PPP and RTK Algorithm Development

Brian Weaver
TREASURE fellow

Oregon GNSS Users Group (OGUG)
Bend, Oregon
June 14, 2019

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TRAINING RESEARCH AND APPLICATIONS NETWORK TO SUPPORT THE ULTIMATE REAL TIME HIGH ACCURACY EGNSS SOLUTION

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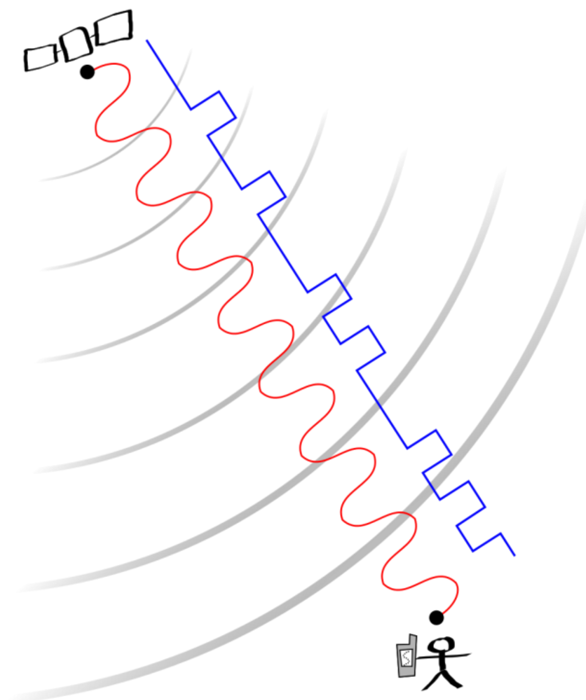
Content

- **Introduction**
- Precise Point Positioning
- Galileo constellation update
- Multi-GNSS PPP
- Conclusions and future work



Source: Wikimedia Commons

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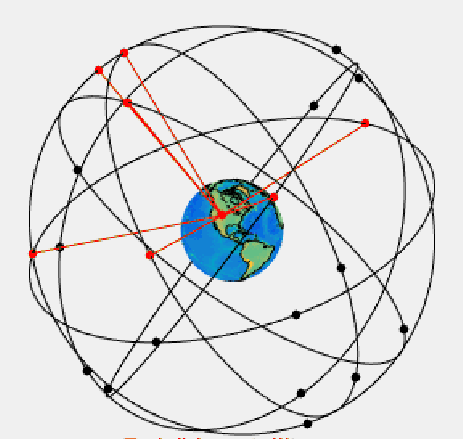
About me

- From Oregon, USA
- Outdoor enthusiast
- Oregon State University
  - Bachelor of Science (B.S.), Civil Engineering: 2015
  - Master of Science (M.Sc.), Geomatics: 2017

- University of Nottingham
  - 2nd Year PhD, Nottingham Geospatial Institute (NGI)
  - PhD Title: PPP/RTK algorithm development



By Paulsava – Wikimedia commons

TREASURE project

- **T**raining, **RE**search and **A**pplications network to **S**upport the **U**ltimate **R**eal time high accuracy **E**GNSS solution
  - http://www.treasure-gnss.eu/
- A Marie Skłodowska-Curie Actions (MSCA) Innovative Training Network (ITN), funded through the European Union's Horizon 2020 Research and Innovation Programme.

Introduction

TREASURE project

Lead beneficiary

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TREASURE
2017-2020

9 beneficiaries

+ 13 Fellows (Early Stage Researchers – ESRs)
+ 21 Associated partners (Oregon State University, ...)

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Aims and objectives:

- Improve ***Precise Point Positioning*** (PPP) user performance with the addition of ***multi-GNSS Galileo*** measurements.
- Incorporate ***external ionosphere*** and ***external troposphere*** information in the PPP user model.
- Mitigate ***ionospheric scintillation*** effects on (multi-GNSS) PPP users in collaboration with TREASURE fellows.
- Study effects of new external information on ***integer ambiguity resolution*** (IAR) for ***PPP-RTK***.
- Implement new algorithms in ***commercial software*** through ***collaboration*** with TREASURE fellows.

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Background

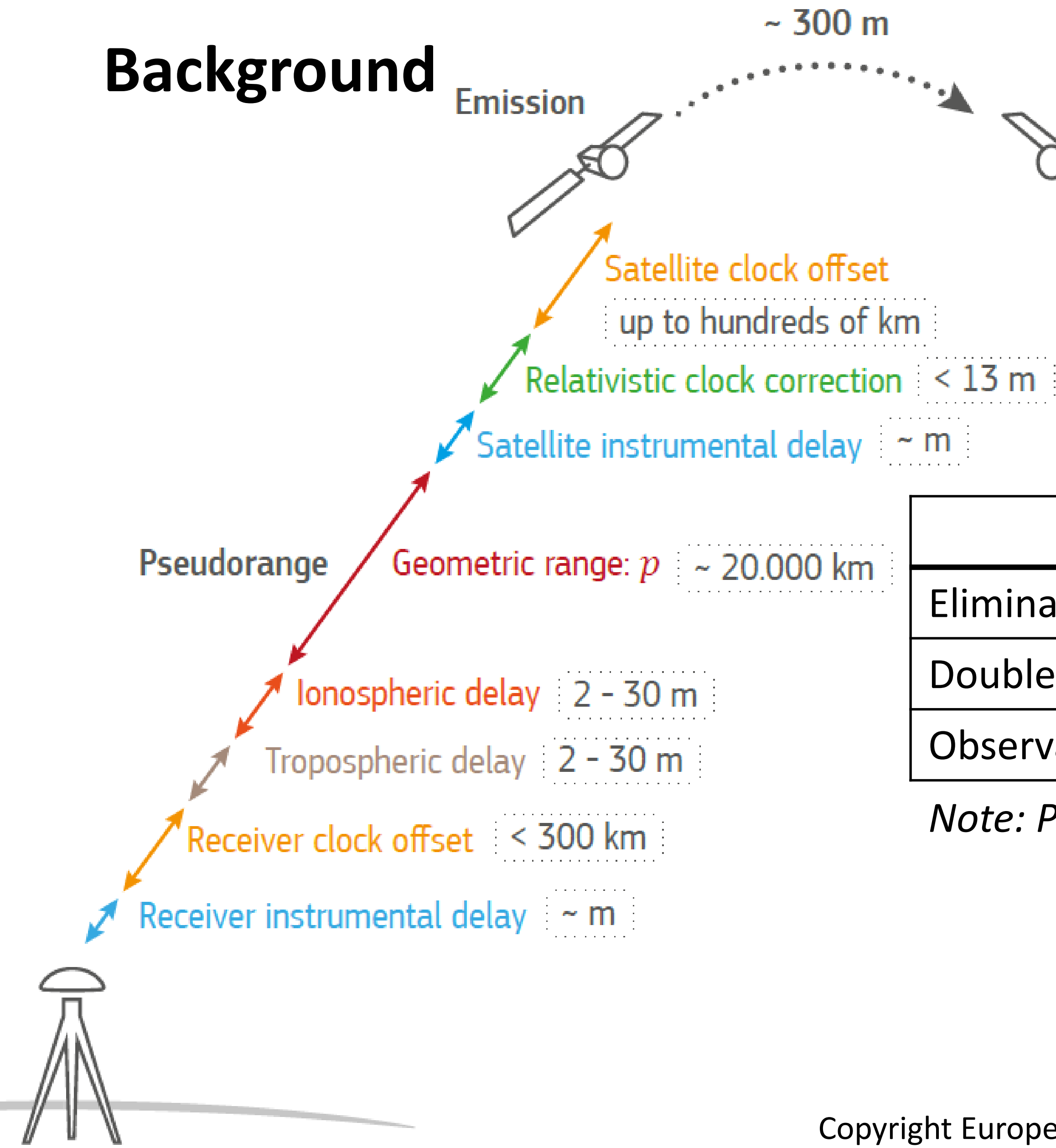
Advantages

- Absolute, **cm-level positioning** in **global** reference frame
- **Ionosphere-free** (IF) LC eliminates 1st order ionosphere

Disadvantages

- Lengthy **convergence time** with **non-integer** ambiguities
- Ionosphere-free combination **amplifies measurement noise**
- External **network information is required**

Background



RTK vs PPP

RTK	PPP
Eliminate errors	Model errors
Double-differenced	Undifferenced
Observation-space	State-space

Note: PPP-RTK is mix of both

Background

- Separate "state-space" into **network** and **user** components
  - Individual satellite error states estimated by network analysis centers

