Towards a flexible real-time and near real-time system for monitoring troposphere

Jan Douša, Pavel Václavovic

Geodetic Observatory Pecný (GOP)
RIGTC, Czech Republic

IGS Workshop

July 3-7, 2017, Paris, France

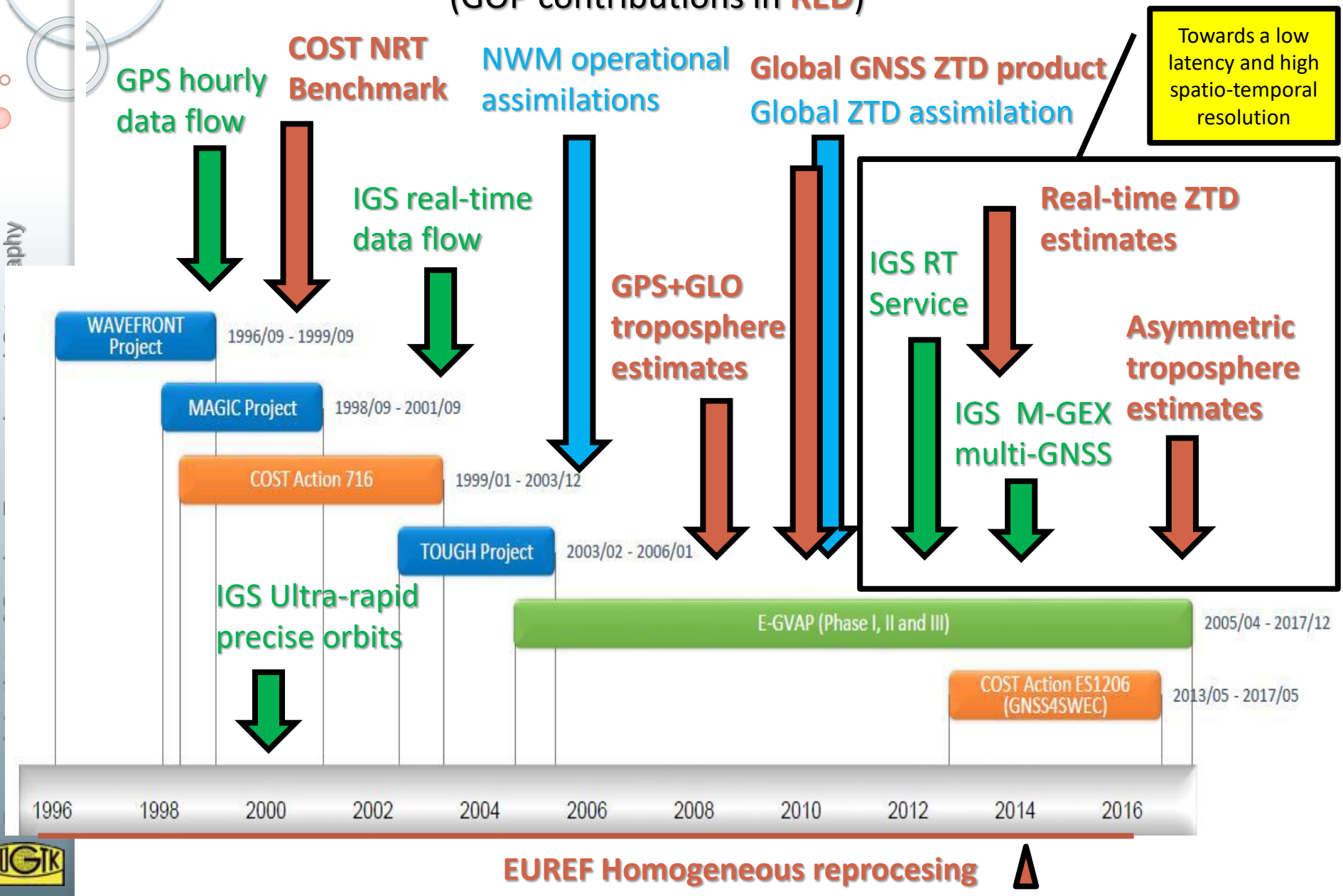
Outline

- Motivation
- Real-time demonstration
- GOP's flexible real-time/NRT system
- Real-time simulation studies
  - Product assessment
  - IWV, gradients, slant delays (severe weather)
  - Synergy with NWM data processing
- Conclusion

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Developments in GNSS meteorology

(GOP contributions in RED)



Standard near-real time processing

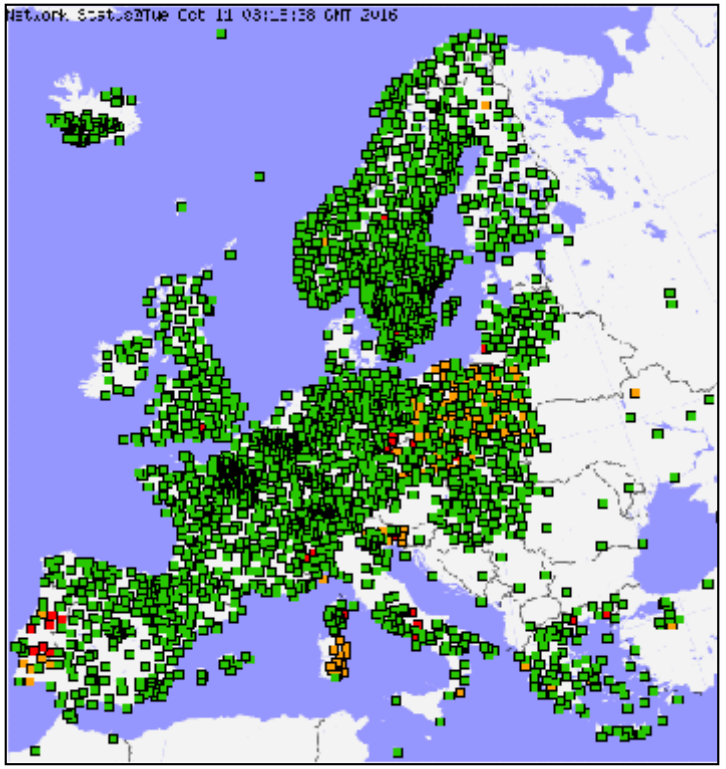
The EIG EUMETNET GNSS Water Vapour Programme, E-GVAP I-III (2005-2019)

Current status:

- Focus is on **hourly processing for** ZTDs near real-time processing for results **within 90 min**
- In support of operational dissemination, quality control and assimilation of GNSS ground-based ZTD
- Contributions of **20 analysis centres**
- Project coordinating the **near real-time** delivery of data from ~2600 GPS sites

EUMETNET
The Network of European Meteorological Services

http://egvap.dmi.dk



Strategy:

- **IGS Ultra-rapid orbits** used in **double-difference** processing strategy within most (18) analysis centres

→ **due to the lack of IGS product for NRT PPP** ☹

- **PPP method** used at GFZ (Germany) and, historically, also at NGA (Sweden) when **both ACs calculated global satellite clocks** before NRT processing

→ **however, since 2013 IGS RTS is available** ☺

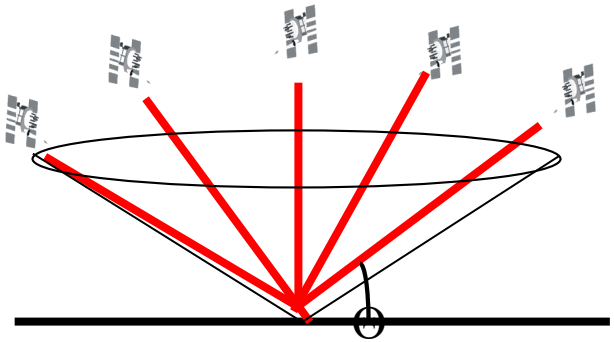
Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

PPP for GNSS meteorology

PPP method is very interesting from different reasons:

- ✓ Autonomous and 'absolute' method
- ✓ Implicitly ready for a global scale
- ✓ Optimally supporting multi-GNSS constellations

- ✓ In particular, highly efficient for
  - real-time processing
  - high temporal resolution of products
  - estimating horizontal gradients
  - retrieving slant delays



