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Influence of the ionospheric model on DCB computation and added value of LEO satellites

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Introduction

In order to compute inter-frequency Differential Code Biases (DCBs), the Geometry-Free combination of a GNSS signal pair needs to be corrected from the ionospheric refraction effect. Such information is obtained using either Global Ionospheric Maps (GIMs) or local models. In this work we investigate the influence of GIMs on the final value and precision of DCB solution. The study covers different ionospheric conditions, ranging from very quiet ionospheric background up to a severe ionospheric storm.

In a first step, the Slant Total Electron Content (STEC) between GIMs is assessed as a function of receiver latitude, elevation mask and ionospheric conditions. Then, daily DCBs are estimated using these different GIMs, receiver and satellite contributions being separated using a zero-mean constraint.

At last, an independent estimation of DCBs is performed using Low Earth Orbit (LEO) observations (such as JASON's GPS data). This solution is compared with our ground network solution and with DCBs coming from Analysis Centers (ACs) of the International GNSS Service providing ionospheric and DCB solutions.

1. GIM influence on STEC

Data

- To investigate the influence of GIMs on DCB computation, we compare STEC derived from GIMs computed by the analysis centers UPC, COD, JPL, ESA and IGS.
- Corresponding mapping function :
  - Single layer model for UPC, JPL and IGS
  - Modified single layer model for COD and ESA
- Different ionospheric conditions :
  - Quiet ionosphere: DOY 310/10
  - Normal ionosphere : DOY 110/13
  - Geomagnetic storm : DOY 076/15
- Different geomagnetic latitudes :
  - Polar (68.6° N) : YELL
  - Mid-latitude (51.8° N) : BRST
  - Equatorial (14.3° N) : KOUR

