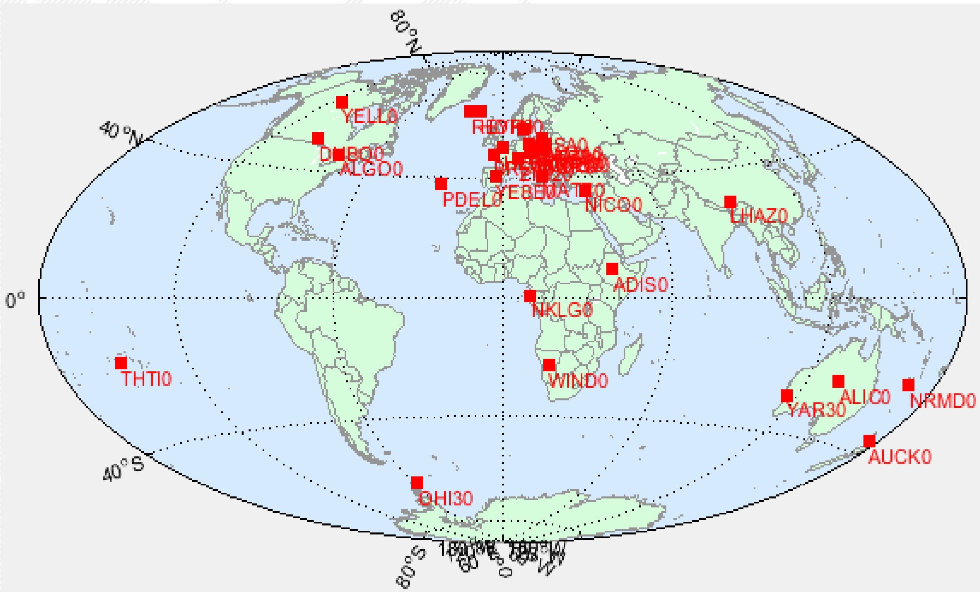
RT ZTD benchmark 1 – simulated real-time

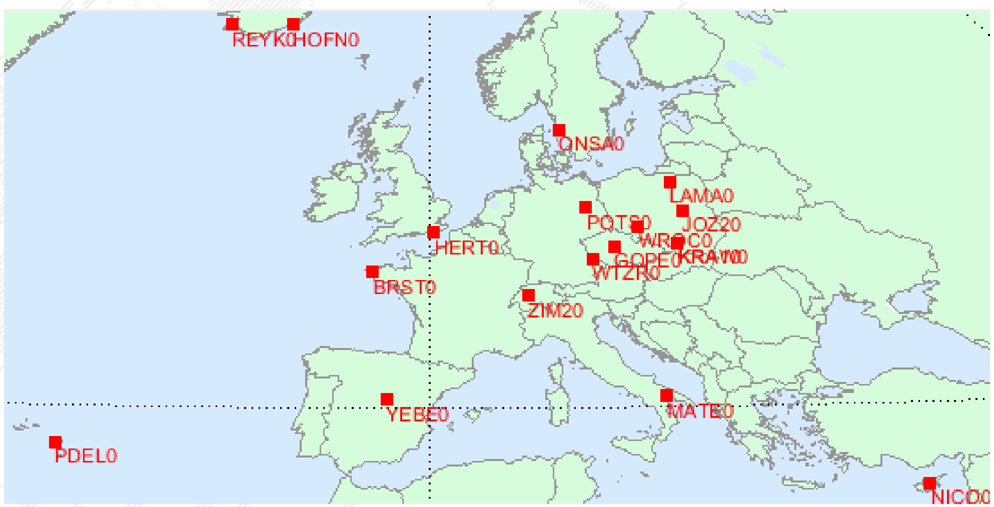
- RTS IGS03 stored (BNC) in **SP3** and **CLK** files, **RINEX** files for **10 stations**, **one week**
- station by station **postprocessing** (0.1Hz) with GNSS-WARP v2
- comparison with **final-ZTD** estimates from EPN (**1 hour sampling**)
- purpose: optimize methodology, evaluate possible quality



An optimal solutions among all stations were obtained for 2mm/h to 5mm/hour random walk. The results were slightly biased: -4 mm to +7 mm (note: DD vs PPP solution) and the standard deviations varies from 7 mm to 12 mm.

