Study of several models to provide ionospheric corrections to GNSS users

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SUMMARY

As it is well known many GNSS users are using single frequency receivers in their applications. These types of receivers are not able to correct directly the delay produced in the ionosphere, that can reach values of tens of meters. To overcome this problem there are several models that can be used to correct this ionospheric term: the GPS Broadcast model available with the GPS navigation message, empirical models like the IRI, and GPS data driven models,the last ones are being computed since June 1998 by the IGS Associate Analysis Centers (CODE, EMR, ESA,JPL and UPC).

These models have different performances and can be or not suitables depending on the desired accuracy for each given application. A comparative study of such models is discussed in this paper, by comparing with independent ionospheric estimates provided by the TOPEX/Poseidon dual frequency altimeter.

New improvements of the ionospheric correction algorithms using GPS data, for real-time and precise navigation purposes, will be also studied.

1. INTRODUCTION

As it is known, the ionosphere is one of the main source of error in the GPS positioning. This is due to the fact that the radio signals are affected by the electron content inside the ionosphere. Thus, this disturbance affects differently codes and carrier phases, producing a delay-advance that can lead to an error about tens of meters (see Davies (1990)).

To overcome this problem there are different strategies, but the limiting factor is which kind of receiver (single or dual frequency) is using the GNSS users. In this context, when a dual frequency receiver is used, the contribution on the error by the ionosphere can be eliminated with a combination of the two signals transmited by the GPS satellites (f1=1574 MHz and f2=1227 MHz). However when a single frequency receiver is used, the ionospheric delay cannot be eliminated directly. In these cases it is necessary to use an external determination. In the GPS system this function is done by the Klobuchar model (see Klobuchar (1996)) that satellites broadcast in the navigation message. However, this model has low accuracy, since it uses only 8 parameters to describe ionosphere. Moreover, there are other kinds of models to correct the ionospheric error like Climatological or Empirical models (such as the International Reference Ionosphere (IRI), Bilitza (1990)) and the GPS data driven models (such as the Global Ionospheric Maps (GIM's) provided at IGS).

In this framework, a study between the different kinds of models and among the GIM's provided by the IGS has been done with the help of TOPEX data. This study provides a determination about the accuracy of the different kind of models. But the accuracy of the improved real time technique (Hernández-Pajares (2001)) has been also studied in order to show the feasibility of computing a real time *precise* ionospheric corrections.

2. UPC MODEL

The UPC model uses a voxel approach in order to compute the GIM's. This model is able to count with carrier phases L_1 and L_2 only (less affected by multipath and measurement errors), through the ionospheric free combination.

To process the data, a Sun fixed reference frame is chosen due to the fact that the Sun is the main source of ionization. With this reference frame, it can be asssumed that the electron content varies slowly. In this scenario the ionosphere is decomposed in cells (or voxels, see Figure 1). Then, in a given time and for a given satellite-receiver ray, the main observation can be expressed as (Hernández-Pajares et al. (1999)):

$$L_I = \sum_i \sum_j \sum_k (Ne)_{i,j,k} \cdot \Delta s_{i,j,k} + b_I \qquad (1)$$

Where *i,j,k* are the indices for each cell corresponding to local time, latitude and height; $Ne_{i,j,k}$ is the electron density for each cell; $\Delta s_{i,j,k}$ is the lenght of the ray path for each cell; and b_I is the arch bias.

Thus the GIM is computed, firstly, estimating the TEC independently for each station (about 100 IGS stations worldwide distributed). This TEC is computed with the voxel model with 2-layers and it is solved with temporal resolution of 2^h in UT, and spatial resolution of 5° in local time and 2.5° in latitude. Secondly, this regional solutions are combined and interpolated with the help of the IRI model. This is useful in zones where there are data sparsity (oceans) and high TEC gradients such as the equator (see details in Hernández-Pajares et al. (1999)).

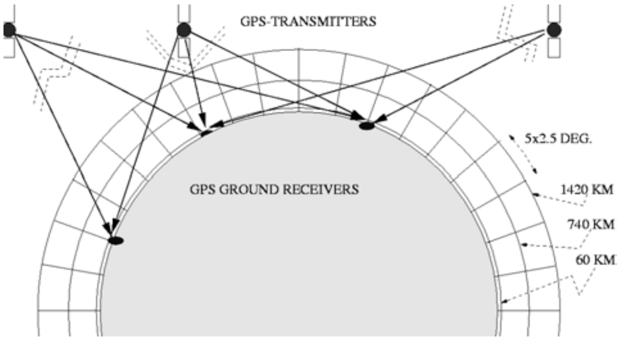

Figure 1: Voxel structure used in the tomographic approach.

