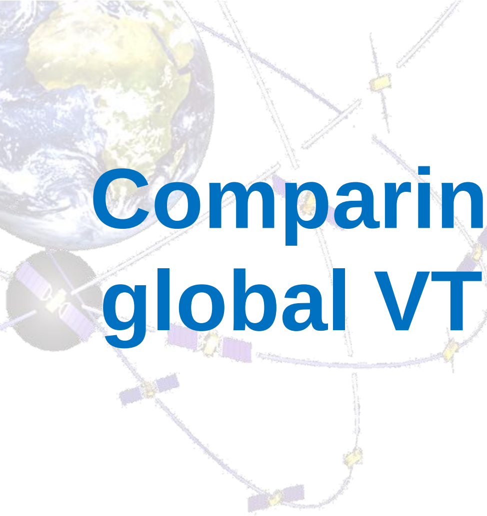

Comparing performances of seven different global VTEC ionospheric models in the IGS context

IGS WS, Feb. 8-12, 2016, Sydney, Australia

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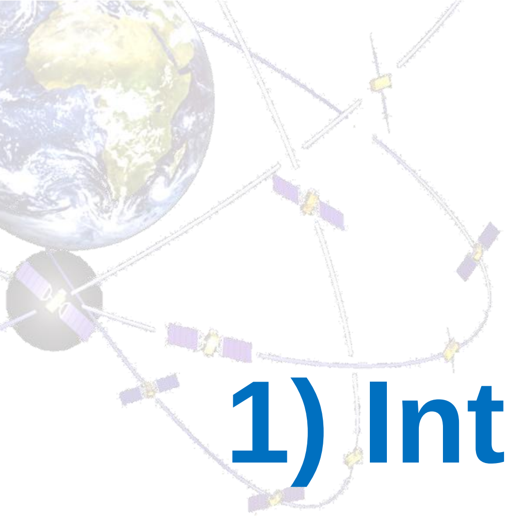
Goals

✓Two independent and external techniques to assess in a fair way the global Vertical Total Electron Content (VTEC) ionospheric models computed from GNSS data (GIMs), are applied in the context of the International GNSS Service (IGS).

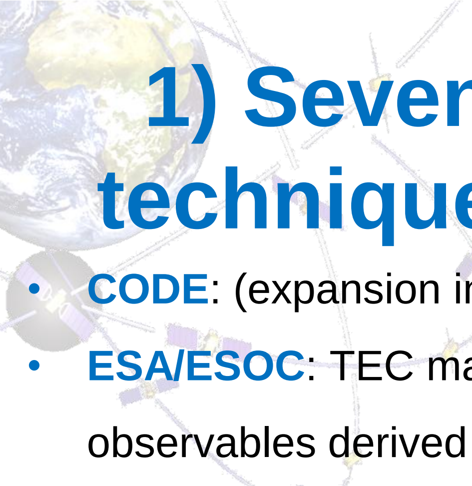
✓The main assessed GIMS are: CODE, ESA, JPL and UPC (analysis centers contributing since 1998.5), NRCAN (resuming), and, Chinese Academy of Sciences (CAS) and Wuhan University (WHU) as new contributors.

Layout

1) Introduction: different ionospheric modelling techniques to be compared
2) VTEC assessment vs. altimeter measurements
3) STEC assessment vs. external GNSS receivers
4) Conclusions and recommendations



1) Introduction : different ionospheric modelling techniques to be compared

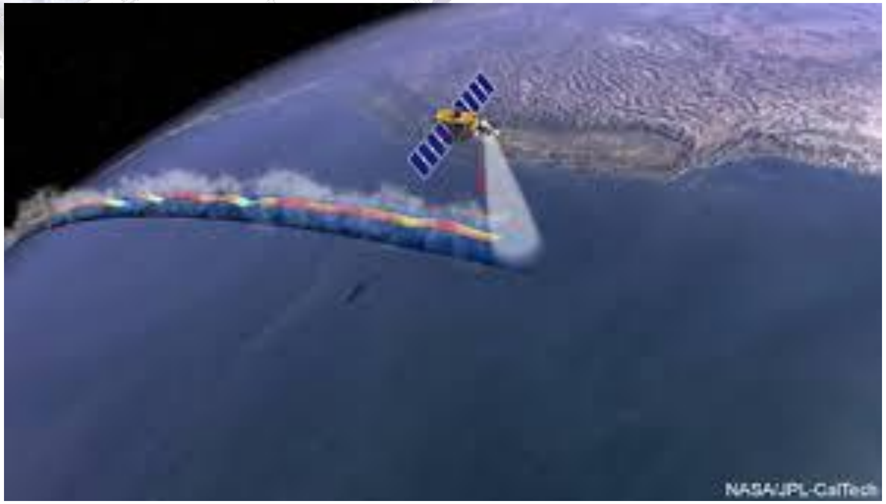


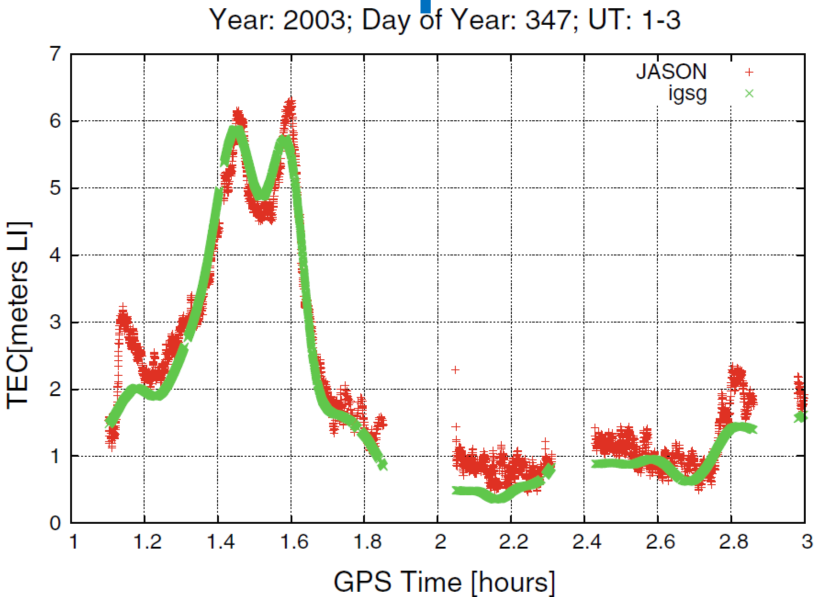
1) Seven different ionospheric modelling techniques and/or software to be assessed

- **CODE**: (expansion in terms of Spherical Harmonics)
- **ESA/ESOC**: TEC maps are still computed with a single-layer approach, taking sTEC observables derived from dual-frequency GPS & GLONASS data (TEC is modelled by spherical harmonics in combination with a daily DCBs fitting).
- **JPL**: Global daily TEC maps with 15-minute temporal and ≥ 5x5 spatial resolution. Three-shell model ionosphere with slabs centered at: 250, 450, and 800 km from 200 globally distributed stations and Kalman-filter approach.
- **UPC**: Global voxel-defined 2-layer tomographic model solved with Kalman filter and splines (UPCG@2h) and kriging (UQRG@15m) interpolation to common grid of 5ºx2.5º in LONxLAT.
- **CAS**: The global and local ionospheric TEC is modeled by SH and GTS functions and then are integrated to generate the global map based on DADS (Different Areas for Different Stations) approach.
- **EMRG**: Canadian Geodetic Survey of Natural Resources Canada (NRCan) has resumed since April 2015 the generation of VTEC GIMs (single-layer + grid + Spherical Harmonics).
- **WHU**: The University of Wuhan is using an expansion in terms of Spherical Harmonics

2) VTEC assessment

VTEC directly observed from dual-frequency altimeters: a GNSS-independent ionospheric truth



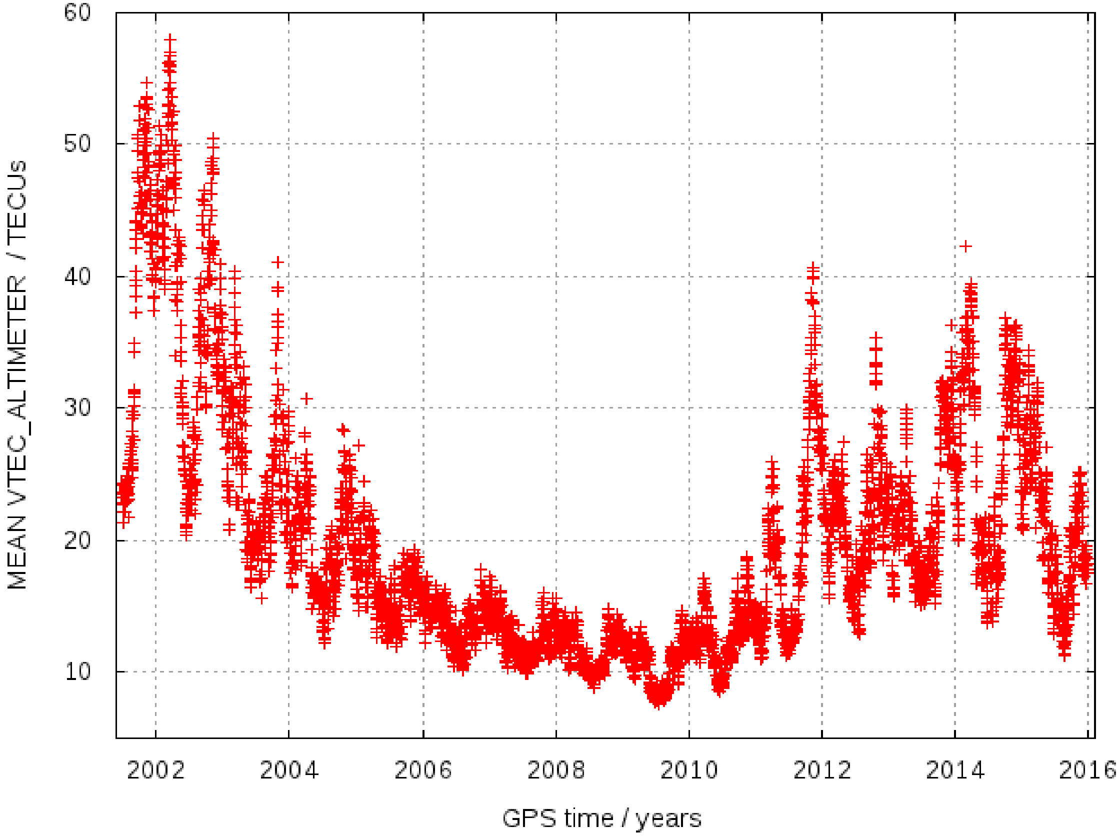


✓**Dual-frequency altimeter measurements provide an excellent and independent source for assessing GNSS-based VTEC models** in difficult conditions (over seas & far from rec.).

✓In spite of the noise of the altimeter measurements (reduced by an sliding window of ~16 sec. in right-hand figure, compared vs. final IGS VTEC), the missing altimeter-topside electron content (typically up to few TECUs only) and the well known altimeter bias excess (few TECUs only), it still **allows a very clear assessment and comparison of the errors of the different ionospheric models (considering in particular the daily standard deviations of VTEC_altimeter – VTEC_GIM),** typically much larger and systematic

(see for instance Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens, J., A. Komjathy, S.C. Schaer & Krankowski, A. (2009). *The IGS VTEC maps: a reliable source of ionospheric information since 1998*. Journal of Geodesy, 83(3-4), 263-275).