Global Network component

Estimate:
- Satellite orbits
- Satellite clocks

IGS, CODE, CNES

→

User component

Estimate:
- Coordinates
- Receiver clock
- Troposphere
- Ambiguities

GPS precise products

Product type	Orbit Accuracy [cm]	Clock Accuracy [cm]	Availability
Broadcast	~100	~150	Real-time
Ultra-rapid	~5	~90	Real-time
Final	~2.5	~2.5	12-18 days

http://www.igs.org/products/data

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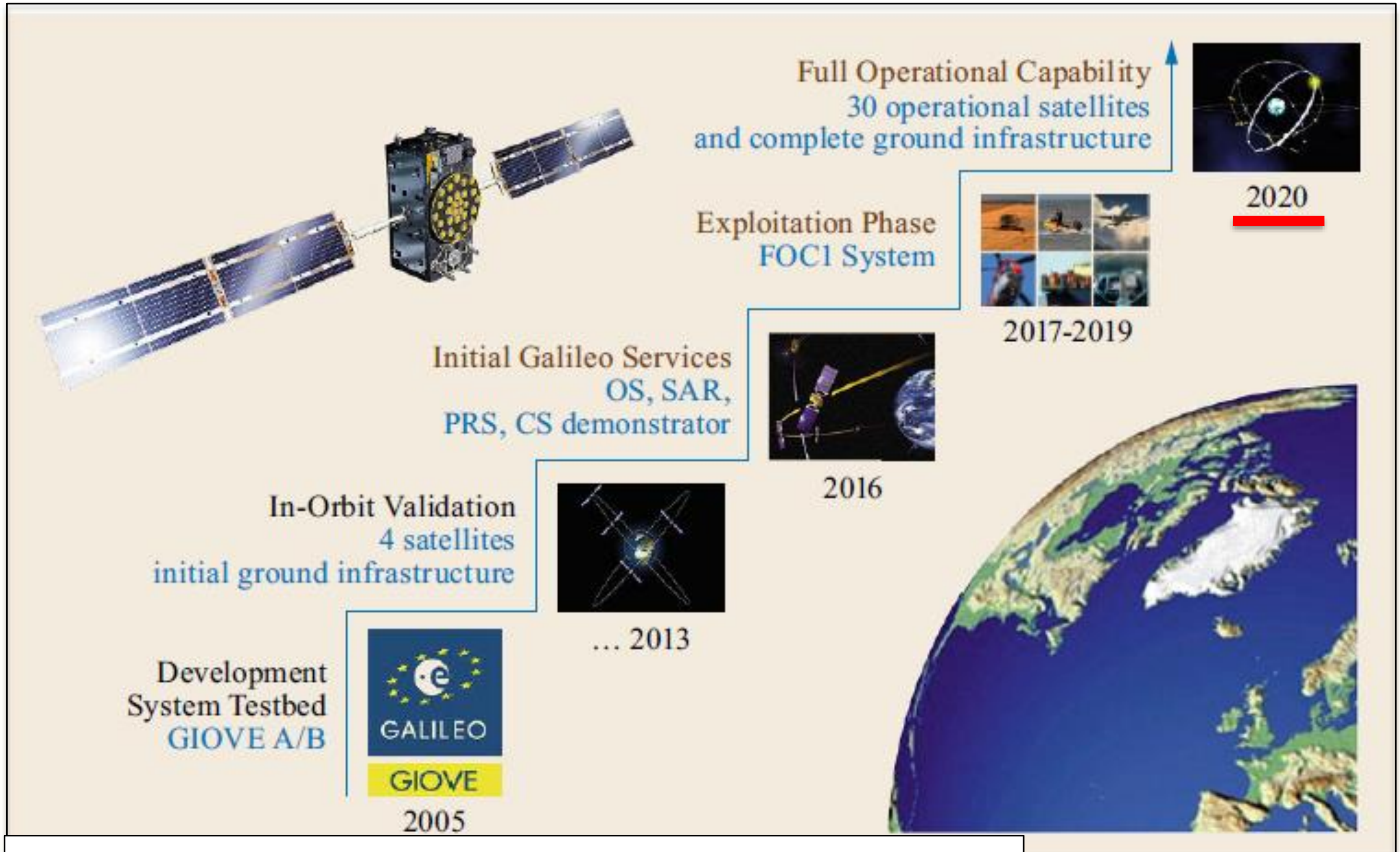
Constellation status update

Fully operational next year!



Source: Springer GNSS Handbook (2017) chapter 9, pp. 248.

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Constellation status update

- Accuracy (i.e. product agreement between analysis centers)

Constellation	Orbit Accuracy [cm]	Clock Accuracy [cm]
Galileo	~5	~5-10
GPS	~5	~3-10

Note: Values from Motenbruck et al., 2018

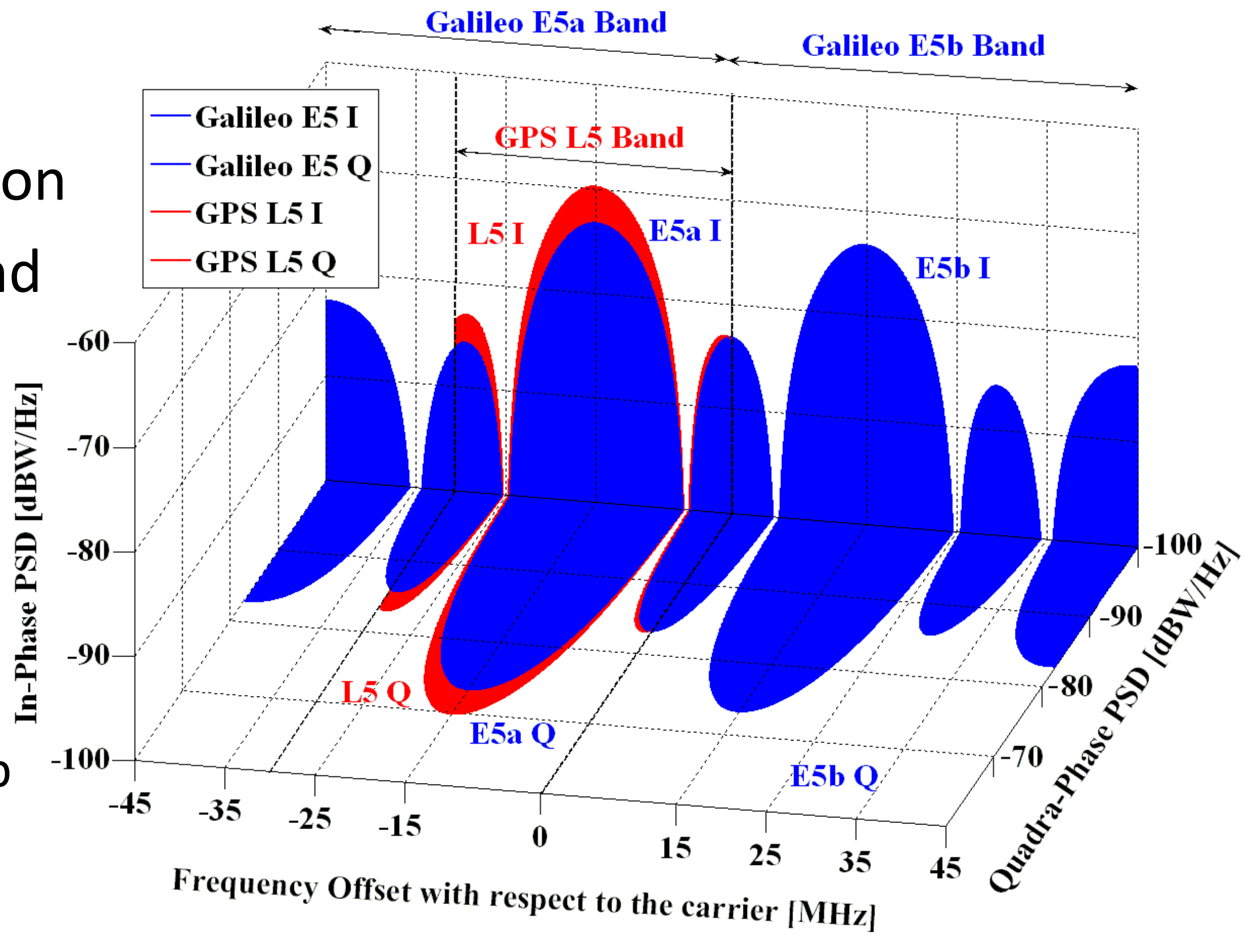
- **26 satellites in orbit** currently[1]
  - (2) Testing, (2) Not available
- **22 usable** since 11 February 2019[2]
- 12 additional FOC procured[3]

[1] https://www.gsc-europa.eu/system-status/Constellation-Information
[2] https://www.gsa.europa.eu/newsroom/news/latest-batch-galileo-satellites-enters-service
[3] ESA Galileo-App-Competition PowerPoint Oct. 16, 2018

Benefits

- AltBOC modulation
- Separate pilot and data channels
- High power transmission[1]
- Five carrier frequencies

  E1, E6, E5, E5a, E5b



https://gssc.esa.int/navipedia/index.php/Galileo_Signal_Plan

[1]Steigenberger et al., 2017

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Data

- Station PPTE, 22-deg S., 15-sec, GRE, 16-17 March 2019

Methodology

- MGEX precise products from CNES (designated GRG**)
- Dual-frequency ionosphere-free PPP with estimated ISBs[1]

Experiment

- Severe ionospheric activity (scintillation) at station PPTE
- Evaluate kinematic PPP performance scenarios:
  - (1) GPS, (2) GPS+GLO, (3) GPS+GAL, (4) GPS + GLO + GAL
- Positioning errors calculated wrt final static position

