Summary and current status of IGS Ionosphere WG activities.
A potential future product: Global maps of effective ionospheric height.

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Abstract

The purpose of this paper is to summarize the present status of the International GNSS Service (IGS) Ionosphere Working Group and some recent activities. The first part will be devoted to show the recent performance of the final and rapid Global Ionospheric maps of Vertical Total Electron Content (VTEC), and inter-frequency delay code biases (DCBs), which constitute the main products and activities of the WG, based on the contribution of the four involved agencies, CODE, ESA, JPL and UPC.

In the second part of the talk, additional activities performed in the context of the WG will be summarized as well: in particular the study of a potential future ionospheric product: global maps of ionospheric effective height.

1. Final and rapid IGS VTEC maps: performance update

The performance update of the IGS VTEC maps, and DCBs, will be based –similarly to previous works, see Hernández-Pajares 2004- on the following comparisons, performed from day 322, 2005 to day 112, 2006:

1) Comparison of GPS VTEC maps (both rapid and finals) to direct VTEC observations over the Seas, provided by dual-frequency altimeters (presently JASON, TOPEX in the past).
2) Comparison of rapid VTEC maps with final IGS ones, for the whole Ionosphere.
3) Stability and comparison of DCBs for satellites.
4) Stability and comparison of DCBs for selected, representative receivers.

And we present as well a new comparison: IGS versus Satellite Based Augmentation System (SBAS) over Europe (EGNOS augmentation system).

1.1 Comparison with JASON VTEC

The final IGS versus JASON VTEC comparison over the Seas shows in particular that the final IGS maps (Figure 1 and Figure 2, black line) are still in better agreement (lower standard deviation) after t~2005.95 (~3TECU, ~20% of relative error, associated to the VTEC reduction due to the Solar cycle approaching to minimum conditions). On the other hand the JASON-GPS bias is more discrepant. However the averaged IGS bias (GPS below JASON ~1.5-2 TECU) is compatible with the supposed JASON VTEC bias (see Figure 2, right hand plot).

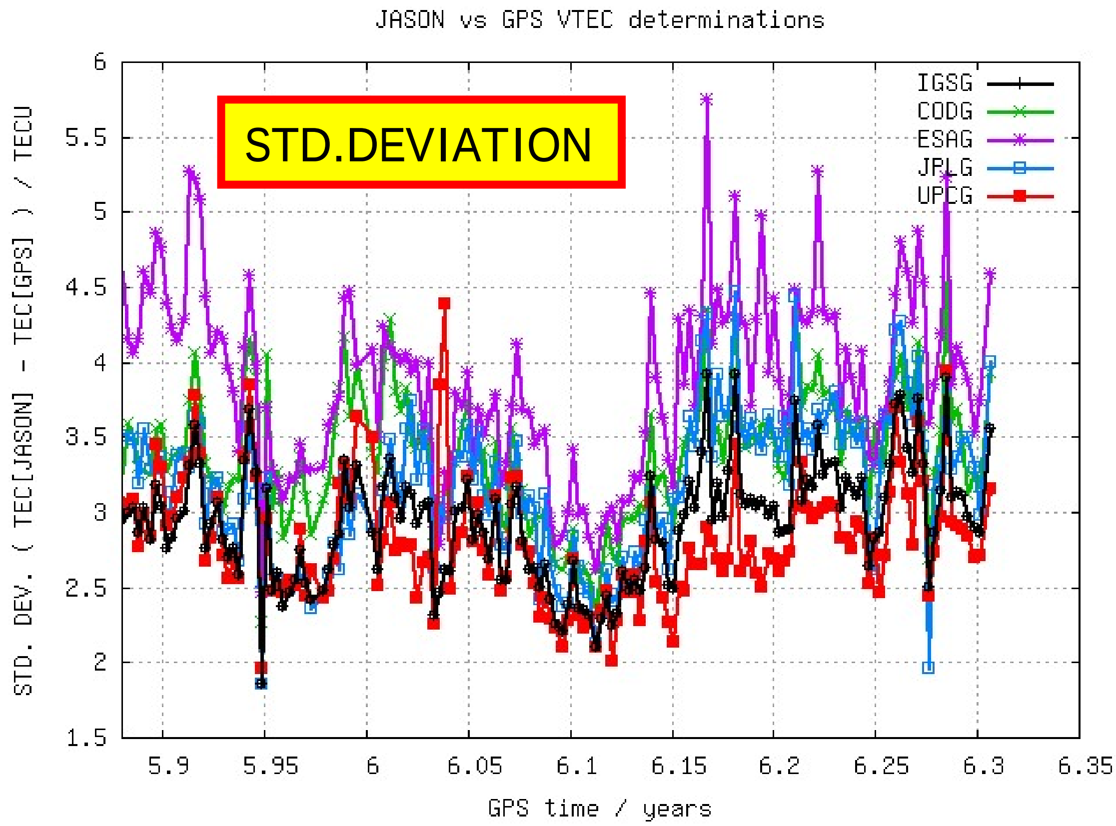

Figure 1: Standard deviation of the difference between final GPS global VTEC maps prediction and direct JASON VTEC measurements, as function of the GPS time, in years referred to 2000.

