University of Stuttgart

Institute of Navigation

DAAD

GNSS meteorology: state of the art, challenges and perspectives

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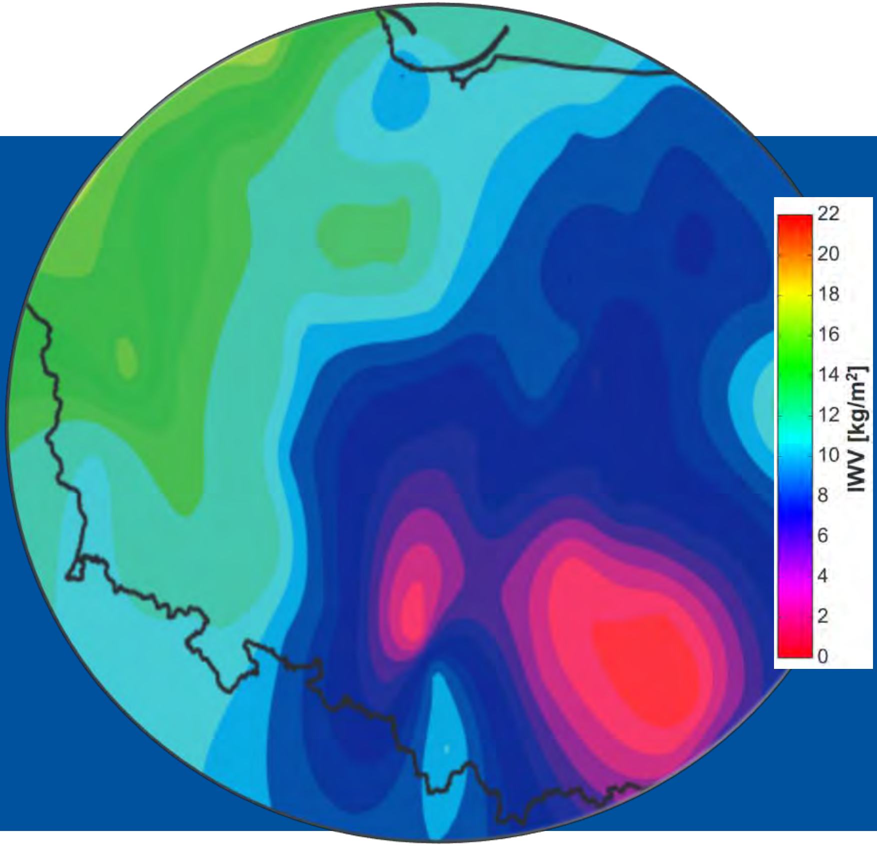

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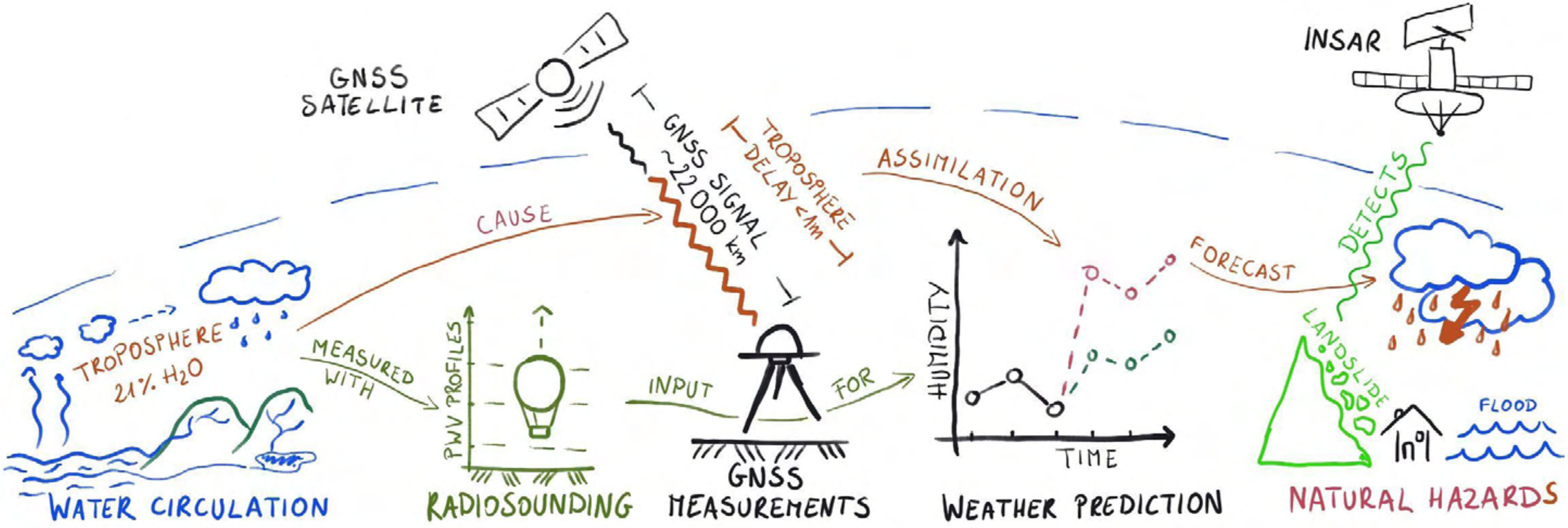
Second Summer School of DAAD Thematic Network

11-16.09.2019, Stuttgart / Germany

GNSS meteorology
General idea



GNSS principles
Tropospheric parameters

$$C_i^s = \rho_0^s + e_r^s \cdot \delta X_r + c(\delta t_r - \delta t^s) + T^s + \mu_i I^s - b_{C,i}^s$$

$$L_i^s = \rho_0^s + e_r^s \cdot \delta X_r + c(\delta t_r - \delta t^s) + T^s - \mu_i I^s + \lambda_i N_i^s - b_{L,i}^s$$

one slant delay per satellie!

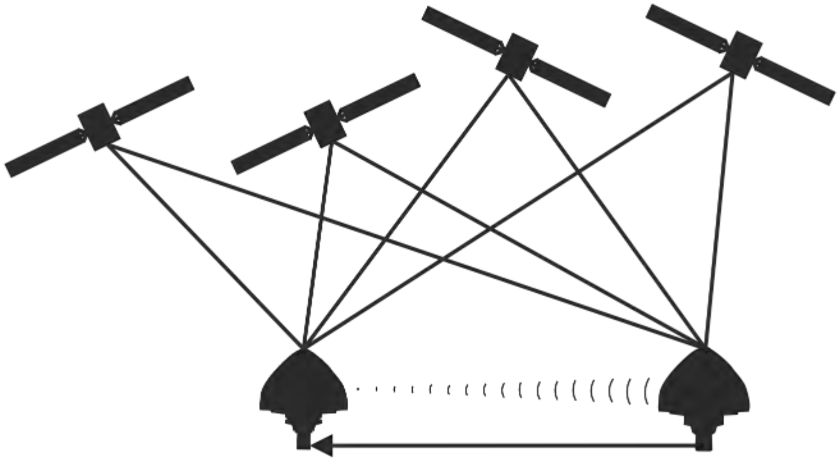
$$T^s = ZHD \cdot mf^h(e) + ZWD \cdot mf^w(e) + mf^G(e) \cdot (G_N \cdot cos(a) + G_E \cdot sin(a))$$

optional

1 or 3 per epoch (period)

e, a – elevation and azimuth of a satellite;
mf^h, mf^w, mf^G - empirical mapping functions for:
ZHD - hydrostatic delay,
ZWD - wet delay,
G_N, G_E - North and East troposhere gradients.

GNSS data processing
Relative mode (double-differencing)



Advantages:

- elimination of unknowns:
  - atmospheric delays (for short vectors),
  - receiver and satellie clock corrections,
  - geophysical effects;
- precise orbits/clocks not required;
- very good accuracy.