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[1]Xia et al., 2018

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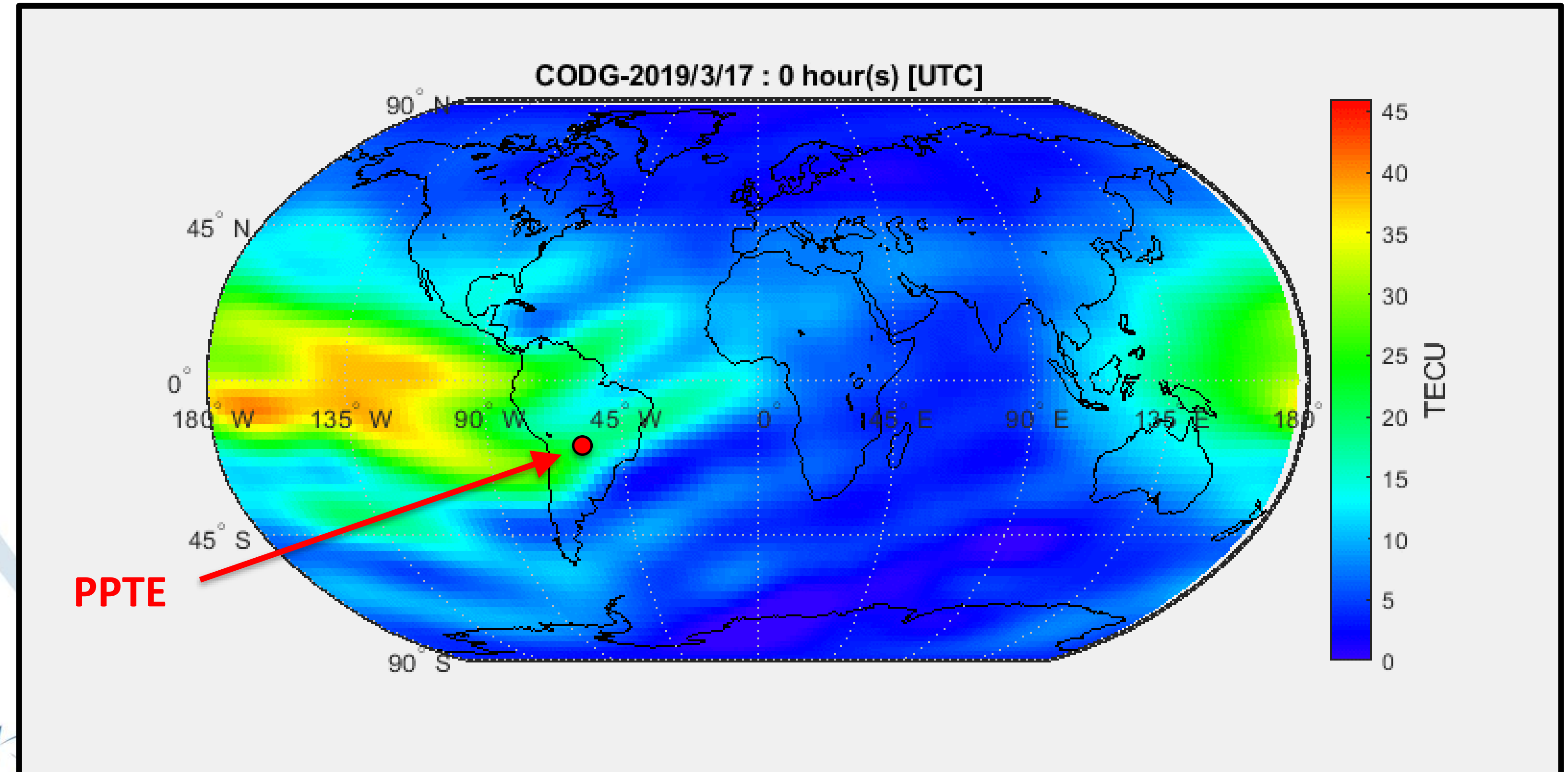
Ionospheric activity assessment

- CODE Global Ionosphere Map (GIM) in IONEX format[1]



Peak TEC	~45 TECU
Delay	~7-8* meters

Peak RMS	~4 TECU
Delay	~0.65* meters

*Delays for GPS L1 frequency

[1]CODE GIM: ftp://ftp.aiub.unibe.ch/CODE

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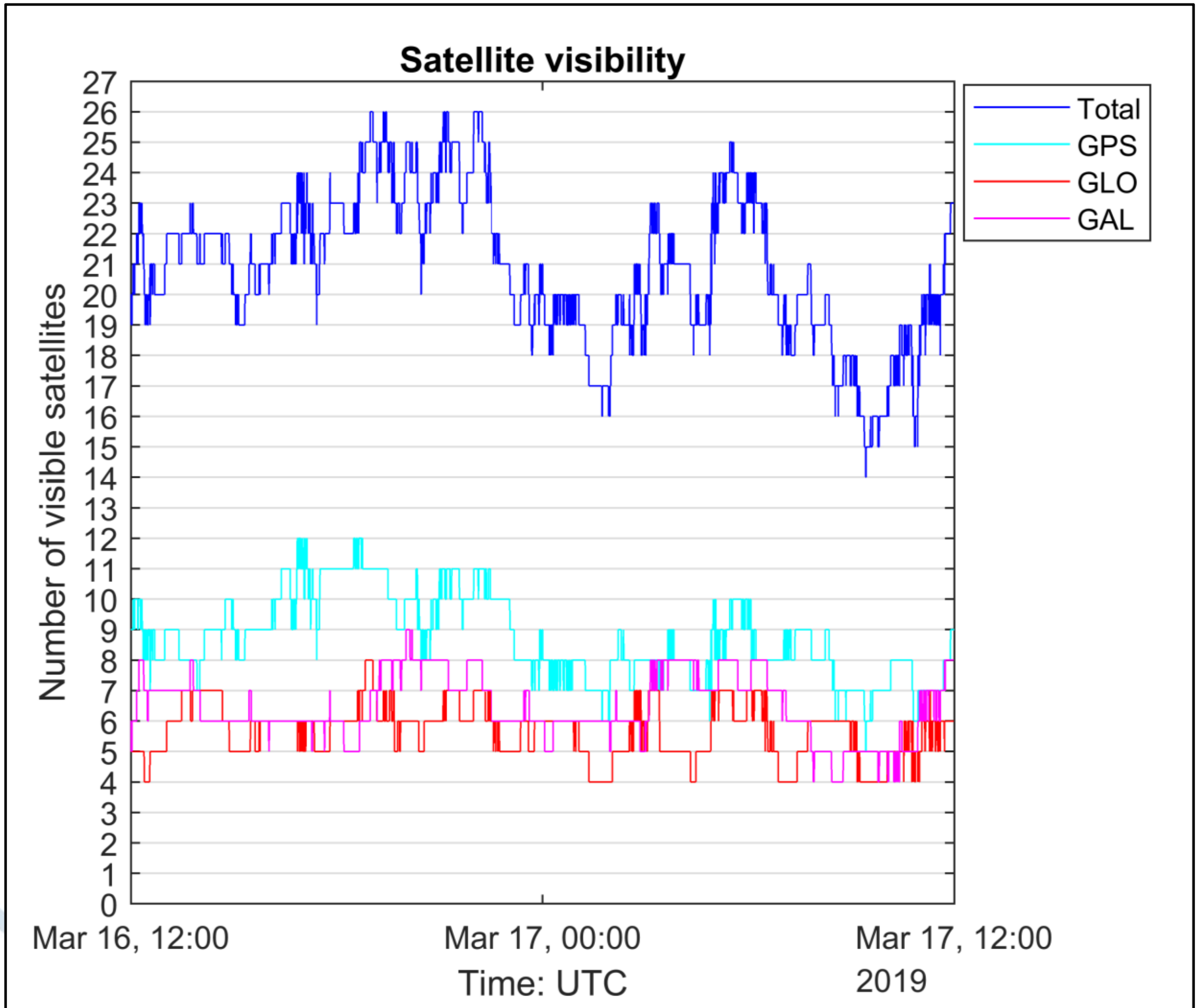
Results



Station location: Brazil 22-deg S.

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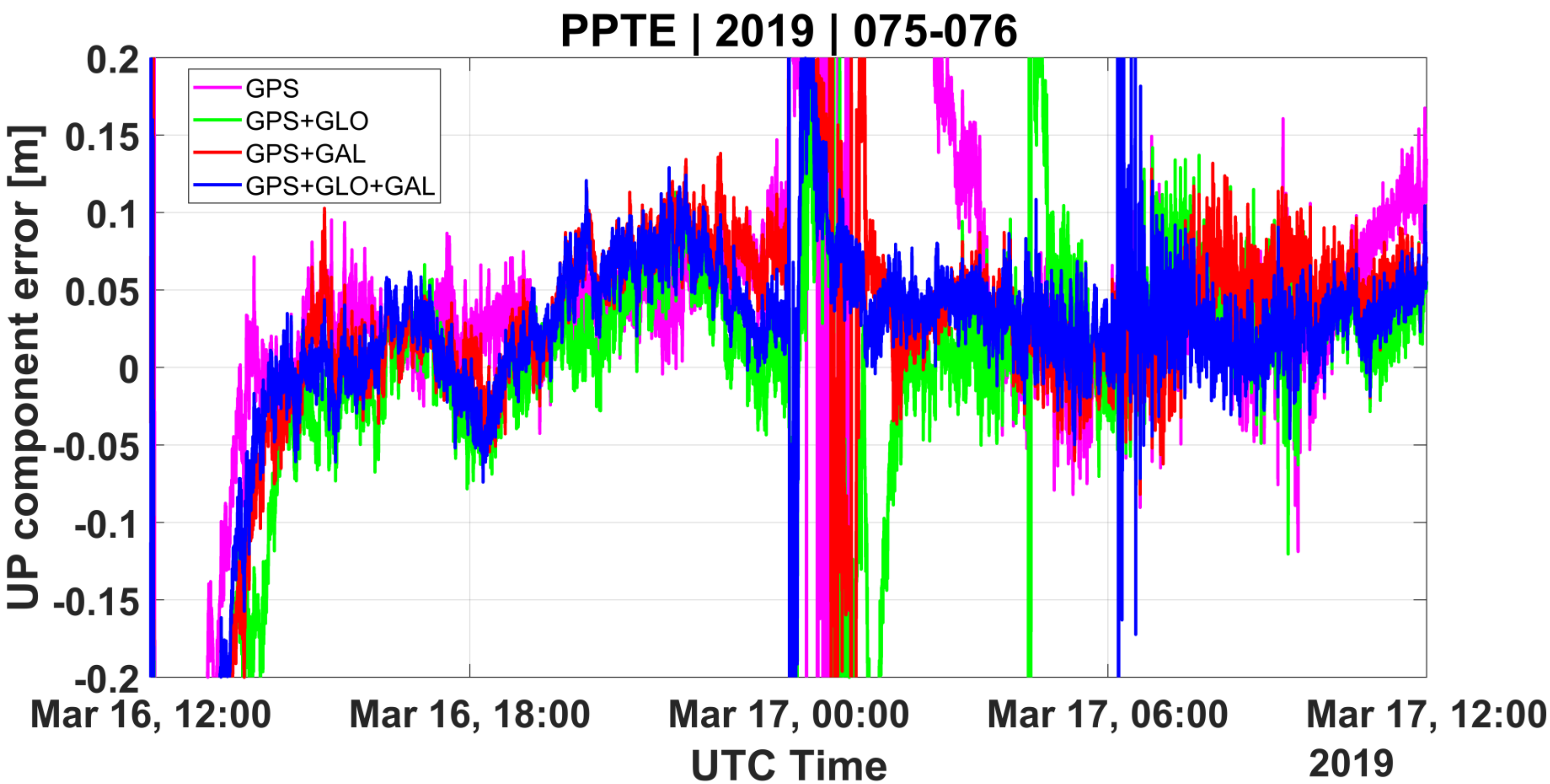
Results

