Generating Global and Regional Ionospheric Delay Model for Real-time Precise Point Positioning Service

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- Model,Algorithm & software (SH/PWL/RW/ICLS)
- Data and Results (RMS,DCB, IONEX)

Real Time European Ionospheric Delay for PPP

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- Receiver DCB effect on PPP
- PPP Convergence Results

Discussion and Summary

- Challenges for RT-ION: PPP requirements, SLM & MF, Receiver's DCB
- Summary

Modeling Ionospheric with SH

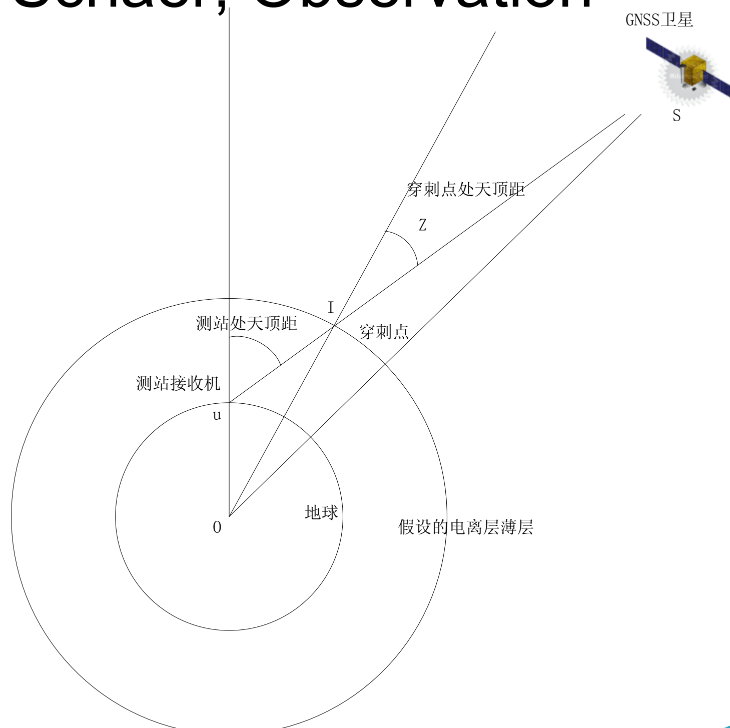
$$STEC(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\beta)(a_{nm}\cos ms + b_{nm}\sin ms) / M + DCB_s + DCB_r$$

Spherical Harmonic Model in SLM for GIM, adopted by CODE from 1998, Dr. Stefan Schaer; Observation equation is as following:

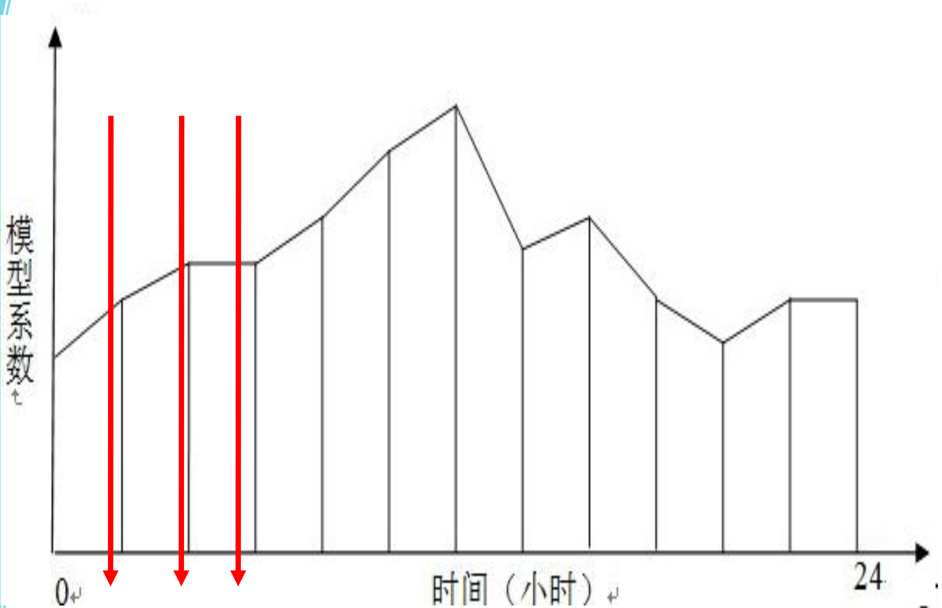
$$\sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\beta)(\tilde{C}_{nm}\cos(ms) + \tilde{S}_{nm}\sin(ms)) - K \cdot \cos z' \cdot B$$
$$= K \cdot (\rho_2{}' - \rho_1{}') \cdot \cos z'$$

Mapping function:

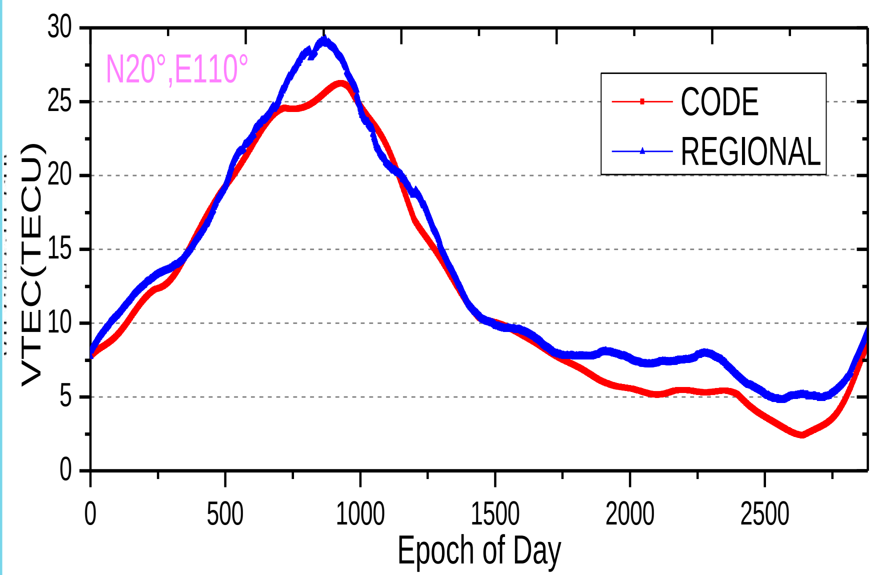
- MSLM
- Cosz
- Extended Slab Model (ESM) mapping function



