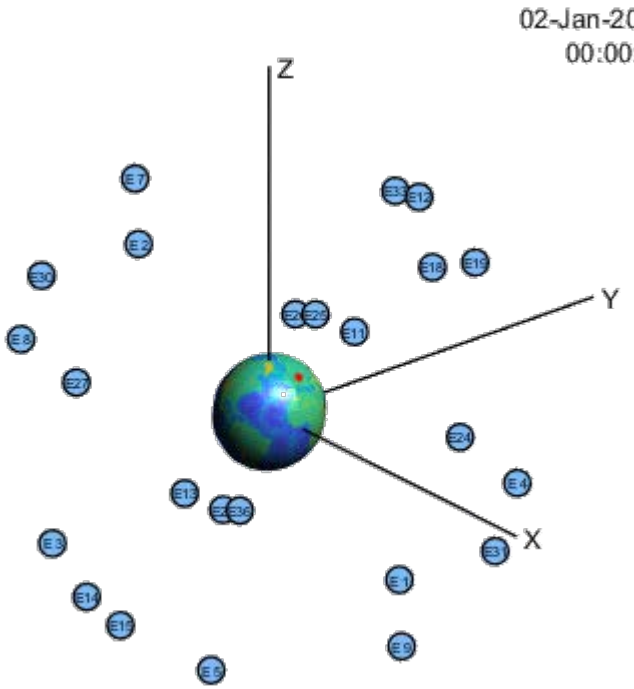
WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

GALILEO-ONLY DUAL-FREQUENCY ABSOLUTE POSITIONING



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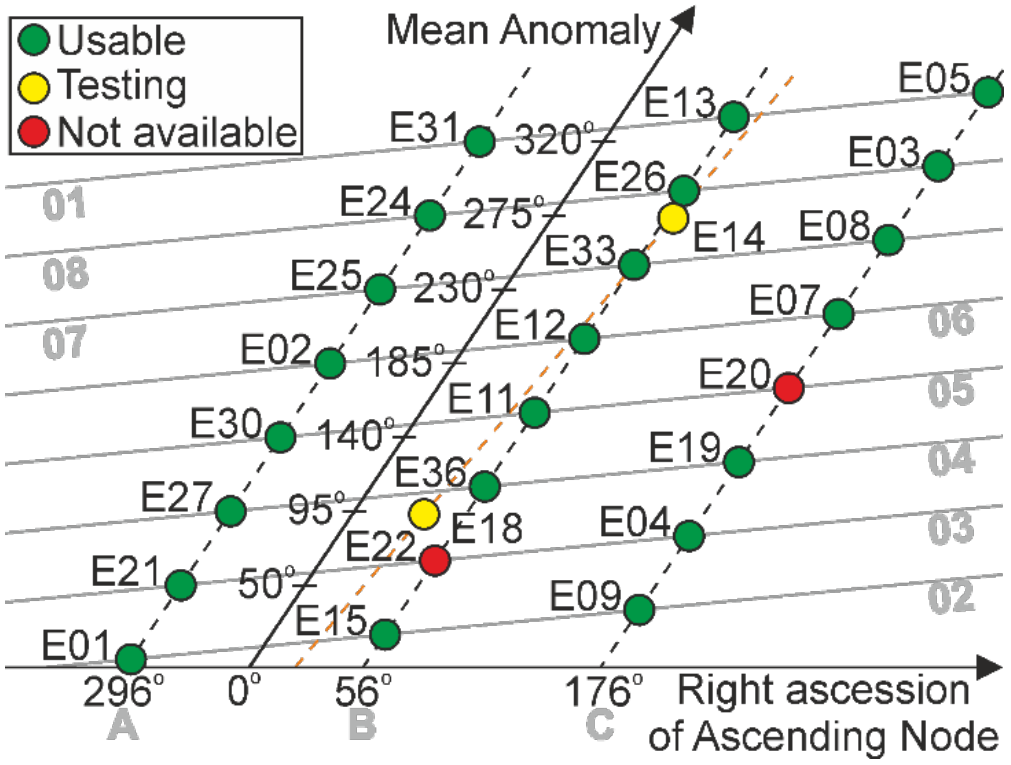
Motivation: Galileo status

22 + 2 + 2 Galileo satellites:

- February 11, 2019: **E11**, **E13**, **E15** and **E33** announced healthy
- **E20** and **E22** are unserviceable (single-frequency; management)
- **E14** and **E18** in elliptical orbits

Products:

- 24 broadcast ephemeris
- 24 IGS MGEX orb+clk
- 18 (+4) IGS RTS orb+clk (no E14/E18)



Galileo constellation status as of January 1, 2019. Satellites are marked with PRN numbers, grey letters and numbers allow identifying a satellite slot

Motivation: Galileo-only positioning

Literature:

☑ GPS only @ BRDC / FIN / RT products

☑ GNSS (=GPS+GLO/GAL/BDS) @ BRDC / FIN / RT products

☒ Galileo only @ BRDC / FIN / RT products ← THE GOAL!

