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

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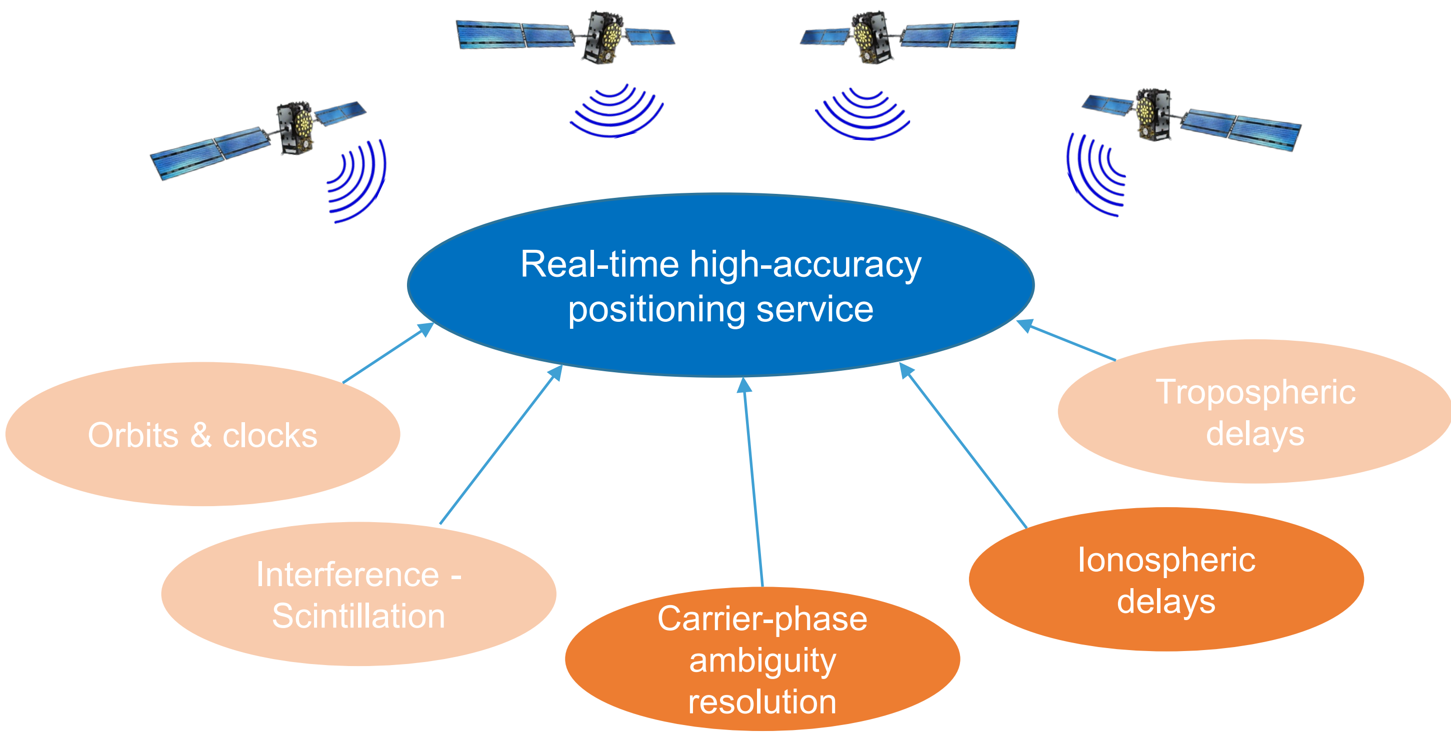
TREASURE

- 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

Contents

- Motivation
  - PPP-RTK
  - Ionosphere – Convergence time
- Methodology
  - Design computations
  - Ionosphere modelling
- Results
- Conclusions

Motivation

Motivation – PPP-RTK (1/2)

- Precise Point Positioning (PPP)
  - Both code and carrier phase measurements are used.