GIM Algorithm: PWL



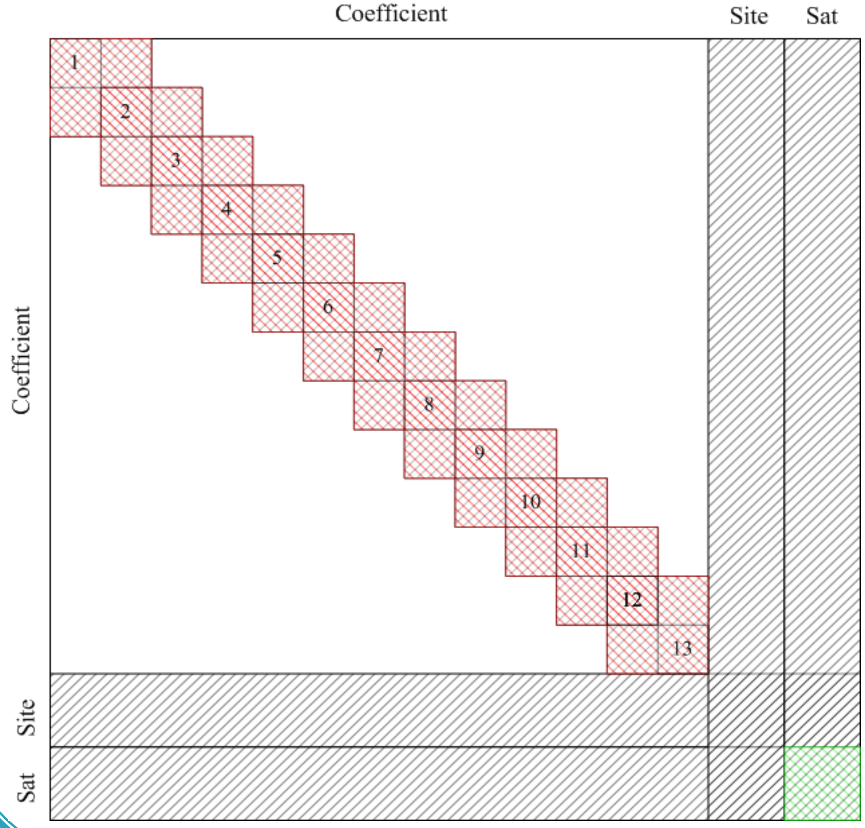
IONEX Map, Piece Wise Linear



Grid VTEC Time Series from PWL

GIM Algorithm: Random Walk

Normal Matrix of PWL

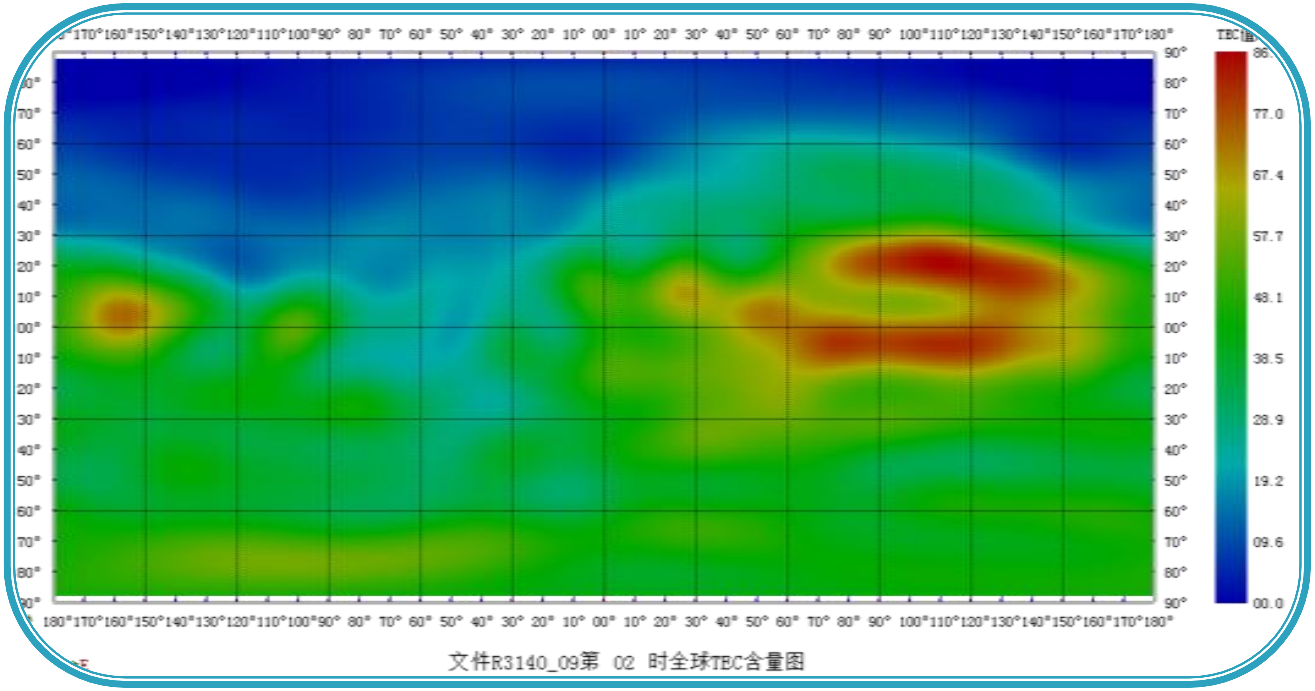


Random Walk for SH Coeff

$$X_i - X_{i+coef} = 0$$

$$N_c = \begin{bmatrix} W & -W \\ -W & W \end{bmatrix}, W = \frac{\sigma_0^2}{\sigma_{constrain}^2}$$

GIM Algorithm: Temporal and Spatial Constraints



Grid Time Random Walk for GIM: ***Grid Points' VTEC Variation with time, VTEC1 – VTEC2 = 0, with a Sigma***

Grid Variation Constraint for GIM: ***Grid Points' VTEC variation with latitude, local time, VTEC1 – VTEC2 = 0, with a Sigma, must consider gradients and Grids' interval, especially two peaks in North and South Hemisphere***

GIM Algorithm: ICLS

- Inequality Constrains for negative Grids

$$\begin{cases} \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\beta)(\tilde{C}_{nm}\cos(ms) + \tilde{S}_{nm}\sin(ms)) - K \cdot \cos z' \cdot B \\ \quad = K \cdot (\rho_2{}' - \rho_1{}') \cdot \cos z' \\ \sum_{n=0}^{n_{\max}} \sum_{k=0}^{n} \tilde{P}_n^k(\sin\theta)\left(A_n^k \cos k\lambda + B_n^k \sin k\lambda\right) \geq 0 \end{cases}$$

$$\hat{\beta}_{ICLS} = (B^T PB)^{-1}(B^T Py + G^T q) = N^{-1}B^T Py + N^{-1}G^T q = \hat{\beta}_0 + N^{-1}G^T q$$

Rough idea in Inequality LSQ:

calibrate LSQ Solution with inequality equations' information

Strategies in "IonosphereEst " Program:

1.LSQ with PWL and Random Walk in Normal Matrix

2. Get Grids' VTEC and find those negatives

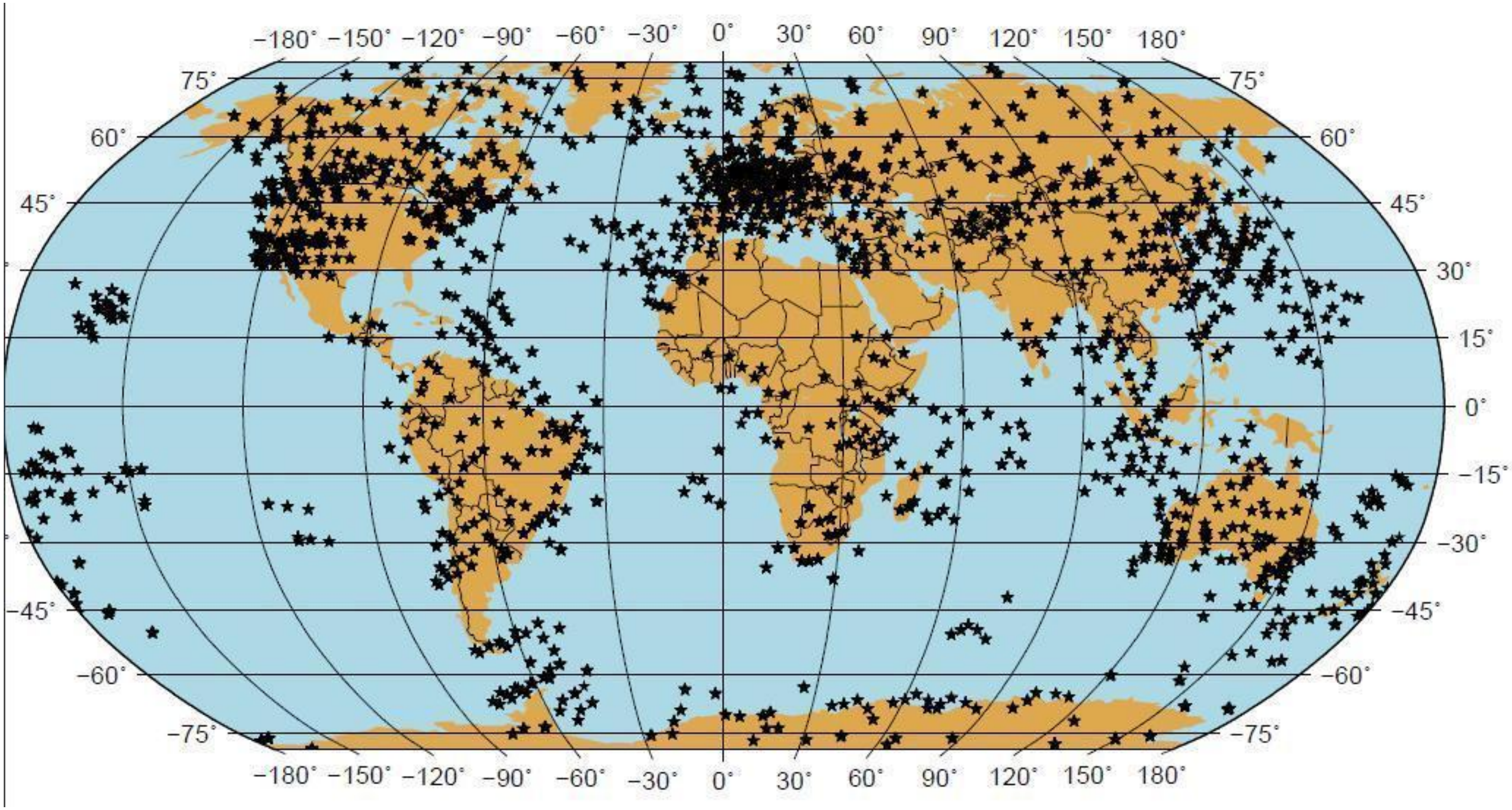
3. make G and q with iteration method

4. Calibrate SH Coefficients

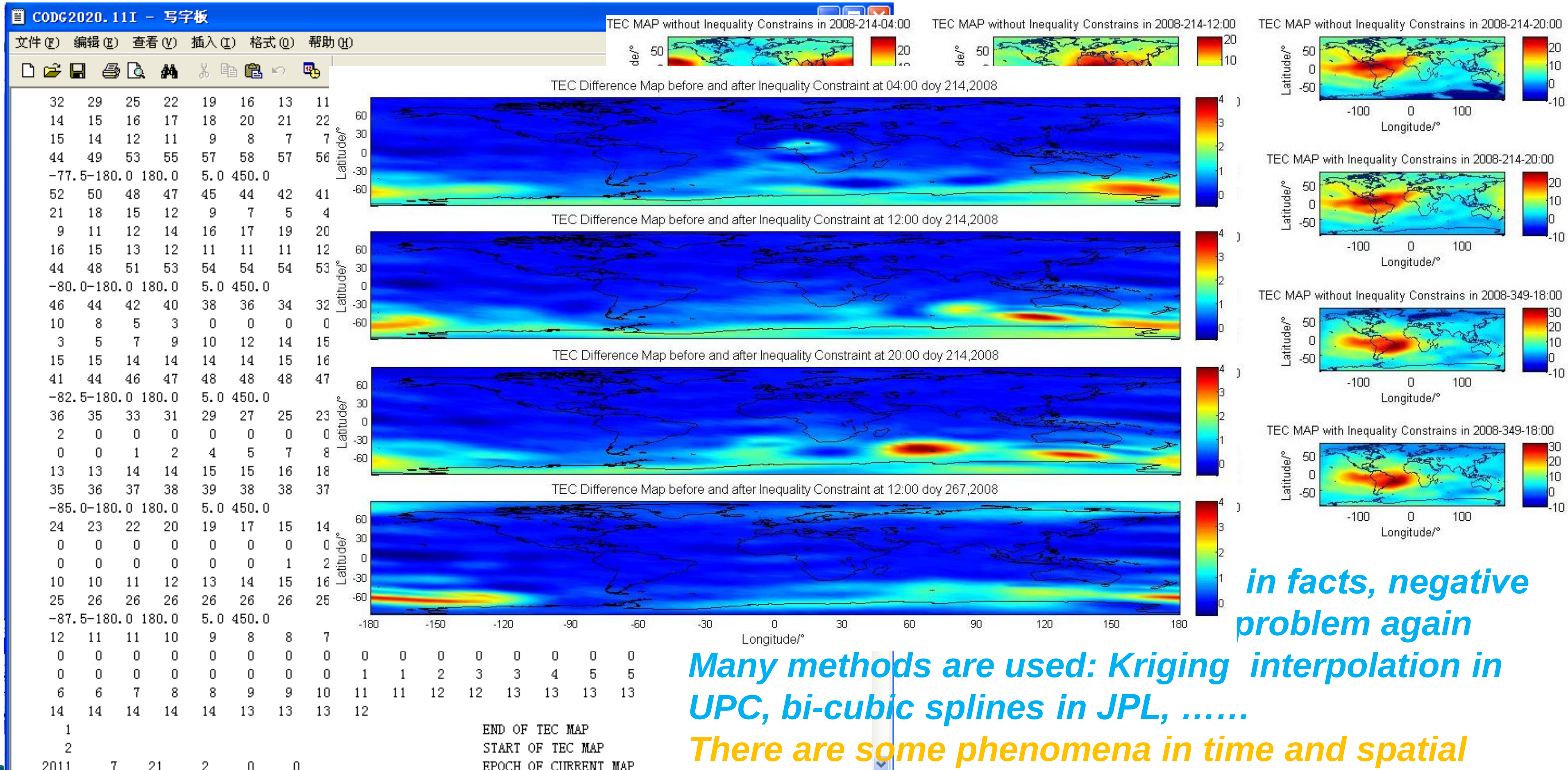
5. Iteration again according to the results

