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Assessment of ionospheric corrections for PPP-RTK using regional ionosphere modeling

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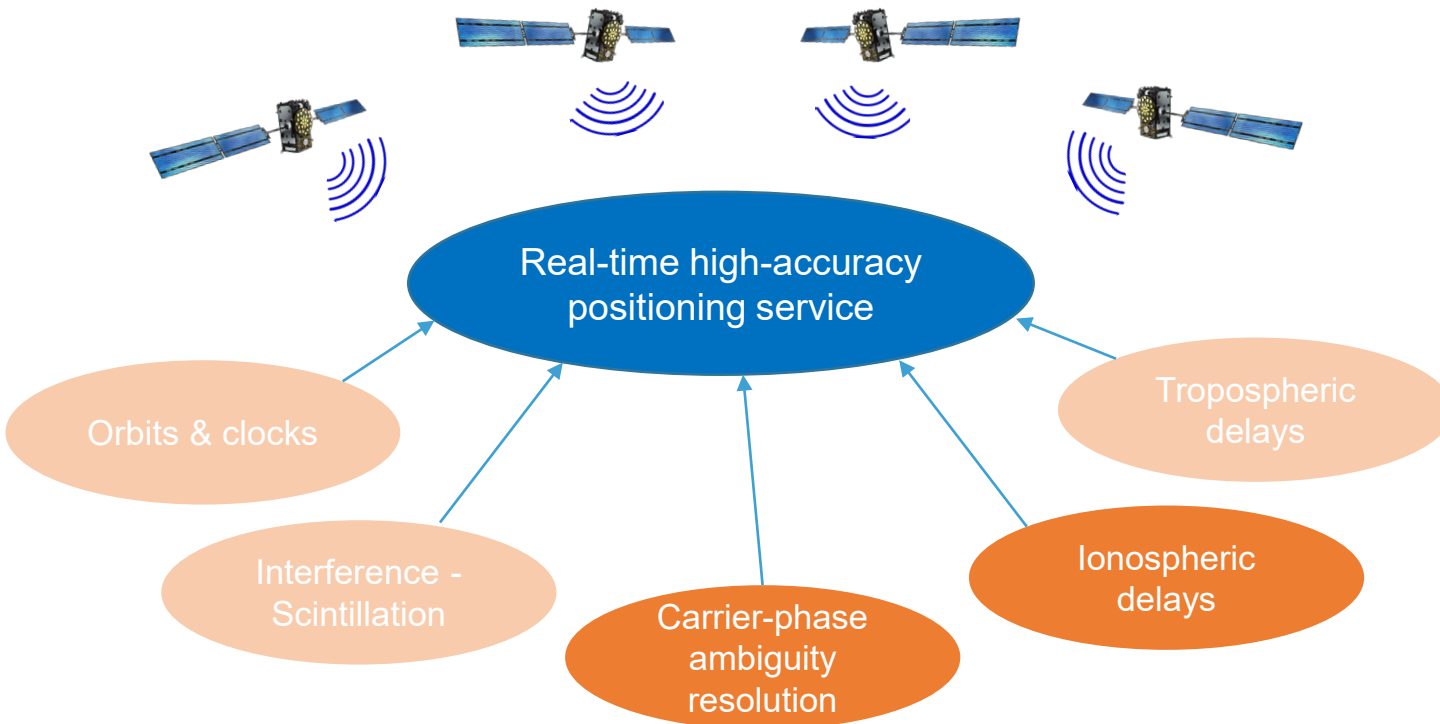
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- Funded by the **European Union's Horizon 2020 Research and Innovative Programme**.
- **Objective:** Development of a new service that will improve the current and introduce advanced models and algorithms to provide **real-time positioning accuracy of a few centimetres using multi-GNSS data**.



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



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Motivation



Motivation – PPP-RTK (1/2)

■ Precise Point Positioning (PPP)

- Both code and carrier phase measurements are used.

$$\varphi_{r,j}^s = \vec{g}_r^{s^T} (\vec{x}_r - \vec{x}^s) + dt_r - dt^s + m_r^s \tau_r - \mu_j^s \iota_r^s + \lambda_j (\delta_{r,j} - \delta_{,j}^s + z_{r,j}^s) + \epsilon_{r,j}^s$$

$$p_{r,j}^s = \vec{g}_r^{s^T} (\vec{x}_r - \vec{x}^s) + dt_r - dt^s + m_r^s \tau_r + \mu_j^s \iota_r^s + d_{r,j} - d_{,j}^s + \eta_{r,j}^s$$