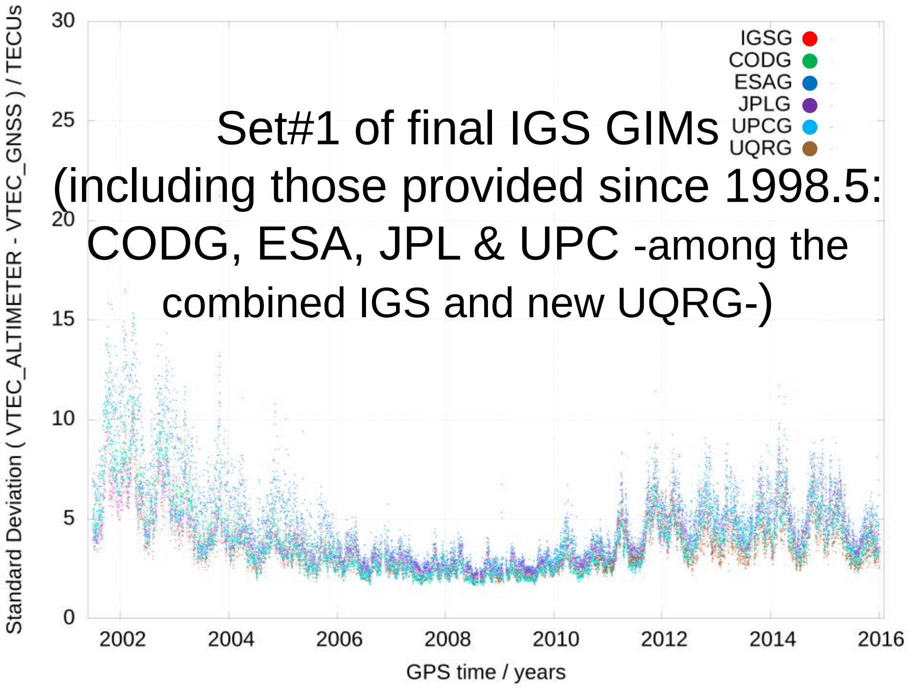
Daily altimetric VTEC during a whole Solar Cycle: Days 180, 2001 to 007,2016 (+190 million dual-freq. altimeter obs. processed)



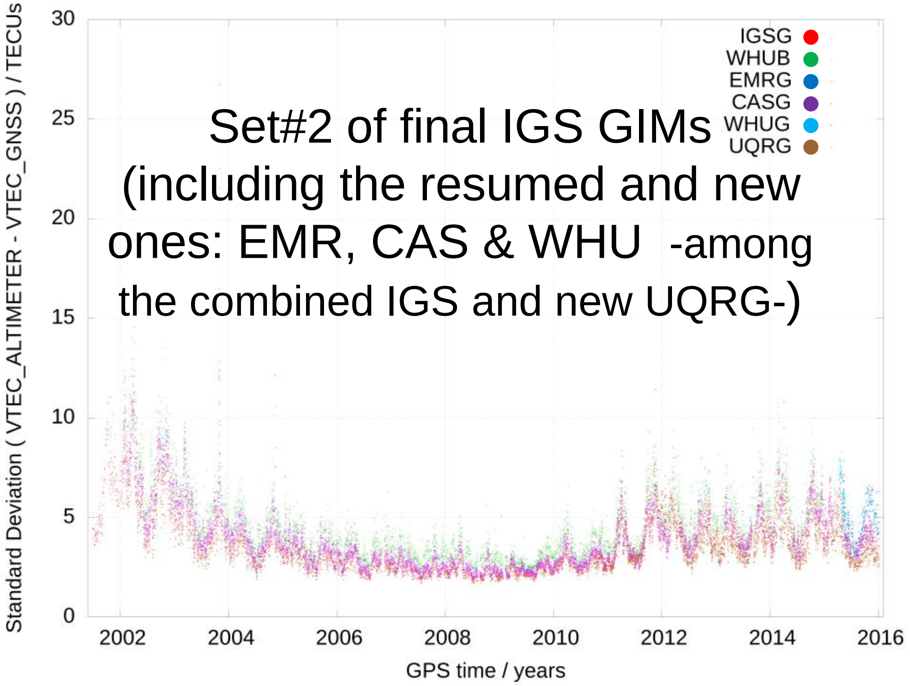
The **Solar Cycle, seasonal and other known VTEC modes can be clearly seen**, in agreement with previous works.

(See for instance Hernandez-Pajares, M.; Juan, J.; Sanz, J.; Orus, R.; García-Rigo, A.; Feltens, J.; Komjathy, A.; Schaer, S.; Krankowski, A. The IGS VTEC maps: a reliable source of ionospheric information since 1998.Journal of geodesy. Vol. 83, 3-4, pp.263 - 275.03/2009)

VTEC GIMS Std. Dev. regarding JASON* VTEC (daily values, since days 2001.6 to 2016.0)



Set#1 of final IGS GIMs (including those provided since 1998.5: CODG, ESA, JPL & UPC -among the combined IGS and new UQRG-)

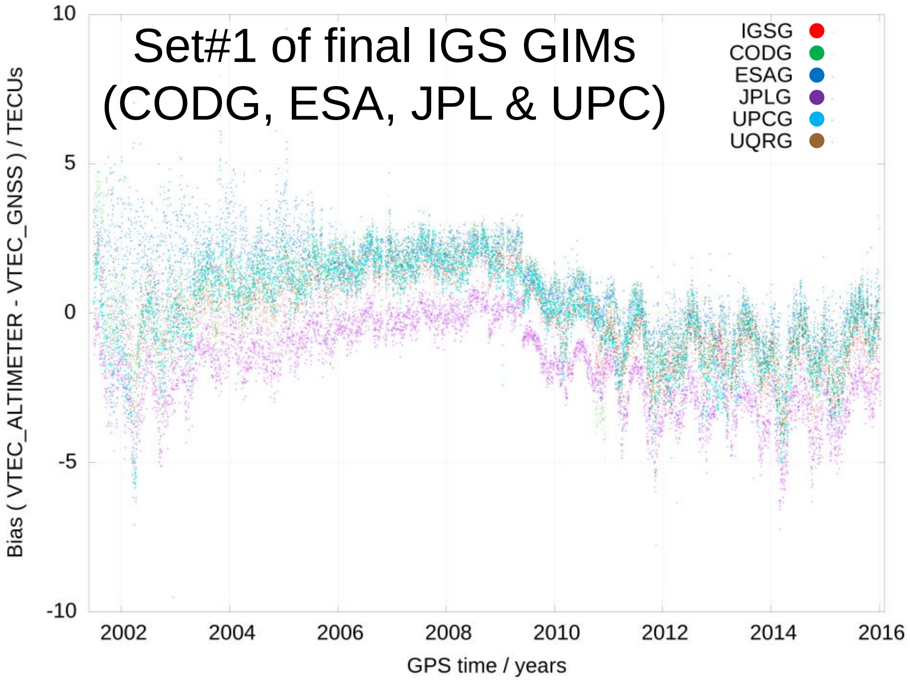


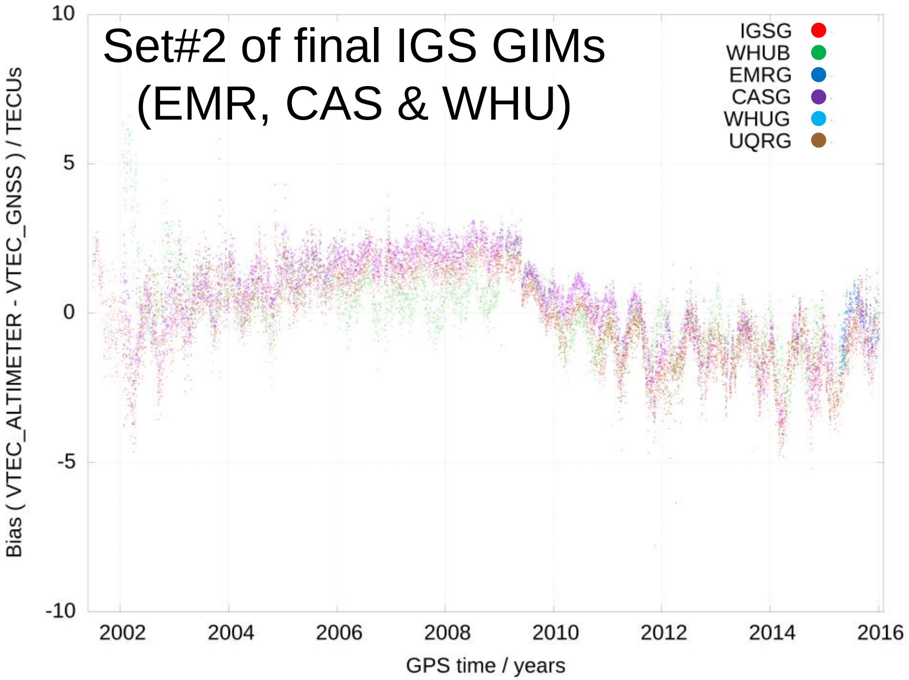
Set#2 of final IGS GIMs (including the resumed and new ones: EMR, CAS & WHU -among the combined IGS and new UQRG-)

✓The discrepancies of all available IGS VTEC GIMS vs +190 millions of altimeter direct VTEC measurements over the seas during the last 15 years, have been analyzed.

✓An **overall general agreement** is found between the 7 analysis centers, with VTEC discrepancies (daily Standard Deviations) typically ranging from 3 to 10 TECUs, depending on the Solar Cycle phase.

VTEC GIMS Bias regarding JASON* VTEC (daily values, since days 2001.6 to 2016.0)