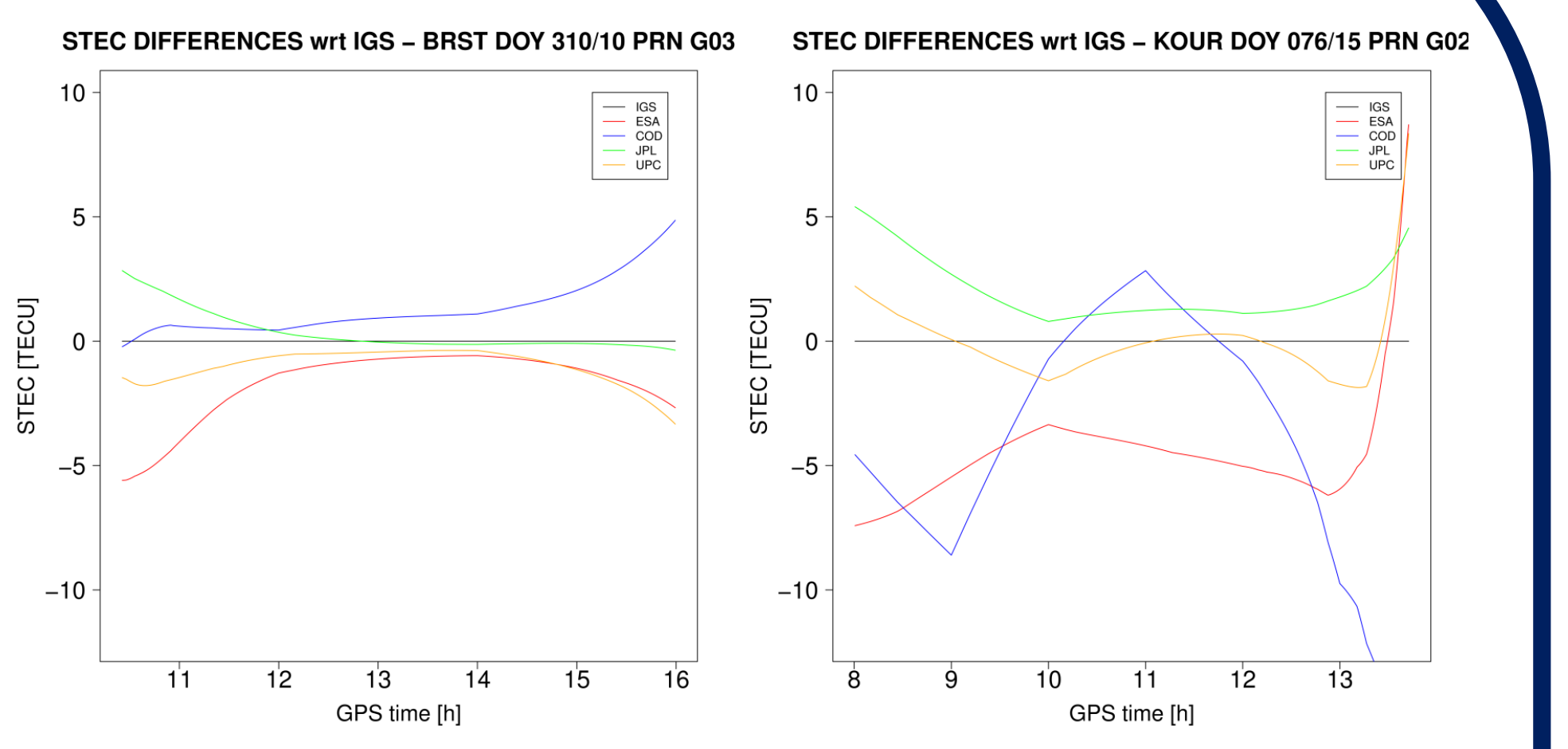

Figure 1: Example of STEC difference derived from GIMs with respect to IGS solution, elevation mask=5°. Left : Quiet day at mid-latitudes (BRST). Right: geomagnetic storm at geomagnetic equator (KOUR).

Results

- STEC differences between GIMs (referred to as STEC/GIM) at low elevation can be as large as more than 10 TECUs (→ > 1,5m) in bad ionospheric conditions (*Figure 1*). Moreover, GIMs are models so that the discrepancies with the real values can be much higher.
- Discrepancies between GIMs is much higher for equatorial stations than for mid-latitude ones. Polar (or near-polar) stations also experience moderate to large discrepancies, especially for the southern hemisphere (*Figure 2, left*).
- Increasing the elevation cut-off angle reduces the discrepancy between GIMs (*Figure 2, right*).

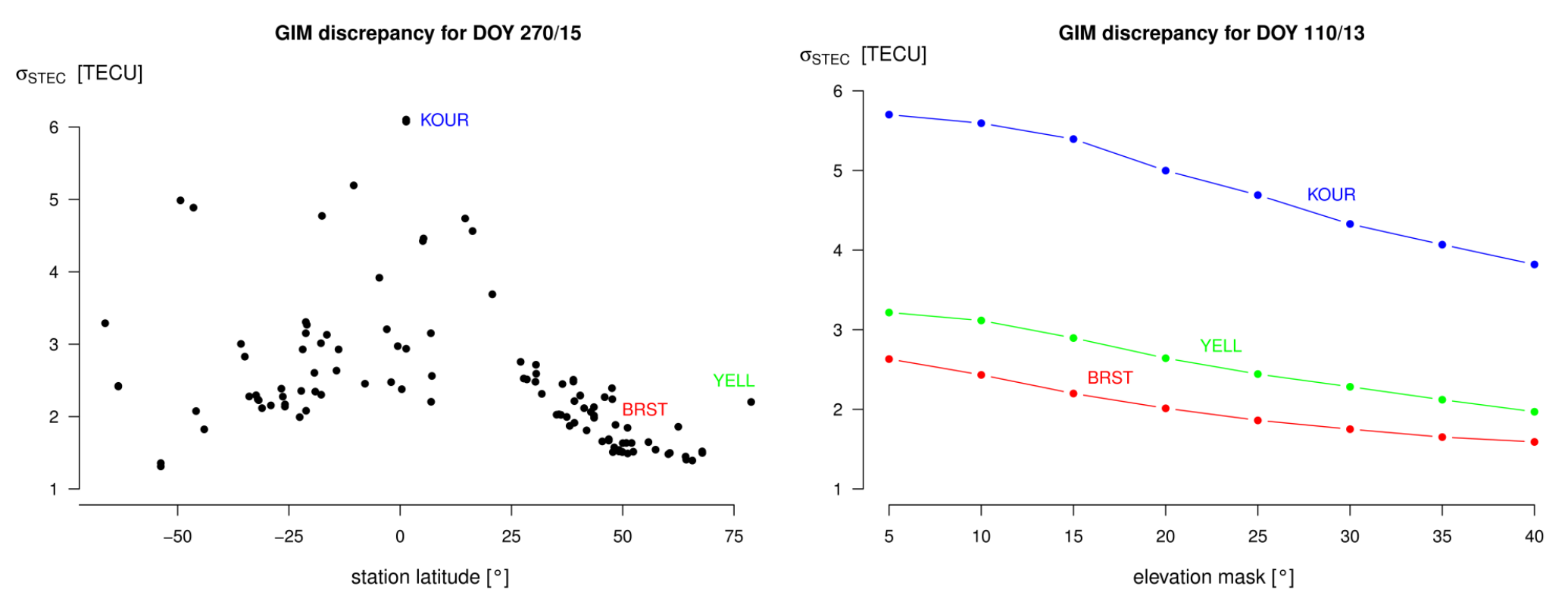

Figure 2: Influence of latitude (left) and elevation cut-off angle on discrepancies between GIMs. σ_{STEC} corresponds to the standard deviation between the five GIMs of the analysis centers UPC, IGS, ESA, COD and JPL.