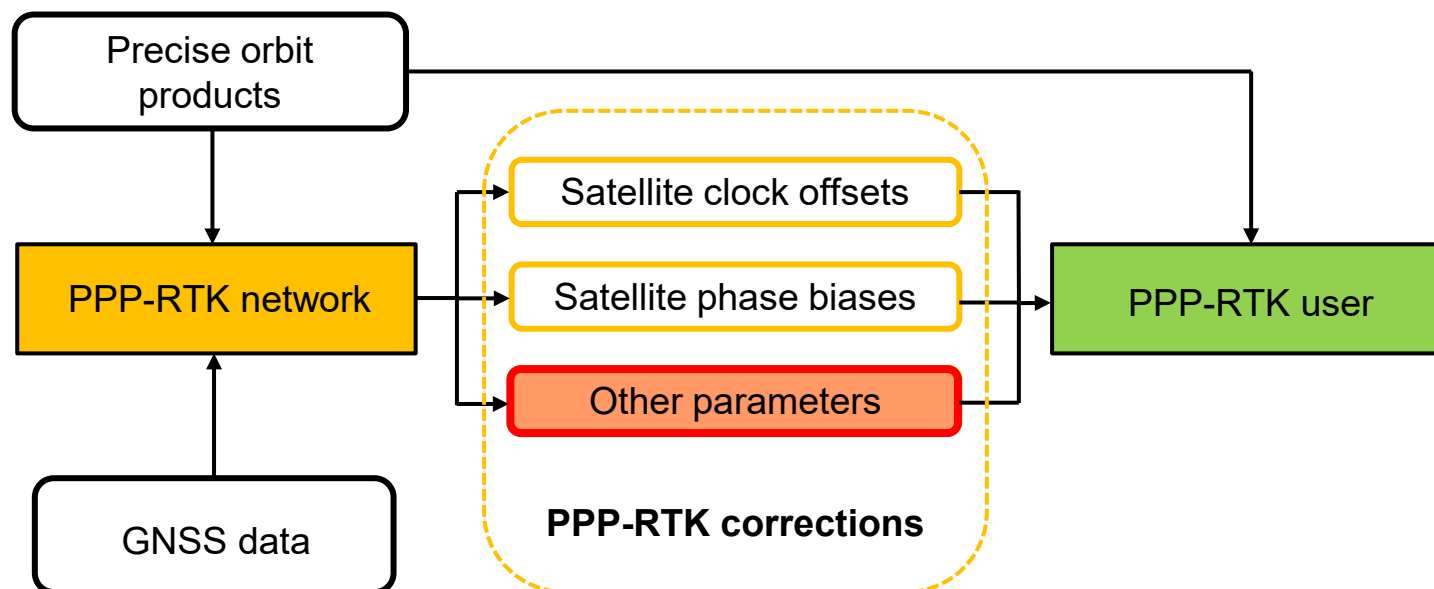
- Use of **satellite orbit and clock offset** information (e.g. IGS products).
- **Inability to resolve** the integer carrier-phase ambiguities.
- Solution: model the phase biases in the **parameter domain**.



← *S*-system theory (*Teunissen, 1985*)

- 1. Integerness** of ambiguities is recovered.
- 2. Single-receiver ambiguity fixing** is achievable

Motivation – PPP-RTK (2/2)



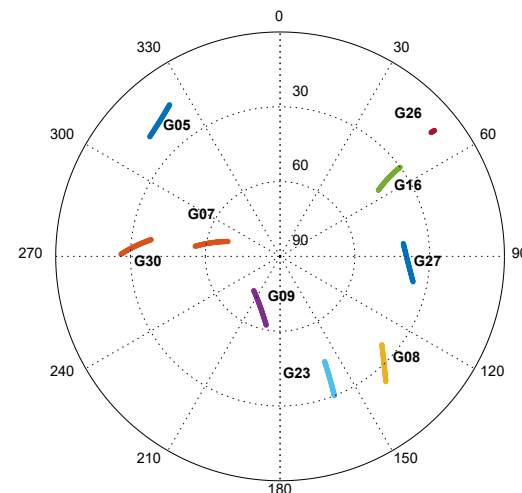
- **Higher positioning accuracy** and **shorter convergence time** compared to PPP → **weak** in terms of integer ambiguity resolution.
- A great **shortening in the convergence time** is expected if **precise ionospheric corrections** are available to users.