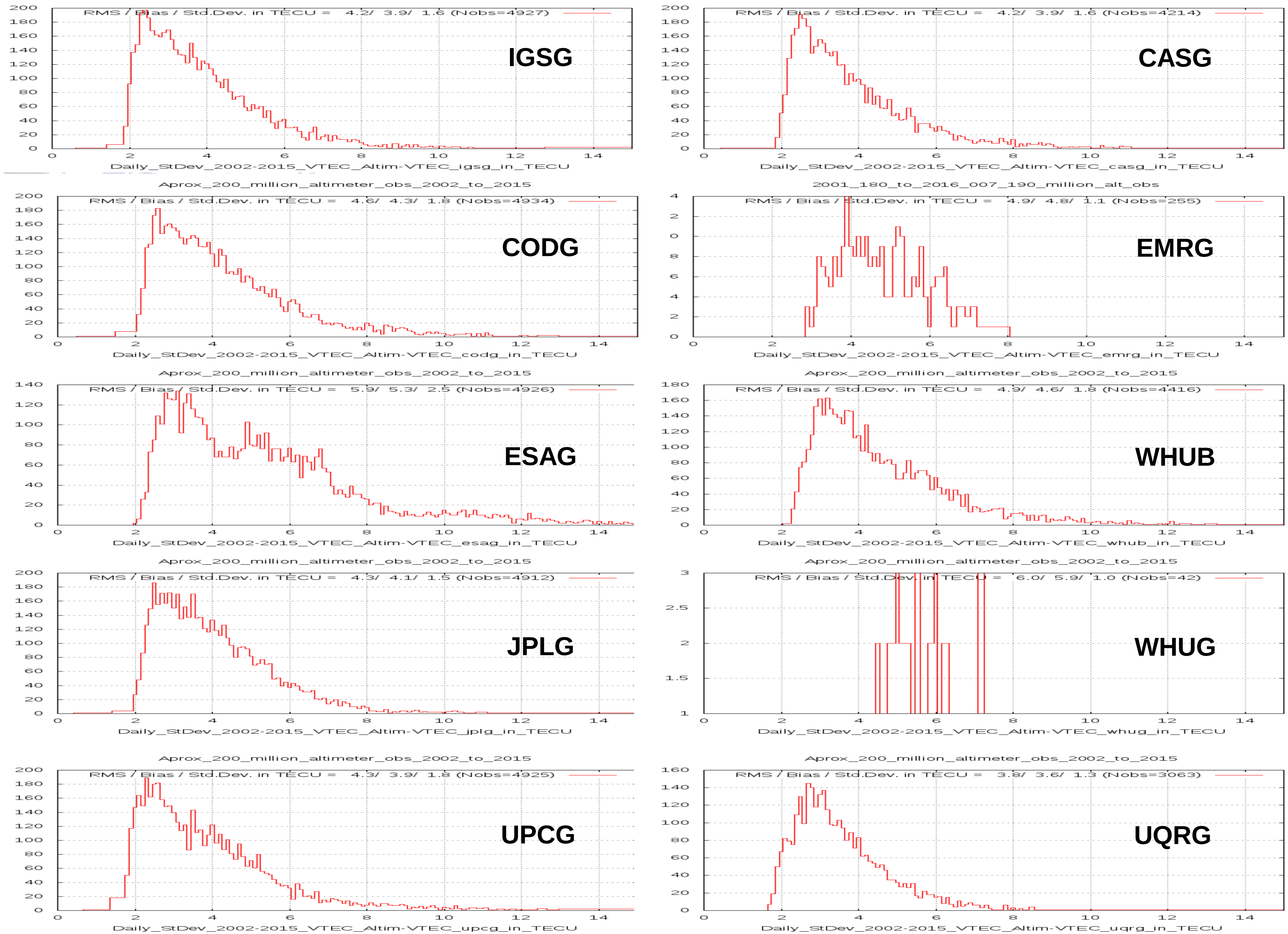




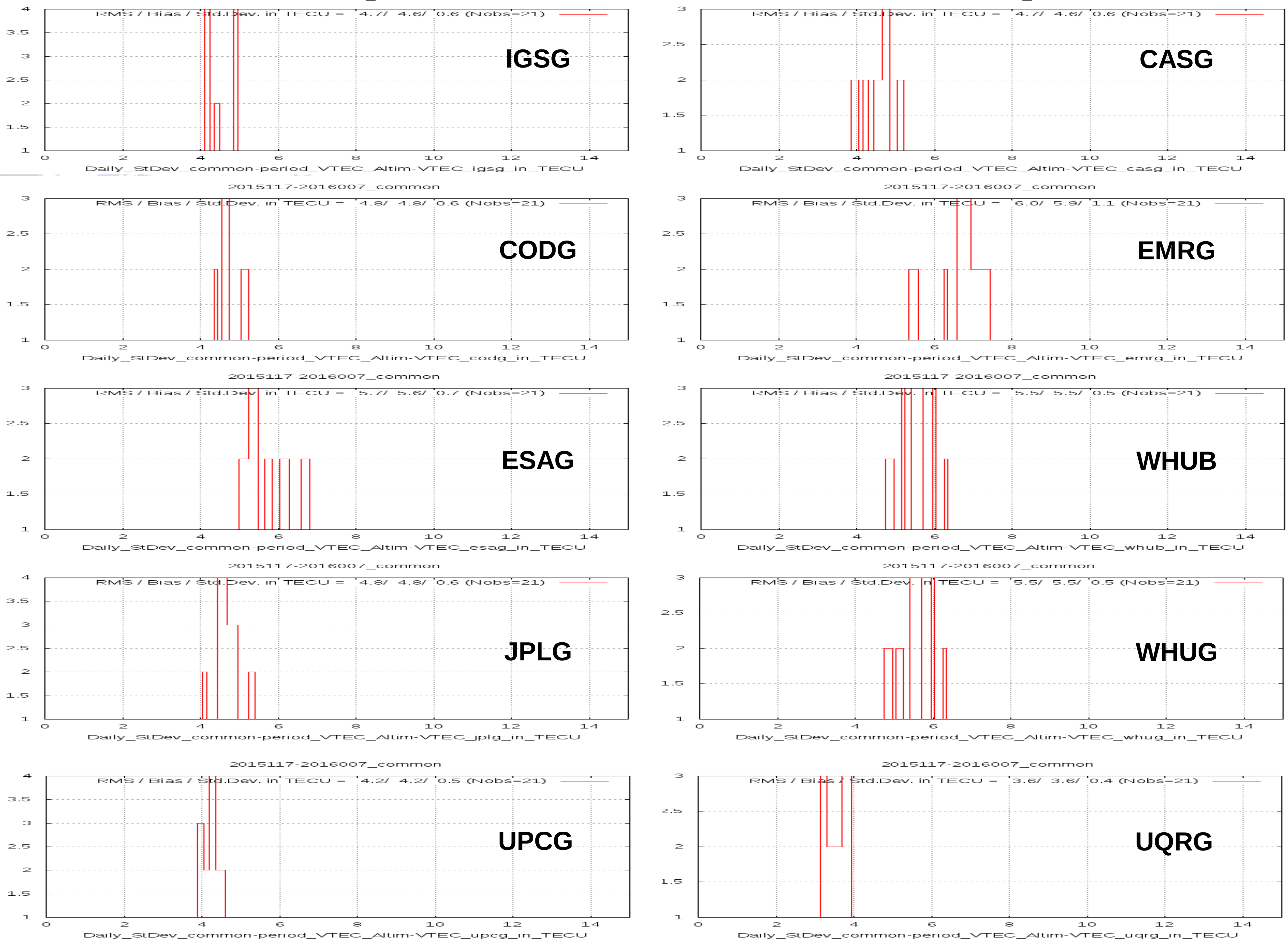
✓It is remarkable as well the **general agreement of the bias**, at 1 to few TECUs level, regarding the altimeter VTEC for the most part of analysis centers.

✓This happens among **different mapping functions used** (related with the general leveling) and the **topside electron content climatology** between the altimeter and GPS orbit (seen as variations interpreted as “inverse climatology”, <VTEC_alt – VTEC_GPS>, in the time series, appearing clearly the Solar Cycle and seasonal cycles, among others, Hernández-Pajares et al. 2004).

Histograms for daily Std.Dev. Values vs Altim. VTEC (2002-2015)



Daily Std.Dev. Values vs Altim. VTEC (21 common days in 2015,117-365)



Std.Dev. Values vs JASON*VTEC Comparative table

Table 1a

GIM Id.	<σ>[2002-2015] / TECUs	# Days
IGSG	3.9	4927
CODG	4.3	4934
ESAG	5.3	4926
JPLG	4.1	4912
UPCG	3.9	4925
CASG	3.9	4214
EMRG[*]	4.8	255
WHUB	4.6	4416
WHUG[**]	(5.9)	42
UQRG	3.6	3063

Table 1b

GIM Id.	<σ>[2015,117-2016,007] / TECUs	# Days
IGSG	4.6	21
CODG	4.8	21
ESAG	5.6	21
JPLG	4.8	21
UPCG	4.2	21
CASG	4.6	21
EMRG	5.9	21
WHUB	5.5	21
WHUG[**]	5.5	21
UQRG	3.6	21

[*] For the newest period of EMR ionospheric product submission to IGS only (d.117-365, 2015).
[**] Very limited sample

Relative Error [100*Std.Dev.VTEC[Alt.-GIM] / VTEC[Alt.]]

Comparative table

Table 2a

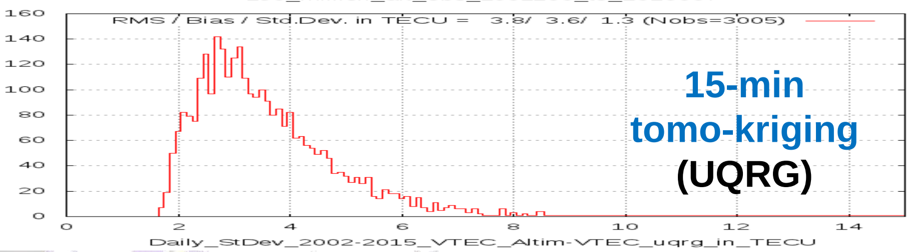
GIM Id.	Rel.Error [2002-2015] / %	# Days
IGSG	19.9	4927
CODG	22.0	4934
ESAG	26.6	4926
JPLG	21.2	4912
UPCG	19.7	4925
CASG	20.9	4214
EMRG[*]	(26.2)	255
WHUB	24.8	4416
WHUG[**]	(26.9)	42
UQRG	17.8	3063

Table 2b

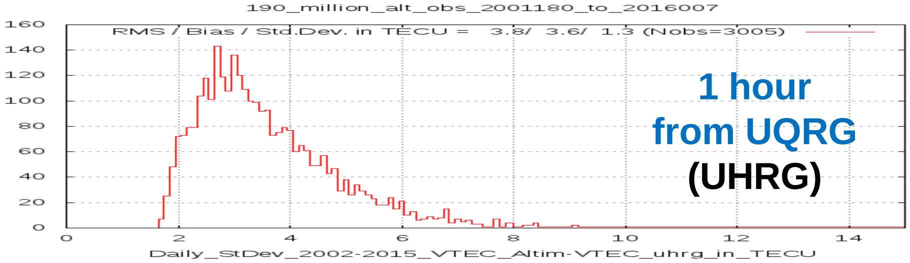
GIM Id.	Re.Error [2015,117-2016,007] / %	# Days
IGSG	21.1	21
CODG	21.8	21
ESAG	25.5	21
JPLG	21.9	21
UPCG	19.1	21
CASG	21.1	21
EMRG	26.5	21
WHUB	25.0	21
WHUG	25.0	21
UQRG	16.3	21

[*] For the newest period of EMR ionospheric product submission to IGS only (d.117-365, 2015).
[**] Very limited sample

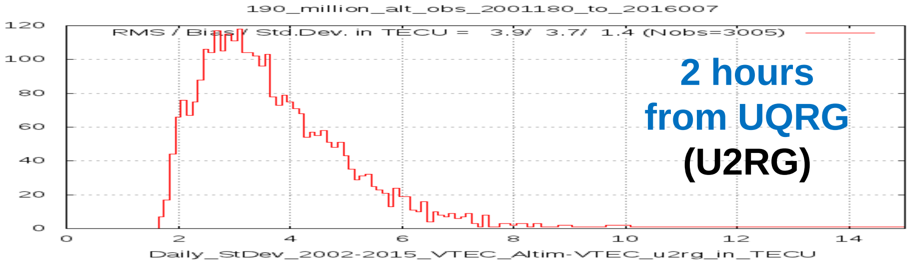
Influence of GIM time update: StDev (2001-180 to 2016-007)



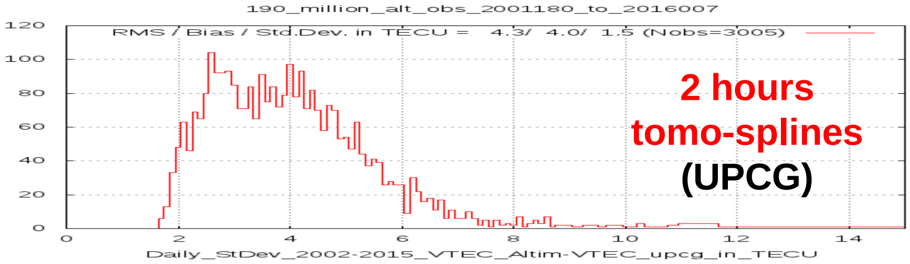
15-min tomo-kriging (UQRG)



1 hour from UQRG (UHRG)



2 hours from UQRG (U2RG)



2 hours tomo-splines (UPCG)

GIM Id.	<σ>[2002-2015] / TECUs	# Days
UQRG	**3.6**	3005
UHRG	**3.6**	3005
U2RG	**3.7**	3005
UPCG	**4.0**	3005

✓It is shown that the **GIM time interval between 15 min to 2 hours has little influence**, when the recommended[*] quadratic interpolation in latitude and local-time is performed.

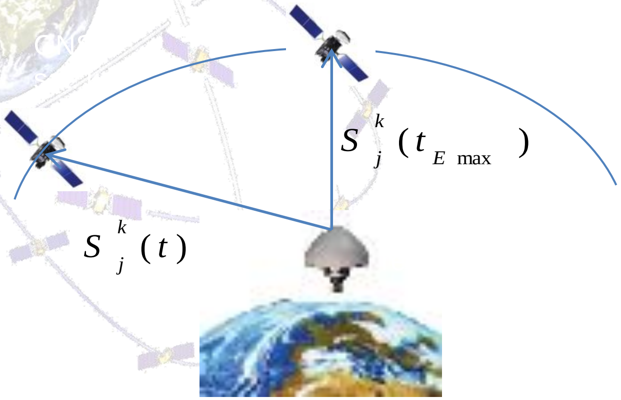
✓However **the change of technique can have a noticiable influence** (just changing the interpolation scheme from splines to kriging, between UPCG and U2RG, both at 2 hours time interval).

✓These results in terms of the standard deviation of the altimeter-GPS VTEC is confirmed when relative error is considered.

[*] Schaer, S., Gurtner, W., & Feltens, J. (1998, February). IONEX: The ionosphere map exchange format version 1. In Proceedings of the IGS AC workshop, Darmstadt, Germany (Vol. 9, No. 11).