RT ZTD benchmark 2 - real-time demonstrator (1)





Real-time ZTD:

33 stations @ 5 sec. sampling:

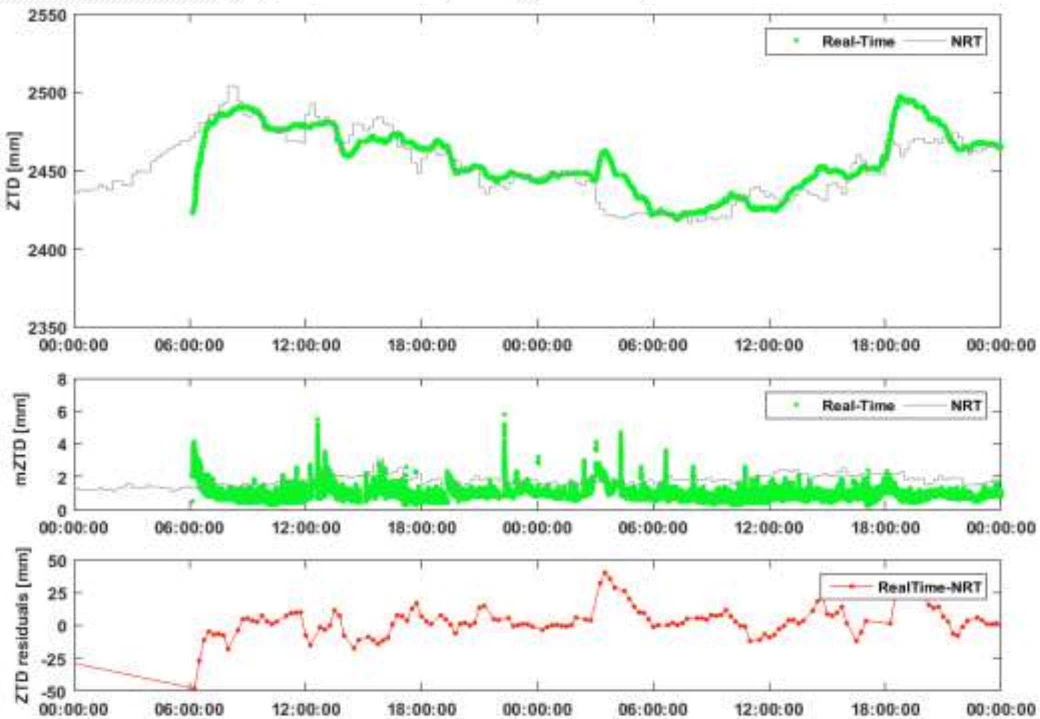
- COST RT TROPO benchmark stations (some have problems!)
- Polish EPN stations

Week 1863 performance (σ - formal error):

- 68% σZTD is below 0.0036 m
- **95% σZTD is below 0.0148 m**
- 99% σ ZTD is below 0.0241 m
- data availability: 88.6%

RT ZTD benchmark 2 - real-time demonstrator (2)

- RTS **IGS03 stream** and **10 observation streams** decoded with BNC, **one week**
- **multi-station real-time** processing with GNSS-WARP v2.1M
- comparison with **NRT** from MetOffice (ROBH, **15min sampling**)
- purpose: optimize methodology, detect bugs & errors