Methodology



Methodology – Design computations (1/2)

- How **precise** does the ionosphere model need to be to enable **faster PPP-RTK** ?
 - Assess the ionospheric corrections precision required to enable a shorter **Time-To-First-Fix**: time to achieve successful integer ambiguity resolution based on a pre-defined success ratio (99.5%).
- Simulated GPS **PPP-RTK user** environment:
 - Measurement noise: 20 cm for code, 2 mm for phase
 - Elevation-dependent weighting (mask 10°)
 - Orbit precision: 2.5 cm



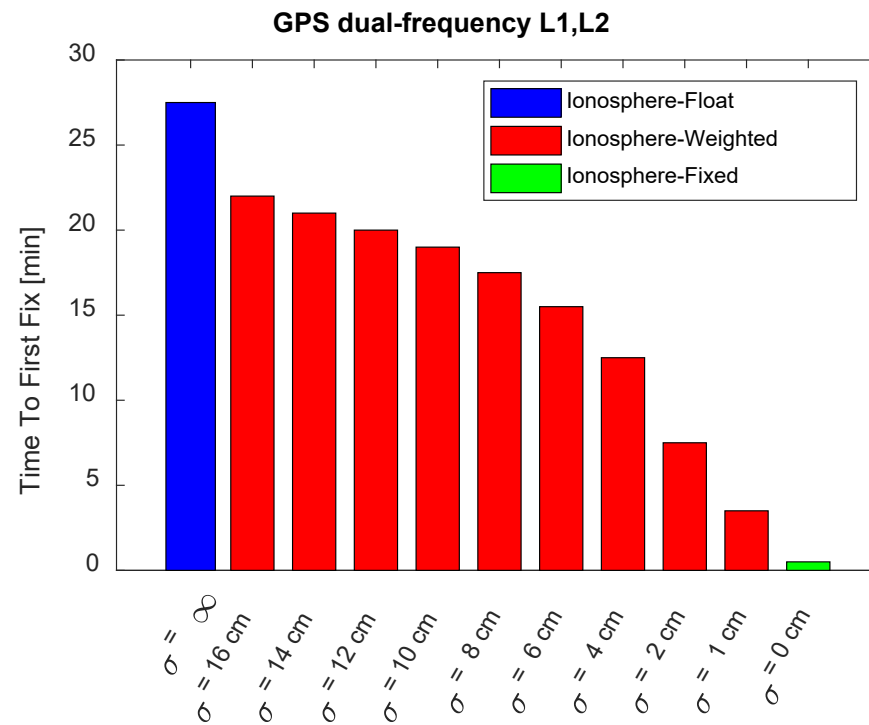
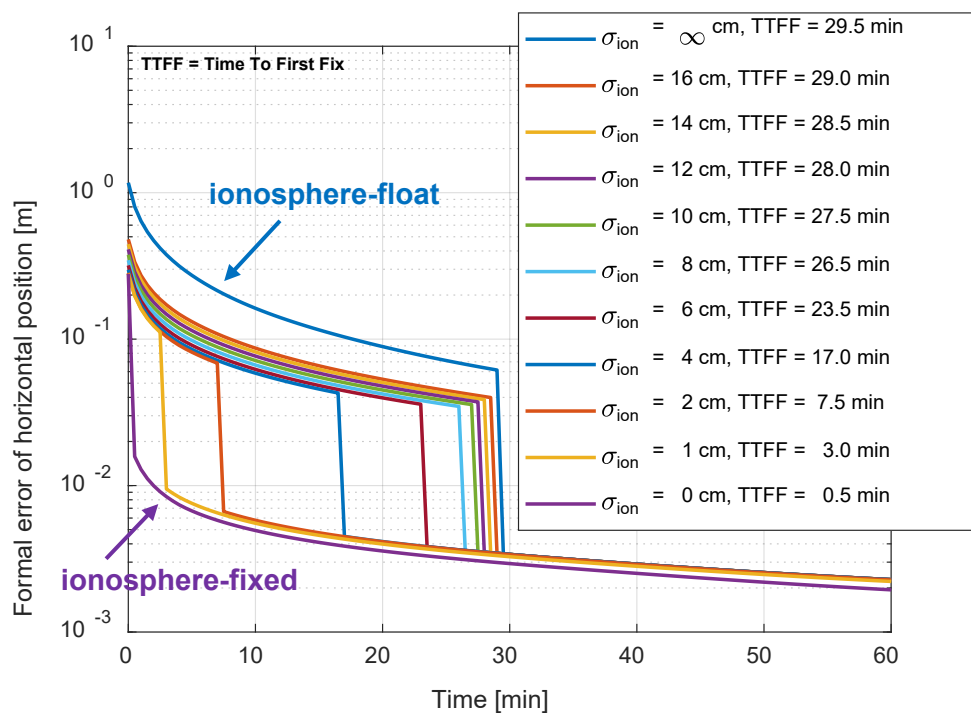
Ionosphere –**float** or –**fixed** model