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

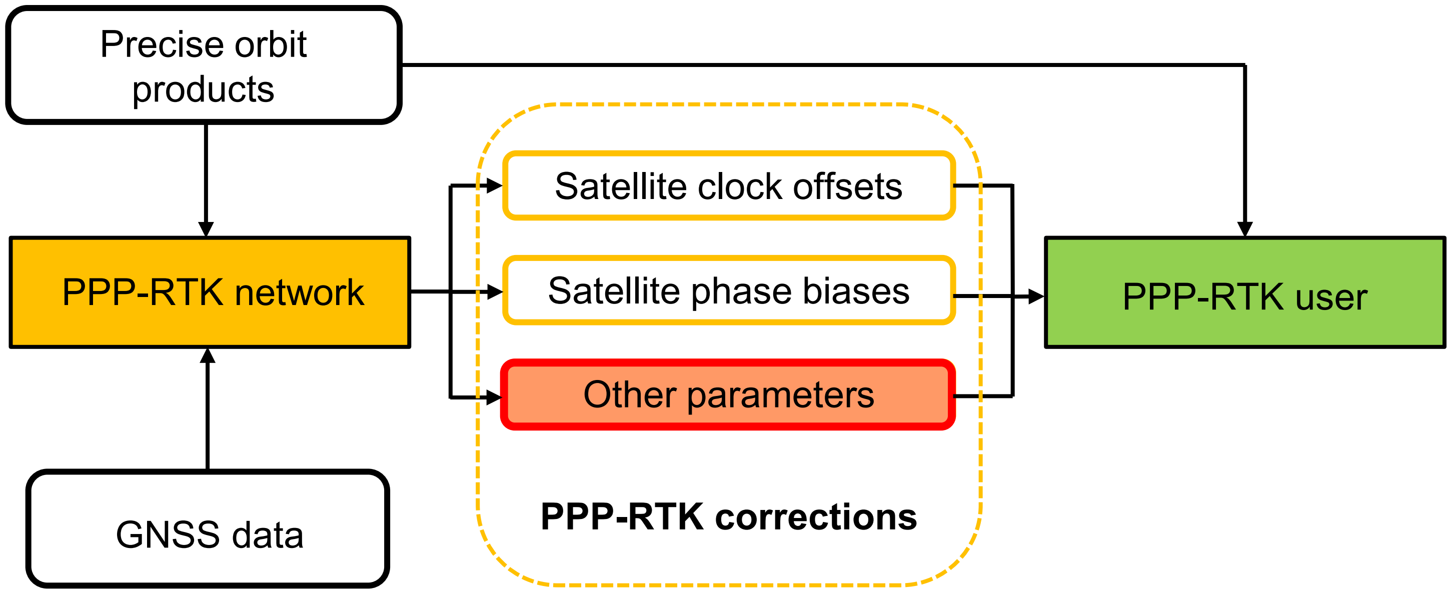
$$p_{r,j}^{s} = \vec{g}_r^{s\,T}(\vec{x}_r - \vec{x}^s) + dt_r - dt^s + m_r^s \tau_r + \mu_j \iota_r^s + d_{r,j} - d_{,j}^s + \eta_{r,j}^s$$

  - 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.

$\mathcal{S}$-system theory (*Teunissen, 1985*)

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

Motivation – PPP-RTK (2/2)