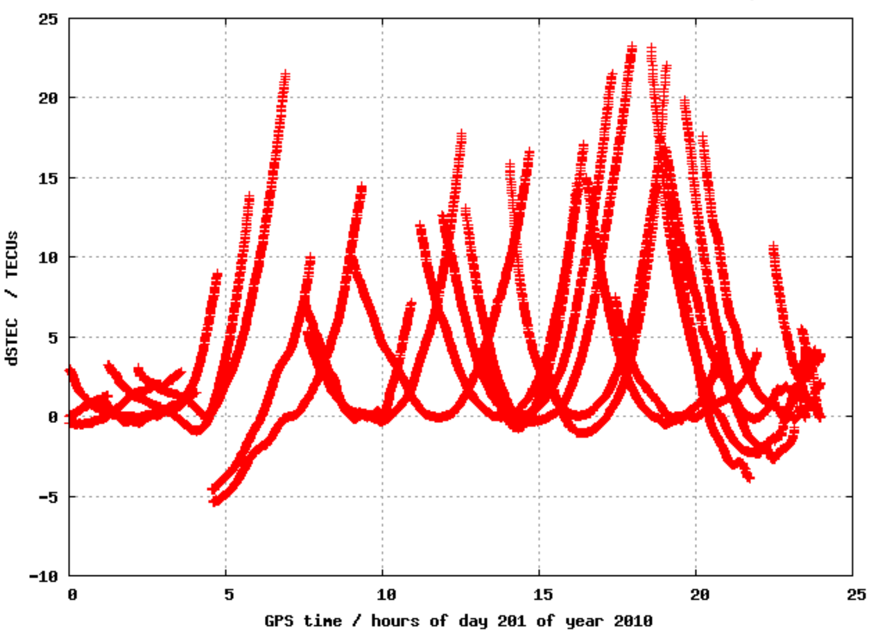
2) STEC assessment

Ionospheric Truth: STEC Variation, dSTEC



$$\Delta S_O \equiv S_j^k(t) - S_j^k(t_{E\ max}) =$$

$$= [(L_I)_j^k(t) - (L_I)_j^k(t_{E\ max})] / \alpha \equiv \Delta L_I / \alpha$$

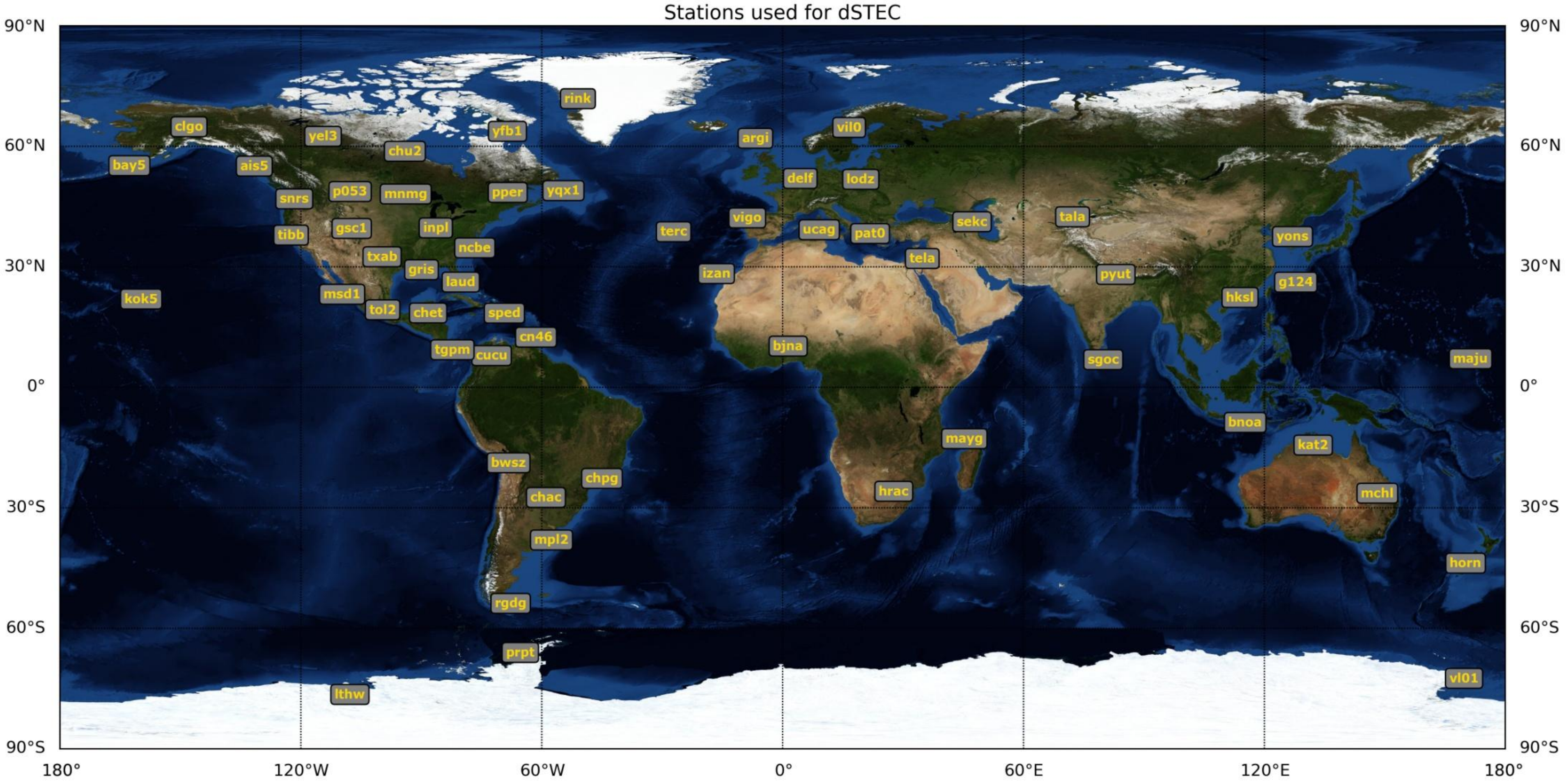


✓The GPS ionospheric carrier phase difference, ΔLI for a given pair rec.(j)-sat.(k), (regarding to the value corresponding to the higher elevation –Emax- ray in the phase-continuous arc of data), provides a **very precise ionospheric truth of the STEC referred to the value at maximum elevation, dSTEC,** in space and time (typically more accurate than 0.1 TECU).

✓**It can be used to compare the performance of ionospheric models,** which can be interpreted as an assessment of the corresponding VTEC (V), mapping function (M) and their time evolution.

(see for instance Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens J., Komjathy, A., Schaer, S., & Krankowski, A. (2009). *The IGS VTEC maps: a reliable source of ionospheric information since 1998*. Journal of Geodesy, 83(3-4), 263-275).

Selection of independent GPS receivers for external dSTEC assessment

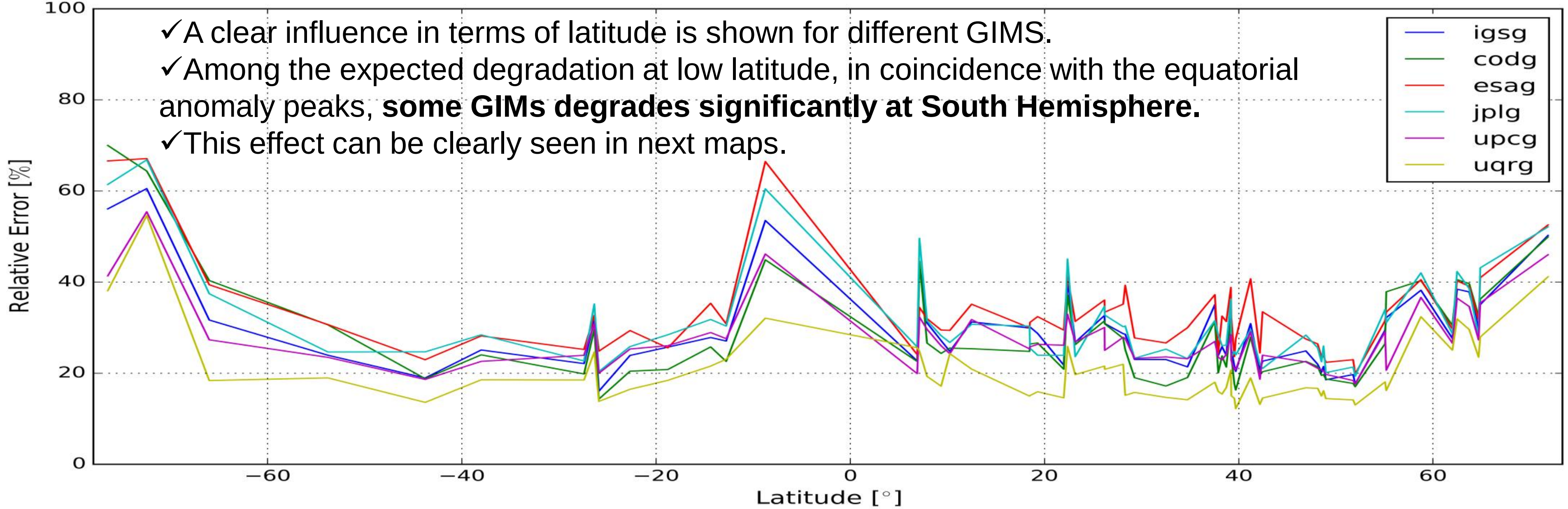


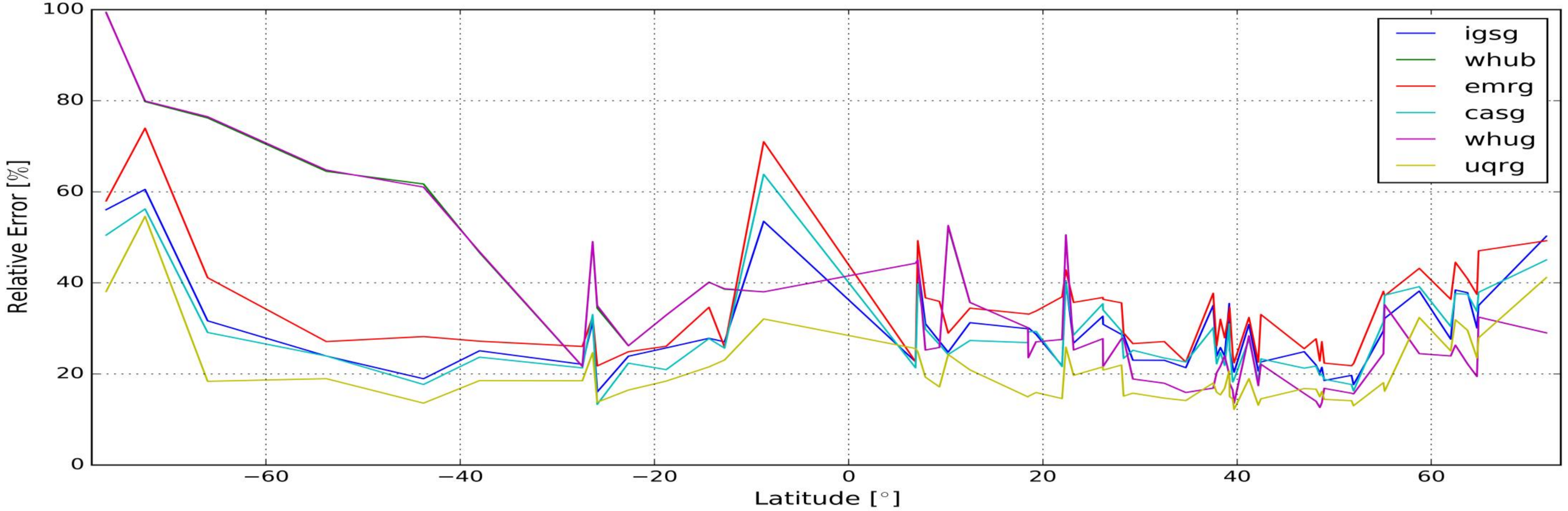
+50 permanent GPS receivers to provide directly observed dSTEC, not used in any of the GIMs under assessment (from their list of receivers used in the IONEX header file)**,** have been selected guaranteeing the most feasible homogenous distribution during 2 solstice and 2 equinox days in 2015: 082, 146, 280 and 330.