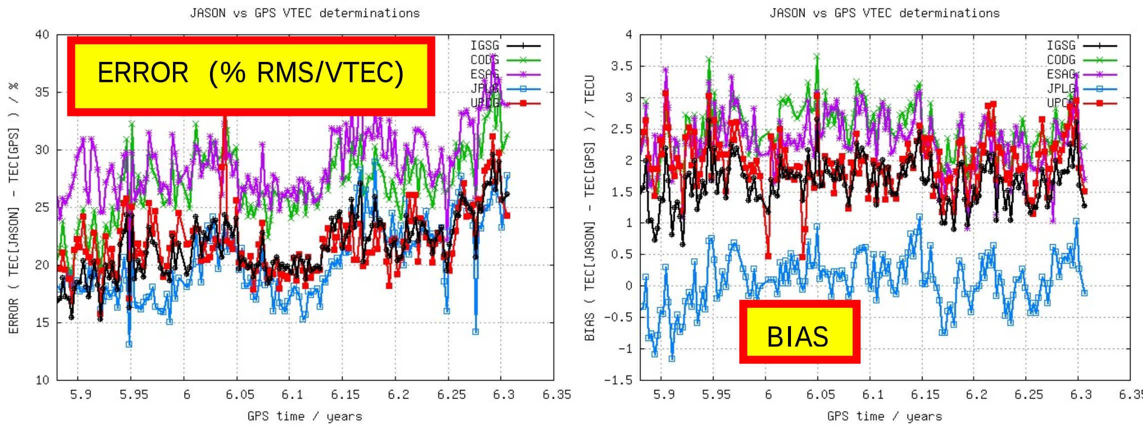

Figure 2: Error, and Bias of the difference between GPS global VTEC maps prediction and direct JASON VTEC measurements, as function of the GPS time, in years referred to 2000.

Regarding to rapid IGS versus JASON VTEC comparison over the Seas (Figure 3 and Figure 4), we can see that the Rapid maps (red line, latency ~24h) are in very good agreement with final ones (the Standard Deviation regarding to TOPEX is only few tenths of TECU below the final performance).

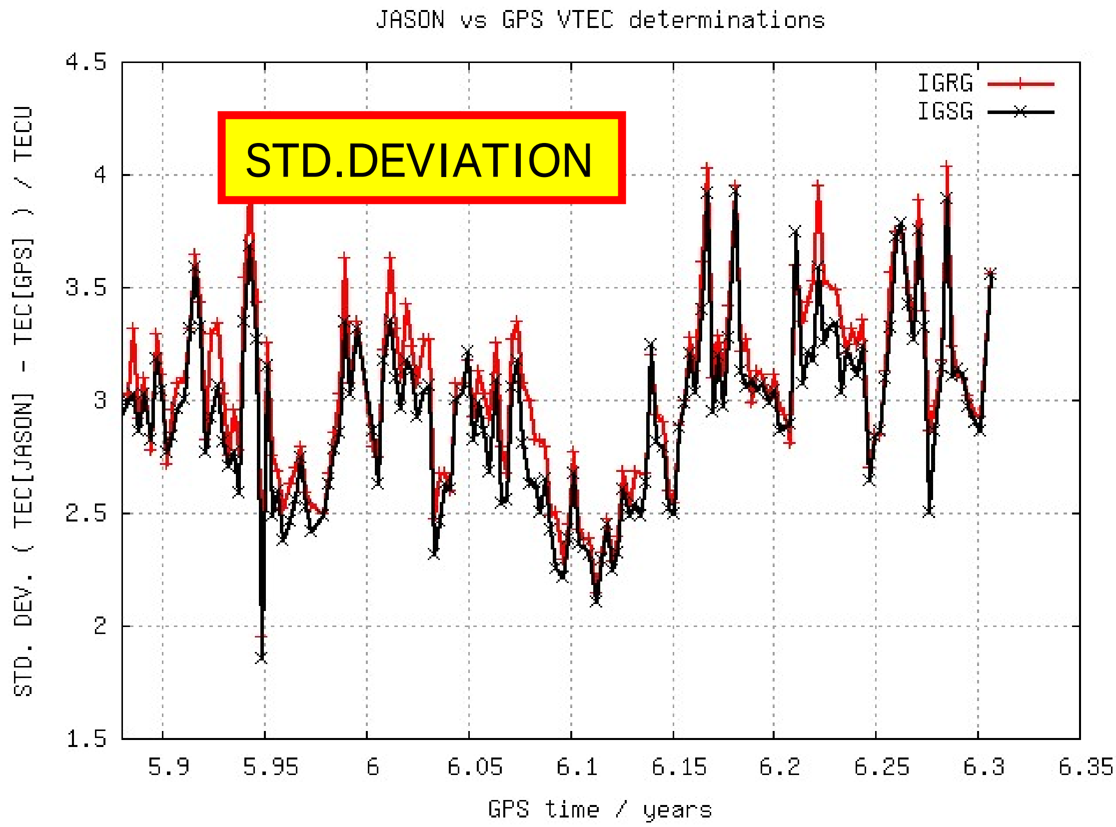

Figure 3: Standard deviation of the difference between rapid and final IGS global VTEC maps prediction (IGRG and IGSG respectively) and direct JASON VTEC measurements, as function of the GPS time, in years referred to 2000.

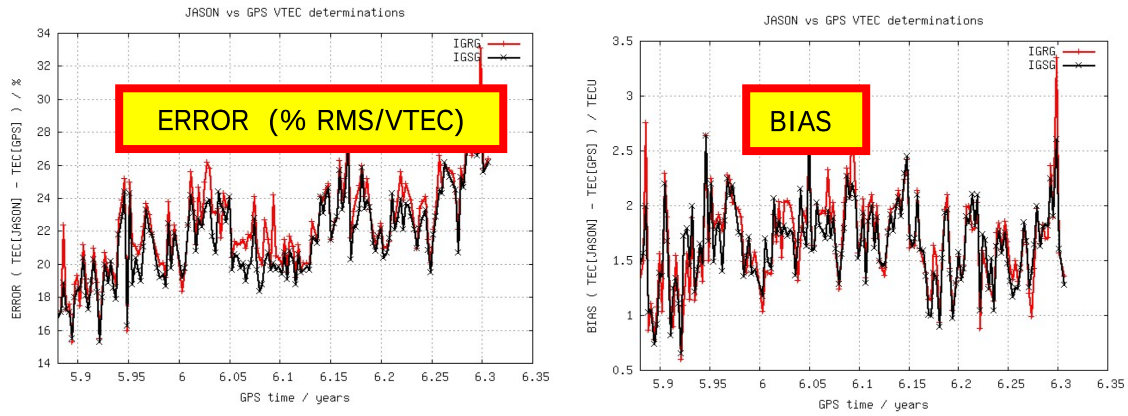

Figure 4: Error, and Bias of the difference between rapid and final IGS global VTEC maps prediction and direct JASON VTEC measurements, as function of the GPS time, in years referred to 2000.