- Kinematic PPP error comparison, 24-hr duration



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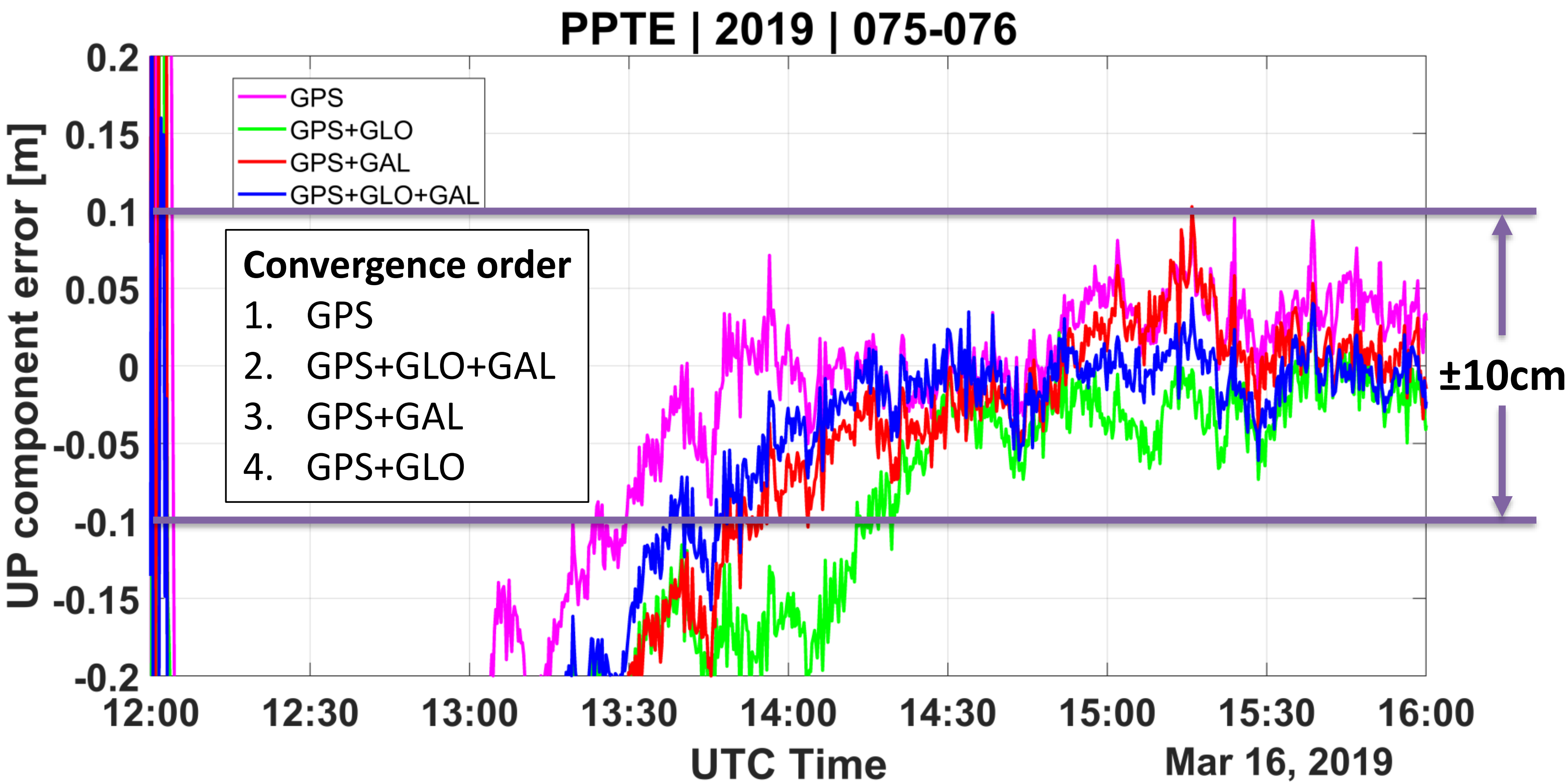
Results

- GPS+GLO+GAL: convergence period



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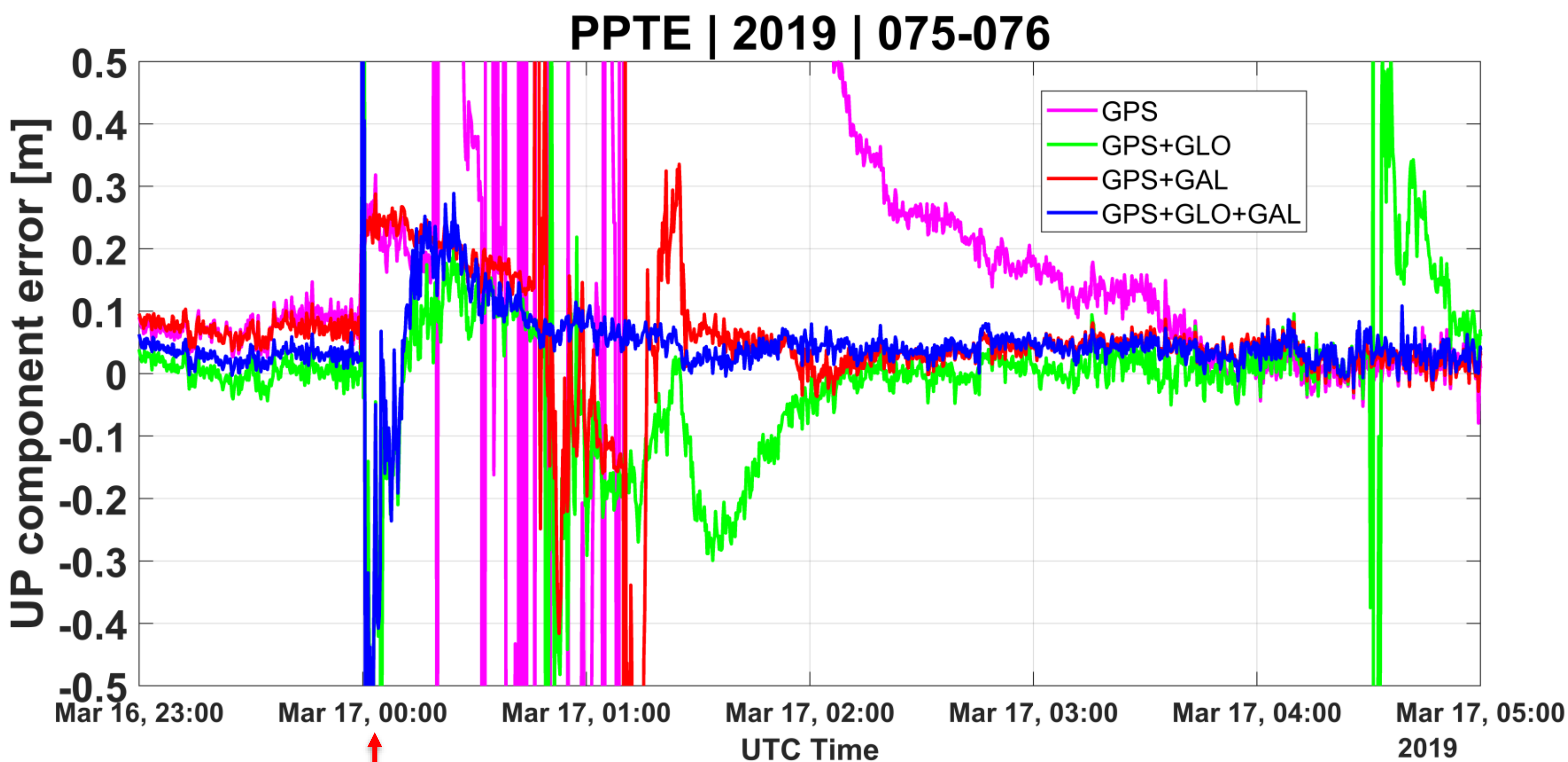
Results

