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Assessment of ionospheric corrections for PPP-RTK using S-system theory

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Motivation



Motivation – PPP-RTK (1/3)

■ Precise Point Positioning (PPP)

Both code and carrier phase measurements are used:

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

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

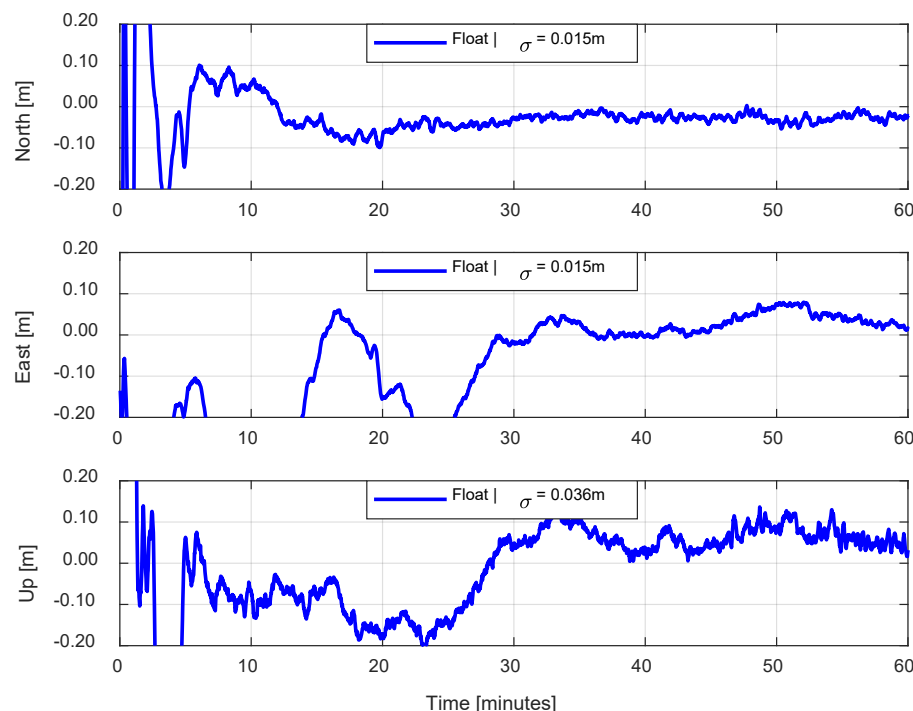
➤ Use of **satellite orbit and clock offset** information (e.g. IGS products).

➤ **Inability to resolve** the *integer* carrier-phase ambiguities.

Dual-frequency PPP solution:



➤ **27 minutes** to reach the 10 cm level



Motivation – PPP-RTK (2/3)

- Long convergence time in float PPP (ionosphere-estimated)
 - Solution: **integer ambiguity resolution-enabled PPP**
 - Model the phase biases in the **parameter domain**
- **S-system theory** (*Baarda 1973, Teunissen 1985*)
 - Rank-deficiency in **uncombined + undifferenced PPP** functional model

Linear model: $E(y) = A x$ with $A \in \mathbb{R}^{m \times n}$ and $\text{rank}(A) = r < n$