$$D\left\{\begin{pmatrix} \tilde{\phi} \\ \tilde{p} \end{pmatrix}\right\} = \begin{pmatrix} C_{\tilde{\phi}} & 0 \\ 0 & C_{\tilde{p}} \end{pmatrix}$$

Ionosphere-**weighted** model

$$D\left\{\begin{pmatrix} \tilde{\phi} + \mu \otimes \iota \\ \tilde{p} - \mu \otimes \iota \end{pmatrix}\right\} = \begin{pmatrix} C_{\tilde{\phi}} + \sigma_{\iota}^2 \mu \mu^T & -\sigma_{\iota}^2 \mu \mu^T \\ -\sigma_{\iota}^2 \mu \mu^T & C_{\tilde{p}} + \sigma_{\iota}^2 \mu \mu^T \end{pmatrix}$$

Methodology – Design computations (2/2)



The precision of ionospheric corrections should be **better than 5 cm** to enable **faster PPP-RTK solutions**.

Methodology – Background on ionosphere modeling

- **Basic requirements for a precise ionosphere map:**

- Ionospheric observable → Various combinations with **different interpretation and precision**
- Mathematical representation of ionosphere → Spherical harmonics for **global** modeling

- **Traditional approach for TEC extraction:**

- Geometry-free (GF) code and phase
 - Carrier-to-Code-Levelling
- Proven inaccurate due to **levelling errors**
 → Formal errors can be up to **several TECUs**

- **Recent approaches:**

- Precise Point Positioning (*Zhang, 2016*)
- Network processing (*Nie et al., 2018*)

* TEC: Total Electron Content

Methodology – Ionosphere modeling for PPP-RTK (1/2)

- PPP-RTK network-derived **ambiguity-fixed ionospheric slant delays**

- Once the ambiguities are resolved, PPP-RTK is able to provide **high-precision ionospheric corrections** than can be modelled and predicted at the user's location.

$$\begin{aligned}\tilde{\iota}_r^s &:= \iota_r^s + \frac{\mu_1}{\mu_1 - \mu_2} \left((d_{r,1} - d_{r,2}) - (d_{,1}^s - d_{,2}^s) \right), \quad \mu_j = (f_1/f_j)^2 \\ &:= \iota_r^s + \underbrace{d_{r,\text{GF}} - d_{,\text{GF}}^s}_{\text{Differential Code Biases (DCB)}} \quad \forall r, s\end{aligned}$$

- Mathematical VTEC representation: **Generalized Trigonometric Series** functions

$$\begin{aligned}v_r^s &= \sum_{a=0}^A \sum_{b=0}^B \left(E_{ab} (\phi_{\text{IPP}} - \phi_{\text{REC}})^a \Lambda_{\text{IPP}}^b \right) \\ &\quad + \sum_{k=1}^K (C_k \cos(k \Lambda_{\text{IPP}}) + S_k \sin(k \Lambda_{\text{IPP}}))\end{aligned}$$