*Station **WROC***

13-14.06.2015

availability: 86%

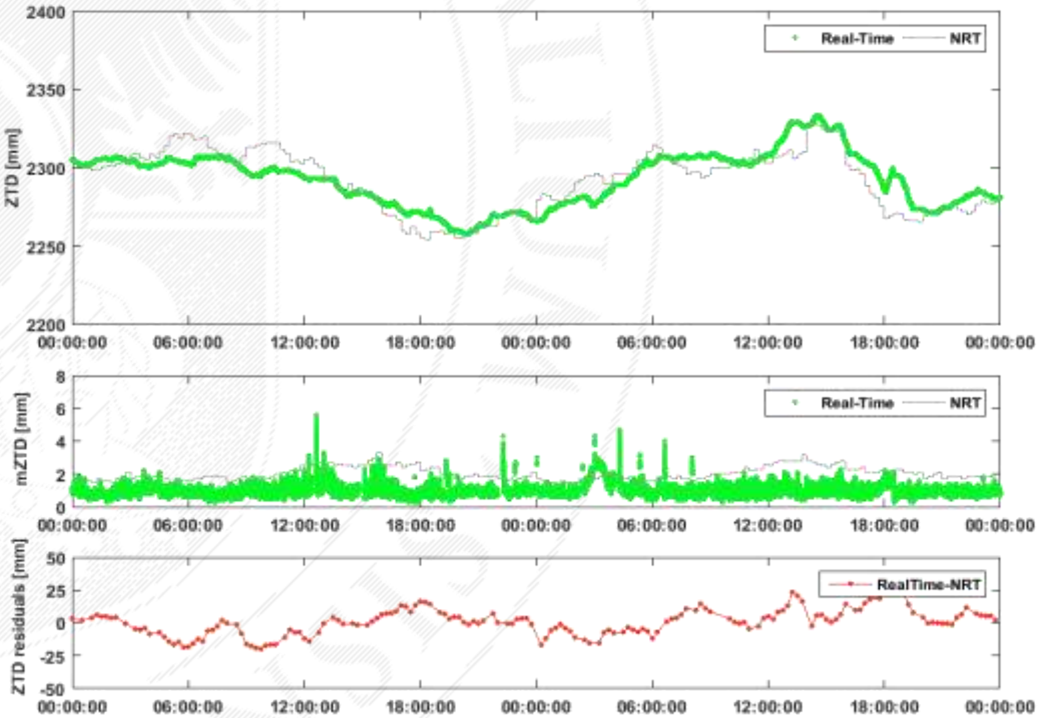
mean formal error: 1.1mm

mean bias: +1.5mm

StdDev of residuals: 15.7mm

RT ZTD benchmark 2 - real-time demonstrator (2)

- RTS **IGS03 stream** and **10 observation streams** decoded with BNC, **one week**
- **multi-station real-time** processing with GNSS-WARP v2.1M
- comparison with **NRT** from MetOffice (ROBH, **15min sampling**)
- purpose: optimize methodology, detect bugs & errors



*Station **WTZR***

13-14.06.2015

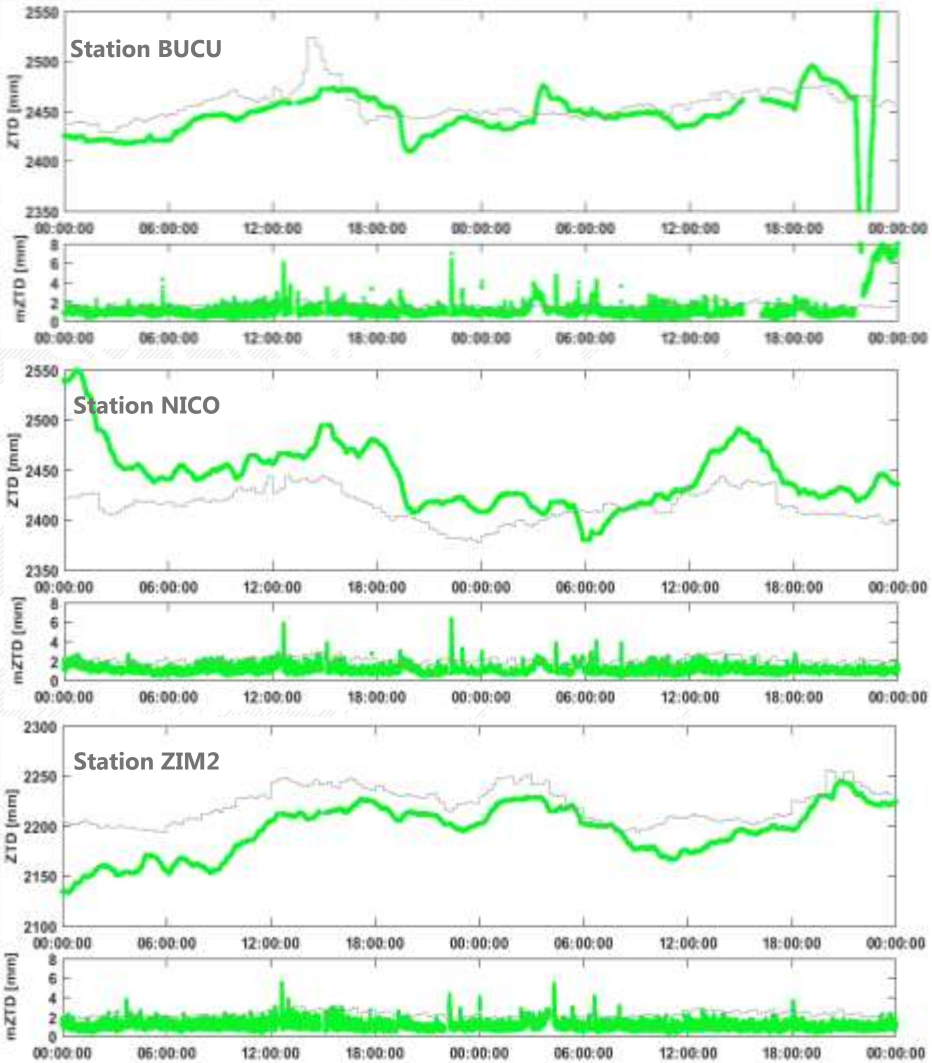
availability: 97%

mean formal error: 1.1mm

mean bias: -1.0mm

StdDev of residuals: 15.5mm

RT ZTD benchmark 2 - real-time demonstrator (3)