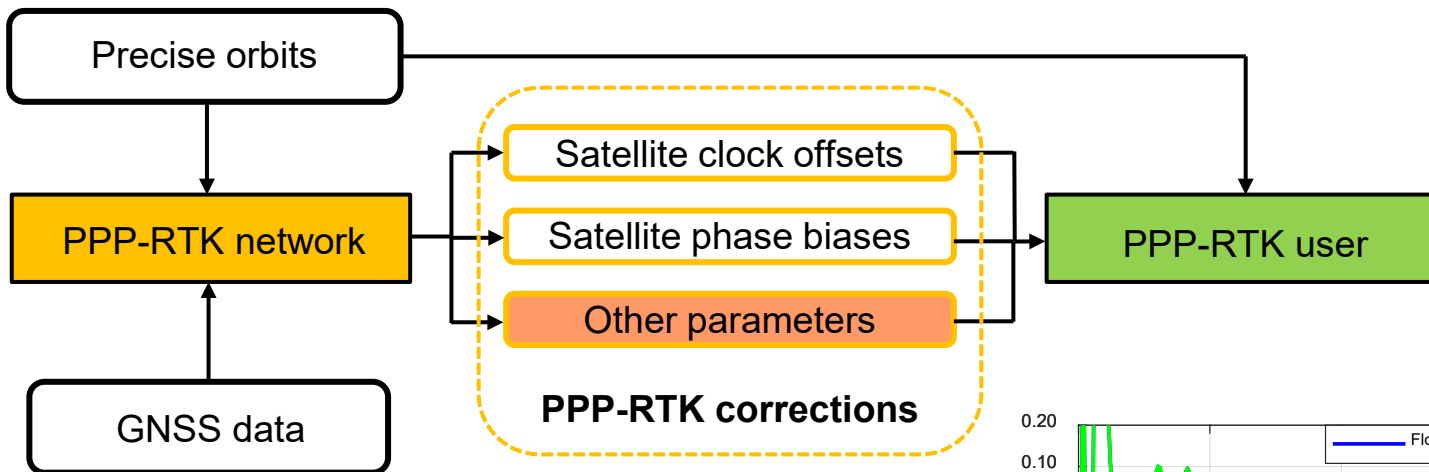
$A V = 0$ with V being a basis matrix of the null-space of A

Decomposition: $x = \underbrace{S \alpha}_{\text{estimable}} + \underbrace{V \beta}_{\text{non-estimable}}$

$$\tilde{\delta}_{,j}^s = f(\delta_{,j}^s, \dots)$$

$$E(y) = A x = A (S \alpha + V \beta) = \underbrace{(A S)}_{\tilde{A}} \alpha$$

Motivation – PPP-RTK (3/3)



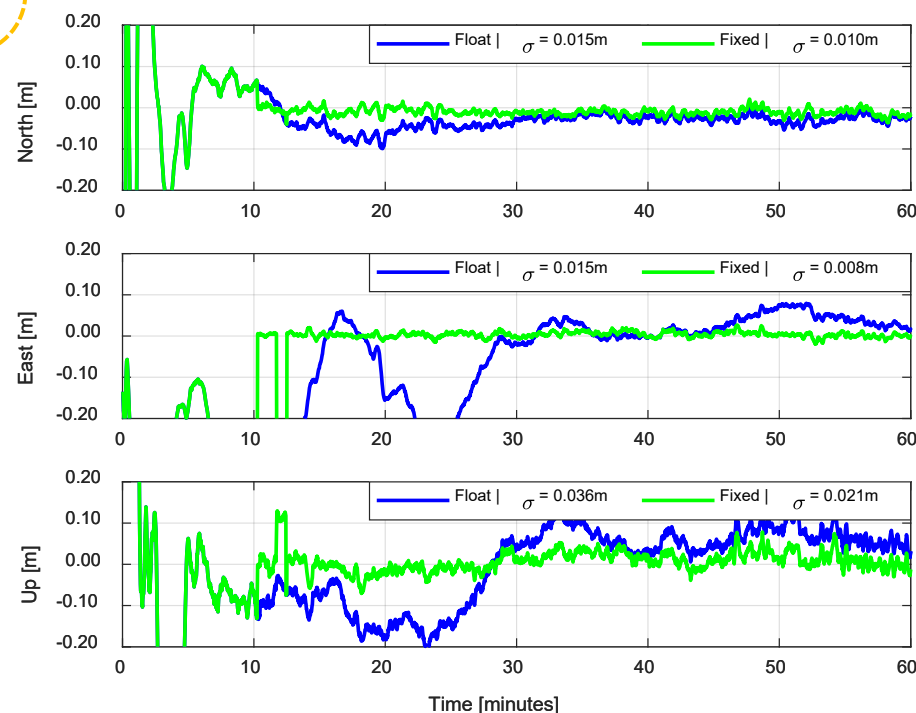
PPP solution

- 27 minutes for reaching 10 cm

PPP-RTK solution

- 12 minutes for reaching 10 cm

- **Faster convergence is needed !**

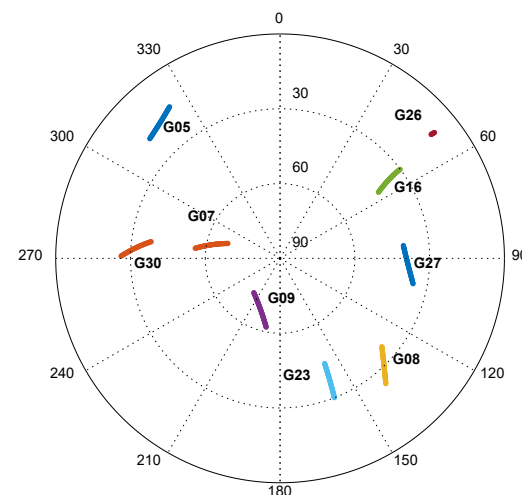


Methodology



Methodology – Design computations (1/2)