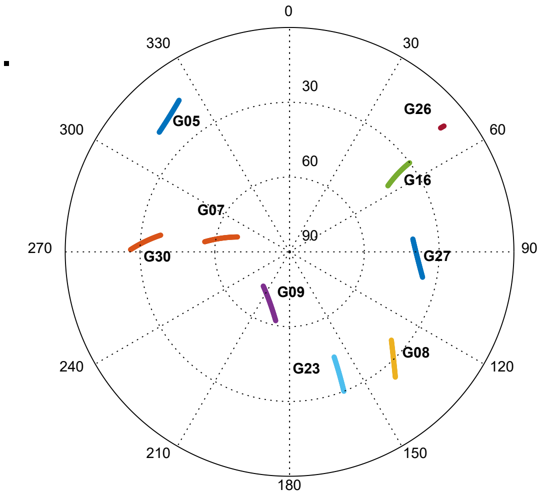


- **Higher positioning accuracy** and **shorter convergence time** compared to PPP → **weak in terms of integer ambiguity resolution.**
- A great **shortening in the convergence time** is expected if **precise ionospheric corrections are available** to users.

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

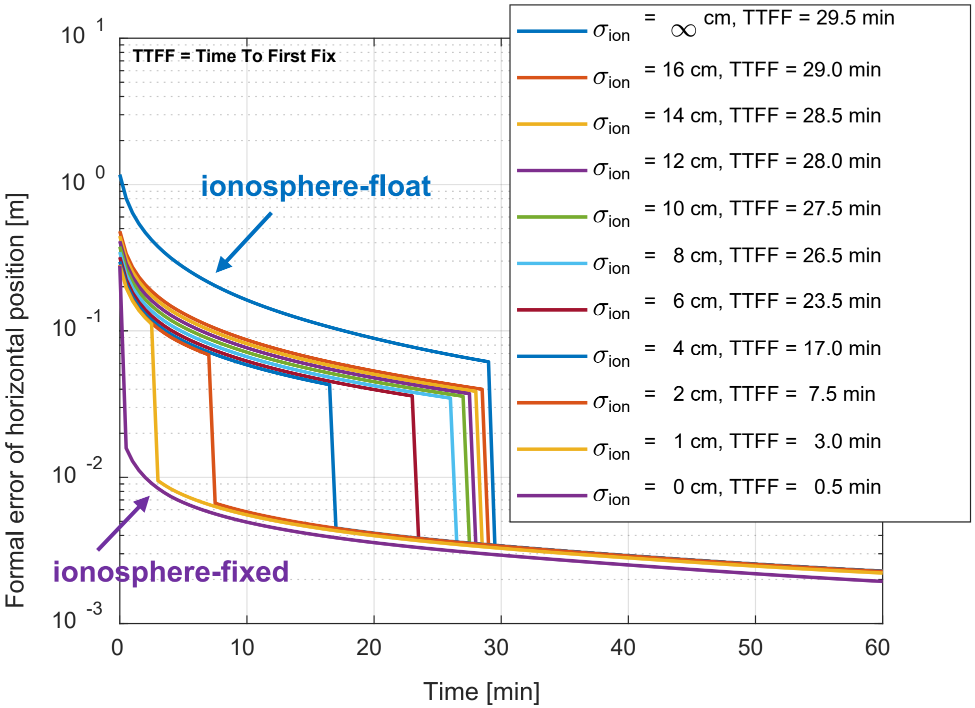
Ionosphere –**float** or –**fixed** model

