High-Fidelity 3-D ionosphere models for Precise Point Positioning

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Introduction (Motivation)

In the last years new approaches for Precise Position have emerged, as examples techniques from: WARTK concept [1], PPP-Wizard [2] and Fast-PPP [3][4].

1. Hernández-Pajares M., J.M. Juan, J. Sanz, O. Colombo, "Application of ionospheric tomography to real-time GPS carrier-phase ambiguities resolution, at scales of 400-1000 km and with high geomagnetic activity", Geophysical Research Letters Vol. 27(13), pp. 2009-2012, 2000.
2. D. Laurichesse, F. Mercier, J.P. Berthias, P. Broca, L. Cerri, "Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination", Navigation, Journal of the institute of Navigation, Vol. 56, N° 2, Summer 2009
3. Hernández-Pajares M., J.M. Juan, J. Sanz, Samson, J., Tossaint, M.(WO2012130252) METHOD, APPARATUS AND SYSTEM FOR DETERMINING A POSITION OF AN OBJECT HAVING A GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVER BY PROCESSING UNDIFFERENCED DATA LIKE CARRIER PHASE MEASUREMENTS AND EXTERNAL PRODUCTS LIKE IONOSPHERE DATA (2011)
4. Rovira-Garcia A., Juan J. M., Sanz J., González-Casado G., Bertran. E (2016). "Fast Precise Point Positioning: A System to Provide Corrections for Single and Multi-Frequency Navigation", NAVIGATION, Journal of The Institute of Navigation, Vol. 63, No. 3, Fall 2016, pp. 231-247. DOI: 10.1002/navi.148

These techniques are a breakthrough for allowing fast and reliable navigation, with PPP-like algorithms.

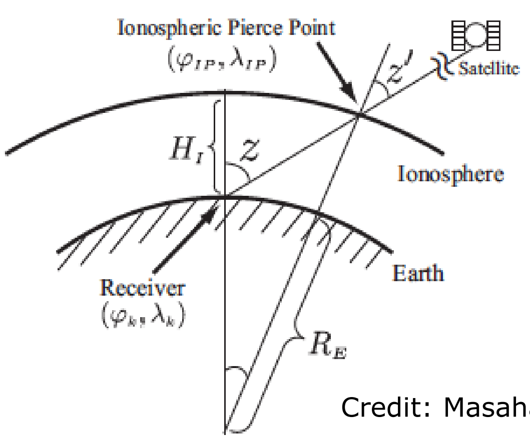
This presentation shows a preliminary assessment of the most suitable models for precise Ionospheric corrections.

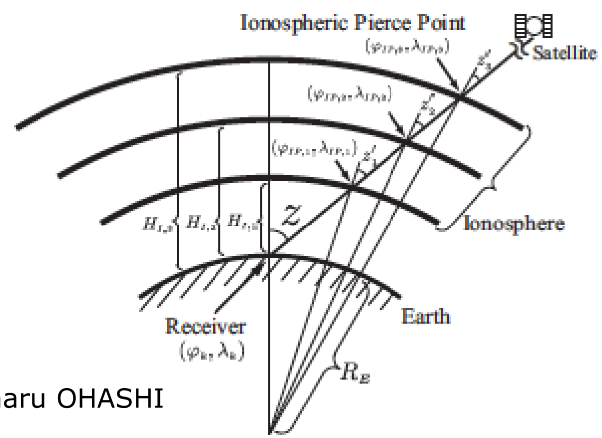
Introduction (3D Iono. modeling)

The most precise approach to compute the ionospheric delay is by means of using a 3D representation of the ionosphere, either multi-layer or voxel ionosphere model.

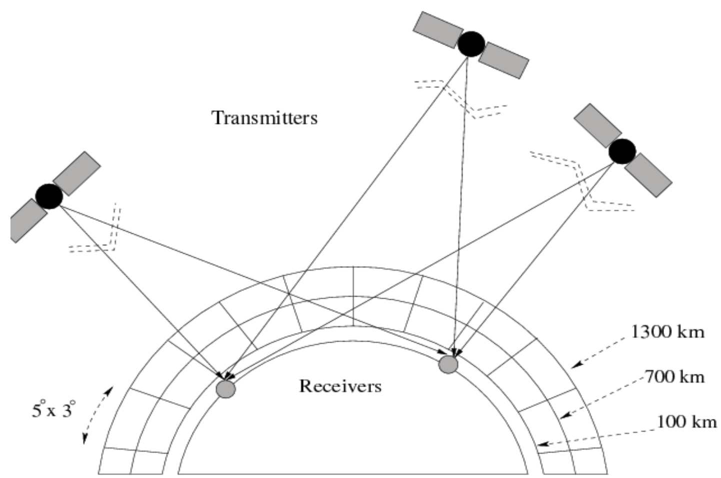
A 2-layer (or at most 3-layer) model already gives most of the benefits of 3D geometry with ground receiver data only.

A higher number of layers could lead to high correlation between the layers, which is not advisable.