2. DCB computation

Methodology

- Method developed by *Montenbruck (2014)* : *a priori* ionospheric information in the GF code combination is provided by GIMs and the remaining contributions in the corrected GF are mixed receiver – satellite hardware biases (DCBs). RINEX files have an interval of 30s.
- Use of the zero-mean constraint to separate satellite and receiver DCBs.
- Minor improvements : cut-off angle = 30° (instead of 20°) and weighted mean computation for mixed DCBs (rather than arithmetic mean).
- Use of COD GIM (as for *Montenbruck* method).
- Use of MGEX network providing « true » C1W and C2W (*codeless Rx*).

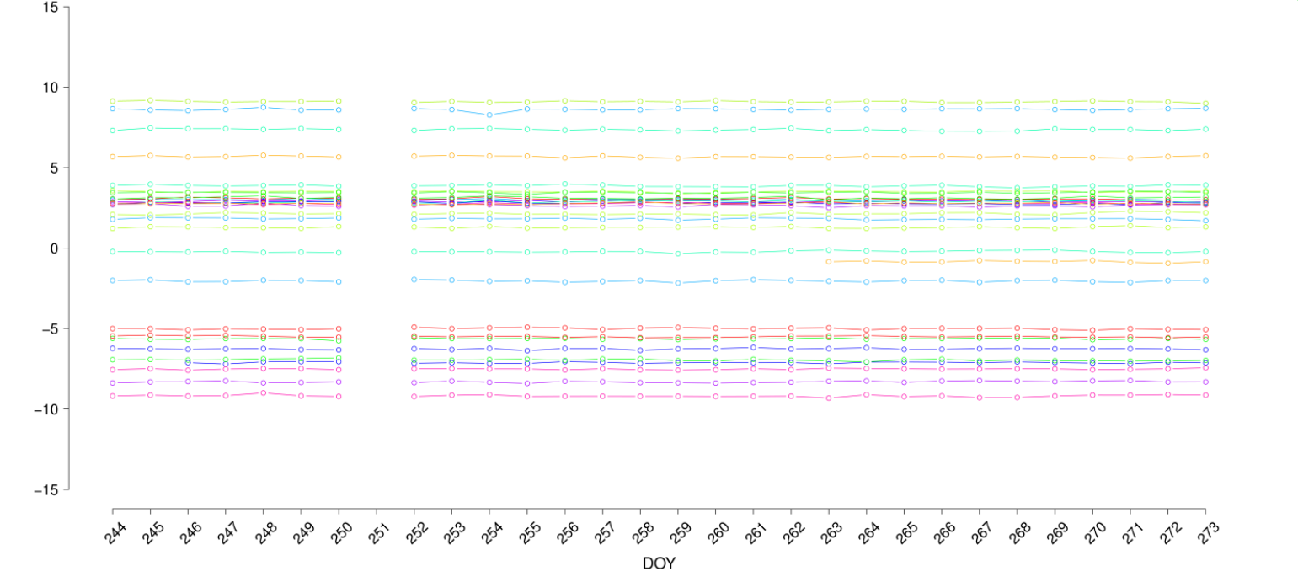

Figure 3: 30-day time series of GPS satellite C1W-C2W DCBs computed from the MEGEX network in September 2015.

Validation

- Daily alignment to 32 satellites solutions .
- Other AC solutions:
  - DLR daily solutions (*Montenbruck* method)
  - CAS daily solutions (*Wang* method)
  - COD monthly solutions (Berne's method)