Bugs & errors

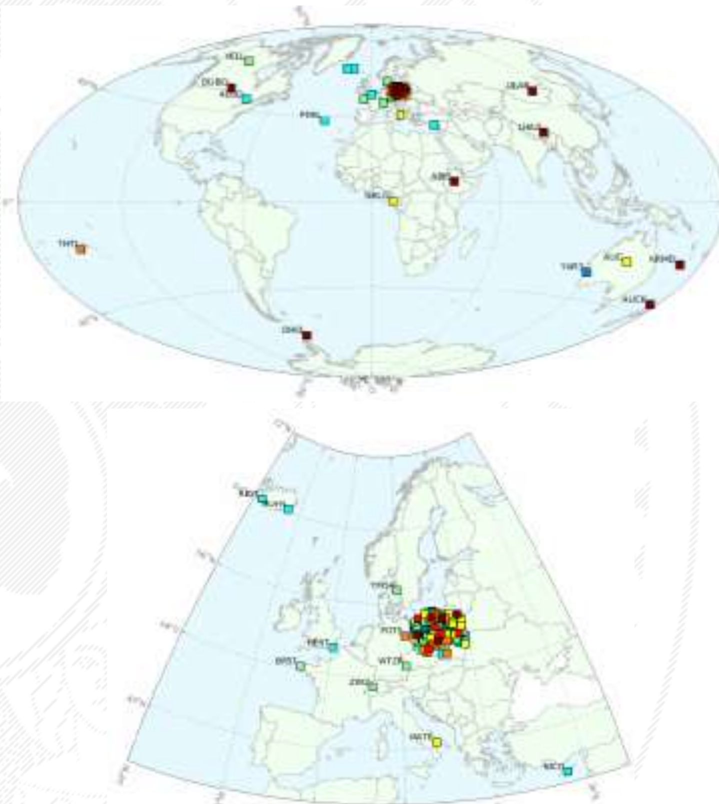
1) Real-time service problems:

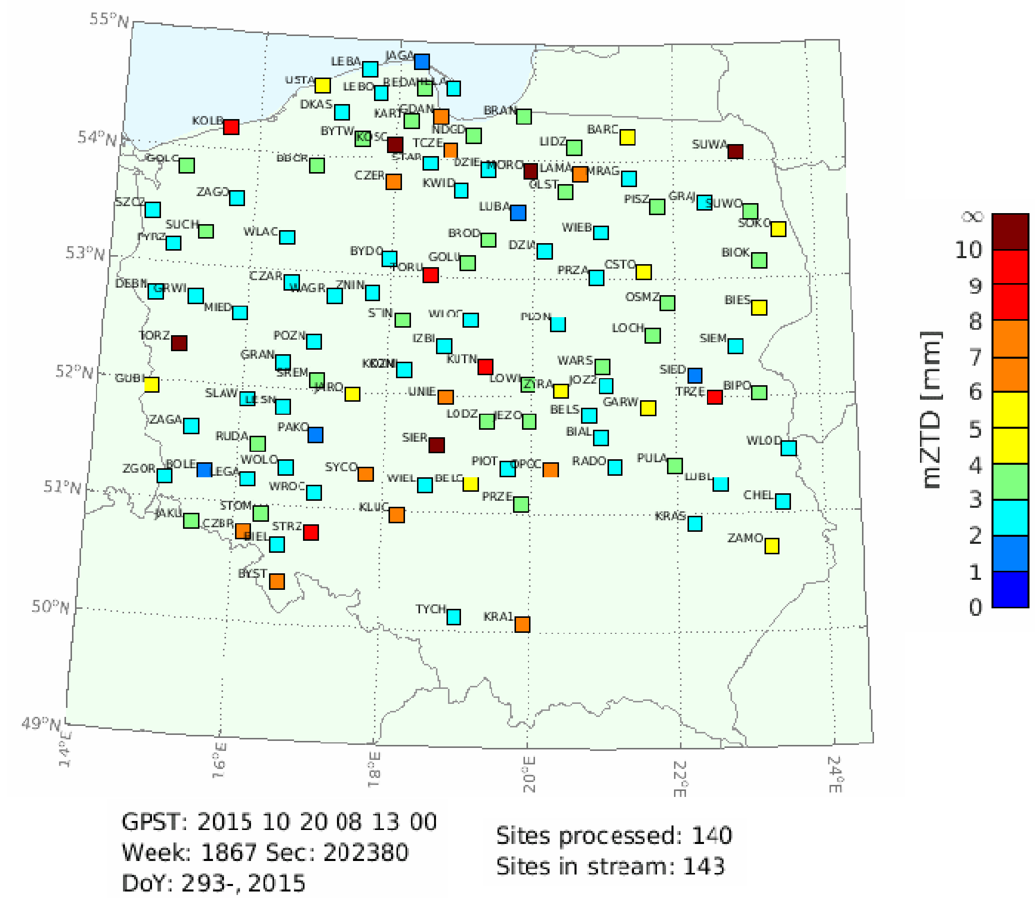
- IGS03/RTCMEPH stream failure (e.g. mismatching IOD's)
- stream recovery failure in BNC (solved: use Ntrip 1, not Ntrip 2)
- long gaps in streams availability (re-initialization of the solution)