Credit: Masaharu OHASHI

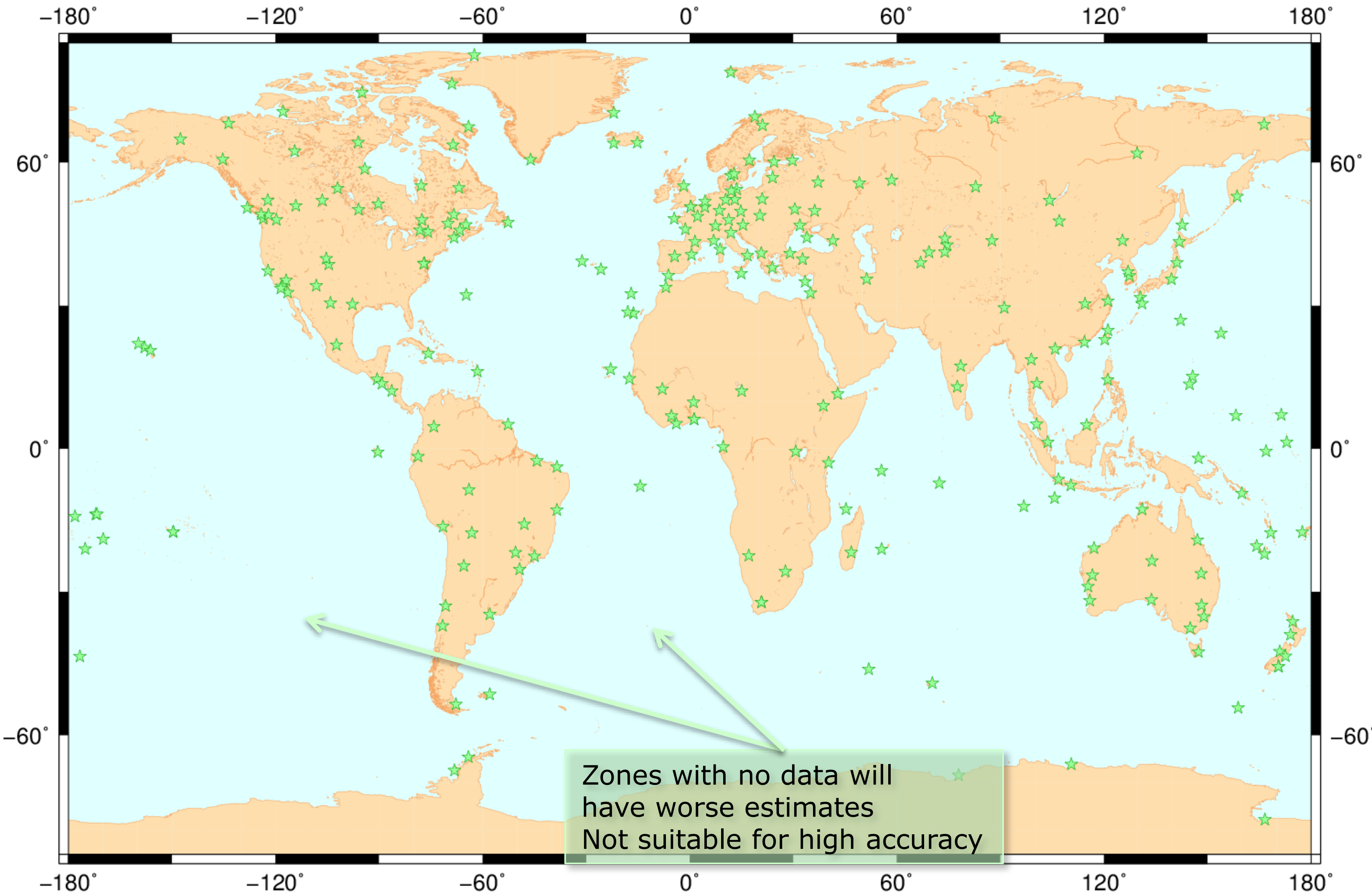


Approach for Ionospheric modeling

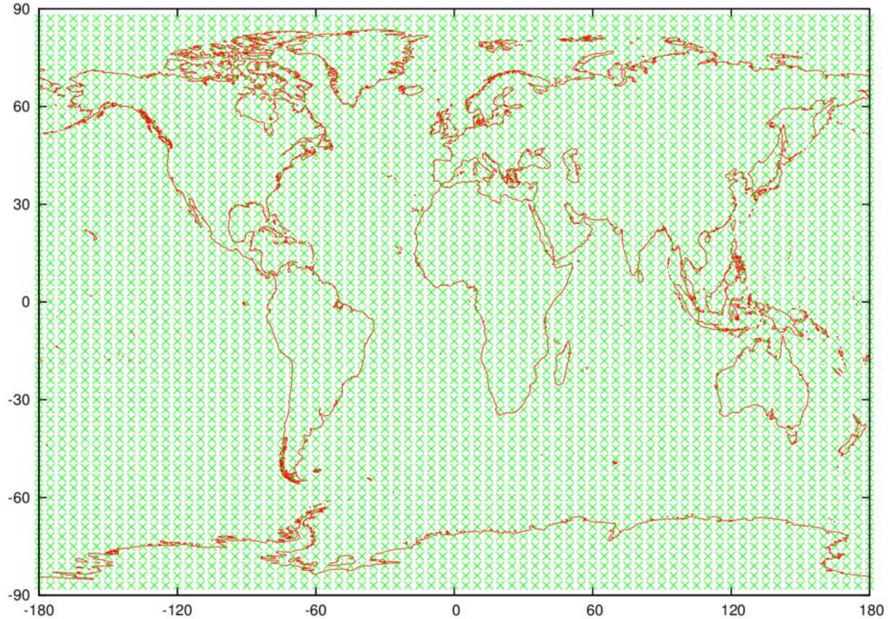
Ionospheric Map characteristics

- Network of 250 dual frequency ground stations (GPS, Galileo, Beidou)
- Modeling based on Voxel and Multilayer (2 layer for both).
- Several grid size tested: 5x3, modified 3x3, modified Gaussian n.32.
- Test day 277, 2017. Solar Minimum
- The 3D modeling is very sensitive to:
  - Ability to fix the ambiguities in *double differences*.
  - Time modeling of ionospheric parameters (i.e. Code Biases in the measures, Process noise)
  - Reference frame of the ionospheric grid (i.e. Fixed to earth reference frame)

Ionospheric model network



Ionospheric modeling grid at each layer



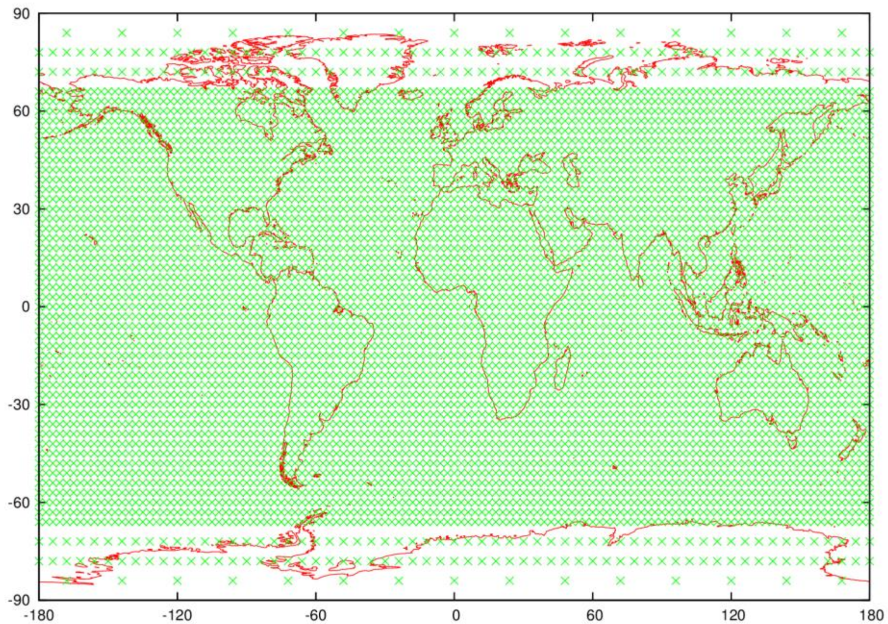
Number of unknowns for each layer:

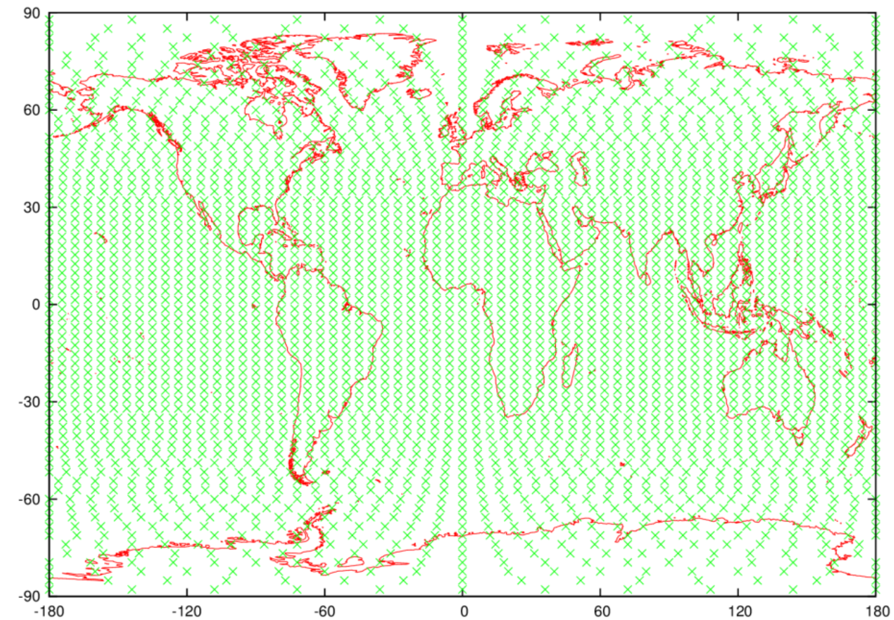
5x3 → 4248

Modified 3x3 → 5670

Similar to MOPS RTCA grid

Modified Gaussian n32 → 3060



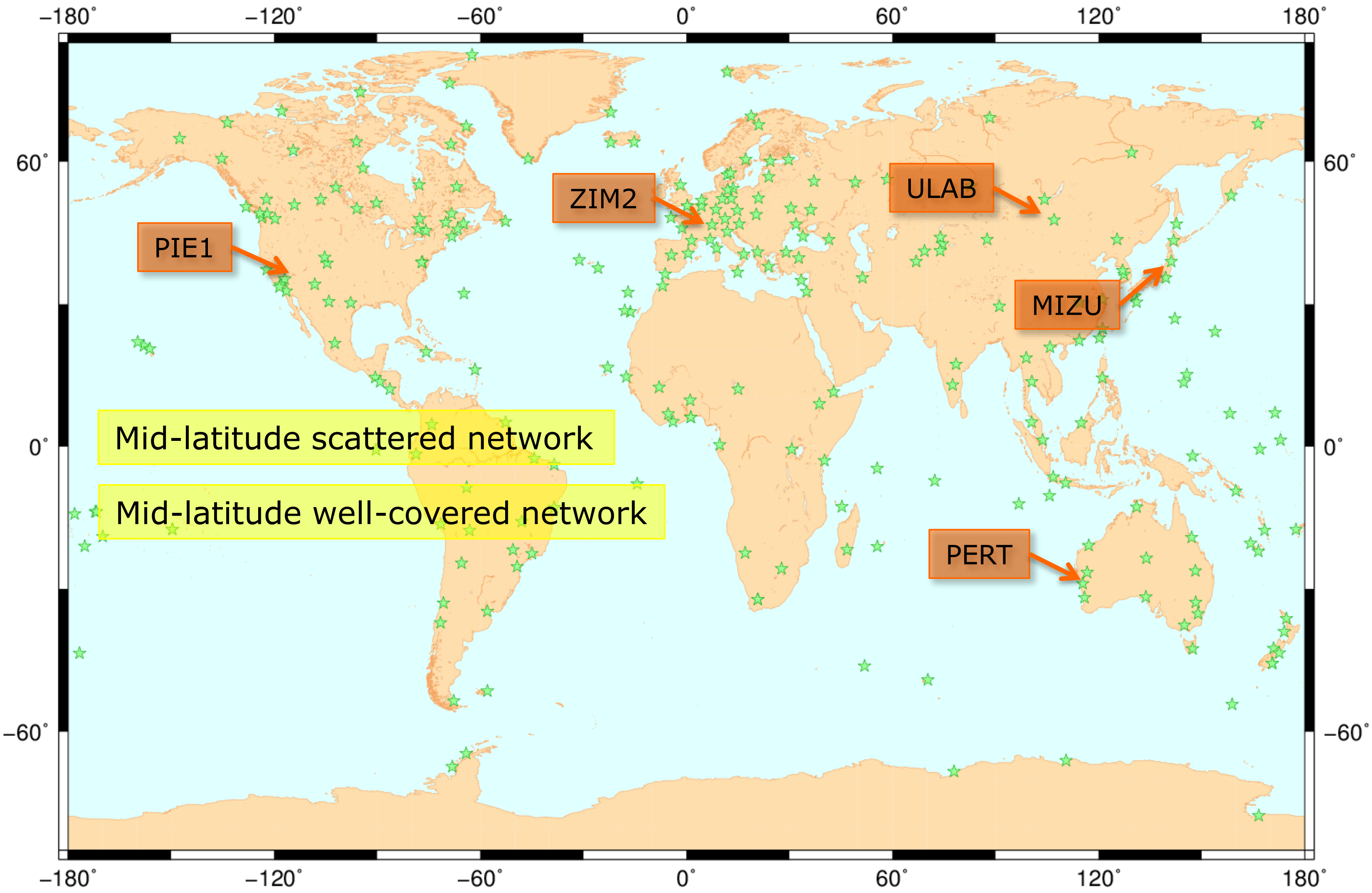


Approach for PPP user

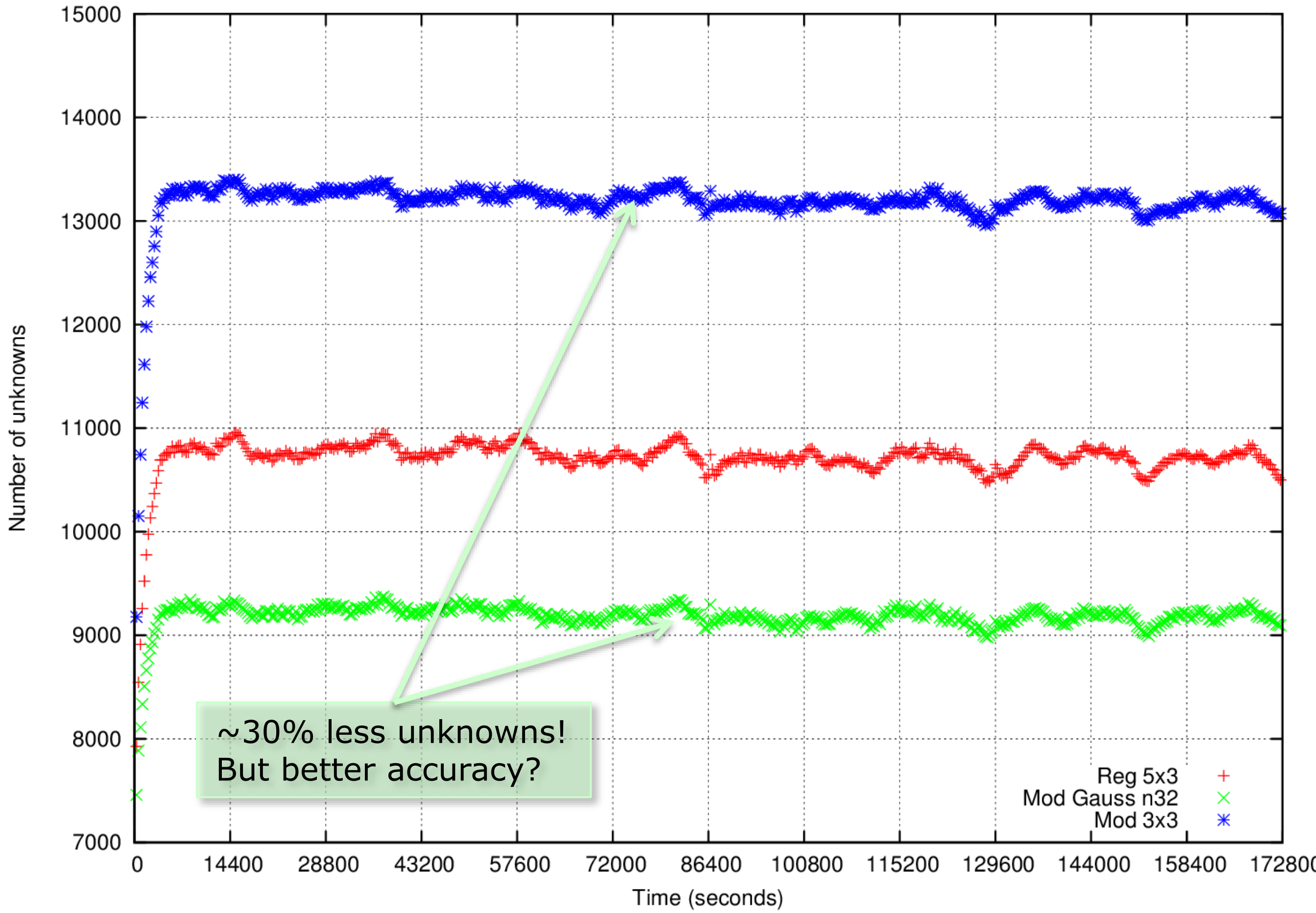
Positioning testing

- Using IGS precise orbits and clock from GFZ and 3D ionospheric model as computed.
- Using Dual Frequency GPS (L1,L2) and Galileo (E1,E5a).
- Floating ambiguities as upper bound of fixing ambiguities performance.
- Reset all carrier phase arch every 2h.
- Test in mid latitudes for different kind of network coverage.
- Test day 277, 2017.

