Real-time Demonstration and Benchmark campaigns for developing advanced troposphere products

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IGS 2016, Sydney, 8.2 – 12.2

Outline

- **Introduction**
- **Benchmark campaign**
  - Design & data collection
  - Assessment of GNSS reference products and NWM-derived products
  - High-resolution gradient estimates, comparisons and animations
  - Study of impact of hydrometeors
- **Real-Time Demonstration campaign**
  - Design, contributions, monitoring
  - Assessment of RT products and smoothing strategy using the Benchmark campaign
  - Monitoring of real-time NWM corrections, dependence on forecast
- **Summary**

GNSS4SWEC Working Groups

COST Action ES1206: GNSS for Severe Weather and Climate (GNSS4SWEC)

POSTER (IGS 2016) by Jones J, Guerova G, Dousa J, Dick G, de Haan S, Pottiaux E, Bock O, Pacione R

WG1 — **Advanced GNSS processing techniques (AGNSS)**

Chair: **Dr Jan Dousa,** GOP (jan.dousa@pecny.cz)
Co-chair: **Dr Galina Dick,** GFZ (galina.dick@gfz-potsdam.de)

WG2 — **GNSS for severe weather monitoring (GNSS4SW)**

Chair: **Dr Siebren de Haan**, KNMI (siebren.de.haan@knmi.nl
Co-chair: **Dr Eric Pottiaux**, ROB (eric.pottiaux@oma.be)

WG3 — **GNSS for climate monitoring (GNSS4C)**

Chair: **Dr Olivier Bock**, IGN (olivier.bock@ign.fr)
Co-chair: **Dr Rosa Pacione**, ASI (rosa.pacione@e-geos.it)

→ 72 members
→ 26 EU+ countries
→ 4 non-EU partners
→ 10 specific activities

Working Group 1 – Main Goals

- **Coordinating the development of advanced troposphere products in support of weather forecasting:** ultra-fast production, asymmetry monitoring, tomography reconstruction, high-resolution products,multi-constellation processing
- **Exploiting numerical weather model data in precise GNSS positioning and navigation**

  generating synthetic troposphere parameters or observations

  evaluating NWM-derived troposphere corrections for real-time applications

  assessing troposphere mapping functions, impact of using mapping factors

  separating hydrostatic and non-hydrostatic parts in final and (near) real-time solutions
- **GNSS data reprocessing** to provide consistent troposphere products for climate research in Europe
- **Stimulating transfer of knowledge**, tools and data exchange in support of new analysis centres and networks setup

→ 10 sub-WG setup with focus on specific topics

Preparation phase: design & data collection

May-June 2013 - floods of Danube/Moldau/Elbe rivers

GNSS: ~500 stations (AT, CZ, DE, PL)

SYNOP: ~200 stations (AT, CZ, DE, PL)

NWM: regional (Aladin-CZ), global (ERA-Interim, NCEP GFS)

RAOBS: E-GVAP + two high-resolution (CZ)

WVR: Potsdam, Lindenberg (DE)

RADAR images: Brdy, Skalka (CZ)

Reference products

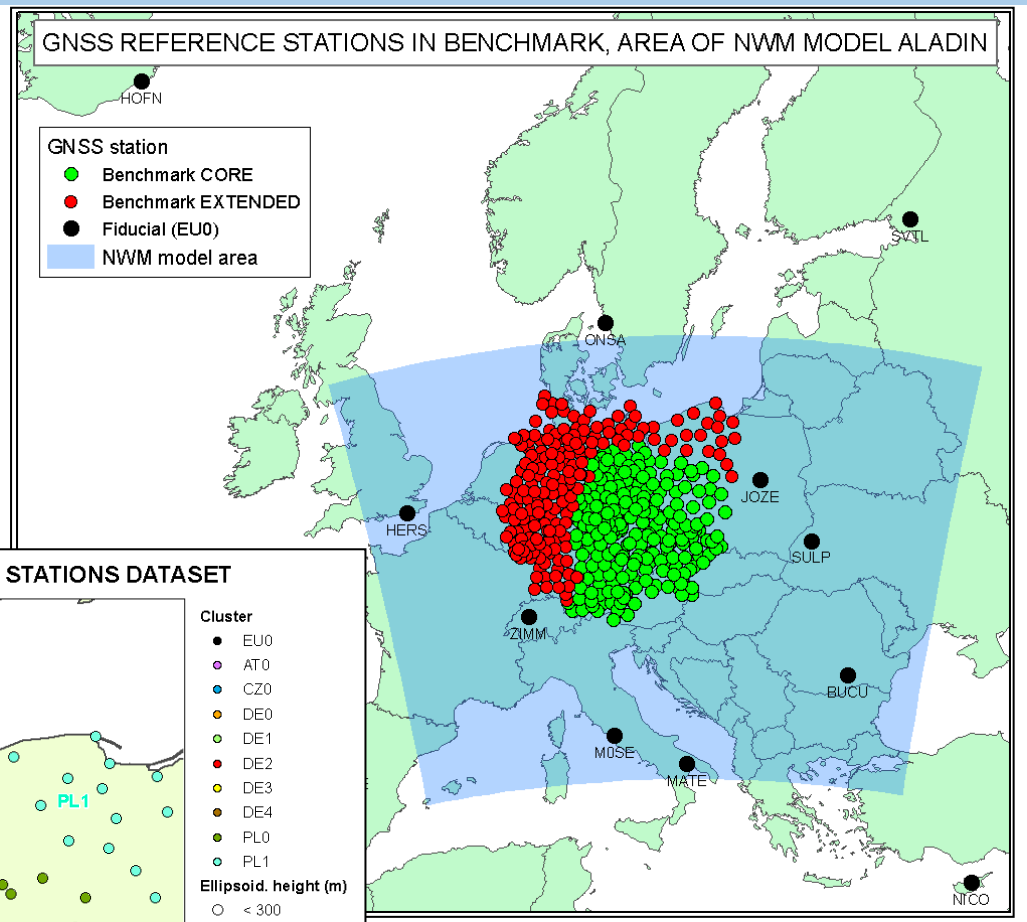
GNSS: Bernese (GOP), EPOS (GFZ)

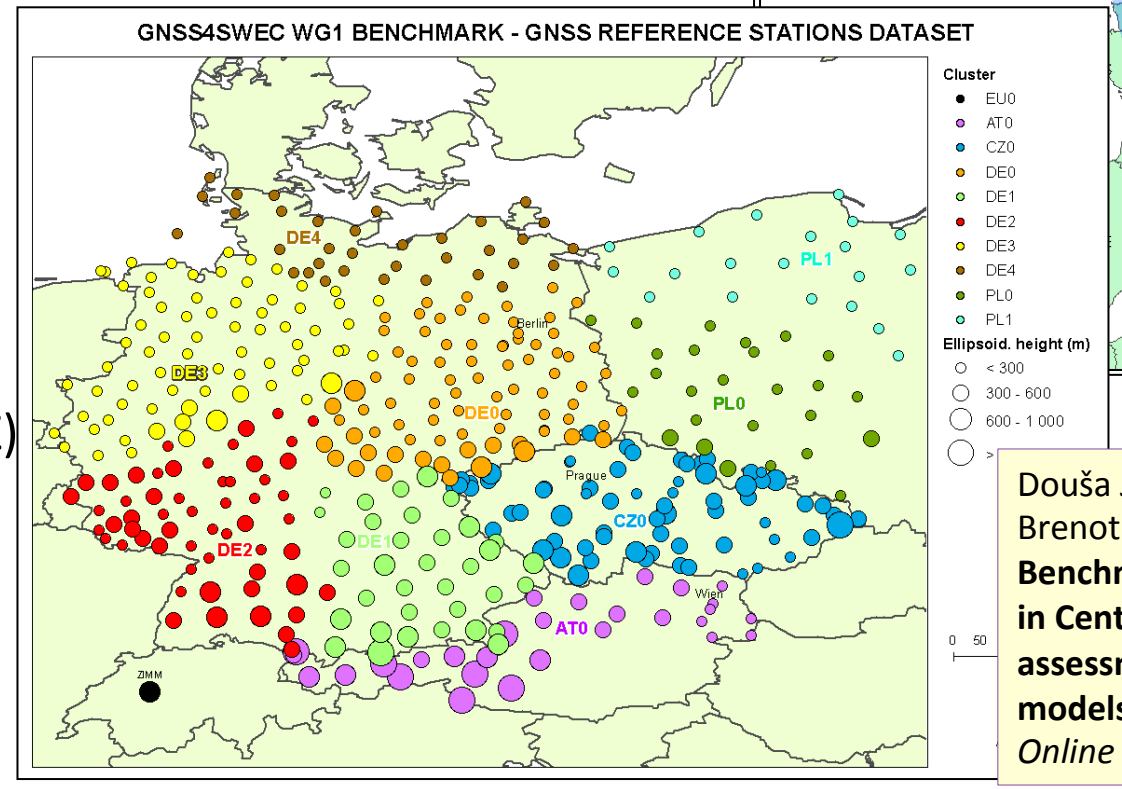
NWM: G-Nut/Shu (GOP), DNS (GFZ)