- GPS+GLO+GAL: active ionosphere



UTC midnight, 17-March-2019

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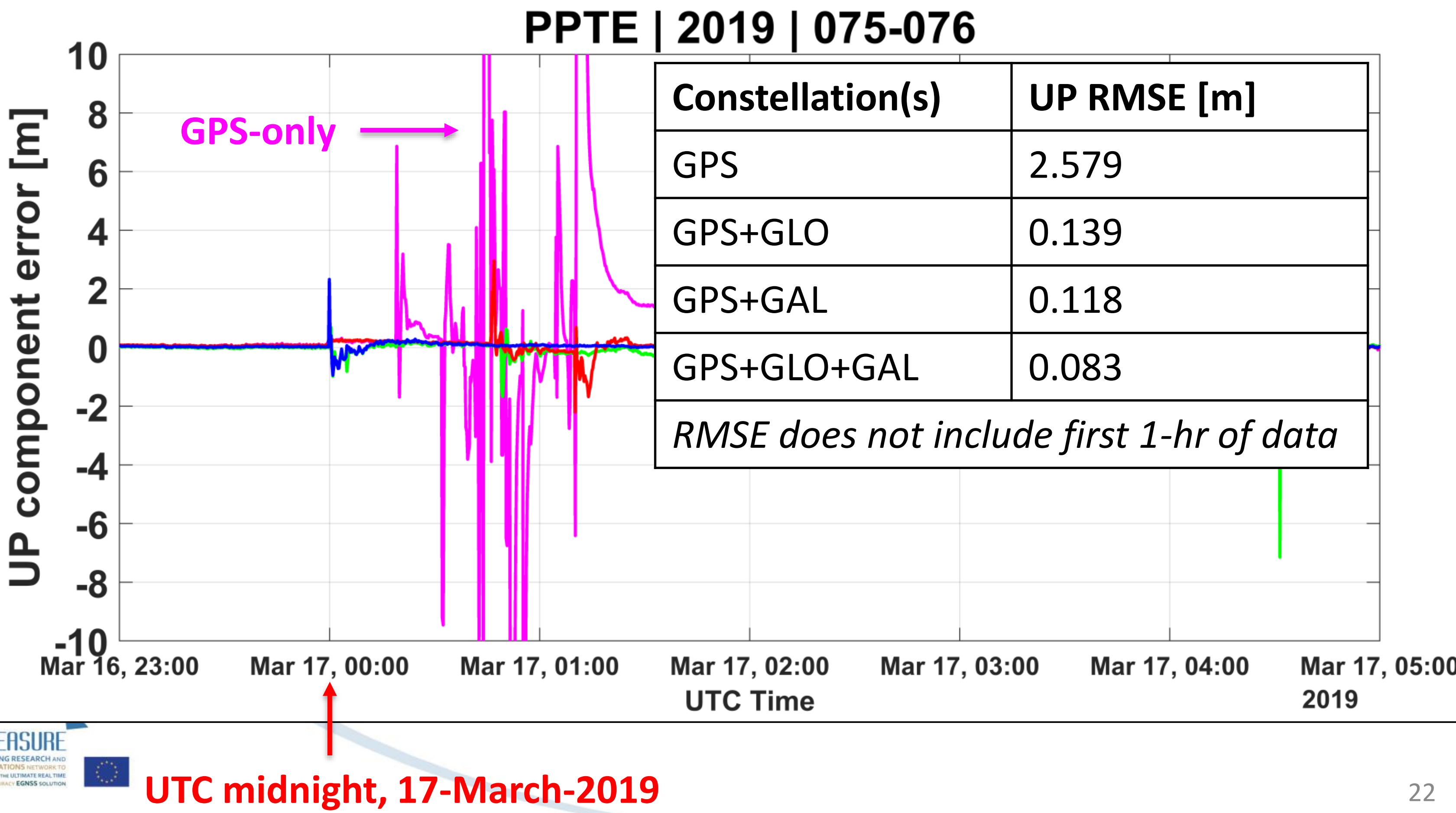
Results

- GPS+GLO+GAL: active ionosphere



Constellation(s)	UP RMSE [m]
GPS	2.579
GPS+GLO	0.139
GPS+GAL	0.118
GPS+GLO+GAL	0.083
RMSE does not include first 1-hr of data	

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Conclusions

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- Galileo constellation is available to use for PPP
  - Nearly complete with many benefits to GNSS users

- Largest positioning errors for GPS-only kinematic PPP during active ionosphere

- Reduced positioning *errors for multi-GNSS PPP
  - *Up RMSE during active (severe) ionosphere

Constellation(s)	UP RMSE [m]
GPS	2.579
GPS+GLO	0.139
GPS+GAL	0.118
GPS+GLO+GAL	0.083

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Future research

- Validate multi-GNSS results for other scenarios
  - Multi-GNSS should improve **convergence time**
- Study **external ionosphere** (GIM) in multi-GNSS PPP
  - Include stochastic information in positioning model
- Improve positioning accuracy during strong ionospheric activity
  - i.e. ionospheric **scintillation mitigation**

References

Marques, H. A., Marques, H. A. S., Aquino, M., Veettil, S. V., & Monico, J. F. G. (2018). Accuracy assessment of Precise Point Positioning with multi-constellation GNSS data under ionospheric scintillation effects. *Journal of Space Weather and Space Climate, 8, A15*. doi:10.1051/swsc/2017043.

Montenbruck, O.; Steigenberger, P.; Hauschild, A., 2018. Multi-GNSS signal-in-space range error assessment—Methodology and results. Adv. Spac Res., 61, 3020–3038.

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Xia, F., Ye, S., Xia, P., Zhao, L., Jiang, N., Chen, D., Hu, G., 2018. Assessing the latest performance of Galileo-only PPP and the contribution of Galileo to Multi-GNSS PPP. Adv. Space Res. 63 (9), 2784–2795. https://doi.org/10.1016/j.asr.2018.06.008.

Questions?

PPP and RTK Algorithm Development

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Multi-GNSS PPP

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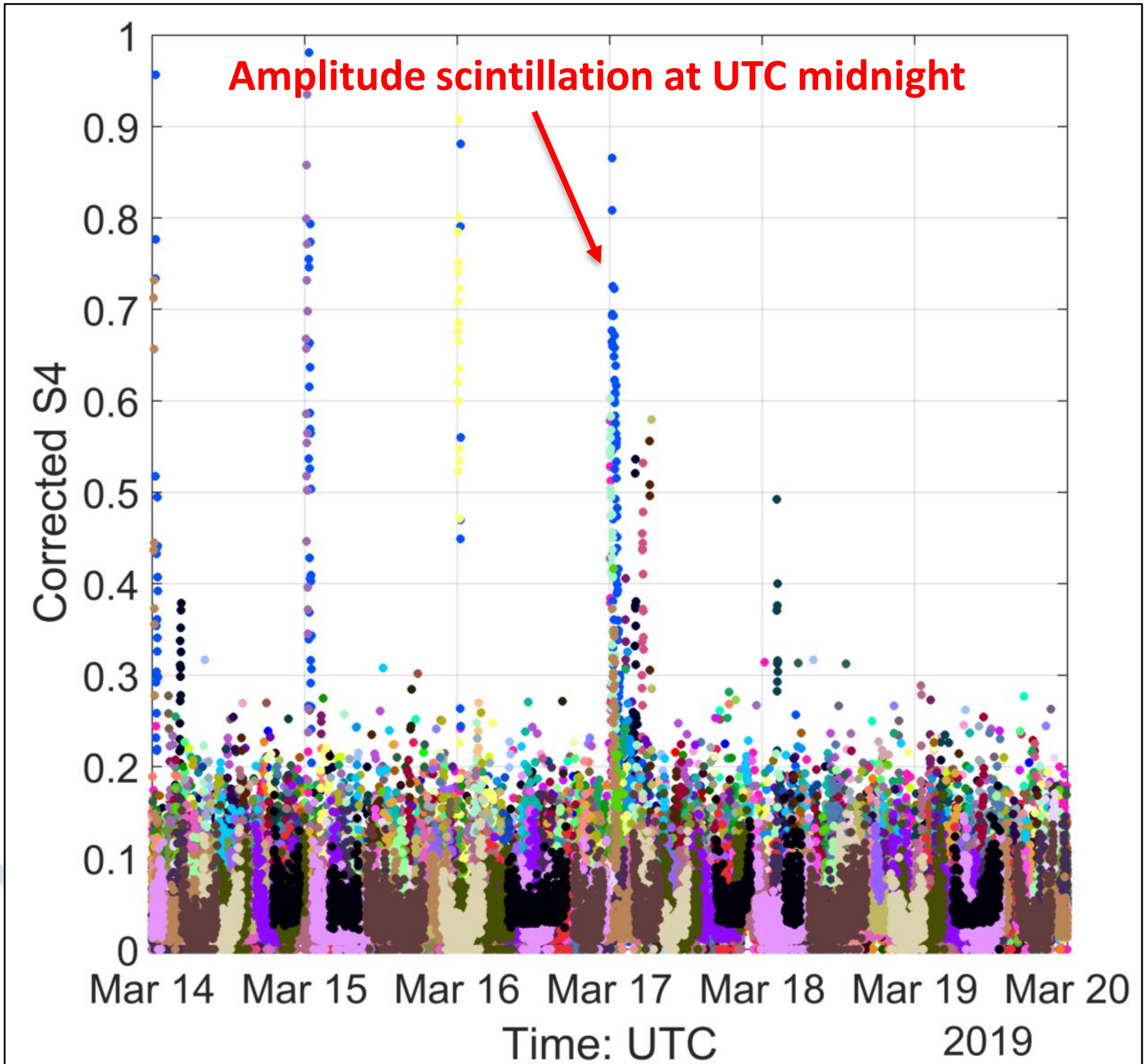
Ionospheric scintillation monitoring receiver