ϕ : geog. latitude
 Λ : solar longitude

- Single-layer model** approximation

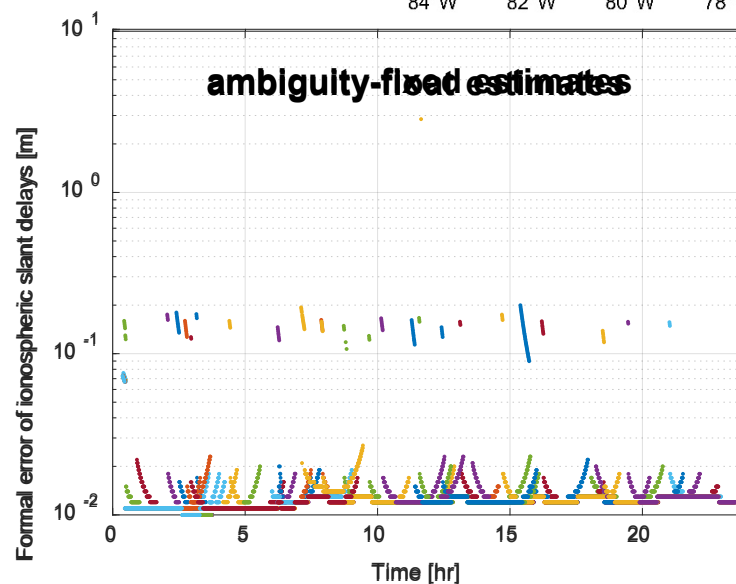
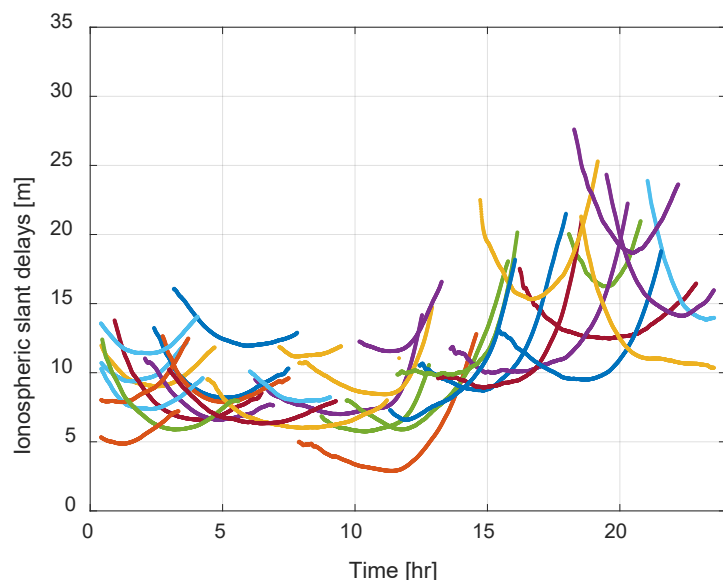
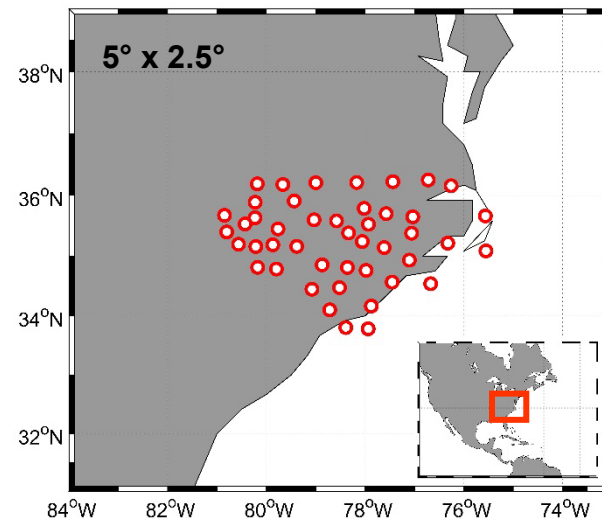
Methodology – Ionosphere modeling for PPP-RTK (2/2)

- **Rank-deficiency** if both receiver and satellite DCBs need to be estimated.
 - Solution: **Lumping a minimum set of parameters** as the \mathcal{S} -basis (*Teunissen, 1985*)
 - Advantage: **Real-time satellite DCBs** are required to **improve PPP-RTK** as well.

- Parameter estimation: **Kalman Filter**
 - States are **updated every epoch (30s)**
 - Random-walk process

Methodology – Data used for ionosphere modeling

- GNSS data (DOY 046/2014) from a CORS network
- **Undifferenced and uncombined PPP-RTK processing**
- **Ionospheric (biased) slant delays** serve as input in the ionosphere modeling step.
 - Formal errors of 1-2 cm (**0.06-0.12 TECU**) are achieved.
 - Pre-processing to eliminate small observational arcs.