User phase

contributions, evaluations

feedbacks, interpretations





Douša J, Dick G, Kačmařík M, Brožková R, Zus F, Brenot H, Stoycheva A, Möller G, Kaplon: **Benchmark campaign and case study episode in Central Europe for development and assessment of advanced GNSS tropospheric models and products**, *Atmosph Meas Tech, Online Discussion, 2016*

GNSS reference products

Bernese + DD (GOP) – ZTDs (1h), GRD(6h)

EPOS-8 + PPP (GFZ) – ZTDs (15min), GRD(1h)

NWM-derived parameters

G-Nut/Shu (GOP): ZWD + ZHD + T/Tm + vert. corrections

DNS (GFZ): ZWD + ZHD + GRAD + MF

ZTD

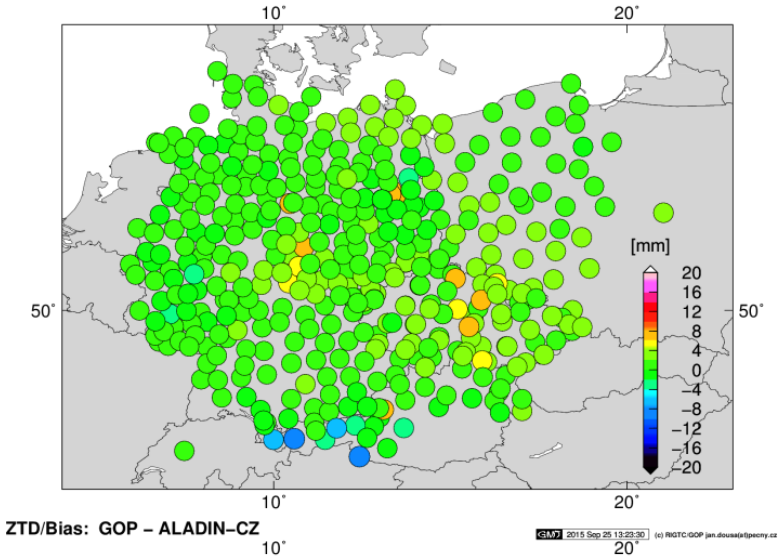
NWM source (software)	Grid Resolution	Analysis [hour]	Forecast [hour]	GNSS source (software)	Pairs #	Excl #	Bias [mm]	Sdev [mm]	RMS [mm]
ERA-Interim (Shu)	1 deg	6	0	GOP (Bernese)	224	2	+0.0	9.6	10.0
ERA-Interim (Shu)	1 deg	6	0	GFZ (EPOS-8)	224	3	+0.3	9.7	10.0
ERA-Interim (DNS)	1 deg	6	0	GOP (Bernese)	224	3	- 0.4	9.4	9.8
ERA-Interim (DNS)	1 deg	6	0	GFZ (EPOS-8)	224	3	- 0.1	9.6	9.8
GFS (DNS)	1 deg	6	0,3	GOP (Bernese)	224	7	- 4.9	11.0	12.0
GFS (DNS)	1 deg	6	0,3	GFZ (EPOS-8)	223	7	- 4.5	10.9	11.8
ALADIN (Shu)	4.7 km	6	0,1,2,3,4,5	GOP (Bernese)	1343	20	+0.8	7.6	7.8
ALADIN (Shu)	4.7 km	6	0,1,2,3,4,5	GFZ (EPOS-8)	1343	22	+0.6	7.3	7.5

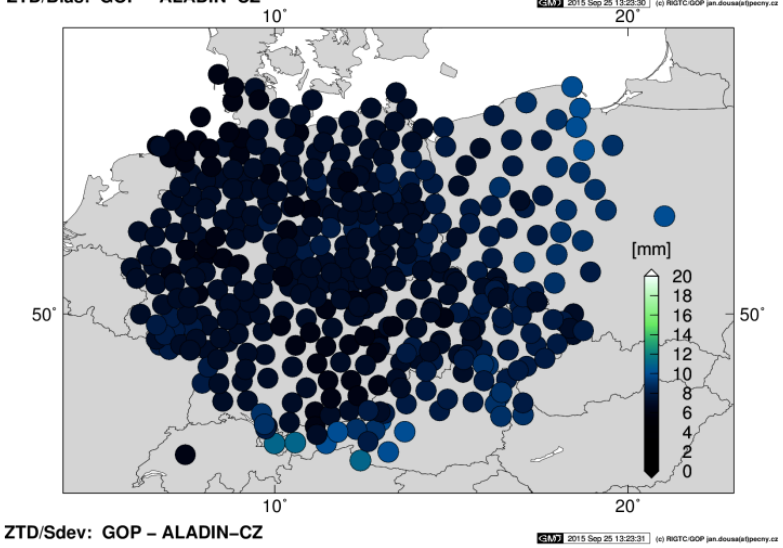
gradients

NWM	GNSS		North gradient			East gradient		
Source (software)	Source (software)	Pairs #	Bias [mm]	Sdev [mm]	RMS [mm]	Bias [mm]	Sdev [mm]	RMS [mm]
ERA-Interim (DNS)	GOP (Bernese)	224	- 0.02	0.41	0.42	- 0.04	0.43	0.46
ERA-Interim (DNS)	GFZ (EPOS)	224	+0.14	0.51	0.53	- 0.08	0.49	0.50
GFS (DNS)	GOP (Bernese)	224	- 0.04	0.44	0.45	- 0.05	0.46	0.50
GFS (DNS)	GFZ (EPOS)	224	+0.13	0.54	0.56	- 0.09	0.53	0.55