Galileo > other GNSS:

- multiple signals and frequencies
- 0.25 m tracking range error of E1 (<0.10 m for E5 AltBOC)
- SISRE=0.15 m (2-3x better than GPS) [1]

[1] Steigenberger and Montenbruck, 2017, Multi-GNSS SISRE Monitoring – Methodology and Results, German Space Operations Center (GSOC)

Global availability and PDOP

Availability (Jan 1-7, 2019)

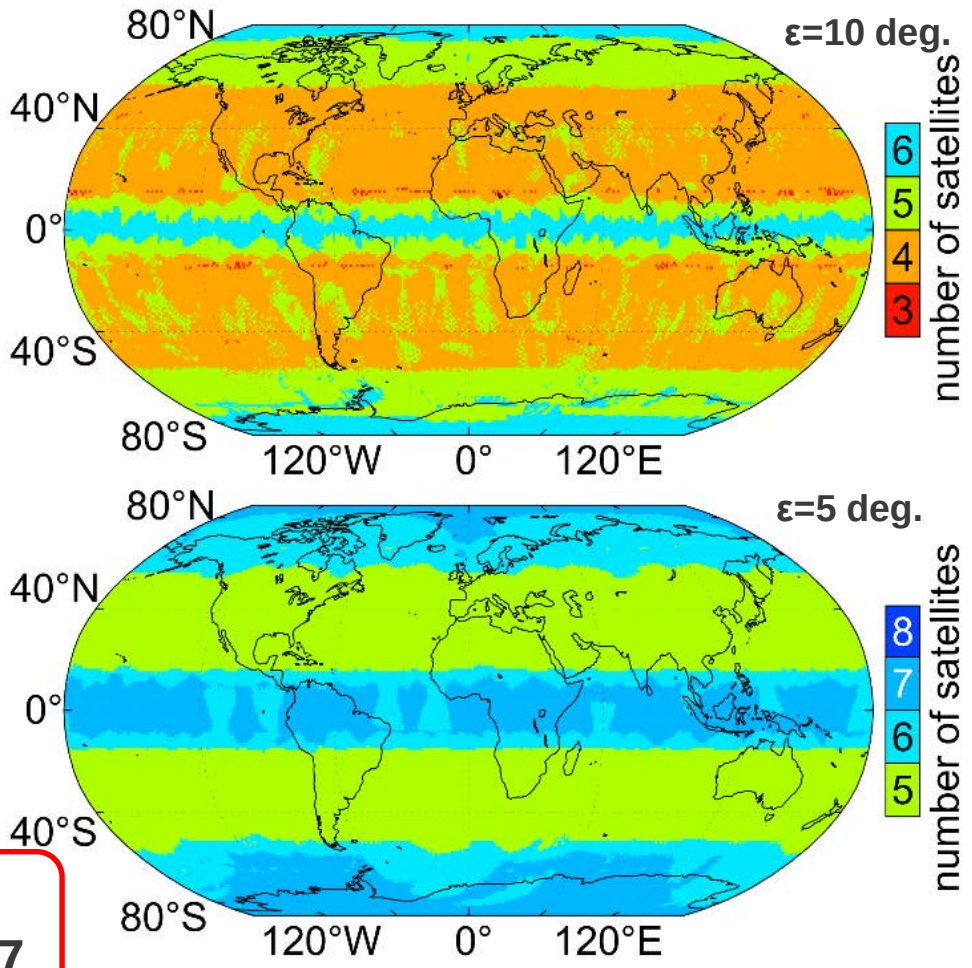
ε [deg]	Min	Max	≥4 [%]	≥5 [%]
0	5	14	100.0	100.0
5	5	13	100.0	100.0
10	3	11	99.9	99.9
15	3	10	99.8	96.9
20	2	10	98.6	88.2

PDOP (Jan 1-7, 2019)

ε [deg]	Avg		
0	2.1		0.0
5	3.0	95.5	0.0
10	4.4	82.7	0.8
15	5.6	55.0	7.7
20	6.0	24.7	23.9

6.0-8.2 in 2017

>98% for S in 2017



Galileo-only positioning – methodology (1)

Undifferenced uncombined functional model [2]

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

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

$$e_r^s = \left[\frac{X_r - X^s}{\rho_0^s} \quad \frac{Y_r - Y^s}{\rho_0^s} \quad \frac{Z_r - Z^s}{\rho_0^s}\right] \qquad \delta X_r = [\delta X_r \quad \delta Y_r \quad \delta Z_r]^T$$

$$\mu_i = f_1^2 / f_i^2 \qquad \rho_0^s = \sqrt{\left(X^s - X_{r,0}\right)^2 + \left(Y^s - Y_{r,0}\right)^2 + \left(Z^s - Z_{r,0}\right)^2}$$

In this study:

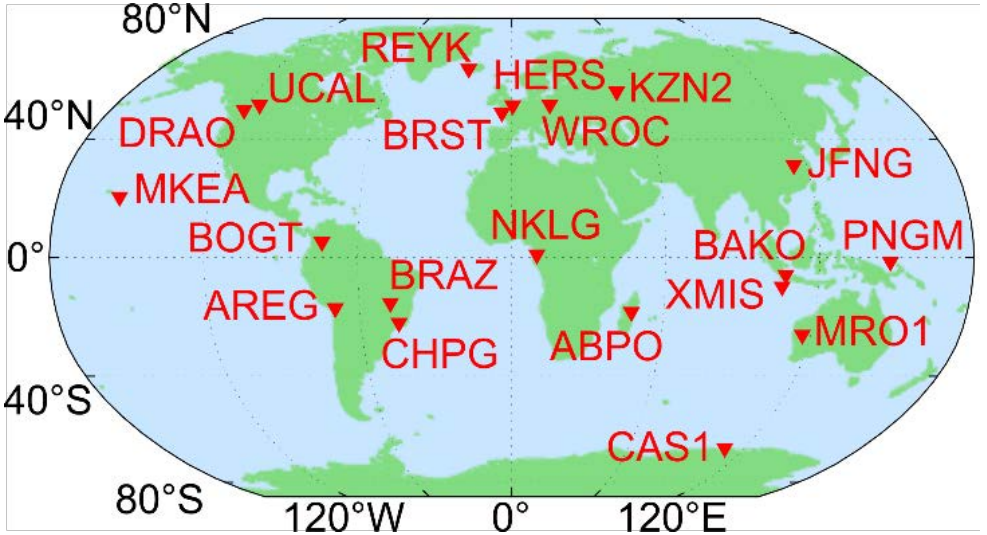
- dual frequency data (*i*=1,2)
- PPP uses C & L observations
- SPP uses C observations only
- no constraints on *I*
- float ambiguities

[1] Schönemann E (2014) Analysis of GNSS raw observations in PPP solutions. Dissertation, Technische Universität Darmstadt

Galileo-only positioning – methodology (2)

Data:

- January 1 to 7, 2019
- 20 IGS stations
- RINEX v3.03
- E1/E5a + I/NAV
- FIN: MGEX CODE
- RTS: CLK93



Location of test stations

Processing variants:

	SPPs +NAV	SPPs +RTS	PPPs +NAV	PPPs +RTS	PPPs+ MGEX	SPPk +NAV	SPPk +RTS	PPPk +NAV	PPPk +RTS	PPPk+ MGEX
Coordinates mode	Static					Kinematic				
Observables	C		C+L			C		C+L		
Orbits and clocks	BRCD	RTS	BRCD	RTS	MGEX CODE	BRCD	RTS	BRCD	RTS	MGEX CODE
Satellite biases	0		0			0		0		
Troposphere delay	fixed		T_Z estimated			fixed		T_Z estimated		

Galileo-only positioning – methodology (3)

GNSS-WARP Software

- post-processing / simulated real-time / real-time
- GNSS: GPS / GLONASS / Galileo / BeiDou
- estimated parameters: $\boldsymbol{XYZ}$, $\boldsymbol{c\delta t_r}$, $\boldsymbol{T_Z}$, $\nabla \boldsymbol{T_Z}$, float $\boldsymbol{N_i^s}$
- purpose: PPP algorithms, real-time ZTD, RTS monitoring