Drawbacks:

- high computational complexity;
- batch post-processing (period);
- relative estimates (non-absolute);
- for ZTD at least one vector >500 km.

GNSS data processing
E-GVAP

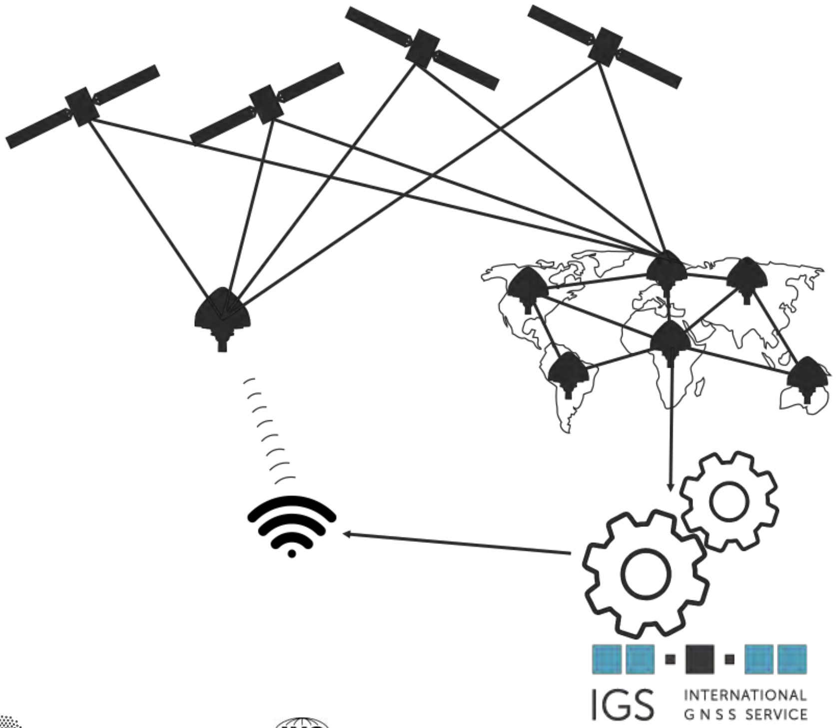
- 20 AC, >2000 station, operational NRT service

AC Name	Name of organisation	Links
ASI	e-geos/Telespazio, Italy	ASI ASIC ASIR ASIS
AUT	Aristotle University of Thessaloniki, Greece	AUT1
BEU	Zonguldak University, Turkey	BEU1
BKG	Federal Agency for Cartography & Geodesy, Germany	BKG BKGH
GFZ	Helmholz Centre Potsdam GFZ German Reseach Centre for Geosciences	GFZ
GOP	Geodetic Observatory Pecny Czech Republic	Home GOP1 GOP2 GOPG GOPX
IES	Institute of Engineering, Surveying and Space Geodesy, Univ. of Nottingham, UK	IES2
IGE	Instituto Geografico National, Spain	IGE IGE2
IMO	Icelandic Meteorlogical Office	IMO1
KNMI	Royal Meteorological Inst. of the Netherlands	KNMI KNM1 KNM2
KTU	Karadeniz Technical University, Turkey	KTU1
LPT	SwissTopo	Agnes network LPT LPTR
METO	UK Metoffice	METO METG
NGAA	Lantmateriet (Swedish Mapping, Cadestre and Land Registration Authority), Gavle	NGAA
NOAA	Nat. Oceanic and Atmos. Adm., USA	NOAA
ROB	Royal Observatory of Belgium	EUREF Network ROB
SGN	Institut Geographique National, France	SGN SGN1
SGOB	Satellite Geodetic Observatory, IGCRS and Dept. of Geodesy and Surveyring, TU Budapest, Hungary	SGOB
UL01	University of Luxembourg, Fac. of Science and Communication	UL01
WUEL	Wroclaw University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Poland	WUEL

https://www.eumetnet.eu

GNSS data processing

Precise Point Positioning (PPP) technique



Advantages:

- low computation complexity:
  - single station processing,
  - epoch-wise processing;
- absolute estimates;
- accuracy comparable to DD.

Drawbacks:

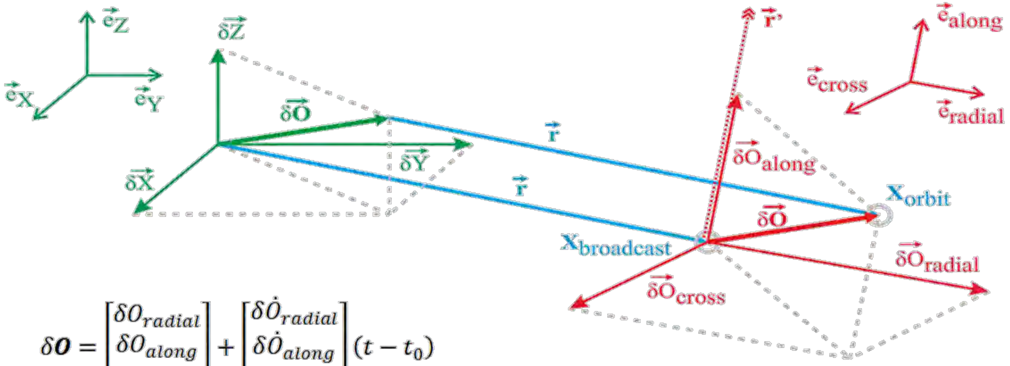
- modeling of all geophysical effects
- ambiguity resolution is challenging;
- precise orbits & clocks required (directly affect solution quality!).

GNSS data processing
IGS Real-Time Service (RTS)

- available since **April 2013**;
- SSR concept: real-time orbit and clock corrections to broadcast ephemeris;
- latency < 10 seconds;
- orbits based on predictions;
- estimated clock corrections.

MAJOR STEP TOWARDS REAL-TIME GNSS METEOROLOGY

IGS INTERNATIONAL GNSS SERVICE



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

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

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

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

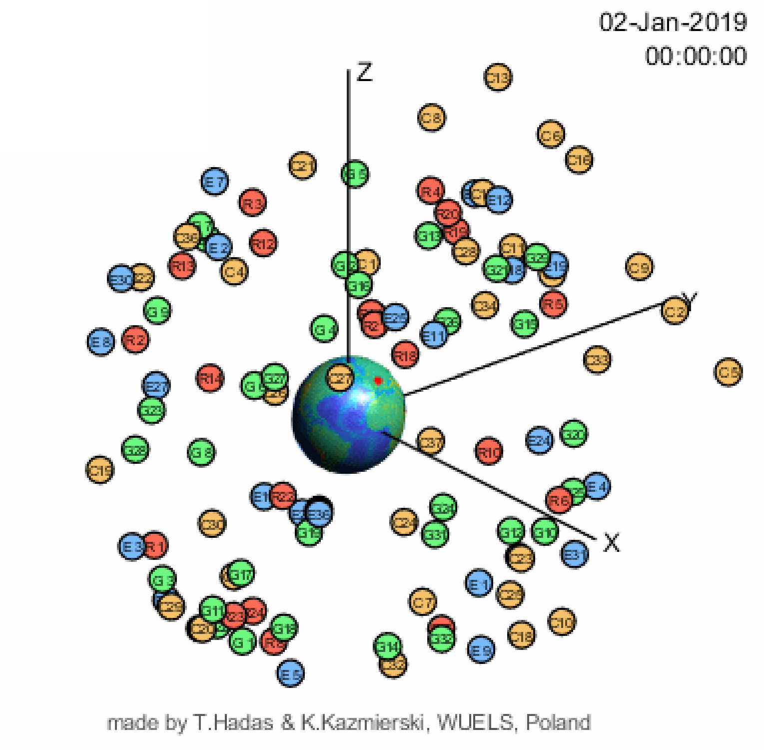
$$\delta C = C_0 + C_1(t - t_0) + C_2(t - t_0)^2$$