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

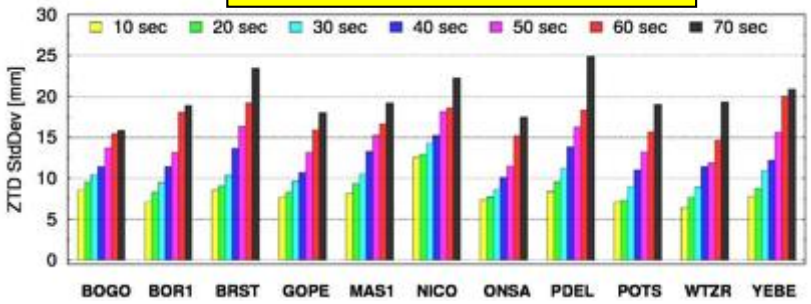
Initial real-time ZTD assessment (2013)

GOP half-year real-time demonstration

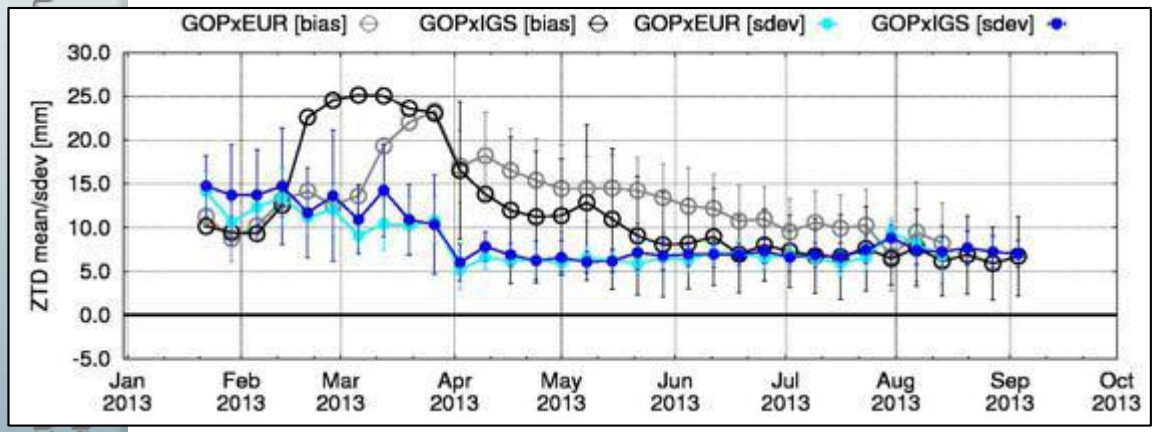
→ GOP's G-Nut/Tefnut PPP software

- ZTD from static processing
- ZTD from pseudo-kinematic processing
- Impact of IGS RTS precise corrections delays
- Impact various RT precise corrections

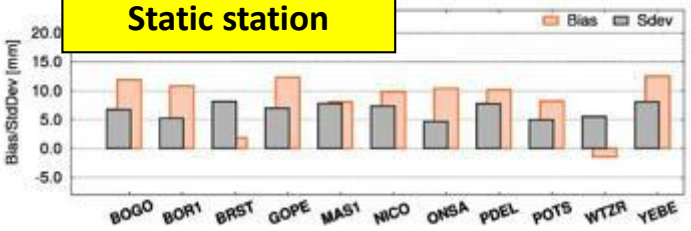
Impact of delay/prediction



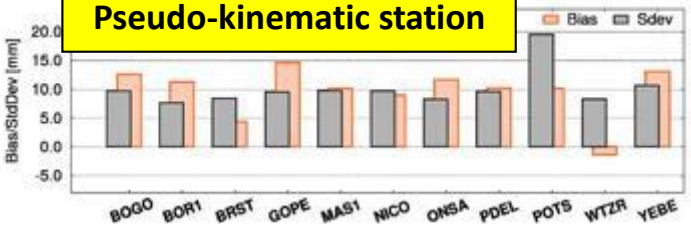
Douša J, Václavovic P, **Real-time zenith tropospheric delays in support of numerical weather prediction applications**, Adv Space Res, 2014



Static station



Pseudo-kinematic station



GOP + Uni Luxembourgh: 2-month RT campaign (Global + Europe)

- Comparison of different software: BNC, PPP-wizard, G-Nut/Tefnut

Ahmed F, Václavovic P, Teferle FN, Douša J, Bingley R, Laurichesse D, **Comparative analysis of real-time precise point poisitioning zenith total delay estimates**, GPS Solutions, 2016

GNSS4SWEC Real-time Demo (2015-..)

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

RT Demo campaign

Scope: Europe (15) + Globe (17)

Start: April 1, 2015

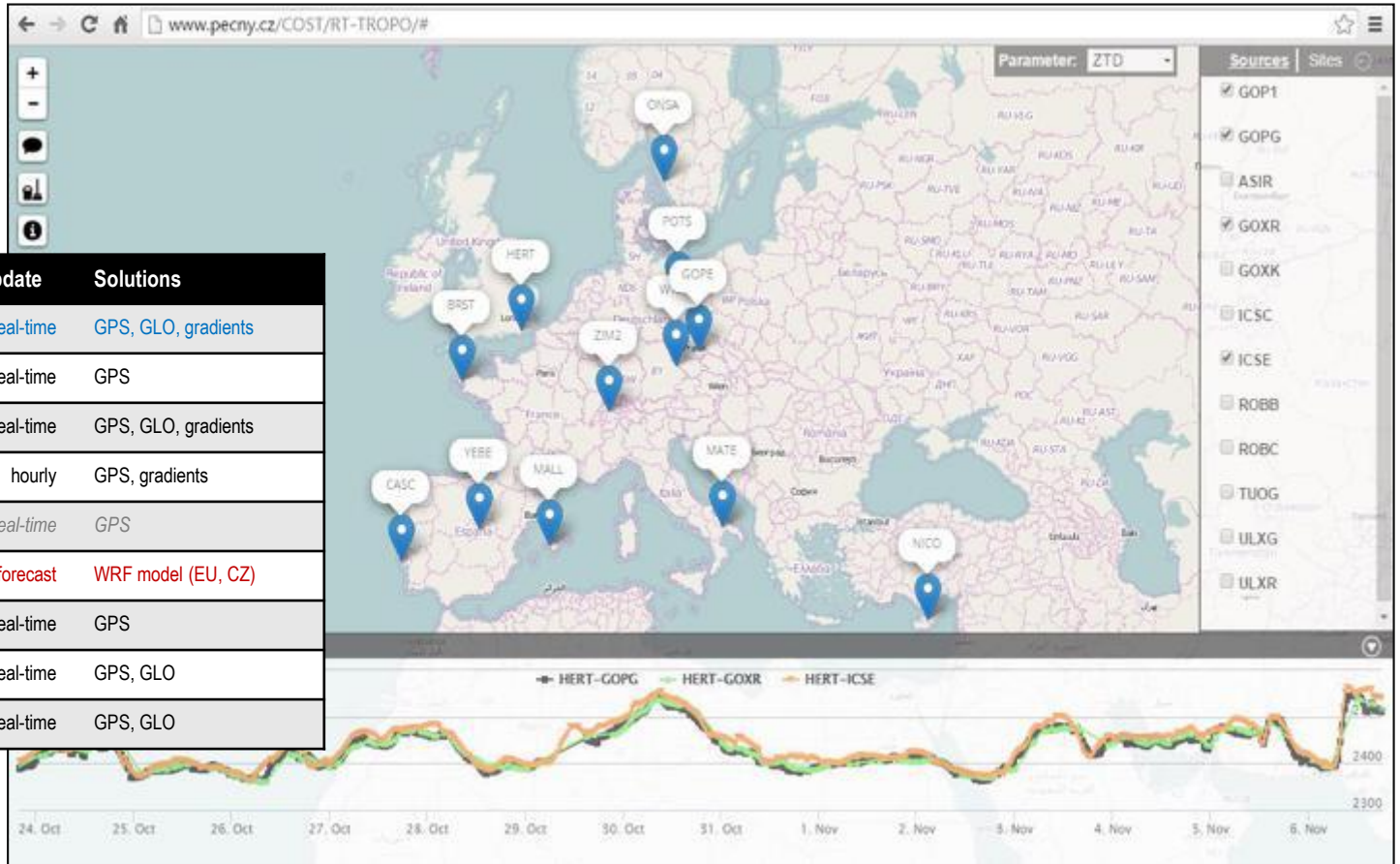
Status: 2 March, 2016

Software: 6+1 types

Contributions: 7+1 ACs

Real-time monitoring: 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	*(PPP-wizard)*	*15.6. 2015*	*real-time*	*GPS*
ICS	G-Nut/Shu (GOP)	12.7.2015	forecast	WRF model (EU, CZ)
TUO	RTKLib	5.11.2015	real-time	GPS
BKG	BNC	1.3.2016	real-time	GPS, GLO
GFZ	EPOS-RT	18.2.2017	Real-time	GPS, GLO