2) Processing errors:

- some rapid ZTD changes not present in RT estimation
- unexpected ZTD peaks in RT
- systematic biases between RT and NRT (DD vs. PPP)

Towards RT-ZTD monitoring service in Poland (1)



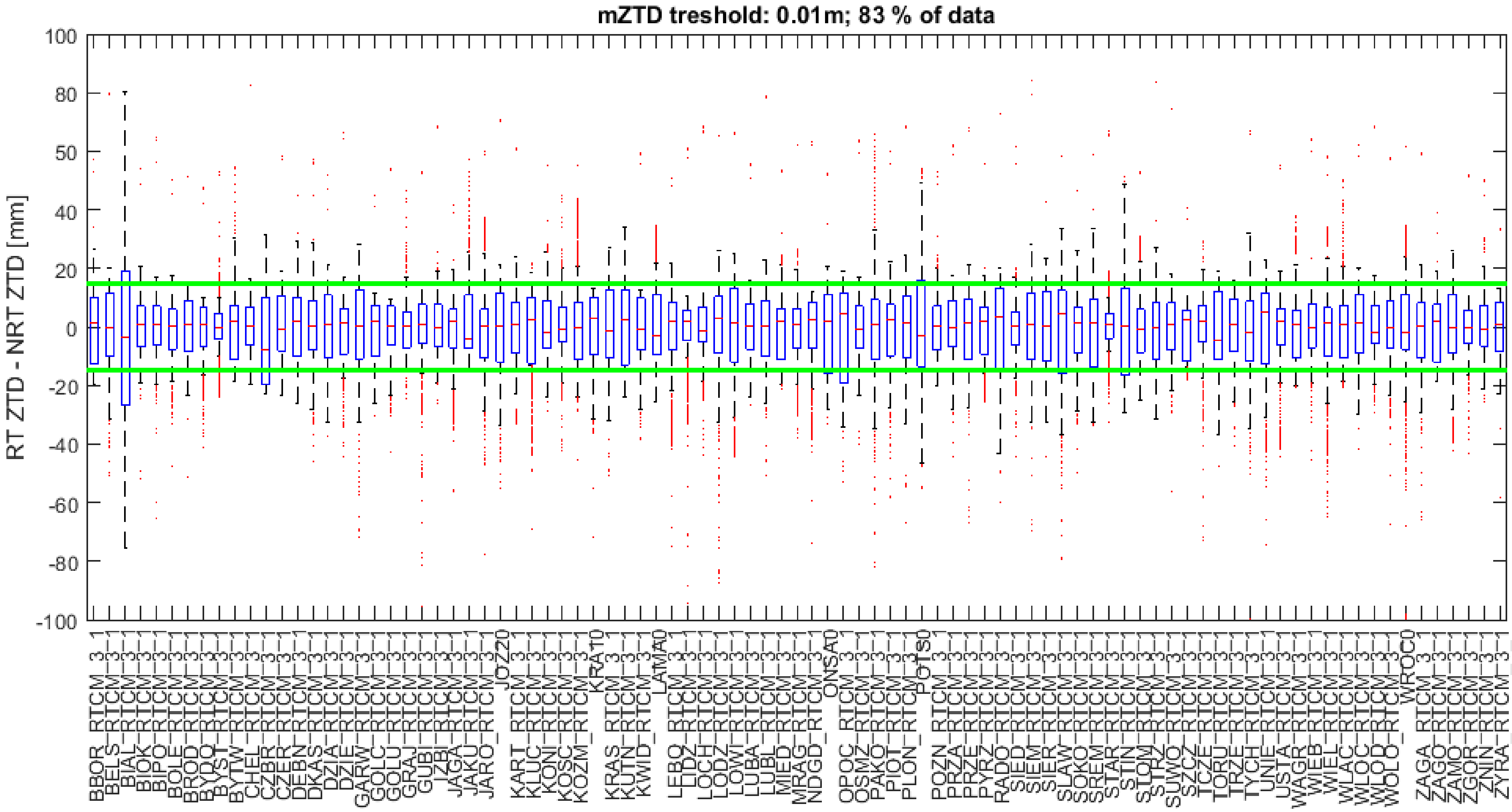


Recent problems:

- bad / missing antenna type (monitor.ant) – station is incorrect / not processed
- BNC 2.11 failure / errors - no data until restarted
- no access to ASG-EPOS streams (all stations) and SmartNet streams (south east)

Towards RT-ZTD monitoring service in Poland (2)

Comparison with NRT ZTD



Towards RT-ZTD monitoring service in Poland (3)

RT ZTD service (under development, improvements required)

- 14 IGS + 19 EPN + 110 Leica SmartNet

Sub-hourly ZTD	Treshold	Target	Optimal
Accuracy	**15 mm**	10 mm	5 mm
Timeliness	1 h	30 min	**15 min**
Spatial coverage	Europe	Europe to **National**	Regional to **National**
Horizontal Sampling	100 km	**50 km**	20 km

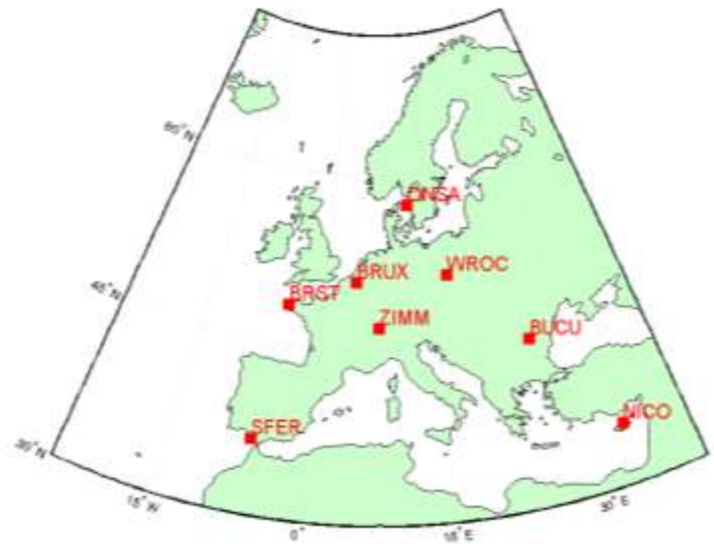
RT tropospheric gradient estimation

Calculation parameters	
Products	RT-IGS RT-CNES
Mapping function	VMF
Model	Chen & Herring $$\delta\kappa \quad \varepsilon,\alpha \quad = \frac{1}{\sin \quad \varepsilon \quad \tan \quad \varepsilon \quad + C} \quad G_N \cos\alpha + G_E \sin\alpha$$
Interval	every epoch
Random walk	0.0003 m/sqrt(h)

RT tropospheric gradient estimation - validation

RT tropospheric gradients (GNSS WARP)
vs
PPP tropospheric gradients (GIPSY 6.2)