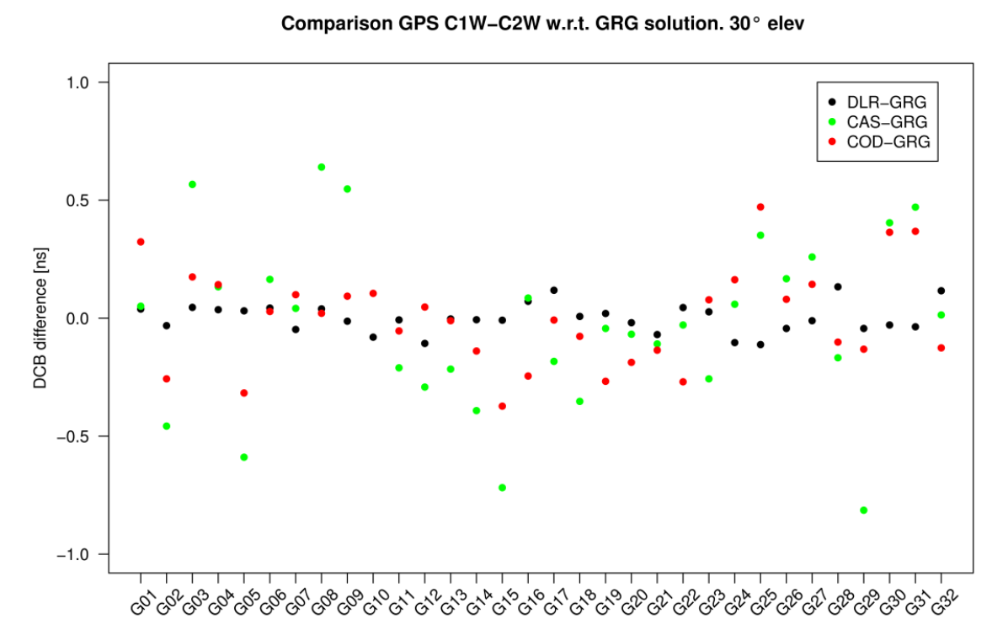

Figure 4: Satellite DCB difference between GRG daily solution and DLR, CAS and COD analysis centers. GPS constellation, C1W-C2W bias and 30° mask.

Results

- Our solution (referred to as "GRG") has the best agreement with DLR solution (*Figure 4* and *Table 1*).
- Agreement GRG w.r.t. other ACs is the same order of magnitude than agreement between others themselves (*Table 1*), which validates our DCB algorithm.

	GRG	COD	DLR	CAS
GRG	—	0.21	0.06	0.37
COD	—	—	0.24	0.28
DLR	—	—	—	0.37
CAS	—	—	—	—

Table 1: Std. dev. of satellite GPS C1W-C2W DCBs between analysis centers expressed in nanoseconds, for DOY 272/15.

3. About DCB precision…

Precision of the estimated DCBs

Precision = σ_{DCB} = standard deviation of the estimated parameter → mathematics

- For September 2015, satellite DCBs lie between 0.05 and 0.07 ns (*Figure 5*) while receiver values range between 0.03 and 0.12 ns (not shown here). Such values are similar to that of other Acs.
- **Satellite** DCB precision greatly depends on the number of observations, and therefore of the size of the network (*Figure 6, left*).
- **Receiver** DCB precision slightly varies with the latitude, suggesting to exclude low latitude stations in an ideal network (*Figure 6, right*).