Location of tested PPP users



Results. Number of Unknowns being solved

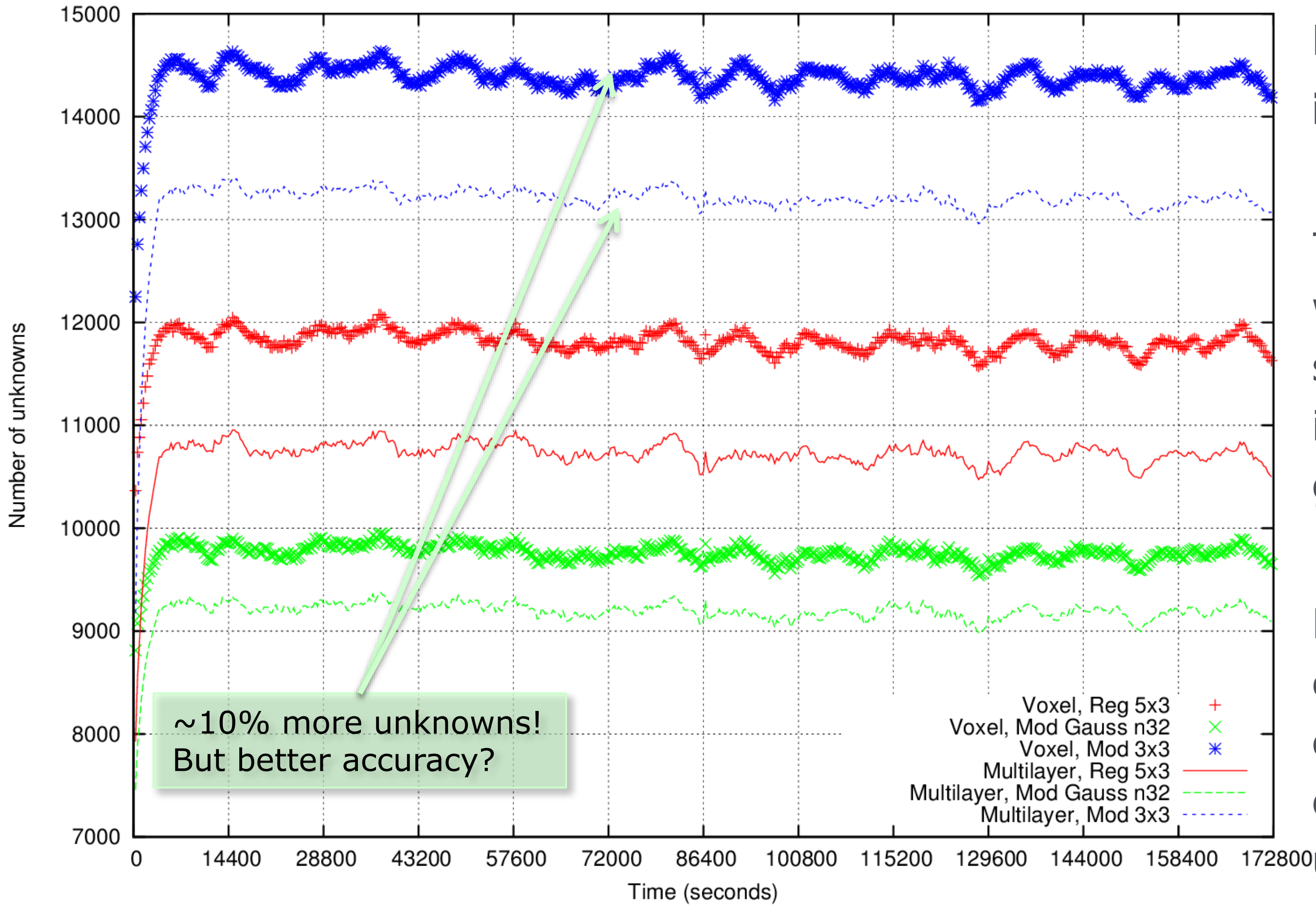


Number of unknowns in Multilayer:

Receiver and satellite code bias and phase ambiguities for GPS, Galileo and Beidou.

There are about 250 receivers world wide distributed

Results. Number of Unknowns being solved

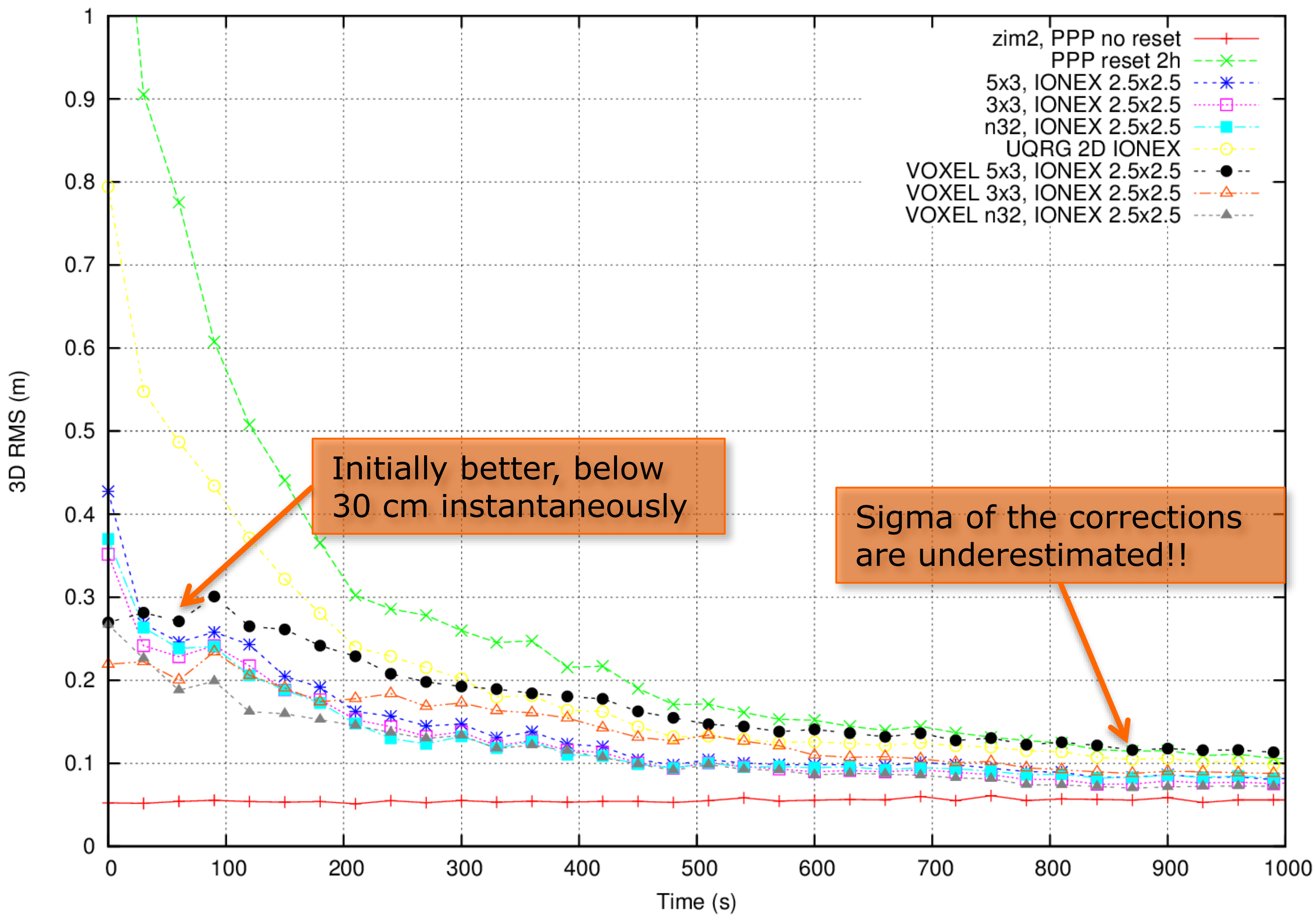


Number of unknowns in Voxel:

The number is increased with respect to multilayer since each ray can illuminate more than 2 grid points.

Higher fidelity but at the expense of more computational load (not only related with the unknowns but with the computation of the ray length in each voxel)

Results. Convergence time. Voxel vs. Multilayer



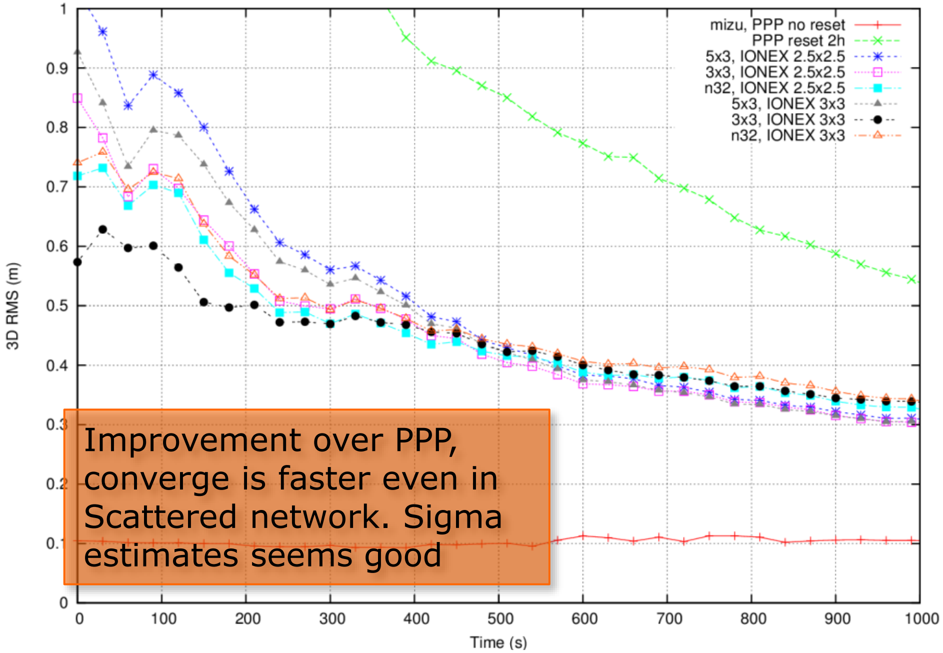
Remarks:

Same assumptions for Receiver and satellite code biases, and phase ambiguities for GPS, Galileo and Beidou.