dSTEC relative error vs latitude

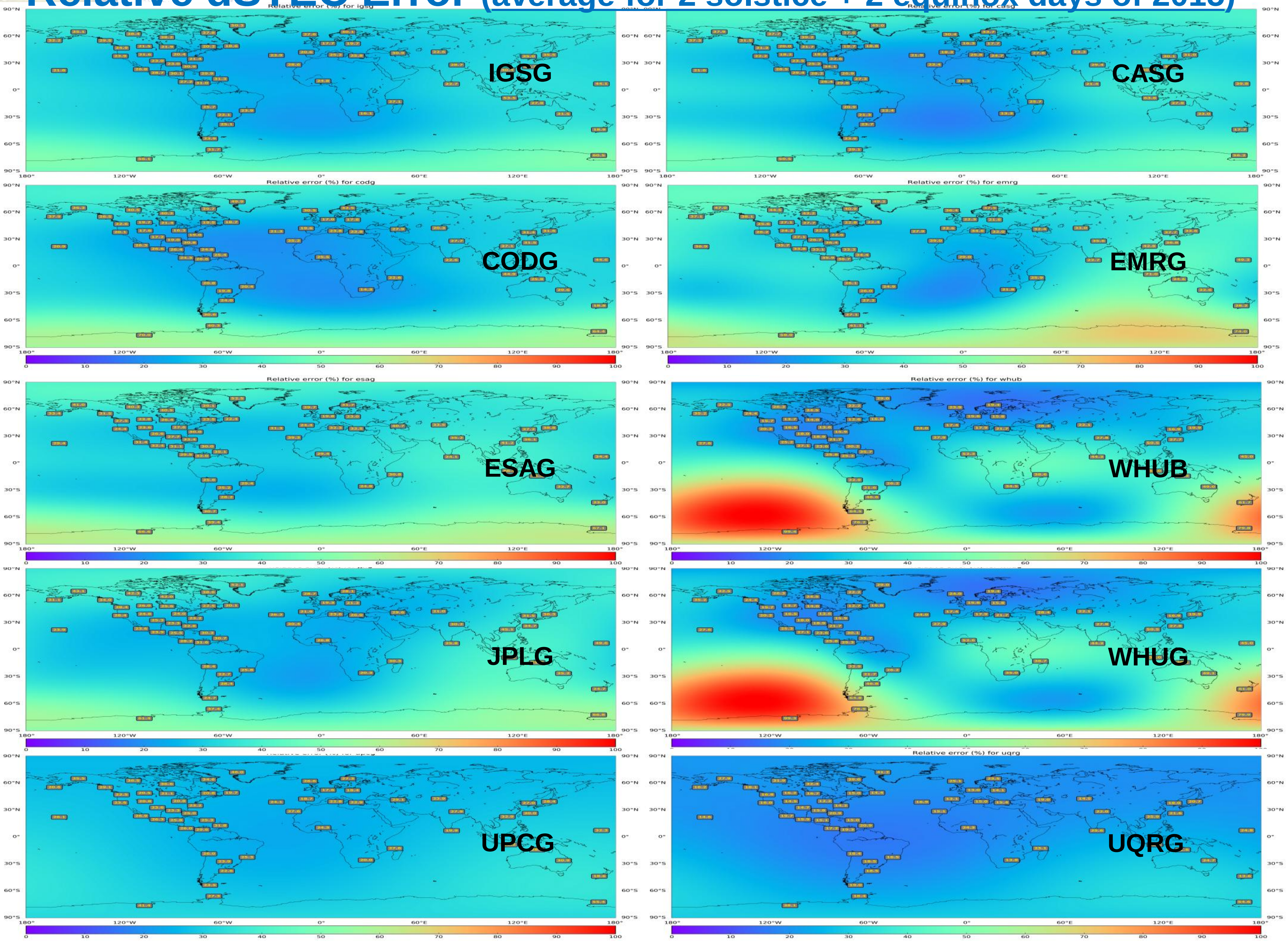
(from +50 indep. GPS receivers, days 082, 146, 280 and 330, 2015)

- ✓A clear influence in terms of latitude is shown for different GIMS.
- ✓Among the expected degradation at low latitude, in coincidence with the equatorial anomaly peaks, **some GIMs degrades significantly at South Hemisphere.**
- ✓This effect can be clearly seen in next maps.





Relative dSTEC Error (average for 2 solstice + 2 equinox days of 2015)



dSTEC Relative Error [%] comparative table

Table 3

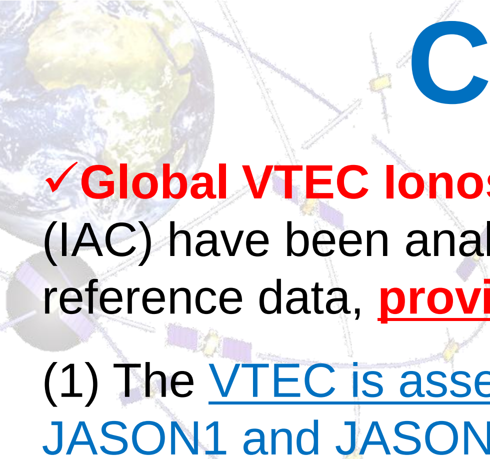
GIM Id.	Rel.Error [average on days 082, 146, 280, 330 2015] / %	# Rec*Days
IGSG	28.9	238
CODG	27.8	238
ESAG	33.0	238
JPLG	31.0	180
UPCG	26.9	238
CASG	28.0	178
EMRG	33.6	178
WHUB	30.7	60
WHUG	30.7	60
UQRG	20.5	233

The external **dSTEC-GPS assessment is qualitatively quite compatible with the one provided by VTEC-altimeters** (Table 2^a) but **with two differences: (1) The relative errors appear larger[*] and (2) for some centers the assessment sorting changes[**]**

[*] This can be related with small reference values of dSTEC, when the given observation is not far from the highest-elevation (i.e. the reference- one).

[**] This could be due to the most reduced statistics in this case and/or by mapping-function related points, implicitely assessed vs observed dSTEC.

Conclusions (1 of 2)



✓**Global VTEC Ionospheric maps provided by 7 Ionospheric Analysis Centers** (IAC) have been analyzed in two different ways and scenarios, always versus external reference data, **providing very consistent results between them:**

(1) The VTEC is assessed during 15 years of (+190 millions) VTEC altimeter (TOPEX, JASON1 and JASON2) measurements.

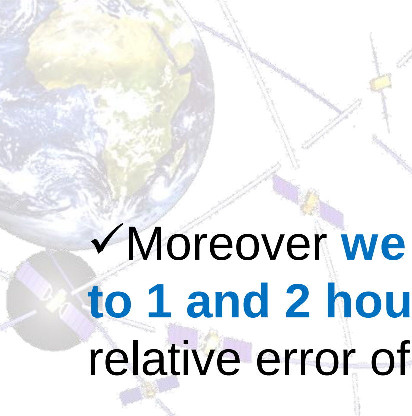
- Such direct VTEC assessment has been performed in the worse case scenario (over the Seas, typically very far from permanent GPS receivers).
- The “**resumed” and new IACs**, EMR[*], CAS & WHU provide a **performance** (relative error of 21-26%[**]) **comparable with the existing IGS IACs,** CODE, ESA, JPL and UPC (relative error of 20[**]-26%).

(2) The STEC is assessed over +50 receivers during 2 +2 equinox and solstice days in 2015 with +50 GPS worldwide receivers not used by any of the GIMs.

- Such direct STEC assessment (vs observed dSTEC values) is performed as well in places not far from GNSS receivers used in the GIM computation.
- The STEC assessment indicates an **overall agreement between different centers, with predominant errors around 20-30%, with the exception of the South Hemisphere, South-Pacific** in particular, for some centers.

[*] In the case of EMR this conclusion has been taken with GIMS in a very recent period only, from day 117, 2015.
[**] Excluding the 15-min tomo-kriging UPC GIMs, UQRG, not available yet for the full period.

Conclusions (2 of 2)



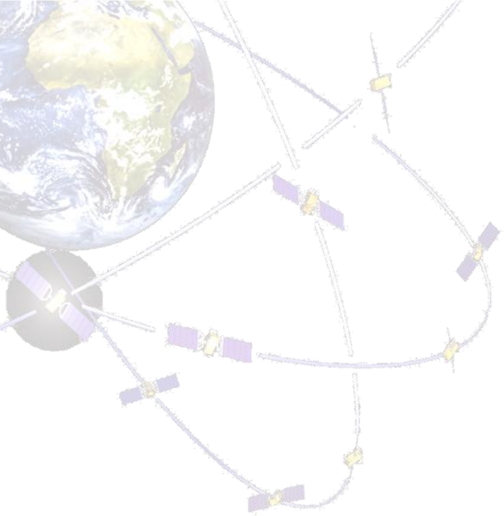
✓Moreover **we have shown that the increase of GIM time update (from 15 min. to 1 and 2 hours) produces a marginal degradation** (from 17.8% to 18.4% of relative error of worsening for UPC products).

✓However the **change of the technique** (just one part,like the final interpolation technique in the case of UPC) **produces much more significant degradations** (from 18.4% to 19.8% in the case of the 2-hours time interval compared UPC GIMs).

✓The last but not the least, **this work illustrates again the discriminant capability of using strictly independent and relevant (direct) reference data in order to assess the global ionospheric maps**:

- ☐ Either **vertically** (altimeter VTEC) **or in slant directions**, most sensitive to mapping function suitability (GNSS dSTEC).
- ☐ Either typically **far**, i.e. testing interpolation strategies (with altimeter data) **or close** (GNSS) **from the GNSS receivers used to compute the different GIMS.**

Backup slides



Baseline: Global ESOC-IONMON runs since 1998.5

ESA/ESOC contributes with IONEX products to the IGS Ionosphere Working Group since its inception in 1998. Major points to be mentioned here are:

- Initially: Daily global ionospheric TEC maps in final mode (11 days latency).
- Spring 2004: Start routine delivery of daily global ionospheric TEC maps in rapid mode (1 day latency).
- December 2005: Start routine delivery of TEC maps in 2-hour time resolution.
- February 2011: Commence submission of ESA IONEX files with 1-hour time resolution.
- August 2013: The IONMON became an integral part of ESOC’s NAPEOS software. Since then, GLONASS data are processed in combination with GPS data.

Currently, ESA TEC maps are still computed with a single-layer approach, taking sTEC observables derived from dual-frequency GPS & GLONASS data, whereby ionospheric TEC is modelled by spherical harmonics in combination with a daily DCBs fitting.

Actual activities focus on the establishment of a 3D modelling approach, also with enhanced time resolutions, which shall replace the old single-layer model in future.