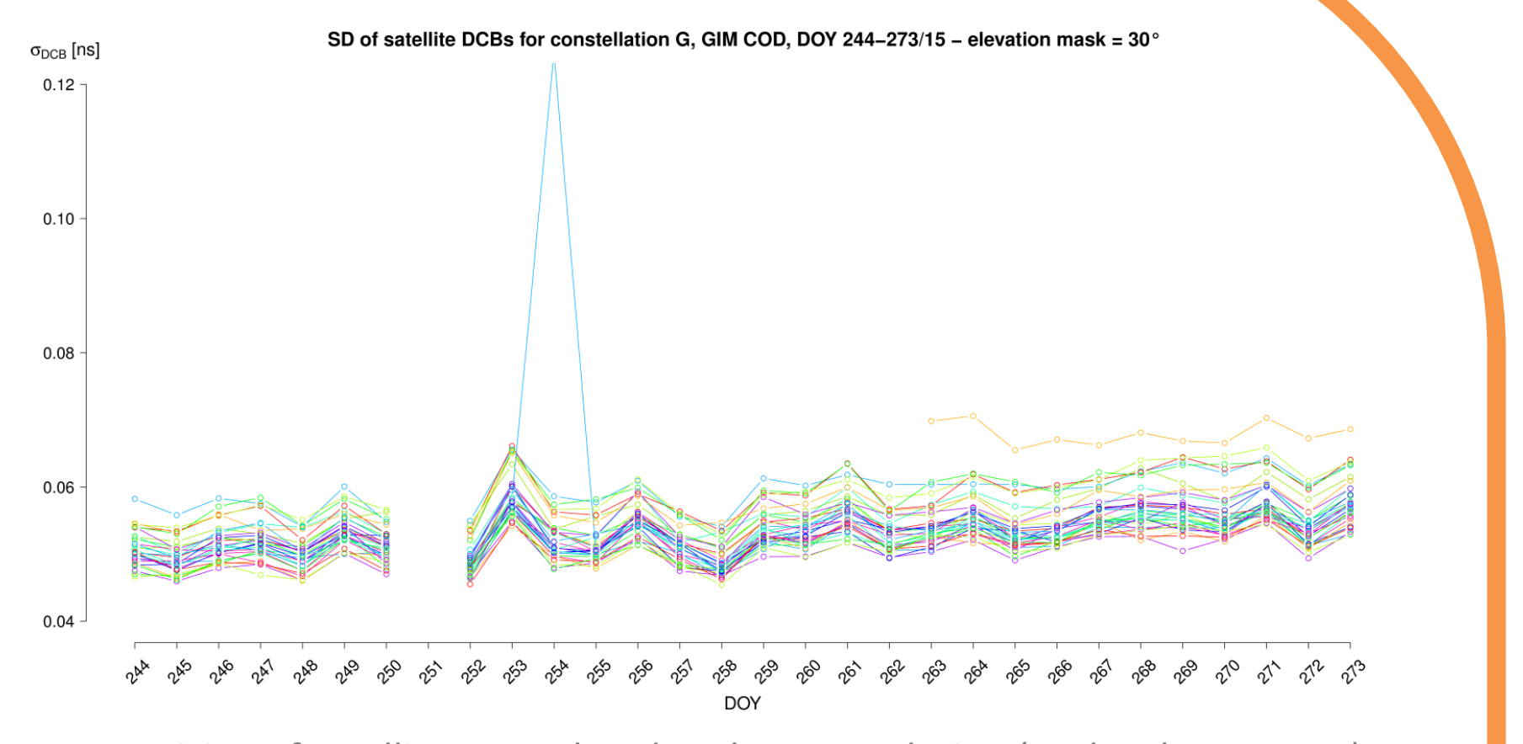

Figure 5: Precision of satellite DCB related to the GRG solution (each color = 1 PRN) in September 2015. GPS constellation, C1W-C2W bias, elevation mask = 30°.

DCB stability

Stability = standard deviation of the 30-day DCB time series (same GIM provider), assuming that DCBs are constant values → empirical inter-daily variability.

- Stability in September 2015 (related to *Figure 3*) :
  - **satellites** : 0.05 to 0.11 ns
  - **receivers** : 0.09 to 0.67 ns (extreme case, typically between 0.1 and 0.4 ns)
- For **satellites**, stability value is the same order of magnitude than the DCB precision; however it is generally not the case for **receiver**'s part.

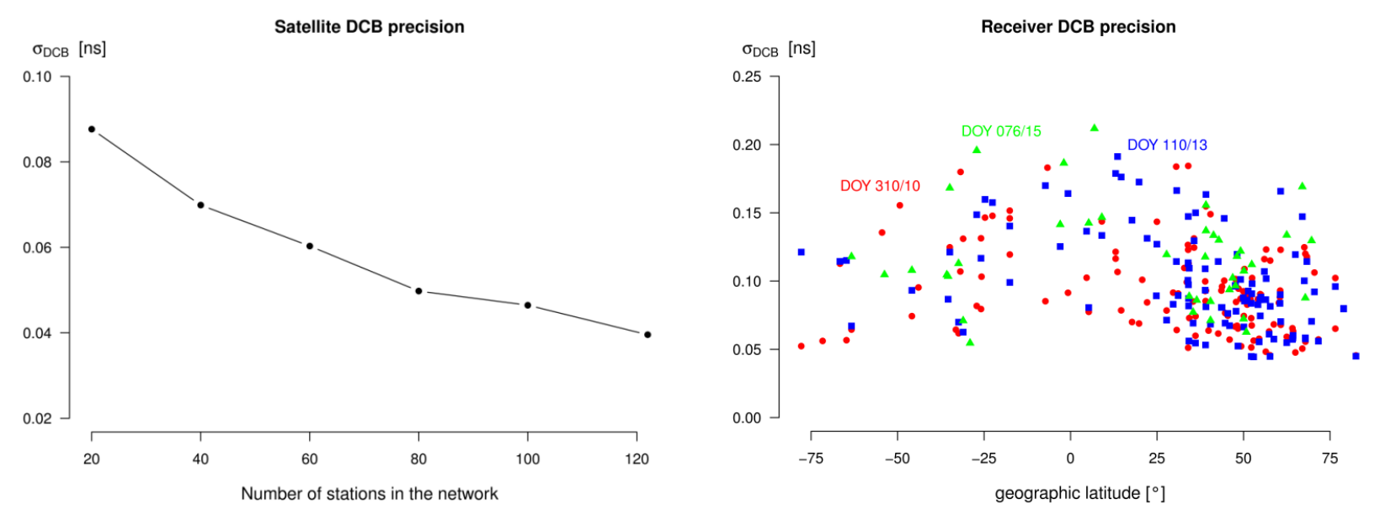

Figure 6: Left: Influence of the number of stations on the satellite DCB precision for DOY 310/10 and an elevation mask of 30°. Right : Influence of latitude on receiver DCB precision, for different ionospheric conditions (see above).