$\boldsymbol{\#SV}$

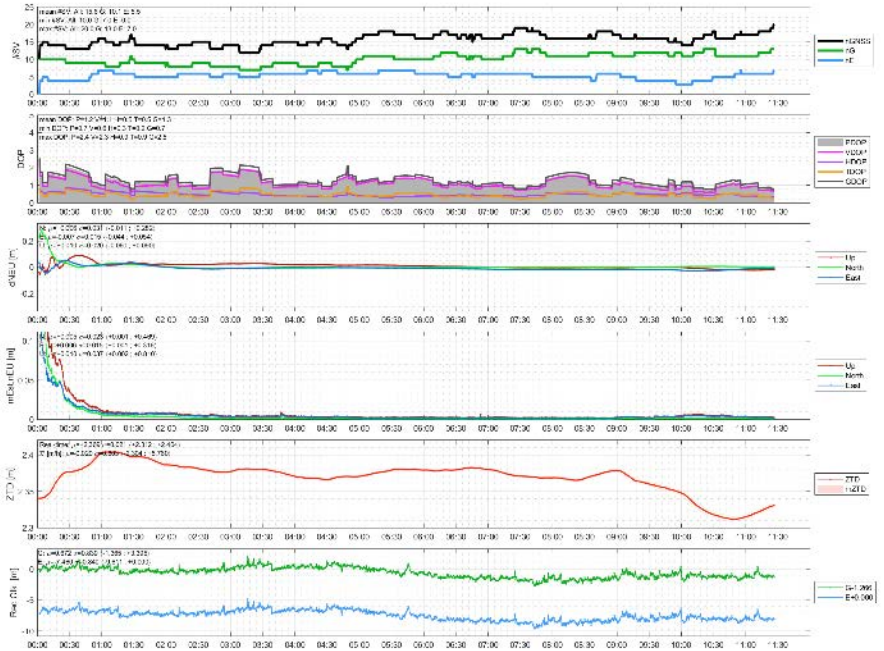
$\boldsymbol{DOPs}$

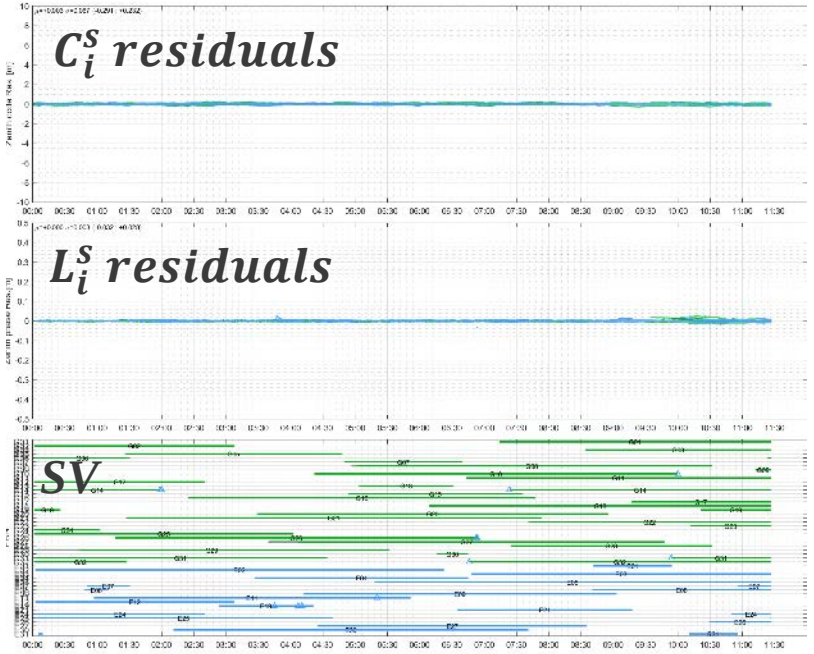
$\boldsymbol{XYZ}$

$\boldsymbol{\sigma XYZ}$

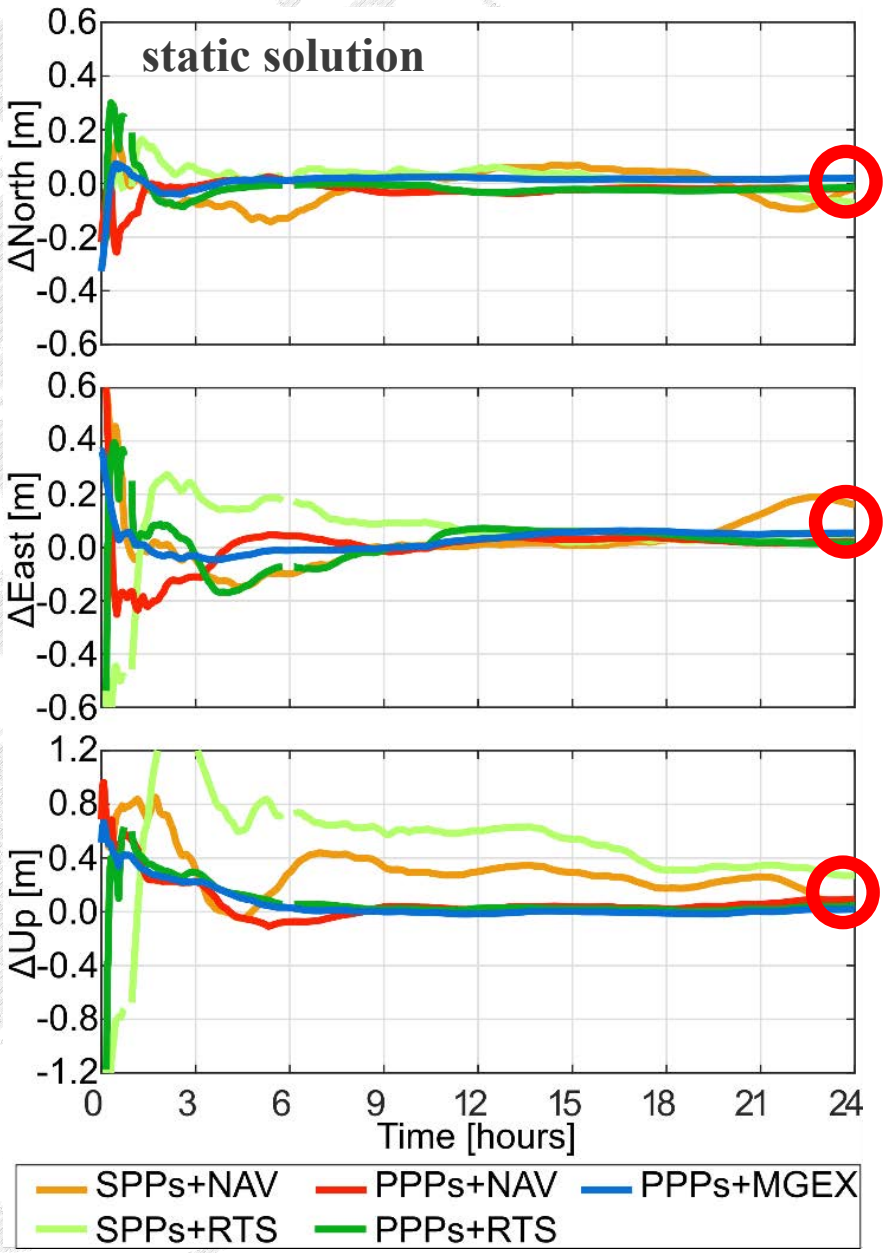
$\boldsymbol{T_Z}$

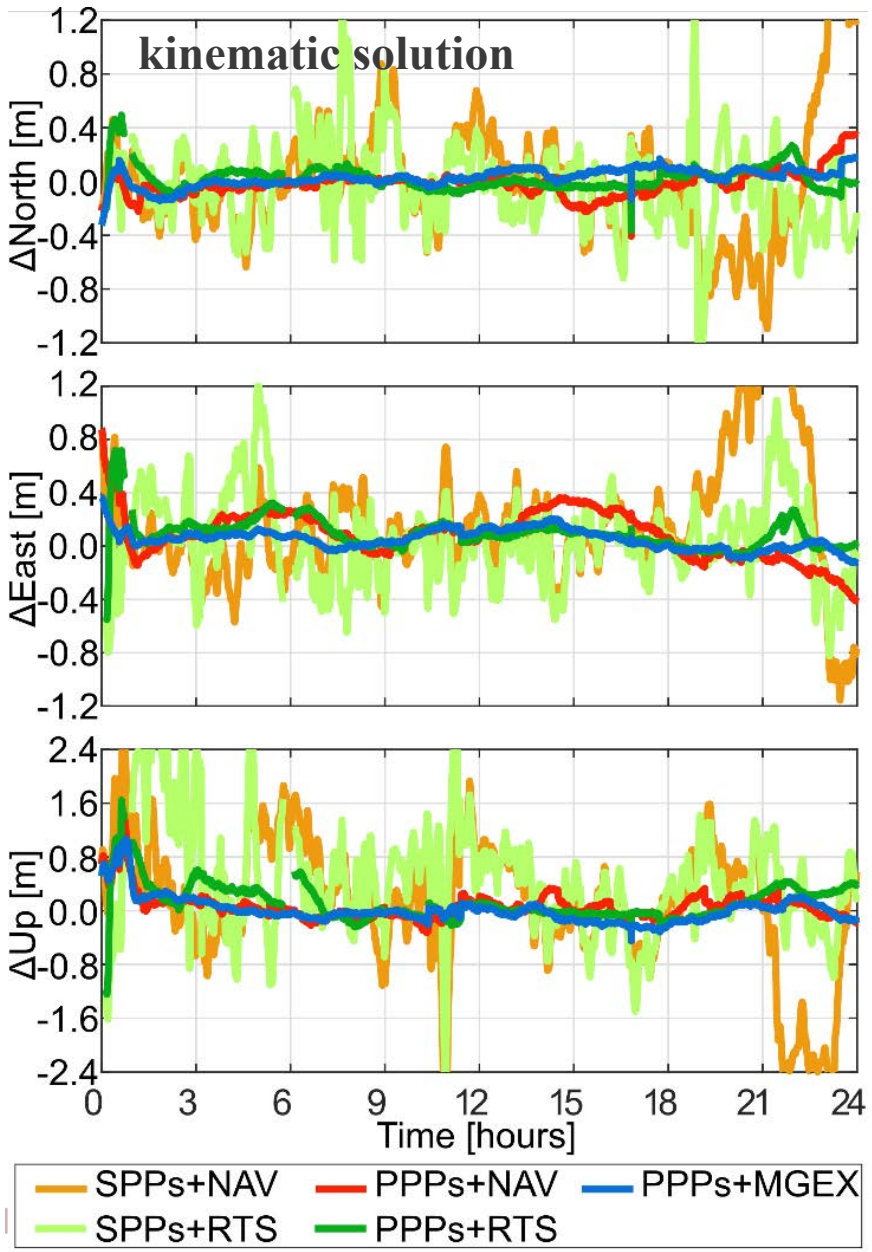