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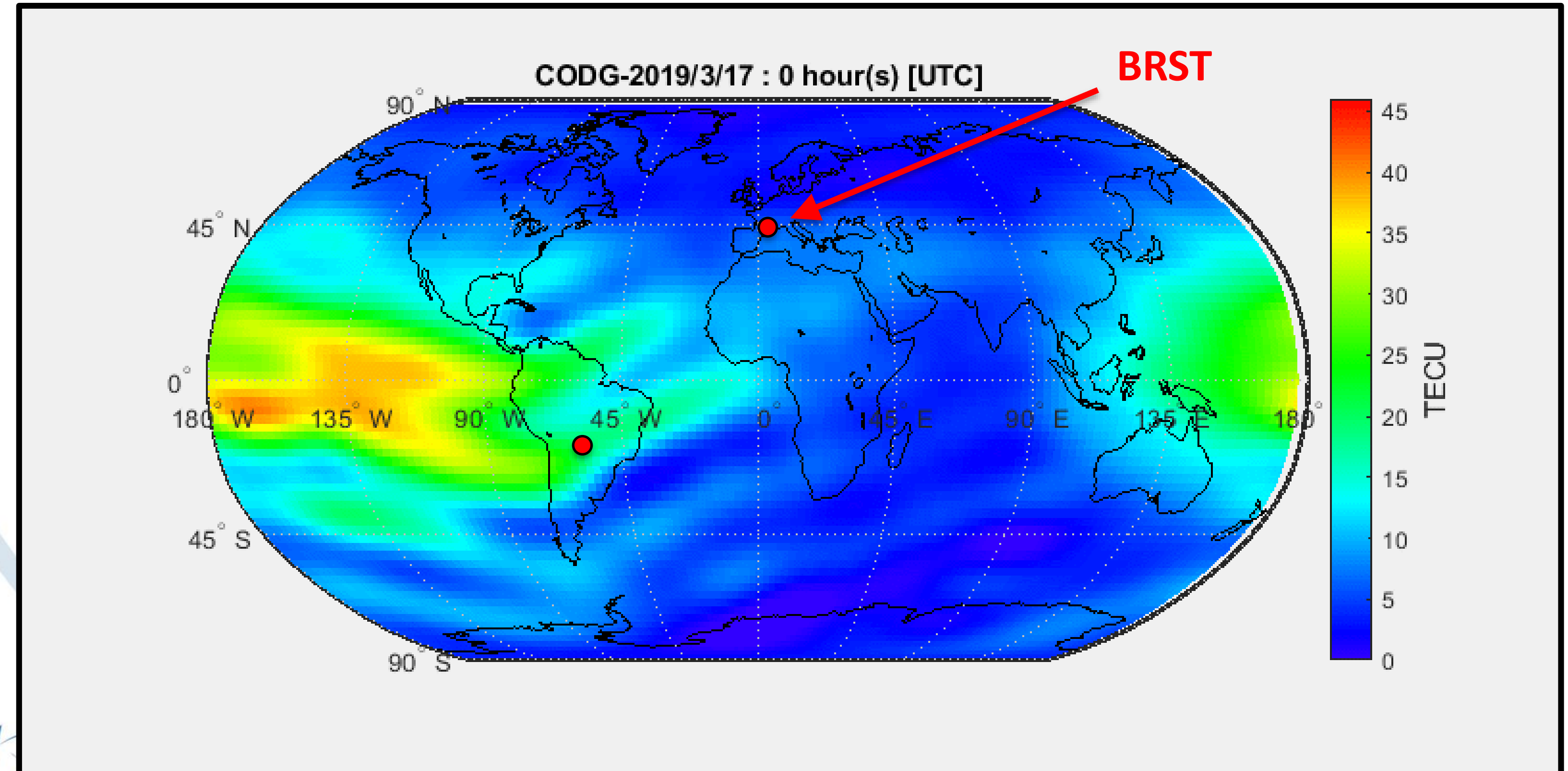

Peak TEC	~45 TECU	Peak RMS	~4 TECU
Delay	~7-8* meters	Delay	~0.65* meters

*Delays for GPS L1 frequency

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[1]CODE GIM: ftp://ftp.aiub.unibe.ch/CODE

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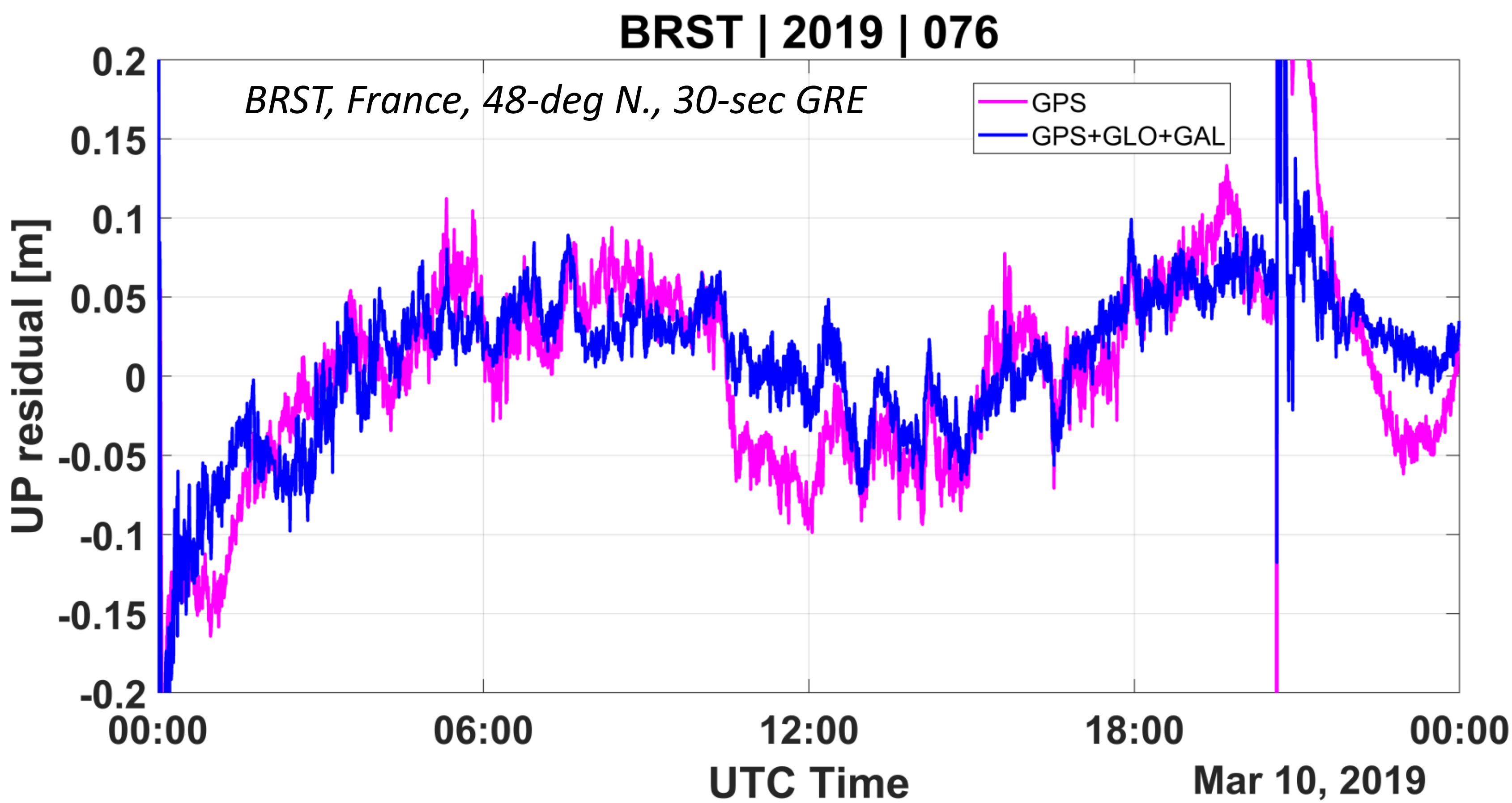
Results

- **Moderate** ionosphere activity



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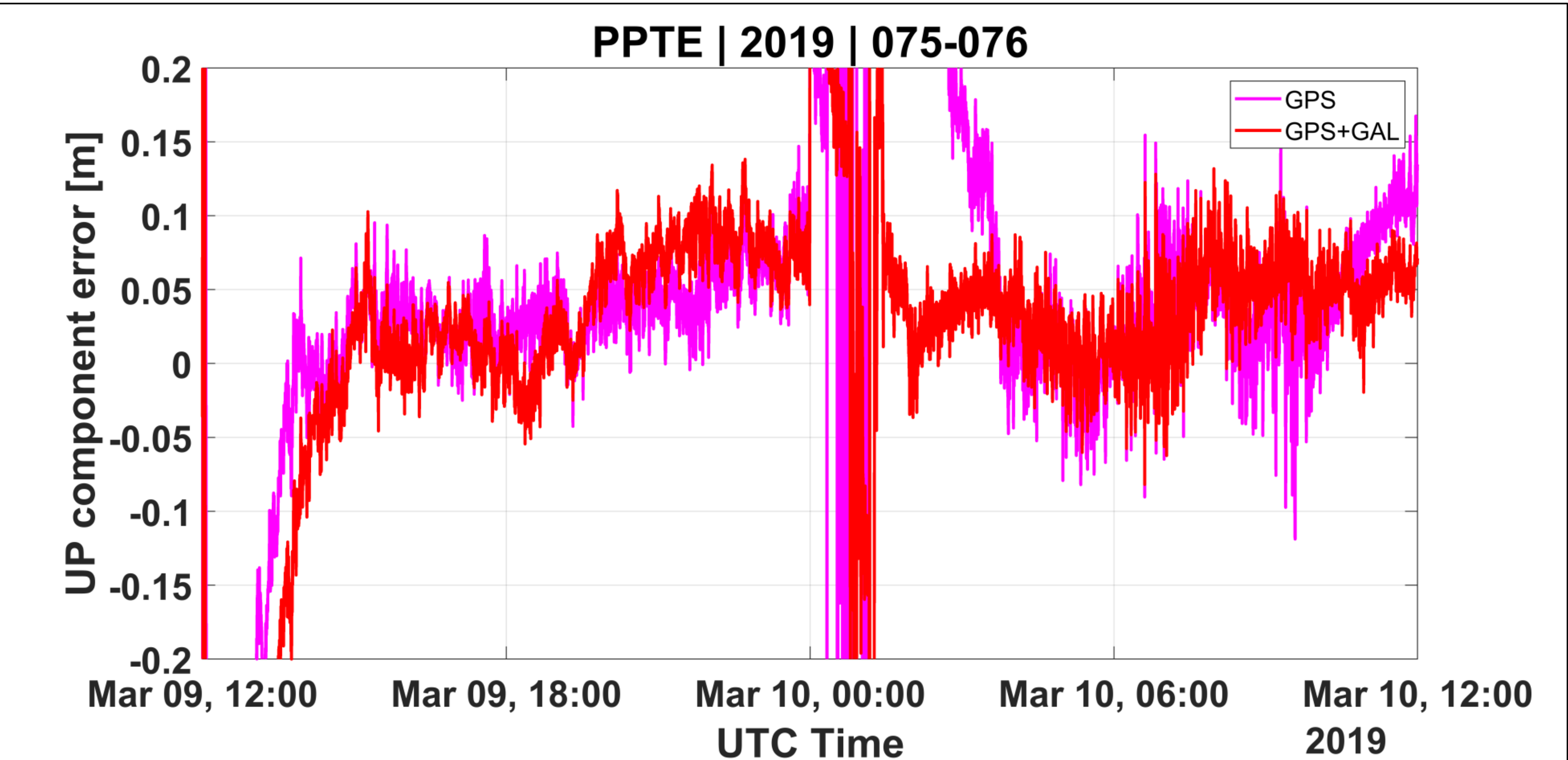
Results