Influence of GIM choice on DCBs

- Computation of the standard deviation of DCBs obtained with the available GIMs: $\sigma_{DCB,GIM}$ It translates the variability of DCB solution due to the choice of the ionospheric model. Typically, it varies 0.02 ns and 0,2 ns for satellites and between 0.3 and 1.1 ns for receivers.
- For **satellites**, $\sigma_{DCB,GIM}$ decreases with increasing elevation mask, especially during disturbed geomagnetic conditions (*Figure 7, left*).
- $\sigma_{DCB,GIM}$ does not strongly depends on **receiver** latitude (*Figure 7, right*), which was not expected as GIMs discrepancies are clearly larger for low latitudes (see *Figure 2, left*).

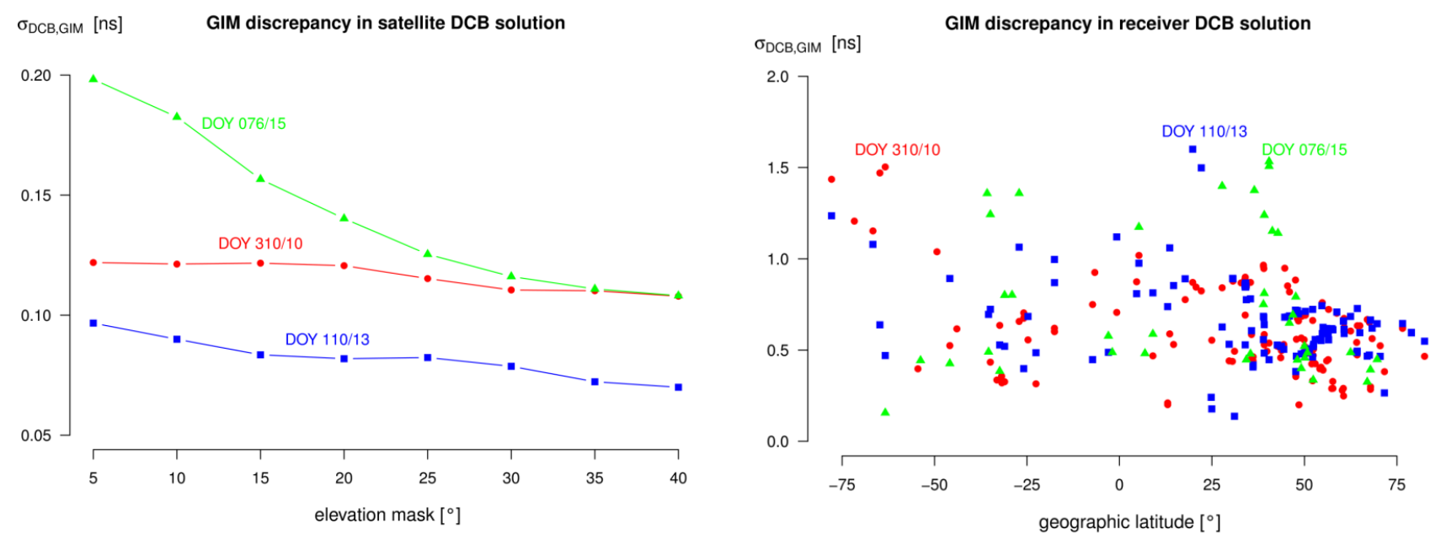

Figure 7: Left: Influence of elevation mask on satellite DCB discrepancies due to GIMs. Each point on the figure corresponds to the average of the satellite DCB for the given day. Right: Influence of latitude on receiver DCB discrepancies due to GIMs for different ionospheric conditions (see above).

The "true" DCB precision is therefore difficult to assess. However, as the variability of the solution clearly depends on the ionospheric model ($\sigma_{DCB,GIM}$ is always larger than σ_{DCB}), it is proposed to get rid of the ionospheric model by considering observations above the ionosphere using altimetry satellites like JASON-2.

4. Added value of JASON-2

Methodology

- JASON-2 altitude = 1350km → orbits higher than the ionosphere → plasmaspheric content to compute together with DCBs.
- DCB computation algorithm modified w.r.t. ground network : need to estimate VTEC for each observation epoch using a spherical symmetry assumption and the geometric mapping function. DCBs computation is achieved in two steps:
  1) VTEC is estimated together with mixed satellite-receiver DCB;
  2) Satellite and receiver DCB contributions are separated using the zero-mean constraint.
- RINEX files have an interval of 10s and the cut-off angle is 30°.