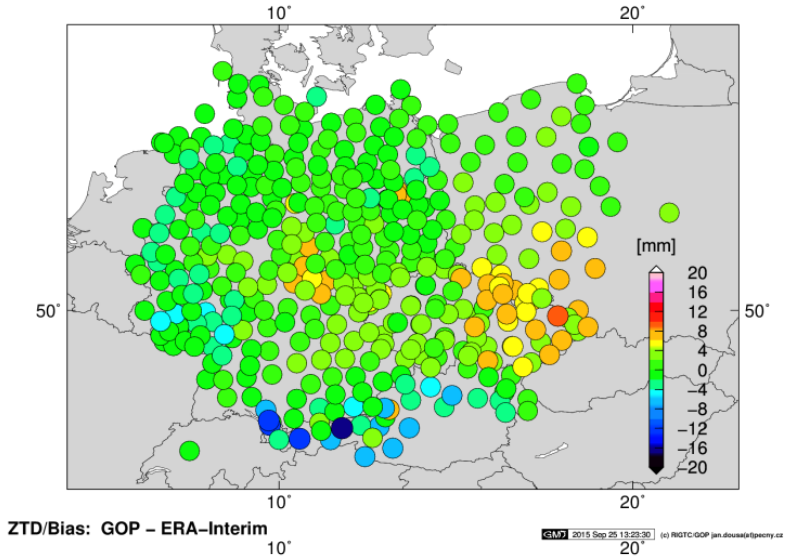
Benchmark - NWM assessment

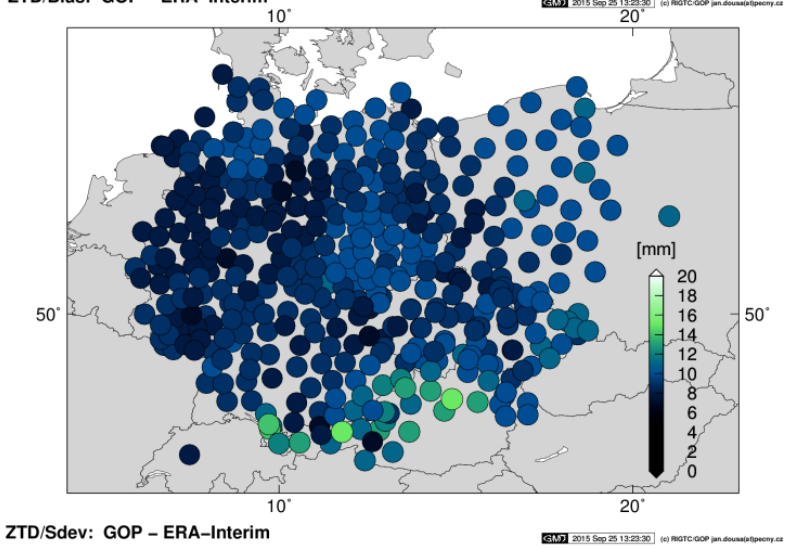
Aladin-CZ – GNSS (GOP)



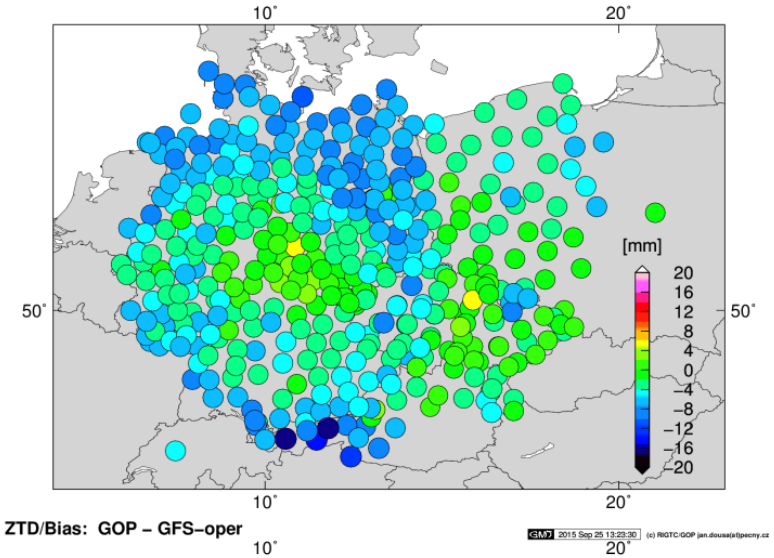


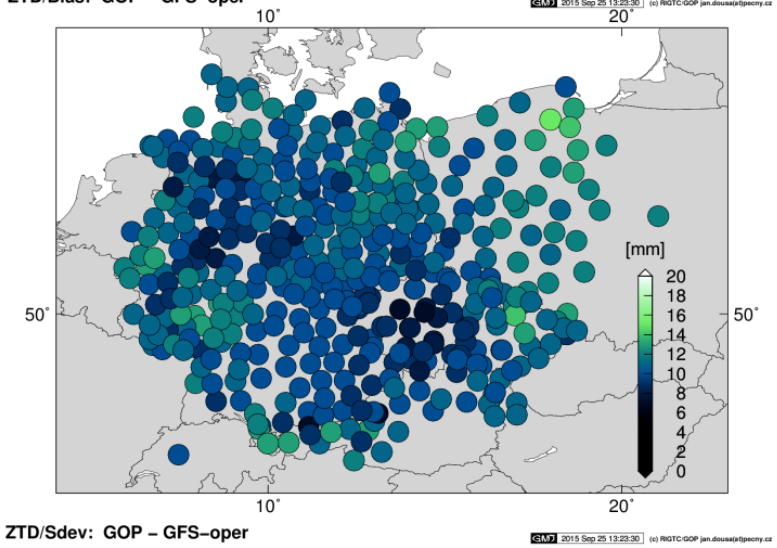
ERA-Interim – GNSS (GOP)





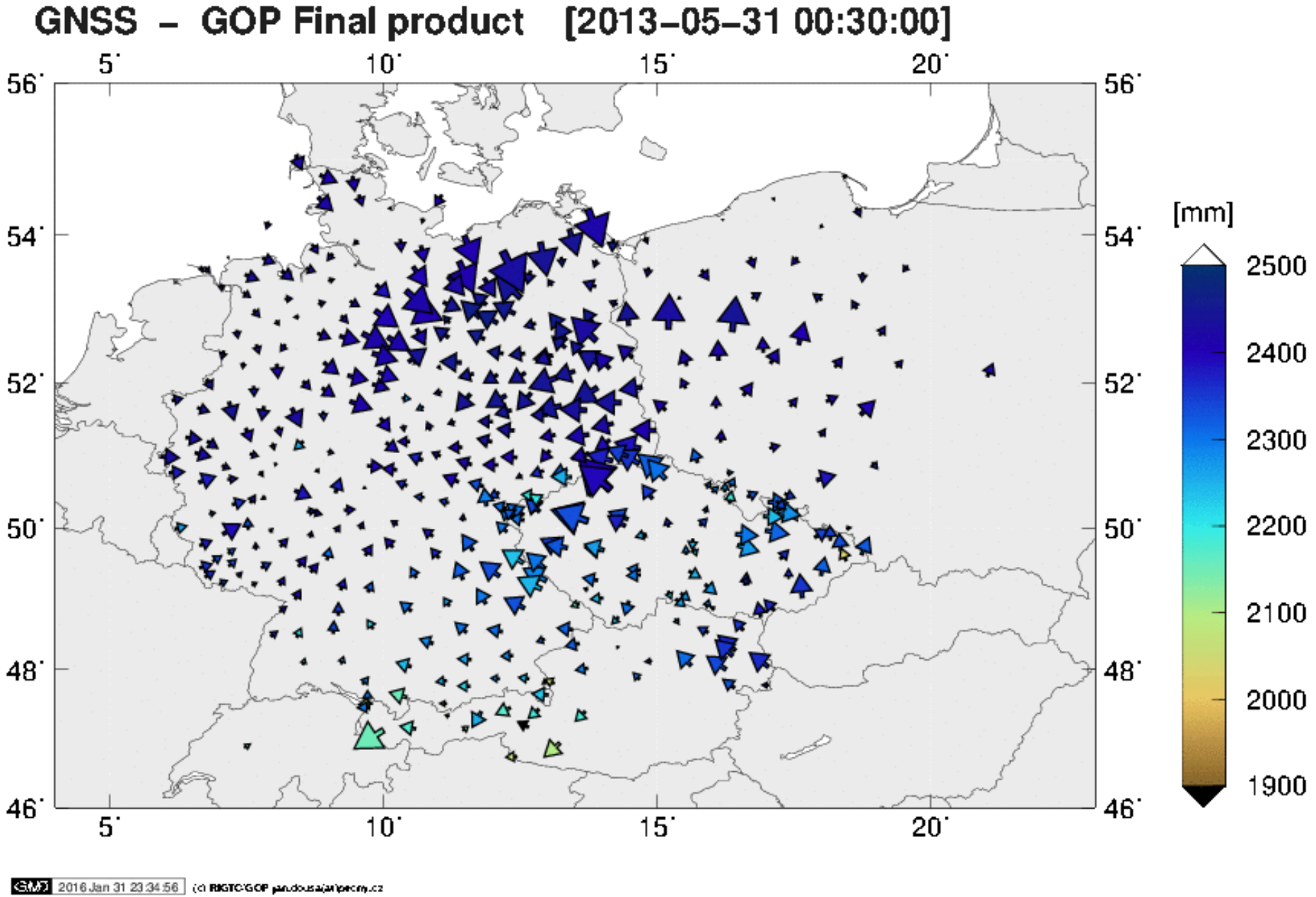
GFS – GNSS (GOP)