- How **precise** does the ionosphere model need to be to enable **faster PPP-RTK** ?
 - Assess the precision required to enable shorter **Time-To-First-Fix**: time to achieve successful integer ambiguity resolution (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



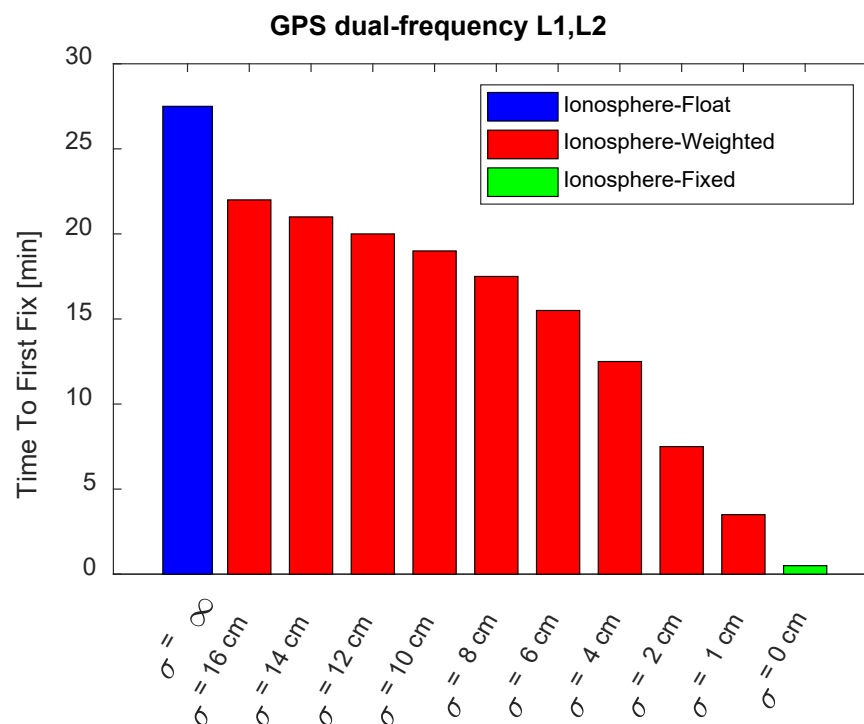
Ionosphere –**float** or –**fixed** model

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

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)



Needs to be **better than 5 cm** to enable **faster PPP-RTK solutions**.