IPP Global Distribution

248sites. PST



Results: GIM Algorithm ICLS

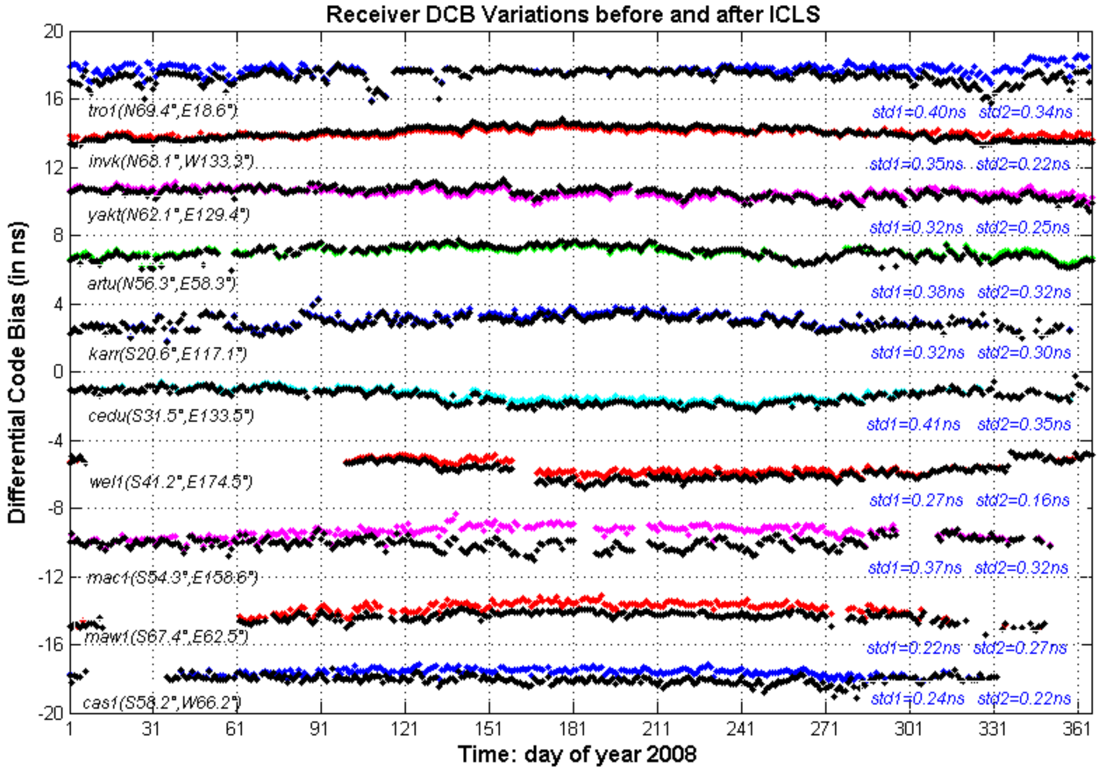


in facts, negative problem again

Many methods are used: Kriging interpolation in UPC, bi-cubic splines in JPL, ……

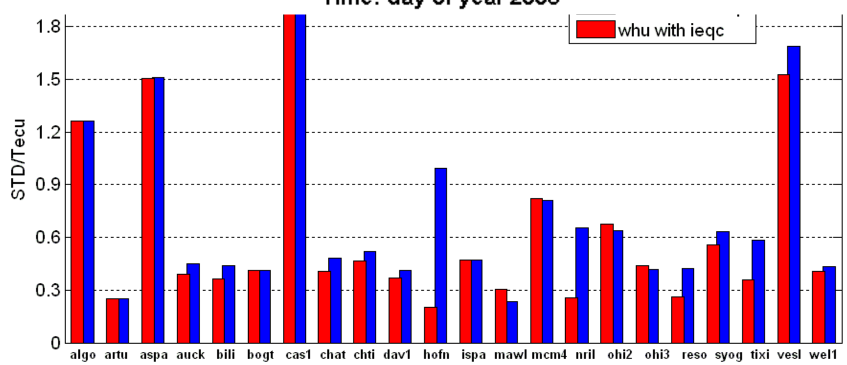
There are some phenomena in time and spatial variation for Negative values' occurance

Results: InEquality Constraint for GIM



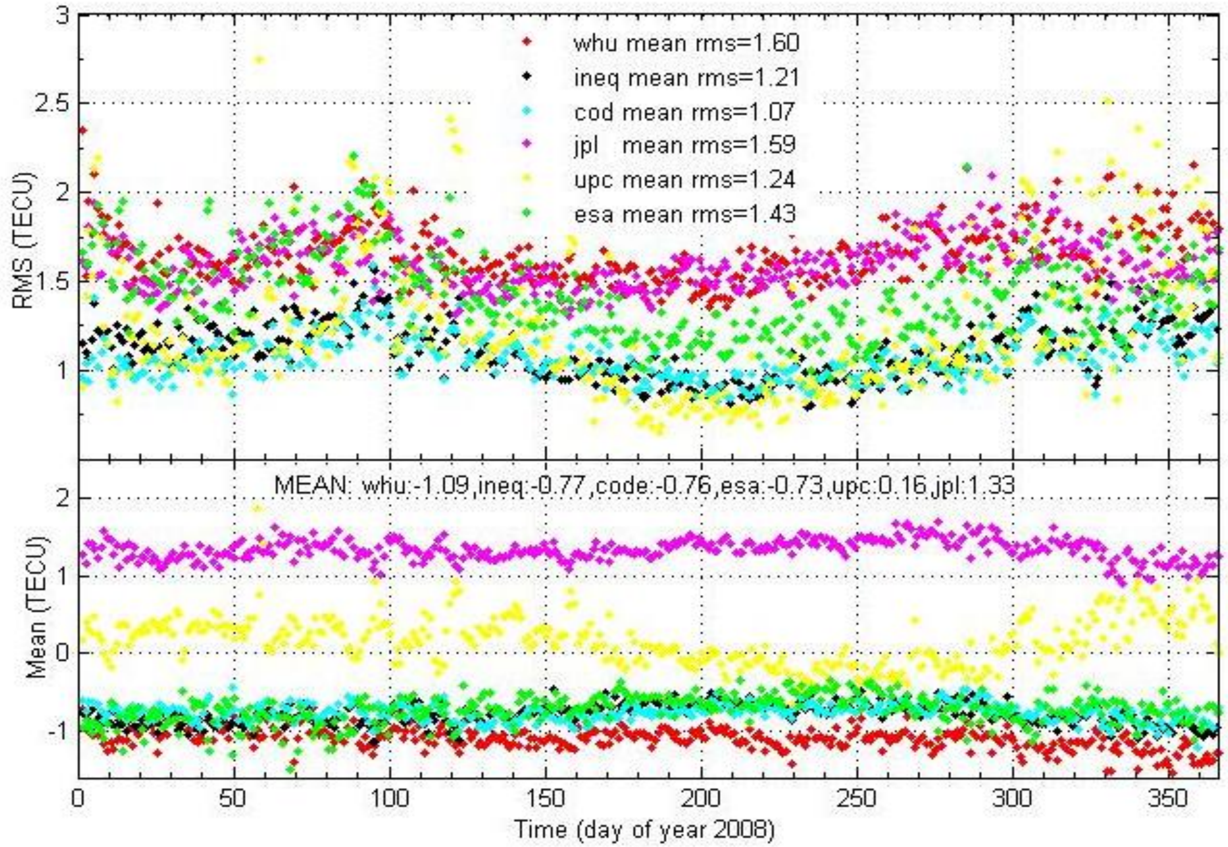
Inequality Constraints on GIM, its Contribution :

- Make RCVR DCB more stable,
- Eliminate the negative values in IONEX products.
- Improve GIM solution in sparse area



GPS sites in this figure is in sparse area, 22sites, 4 sites' std become a little larger, others become a little smaller.