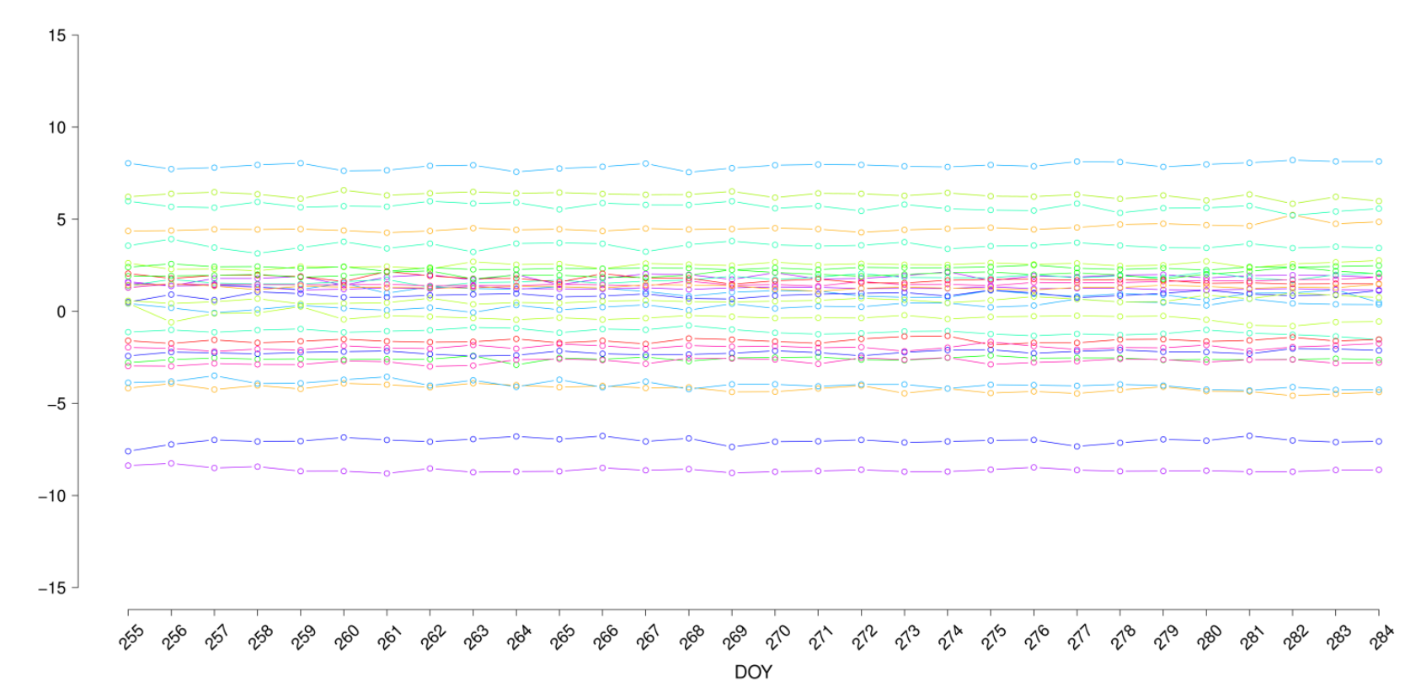

Figure 8: 30-day time series of GPS satellite C1W-C2W DCBs computed from JASON-2 measurements in September-October 2015.

Results

- As for ground network, computation of daily (*Figure 8*) and monthly DCB solutions .
- The JASON-2 monthly solution agrees well with other ACs and with our GRG ground network solution (called "GRG ground"), despite a larger variability for JASON-2 solution (*Figure 9* and *Table 2*).
- DCB precision (σ_{DCB}) lies between 0.09 and 0.2 ns for satellites and ranges between 0.02 and 0.05 ns for JASON-2 receiver.
- DCB precision (σ_{DCB}) is lower than that related to ground network because of the number of degrees of freedom is smaller :
  - much more unknowns than using ground network due to VTEC estimation for each observation epoch;
  - there is only one receiver.
- Stability of the daily solutions is between 0.1 and 0.2 ns for satellites and around 0.25 ns for JASON-2 receiver.

	GRG JAS-2	GRG ground	COD	DLR	CAS
GRG JAS-2	—	0.35	0.28	0.37	0.54
GRG ground	—	—	0.22	0.05	0.40
COD	—	—	—	0.24	0.33
DLR	—	—	—	—	0,41
CAS	—	—	—	—	—

Table 2: Std. dev. of satellite GPS C1W-C2W DCBs between existing ACs and our ground (GRG ground) and our monthly JASON-2 solutions (GRG JAS-2) , expressed in nanoseconds, for DOY 255/15.