Methodology – Ionosphere modeling for PPP-RTK

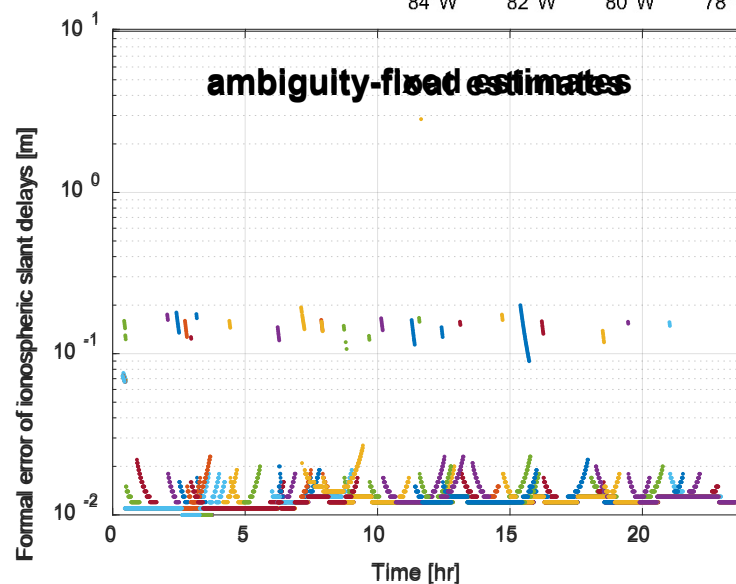
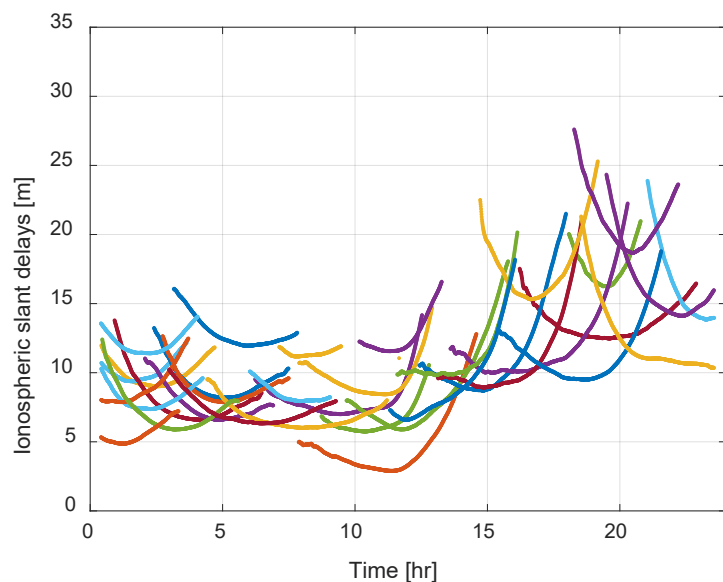
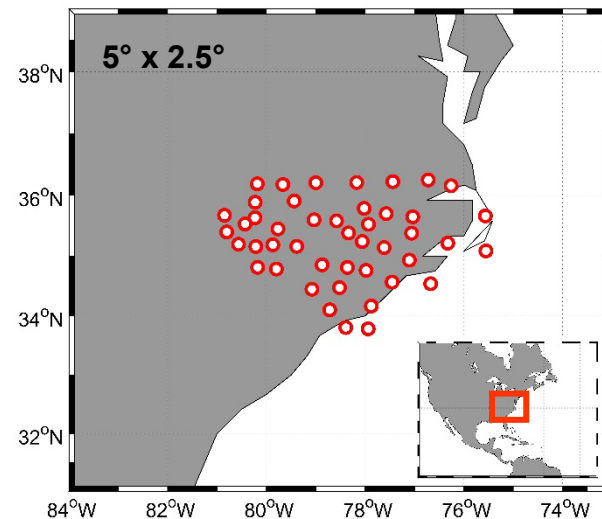
- **Uncombined PPP-RTK** can provide ionospheric slant delays, unaffected by levelling errors:

$$\tilde{\iota}_r^s = \iota_r^s - \frac{f_2^2}{f_1^2 - f_2^2} \left((d_{r,1} - d_{r,2}) - (d_{,1}^s - d_{,2}^s) \right) \quad \text{Differential Code Biases (DCB)}$$

- **Rank-deficiency** if both receiver and satellite DCBs need to be estimated.
 - Solution: **Lumping a minimum set of parameters** as the $\mathcal{S}$ -basis
- **Single-layer model** approximation
- Mathematical representation: **Generalized Trigonometric Series** functions
- Parameter estimation: **Kalman filter**

Methodology – Data used for ionosphere modeling

- GNSS data (DOY 046/2014) from a CORS network
- **Undifferenced and uncombined PPP-RTK processing**



Methodology – Assessment of ionospheric corrections

- **Self-consistency test:** quality metric to assess the modelled STECs
 - **RMS of variations between STECs** along a continuous arc