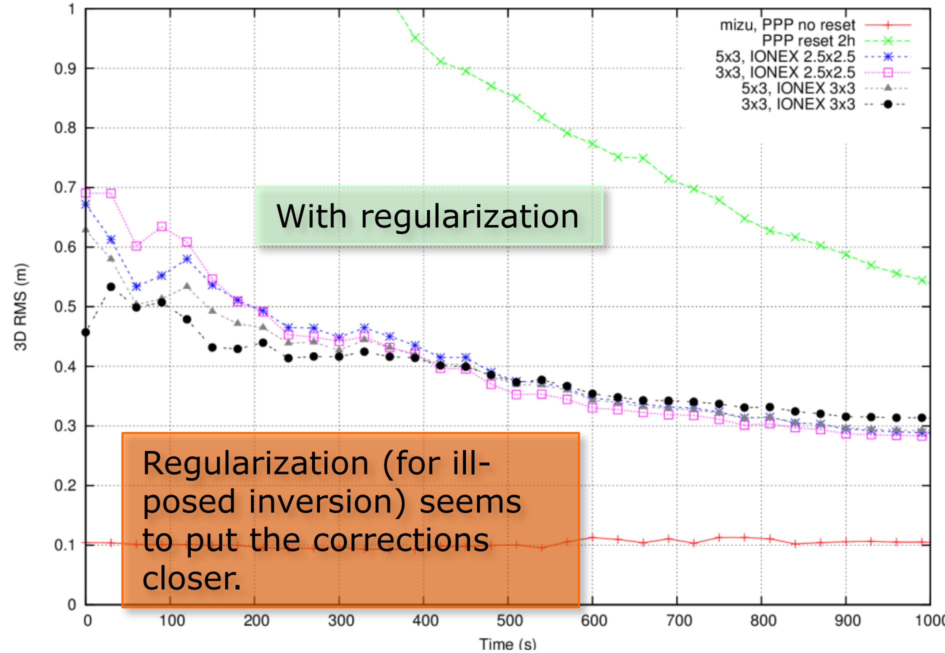
Process noise suboptimal for both models

Corrections distributed as multilayer (3D IONEX format)

Results. Scattered network

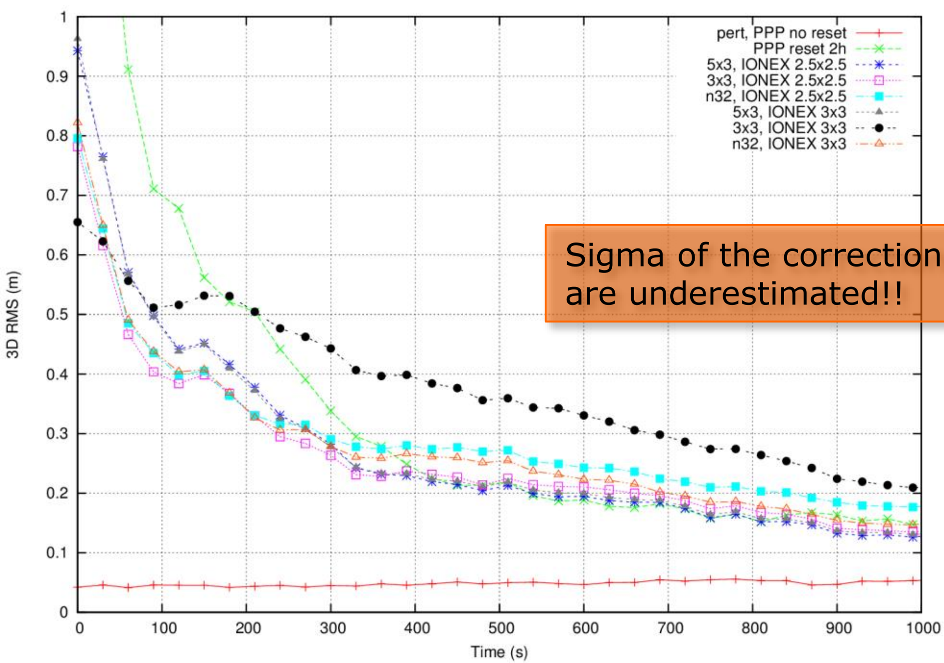


Improvement over PPP, converge is faster even in Scattered network. Sigma estimates seems good

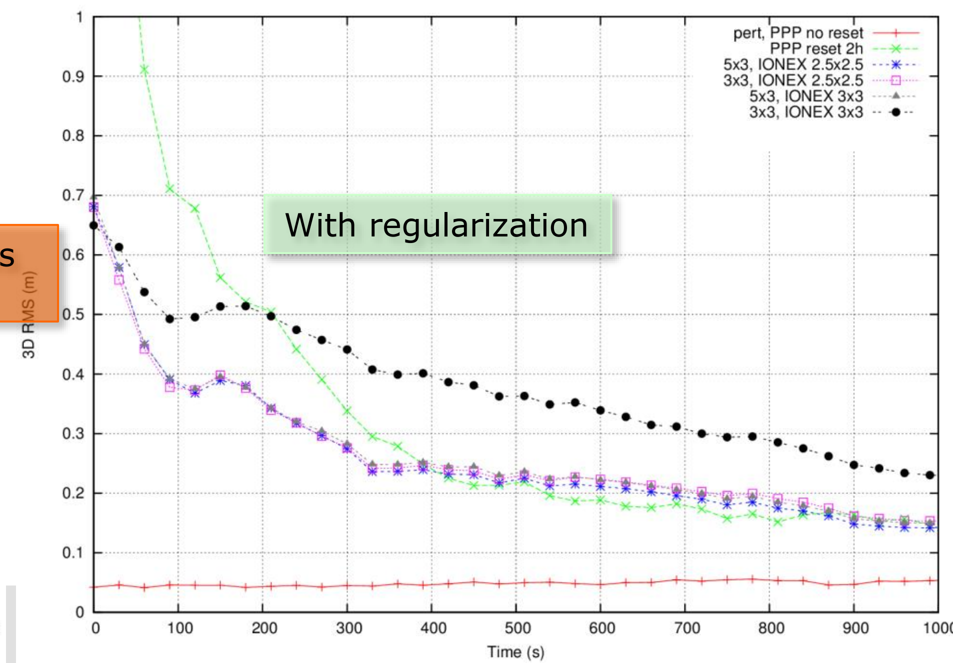


With regularization

Regularization (for ill-posed inversion) seems to put the corrections closer.