An additional metrics of the rapid global VTEC, corresponding to the overall ionosphere, can be obtained by comparing rapid vs final IGS VTEC maps (see Figure 5 and Figure 6). It can be seen that rapid maps are in very good agreement with final ones (black line, ~1 TECU in Std.Dev, 0 TECU in Bias, global discrepancy ~5%). At the the same time, it shows good integrity, being the rapid IGS maps quite insensitive to few ESA and UPC problems (within red circle).

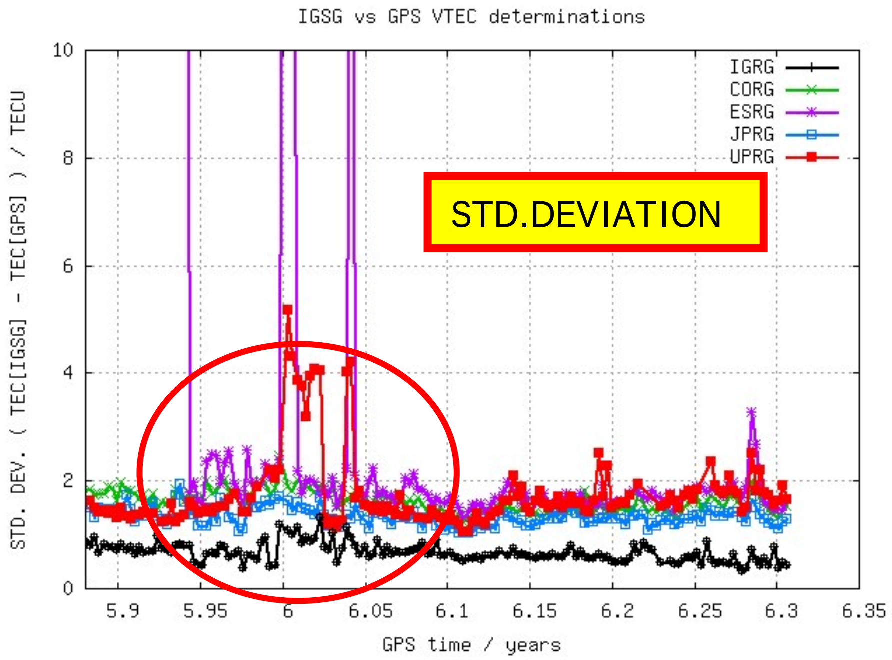

Figure 5*:* Standard deviation of the difference between rapid global VTEC maps and final IGS VTEC map, as function of the GPS time, in years referred to 2000.

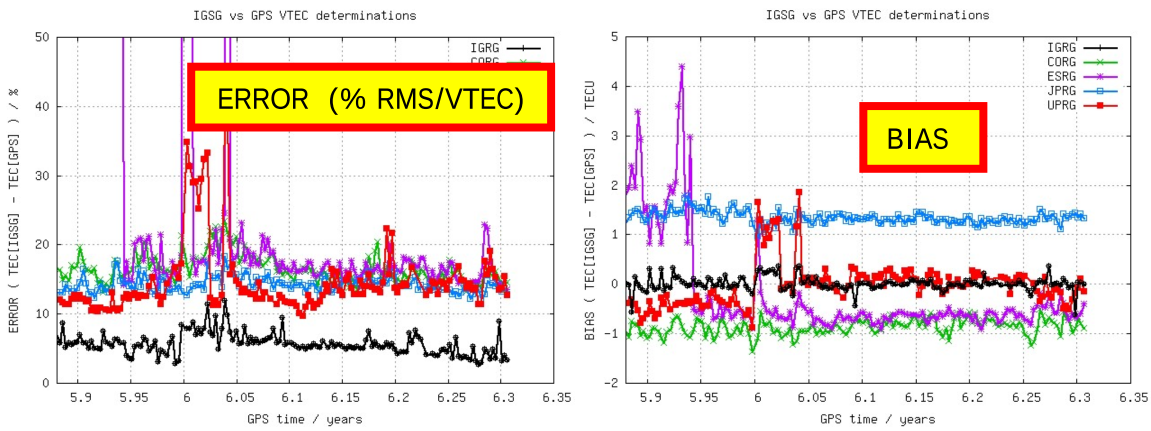

Figure 6*:* Error, and Bias of the difference between rapid global VTEC maps and the final IGS VTEC map, as function of the GPS time, in years referred to 2000.

1.2 Stability of instrumental delays

Looking at the satellite DCB agreement we can see that Final versus Rapid DCB averaged difference (points in Figure 7) and temporal variability (error bars) is quite compatible (<~0.1ns, except for PRN25, see again Figure 7). Looking into more detail, for the case of PRN25 which shows a higher discrepancy over the time, it can be seen that there is a real change in the value of the DCB, very well tracked independently from all the analysis centers, and combined IGS products (Figure 8 and Figure 9).

From the point of view of receiver DCB agreement, several representative examples can be seen in Figure 10. It can be seen that the typical final-rapid IGS DCB agreement ranges from ~1 to several tenths of ns, depending on the latitude as well.