Methodology – Assessment of ionospheric corrections

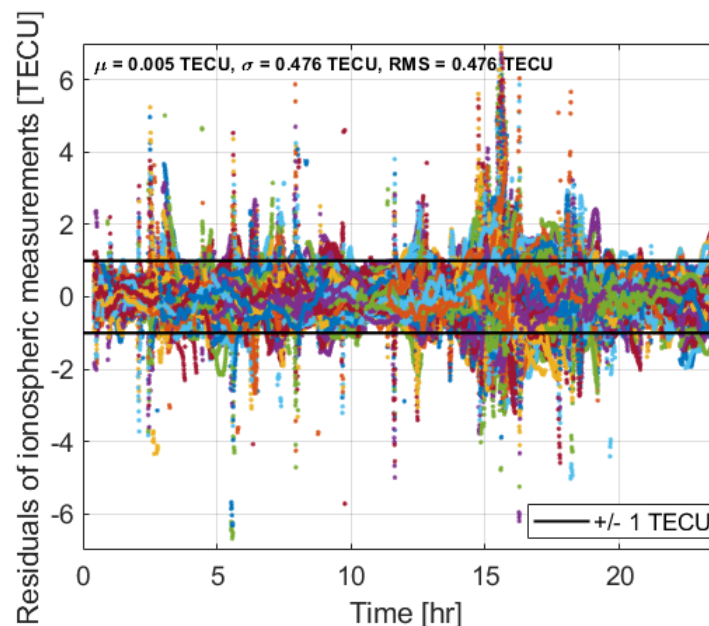
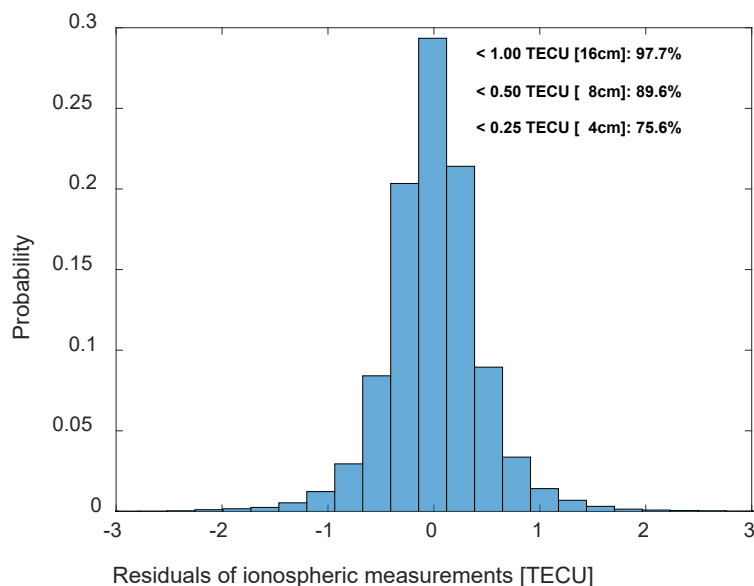
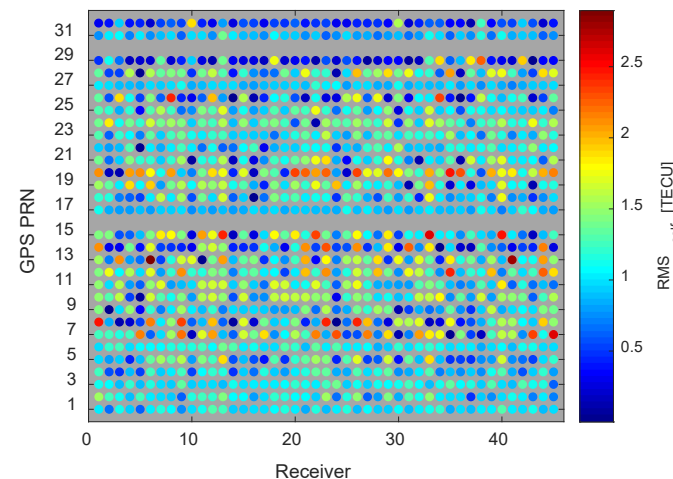
- **Self-consistency test:** quality metric to assess the modelled STECs
 - **RMS of variations between STECs** along a continuous arc over a single station between 2 epochs (*Orus et al., 2005*)
 - The reference epoch is the one where the satellite is at its **highest elevation** (*Hernandez-Pajares et al., 2017*)
- **External validation:** CODE Global Ionosphere Maps
 - Linear interpolation of VTEC both in space and time at all formed IPPs.