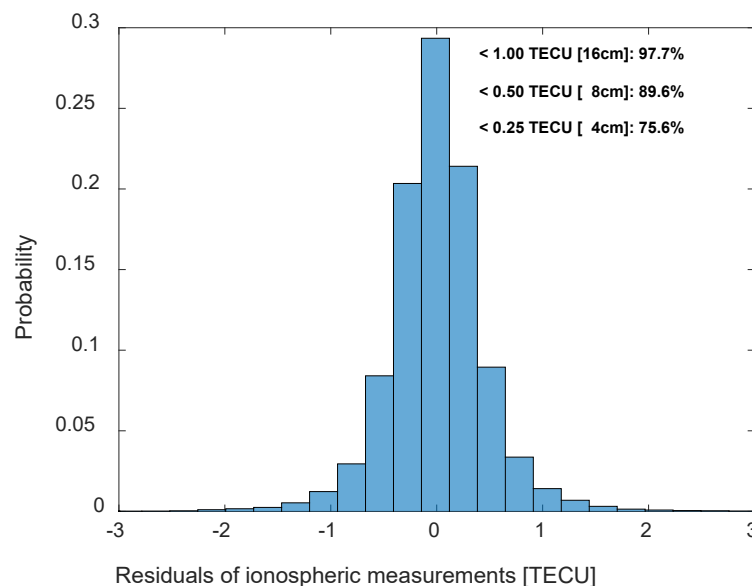
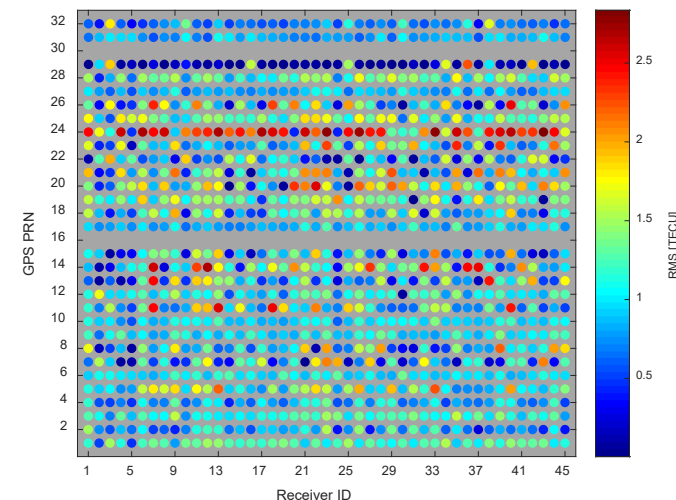
- **External validation:** CODE Global Ionosphere Maps
 - Linear interpolation of VTEC both in space and time at all formed IPPs

Results



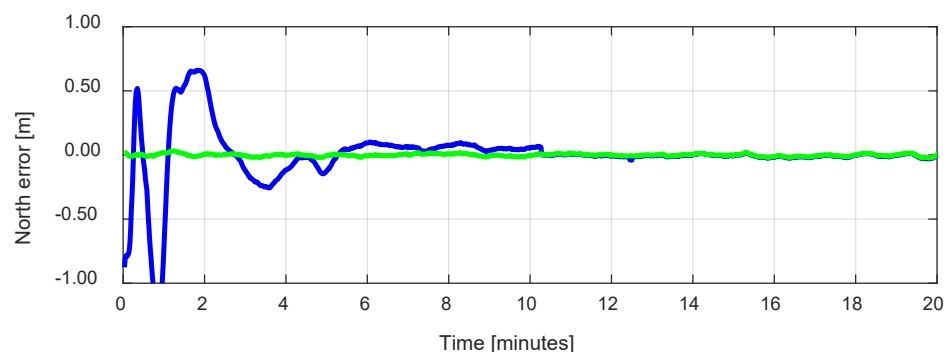
Results – Ionosphere (1/2)

- **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:**



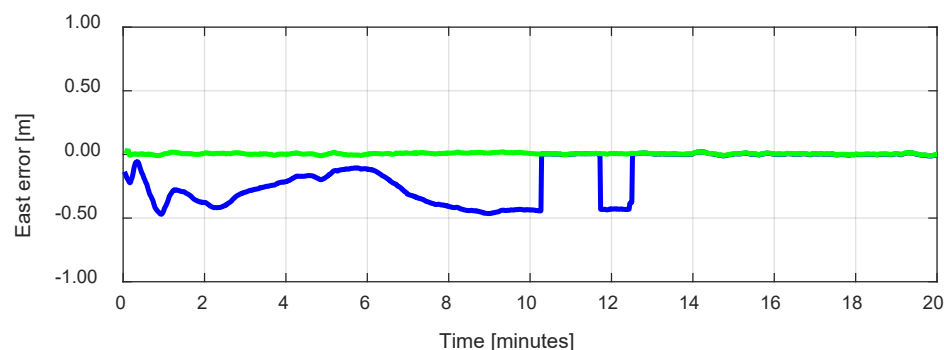
Results – Ionosphere (2/2)

- **Case study** using precise ionospheric corrections



13 min to reach 10 cm

0 min to reach 10 cm !