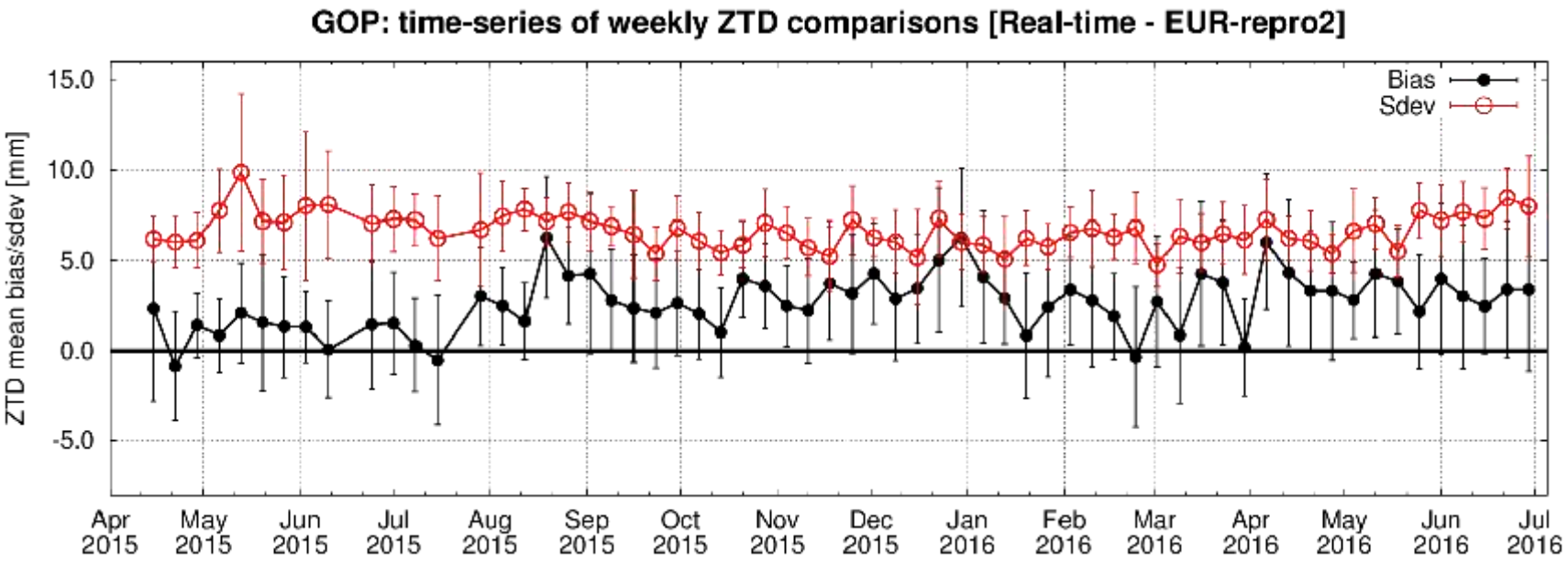


Results of RT-Demonstration campaign

Statistics over selected IGS/EUREF stations and all solutions since the beginning of RT-Demo (2015/Mar – 2016/Aug)

– GOP RT PPP solutions w.r.t. EUREF Final combined product

Solution (Europe) – reference (R2_EUR)	BIAS [mm] median ± sdev	SDEV [mm] median ± sdev	RMSE [mm] median ± sdev	PAIRS [#] Median
RT_GOPQ	1.8 ± 2.9	6.7 ± 1.2	7.5 ± 2.5	4184
RT_GOPR	2.0 ± 2.8	7.2 ± 1.0	7.9 ± 1.5	5682



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Impact of RT products on tropo estimates

G-Nut/Tefnut's PPP tropospheric products in GNSS4SWEC Benchmark

- IGS final orbit and clocks
- IGS real-time orbits and clocks

Dousa et al (2016): Benchmark campaign and case study episode in Central Europe, AMT

Zenith total delays (over 400 European stations)

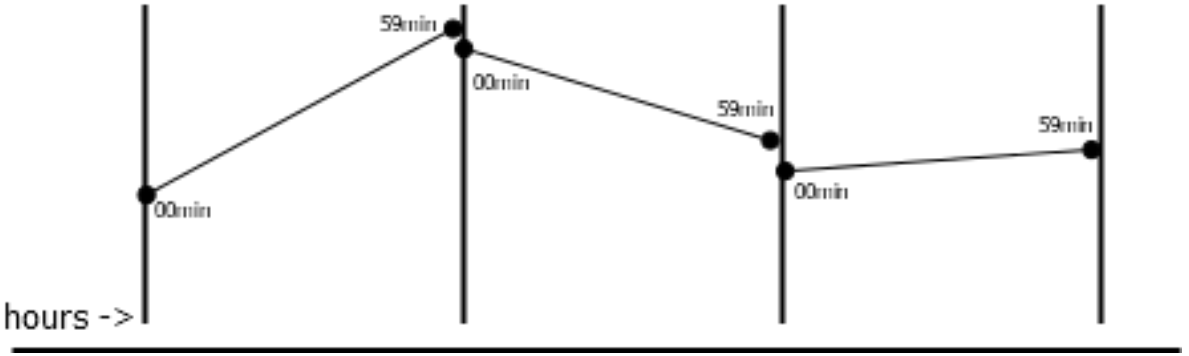
G-Nut/Tefnut PPP Input precise products	ZTD reference product	Pairs #	Bias [mm]	Sdev [mm]	RMS [mm]
IGS final SP3	GOP final (Bernese/DD)	1319	+0.9	5.1	5.2
IGS01 RT simulated	**GOP final (Bernese/DD)**	**1158**	**+2.4**	**5.8**	**6.4**
IGS final SP3	GFZ final (EPOS/PPP)	1319	+0.4	4.1	4.2
IGS01 RT simulated	**GFZ final (EPOS/PPP)**	**1158**	**+2.8**	**4.9**	**5.7**

Tropospheric horizontal linear gradients (over 400 European stations)

G-Nut/Tefnut input products	Gradients reference product	Pairs #	N - Bias [mm]	N - Sdev [mm]	E - Bias [mm]	N - Sdev [mm]
PP – IGS final	GOP (Bernese)	1318	+0.09	0.35	+0.03	0.36
RT – IGS01	**GOP (Bernese)**	**1158**	**- 0.03**	**0.45**	**+0.26**	**0.44**

GOP's flexible RT+NRT product

Standard NRT solution (e.g. GOP's Bernese V52):