$\boldsymbol{c\delta t_r}$



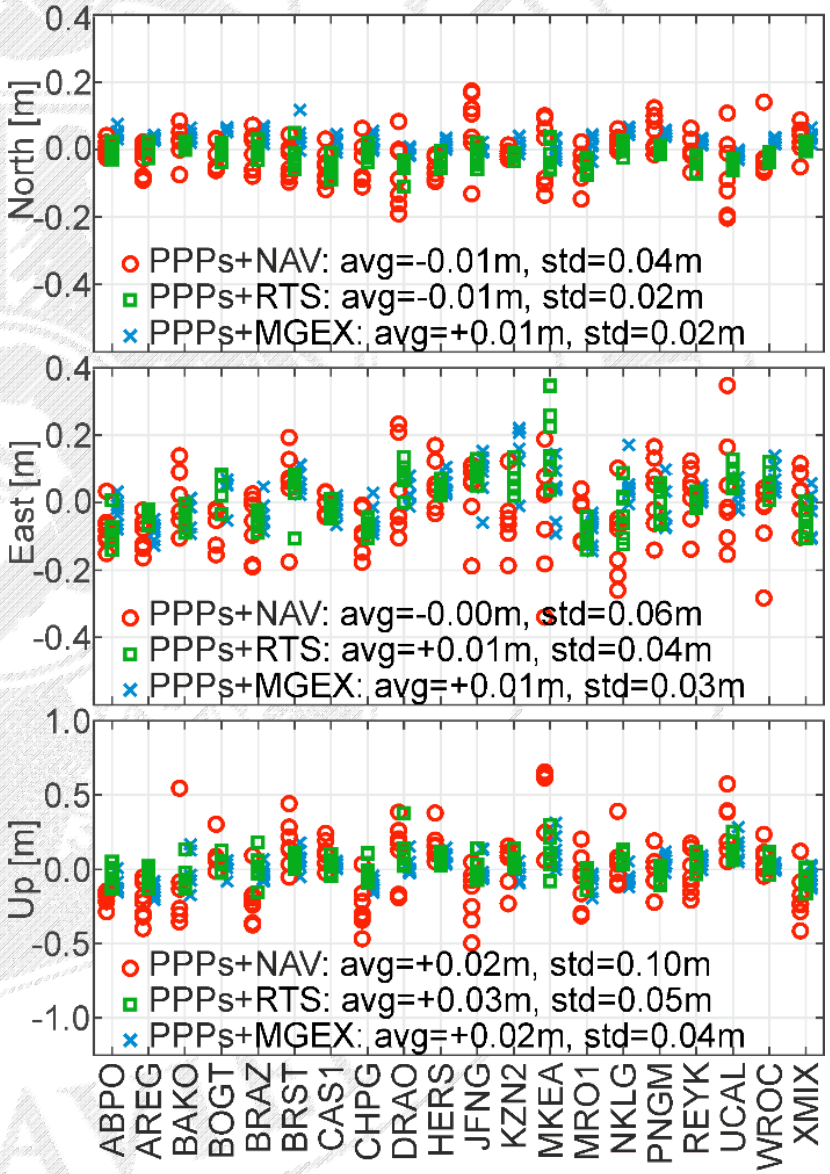


Examplary results for station WROC, January 1, 2019





Static positioning results (1)



PPP (E1C/E5C + E1W/E5W) accuracy (99%):

a) **+NAV**
- Hz < 0.2 m
- V < 0.5 m

} accurate NAV