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

δO - orbit corrections terms, $\delta\dot{O}$ - orbit correction velocity, C_i - clock corrections polynomial coefficients
r is satellite broadcast position vector, $\dot{r}$ is satellite broadcast velocity vector
t – current epoch, t_0 - message reference time

source: *Hadas, T. & Bosy, J. GPS Solut (2015) 19: 93. https://doi.org/10.1007/s10291-014-0369-5*

GNSS status
Multi-GNSS constellation



Operational satellites (>100):

GPS	31 (+2)
GLONASS	22
Galileo	22 + 2
BeiDou 2/3	15 + 18

Final products:

- CODE MGEX
- experimental
- GPS >> other GNSS

Real-time products:

- GPS official, GLO unofficial
- all GNSS in CLK93 (CNES AC)

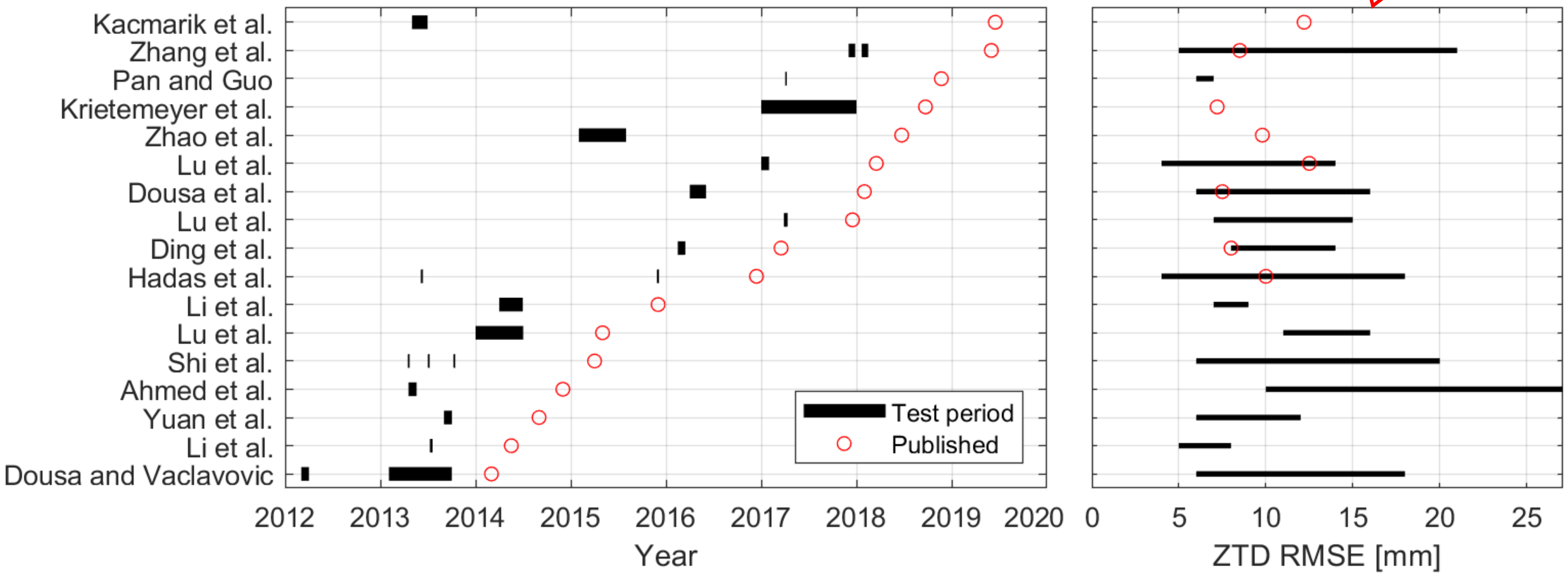
RT GNSS meteorology
Research (IF journals)

	Authors	Year	GNSS	Amb. Res.	Interval [s]	ZTD MF	G_N/G_E	e mask	ZTD RMS [mm]
1	Dousa and Vaclavovic	2014	G	N	10	GMF	N	7	6 – 18
2	Li et al.	2014	G	Y	N/A	GMF	N	7	5 – 8
3	Yuan et al.	2014	G	N	30	GMF	N	N/A	6 – 12
4	Ahmed et al.	2016	G	N	5	GMF	N	7	10 – 40
5	Shi et al.	2015	G	N	N/A	GMF	N	13	6 – 20
6	Lu et al.	2015	GC	N	30	GMF	Y	5	11 – 16
7	Li et al.	2015	GREC	N	30	GMF	Y	N/A	7 – 9
8	Ding et al.	2016	G(RE)	Y	5	N/A	N	7	8 – 14
9	Hadas et al.	2017	G	N	30	VMF1	N	5	4 – 18
10	Lu et al.	2017	GREC	N	5	GMF	N	7	7 – 15
11	Lu et al.	2018	GREC	Y	30	GMF	Y	7	4 – 14
12	Zhao et al.	2018	G	N	30	GMF	N	10	10
13	Krietemeyer et al.	2018	G	N	30	GMF	N	10	7
14	Pan and Guo	2018	GREC	N	30	GMF	Y	7	6 – 7
15	Dousa et al.	2019	GRE	N	30	GMF	N	N/A	6 – 16
16	Zhang et al.	2019	G	N	60	VMF1	Y	7	5 – 21
17	Kacmarik et al.	2019	G(R)	N	300	GMF	Y	3	12
	Most used:		**G**	**N**	**30**	**GMF**	**N**	**7**	**4 - 40**

RT GNSS meteorology

Research since 2014 (IF journals)

ZTD accuracy: 4-21 mm



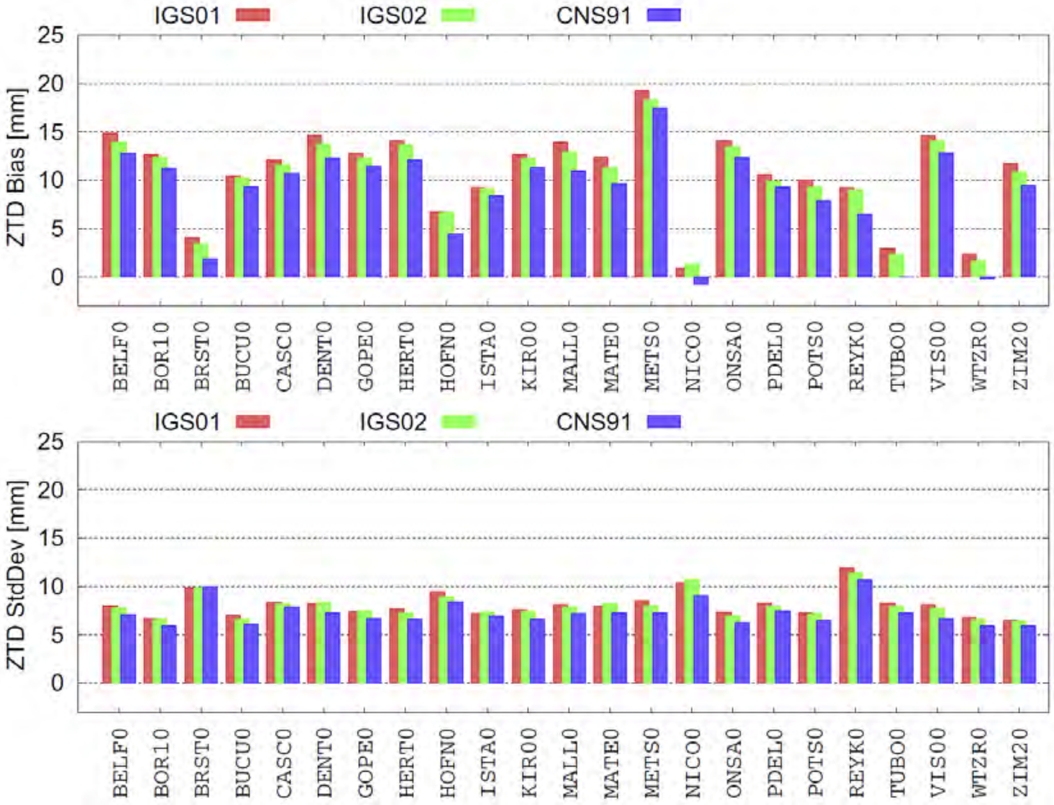
Accuracy depends on: strategy (software), station, time, ...