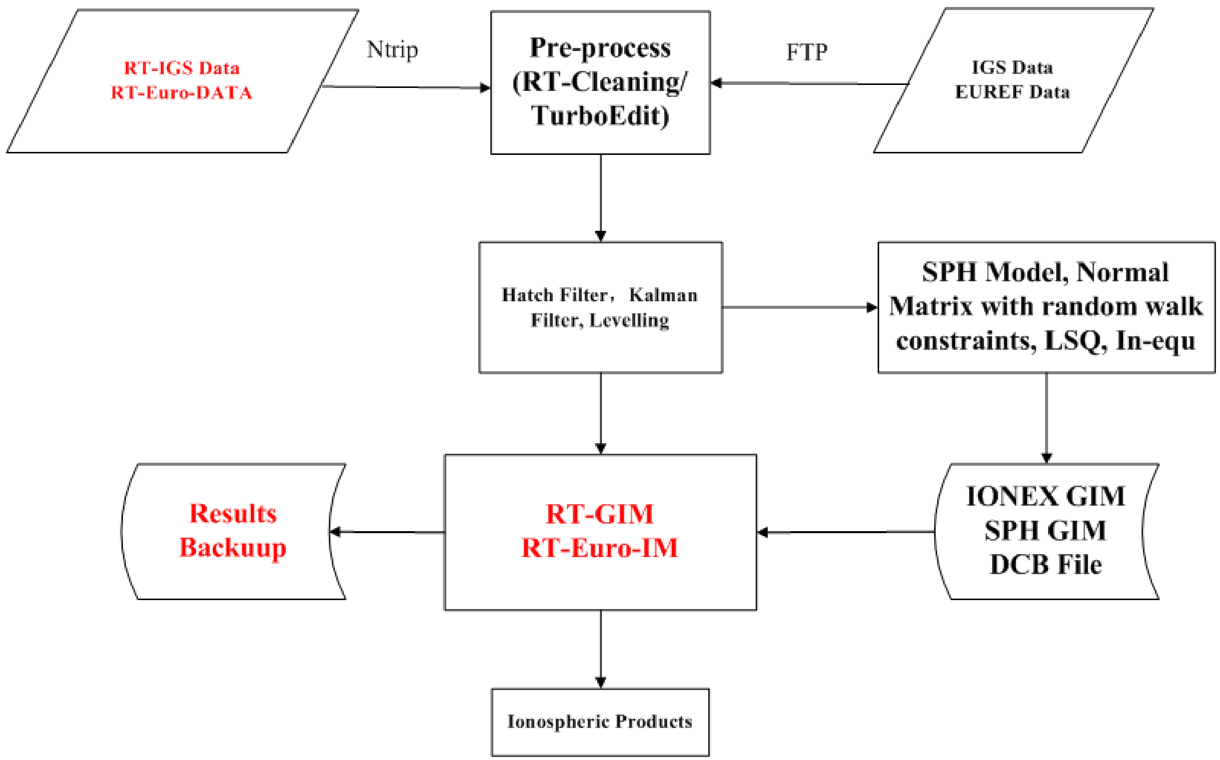
Results—GIM DIFF



JPL and UPC have large differences compared with CODE

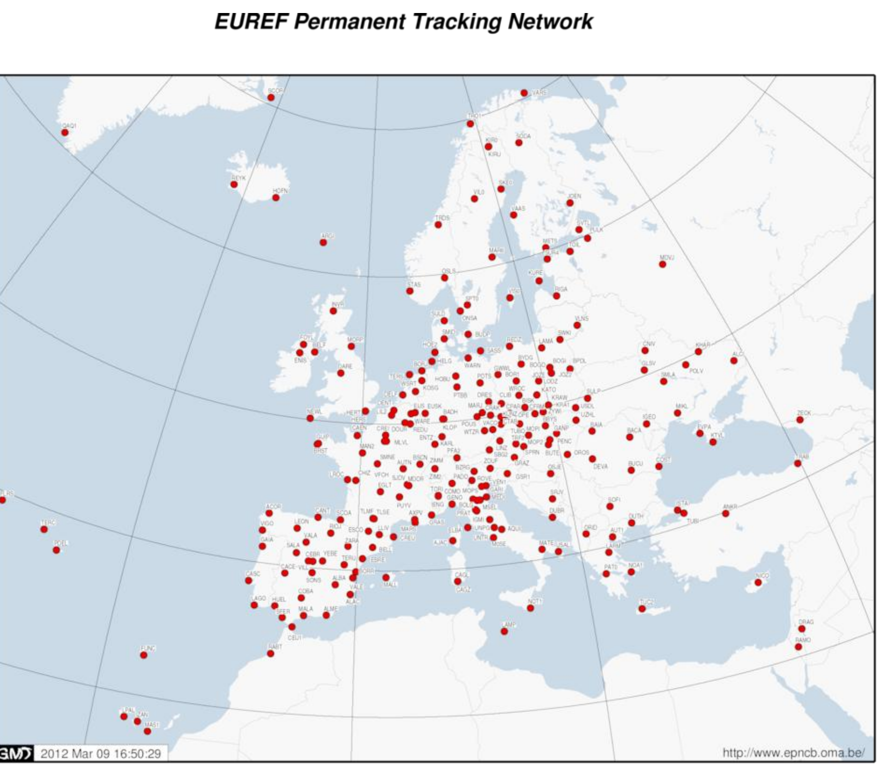
GFZ is almost the same level with IGS

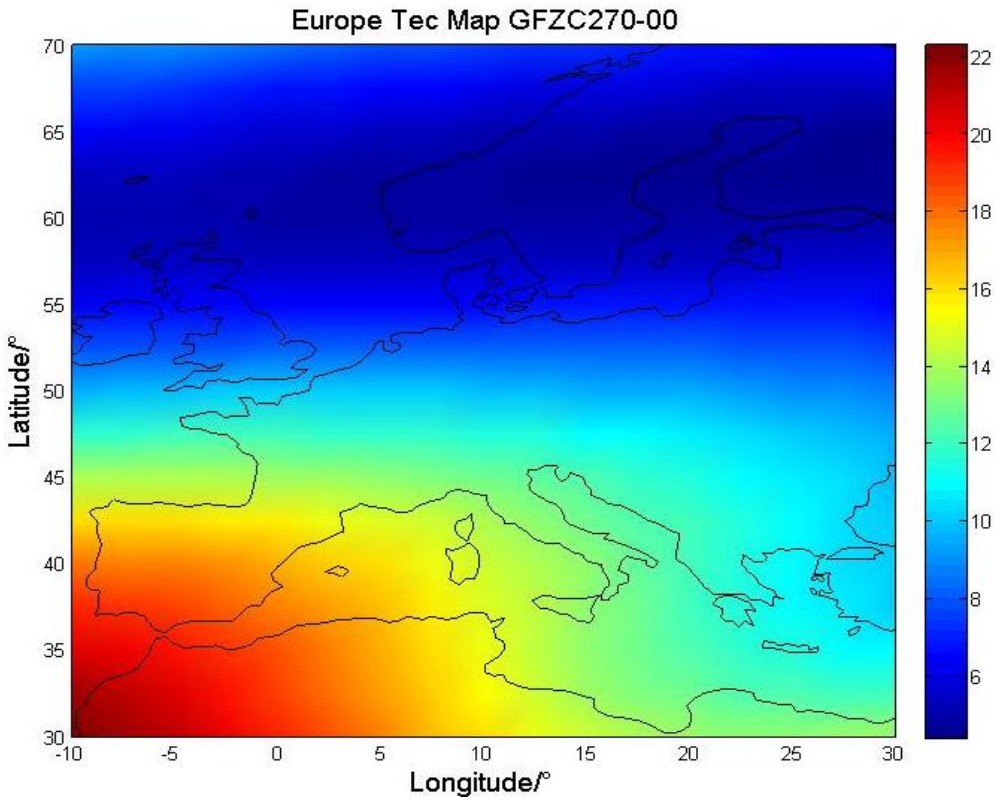
Software Procedure



1. *Daily Automatic Solution running*
2. *Hourly Automatic Solution running*
3. *Real-time ionospheric Mapping*