May 1 – June 30, 2013 - GNSS4SWEC Benchmark

24-hour Evolution of Troposphere Gradients



Troposphere products for asymmetry monitoring

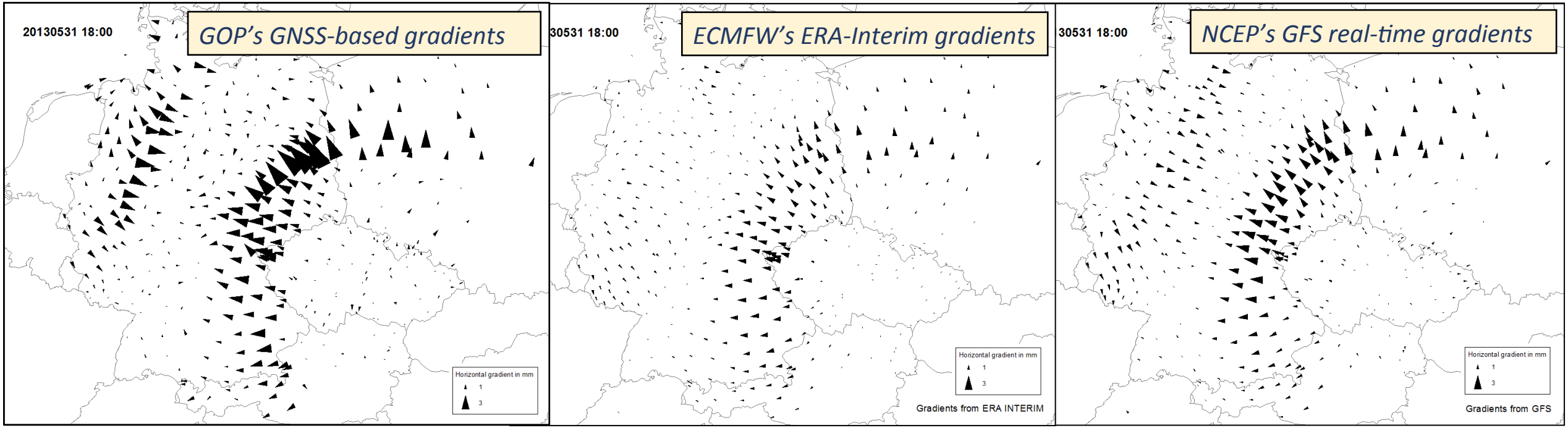


Figure: May 31, 2013 (Benchmark) – estimates of tropospheric gradients from GNSS & NWM

Advanced tropo-products: horizontal tropospheric gradients & slant delays

- Development of NRT/RT high-resolution gradients
- Development of NRT/RT slant delay retrievals including definition for new Tro-SINEX format standards
- Derivation of 1st and 2nd order troposphere gradients from NWM
- Inter-comparison of gradients and slant delays from GNSS, NWM and WVR

Benchmark – Impact of Hydrometeors

Hydrometeors (Solheim et al., 1999):