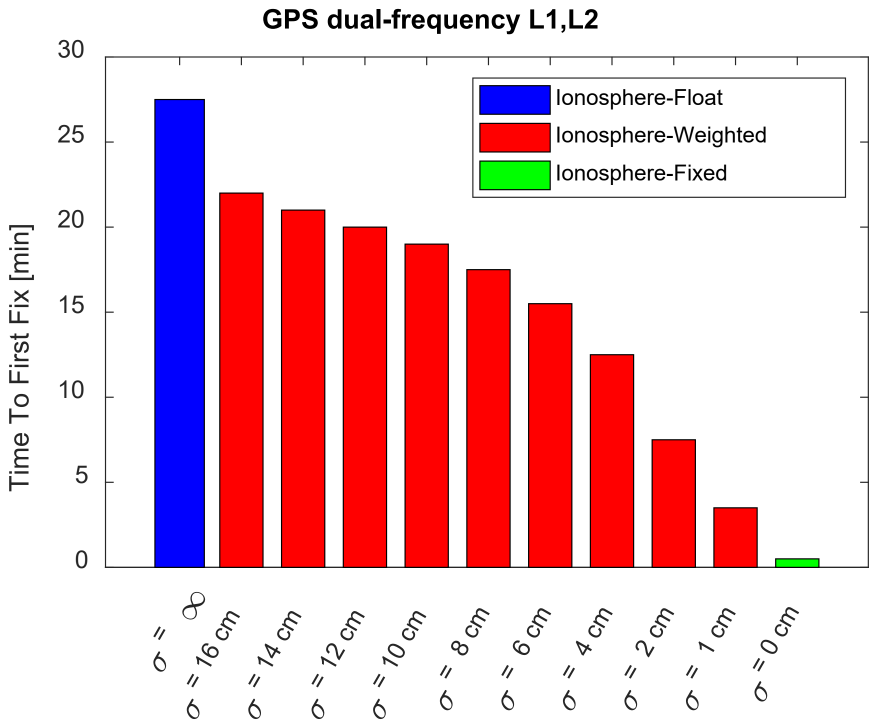
$$D\{\begin{pmatrix}\tilde{\phi}\\ \tilde{p}\end{pmatrix}\} = \begin{pmatrix}C_{\tilde{\phi}} & 0\\ 0 & C_{\tilde{p}}\end{pmatrix}$$

Ionosphere-**weighted** model

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

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.

$$\tilde{\iota}_r^s := \iota_r^s + \frac{\mu_1}{\mu_1 - \mu_2}\left((d_{r,1} - d_{r,2}) - (d_{,1}^s - d_{,2}^s)\right) \,, \qquad \mu_j = (f_1/f_j)^2$$

$$:= \iota_r^s + d_{r,\mathrm{GF}} - d_{,\mathrm{GF}}^s \quad \forall\, r, s$$

Differential Code Biases (DCB)

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

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

ϕ : geog. latitude
Λ : solar longitude

- **Single-layer model** approximation

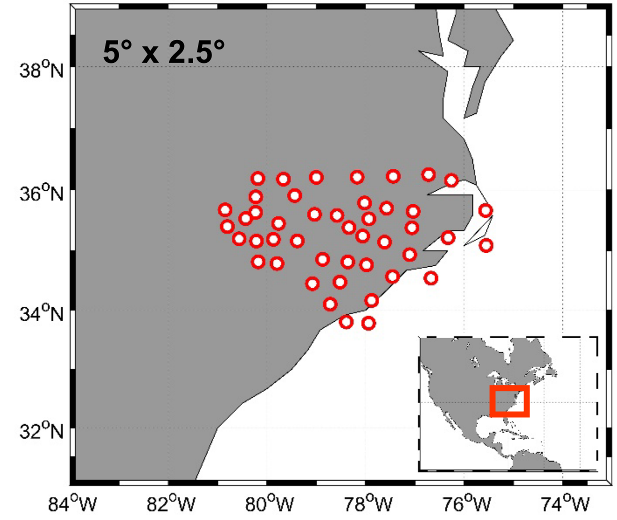
Methodology – Ionosphere modeling for PPP-RTK (2/2)