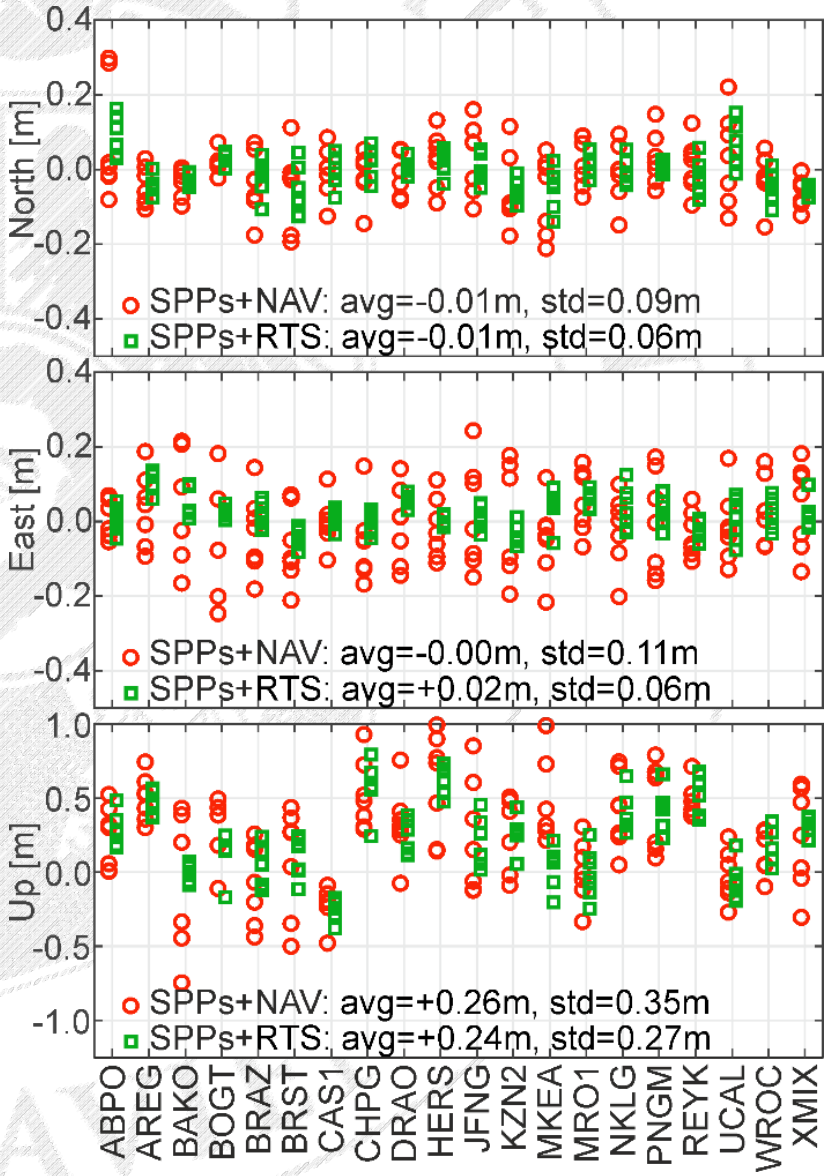
b) **+RTS**
- Hz < 0.1 m
- V < 0.2 m

c) **+MGEX**
- Hz < 0.1 m
- V < 0.2 m

} RTS ≈ MGEX

Differences between coordinates obtained from Galileo-only pseudorange and carrier-phase daily static solutions and IGS weekly combined solution