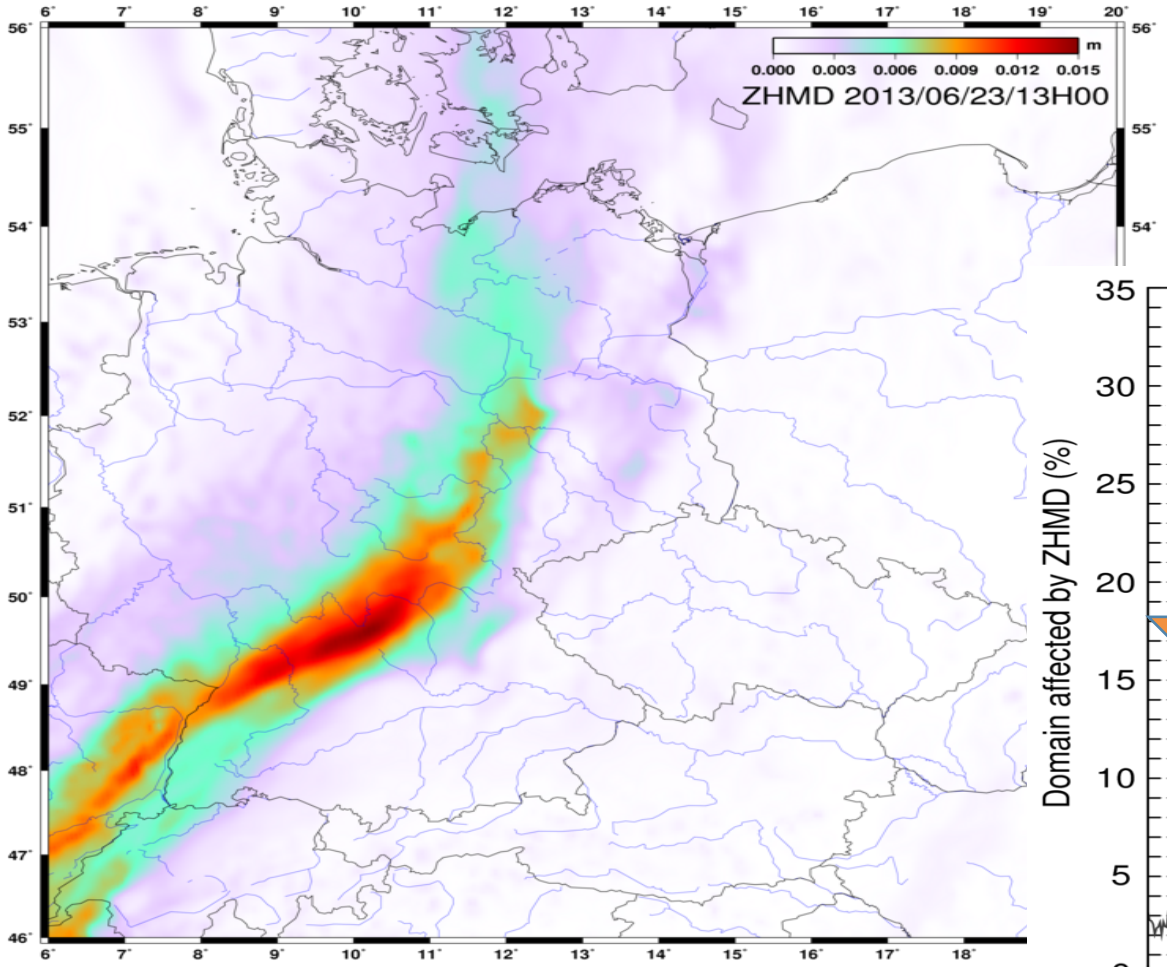
→ liquid water, ice, snow, graupel

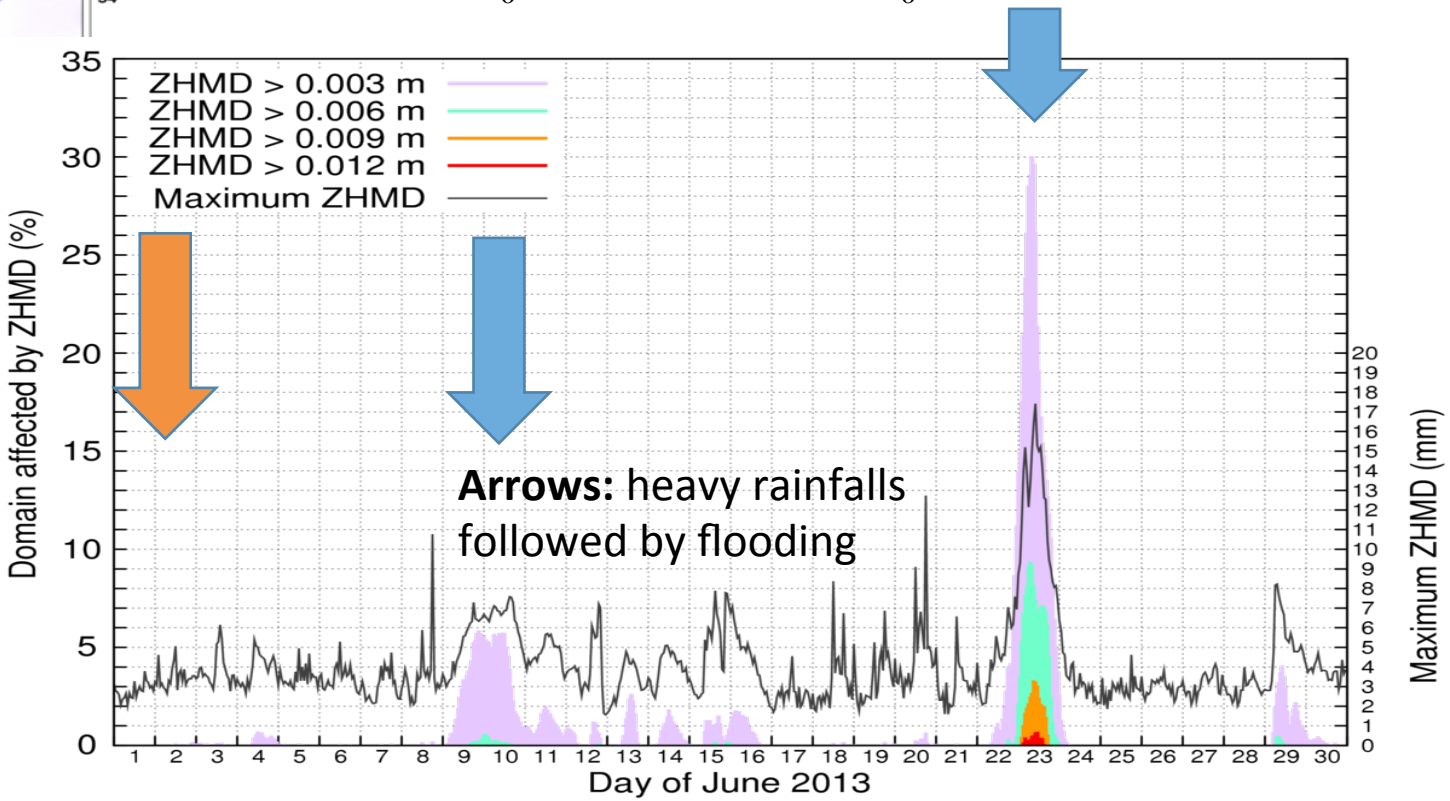
$$ZTD = ZHD + ZWD + ZHMD$$

$$ZHD = 10^{-6}\int_0^{\infty} N_h dz = 10^{-6} k_1 R_d \int_0^{\infty} \rho_m dz$$

$$ZWD = 10^{-6}\int_0^{\infty} N_v dz = 10^{-6}\int_0^{\infty}\left(k_2^{'}\frac{e}{T} + k_3\frac{e}{T^2}\right) dz$$

$$ZHMD = 10^{-6}\int_0^{\infty}\left(N_{lw} + N_{ice}\right) dz = \int_0^{\infty}\left(1.45M_{lw} + 0.69M_{ice}\right) dz$$





Real-Time products - Demonstration Campaign

- Developing, testing and assessing new software and strategies
- Use of IGS Real-Time Service global products for PPP (GNSS satellite orbits & clocks)

RT Demo campaign

Scope: Europe (15) + Globe (17)

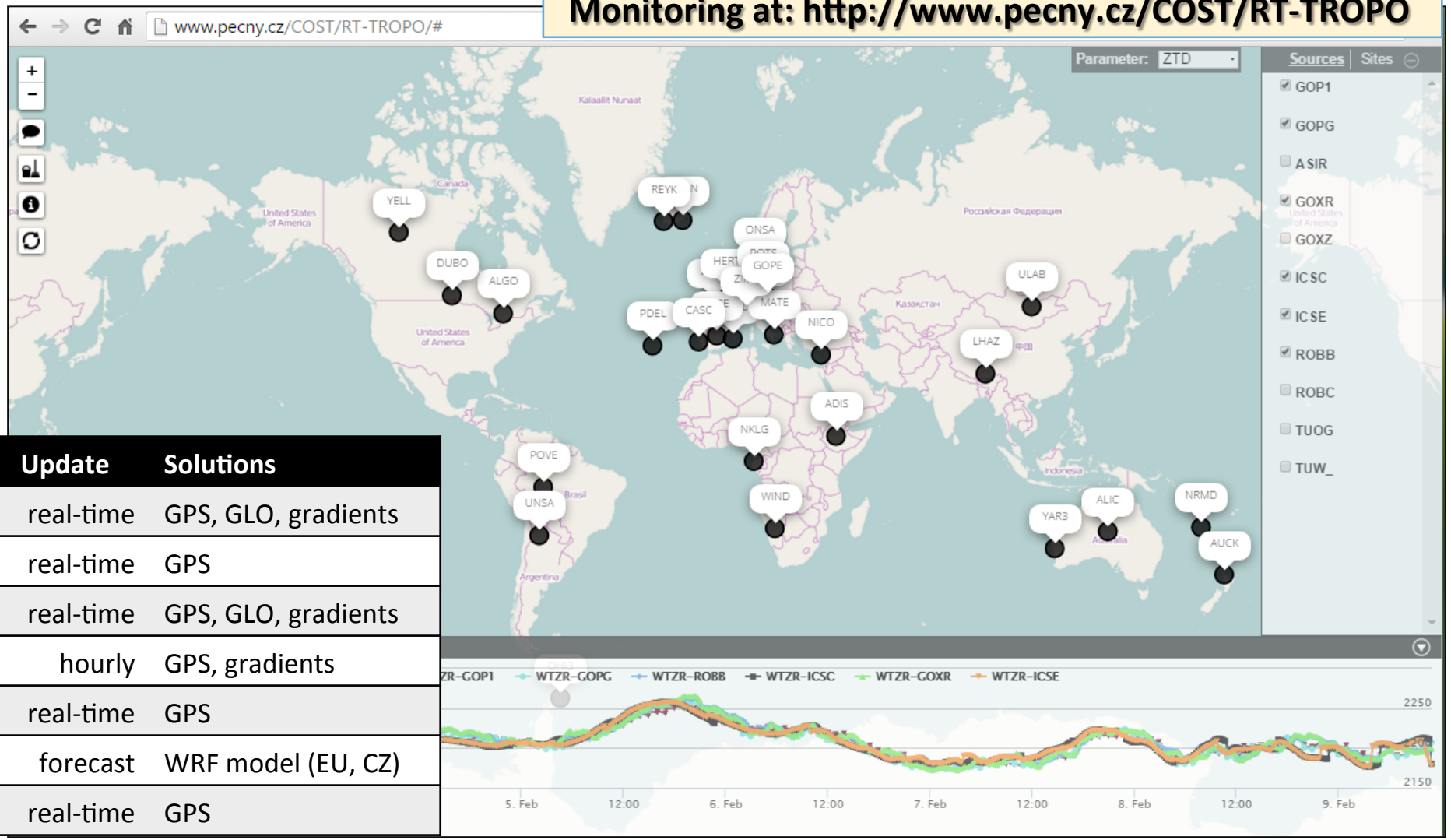
Start: April 1, 2015

Status: 2 Feb, 2016

Software: 6+1 types

Contributions: 6+1 ACs

Monitoring at: http://www.pecny.cz/COST/RT-TROPO



AC	Software	Start	Update	Solutions
GOP	G-Nut/Tefnut	9.4. 2015	real-time	GPS, GLO, gradients
TUW	TUW software	15.4. 2015	real-time	GPS
ROB	G-Nut/Tefnut	23.4. 2015	real-time	GPS, GLO, gradients
ASI	Gipsy-Oasis	5.5. 2015	hourly	GPS, gradients
UL	BNC, PPP-wizard	15.6. 2015	real-time	GPS
ICS	G-Nut/Shu	12.7.2015	forecast	WRF model (EU, CZ)
TUO	RTKLib	5.11.2015	real-time	GPS