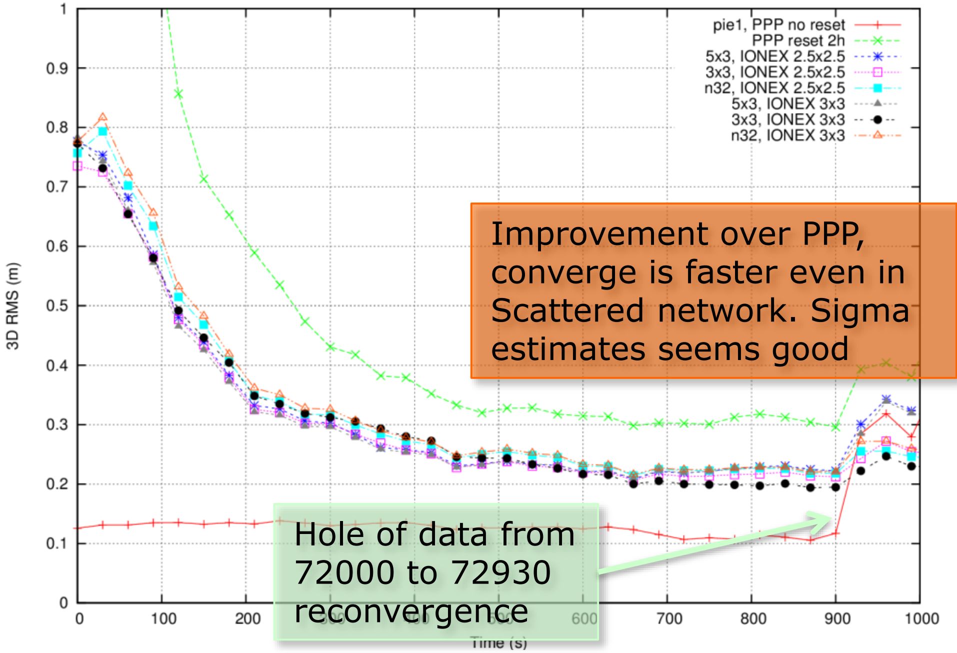


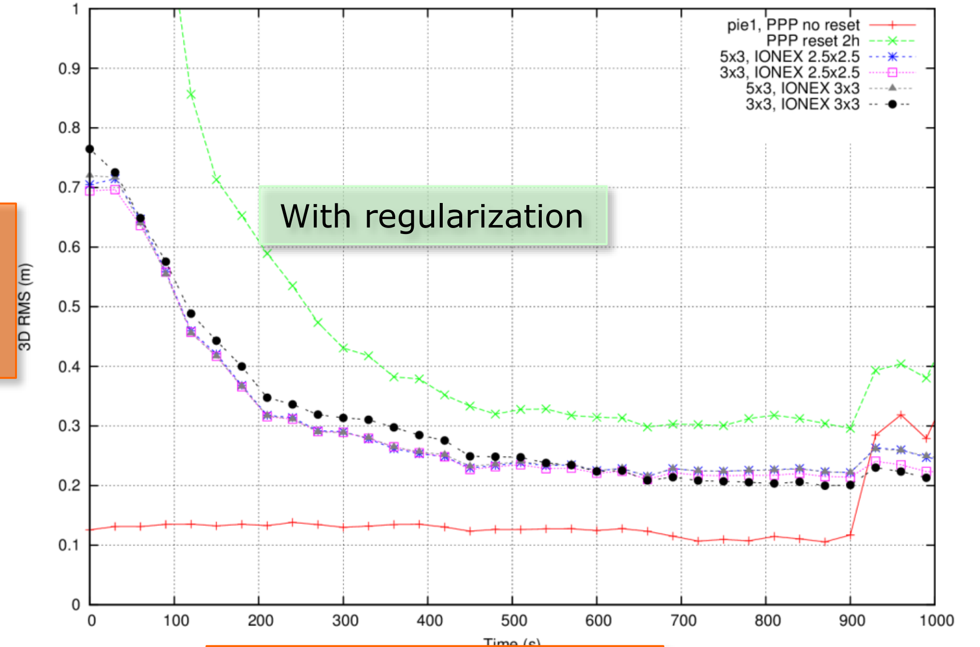
Sigma of the corrections are underestimated!!