Providing GIMs ESAG (2h-final) to this study

GIM TEC Derivation

TEC Observation Equation

TEC Retrieval: GIM Fundamentals

Providing GIMs
JPLG (2h-final)

- Global daily TEC maps with 15-minute temporal and ≥ 5x5 spatial resolution
- Three-shell model ionosphere with slabs centered at: 250, 450, and 800 km
- GIM uses observations from 200 globally distributed stations (*zeta* function)
- A Kalman-filter approach is used to estimate the basis functions and biases

$$TEC = M_1(h_1, E_1)\sum_i C_{1i}B_{1i}(\lambda_1, \phi_1) + M_2(h_2, E_2)\sum_i C_{2i}B_{2i}(\lambda_2, \phi_2) +$$

$$M_3(h_3, E_3)\sum_i \underset{\downarrow}{C_{3i}B_{3i}}(\lambda_3, \phi_3) + \underbrace{b_{s,GPS} + b_{r,GPS} + b_{r,GLONASS_f}(GLONASS_f)}_{},$$

Basis functions
(functions of lat/lon)

Ground-based receiver differential code biases
GPS and GLONASS satellite biases

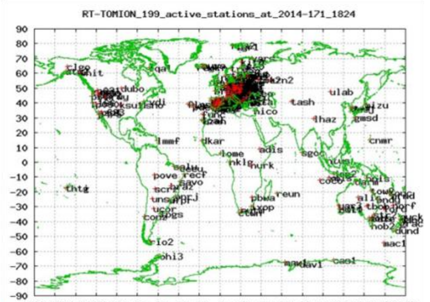
Baseline: Global tomographic UPC-IonSAT runs since 1998.5

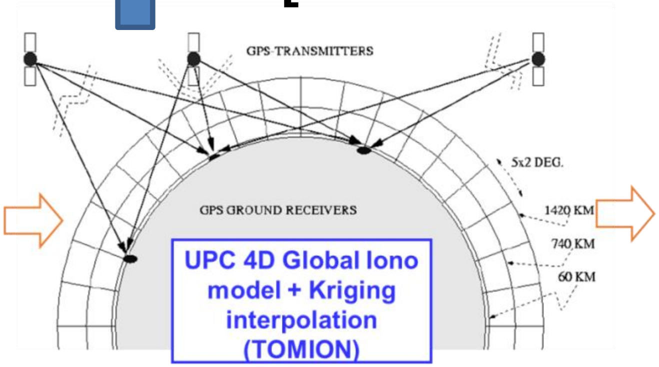
Providing GIMs UPCG (2h-final w tomo-splines) and UQRG (15min-rapid w. tomo-kriging) to this study

From each obs. we get one STEC value: V=S/M=(Li-Bi)/M. [~1500 val. / 30 s]

Interpol. by Splines (UPCG)

RT IGS ground GPS data (70 to 195 worldwide receivers)

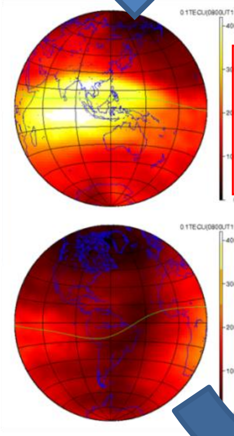




UPC 4D Global Iono model + Kriging interpolation (TOMION)

$$L_I = S + B_I \simeq \sum_{i=1}^{n} N_{e,i} \Delta l_i + B_I$$

UPC global VTEC maps



Kriging Interpolation

Layout summarizing the global VTEC computation from ground GPS data by means of the UPC TOMION software, including the main tomographic model equation[*]

[*](data: ionospheric combination of carrier phases LI, and length intersection within each voxel, ∆li; unknowns: its ambiguity BI, the STEC, S, which includes the mean electron density within each given voxel, Ne,i).

New VTEC maps (UQRG)

(see for instance Hernandez-Pajares, M., Juan, M. and Sanz, J., 1999. *New approaches in global ionospheric determination using ground GPS data*. Journal of Atmospheric and Solar-Terrestrial Physics 61, pp. 1237–1247.).

CAS: New Approach for generating GIM with high accuracy

The global and local ionospheric TEC is modeled by SH and GTS functions and then are integrated to generate the global map based on DADS (Different Areas for Different Stations) approach.

Spherical Harmonic Function + Trigonometric Series Function

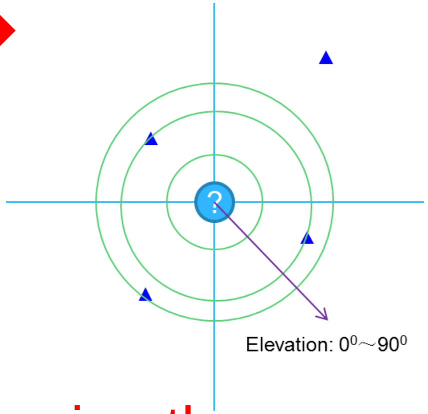
$$VTEC(\phi,\lambda) =$$

$$\sum_{n=0}^{n_{d\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\varphi)\cdot\left(\tilde{A}_{nm}\cos(m\lambda)+\tilde{B}_{nm}\sin(m\lambda)\right)$$

$$\begin{cases} \mathrm{TEC}(\varphi,\lambda,z) = \mathrm{VTEC}(\varphi,\lambda)\cdot M(z) \\ \mathrm{VTEC}(\varphi,\lambda) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} \left\{E_{nm}(\varphi-\varphi_0)^n \lambda^m\right\} \\ \qquad + \sum_{k=1}^{k_{\max}} \{C_k\cos(k\lambda) + S_k\sin(k\lambda)\} \\ \lambda = \frac{2\pi(t-14)}{T}, (T = 24h) \end{cases}$$

$$E_i = \begin{cases} VTEC_{g,i} & M = 0 \\ \dfrac{\sum_{m=1}^{M} P_m \cdot VTEC_{s,i,m}}{\sum_{m=1}^{M} P_m} & M \neq 0 \end{cases}$$

$$P_m = \frac{1}{\sigma_{0,m}^2\cdot\left[\cos^2\left(elev_{i,m}\right)+1\right]}$$



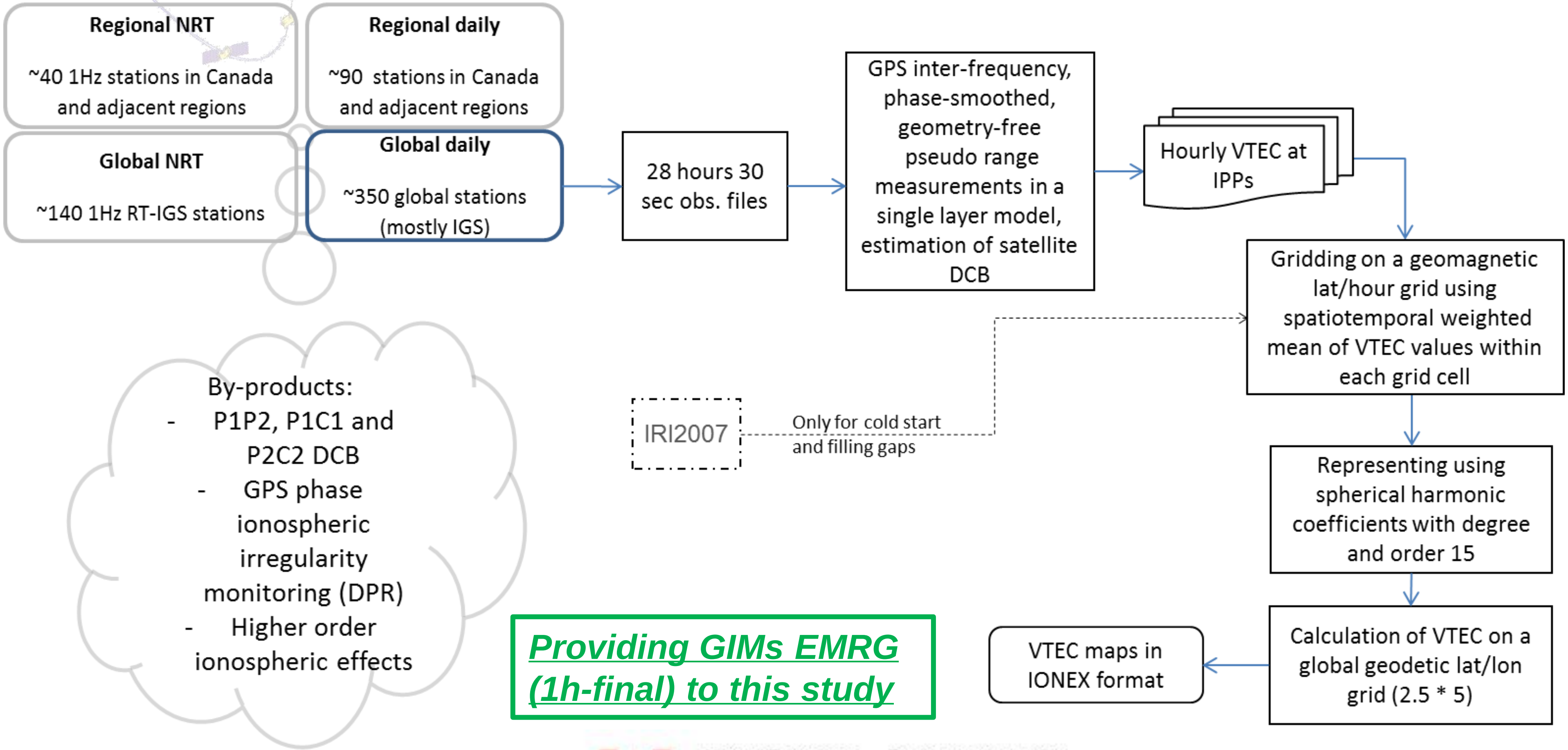
Highlight: estimate the TEC at each grid point only using the nearby data so as to improve its accuracy.

Providing GIMs CASG (2h-final) to this study

(see for instance Zishen Li, Yunbin Yuan, Ningbo Wang, Manuel Hernandez-Pajares, Xingliang Huo(2015). SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions. Journal of Geodesy.

Natural Resources Canada

Canadian Geodetic Survey of Natural Resources Canada (NRCan) has developed a number of products from GPS sensing of the ionosphere. Figure below lists the products generated with a summary of processing steps for global daily product. The global daily product (emrg) submission to IGS data centers has resumed since April 2015 and is considered for comparisons in this presentation.



Regional NRT

~40 1Hz stations in Canada and adjacent regions

Regional daily

~90 stations in Canada and adjacent regions

Global NRT

~140 1Hz RT-IGS stations

Global daily

~350 global stations (mostly IGS)

28 hours 30 sec obs. files

GPS inter-frequency, phase-smoothed, geometry-free pseudo range measurements in a single layer model, estimation of satellite DCB

Hourly VTEC at IPPs

Gridding on a geomagnetic lat/hour grid using spatiotemporal weighted mean of VTEC values within each grid cell

IRI2007

Only for cold start and filling gaps

Representing using spherical harmonic coefficients with degree and order 15

Calculation of VTEC on a global geodetic lat/lon grid (2.5 * 5)

VTEC maps in IONEX format

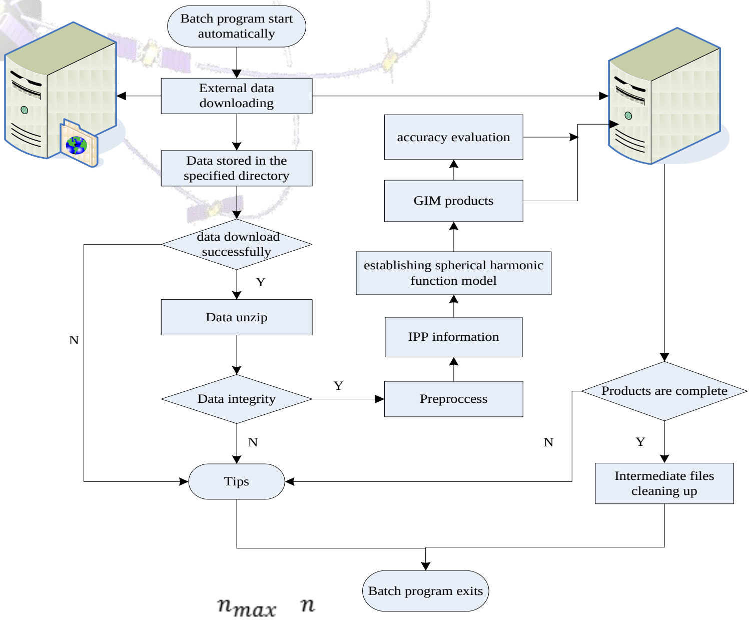
By-products:
- P1P2, P1C1 and P2C2 DCB
- GPS phase ionospheric irregularity monitoring (DPR)
- Higher order ionospheric effects