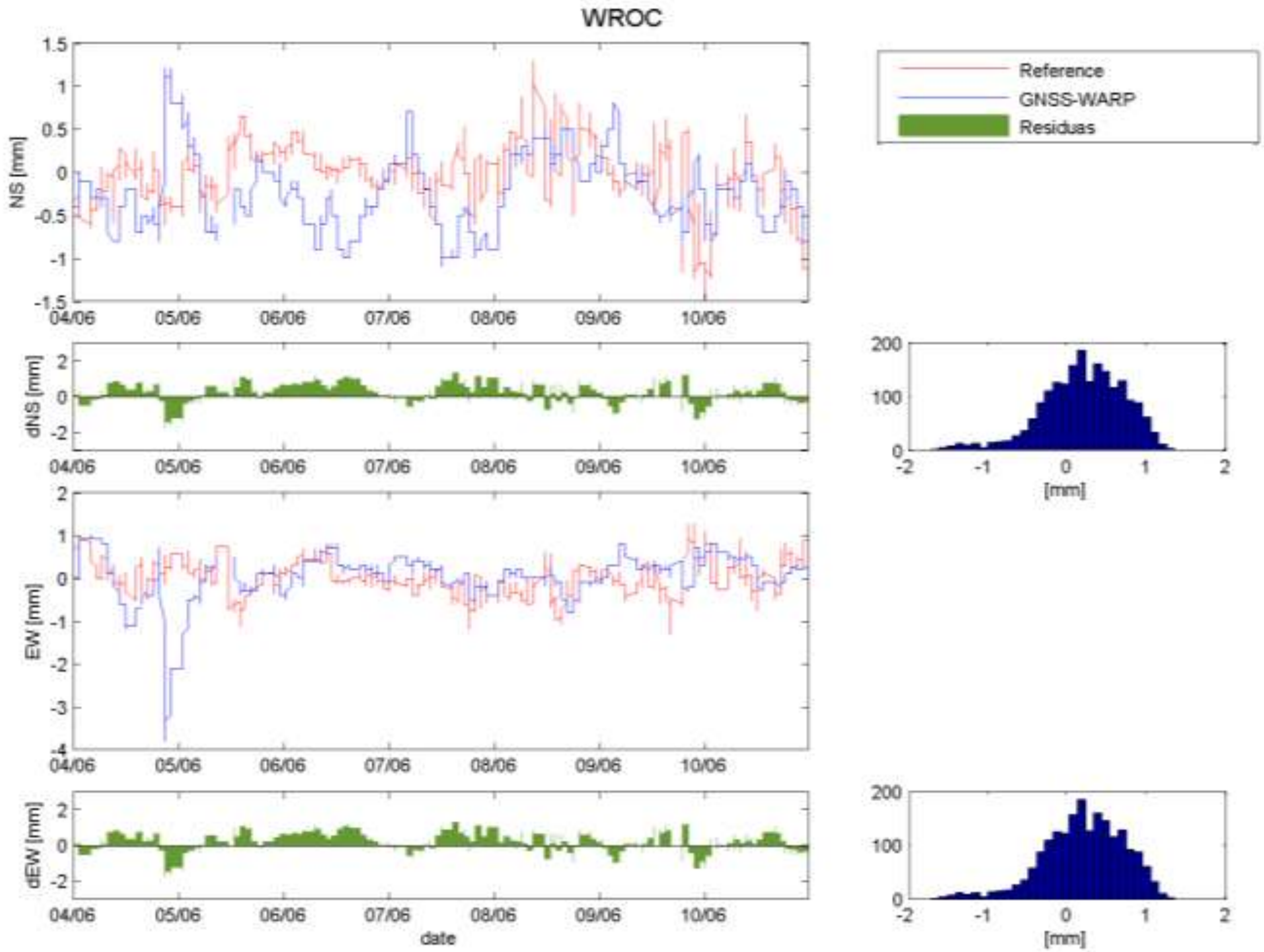
- 8 European station
- 5min sampling
- DoY 155-161 2013
- GPS
- Real-time



	BIAS [mm]		Std.Dev. [mm]		RMSE [mm]	
	NS	EW	NS	EW	NS	EW
'BRST'	-0,03	-0,13	0,97	0,67	0,99	0,72
'BRUX'	0,07	-0,06	0,54	0,48	0,62	0,50
'BUCU'	0,11	-0,26	0,69	0,70	0,75	0,73
'NICO'	0,05	0,01	0,60	0,72	0,65	0,74
'ONSA'	-0,01	-0,01	0,55	0,78	0,86	1,08
'SFER'	0,15	0,05	0,60	0,72	0,66	0,73
'WROC'	-0,02	0,00	0,53	0,68	0,56	0,68
'ZIMM'	-0,07	0,09	0,61	0,55	0,64	0,55
	0,06	0,08	0,64	0,66	0,72	0,72

RT tropospheric gradient estimation - validation

BIAS [mm]	
NS	EW
-0.02	0.00
Std.Dev. [mm]	
SN	EW
0.53	0.68
RMSE [mm]	
SN	EW
0.56	0.68



Conclusion

1. The NRT ZDT service is operational and stable in DD for 1h timeliness and will be developed to PPP and 15 min. timeliness.
2. The RT PPP is the alternative technique in GNSS meteorology and will be developed in future.
3. The gradients estimated in NRT and RT are significant information for the meteorology and should be developed in future.
4. The PPP positioning technique by external RT ionosphere and troposphere models gives a stable solution and research in this area should be continued.

GNSS&Meteo group projects

1. ***Innovative Methods of the Troposphere Delay Modeling for Satellite Laser Ranging Observations****, (UMO-2014/15/N/ST10/00824, Project manager: Krzysztof Sosnica), Duration: 15.02.2016 - 14.02.2019;*
2. ***Prognostic troposphere model based on meteorological data, GNSS products and Numerical Weather Prediction models*** *(UMO-2014/15/N/ST10/00824, Project manager: Karina Wilgan) , Duration: 04.09.2015 - 03.09.2017;*
3. ***Multi-GNSS real-time Precise Point Positioning*** *(UMO-2014/15/B/ST10/00084, Project manager: Jaroslaw Bosy) , Duration: 14.07.2015 - 13.07.2018;*
4. ***GNSS observations as a numerical weather prediction data source, a way forward to enhanced forecast quality*** *(UMO-2013/11/D/ST10/03473, Project manager: Witold Rohm), Duration: 14.08.2014 - 13.08.2017;*
5. ***Higher Order Ionospheric modelling campaigns for precise GNSS applications – HORION****, (ESA Contract No. 4000112665/14/NL/Cbi, Project coordinator: Leica Geosystems Poland), Duration: 28.11.2014 - 27.11.2016, URL: http://pl.smartnet-eu.com/;*
6. ***E-GVAP (The EUMETNET EIG GNSS water vapour programme)****, URL: http://egvap.dmi.dk/;*
7. ***COST Action ES1206 - Advanced Global Navigation Satellite* Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)**, URL: http://www.cost.eu/domains_actions/essem/Actions/ES1206;