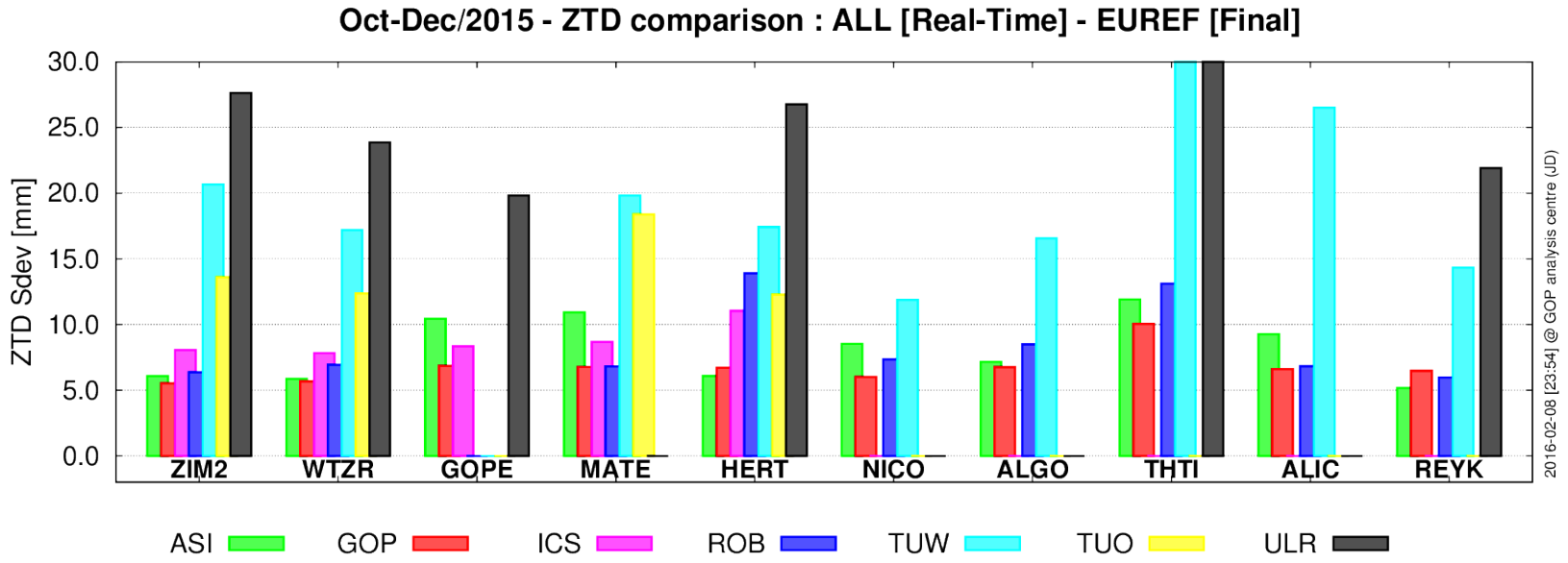
Real-Time Campaign – Recent Evaluations

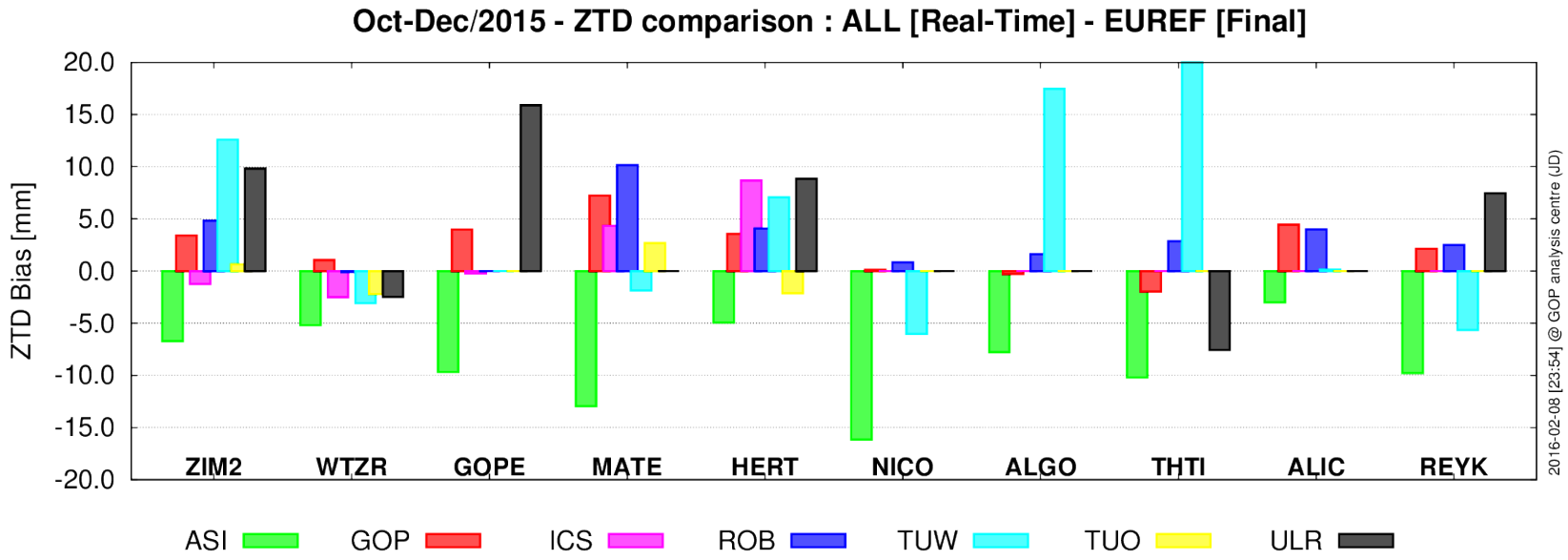
Initial phase

- Common settings
- Software development
- Strategy enhancement
- Parameter extension
- Stability improvement
- Format standardization
- Continuous monitoring
- Benchmark exploitation