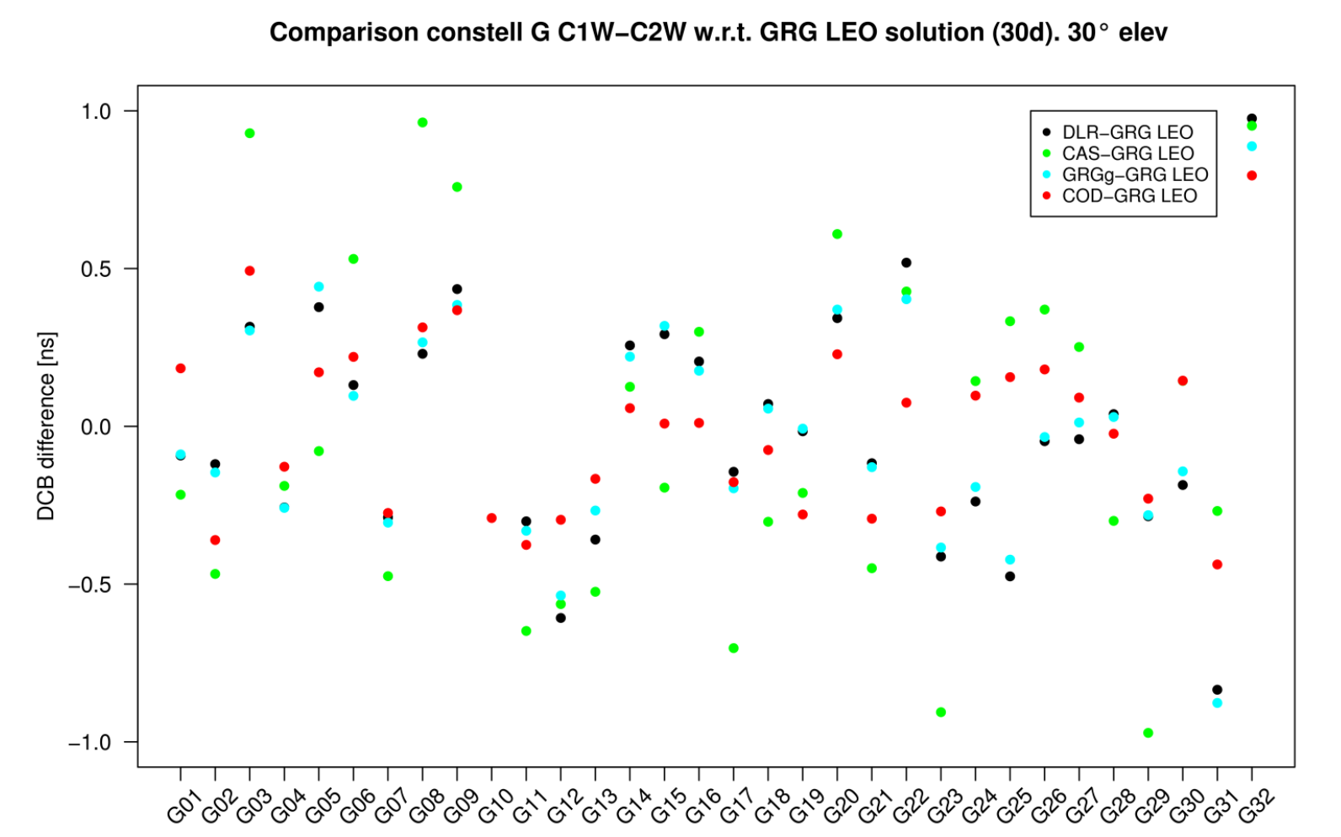

Figure 9: Satellite DCB difference between our 30-day mean JASON-2 ("GRG-LEO") solution and solutions of other analysis centers (DLR, CAS and COD), in addition to our daily solution computed from ground stations (GRGg), for DOY 255/15.

Conclusions and future work

- The paper addresses DCB computation based on a known method and assesses its general performance. Thanks to comparisons with IGS analysis centers, we showed that our implementation of the method was correct. We can provide daily and monthly DCB values.
- Considering a ground network solution, precision limitation mainly concerns GIM precision so that "true" DCB precision is larger than the estimated parameter covariance matrix.
- The method has been adapted to JASON-2 satellite and provides similar solutions than using ground methods. However, its added value is limited as its performance is lower, in terms of both precision and stability. However, it has the advantage to provide a "nearly ionosphere-dependent" solution, with a single receiver only.
- Future work may concern the LEO method: the use of several satellites simultaneously, the study of the influence of the cut-off angle, the improvement of the mapping function, the study of the intra-daily variability of the receiver DCB, etc.

References

1) **Montenbruck, O., Hauschild, A., Steigenberger, P**. (2014). "Differential Code Bias Estimation Using Multi-GNSS Observations and Global Ionosphere Maps," *Proceedings of the 2014 International Technical Meeting of The Institute of Navigation*, San Diego, California, January 2014, pp. 802-812.
2) **Wang N., Yuan Y., Li Z., Montenbruck O. & Tan B.** (2016). "Determination of differential code biases with multi-GNSS observations", *Journal of Geodesy,* Vol. 90 (3), pp. 209-228.

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