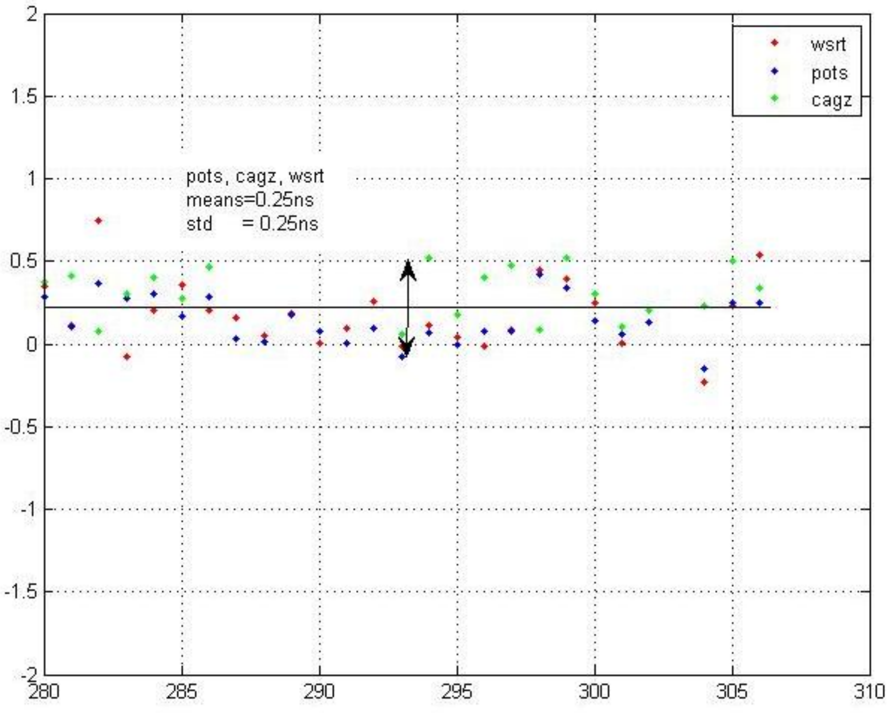
European Ionospheric Mapping: Data

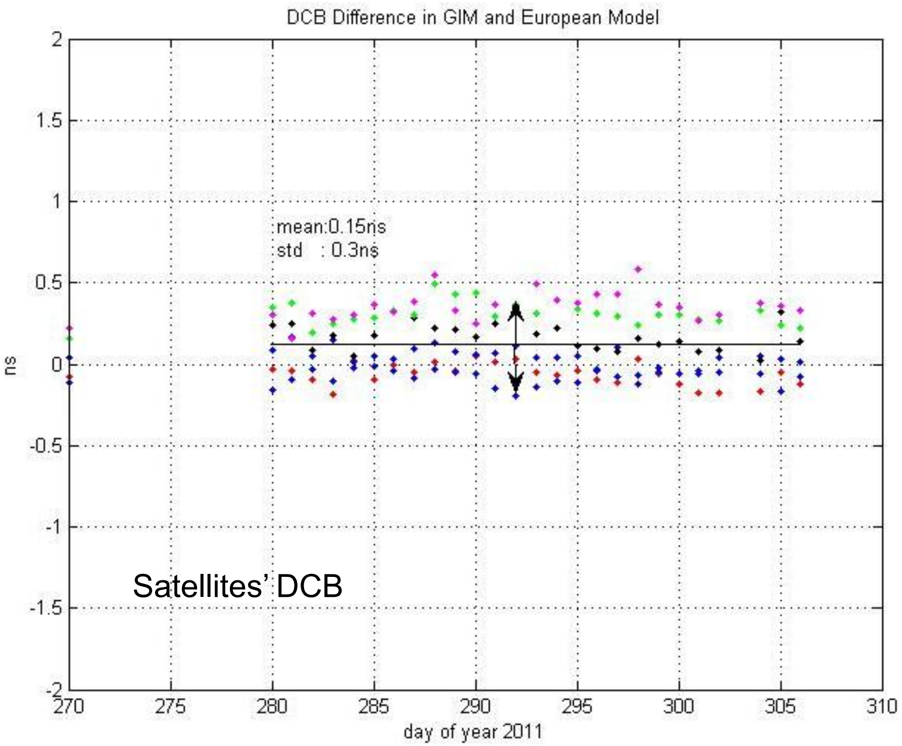




1. In Small values, quite quiet
2. Variation along latitude
3. Boundary effects in building regional Ionosphere mapping

EIM DCB Results





◆There is a bias in DCB results between GIM and EIM daily solution, which is caused mostly by the geometry distribution.
◆GNSS satellites are all viewed by all sites in the whole day, but receivers are fixed there, the geometry is not so strong as the satellites'. RCVR DCB variate much.

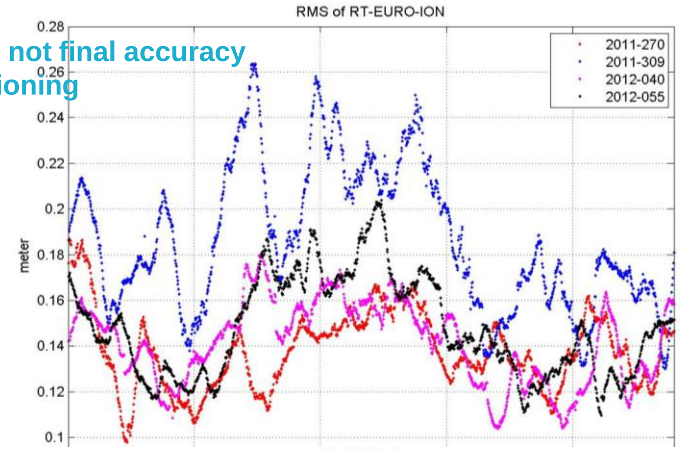
RT-EURO-ION: Algorithm & Procedure

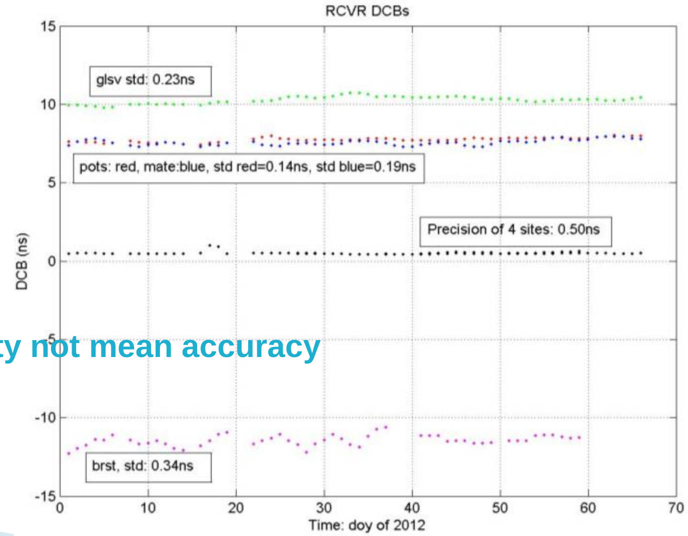
```
GFZ's Epoch VTEC SOLUTION, Polynomial Coefficients of Y
  2012      2      9     13      0
-------------------------------------------------------

Polynomial Fitting Error    : 0.159965
Polynomial MAX Lat Order    : 9
Polynomial MAX Lon Order    : 9
Polynomial Center Latitude : 52.500000
Polynomial Center Longitude: 7.500000
Valid Obs number in Fitting: 596
Polynomial Valid Range Lat :    30.000    75.000
Polynomial Valid Range Lon :   -25.000    40.000
Lat_order/Lon_order       VALUE (M)   RMS (M)
***    ****************     *****.***   *****.***
   0    0     1.36042609817926 77     0.00001360721 60195
   0    1     0.00020401921 54862     0.00000023610 96449
   0    2     0.00051040522 69394     0.00000000142 05542
   0    3     0.00000558961 05577     0.00000000000 47907
   0    4    -0.00000395596 0508     0.00000000000 00055
   0    5    -0.00000001079 80724     0.00000000000 00000
   0    6     0.00000000005 27073     0.00000000000 00000
   0    7     0.00000000000 39502     0.00000000000 00000
   0    8     0.00000000000 00298     0.00000000000 00000
   1    0    -0.02213731022 39887     0.00000077126 73744
   1    1    -0.00245072991 17050     0.00000000926 16754
   1    2     0.00001296364 20184     0.00000000006 72905
   1    3     0.00000735881 30904     0.00000000000 01563
   1    4    -0.00000006861 30891     0.00000000000 00002
   1    5    -0.00000000735 22989     0.00000000000 00000
   1    6     0.00000000000 57316     0.00000000000 00000
   1    7     0.00000000000 24475     0.00000000000 00000
   1    8     0.00000000000 00192     0.00000000000 00000
   2    0     0.00255687463 26179     0.00000002069 42934
   2    1    -0.00000831499 70786     0.00000000002 238915
   2    2    -0.00000254206 42838     0.00000000000 17054
```

```
GFZ's Epoch VTEC SOLUTION, GRID VTEC of YEAR-MONTH-DAY-HOUR-MINUTE
--------------------------------------------------------------------
 2012    2    24    12     0
Valid Obs number in Fitting: 586
Spherical Fitting Error     : 0.195438
GRID VTEC Valid Range Lat  :    30.000    75.000
GRID VTEC Valid Range Lon  :   -25.000    40.000
GRID VTEC Lat & Lon Step   :      2.50      2.50
--------------------------------------------------------------------
                                                        START OF TEC MAP
  2012     2    24    12     0  0.00                    EPOCH OF CURRENT MAP
    75.0 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  110  111  114  119  125  131  137  142  146  149  150  149  147  143  138  132
  126  121  117  114  113  115  119  126  134  143  152
    72.5 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  132  134  138  142  147  152  157  161  164  166  167  166  165  162  159  156
  153  150  148  147  147  147  149  151  152  152  149
    70.0 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  150  151  153  156  159  162  166  169  171  173  174  175  174  173  172  170
  168  166  164  163  162  162  162  161  161  159  154
    67.5 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  158  159  160  162  164  167  169  171  173  174  175  175  175  174  174  173
  171  170  170  169  168  168  167  166  165  163  160
    65.0 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  160  161  163  165  167  169  171  172  172  172  172  171  170  169  168  168
  167  167  168  168  169  170  171  171  170  169  167
    62.5 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  163  164  166  168  170  171  172  172  172  170  169  167  165  163  161  161
  161  162  163  166  169  172  174  176  177  176  175
    60.0 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  168  169  171  173  174  175  175  174  172  170  168  165  162  159  158  157
  157  159  161  165  169  174  179  183  185  187  186
    57.5 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  176  177  178  178  179  179  178  177  175  173  170  167  164  161  160  159
  159  161  164  168  173  179  185  190  195  197  198
    55.0 -25.0  40.0   2.5 450.0                        LAT/LON1/LON2/DLON/H
  184  184  184  184  184  184  183  182  180  178  176  174  172  169  168  167
```

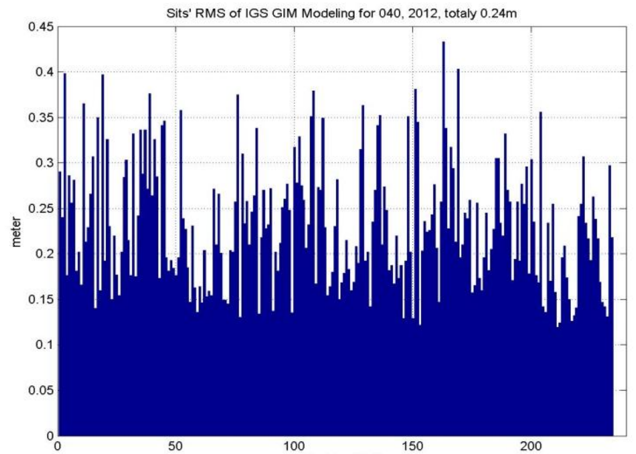
RT–EURO–ION: Errors

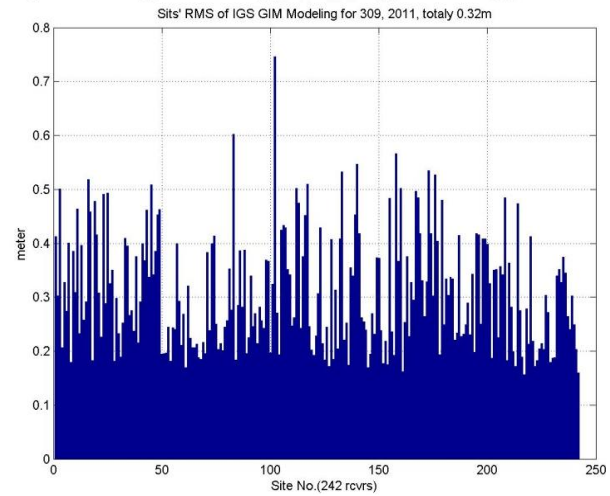
Fitting errors, not final accuracy for positioning





Stability not mean accuracy





RCVR DCB, ION-Delay model, coupling together.