Flexible RT+NRT solution (G-Nut/Tefnut) … enabled by IGS RTS and PPP

1. RT - Kalman filter
2. NRT - Kalman+smoother

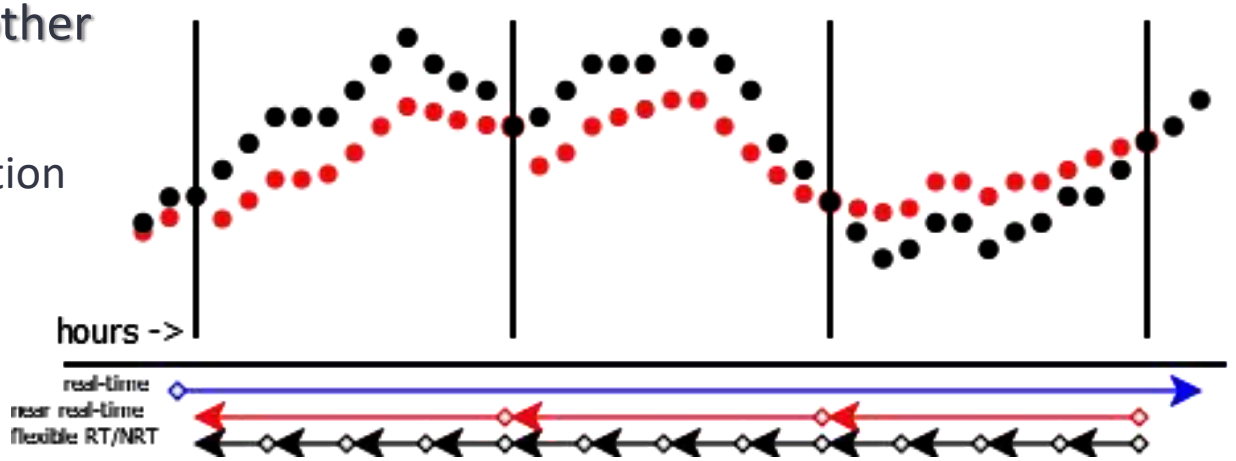
➔ one-pass process

➔ NRT/RT smooth transition

➔ flexible configuration

PLAYING AROUND

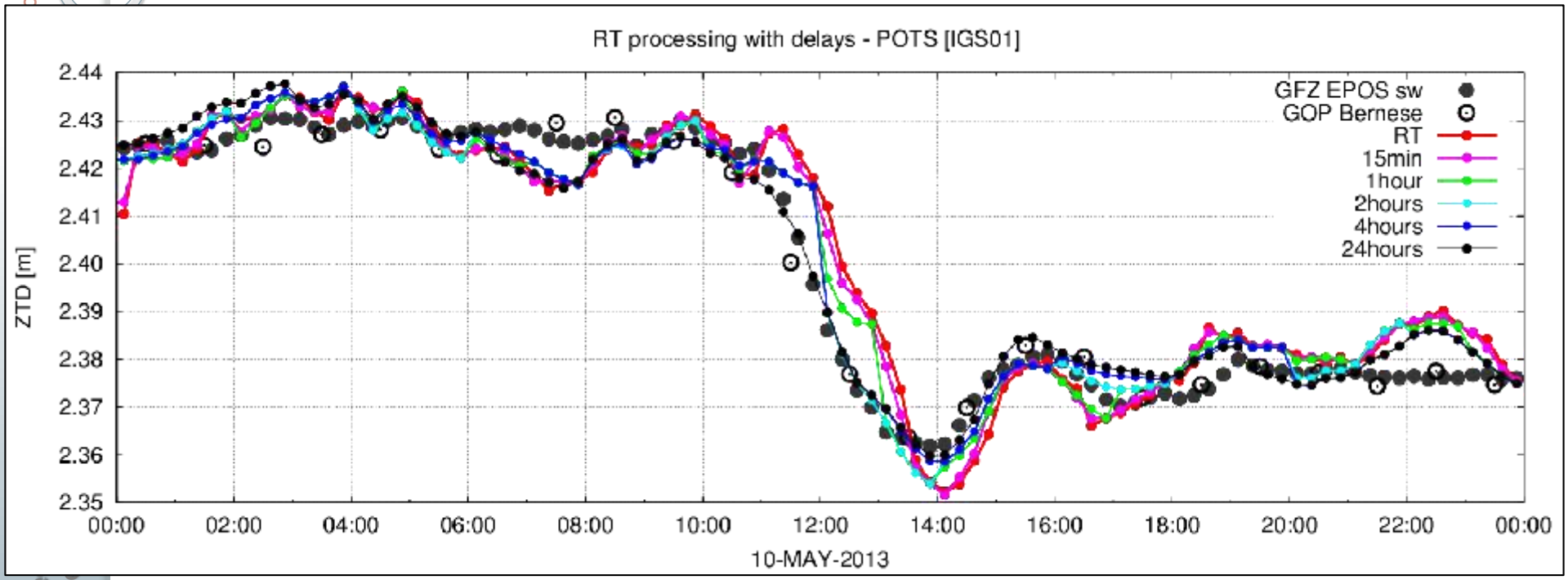
ACCURACY & LATENCY



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Václavovic P, Douša J (2015), Backward smoothing for precise GNSS applications, Adv Space Res, 56(8):627-1634

Testing optimal strategy (Benchmark)

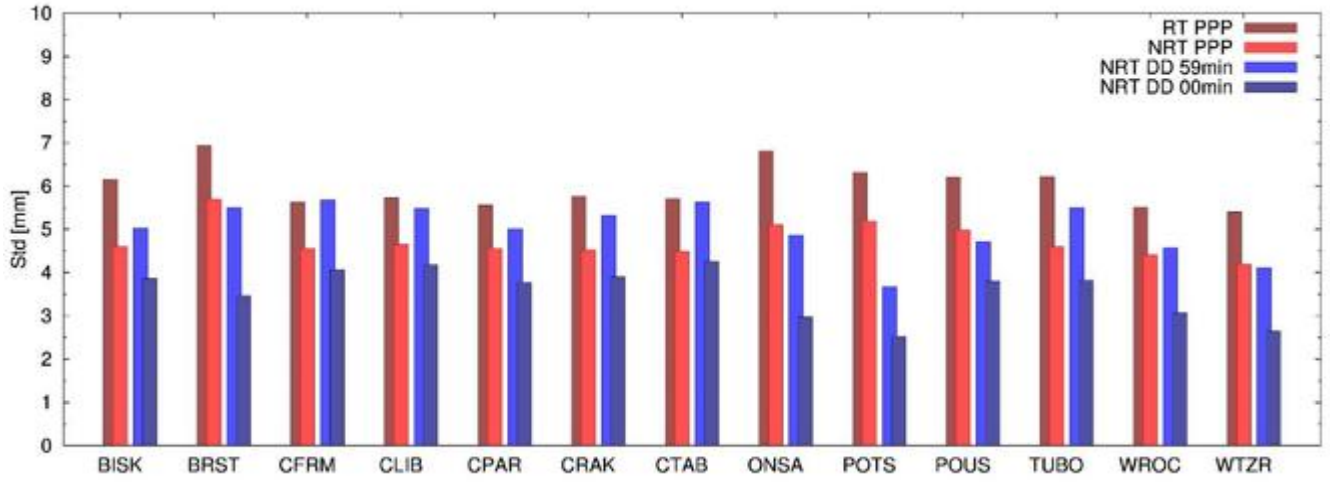


- Final ZTDs: GOP's Bernese (1h, network solution) and GFZ's (15min, PPP)
- Simulated RT ZTDs (IGS01): GOP's G-Nut/Tefnut software (5 min, PPP)
- Kalman+smoother – different smoothing update: 15min, 1h, 2h, 4h, 24h

GOP's flexible RT vs NRT PPP results

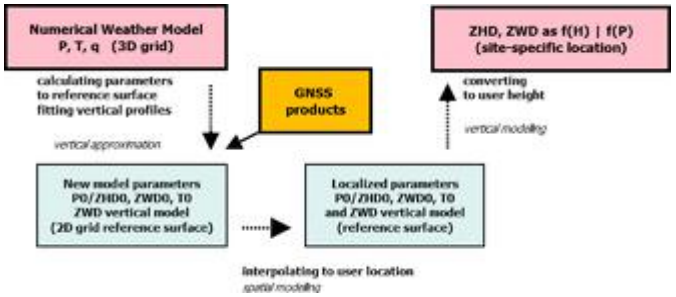
Comparison of new PPP results w.r.t. GOP NRT contribution to E-GVAP

Solution	Software	Description	Mean StdDev	Improvement
RT - PPP 59 min	*G-Nut/Tefnut*	Current estimates based on Kalman filter only	5.9 mm	20 %
NRT - PPP 00 min	*G-Nut/Tefnut*	Last smoothed epoch from hourly backward smoothing	4.7 mm	
NRT - DD 59 min	*Bernese V52*	Second value of hourly peace-wise linear ZTD given at every 59 min	5.0 mm	24 %
NRT - DD 00 min	*Bernese V52*	First value of hourly peace-wise linear ZTD given at every 00 min	3.8 mm	