Final solution

- For a limited interval
- Synchronized data inputs
- Product final evaluation





Impact of NWM forecast length

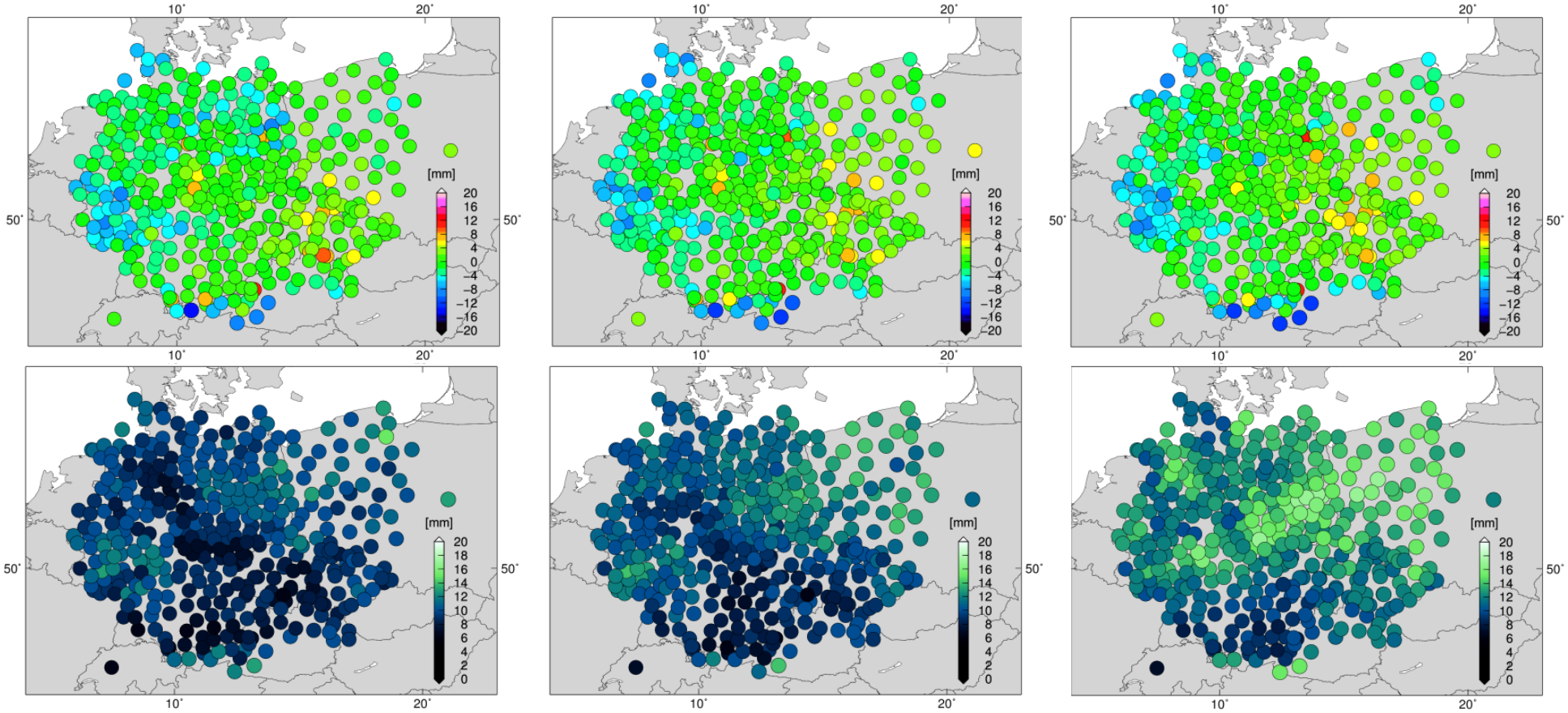
NWM forecast

Provider: Institute of Computer Science, Czech Republic

Model: WRF 3.6
Domain: EU
Resolution: 9×9 km
Levels: 38 vertical
Software: G-Nut/Shu (GOP)

Assessment

Network: All benchmark
Period: 14 days



Predicted ZTD

Degradation:

1-2 mm / 6 hours

NWP domain	Forecast window	Bias [mm]	Sdev [mm]	RMS [mm]
D01/EUR	0-6 h	- 1.50	9.93	10.42
D01/EUR	**6-12 h**	**- 0.89**	**10.95**	**11.55**
D01/EUR	12-18 h	- 0.51	12.91	13.48

Real-Time Simulation within Benchmark

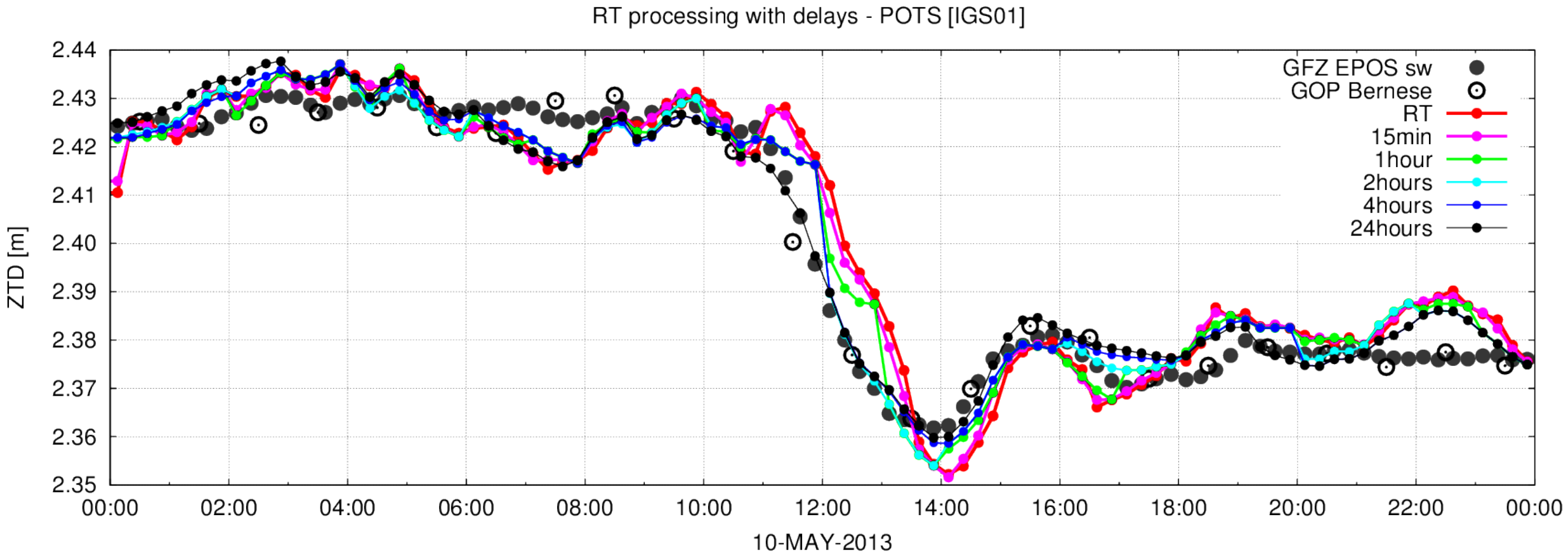
- GOP's PPP with G-Nut/Tefnut using IGS Final and IGS real-time orbits + clocks

ZTD (PPP, different inputs)	GNSS reference product (various)	Pairs #	Bias [mm]	Sdev [mm]	RMS [mm]
IGS final SP3	GOP final (Bernese/DD)	1319	+0.9	5.1	5.2
IGS01 RT simulated	**GOP final (Bernese/DD)**	**1158**	**+2.4**	**5.8**	**6.4**
IGS final SP3	GFZ final (EPOS/PPP)	1319	+0.4	4.1	4.2
IGS01 RT simulated	**GFZ final (EPOS/PPP)**	**1158**	**+2.8**	**4.9**	**5.7**
IGS final SP3	ERA-Interim (DNS)	219	- 0.4	9.1	9.3
IGS01 RT simulated	**ERA-Interim (DNS)**	**154**	**+2.1**	**9.0**	**9.4**
IGS final SP3	Aladin-CZ (G-Nut/Shu)	1317	+0.7	7.6	7.8
IGS01 RT simulated	**Aladin-CZ (G-Nut/Shu)**	**1158**	**+2.8**	**8.0**	**8.8**

GNSS PPP inputs	GNSS reference product	North gradient				East gradient		
		Pairs #	Bias [mm]	Sdev [mm]	RMS [mm]	Bias [mm]	Sdev [mm]	RMS [mm]
PP – IGS final	GOP (Bernese)	1318	+0.09	0.35	0.38	+0.03	0.36	0.37
RT – IGS01	**GOP (Bernese)**	**1158**	**- 0.03**	**0.45**	**0.46**	**+0.26**	**0.44**	**0.52**
PP – IGS final	ERA-Interim	219	+0.09	0.34	0.36	+0.01	0.37	0.38
RT – IGS01	**ERA-Interim**	**154**	**- 0.05**	**0.42**	**0.43**	**+0.19**	**0.42**	**0.47**