Providing GIMs EMRG (1h-final) to this study

Natural Resources Canada

Ressources naturelles Canada

Global ionospheric VTEC maps from WHU



Batch program start automatically

External data downloading

Data stored in the specified directory

data download successfully

Y

N

Data unzip

Data integrity

Y

N

Preprocess

IPP information

establishing spherical harmonic function model

GIM products

accuracy evaluation

Products are complete

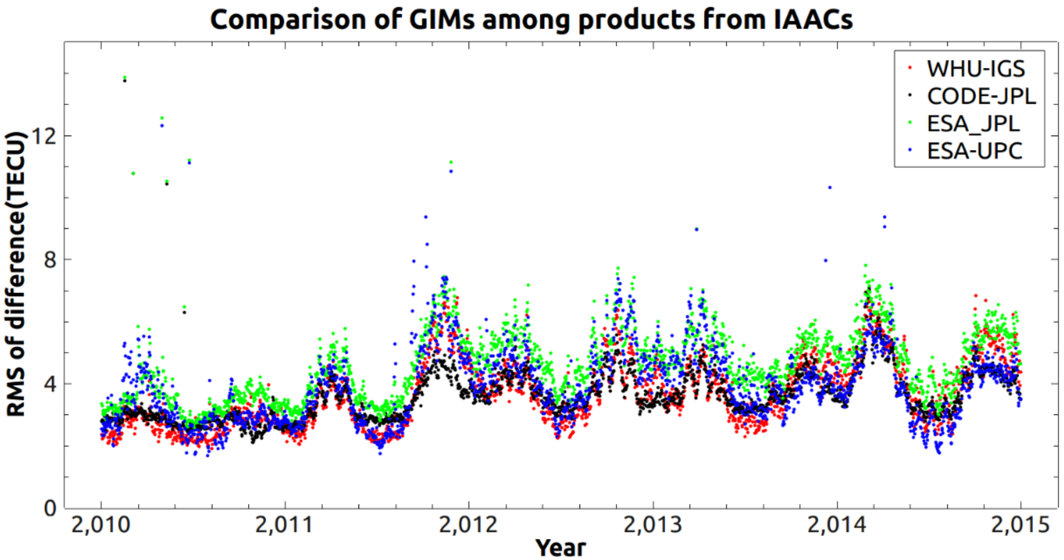
N

Y

Intermediate files cleaning up

Tips

Batch program exits



Comparison of GIMs among products from IAACs

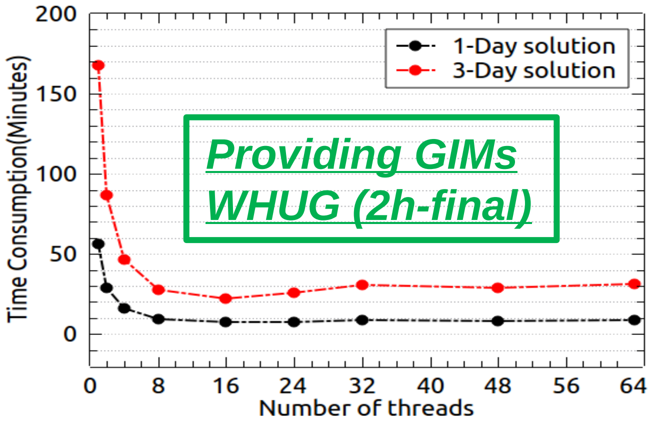
$$VTEC(\varphi,\lambda)=\sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\tilde{P}_{nm}(\sin\varphi)(a_{nm}\cos(m\lambda)+b_{nm}\sin(m\lambda))$$

$$\left\{\begin{array}{l}\sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\frac{\tilde{P}_{nm}(\sin\beta)(\tilde{C}_{nm}\cos(ms)+\tilde{S}_{nm}\sin(ms))}{M}-DCB^{SV}-DCB_{rcvr}=\rho_2'-\rho_1'\\ \sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\tilde{P}_{nm}(\sin\beta)(\tilde{C}_{nm}\cos(ms)+\tilde{S}_{nm}\sin(ms))\geqslant c\end{array}\right.$$

c is a non-negative constant and varies with latitudes and seasons. Implement inequality-constrained least square (ICLS) method to eliminate non-physical negative values.

Zhang, H., P. Xu, W. Han, M. Ge and C. Shi, Eliminating negative VTEC in global ionosphere maps using inequality-constrained least squares, *Advances in Space Research* Vol. 51, No. 6, 2013, pp. 988-1000.

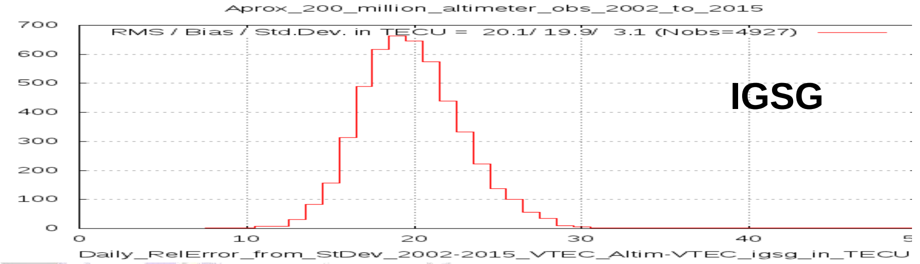
Multithreaded parallel estimation

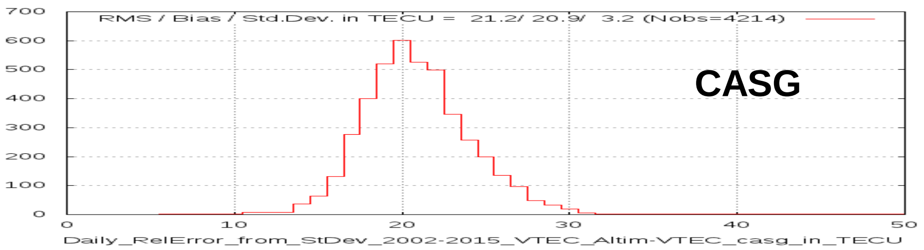


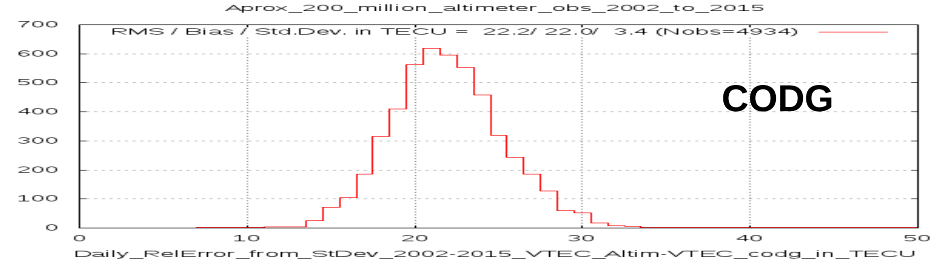
Providing GIMs WHUG (2h-final)

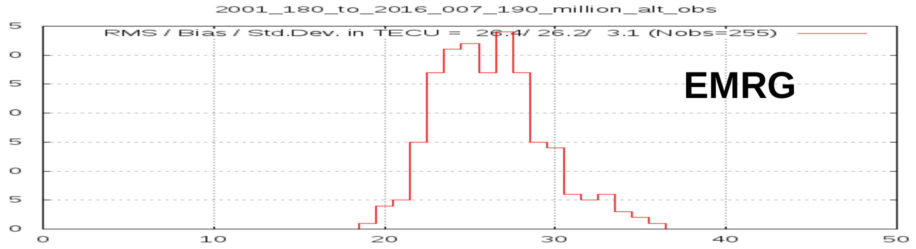
website: http://ionosphere.cn

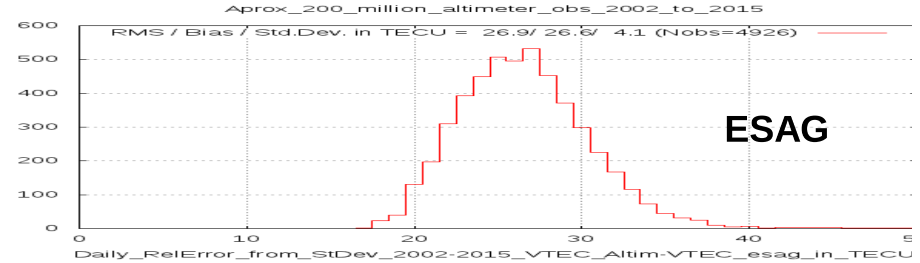
Hist. Rel. Error: 100*Std.Dev.VTEC[Alt.-GIM] / VTEC[Alt.] (2002-2015)