Static positioning results (2)



SPP (E1C/E5C) accuracy (99%):

a) **+NAV**
- Hz < 0.3 m
- V < 1.0 m
  - +0.25 m avg. bias (~~tropo~~)

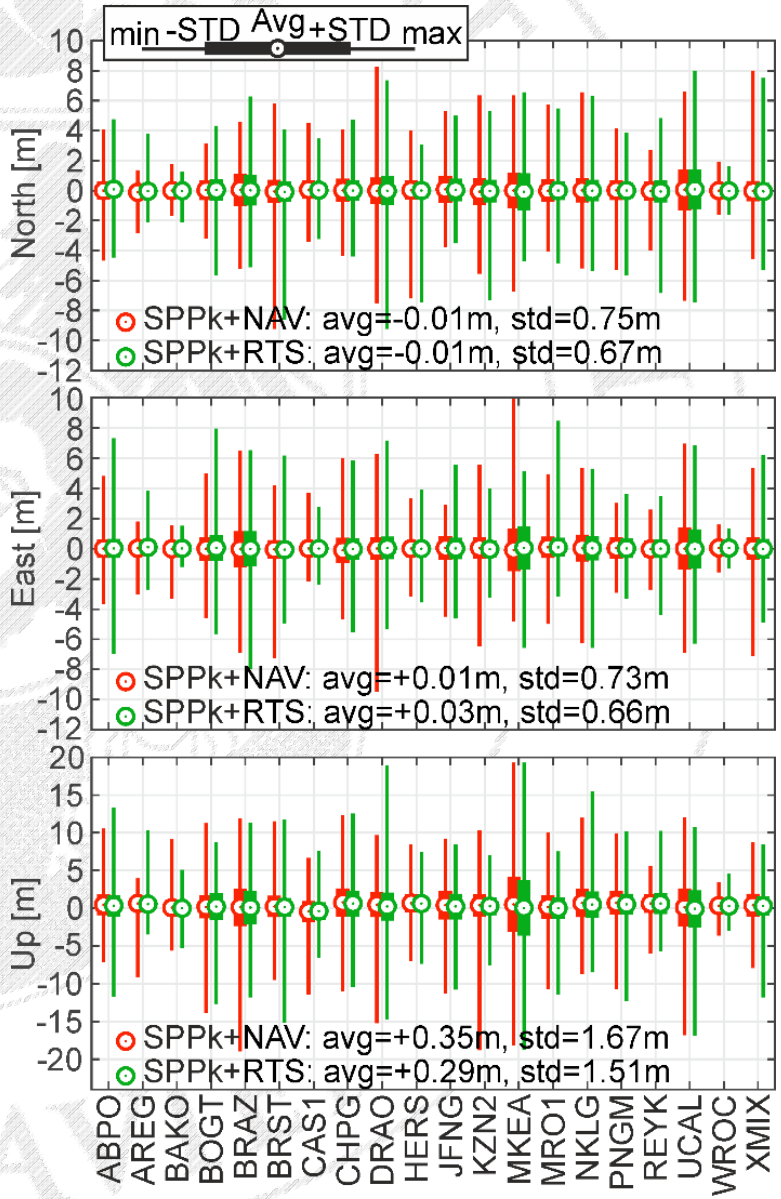
} still very good!

b) **+RTS: improves:**
- Hz by 37%
- V by 16%

} use RTS for SPP!

Differences between coordinates obtained from Galileo-only daily static solutions and IGS weekly combined solution

Kinematic positioning results (1)



SPP (E1C/E5C) accuracy (99%):