RT-ZTD sensitivity
Quality of orbits & clocks

J. Dousa, P. Vaclavovic / Advances in Space Research 53 (2014) 1347–1358:

- „(...) the quality of ZTD complies with the threshold requirements for the operational NWP nowcasting – the relative accuracy of 5 kg/m2 in IWV with the 60 min repetition cycle and the 30 min product latency”

- <u>missmodeling of systematic or geophysical effects leads to ZTD bias.</u>

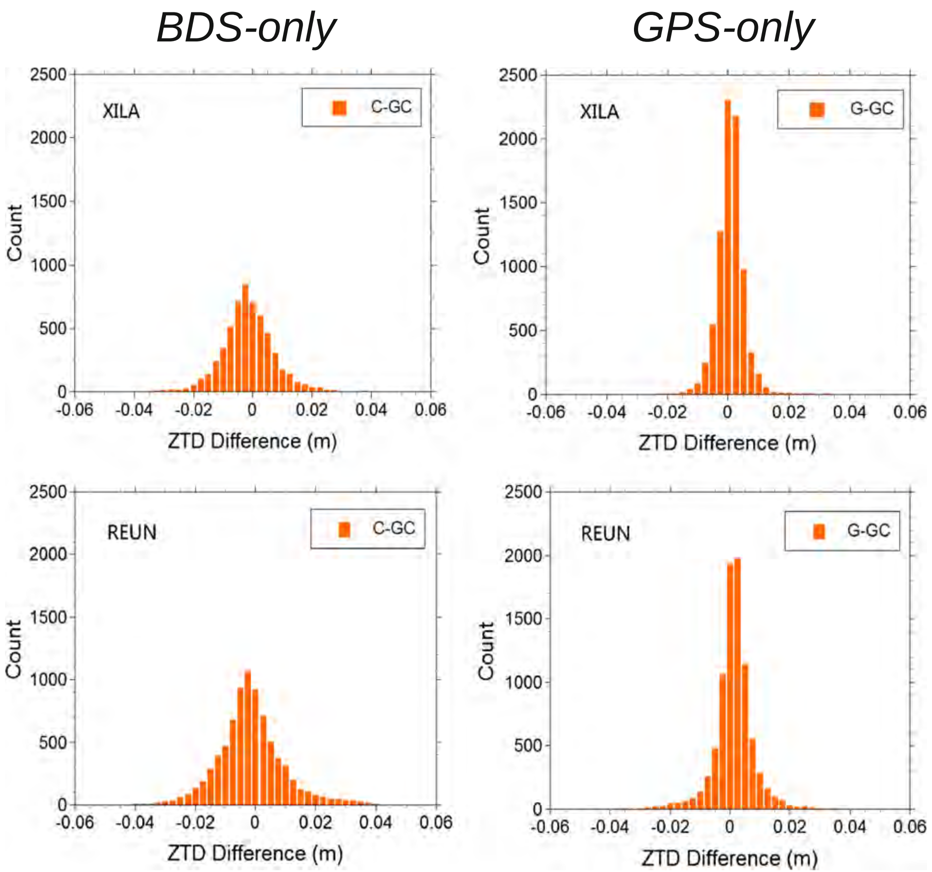


RT ZTD comparisons with respect to EUREF final products – biases (top) and standard deviations (bottom)

RT-ZTD sensitivity
GPS vs BeiDou solution

C. Lu, et al. / Journal of Geodesy 89 (2015) 843-856:

„(...) the ZTD/PWV with BDS-only observations of the current constellation can also significantly contribute to weather nowcasting, although their accuracy is worse than the one of the current GPS-only solution (about 1.5 mm in PWV).”

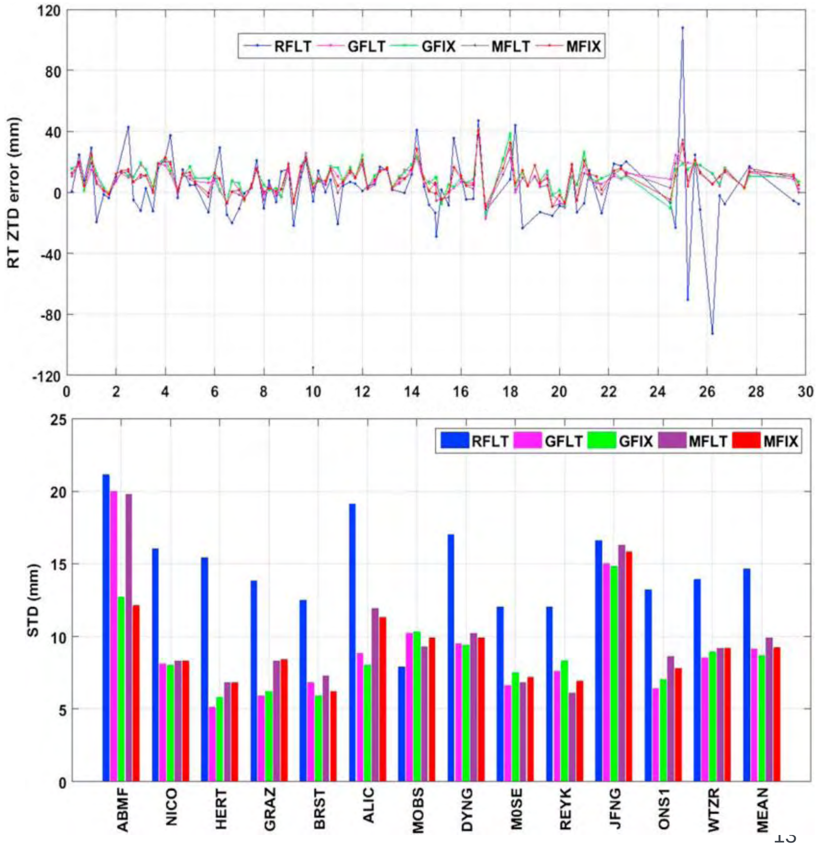


Distribution of ZTD differences of BDS-only and GPS-only solutions with respect to the GPS/BDS combined solutions (March 2014)

RT-ZTD sensitivity
GPS vs GLONASS; float vs fixed ambiguity

W. Ding, et al. / JGR: Atmospheres 122 (2017) 2779-2790:

- Poor quality of GLONASS-only solution
- „(...) RT troposphere estimates generated by single-system or multisystem observations can all fulfill the accuracy requirements for nowcasting”
- „RT PPP ambiguity resolution can improve the accuracy (...)”