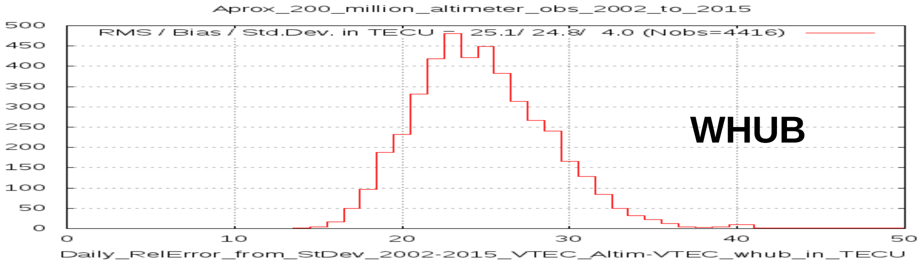


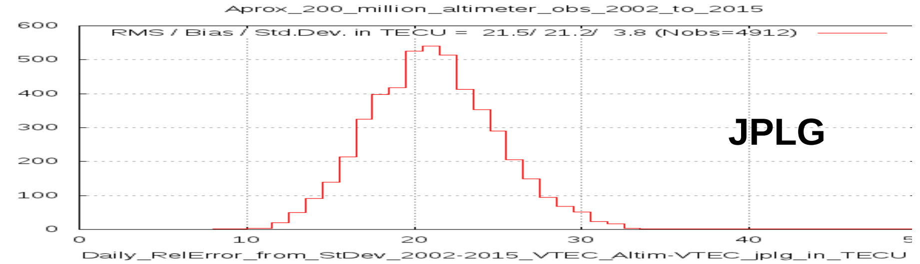


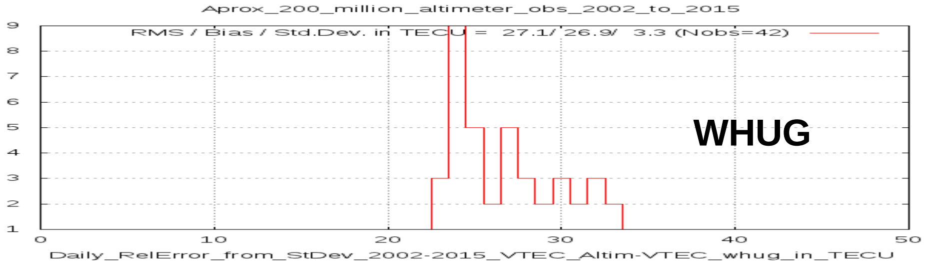


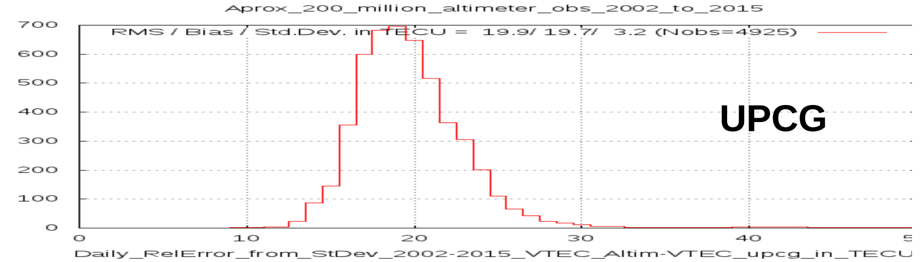


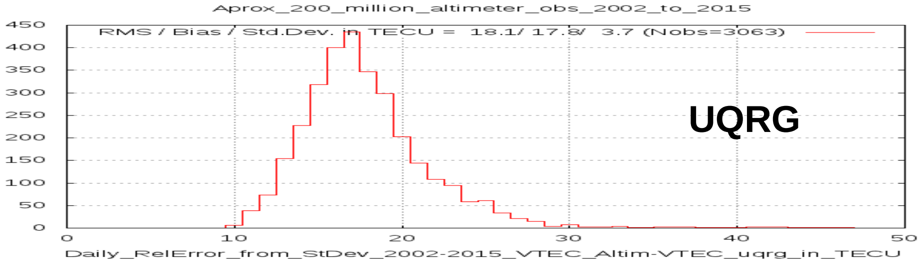




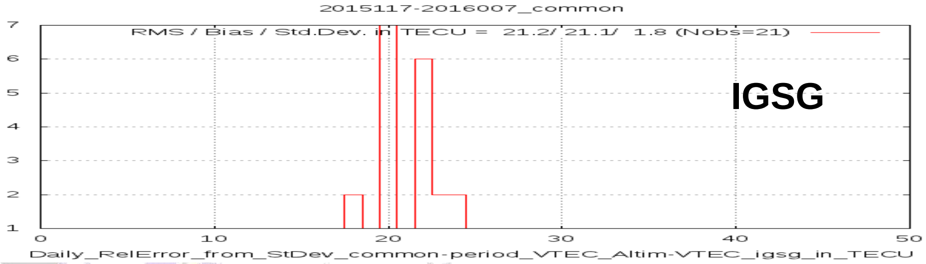


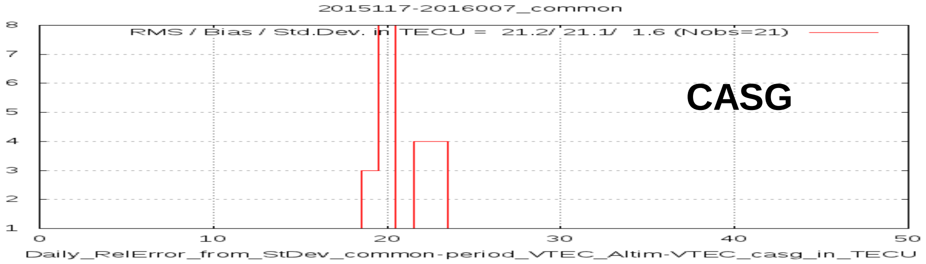


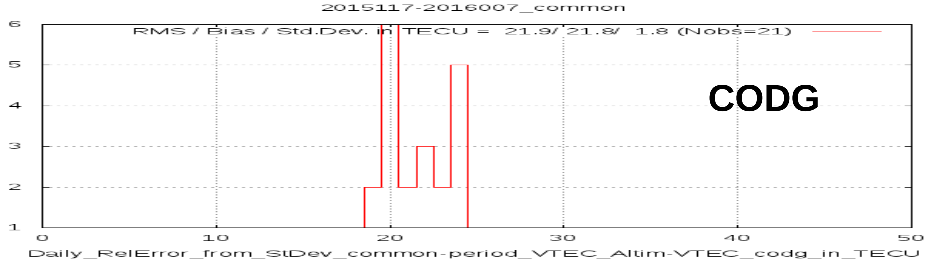


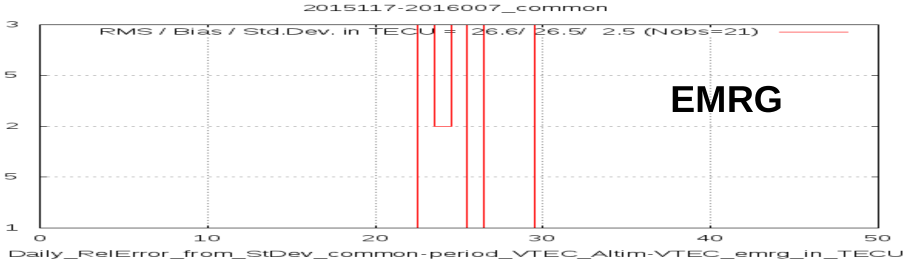


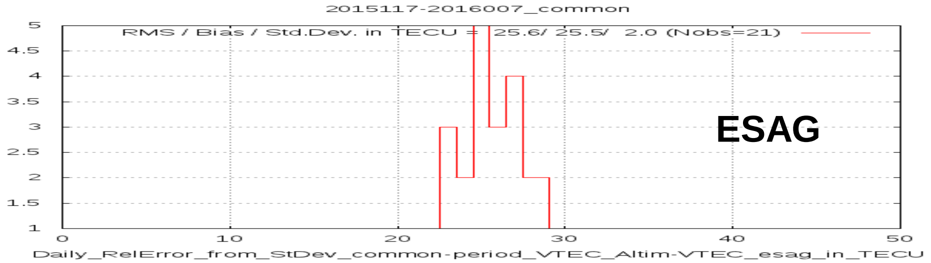
Relative Error [100*Std.Dev.VTEC[Alt.-GIM] / VTEC[Alt.] **] (21 common days in 2015,117-365)**

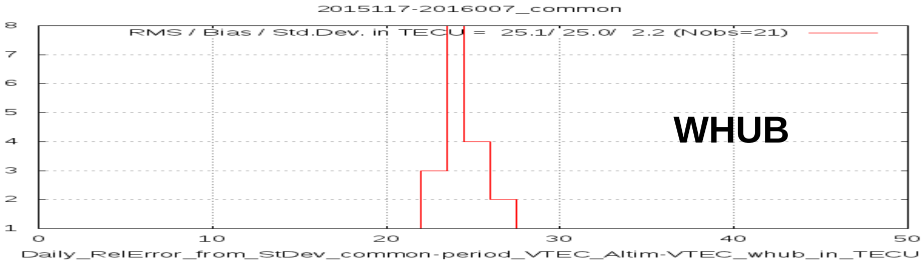


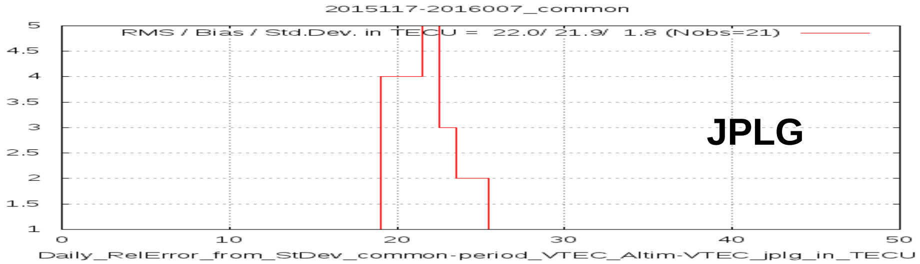


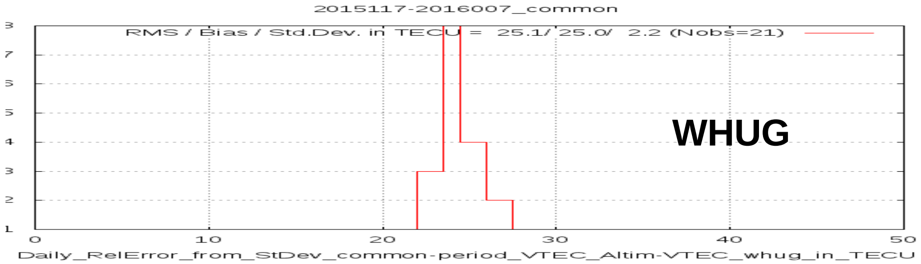


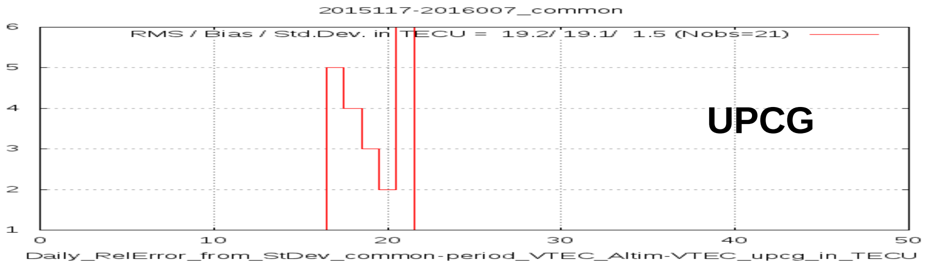


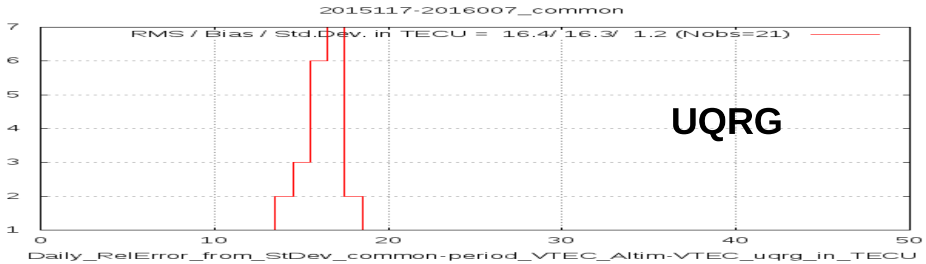




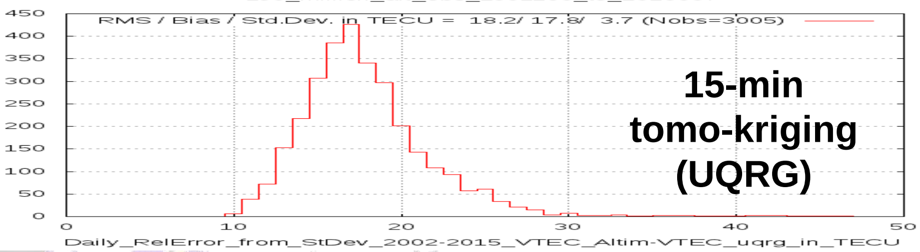


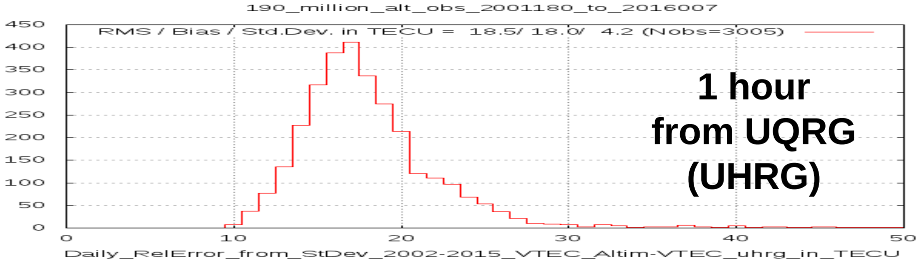


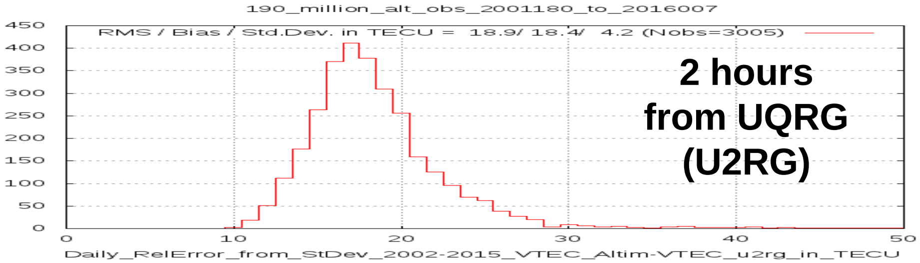


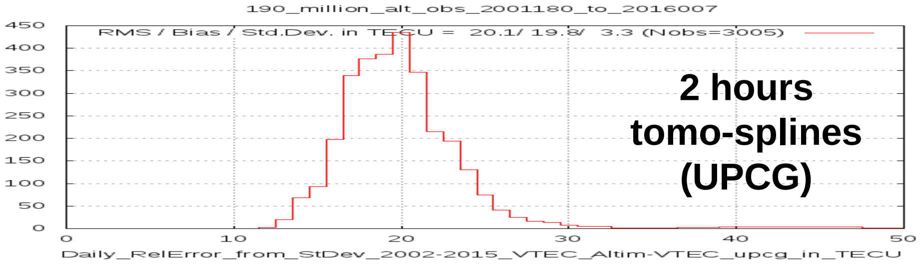


Influence of GIM time update: Rel.Error (2001-180 to 2016-007)









GIM Id.	Re.Error [2015,117-2016,007] / %	# Days
UQRG	17.8	3005
UHRG	18.0	3005
U2RG	18.4	3005
UPCG	19.8	3005

✓The previous results in terms of the standard deviation of the altimeter-GPS VTEC are confirmed when relative error is considered.

✓The influence of increasing the GIM time interval from 15 min., to 1 and 2 hours, provide a marginally increasing error vs. altimeter VTEC of 17.8, 18.0 and 18.4% (**the same, 18% rounded**) in front of a relative error of 19.8% **(20% rounded) when we consider the previous interpolation technique used at UPC** (the tomographic part is the same).

dSTEC relative error in descending order

(from +50 indep. GPS receivers, days 082, 146, 280 and 330, 2015)