- GPS+GAL



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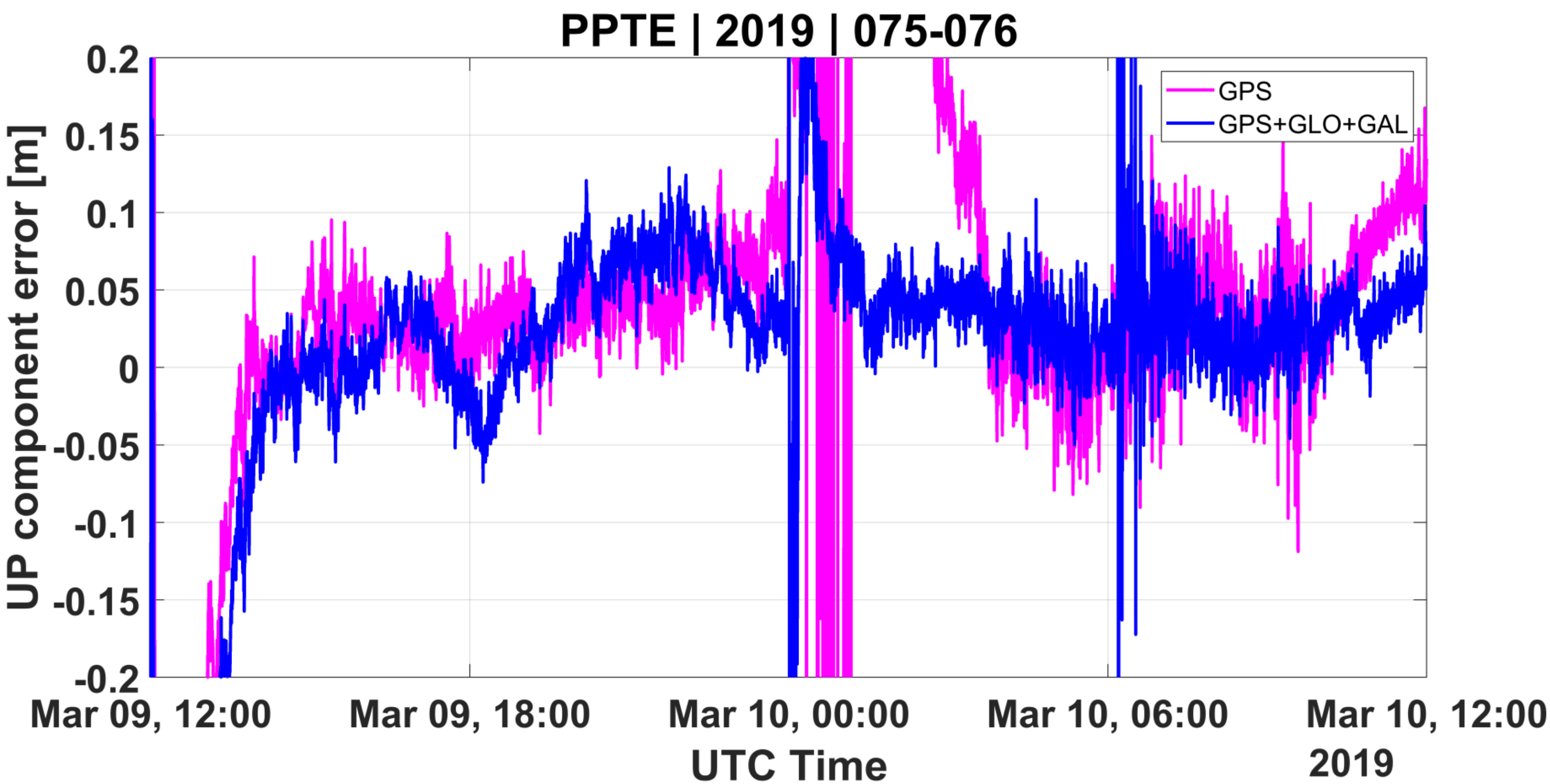
Results

- GPS+GLO+GAL



Results

- GPS+GLO

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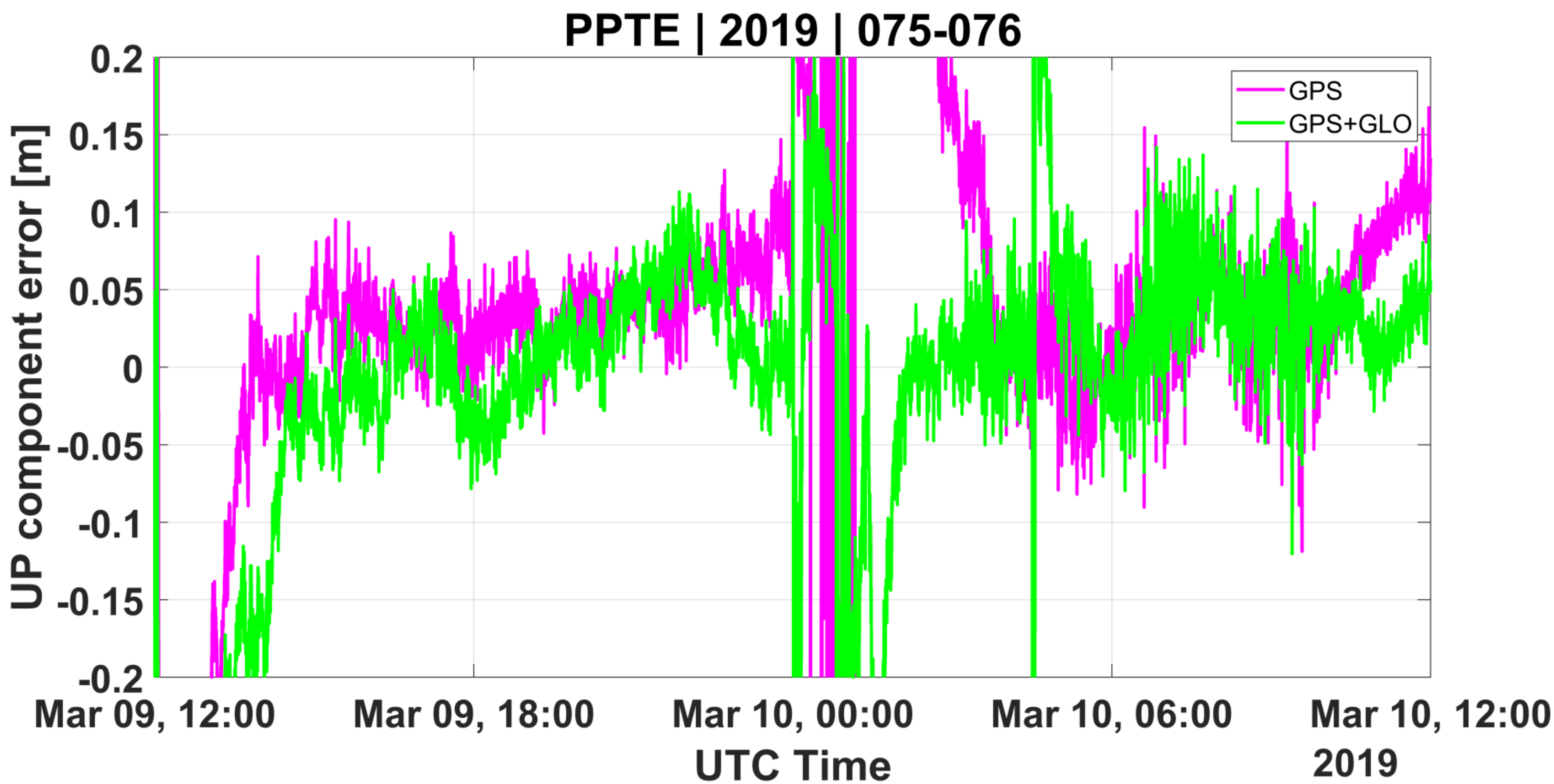

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Ionosphere activity

- CODE Global Ionosphere Map (GIM) in IONEX format[1]

Property	Value
ΔLat.	2.5-deg
ΔLon.	5.0-deg
Interval	1-hr
Peak TEC	~45 TECU
Delay	~7-8* meters
Peak RMS	~4 TECU
Delay	~0.65 meters

**Delay for GPS L1 frequency*

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[1]CODE GIM: ftp://ftp.aiub.unibe.ch/CODE

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Functional model for multi-GNSS PPP

- One extra parameter (ISB) per constellation (Xia et al., 2018)

$$p_{IF}^{G} = \rho^{G} + c \cdot dt - c \cdot dt^{G} + d_{trop}^{G} + \varepsilon_{p}^{G},$$

$$\Phi_{IF}^{G} = \rho^{G} + c \cdot dt - c \cdot dt^{G} + d_{trop}^{G} + \lambda N^{G} + \varepsilon_{p}^{G},$$

$$p_{IF}^{R} = \rho^{R} + c \cdot dt - c \cdot dt^{R} + ISB_{sys}^{G,R} + d_{trop}^{R} + \varepsilon_{p}^{R},$$

$$\Phi_{IF}^{R} = \rho^{R} + c \cdot dt - c \cdot dt^{R} + ISB_{sys}^{G,R} + d_{trop}^{R} + \lambda N^{R} + \varepsilon_{p}^{R},$$

$$p_{IF}^{E} = \rho^{E} + c \cdot dt - c \cdot dt^{E} + ISB_{sys}^{G,E} + d_{trop}^{E} + \varepsilon_{p}^{E},$$

$$\Phi_{IF}^{E} = \rho^{E} + c \cdot dt - c \cdot dt^{E} + ISB_{sys}^{G,E} + d_{trop}^{E} + \lambda N^{E} + \varepsilon_{p}^{E},$$