Different RMS from different sites mean accuracy distributes unevenly

PPP Convergence Analysis

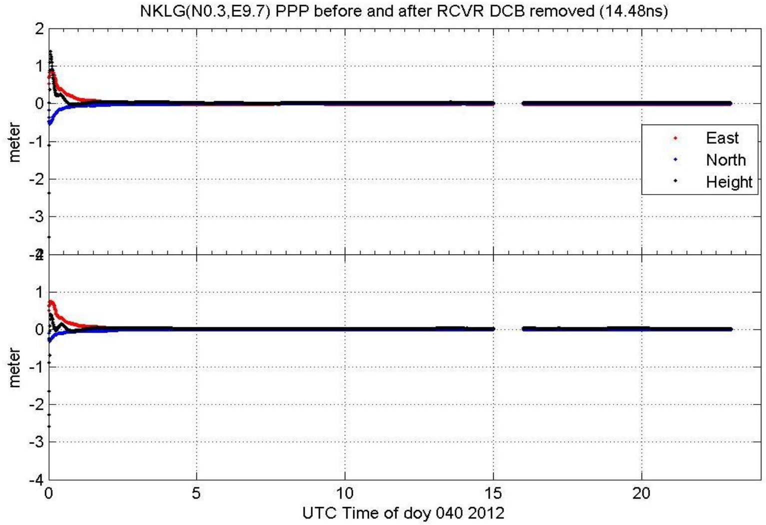
•PPP Algorithm

•P1,P2,L1,L2 used, zero-differenced observations, ion viewed as pseudo-obs
•Estimates: Position, rcvr clock, iono-delay, ztd, ambiguities of all L1 & L2
•dual-frequency: classic LC solution and P1/C1/P2+Iono model;

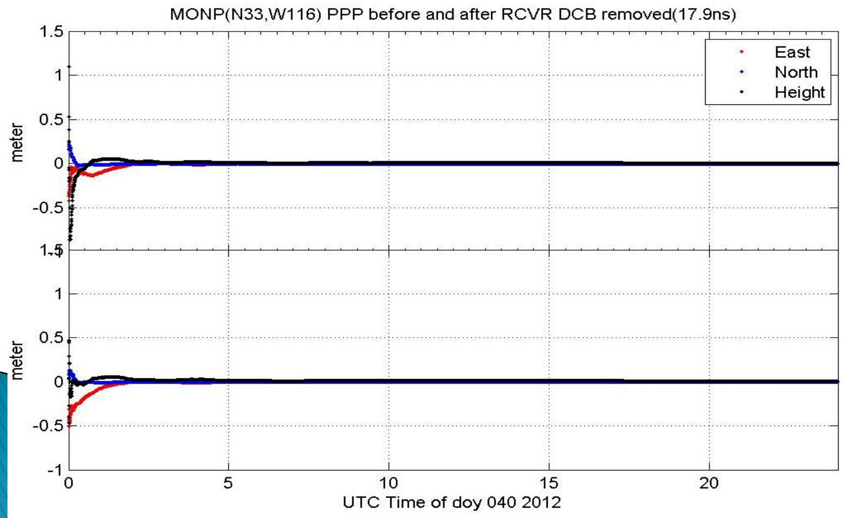
•PPP Convergence speed is up to several factors

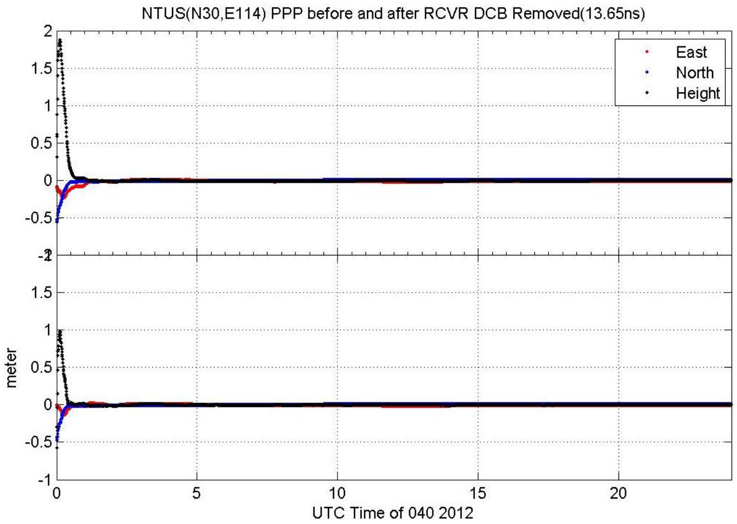
•Accuracy of Initial coordinate (if constrained by priori-initial position)
•Ionospheric Parameters' constraints (prior information for PPP, precision problem)
•SV Geometry observed at receiver side
•P1 & P2Observations' noise
•Receiver's DCB (cause bad initial position before carrier phase dominating)
• Weighting strategies, absolute weighting, relative weighting…

RCVR DCB on PPP Convergence

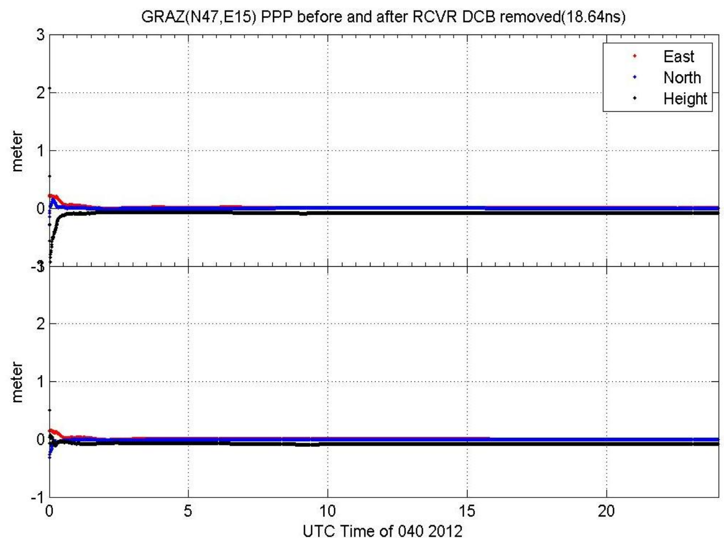


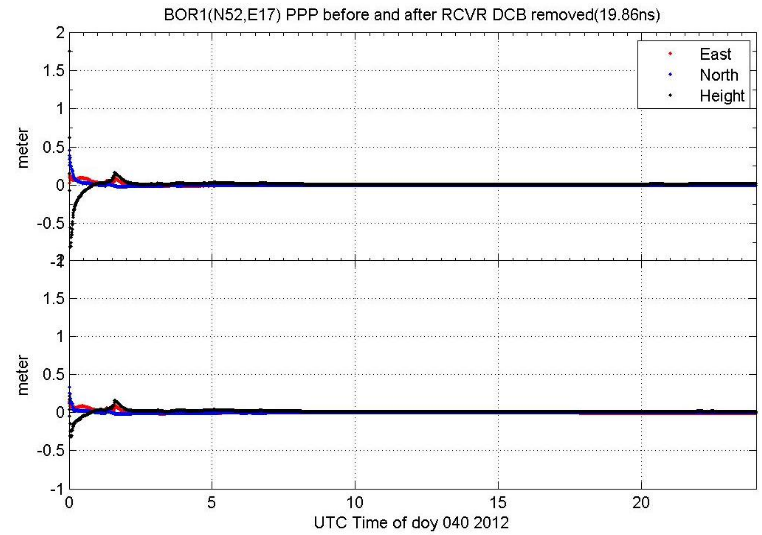
1. Existed and inhabited DCB means different receiver clock error in C1, P1 and P2 observations, which cause the fact that PPP can not estimate only one clock error while using zero-difference of P1 and P2 together to initial PPP based on carrier-phases. To make PPP converged rapid, RCVR DCB should be removed.
2. Big RCVR DCB means bad initial position for PPP