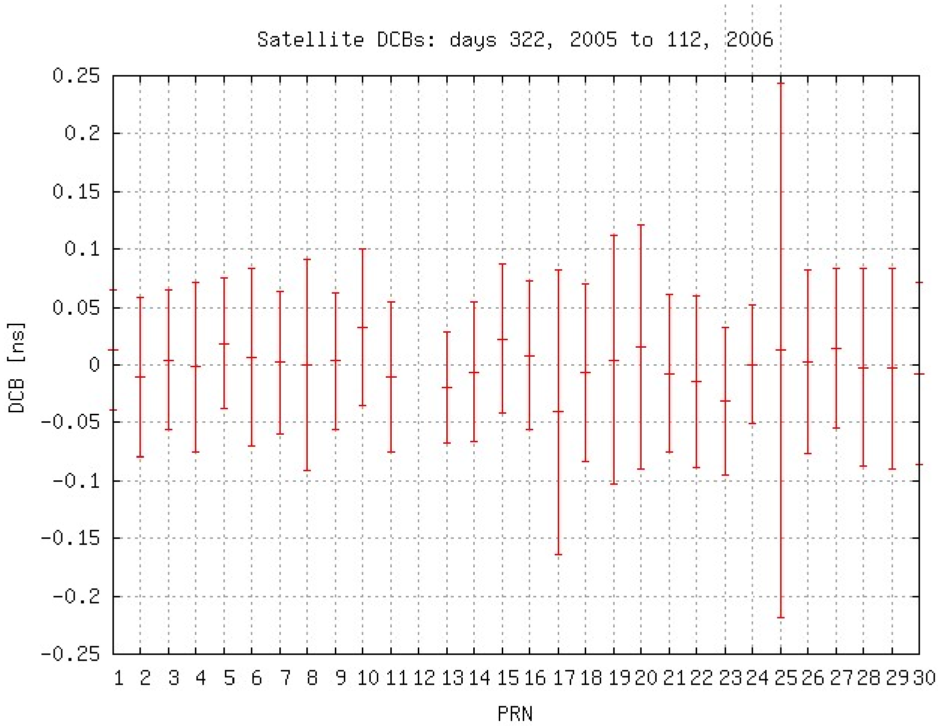

Figure 7: Averaged difference (and standard deviation in error bars) between rapid and final DCBs, in terms of the satellite PRN (from day 322, 2005 to day 112, 2006).

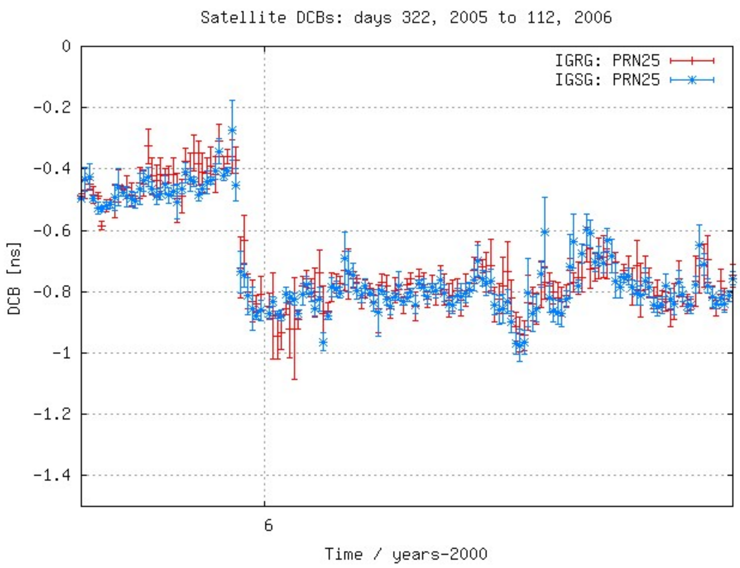

Figure 8: Evolution of rapid (IGRG) and final (IGSG) DCB estimations corresponding to PRN25, from day 322, 2005 to day 112, 2006.

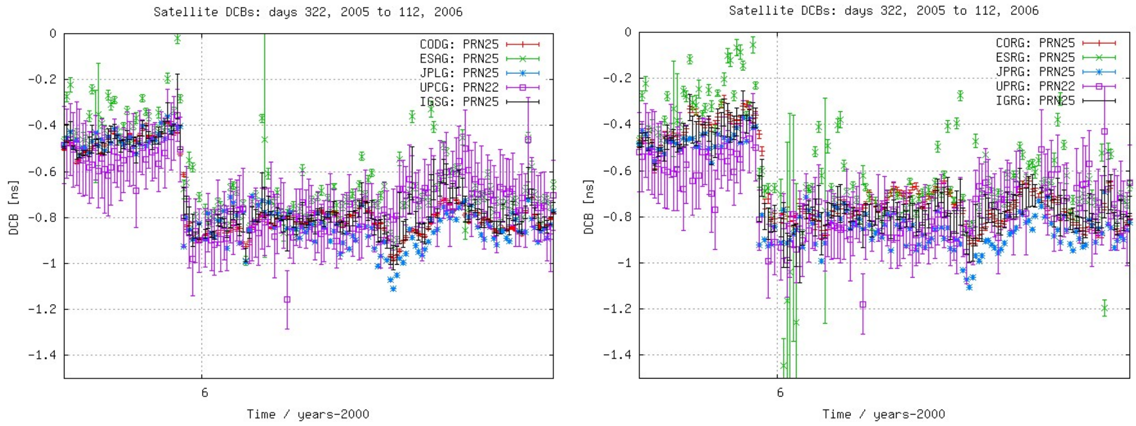

Figure 9: Evolution of different final DCB estimations (left hand plot) and rapid ones (right hand plot) corresponding to PRN25, from day 322, 2005 to day 112, 2006.