a) +NAV

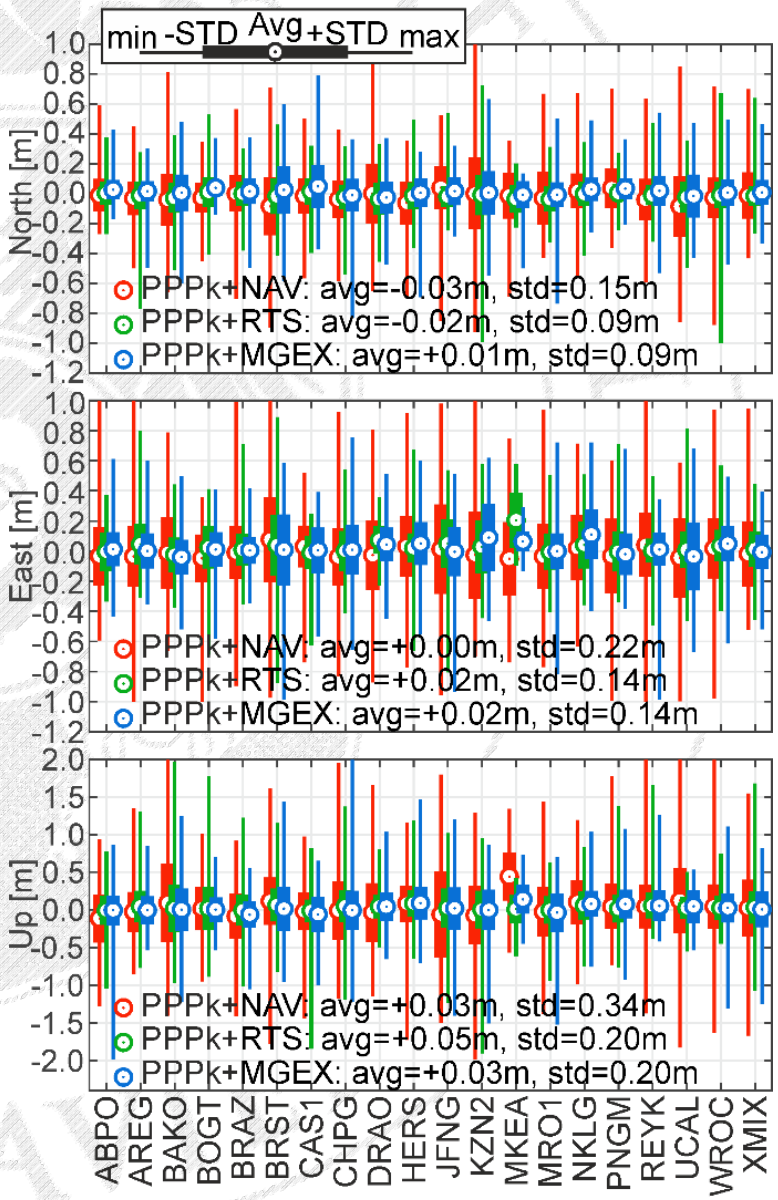
- **Hz < 10 m**
- **V < 20 m**
  - **+0.3 m avg. bias (~~tropo~~)**

b) +RTS: improves:

- **Hz by 10%**
- **V by 10%**

Differences between coordinates obtained from Galileo-only pseudorange kinematic solutions and IGS weekly combined solution

Kinematic positioning results (2)



PPP (E1C/E5C + E1W/E5W) accuracy (99%):

a) **+NAV**
- Hz < 1.0 m
- V < 2.0 m

b) **+RTS**
- Hz < 0.5 m
- V < 1.0 m

c) **+MGEX**
- Hz < 0.5 m
- V < 1.0 m

RTS ≈ MGEX

Differences between coordinates obtained from Galileo-only pseudorange and carrier-phase kinematic solutions and IGS weekly combined solution

Galileo vs GPS (static mode)

RMSE between estimated coordinates and IGS weekly combined solution for GPS-only and Galileo-only dual-frequency static positioning

Processing variant	Horizontal [m]		Vertical [m]	
	GPS	Galileo	GPS	Galileo
SPPs+NAV	0.279	0.141	0.701	0.433
SPPs+RTS	0.115	0.089	0.418	0.365
PPPs+NAV	0.197	0.067	0.188	0.098
PPPs+RTS	0.031	0.049	0.044	0.060
PPPs+MGEX	0.012	0.039	0.013	0.045

- precise Galileo static positioning still not as good as with GPS (less accurate orbit and clock products, less satellites)
- outsdanding accuracy of Galileo static SPP/PPP+NAV
- code based static positioning benefits from RTS (even more for GPS)
- best performance: GPS+MGEX (1 cm level PPP)

Galileo vs GPS (kinematic mode)

RMSE between estimated coordinates and IGS weekly combined solution for GPS-only and Galileo-only dual-frequency kinematic positioning

Processing variant	Horizontal [m]		Vertical [m]	
	GPS	Galileo	GPS	Galileo
SPPs+NAV	1.269	1.045	2.211	1.702
SPPs+RTS	0.921	0.938	1.557	1.536
PPPs+NAV	0.313	0.267	0.352	0.337
PPPs+RTS	0.080	0.164	0.103	0.210
PPPs+MGEX	0.160	0.165	0.178	0.205

- code based kinematic positioning benefits from RTS (but not that much as static)
- kinematic Galileo SPP/PPP+NAV better than GPS (ca. 10%)
- Galileo kinematic RT-PPP 2x worse than GPS
- low accuracy of kinematic GPS+MGEX (similar to Galileo+MGEX)

Conclusions

- **Development of space segment and IGS:**

  Galileo-only absolute positioning is available!

- **Broadcast ephemeris allows for accurate SPP/PPP.**

- **Further improvement of the quality of final and real-time products for Galileo is required;**

  Galileo should outperform GPS!

- **Code-only positioning(GPS and Galileo) benefit from RTS.**

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Thank You!

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