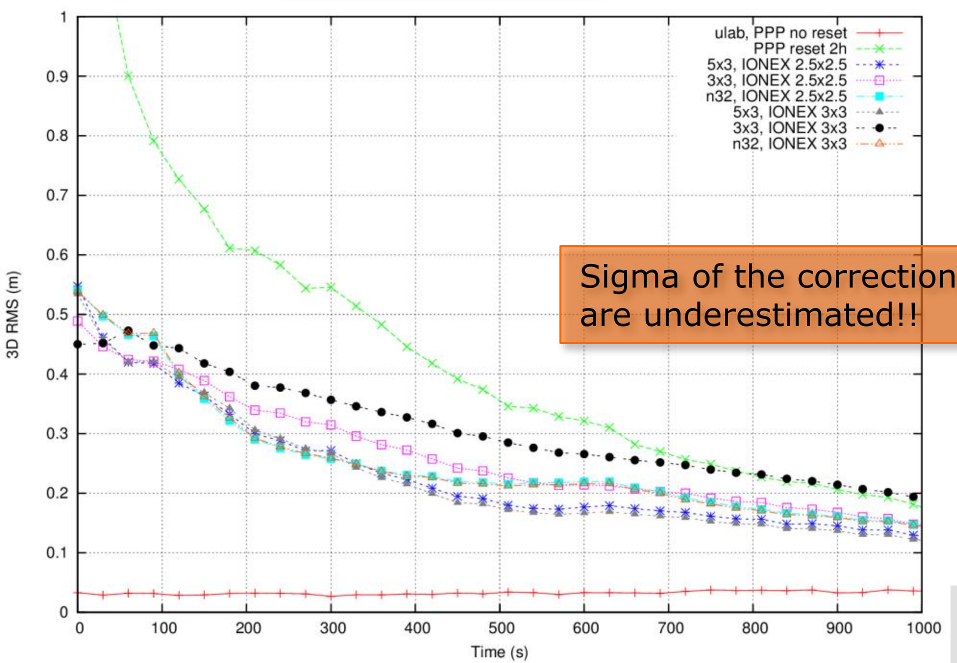


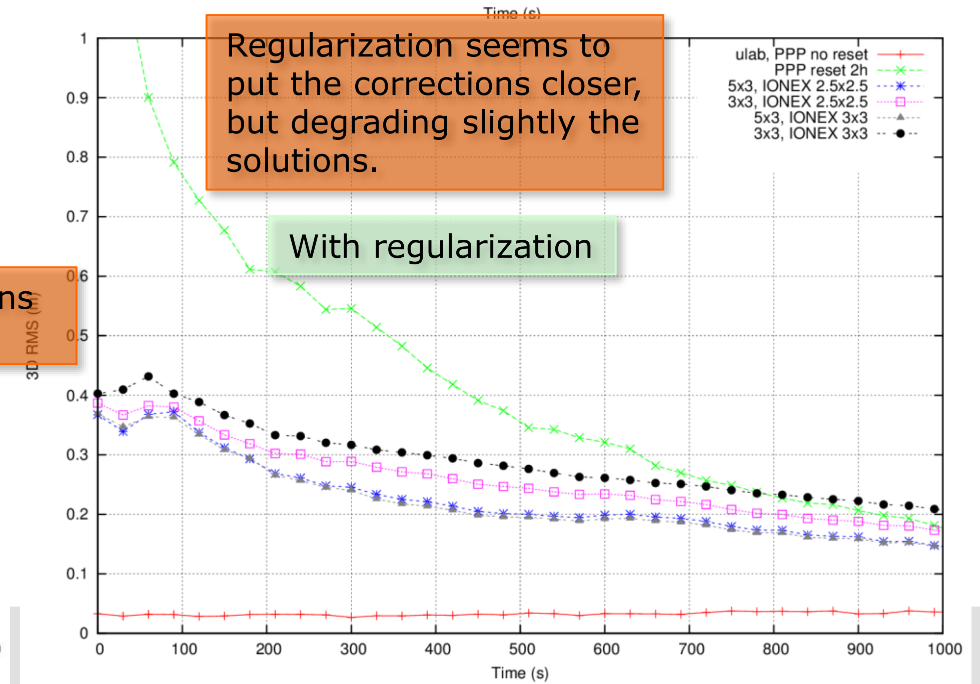
With regularization

Results. Scattered network

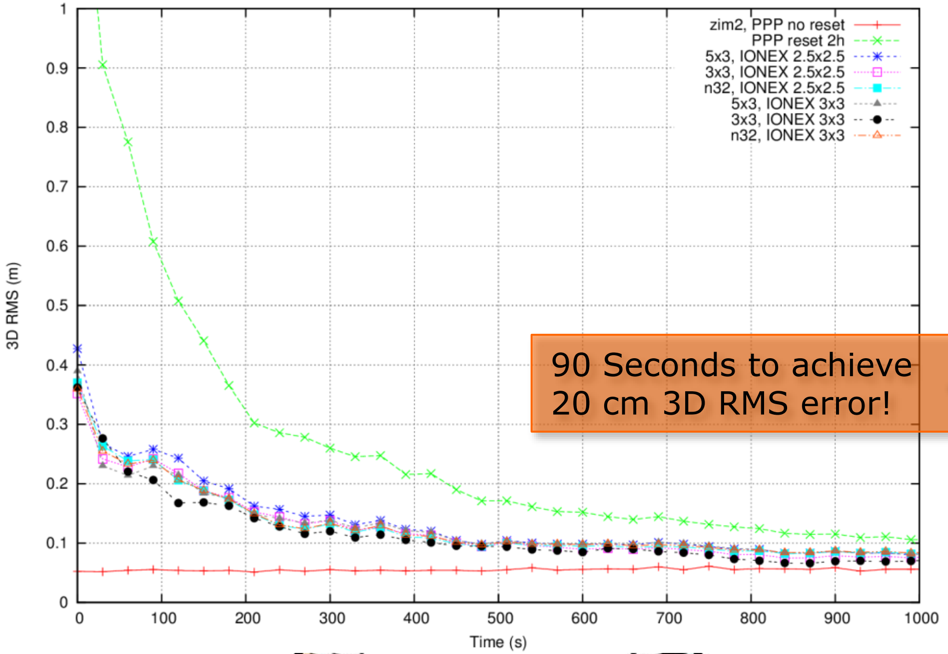


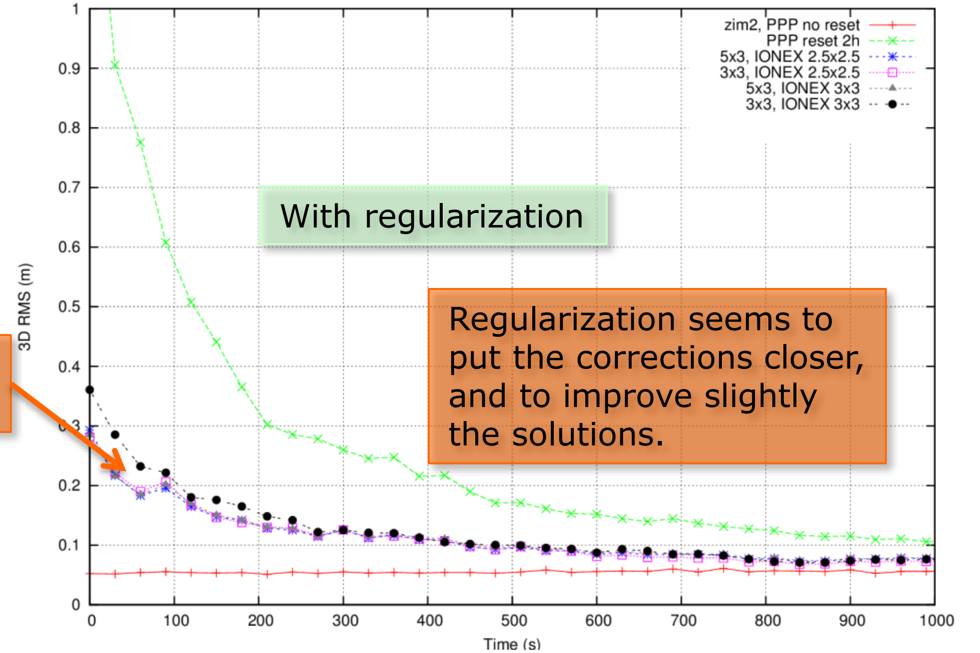


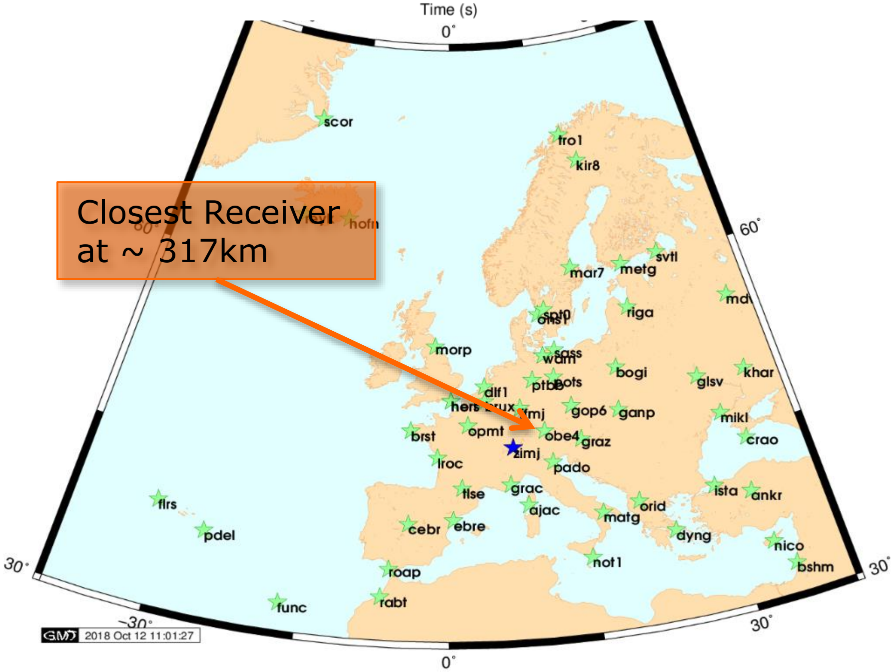


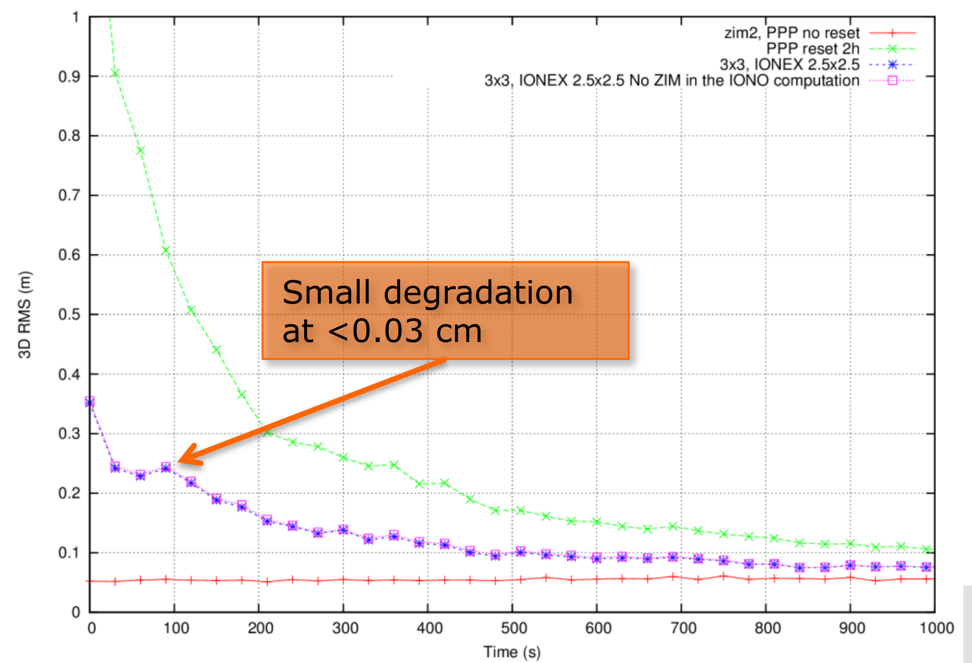


Results. Impact of distance to reference station

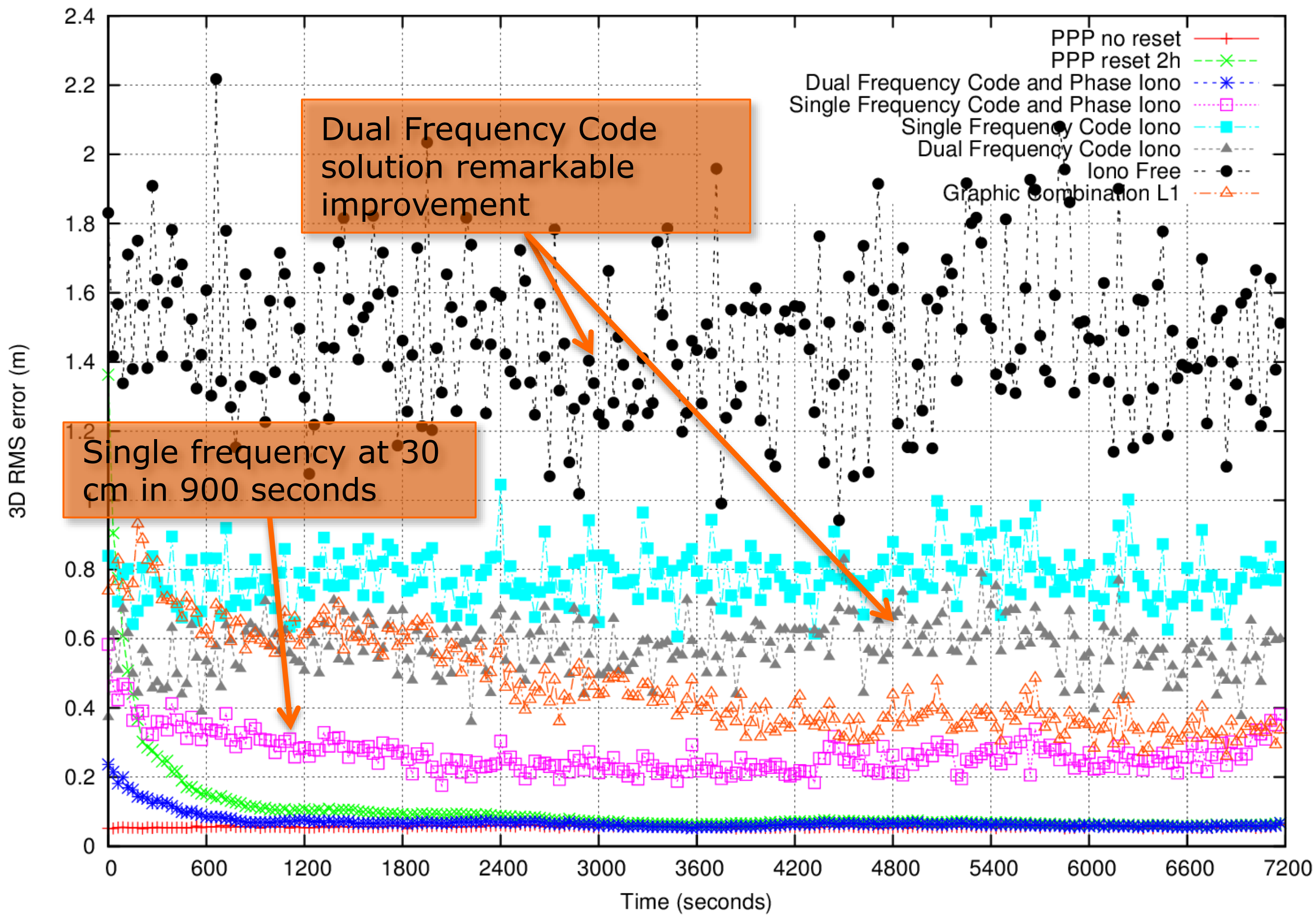








Convergence for 'other' user cases



Remarks:

The use of precise ionospheric correction in an uncombined filter benefits all kind of users.

Dual Frequency Code solution moves from Iono Free (noise P1x (2 – 3)) to Narrow lane (noise P1 / 1.41)

Conclusions

- High-Fidelity 3D ionospheric models improves the time of convergence for PPP users dramatically.

- Voxel and Multi-layer models perform very similar. However, the Voxel ionospheric model requires more computational time, which could be a bottleneck for real time implementation.

- For Mid latitudes and low solar activity, it has been shown that there are no significant degradation in performance for distance rover to the nearest reference station of 300 Km or more. The minimum distance for getting high accurate estimates for all Solar cycle conditions and geographical location should be assessed.

Future Work

- Check the influence of the Troposphere and Code Biases in the convergence time for the first 2 hours of all calculations.

- Study low latitude regions with well covered networks to study the limits of High-Fidelity 3D ionospheric modeling. Fine-tune the parameters

- **Recommendation**

WG-B to include within its work-plan, the assessment of the inter-operability of ionospheric/tropospheric models *and formats* to support High Accuracy services.

WG-B to assess the availability and adequacy of external sources of ionospheric/tropospheric models to support High Accuracy Services.