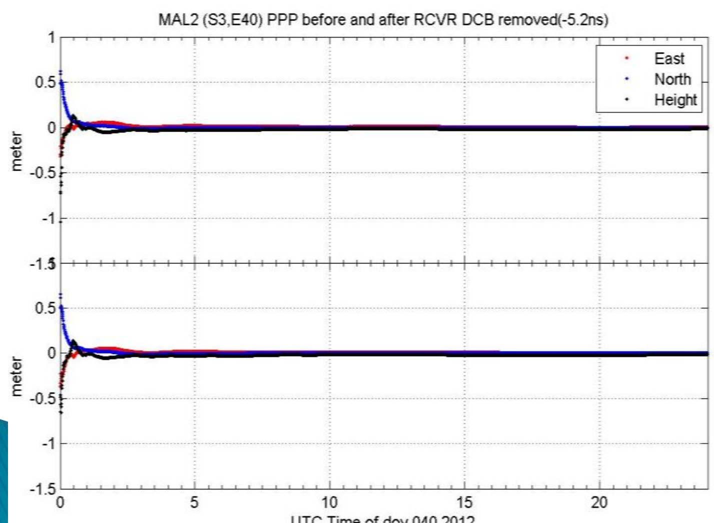


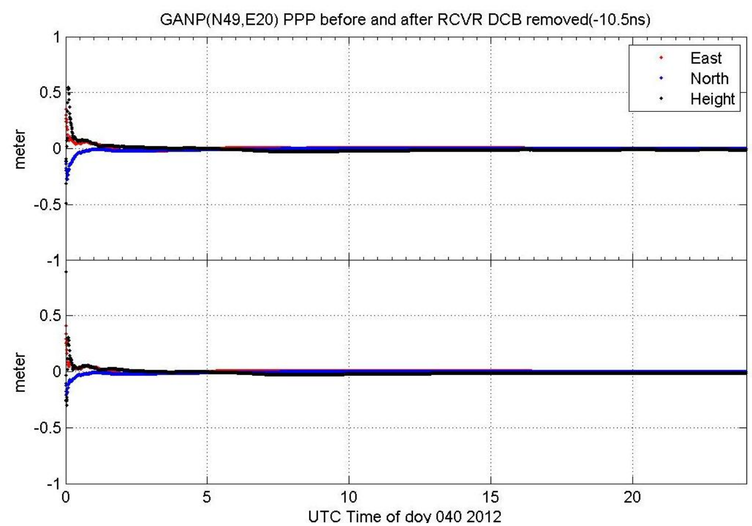


RCVR DCB on PPP Convergence



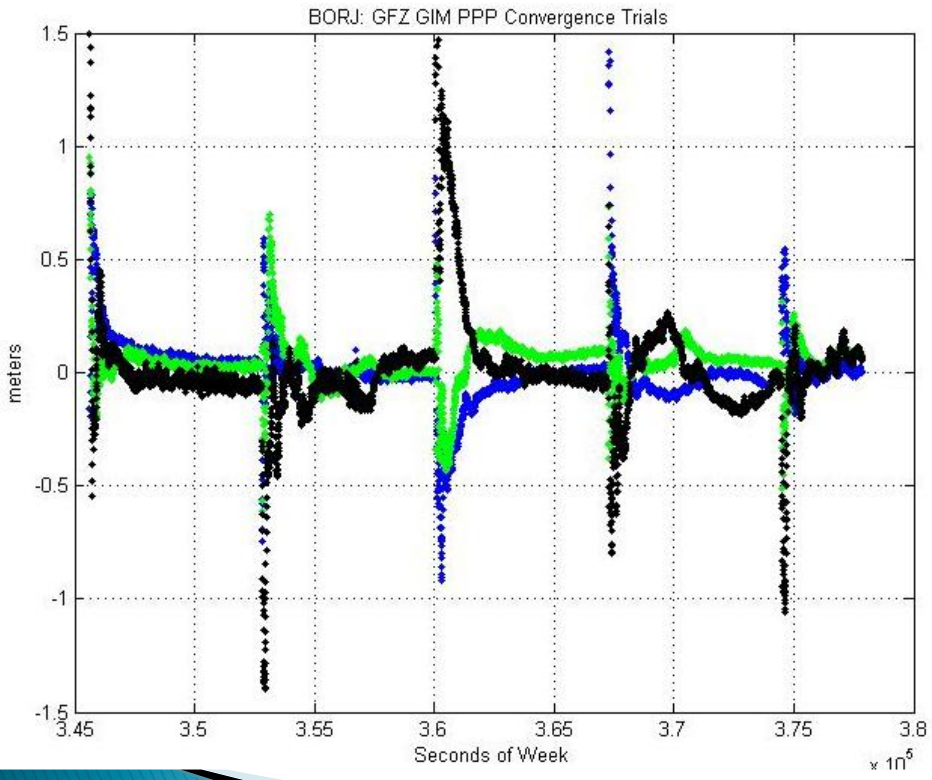


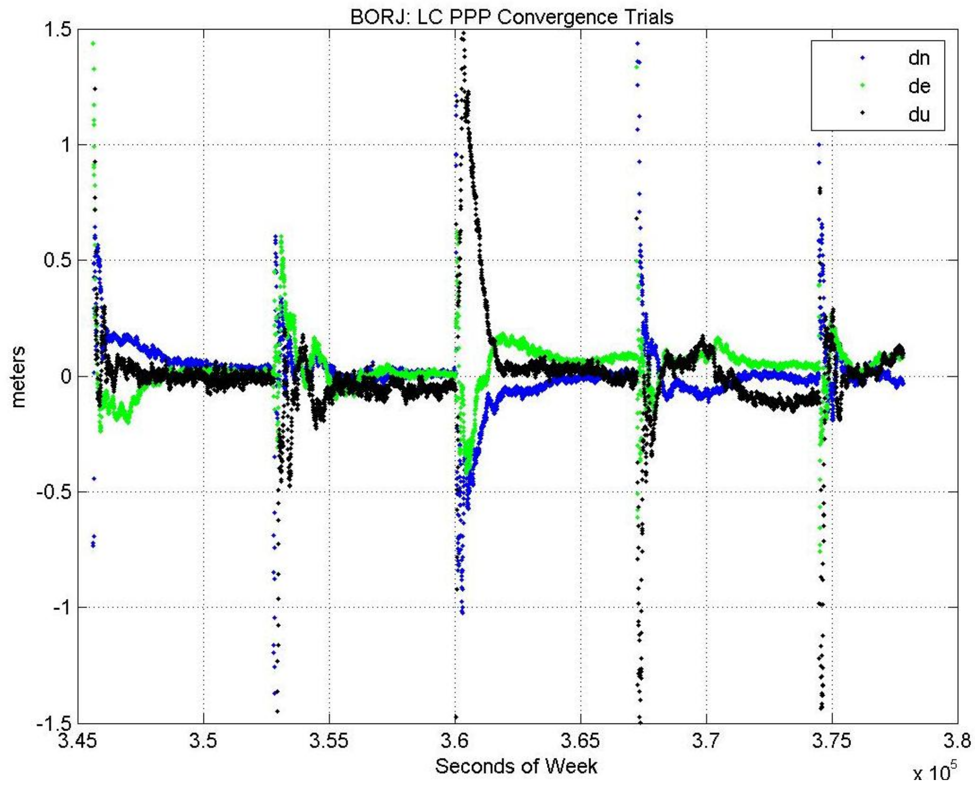




PPP Convergence Analysis

- No UPD used for integer-ambiguity in PPP solution
- GFZ_GIM used for PPP as prior-info , comparing with LC PPP, doy300, 2011
- Simulated trials as initializing PPP each hour with three models, each 2hours with LC PPP



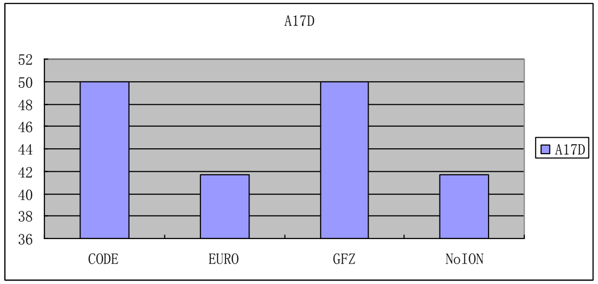


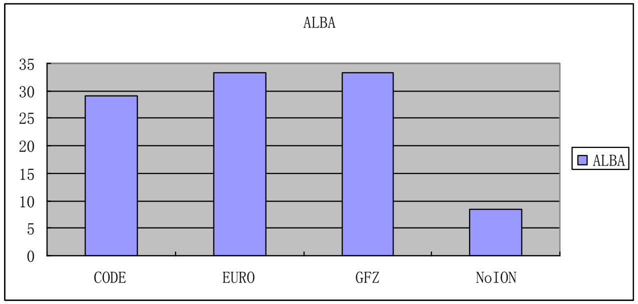
PPP Convergence Analysis

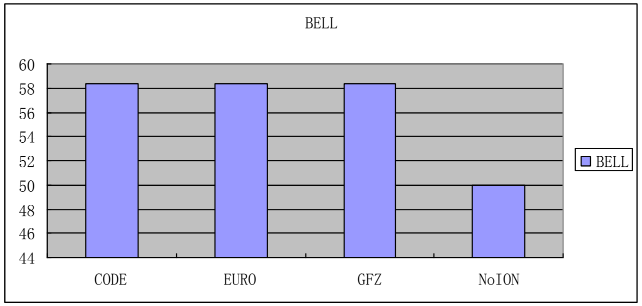
- Convergence criteria: dn < 15cm, de < 15cm,
- Percentages: in 10 minutes, how many trials success
- 40 sites, only 3 sites convergence time become worse while Ionospheric Maps used in PPP
- CODE_GIM, GFZ_GIM, EURO-IM are at the same level

	A17D	WTZR	VEN1	POTS	ONSA	LEIJ	DRES	DENT	BORJ	ALBA
LC	15.91	16.18	7.65	4.16	2.75	8.83	7.55	2.28	6.57	2.67
CODE	16.37	7.05	7.05	6.22	3.07	6.85	7.35	2.20	3.38	2.58
GFZ	12.56	7.05	7.05	6.23	3.05	6.82	6.13	2.22	3.37	2.78
EURO	13.30	7.01	9.56	5.05	3.55	8.56	5.05	1.15	3.10	24.45