GNSS&Meteo group selected publications (1)

1. *Hadaś T., Bosy J.* ***IGS RTS precise orbits and clocks verification and quality degradation over time****. GPS Solutions, Vol. 19 No. 1, Berlin Heidelberg 2015, pp. 93-105;*
2. *Hordyniec P., Bosy J., Rohm W.* ***Assessment of errors in precipitable water data derived from global navigation satellite system observations****. Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 129 2015, pp. 69-77;*
3. *Norman R. J., Le Marshall J., Rohm W., Carter B. A., Kirchengast G., Alexander S., Liu C., Zhang K.* ***Simulating the Impact of Refractive Transverse Gradients Resulting From a Severe Troposphere Weather Event on GPS Signal Propagation****. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (J-STARS), Vol. 8 No. 1, 2015, pp. 418-424;*
4. *Sośnica K., Thaller D., Dach R., Steigenberger P., Beutler G., Arnold D., Jäggi A.* ***Satellite laser ranging to GPS and GLONASS****. Journal of Geodesy, Vol. 89 No. 7, Berlin Heidelberg 2015, pp. 725-743;*
5. *Wilgan K., Rohm W., Bosy J.* ***Multi-observation meteorological and GNSS data comparison with Numerical Weather Prediction model****. Atmospheric Research, Vol. 156 No. , Amsterdam, the Netherlands 2015, pp. 29-42;*
6. *Rohm W., Yang Y., Biadeglgne B., Zhang K., Le Marshall J.* ***Ground-based GNSS ZTD/IWV estimation system for numerical weather prediction in challenging weather conditions****. Atmospheric Research, Vol. 138 No. , 2014, pp. 414-426;*
7. *Rohm W., Zhang K., Bosy J.* ***Limited constraint, robust Kalman filtering for GNSS troposphere tomography****. Atmospheric Measurement Techniques, Vol. 7 No. 5, 2014, pp. 1475-1486;*

GNSS&Meteo group selected publications (2)

8. *Yuan Y., Zhang K., Rohm W., Choy S., Norman R., Wang C.-S.* ***Real-time retrieval of precipitable water vapor from GPS precise point positioning****. Journal of Geophysical Research: Atmospheres, Vol. 119 No. 16, Wiley 2014, pp. 10044-10057;*
9. *Hadaś T., Kapłon J., Bosy J., Sierny J., K Wilgan* ***Near-real-time regional troposphere models for the GNSS precise point positioning technique****. Measurement Science and Technology, Vol. 24 No. 5, 2013, pp. 055003 (12 pp.);*
10. *Rohm W.* ***The ground GNSS tomography - unconstrained approach****. Advances in Space Research, Vol. 51 No. 3, 2013, pp. 501-513*
11. *Bosy J., Kapłon J., Rohm W., Sierny J., Hadaś T.* ***Near real-time estimation of water vapour in the troposphere using ground GNSS and the meteorological data****. Annales Geophysicae, Vol. 30 No. , Göttingen, Germany 2012, pp. 1379-1391;*
12. *Rohm W.* ***The precision of humidity in GNSS tomography****. Atmospheric Research, Vol. 107 No. , 2012, pp. 69-75;*
13. *Rohm W., Bosy J.* ***The verification of GNSS tropospheric tomography model in a mountainous area****. Advances in Space Research, Vol. 47 No. 10, 2011, pp. 1721-1730;*
14. *Bosy J., Rohm W., Borkowski A., Figurski M., Kroszczyński K.* ***Integration and verification of meteorological observations and NWP model data for the local GNSS tomography****. Atmospheric Research, Vol. 96 No. , 2010, pp. 522-530*
15. *Rohm W., Bosy J.* ***Local tomography troposphere model over mountains area****. Atmospheric Research, Vol. 93 No. 4, 2009, pp. 777-783;*

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Multi-GNSS real-time troposphere delay estimation

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Thank You!

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