→ Follow the experience of RTCA MOPS for delivering an optimal grid message should be followed, but updated for High-Fidelity 3D ionospheric models. Study the most optimal message characteristics to be broadcasted globally to the users. Grid spacing for 1st and 2nd layer should be the highest priority. A good start is the Modified 3x3.

Thank you!

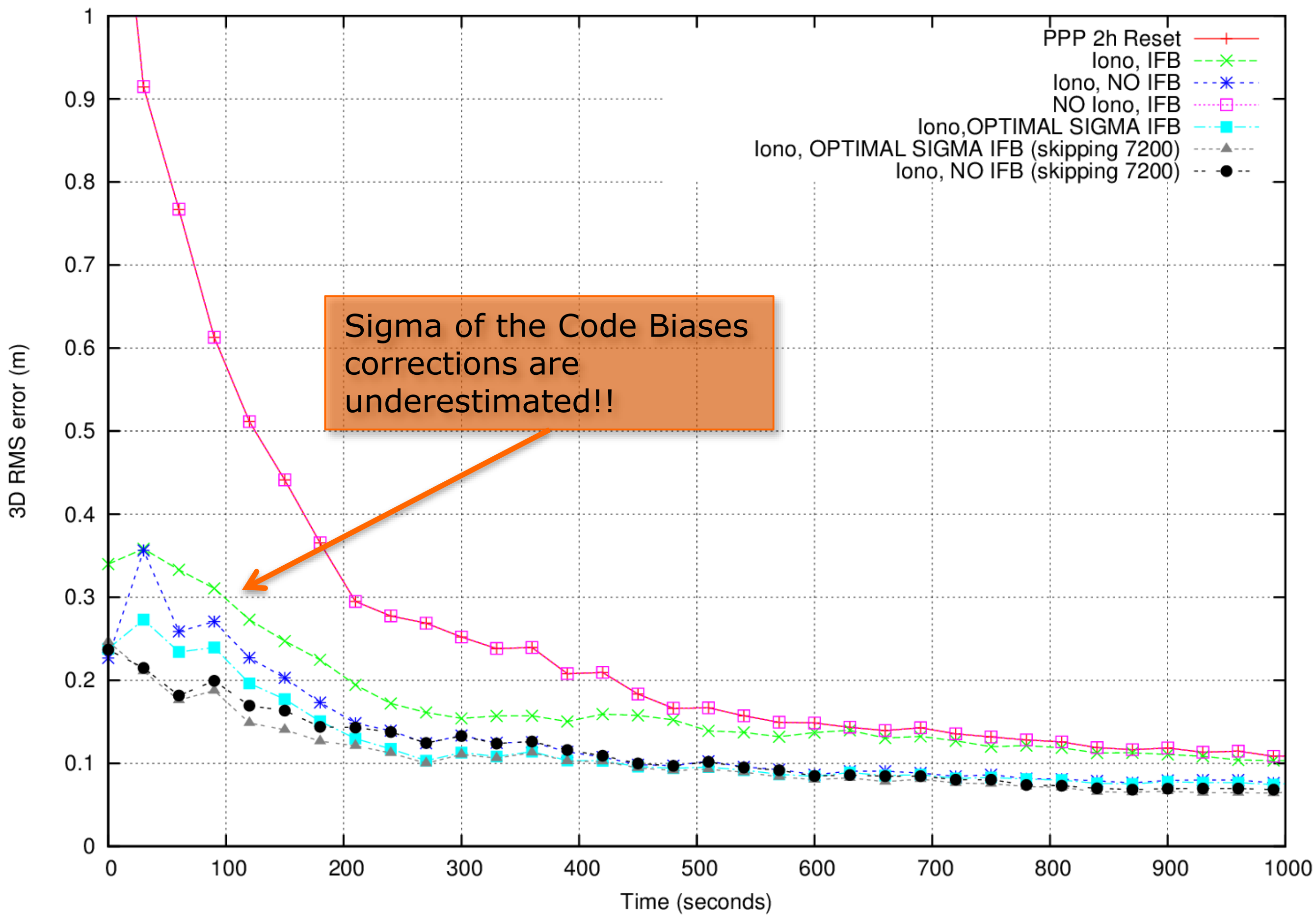
Navigation equations

The basic GNSS observable for absolute navigation for dual frequency the code an phase:

$$P_1^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j + \tilde{\alpha}_1\left(STEC^j + DCB_r - DCB^j\right) + \varepsilon_{P_1}^j$$
$$L_1^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j - \tilde{\alpha}_1\left(STEC^j + DCB_r - DCB^j\right) + B_1^j + \lambda_1\omega + \varepsilon_{L_1}^j$$
$$P_2^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j + \tilde{\alpha}_2\left(STEC^j + DCB_r - DCB^j\right) + \varepsilon_{P_2}^j$$
$$L_2^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j - \tilde{\alpha}_2\left(STEC^j + DCB_r - DCB^j\right) + B_2^j + \lambda_2\omega + \varepsilon_{L_2}^j$$
$$STEC_{cor}^j = STEC^j + \varepsilon_{ion}^j$$
$$DCB_{cor}^j = DCB^j + \varepsilon_{DCB}^j$$

For more advance concepts the equations are connected via the Ionosphere delay and Hardware biases. With equivalent weights this is the same as doing the "iono free" but the number of unknowns is increased. However, if the ionosphere model is ***precise enough*** and ***well weighted*** the convergence time decreases since the information is well received by the navigation filter and the ambiguities preserve their integer nature.

Parameter Individual Convergence



Remarks:

Code biases for GPS, Galileo and Beidou seems overestimated.

Initial removing of 7200 seems a good approximation for Iono convergence with optimal Code biases sigma.