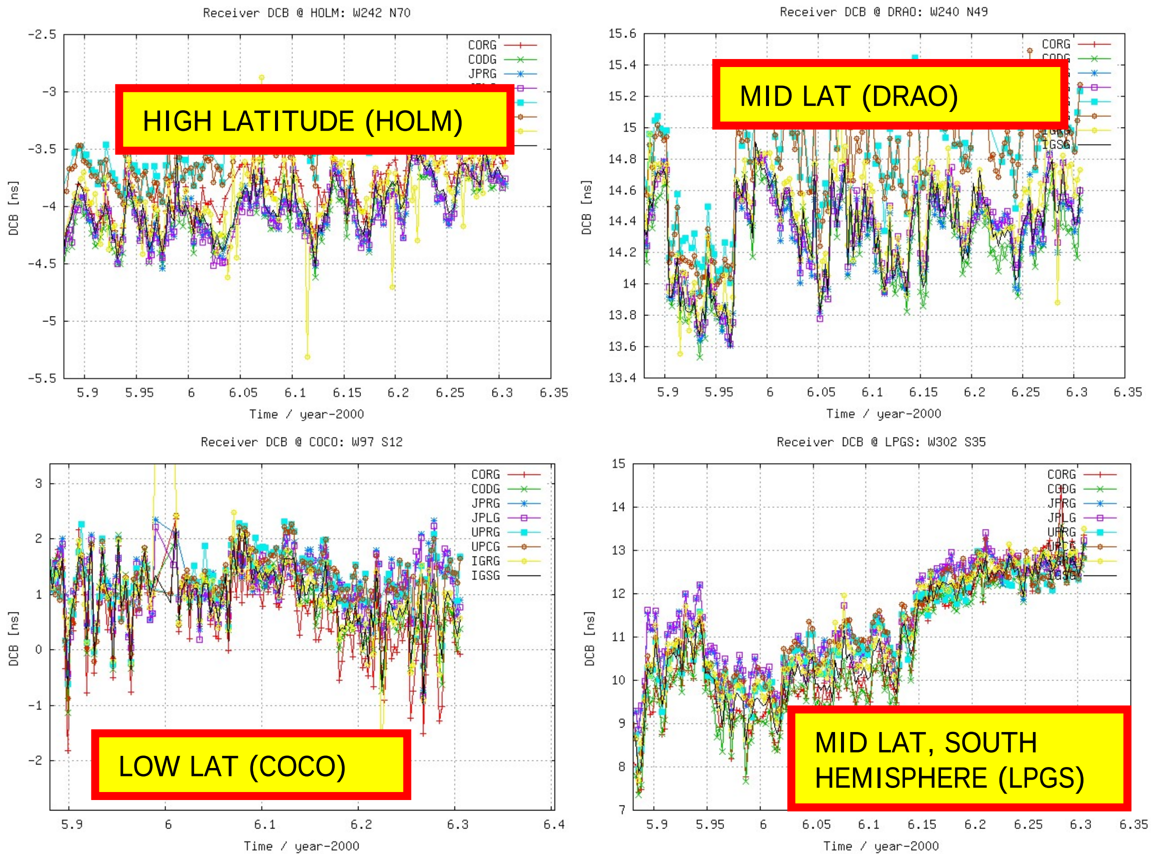

Figure 10: Comparisons of rapid and final DCB estimations for four typical receivers, at high, mid and low latitude, including southern hemisphere, in terms of GPS time (years referred to 2000).

1.3 Comparison between IGS and SBAS (EGNOS) model

The performance in double-differences –between pairs of satellites and receivers- of Slant TEC estimations, the magnitude affecting positioning, is compared between final IGS and real-time EGNOS ionospheric models. This is done over European baselines ranging from 100 to 1300 km (see Figure 11, taking as reference receiver Toulouse –toul-), being the ground truth provided by WARTK in postprocessing (see Hernández-Pajares et al. 2000 and 2002).

It can be seen in Figure 11 that the performance is quite good for post-processed IGS model (~30% better). This happens in spite of its poorer temporal resolution (2-hours) compared to the real-time SBAS/EGNOS model (~6 minutes updating time), specially taking into account the high geomagnetic activity conditions (reaching Kp index to a value close to the maximum of 9, at the noon).

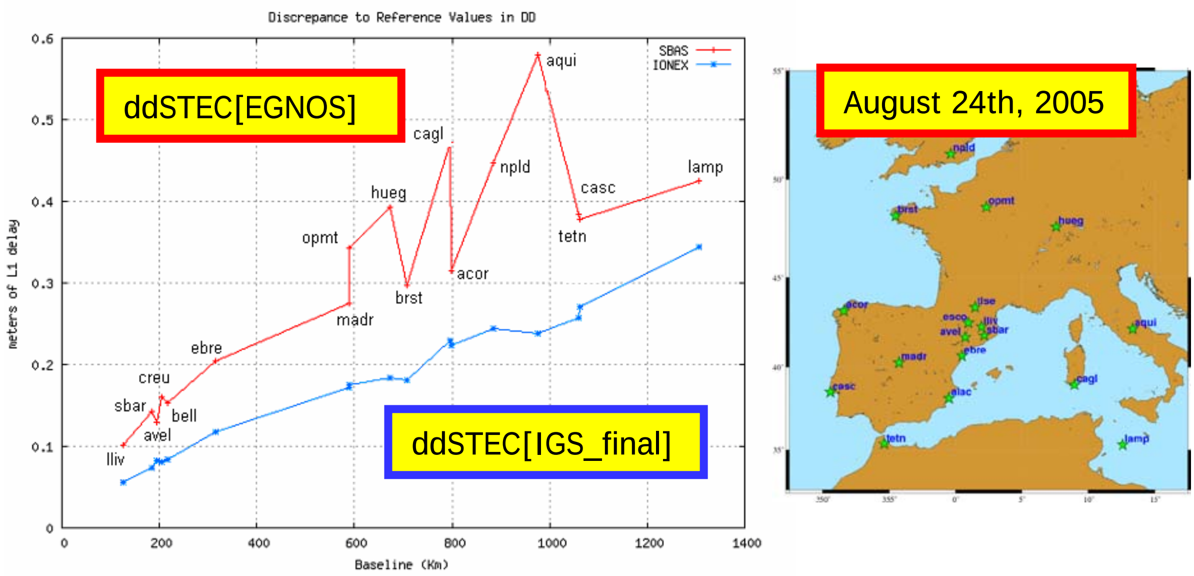

Figure 11*:* Comparison of the performance of EGNOS ionospheric model (red line) versus the IGS Final model (blue line) in order to predict the double-difference ionospheric corrections (left hand plot) for different baselines over Europe, taking as reference Toulouse (tlse, see map at righ hand plot). The reference values are provided by WARTK in post-processing mode.