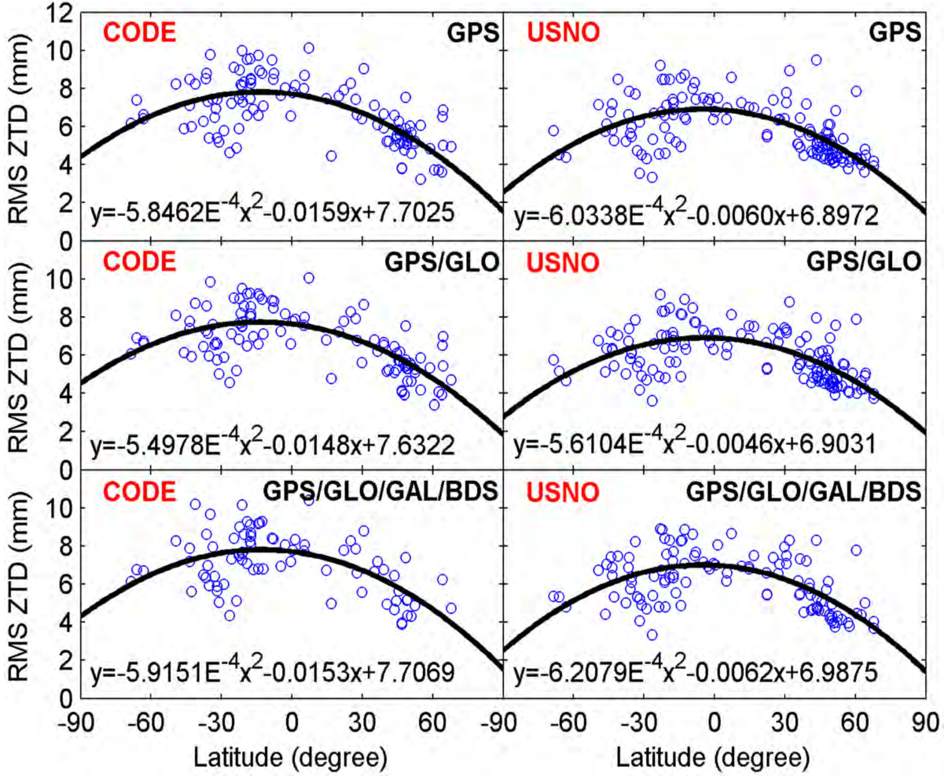
(top) RT ZTD error of WTZR with respect to radiosonde observations
(bottom) of RT ZTD errors with respect to the radiosonde observations in all data processing modes

RT-ZTD sensitivity
Station latitude

L. Pan, F. Guo / Iscientific Reports 8 (2018) 17067:

- „The RMS values of real-time ZTD errors at a station are latitude dependent”

- „(...) consideration of tropospheric gradients in the PPP processing, the accuracy of real-time ZTD estimates is slightly improved (...).”



Station-specific RMS values of real-time ZTD errors as a function of geographical latitudes. The black line refers to the second-order polynomial fitting of RMS ZTD errors.

ZWD stochastic model
Review of strategies

T. Hadas et al. / GPS Solutions 21 (2017) 1069-1081:
Optimum stochastic modeling for GNSS tropospheric delay estimation in real-time

Stochastic modeling - **random walk** (RW) with process noise (PN):

- RWPN=**5mm/√h** for ZWD in PPP (Kouba and Horoux 2001),
- RWPN=**20mm/√h** for ZWD constraint (Pacione et al. 2009),
- constraining based on **initial empirical test** (Dousa et al. 2013),
- RWPN of **about 5-10 mm/√h** (Lu et al. 2015).

ZWD stochastic model
Random walk theory

ZWD random walk - Markov (memory-less) process:

$$\boldsymbol{E(|S_n(\varepsilon)|) = \varepsilon\sqrt{n}}$$

S - translation distance, *n* – number of steps, $\boldsymbol{\varepsilon}$ – step length

Adopting for troposhere :

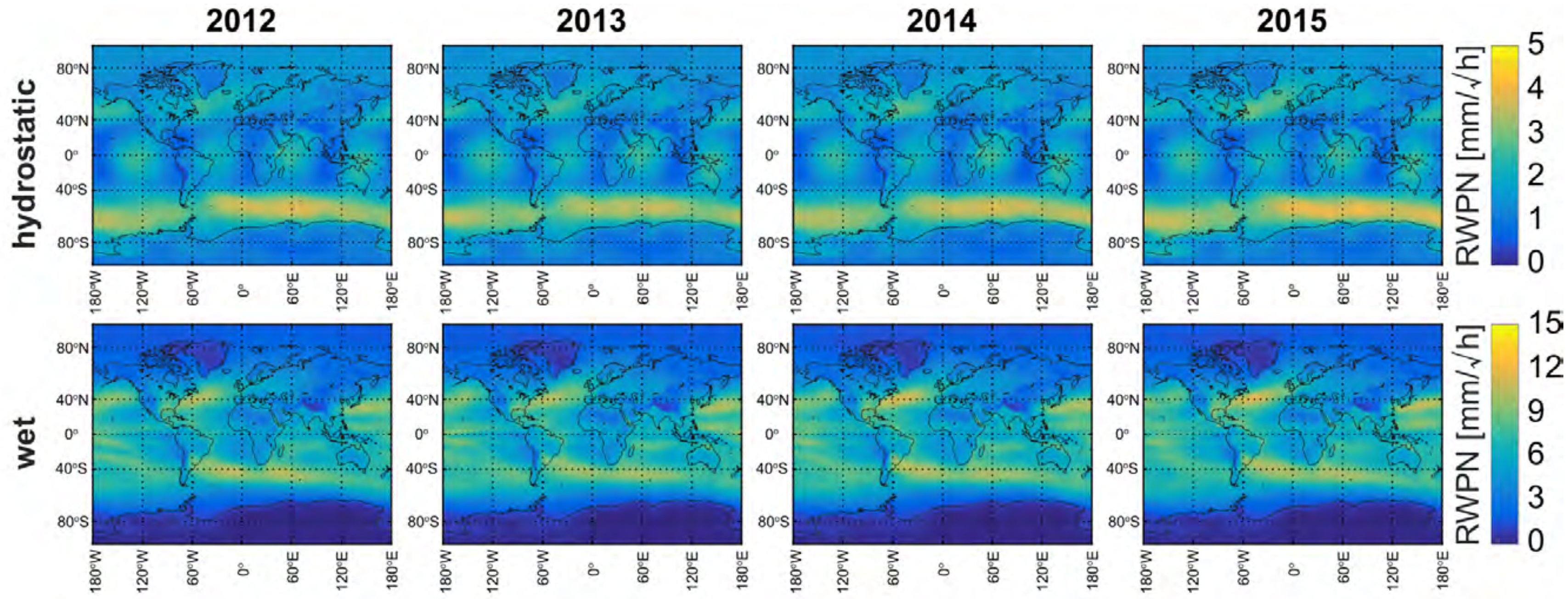
$$\boldsymbol{E(|\Delta T_{t+\delta t} - \Delta T_t|) = \varepsilon\sqrt{\delta t}}$$

ΔT – tropo delay, *δt* – time interval, *ε* = RWPN

To estimate RWPN if a time series of *ΔT* is known:

$$\boldsymbol{E(\varepsilon) = |\Delta T_{t+\delta t} - \Delta T_t|/\sqrt{\delta t}}$$

ZWD stochastic model
Yearly mean RWPN grids



- Hydrostatic and wet RWPN are geographically dependent
- RWPN repeats year by year
- Wet RWPN: 0.1 – 12.0 mm/√h, mean – 5.0mm/ √h, Europe ~ 5mm√h