Instantaneous convergence to the 10 cm level !

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.

References

- Baarda, W. (1973). **S-transformations, criterion matrices**. *Publications on Geodesy*, 18 vol 5 (Delft: Netherlands Geodetic Commision)
- Teunissen, P. J. G. (1985). **Generalized inverses, adjustment, the datum problem and S-transformations**. In E. Grafarend & F. Sanso (Eds.), *Optimization and design of geodetic networks*. (p. 11-55).

Thank you for your attention !

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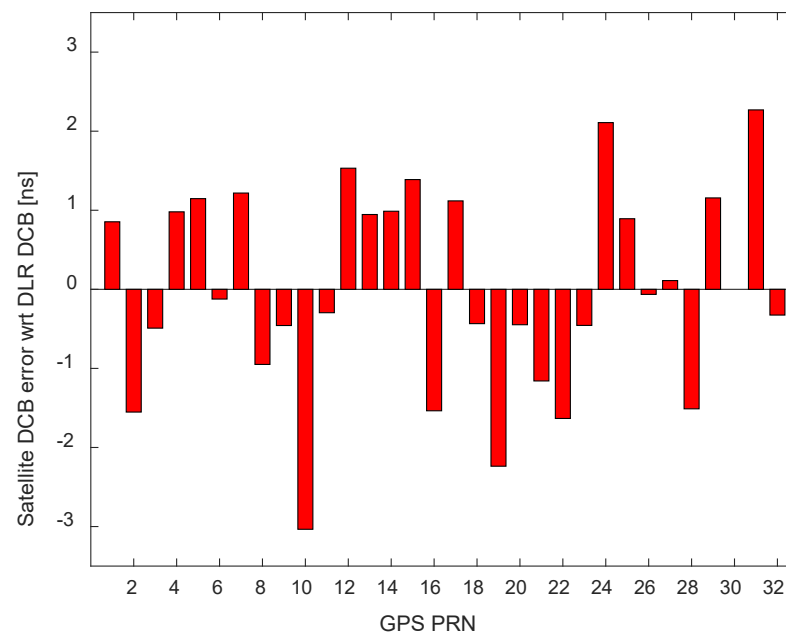
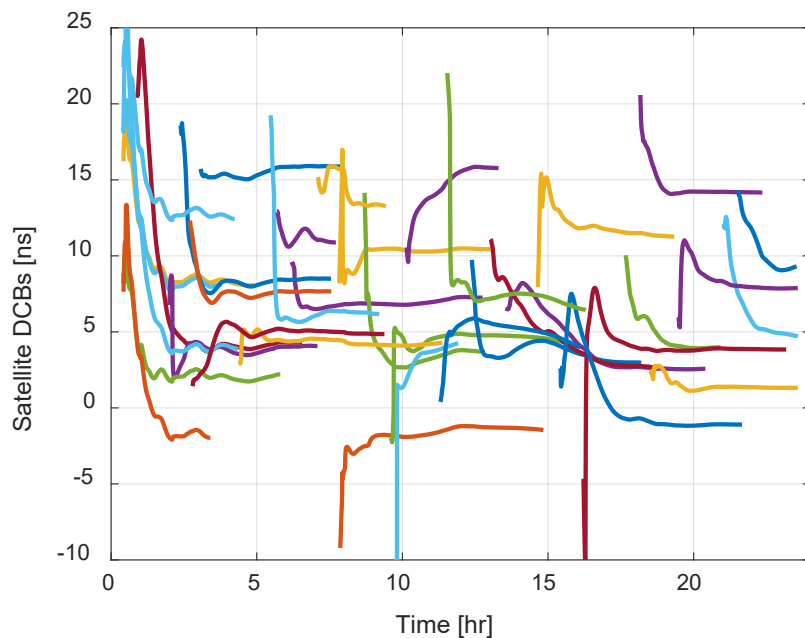
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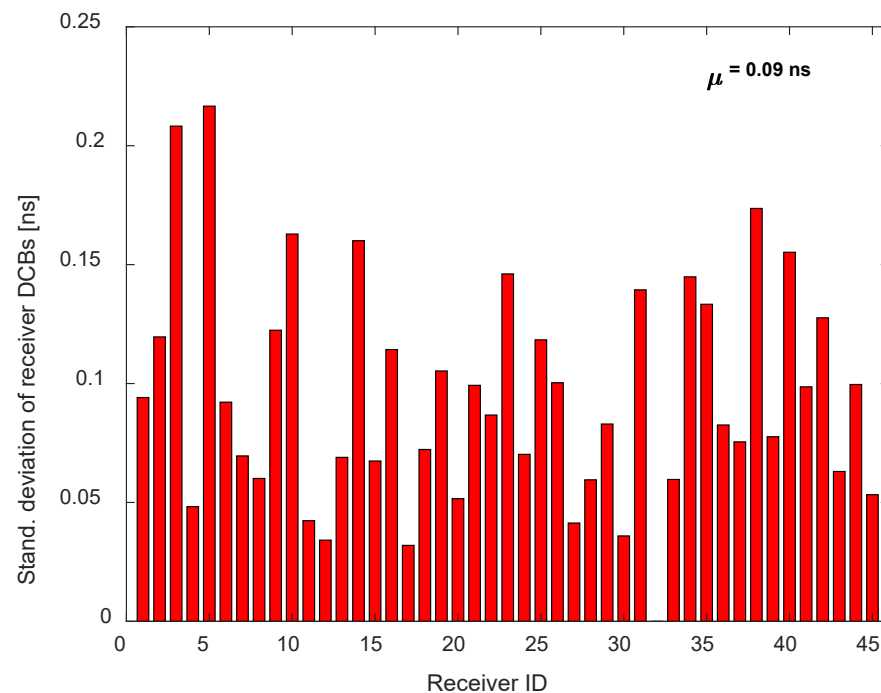
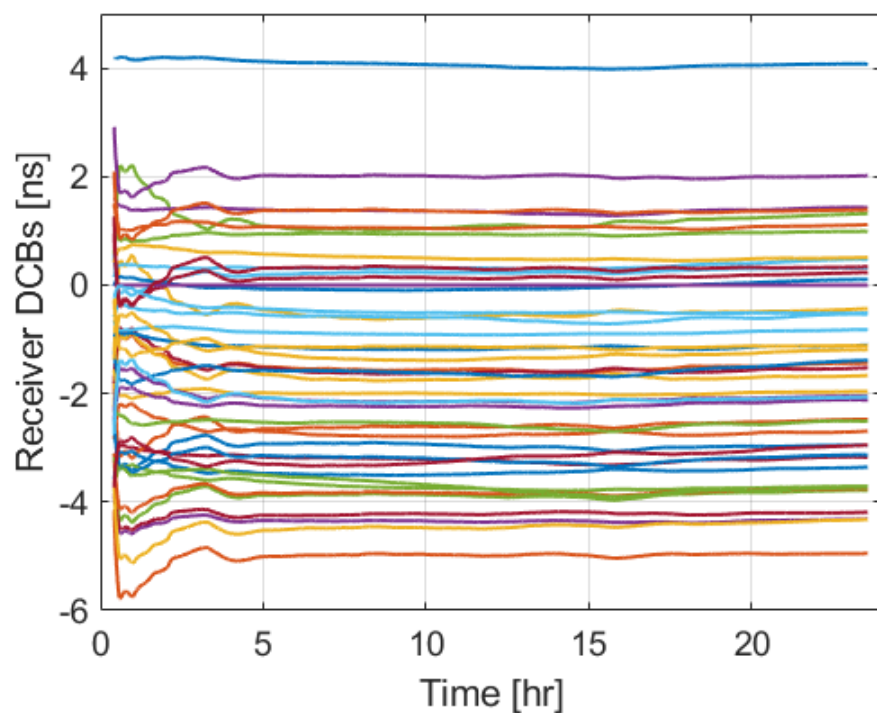
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Backup – Satellite DCBs



- **Validation with IGS DCBs (C1C-C2W)**
 - **Common $\mathcal{S}$ -basis is needed**
 - **RMS equal to 1.3 ns**
 - **70% of the satellites show error < 1.5 ns**

Backup – Receiver DCBs



Stability analysis

➤ Mean STD: 0.09 ns