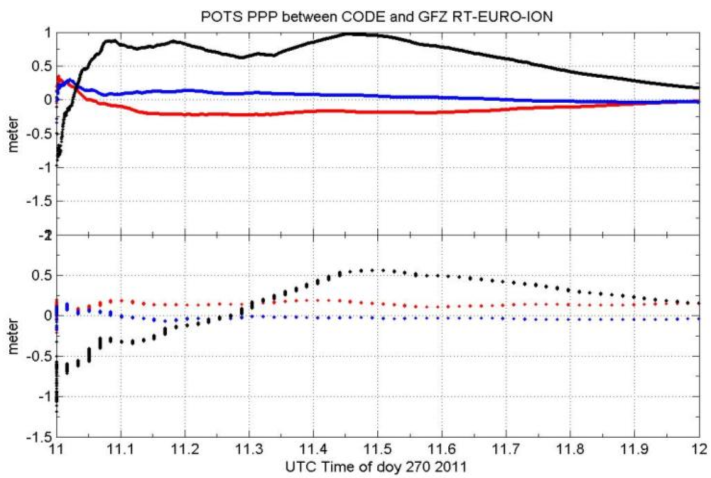
Convergence time in minutes

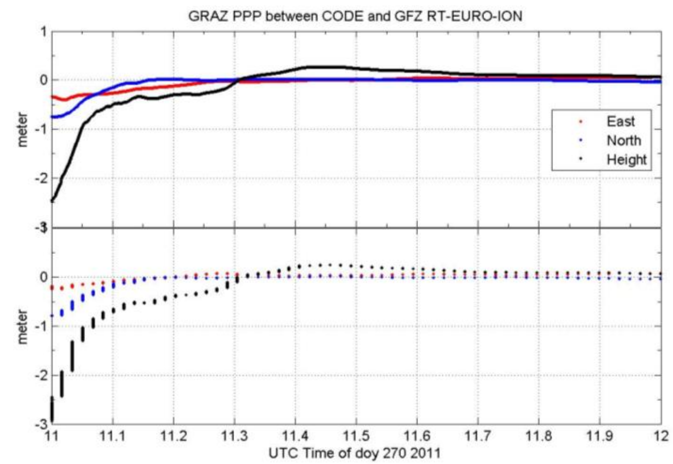


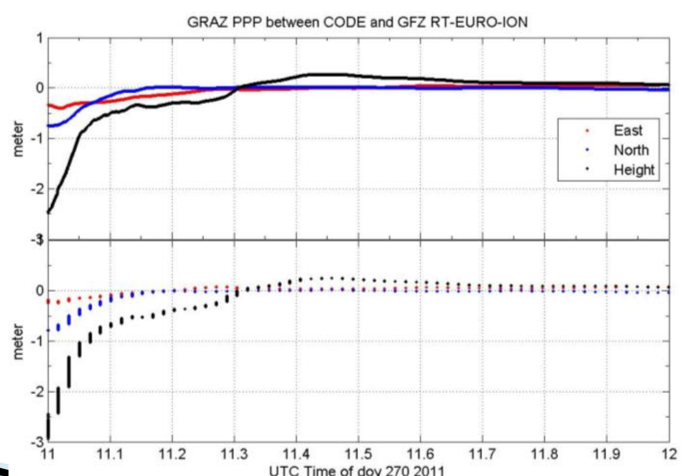


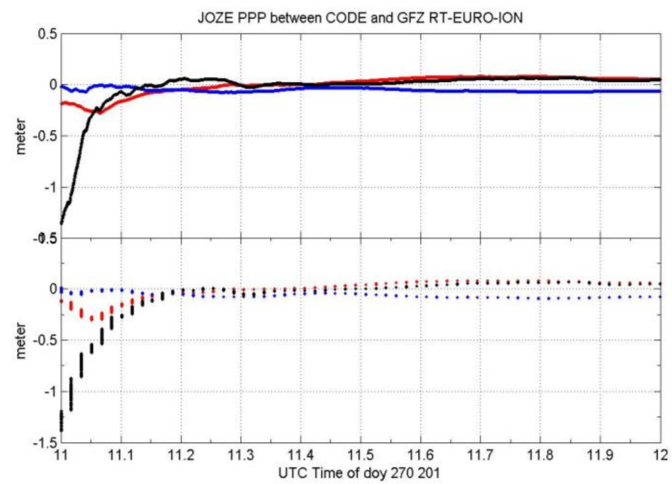


PPP Convergence with RT-EURO-ION

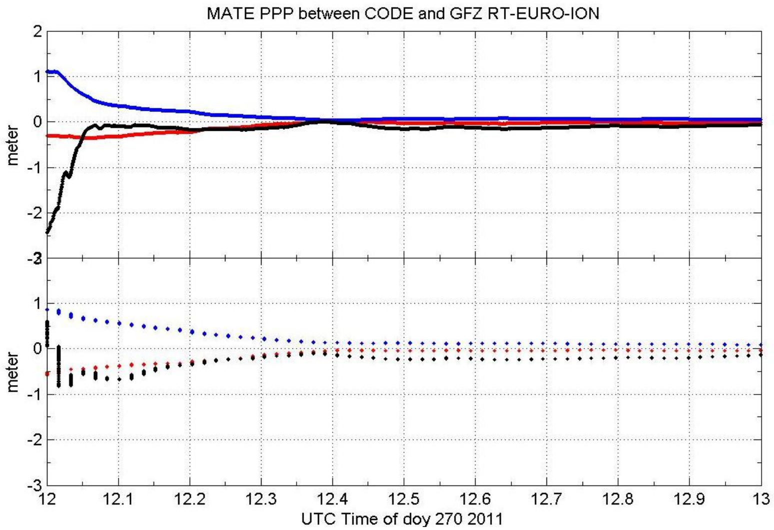


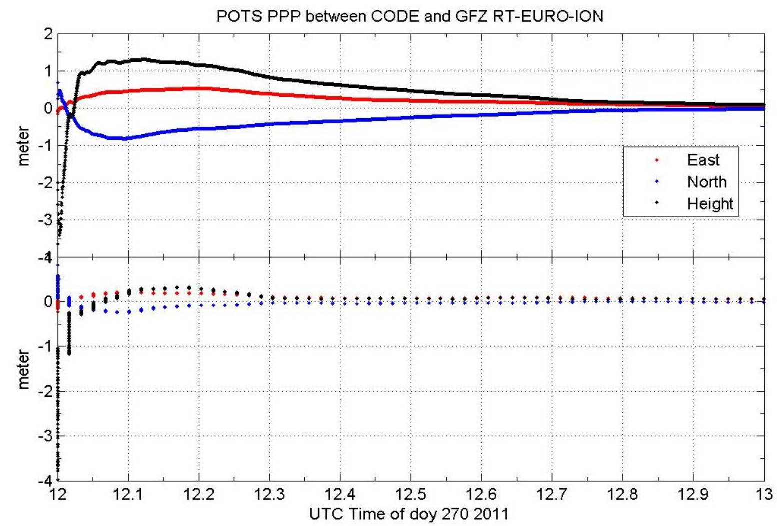


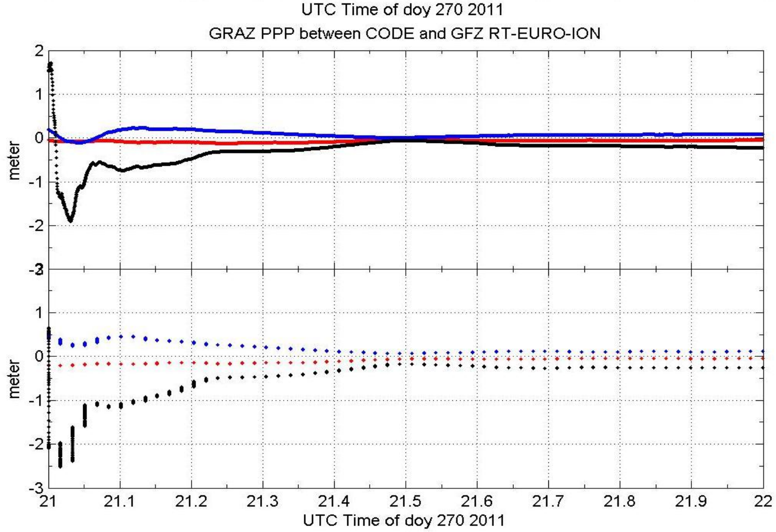


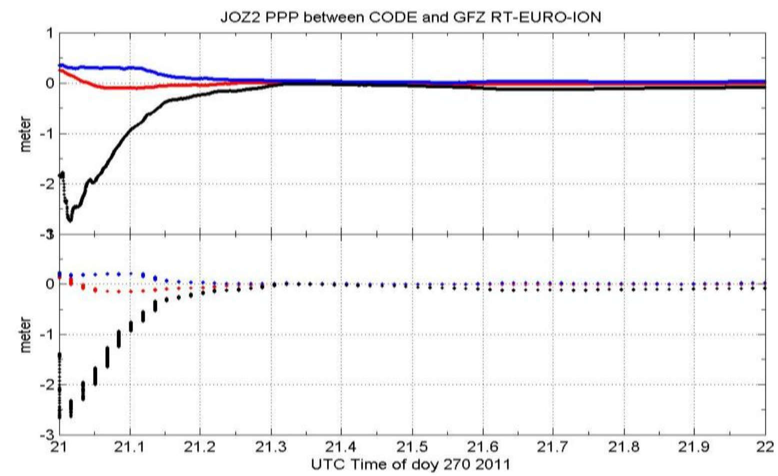


PPP Convergence with RT-EURO-ION









Discussion & Summary

Challenges for High Precision ION-Mapping

- Large-scale cm-level PPP Rapid Convergence requirements
  - 10cm—20cm at LOS pair (PPP-RTK, UDP-PPP)
- Limitation of current ION-Mapping
  - SLM assumption, mapping function, RCVR DCB seperation
- Unevenly-distribution of ground-based GNSS sites limits GIM precision
- Stochastic characteristic of the Ionosphere, unpredictable precisely

Discussion & Summary

Summary

- GFZ has developed IGS comparable GIM processing procedure
- RT-EURO-ION mapping is running in GFZ, whose accuracy is comparable to post-processed GIM
- ICLS can improve GIM solution due to the shortage of IGS sites' unevenly distribution
- Priori-Ionospheric delay is useful to PPP Convergence, compared with LC PPP
- RCVR DCB affect the convergence of dual-frequency zero-differenced PPP

Thanks To BKG, IGS For Providing Daily and Real-Time Data !

Thanks for your attention!!