ZWD stochastic model
Processing variants

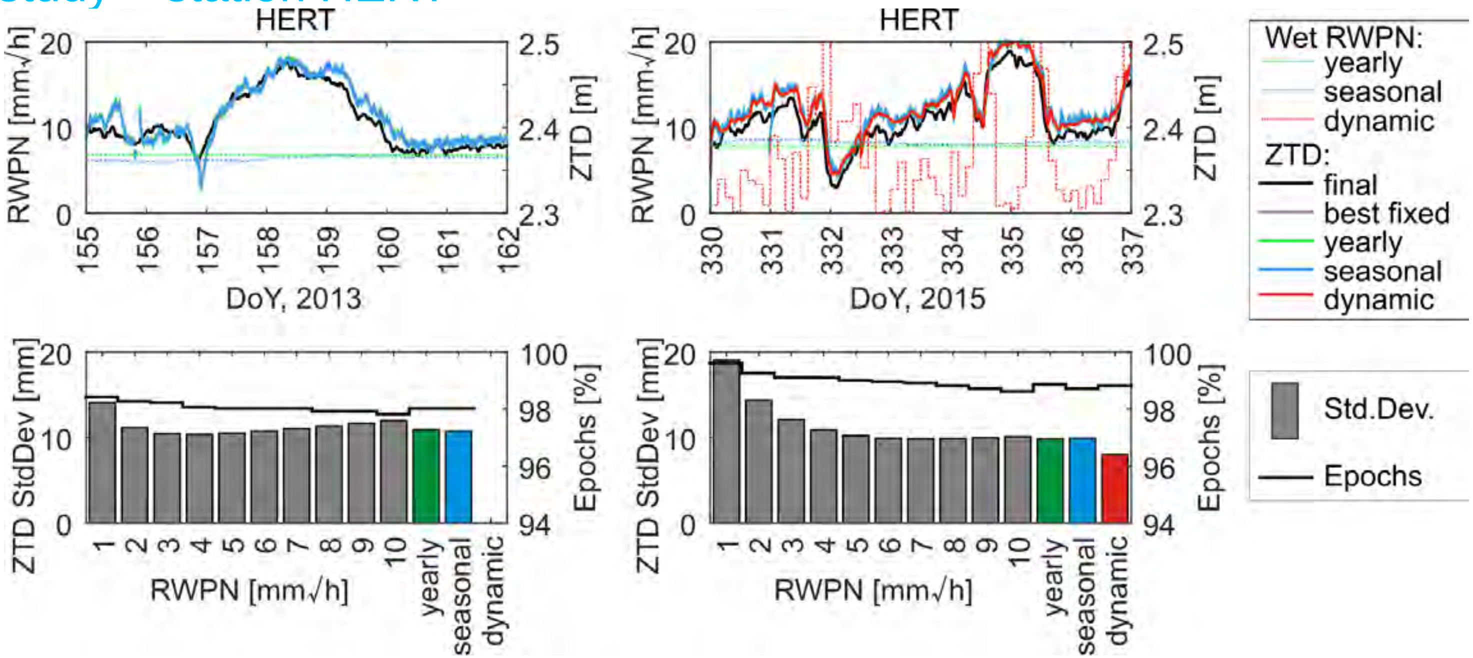
Simulated real-time mode in GNSS-WARP software:

1. **Fixed** – initial empirical testing
   - RWPN: from 1 mm/√h to 10 mm/√h (with 1 mm/√h step)
2. NWP based **yearly** mean RWPN
   - use ZWD time-series from the past year
3. NWP based **seasonal** mean RWPN
   - use 30-day window of corresponding season, last year
4. NWP forecast based **dynamic** RWPN
   - use NWM forecast to estimate RWPN in real-time

Test campaigns:
- DoY 155-161,2013
- DoY 330-336, 2015

NWP model:
- GFS4 forecast (ray-tracing) (0.5 x 0.5 deg grid, 3 hours

ZWD stochastic model
Case study – station HERT



- good agreement of RT solutions with the Final solution, small differences among RT solutions
- best fixed =3 in 2013, =7 in 2015
- yearly and seasonal approach are almost as good as the best fixed (StdDev & %)
- dynamic approach reduced StdDev (18%!), % of epochs is high

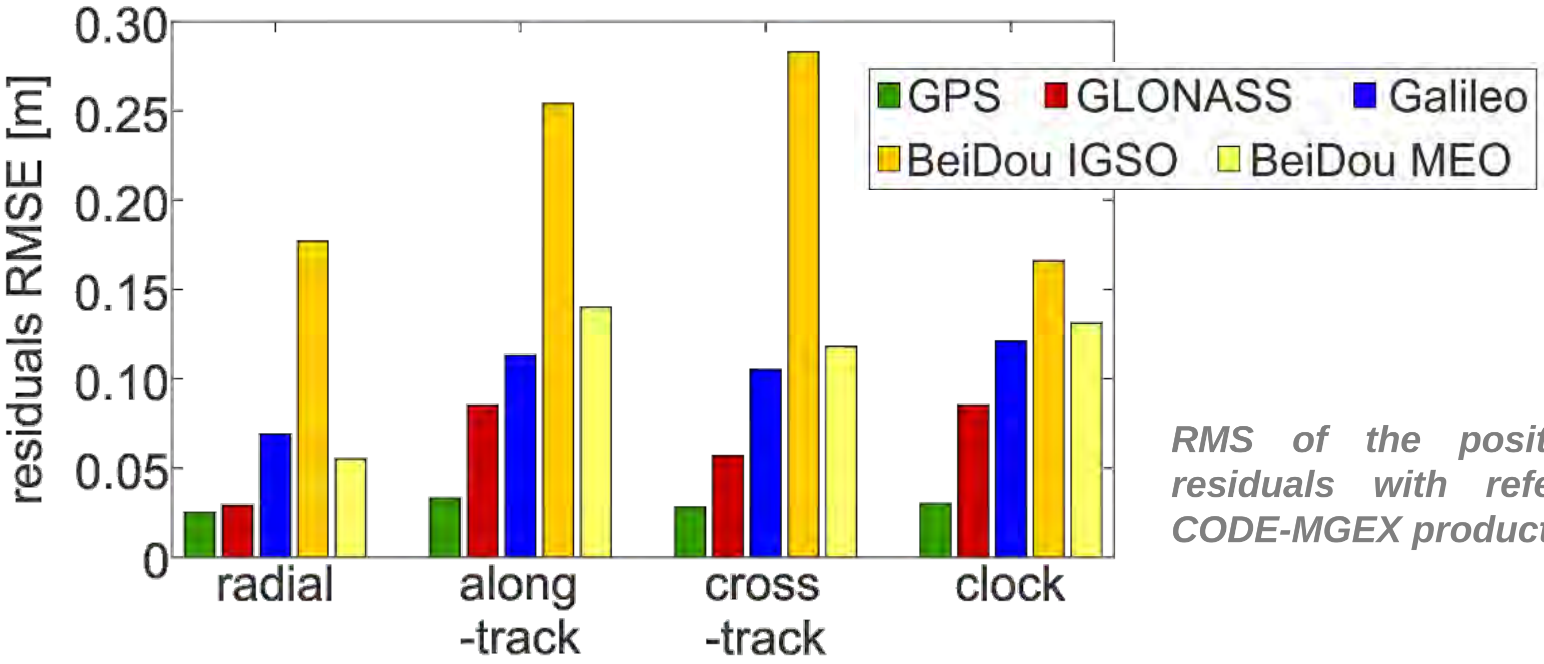
ZWD stochastic model
Conclusions and recommendations

1. Optimum RWPN is **location and time dependent** parameter.
2. There is no single globally optimum value of RWPN.
3. Instead of using empirical approach, one can:

- use global yearly RWPN grid (static, look-up table)
- perform NWP ray-tracing using short-term forecast data to apply dynamic RWPN

RT Multi-GNSS Meteorology

Quality of RT CNES orbits/clocks



RMS of the position and clock residuals with reference to final CODE-MGEX products; 01-30.04.2016

Should an inter-system weighting be applied?