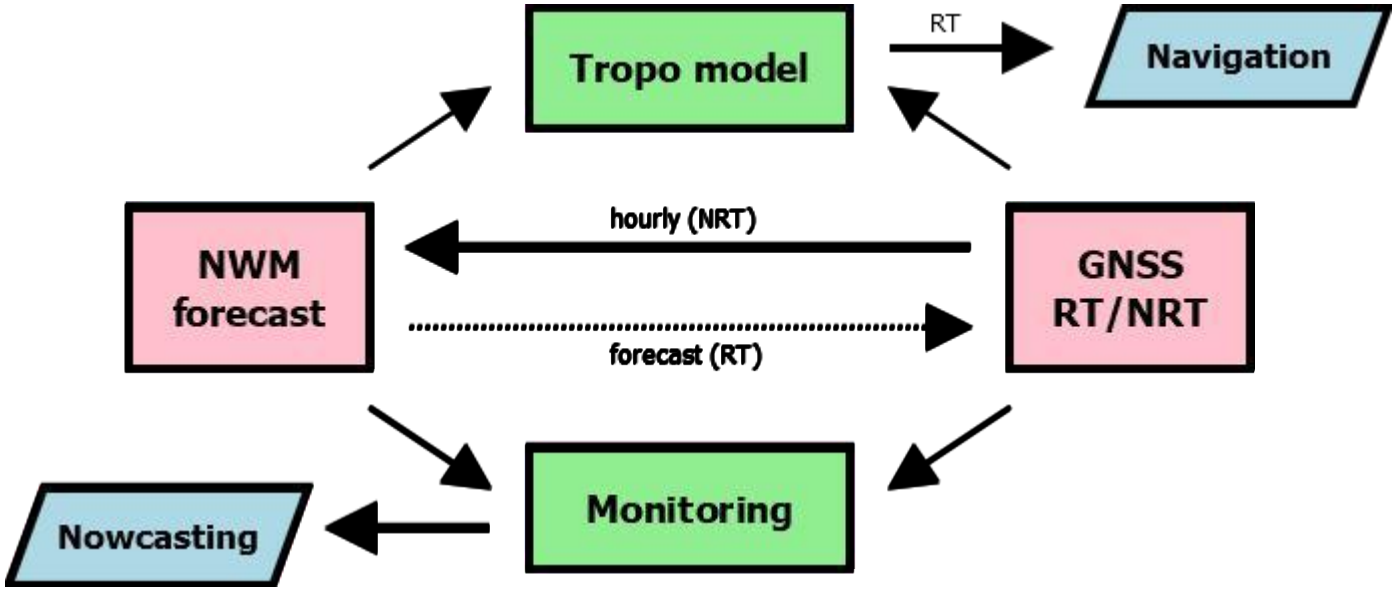


Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Synergy in Tropo modelling & monitoring



- Troposphere modelling (NWM)
- Troposphere monitoring (GNSS)
- Assimilation of GNSS in NWM
- Exploitation of Tropo corrections in GNSS real-time kinematic applications



→ Completing prototype in Czech Republic using NWM and GNSS RT/NRT processing

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

Troposphere asymmetry monitoring

Hydrostatic (ZHD) and non-hydrostatic (ZWD) zenith tropospheric delays

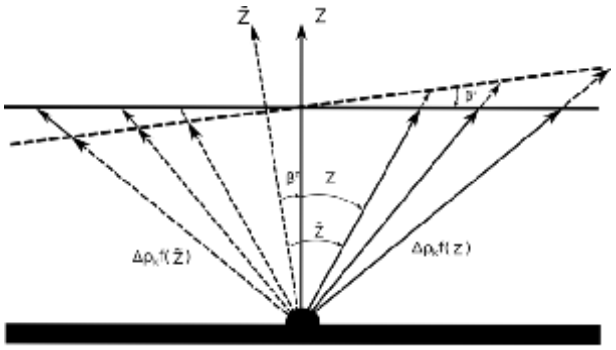
elevation *dependent model*

$$\Delta\rho_{rec}^{sat}(e,A) = mf_h(e)\cdot ZHD + mf_w(e)\cdot ZWD + mf_g(e)\left[G_N\cos(A) + G_E\sin(A)\right] + res - mpt$$

mf_h, mf_w, mf_g - mapping functions (hydrostatic, non-hydrostatic and gradient)

elevation/azimuth *dependent model*

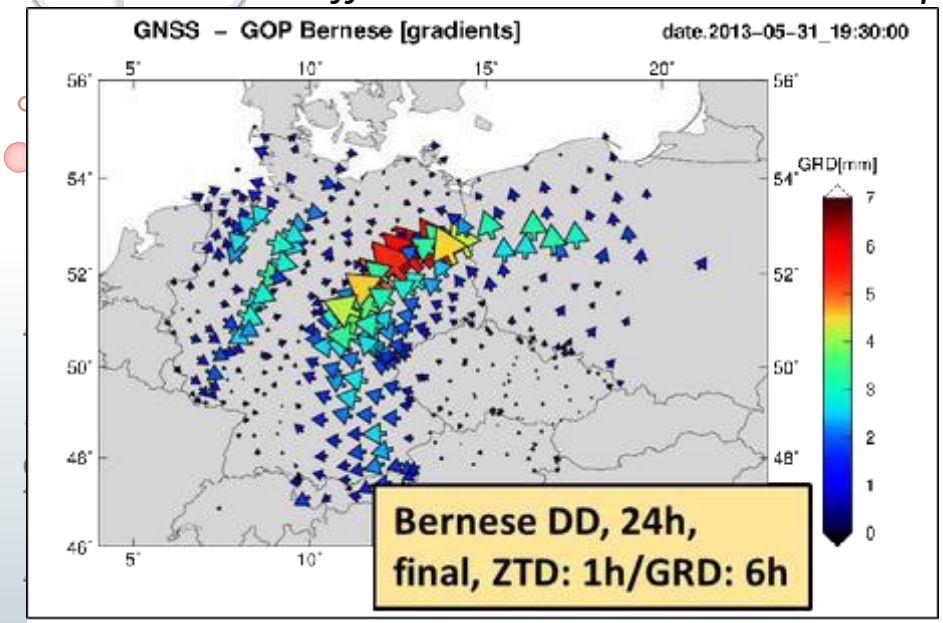
Total (slant) *tropospheric delay btw. satellite and receiver*

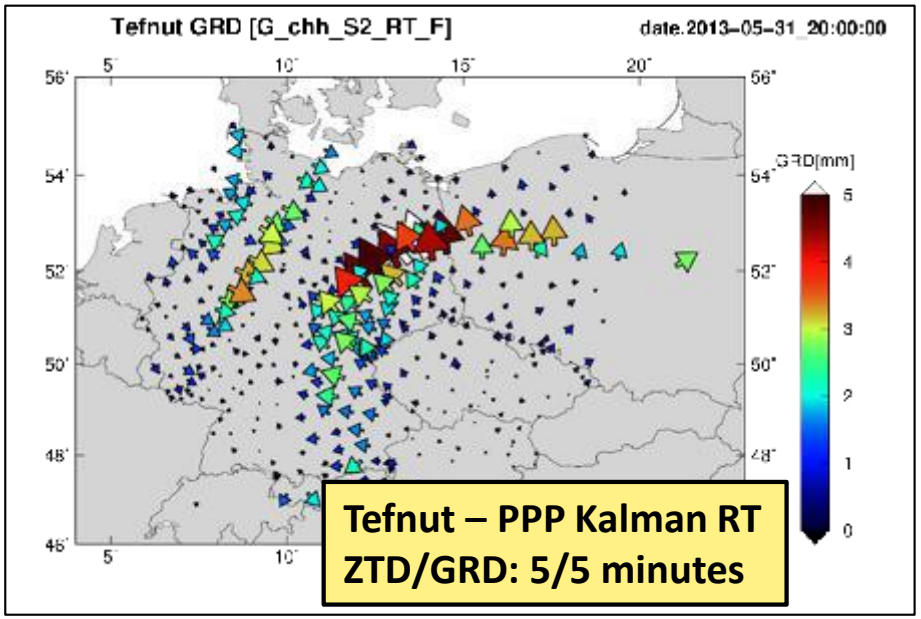


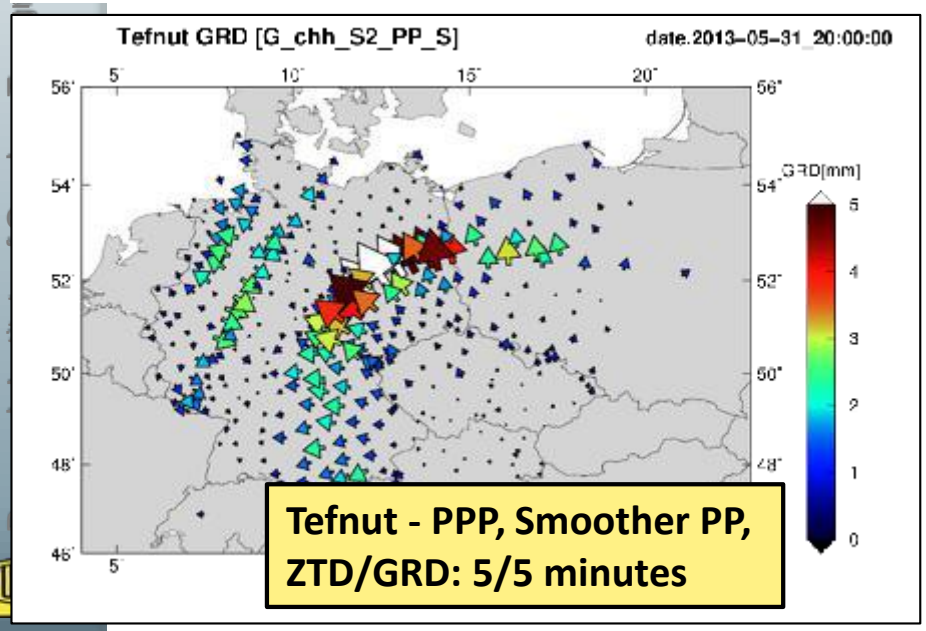
Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