Results

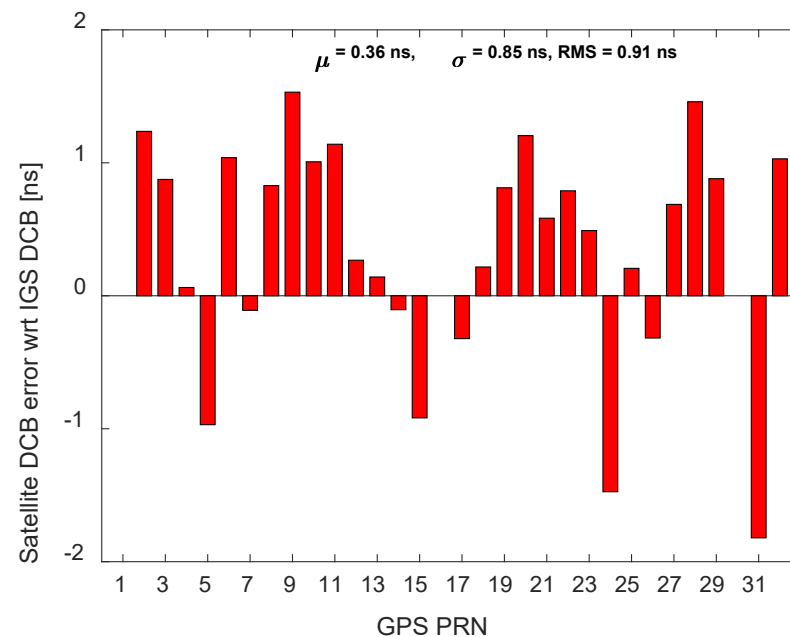
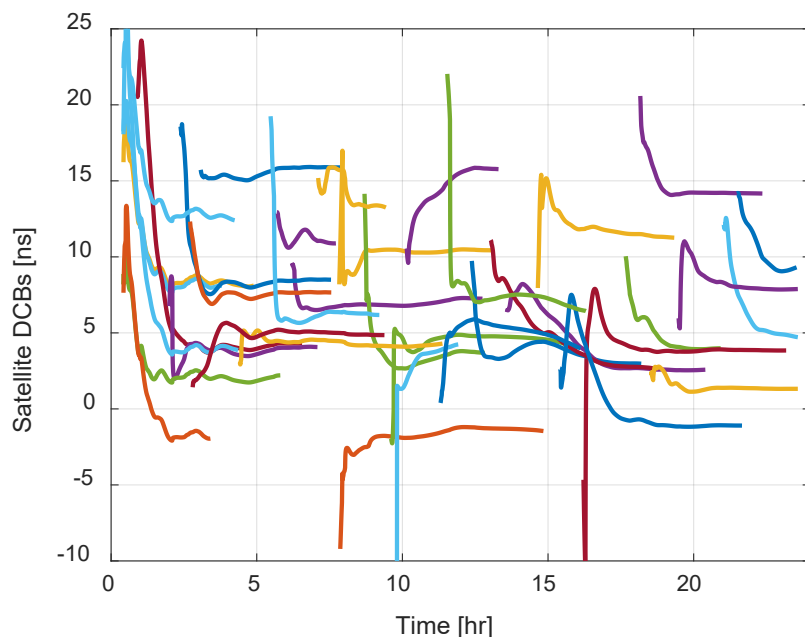


Results - Ionosphere

- **Self-consistency** test for every receiver-satellite link:
 - Most of the RMS values are below 1.5 TECU.
 - Overall RMS is **1.1 TECU**.
- **External validation** with CODE GIM:
 - RMS of VTEC differences is **2.1 TECU**.
- **Measurement residuals:**



Results – Satellite DCBs



▪ Validation with IGS DCBs (C1C-C2W)