Real-Time Simulation – Kalman filter + smoother

- Final ZTDs: GOP's Bernese (1h, network solution) and GFZ's (15min, PPP)
- Simulated RT/NRT ZTDs (IGS01 from IGS RTS): GOP's G-Nut/Tefnut software (5 min, PPP)
- NRT simulation (Kalman+smoother): different smoothing update: 15min, 1h, 2h, 4h, 24h



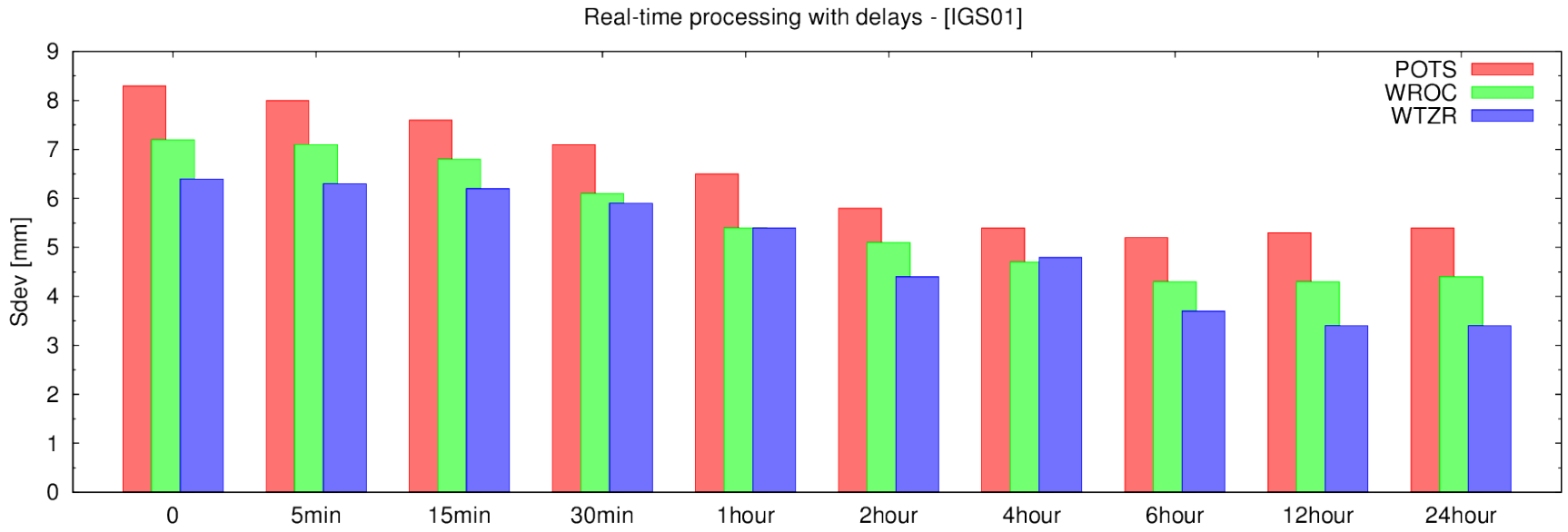
Real-Time Simulation – Kalman filter + smoother

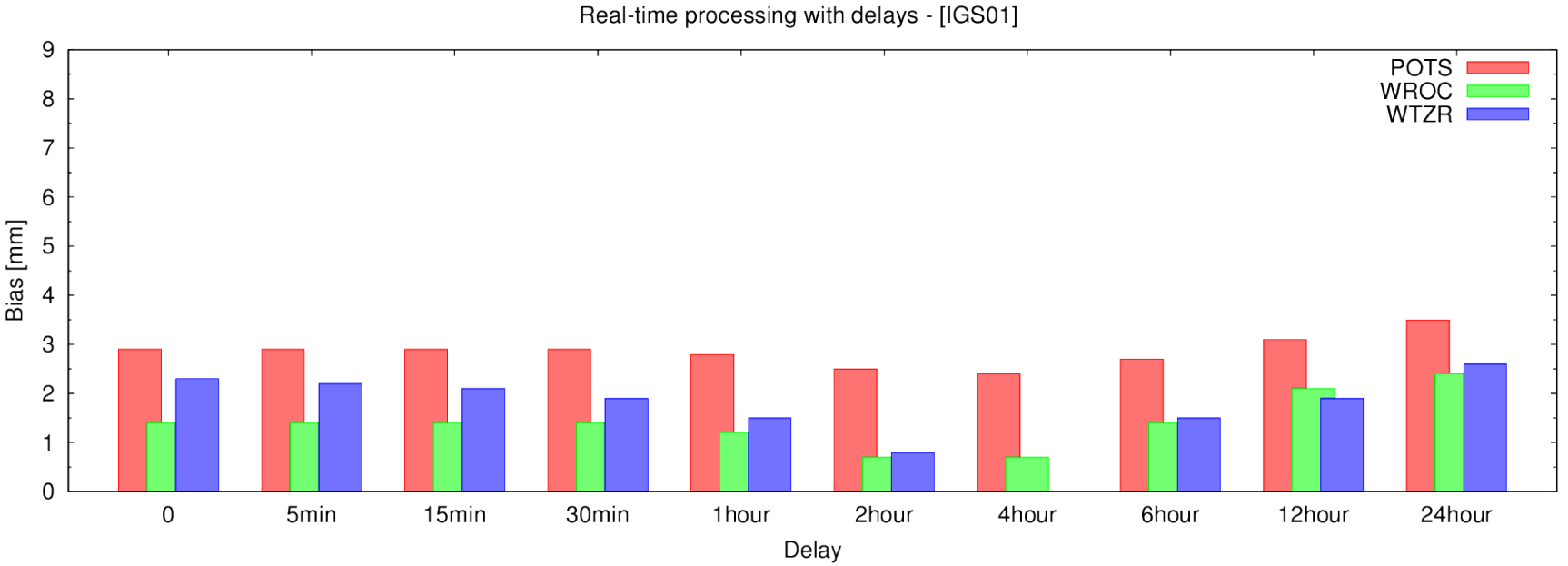
- PPP, G-Nut/Tefnut (GOP)
- IGS01 orbit & clocks

- Simulated near real-time
- Converged solutions
- High-resolution product

→ The precision of high-resolution ZTDs has been improved by smoother with delays up to 4 hours

→ Smoother hasn't been able to improve accuracy of ZTD for sub-daily run





Summary

Troposphere gradients

- Extreme gradients observed in a dense network (up to 7mm)
- Significantly lower magnitudes of gradients observed in all NWPs
- In some situations varies significantly, new information for NWP nowcasting …

Real-time development

- RT ZTDs using PPP and IGS RTS products in RT Demo campaign (6 contributions)
- StdDev 5-9 mm for stable solutions, Bias < 5mm (but still highly site-specific)
- Offline simulated ZTD estimates using IGS RTS and IGS Final products showed a mean degradation of 1 mm in StdDev and about 2 mm mean bias

NWM for external troposphere corrections

- Accuracy of NWMs is 8-12 mm
- ZTD mean accuracy degradation with longer prediction is 1-2 mm / 6 hours

Hydrometeors

- Non-negligible components in rare situations, may impact ZTDs up to 2 cm!

Acknowledgements

- IGS for data and variety of GNSS products and models (RTS, MGEX, Final, PCO/PCVs, …)
- EUREF for reference frame GNSS stations
- EPOSA, SAPOS, ASG-EUPOS, CZEPOS, VESOG, GEONAS, Trimble for GNSS data
- ECMWF for global ERA-Interim re-analysis numerical weather model
- NCEP for Global Forecast System (GFS) numerical weather model
- CHMI for mesoscale Aladin-CZ numerical weather model

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