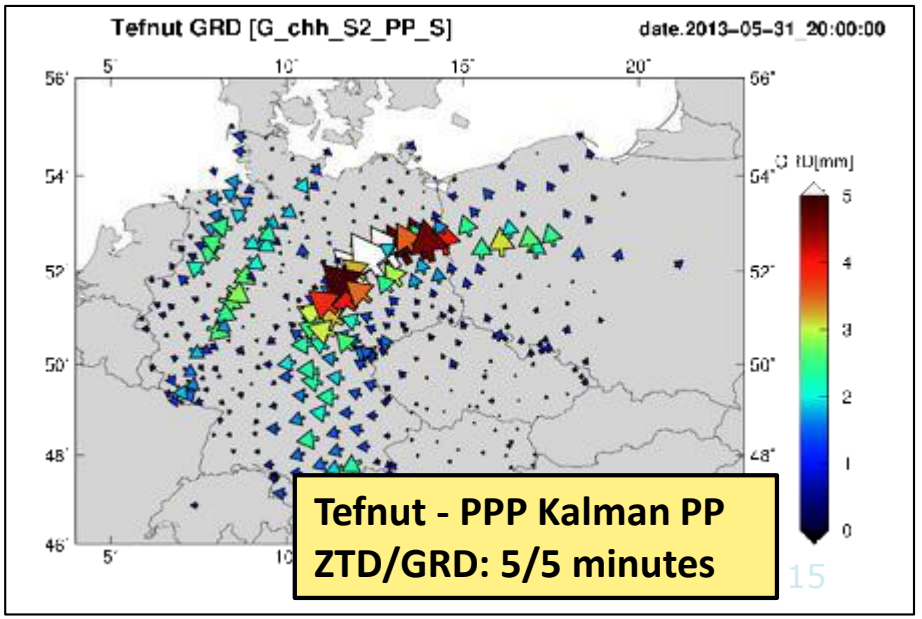
GNSS Tropospheric Gradients

offline and simulated real-time processing (Bernese DD & G-Nut/Tefnut PPP)