➤ **Common \mathcal{S} -basis is needed.**

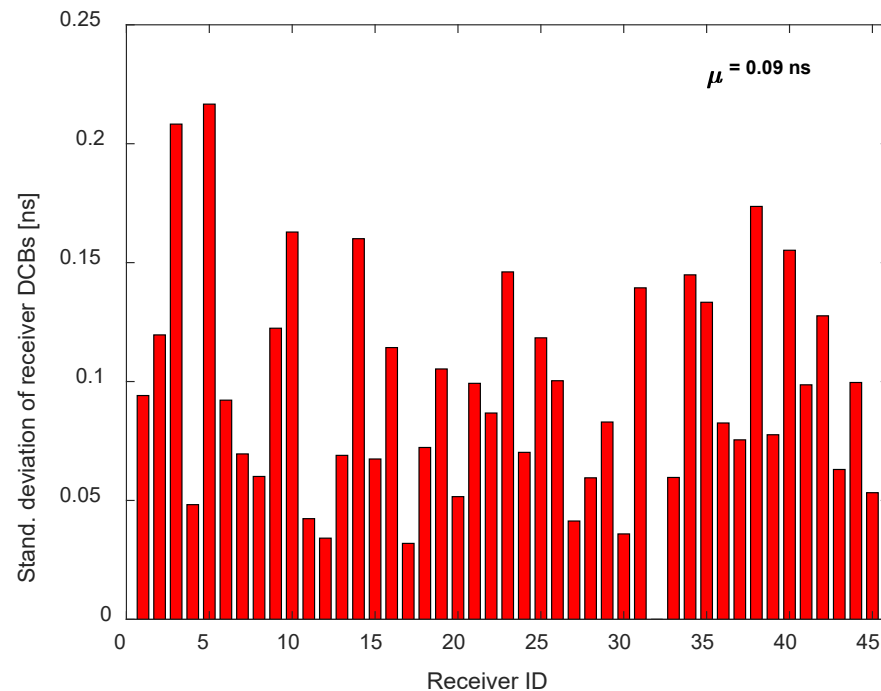
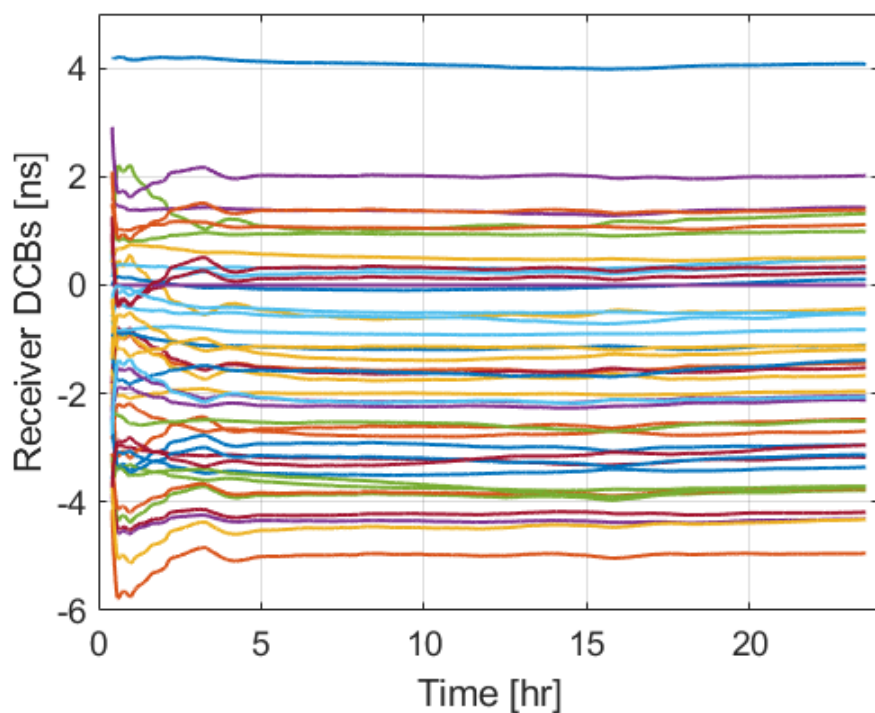
$|d_{\text{EST}}^s - d_{\text{IGS}}^s| < 1.5\text{ns} : 27 \text{ sats, } 93\%$

$|d_{\text{EST}}^s - d_{\text{IGS}}^s| < 1.0\text{ns} : 19 \text{ sats, } 66\%$

$|d_{\text{EST}}^s - d_{\text{IGS}}^s| < 0.5\text{ns} : 10 \text{ sats, } 35\%$

$|d_{\text{EST}}^s - d_{\text{IGS}}^s| < 0.2\text{ns} : 4 \text{ sats, } 14\%$

Results – Receiver DCBs



Stability analysis

➤ Mean STD: 0.09 ns

Conclusions



Conclusions

■ Conclusions

- Faster PPP-RTK solutions are expected if precise ionospheric corrections are available to the users.
- PPP-RTK can provide high-precision ionospheric delays for ionosphere modeling.
- The proposed methodology can be used for reliable regional ionosphere modeling and satellite DCB estimation.

■ Outlook

- A **two-layer model** and **alternative ionosphere representation models** will be employed to better model the structure of ionosphere.
- **Large-scale investigation** is required to validate the performance of the proposed methodology.
- Assessment of ionosphere-weighted PPP-RTK achieved **convergence time using precise ionospheric corrections**.

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Thank you for your attention !

Acknowledgements

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