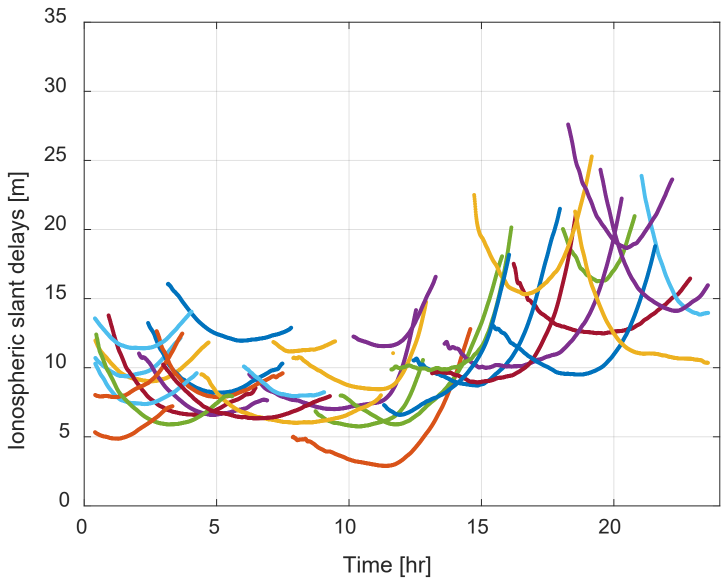
- **Rank-deficiency** if both receiver and satellite DCBs need to be estimated.
  - Solution: **Lumping a minimum set of parameters** as the $\mathcal{S}$-basis (*Teunissen,1985*)
  - Advantage: **Real-time satellite DCBs** are required to **improve PPP-RTK** as well.

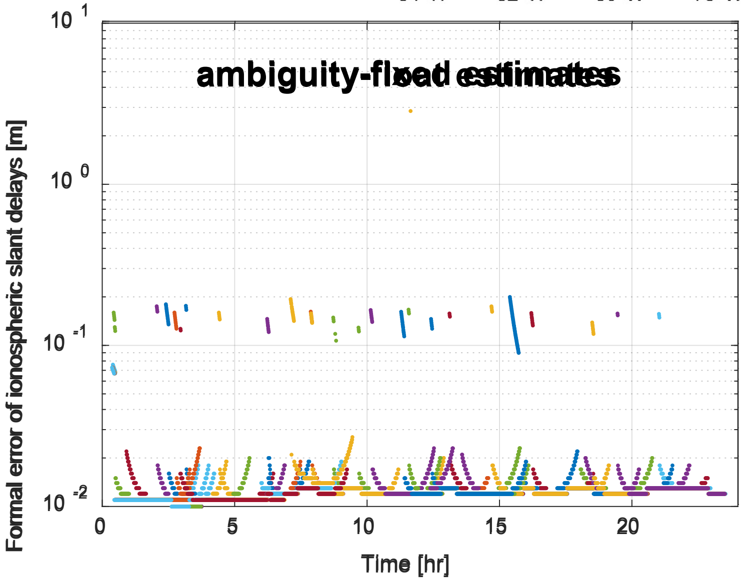
- Parameter estimation: **Kalman Filter**
  - States are **updated every epoch (30s)**
  - Random-walk process

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.







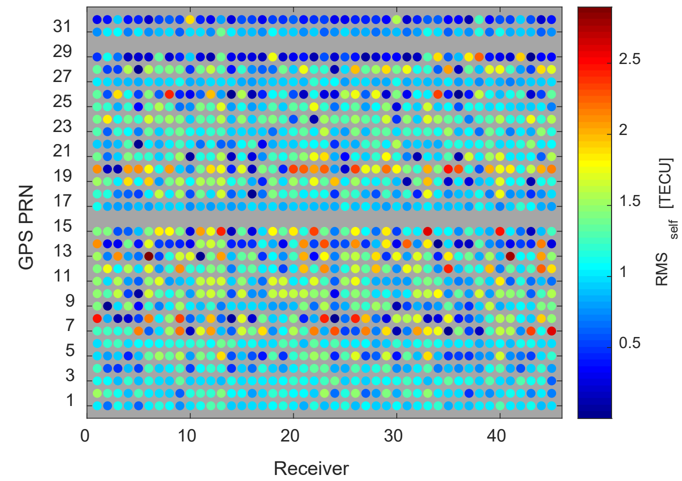
Methodology – Assessment of ionospheric corrections

- **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.