RT Multi-GNSS Meteorology

Intra-system weighting for RT-ZTD

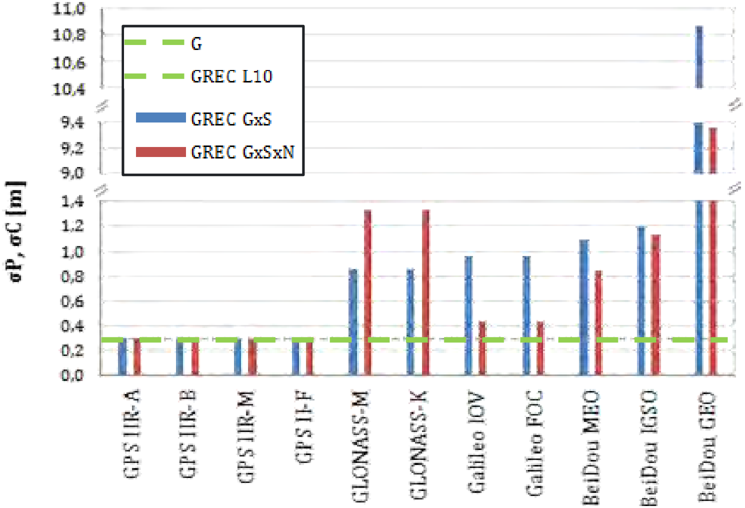
$$SISRE = \sqrt{[RMS(w_R \cdot \Delta r_R - \Delta cdt)]^2 + w_{A,C}^2 \cdot (A^2 + C^2)}$$

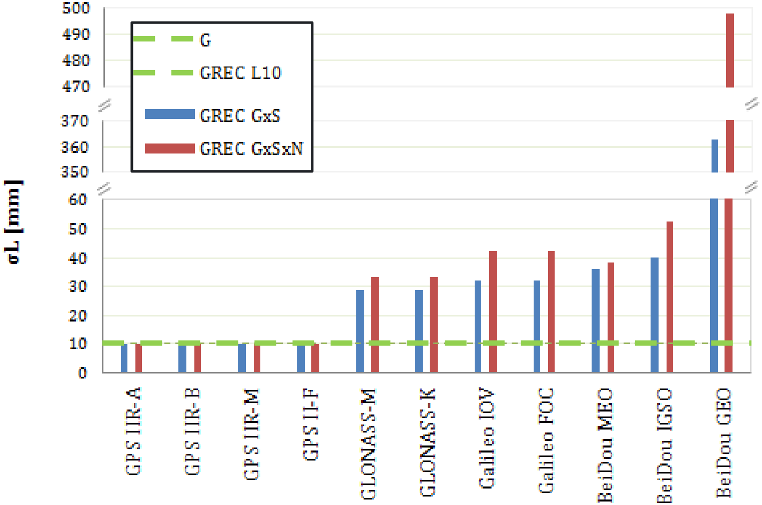
$$\sigma P_{GPS} = 0.30\ m$$
$$\sigma L_{GPS} = 0.01\ m$$

$$\sigma P_{syst} = \sigma P_{GPS}$$
$$\sigma L_{syst} = \sigma L_{GPS}$$

$$\sigma P_{syst} = \sigma P_{GPS} \frac{SISRE_{syst}}{SISRE_{GPS}}$$
$$\sigma L_{syst} = \sigma L_{GPS} \frac{SISRE_{syst}}{SISRE_{GPS}}$$

$$\sigma P_{syst} = \sigma P_{GPS} \cdot \frac{SISRE_{syst}}{SISRE_{GPS}} \cdot \frac{P\_NOISE_{syst}}{P\_NOISE_{GPS}}$$
$$\sigma L_{syst} = \sigma L_{GPS} \cdot \frac{SISRE_{syst}}{SISRE_{GPS}} \cdot \frac{L\_NOISE_{syst}}{L\_NOISE_{GPS}}$$



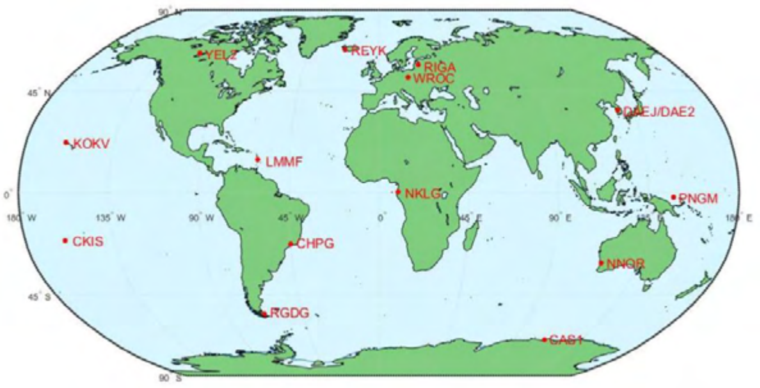


RT Multi-GNSS Meteorology
Data and strategy

Observables	ionosphere-free pseudorange and carrier-phase
Frequencies (RINEX 3.03 notation)	GPS: L1/L2, GLONASS: G1/G2, Galileo: E1/E5a, BeiDou: B1/B2
Inter-system weighting	elevation *e* dependent weighting: sin(*e*)
Elevation cut-off angle	5°
Sampling rate	30 s
Troposphere delay modeling	UNB3m mapping functions and a priori value for hydrostatic delay, wet delay estimated as 4 mm/√hour random walk process
Receiver clock	estimated as white noise, individual clock for each GNSS
Satellite orbits and clocks	fixed from real-time CNES stream (mountpoint CLK93)
Code and phase biases	observation specific biases from real-time CNES stream (mountpoint CLK93)
Solution type	daily static with float ambiguities
Correction models	phase wind-up, relativistic delays, solid earth tides, receiver antenna phase center offset and variation

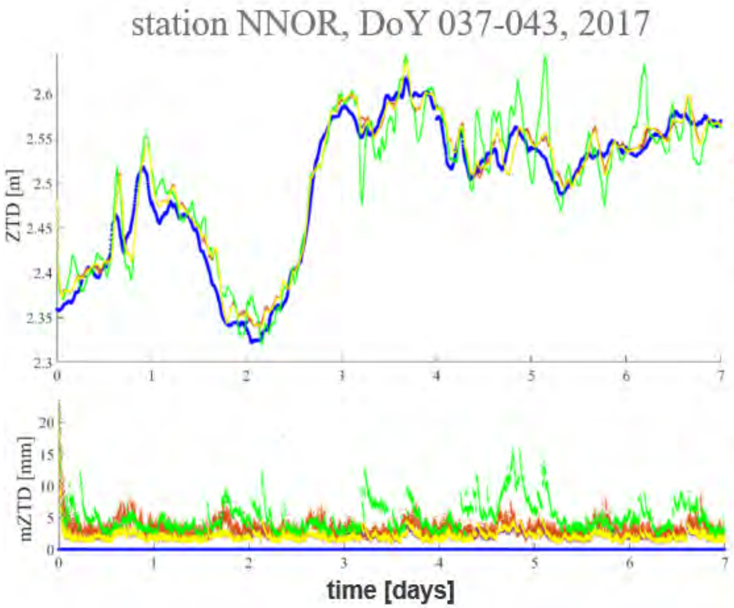
Time periods:

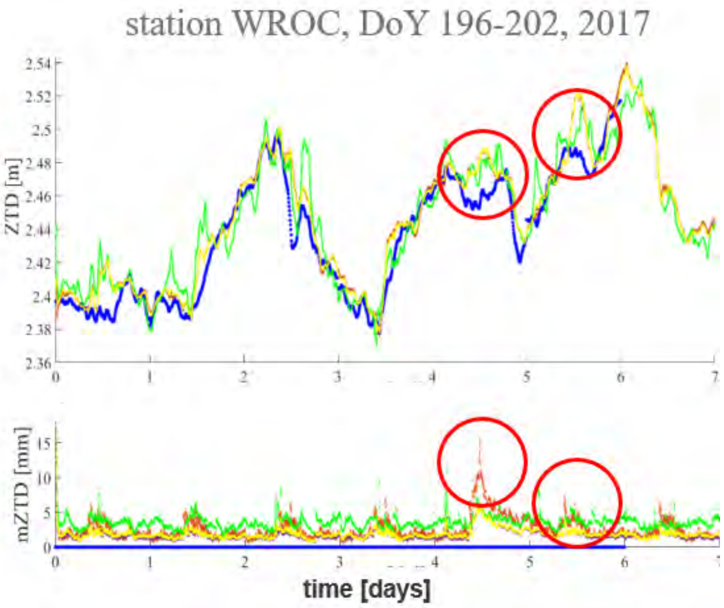
- 06-12.02.2017 (DoY 037-043, 2017)
- 15-21.07.2017 (DoY 196-202, 2017)