1.4 IGS ionospheric product usage

The usage of IGS Ionospheric files, taking only into account the main IGS distribution server cddis.gsfc.nasa.gov, can be summarized from the information about the downloads in 2005 in the following way:

- ✓ More than 800 daily downloads of Ionospheric files.
- ✓ Typically ~100 daily downloads or more for each individual final IONEX file.
- ✓ The new rapid product show a significant download activity (~100 daily downloads all of them).

2. Ways of ionospheric correction improvement: Companion maps of ionospheric effective height

The particular relationship between slant and vertical total electron content (TEC) -the ionospheric mapping function- is one of the worst assumptions to consider typically when ionospheric corrections are estimated or applied from Global Navigation Satellite System (GNSS) data. On one hand it depends at a given time on the 3D electron content distribution and varies in terms of local time, latitude, season, Solar cycle epoch or ionospheric activity (see for instance

Komjathy & Langley, 1996). But on the other hand, and for the sake of easiness, the typical assumption in many GNSS imaging and navigation systems is to consider a fixed mapping function, constant, and associated to a 2D distribution of electron content at a given effective height (typically some value between 300 and 500 km). This can introduce, as it has been demonstrated by several authors, a significant and sometimes very important mismodelling that can affect to different applications such as global VTEC determination (see for example Hernández-Pajares et al. 1999a) and precise navigation (shown in Hernández-Pajares et al. 1999b).

2.1 Tomographic estimation and validation of the effective height

2.1.1 Definition from ground GPS data

The first point is to show the feasibility of estimating a more realistic (and accurate) mapping function at global scale, in terms of a variable GPS ionospheric effective height (hereinafter GIEH), and from dual frequency GPS ground stations. This can be done using a Ionospheric Voxel model (hereinafter IVM), contemplating several shells or layers, solved by means of Kalman filtering of geometry-free carrier phase measurements. This can provide the relative vertical distribution of electron content which leads to estimating the corresponding effective heights. The IVM approach has shown its greater accuracy in previous works in both global scale VTEC determination and real-time ionospheric determination supporting accurate GPS navigation (see for instance Hernández-Pajares et al. 2002).

In order to validate such GIEH estimation, an independent dataset and tomographic technique will be used: dual frequency data in an occultation scenario (with negative elevations) gathered from the SAC-C LEO GPS receiver during 2002 which provides vertical accurate electron density profiles by applying the improved inverse Abel transform (hereinafter IIAT, see for instance Hernández-Pajares et al. 2001). From each complete density profile, a GIEH value is derived and compared with the corresponding estimate from the IVM solution obtained from global ground GPS data. In both cases the corresponding GIEH has been derived, neglecting the horizontal VTEC gradient among other assumptions, by means of the following expressions 1 and 2:

$$M = \frac{S}{V} \simeq \int_{REC}^{TRA} \frac{N}{V} \frac{1}{\cos X}\, dh \simeq \sum_i \frac{P_i}{V} \frac{r_i}{\sqrt{r_i^2 - p^2}} \tag{1}$$

$$h = \frac{M}{\sqrt{M^2 - 1}} p - r_e \tag{2}$$

being M the mapping function computed for a ray of impact parameter p (p is taken corresponding to receiver elevation of 20 deg), S the Slant Total Electron Content (STEC), V the Vertical TEC, X is the zenith angle at the given height, N the electron density, Pi and ri the partial TEC and geocentric distance corresponding to the i-th layer, and p is the ray impact parameter and re is the Earth radius. Finally to say that h represents the GPS ionospheric effective height (also known as ionospheric shell height) defined by means of equation 2: It corresponds to a thin layer fitting to the estimated mapping by tomographic techniques by equation 1. Such value is typically higher than the hmF2 values due to the topside electron content included in h definition.

2.1.2 Validation with SAC-C data

The main comparison presented in this manuscript is performed for six consecutive days (days 258-263 of year 2002) of both global ground IGS data (about 160 permanent selected stations each day) and LEO SAC-C occultation data (about 1600 occultations), still corresponding to the more difficult Solar and Seasonal Maximum conditions. In Figure 12 you can see the GPS Ionospheric effective height obtained from IVM runs using ground data and with different vertical layout: 2 layers (@ 300-700 km height) and 3 layers (@ 250-550-850 km height). Similar results are obtained with 10 layers (@ 100 to 1000 km height). It can be seen that such determinations are quite compatible between then and with the value deduced from SAC-C data. Both vary mostly due to the periodic change in local time, and latitude, along the LEO orbit.