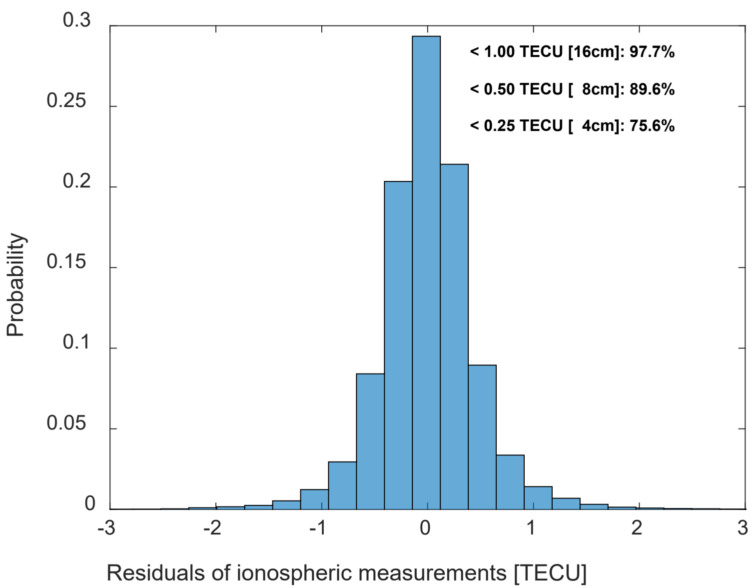
Results

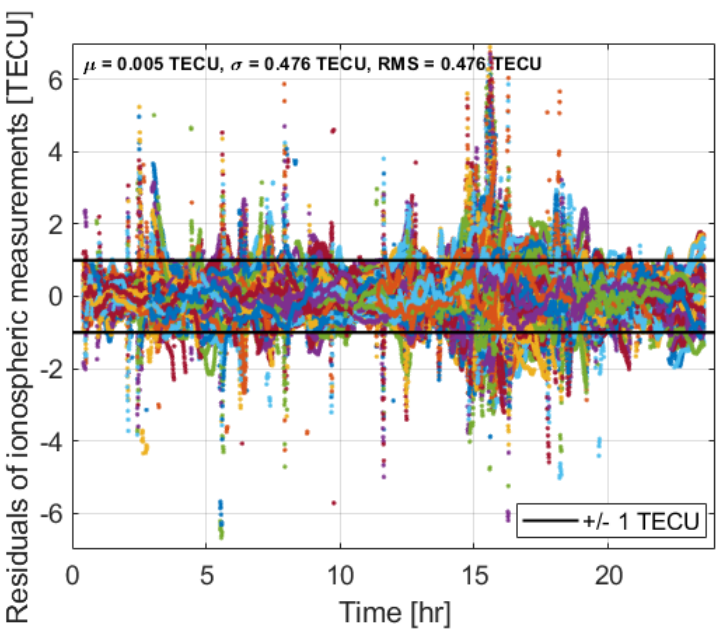
Results - Ionosphere

- **Self-consistency** test for every receiver-satellite link:
  - Most of the RMS values are below 1.5 TECU.
  - Overall RMS is **1.1 TECU**.