14 IGS stations (GREC in RINEX 3.03)

RT Multi-GNSS Meteorology
Exemplary ZTD time series





- **G only** ≈ **GREC GxS** ≈ **GREC GxSxN**
- and in good agreement with **IGS Final ZTD**
- **GREC L10** returns very inaccurate results
- small formal errors - ca. 5 mm (except **GREC L10**)

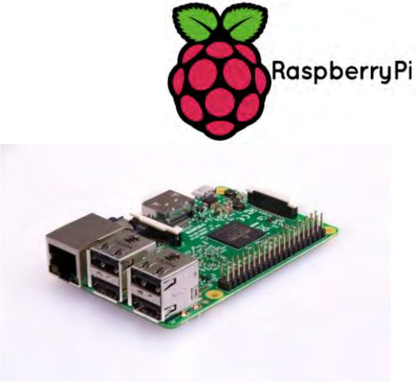
RT Multi-GNSS Meteorology
RMSE of ZTD differences

ΔZTD [mm]	G	GREC L10	GREC GxS	GREC GxSxN
mean	-4.3	-1.5	-3.7	-3.8
std.dev.	12.2	18.9	11.7	11.7
RMSE	12.2	18.9	11.7	11.7

$$\sigma P_{syst} = \sigma P_{GPS} \frac{SISRE_{syst}}{SISRE_{GPS}}$$

$$\sigma L_{syst} = \sigma L_{GPS} \frac{SISRE_{syst}}{SISRE_{GPS}}$$

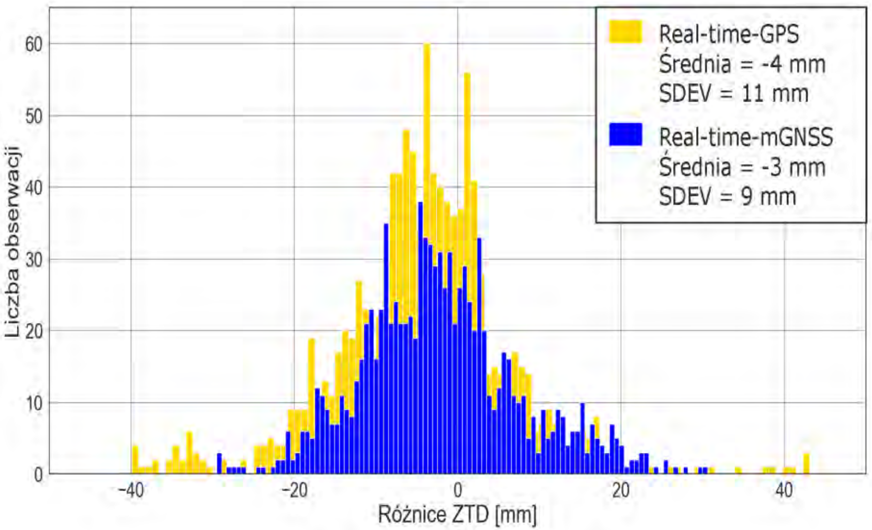
Challenges for Real-Time GNSS Meteorology
Perspectives: Low-cost receivers



Total cost of GNNS and METEO:
500 $

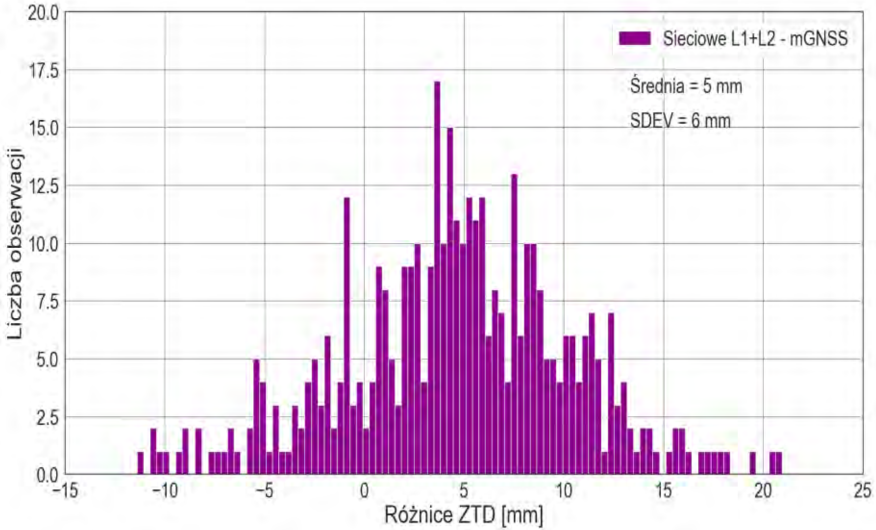
Challenges for Real-Time GNSS Meteorology
Perspectives: Low-cost receivers

Real-time ZTD (PPP)



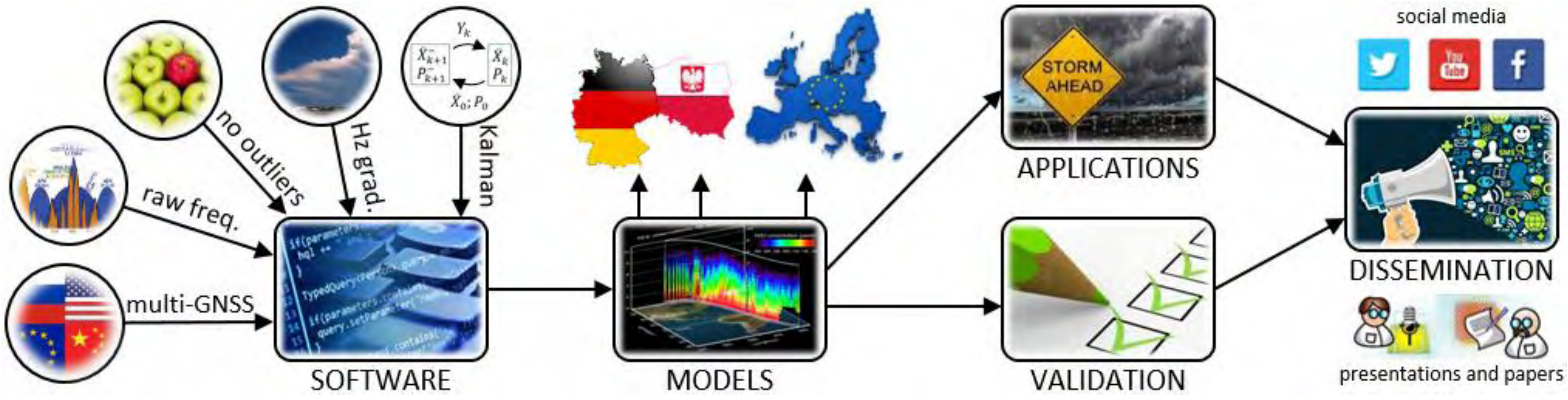
- GPS: RMSE = 11 mm
- mGNSS: RMSE = 10 mm

NRT ZTD (DD)



- GPS: RMSE = 7 mm

Challenges for Real-Time GNSS Meteorology
H2020 MSCA-IF: ReS4ToM



- real-time state-of-the-art troposphere products from GNSS (ZTD, $G_{N/E}$, STD);
- operational system for Poland, Germany (BKG support) and European stations;
- tropopshere mitigation in PPP and InSAR;
- campaigns for data assymilation into NWP models (DWD support).

Thank you!

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