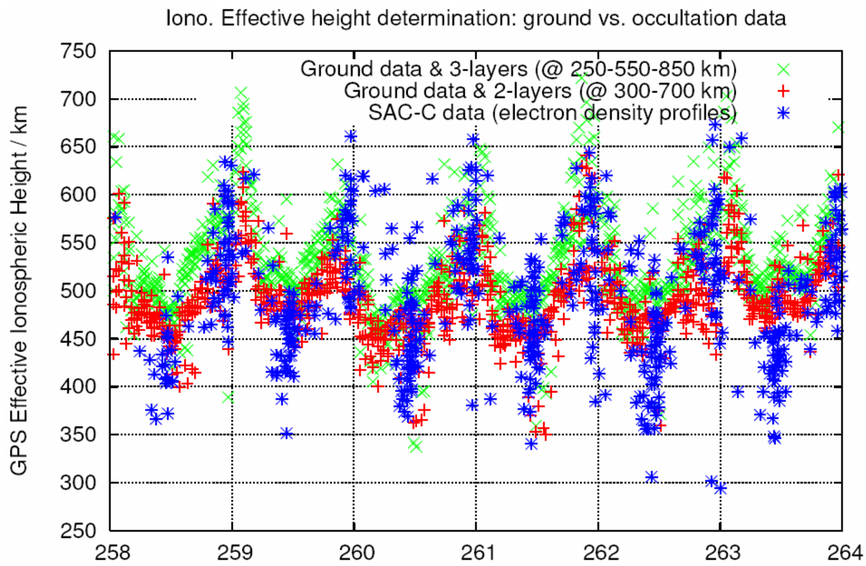

Figure 12: Validation of Ionospheric effective height determined from global ground GPS data compared to values derived from electron density profiles computed from SAC-C LEO data (days 258-263 of 2002).

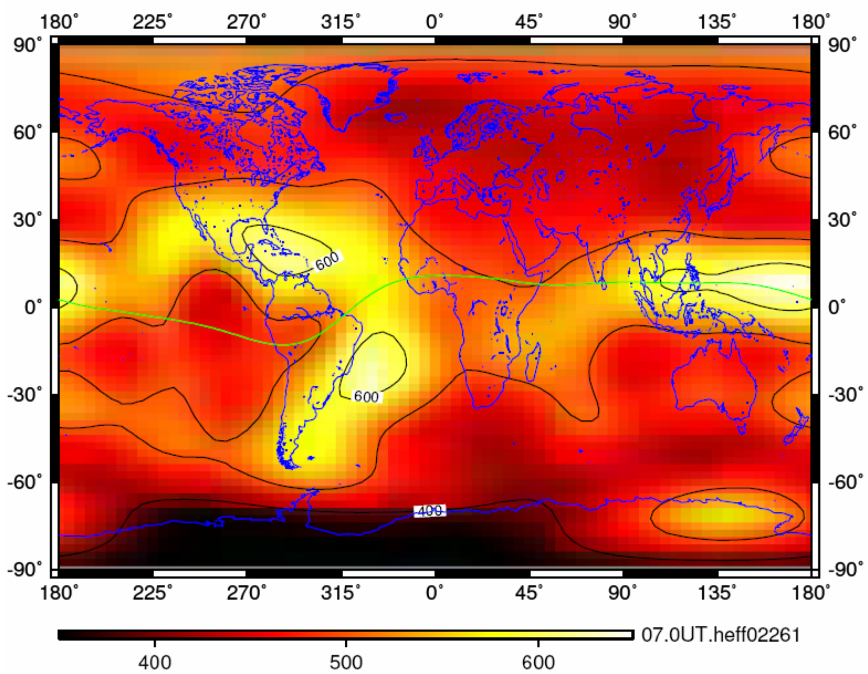

Figure 13: Example of GPS Ionospheric Effective height (in kilometers) computed from global IGS data for 0700UT, day 261 of 2002.

As examples you can see typical snapshots of the effective height and VTEC estimations in Figure 13 and Figure 14 respectively (0700 UT, day 261, 2002). It can be seen in particular the known increase of effective height at the beginning and last part of the night, compatible with variations predicted by climatological ionospheric model, such as IRI. Such increase is more important at low latitudes, and shows a bimodal pattern, around the magnetic equator, before the sunrise.

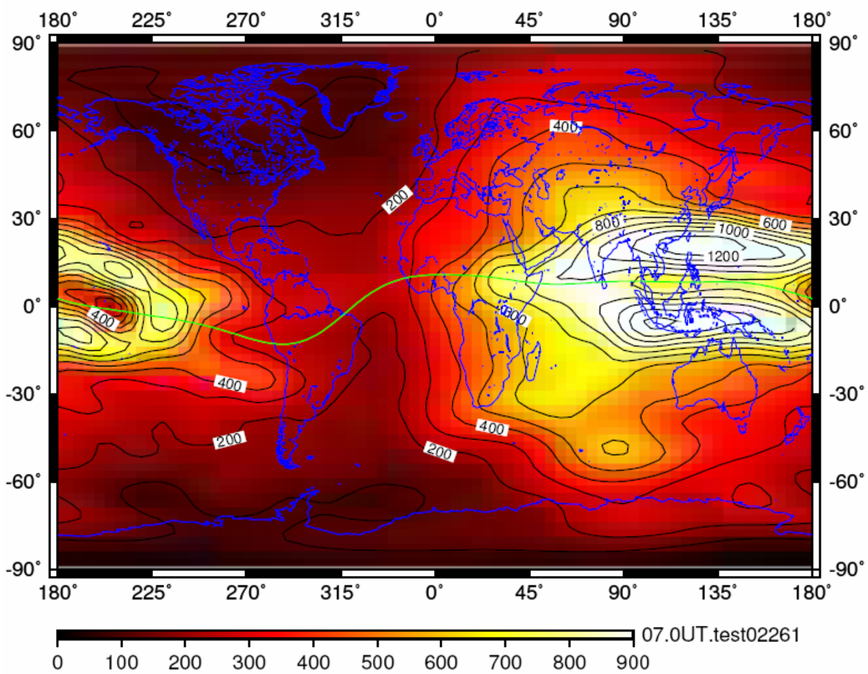

Figure 14: Total Electron Content (in tenths of TECU) snapshot computed simultaneously to the effective height map shown in the previous figure (0700UT, day 261 of 2002).