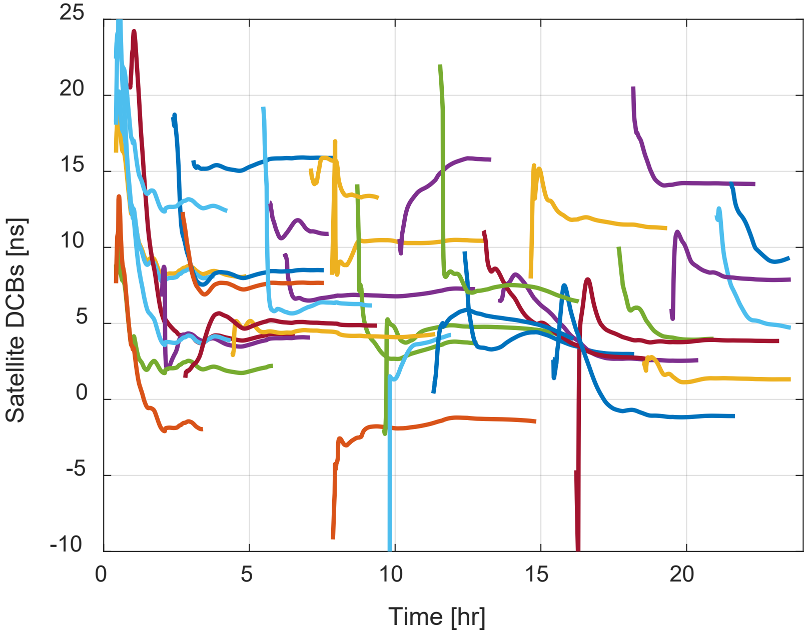


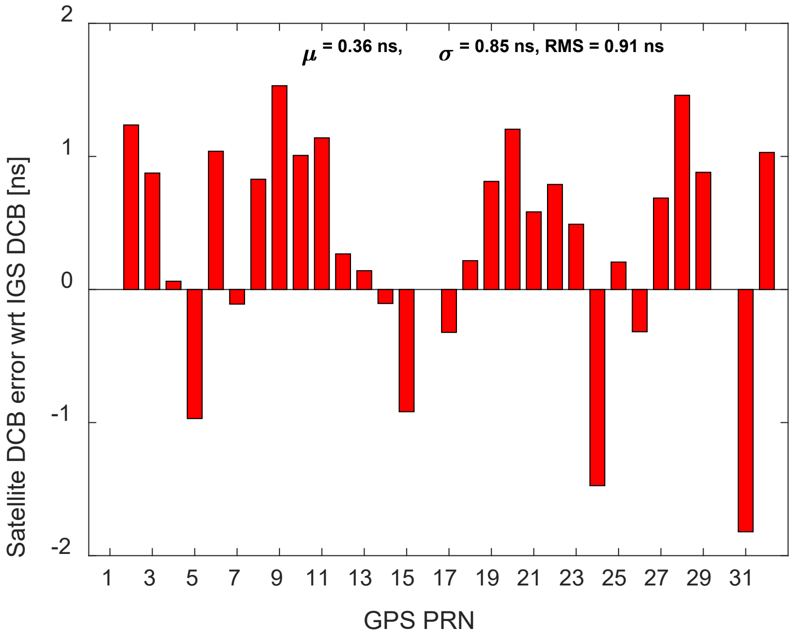
- **External validation** with CODE GIM:
  - RMS of VTEC differences is **2.1 TECU**.
- **Measurement residuals:**