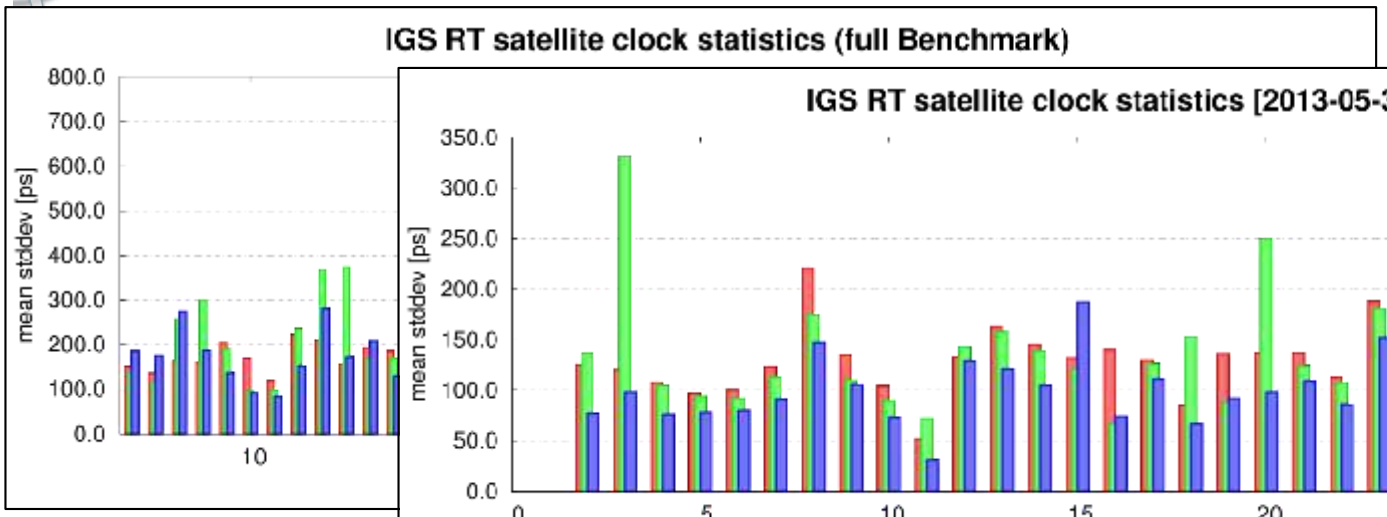


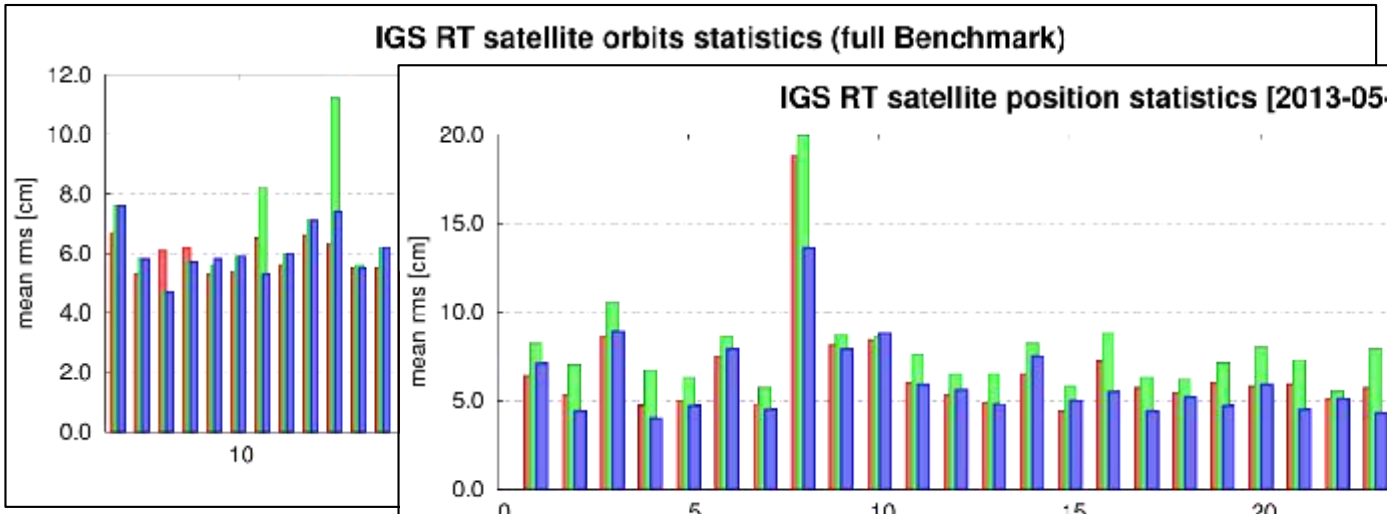




Assessment of IGS RT products

GNSS4SWEC Benchmark (May-June 2013) and particular day 2013-05-31



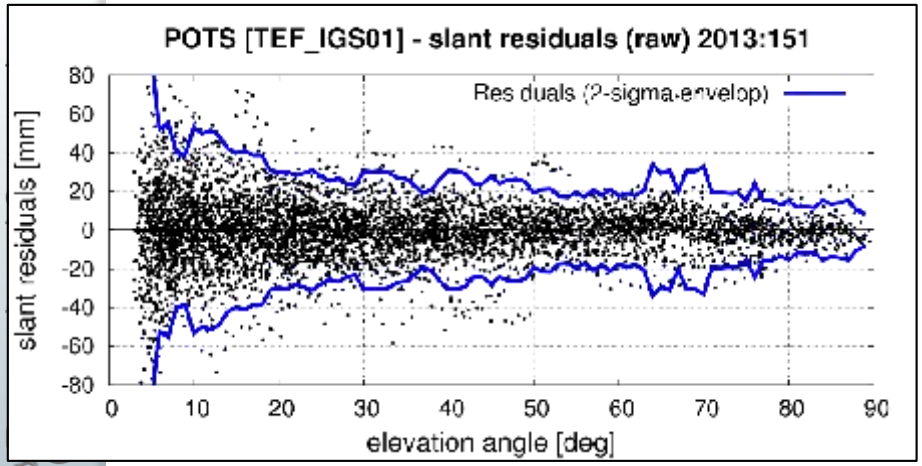


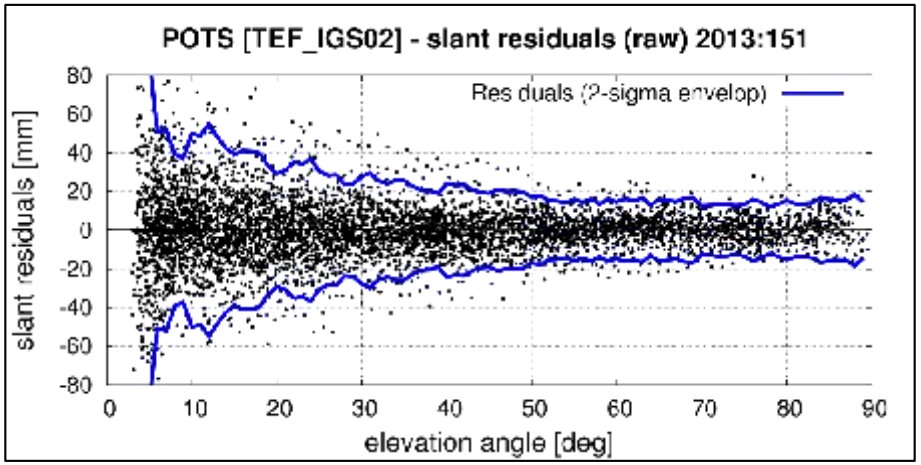
Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

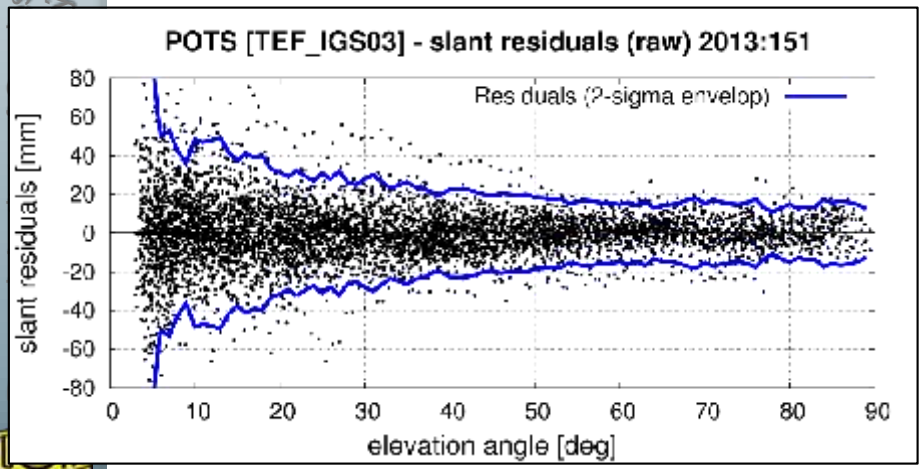
Slant residuals (G-Nut/Tefnut PPP)

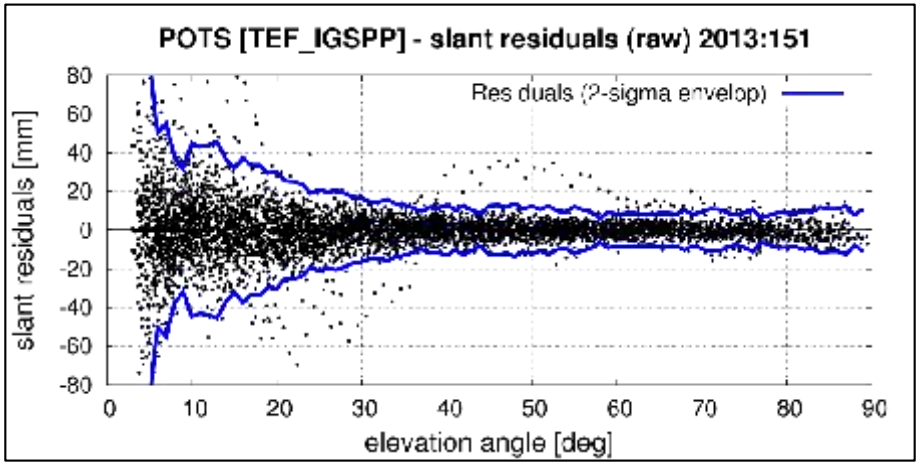
Visualization of slant residuals for different precise products:

1. Real-time IGS01
2. Real-time IGS02
3. Real-time IGS03
4. IGS Final (operational)





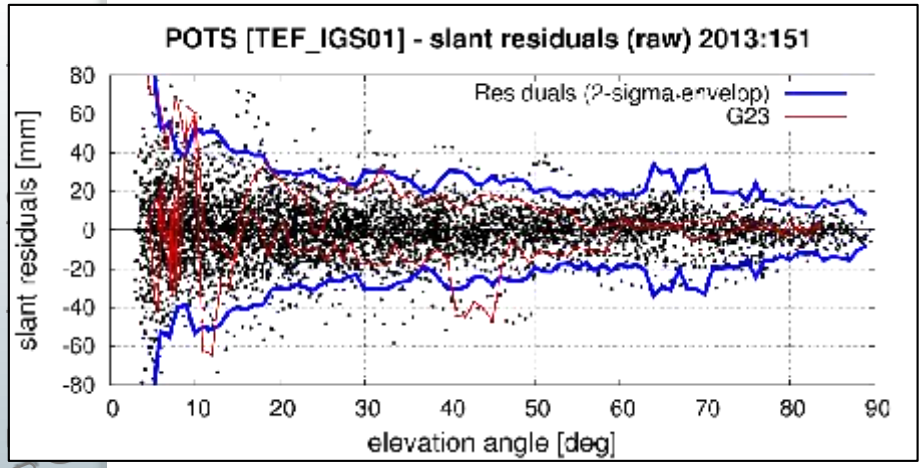


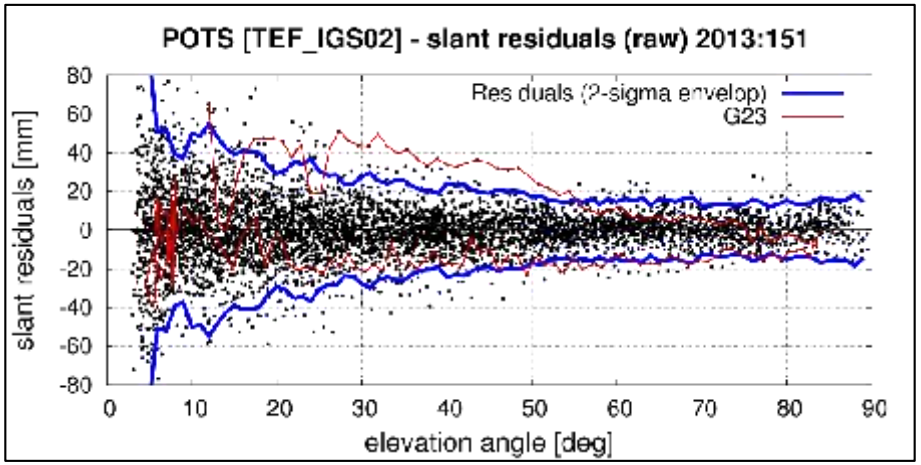


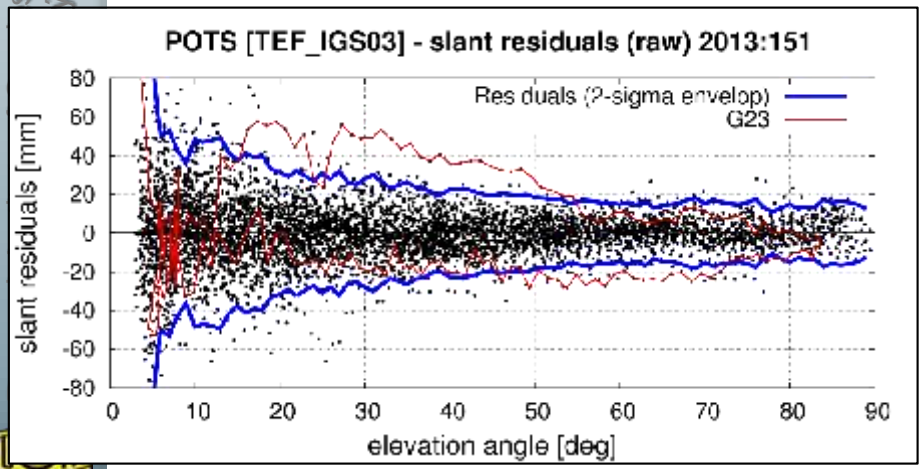
Slant residuals (G-Nut/Tefnut PPP)