2.2 Applications: impact on precise navigation

In order to give a first glance assessment of the estimated effective height impact on precise navigation, the following experiment has been performed: Several ground GPS stations of the CORS network (Figure 15) have been processed (black) to generate ionospheric corrections which are compared to the true values (obtained by WARTK, fixing phase ambiguities) over an additional station MCON (Figure 16).

It can be seen that the interpolation with standard single thin layer model (red) provides worst results than the results with the mapping obtained from the estimated ionospheric effective height in the network (blue), specially when the effective height (black) diverges regarding to the fixed value of 450km. The VTEC is represented in green.

3. Conclusions and additional activities

We can conclude that:

- The updated performance of the rapid and final IGS VTEC and associated DCBs maintains a good figure of accuracy and integrity.

- We have shown as well the feasibility of estimating reliable ionospheric effective heights from ground GPS measurements at global scale, providing a way to get more realistic and accurate mapping functions for GPS users.

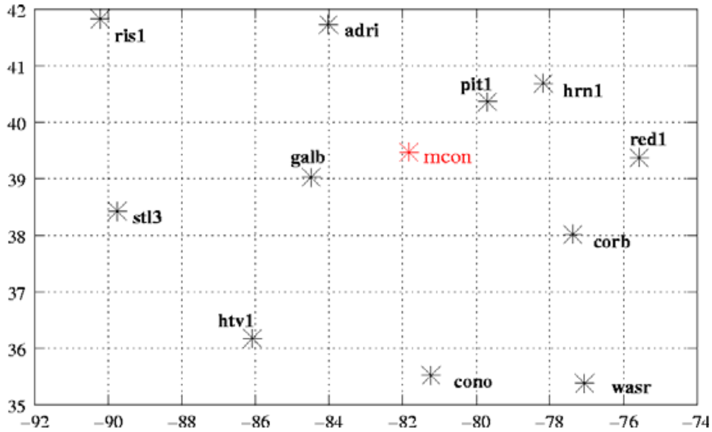

Figure 15: Layout representing the reference station network (black stars) and the fixed site treated as rover (red), all of them extracted from the CORS GPS network in North America.

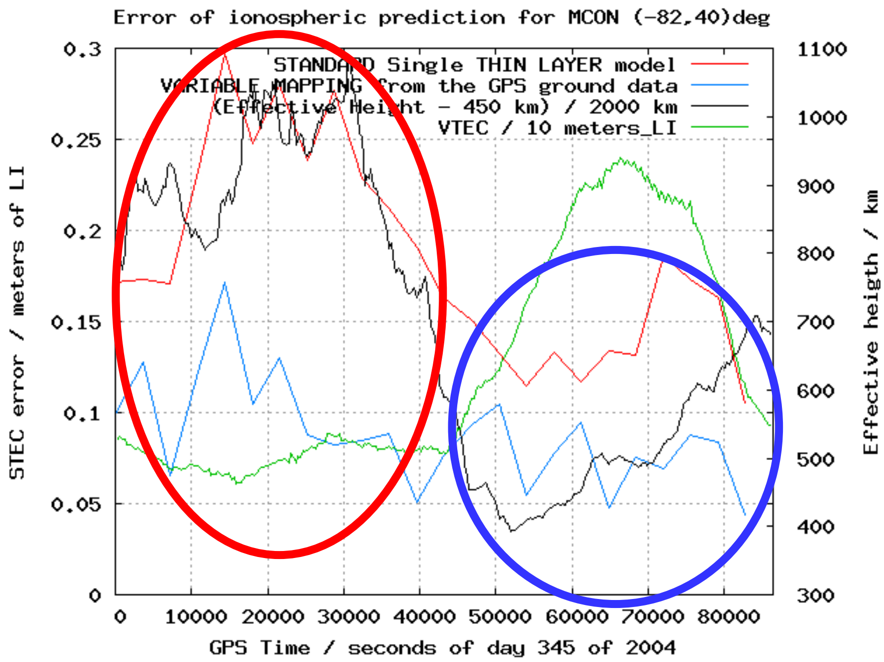

Figure 16: Error in the ionospheric correction provided to a roving user (mcon, see previous figure) when a variable effective height is used (blue line). It is compared versus using a fixed height layer approach (red line). The effective height (black line) and the VTEC (red line) are also represented.

Moreover other activities performed in the context of the Ionosphere IGS working group are:

- IGS VTEC temporal resolution increase, from 120 to 5 minutes, using all the available receivers, where ionospheric carrier phase combination is aligned with the 2-hours map and averaged in each pixel without interpolation. It was tested in CAWSES campaign during Sept.05 campaign: ftp://gage152.upc.es/rapid_iono_igs/high_rate/2005.
- 2nd order ionospheric term: its assesment has been performed on practical aspects in particular (it can be applied from either VTEC maps or P2-P1 and DCBs, importance of

using a more realistic geomagnetic model –reduction of ~50% of error in certain regions among other aspects).

- Potential improvements are envisaged in an ionospheric reprocessing campaign (Orus et al. paper, in the same proceedings).

Additionally, the following potential ionospheric recommendations have been identified in the context of the IGS 2006 Technical meeting:

1. For analysis centers: To test the reprocessing performance and required resources in the IGS pilot reprocessing campaign (January-March 2000).
2. For analysis centers: To consider the temporal resolution increase of the maps to 15 min (during pilot reprocessing campaign?).
3. For analysis centers: To consider the possibility of estimating maps of ionospheric effective heights (during pilot reprocessing campaign?).
4. For users, second order ionospheric correction: Importance of using a more realistic geomagnetic model, such as the International Geomagnetic Reference Model (IGRM, Geopack subroutines, Tsyganenko, 2003), with a reduction of up to ~60% correction error in certain regions.

Acknowledgments

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