Results – Satellite DCBs

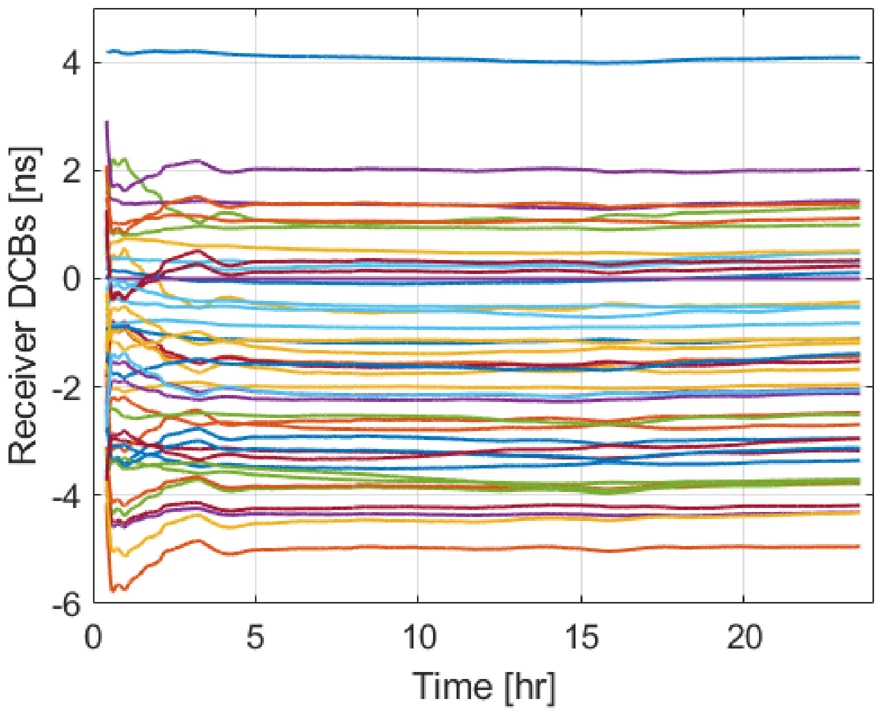


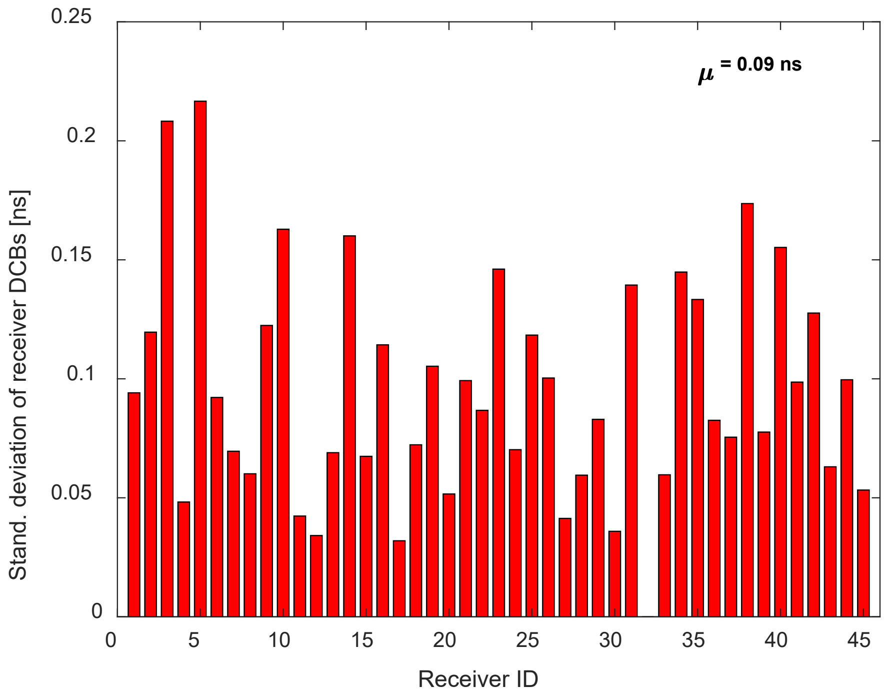


- **Validation** with IGS DCBs (C1C-C2W)
  - **Common** $\mathcal{S}$-basis is needed.

$$|d^s_{\mathrm{EST}} - d^s_{\mathrm{IGS}}| < 1.5\mathrm{ns}: \quad 27\,\mathrm{sats}, \; 93\%$$
$$|d^s_{\mathrm{EST}} - d^s_{\mathrm{IGS}}| < 1.0\mathrm{ns}: \quad 19\,\mathrm{sats}, \; 66\%$$
$$|d^s_{\mathrm{EST}} - d^s_{\mathrm{IGS}}| < 0.5\mathrm{ns}: \quad 10\,\mathrm{sats}, \; 35\%$$
$$|d^s_{\mathrm{EST}} - d^s_{\mathrm{IGS}}| < 0.2\mathrm{ns}: \quad 4\,\mathrm{sats}, \; 14\%$$

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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