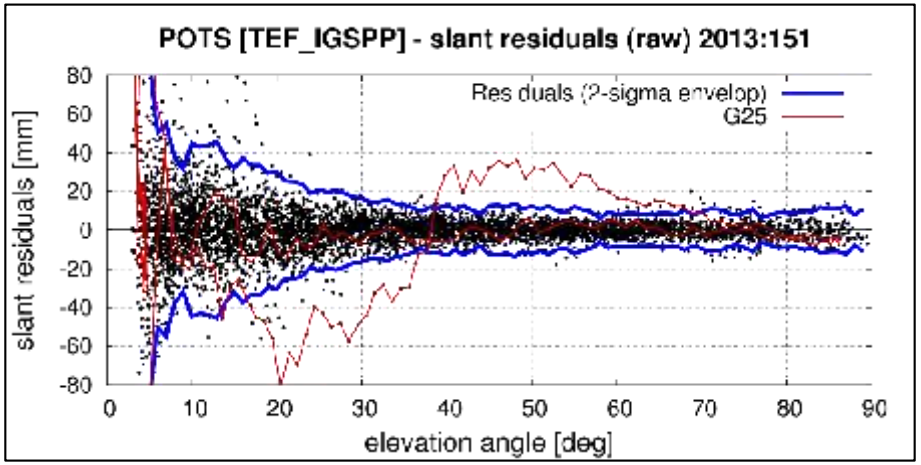
Visualization of slant residuals for different precise products:

1. Real-time IGS01
2. Real-time IGS02
3. Real-time IGS03
4. IGS Final (operational)









Conclusions

- The IGS Real-time service is highly appreciated
  - filling the gap in IGS products for current GNSS meteorology
  - suggesting to enhance current tropospheric products towards
    - high spatio-temporal resolution
    - ultra-fast production and
    - optimal multi-GNSS processing
- RT ZTD products are reliable and satisfactory for nowcasting
  - particularly in precision of estimated ZTD/gradients
  - but still sensitive to significant systematic errors
- GOP's flexible RT/NRT processing system
  - initial contribution to E-GVAP will use GOP hybrid NRT PPP solution
  - in the second step it will be optimized to an ultra-fast or RT production

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

SINEX_TRO v 2.0

```
%=TRO 2.00 GOP 2017:157:61799 GOP 2013:168:64500 2013:168:86100 P  MIX
*-------------------------------------------------------------------------------
+FILE/REFERENCE
*INFO_TYPE_________ INFO_____________________________________________________
 DESCRIPTION        GOP - Geodetic Observatory Pecny, RIGTC
 OUTPUT             Solution parameters
 CONTACT            gnss@pecny.cz
 SOFTWARE           G-Nut/Geb
 INPUT              GNSS/NWM/RAO/OTH data
 VERSION NUMBER     001
-FILE/REFERENCE
*-------------------------------------------------------------------------------
+TROP/DESCRIPTION
*_________KEYWORD_____________ __VALUE(S)_____________________________________
 TROPO SAMPLING INTERVAL       300
 SLANT SAMPLING INTERVAL       300
 DATA SAMPLING INTERVAL        300
 GNSS SYSTEMS                  G
 TROPO MODELING METHOD         KALMAN FILTER
 GEOID MODEL                   GMF/EGM96
 OCEAN TIDE LOADING MODEL      FES2004
 ATMOSPH TIDE LOADING MODEL    NOT APPLIED
 ELEVATION CUTOFF ANGLE        7
 OBSERVATION WEIGHTING         SINEL
 A PRIORI TROPOSPHERE          EXTERN
 TROPO MAPPING FUNCTION        GMF
 GRADS MAPPING FUNCTION        CHEN_HERRING
 REFRACTIVITY COEFFICIENTS     77.60 70.40 373900.0
 SOURCE OF MET/DATA            NWP
 TROPO PARAMETER NAMES         TROTOT STDDEV TRODRY TROWET TGNTOT STDDEV TGETOT STDDEV   NSAT   GDOP    IWV  PRESS TEMDRY WMTEMP TEMLPS WMTLPS ZWDDEC
 TROPO PARAMETER UNITS          1e+03  1e+03  1e+03  1e+03  1e+03  1e+03  1e+03  1e+03      1      1      1      1      1      1  1e+03  1e+03      1
 TROPO PARAMETER WIDTH              6      6      6      6      6      6      6      6      4      4      6      7      6      6      6      6      6
 SLANT PARAMETER NAMES         SLTTOT STDDEV SLTDRY SLTWET SLTIWV SLTGRD SATRES SATMPT    SAT SATELE SATAZI FACDRY FACWET FACGRD
 SLANT PARAMETER UNITS          1e+03  1e+03  1e+03  1e+03      1  1e+03  1e+03  1e+03      1      1      1      1      1      1
 SLANT PARAMETER WIDTH              8      6      8      6      6      6      6      6      4      7      7      9      9      9
-TROP/DESCRIPTION
*-------------------------------------------------------------------------------
+TROP/SOLUTION
*STATION__ ____EPOCH_____ TROTOT STDDEV TRODRY TROWET TGNTOT STDDEV TGETOT STDDEV NSAT GDOP    IWV   PRESS TEMDRY WMTEMP TEMLPS WMTLPS ZWDDEC
 GOPE       2013:168:64500 2334.3    5.3 2166.8  167.4   0.99   0.85   0.14   0.93    7  2.2  27.26  951.92  299.6  285.7   7.20   7.21   3.32
 GOPE       2013:168:64800 2334.2    5.2 2166.8  167.4   1.00   0.84   0.17   0.92    6  1.9  27.25  951.90  299.6  285.7   7.20   7.21   3.32
 GOPE       2013:168:65100 2333.0    5.1 2166.8  166.2   1.00   0.83   0.29   0.91    7  2.2  27.06  951.90  299.6  285.7   7.20   7.21   3.33
...
 ZIMM       2013:168:85800 2275.0    4.6 2081.5  193.5  -0.18   0.65   0.79   0.86    9  1.1  31.16  913.97  296.3  282.6   7.21   6.74   2.94
 ZIMM       2013:168:86100 2274.7    4.7 2081.5  193.2  -0.20   0.66   0.84   0.85    8  1.4  31.11  914.01  296.2  282.5   7.20   6.74   2.94
-TROP/SOLUTION
*-------------------------------------------------------------------------------
+SLANT/SOLUTION
*STATION__ ____EPOCH_____ SLTTOT STDDEV SLTDRY SLTWET SLTIWV SLTGRD SATRES SATMPT SAT SATELE SATAZI FACDRY FACWET FACGRD
 GOPE       2013:168:64500 8363.0    9.9 7748.2  603.3   98.2   10.4    1.1    0.0 G05 16.000  39.323 3.575822 3.603292 12.159794
 GOPE       2013:168:64500 5635.5    8.2 5226.3  405.1   66.0   -0.2    4.2    0.0 G06 24.340 276.596 2.411963 2.419605 5.273237
 GOPE       2013:168:64500 3527.2    6.5 3266.0  252.6   41.1    0.8    7.8    0.0 G16 41.483 305.307 1.507287 1.508554 1.698072
 ...
 ZIMM       2013:168:86100 6721.5    8.0 6146.0  573.3   92.3   -7.0    9.3    0.0 G28 19.603 279.934 2.952592 2.967259 8.150843
 ZIMM       2013:168:86100 2366.6    4.7 2156.7  200.2   32.2   -0.2    9.8    0.0 G32 74.810 235.655 1.036111 1.036160 0.281091
-SLANT/SOLUTION
%=ENDTRO
```

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

Thank you for your attention

Acknowledgements

IGS for providing final and real-time GNSS products

ICS for providing WRF forecasts

All GNSS contributors to GNSS4SWEC WG1 Benchmark dataset (Douša et al, 2016)

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)