G = GPS
R = GLONASS
E = Galileo

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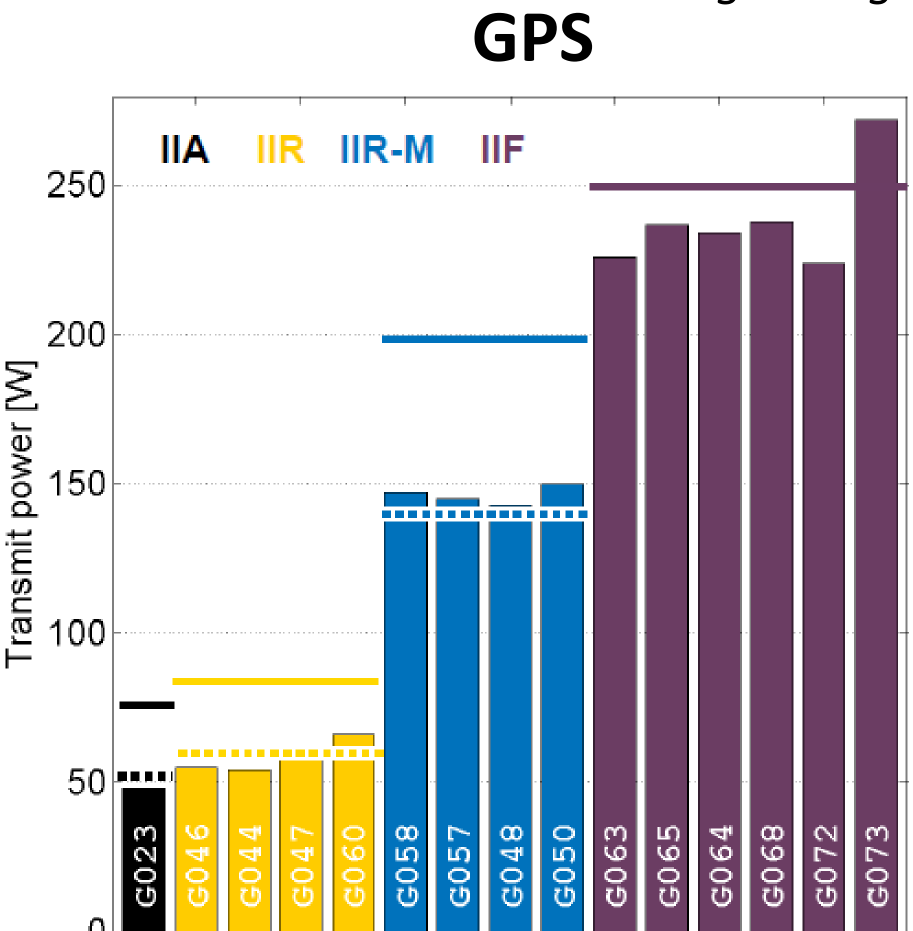
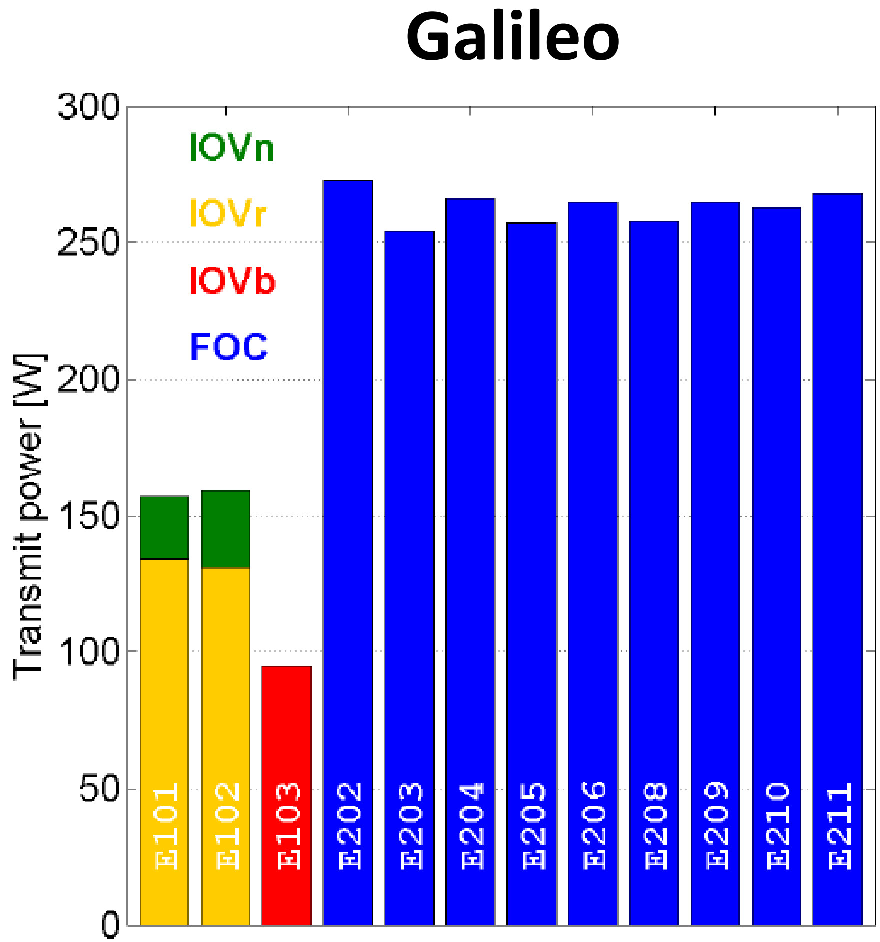
Compare transmit power

Steigenberger et al., 2017





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POINT weighting

- **Elevation**

$$weight = noise\_std * \frac{1.001}{\sqrt{(0.002001 + \sin(elevation)\ ^2)}}$$

- **SNR**

$$\sigma L1, L2(m) = \sqrt{\frac{B}{c/n_0}} . \frac{\lambda}{2\pi}$$

- **Extended SNR**

$$weight\ P_i = 300 * \sqrt{0.244 * 10^{\frac{-SNR}{10}}} \quad weight\ L_i = 2 * \sqrt{0.244 * 10^{\frac{-SNR}{10}}}$$

- **Multipath**

$$= \left(\frac{f_1^2}{f_1^2 - f_2^2} * \mathrm{PR}_1 - \frac{f_2^2}{f_1^2 - f_2^2} * \mathrm{PR}_2\right) - \left(\frac{f_1^2}{f_1^2 - f_2^2} * \emptyset_1 * \lambda_1 - \frac{f_2^2}{f_1^2 - f_2^2} * \emptyset_2 * \lambda_2 - \text{ionospheric free ambiguity} * \lambda_1\right)$$

$$tmp\ weight = \sqrt{\frac{calulated\ multipath^2}{\left(\frac{f_1^2}{f_1^2 - f_2^2}\right)^2 + \left(\frac{f_2^2}{f_1^2 - f_2^2}\right)^2}} \qquad weight = tmp\ weight + 0.25$$

- **Stochastic**

$$C_1, P_1 weight = \left(0.1773 + 0.9232 * e^{-0.0945 * (elevation\ angle)}\right)$$

$$P_2 weight = \left(0.1983 + 0.722 * e^{-0.1183 * (elevation\ angle)}\right)$$

$$C_2 weight = \left(0.2188 + 1.4488 * e^{-0.1655 * (elevation\ angle)}\right)$$

$$L_1, L_2 = noise\_std$$

Source: Jareer (2017)

Additional references

Aquino, M., Monico, J. F. G., Dodson, A. H., Marques, H., De Franceschi, G., Alfonsi, L., Andreotti, M. (2009). Improving the GNSS positioning stochastic model in the presence of ionospheric scintillation. *Journal of Geodesy*, 83(10), 953-966. doi:10.1007/s00190-009-0313-6.

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Kalman Filter Algorithm

Pre-determined system model: $\mathbf{\Phi}, \mathbf{H}, \mathbf{Q}, \mathbf{R}$

0. Set initial values

$$\hat{\mathbf{x}}_0, \mathbf{P}_0$$

1. Predict state and error covariance

$$\hat{\mathbf{x}}_k(-) = \mathbf{\Phi}_k \hat{\mathbf{x}}_{k-1}(+)$$

$$\mathbf{P}_k(-) = \mathbf{\Phi}_k \mathbf{P}_{k-1}(+) \mathbf{\Phi}_k^T + \mathbf{Q}_{k-1}$$

2. Compute Kalman gain

$$\overline{\mathbf{K}}_k = \mathbf{P}_k(-) \mathbf{H}_k^T \left(\mathbf{H}_k \mathbf{P}_k(-) \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1}$$

3. Compute state estimate

Measurement vector $\mathbf{z}_k$ →

$$\hat{\mathbf{x}}_k(+) = \hat{\mathbf{x}}_k(-) + \overline{\mathbf{K}}_k\left(\mathbf{z}_k - \mathbf{H}_k \hat{\mathbf{x}}_k(-)\right)$$

→ Estimate of state vector $\hat{\mathbf{x}}_k$

4. Compute error covariance

$$\mathbf{P}_k(+) = \mathbf{P}_k(-) - \overline{\mathbf{K}}_k \mathbf{H}_k \mathbf{P}_k(-)$$

Source: Dr. Chris Parrish (Oregon State University)