3. TOPEX COMPARISON

In order to evaluate the performance of the different models, the data provided by the altimeter satellite TOPEX/Poseidon is used. This satellite has, among other instruments, a dual transmiter-receptor that has the capability of measuring the vertical TEC, below its mean orbit (about 1350 Km), with an accuracy of several TECU ~10^{16} e^- / m^2 (see Ho et al. (1995)).

Then, to compute the accuracy of the different kind of models, the comparison is done in two ways:

- The GPS broadcast model, the IRI, and the GPS data driven model (such as UPC GIM), are evaluated.
- The differents GIM's computed from GPS data by the IAAC's are evaluated.

In this context, the comparison is done by means of computing the Bias and RMS regarding to TOPEX data as:

$$BIAS = \langle TEC_{TOPEX} - TEC_{Model} \rangle \qquad (2)$$

$$RMS = \langle (TEC_{TOPEX} - TEC_{Model})^2 \rangle \qquad (3)$$

Since the interpolation is an important source of error for the GIM's computed from GPS data, two different kind of studies are done.

In the first study, trying to diminish the effect of interpolation, two zones with close GPS receivers have been choosen; the first is in the Mediterranean Sea, which is centered at mid latitudes (notice that is where there are the vast majority of users); the second is in Indonesia, which is centered at equatorial latitudes (notice this is a "worse case" scenario).

Table 1 – Results among the differents models for the two selected areas for the year 2000. The third column corresponds the relative error computed as (Err = RMS_{GIM} / TEC_{TOPEX}).

Mediterranean Sea (101,00 obs.)			
	Bias$_{\text{IN TECU}}$	**Rms$_{\text{IN TECU}}$**	**Error %**
Br.GPS	6.3	12.0	35
IRI	2.6	8.9	26
UPC GIM	0.7	4.0	12

Indonesia (656,000 obs.)			
	Bias$_{\text{IN TECU}}$	**Rms$_{\text{IN TECU}}$**	**Error %**
Br.GPS	24.9	32.3	60
IRI	11.6	22.2	41
UPC GIM	-1.0	9.1	17

The results for this study show that the best performance, as it could be expected, is for the GPS data driven model (UPC GIM). Then, it is possible to see that in Indonesia zone the relative error for the GPS Broadcast model and for IRI model are increased, at least, by a factor 1.5, mainly due to the fact that in this zone the TEC gradients are stronger than in the Mediterranea Sea zone. Meanwhile the error for the GPS data driven is more or less the same. This fact makes the GPS data driven model more compatible with TOPEX observations.

In the second study, the whole source of data are taken into account in order to determinate the global accuracy of the differents models. In this study the error due to interpolation scheme is taken into account as well.

Table 2 – Results of the global comparison for the differents models for the year 2000.

Global (15,600,000 obs.)			
	Bias$_{\text{IN TECU}}$	**Rms$_{\text{IN TECU}}$**	**Error %**
Br.GPS	12.2	19.9	54
IRI	1.1	15.1	41
UPC GIM	-0.2	9.0	24

Looking at Table 2, the best performance, as in the previous study, is for the GPS data driven model. For the GPS Broadcast model, the global relative error (54 %) is compatible with previous studies (see Klobuchar et al. (1996)). This high error may be produced by the few parameters that are used in the computation. This fact makes impossible to take into account complex structures, like the equatorial anomalies. For the IRI model the error (41 %) is high compared to the number of parameters used in the GIM computation, this error may be produced by the overestimation that the IRI makes at high latitudes. The GPS data driven model present a negative bias (close to zero) and the lowest relative error (24 %) that makes this model the most compatible with TOPEX observations.

In the same way, a similar study can be done for the different IAAC's. Notice that in the previous section it has been demostrated that the best performance is for the GPS data driven models. But inside the IAAC's there are significant differences.

Table 3 – Results of the global comparison for the differents IAAC's for the years 2000 and 2001.

Global 2000 (15,600,000 obs.)			
	Bias$_{\text{IN TECU}}$	**Rms$_{\text{IN TECU}}$**	**Error %**
CODE	4.5	9.7	26
EMR	3.8	12.7	34
ESA	3.5	11.6	31
JPL	-1.4	7.2	20
UPC	-0.2	9.0	24

Global 2001 (14,000,000 obs.)			
	Bias$_{\text{IN TECU}}$	**Rms$_{\text{IN TECU}}$**	**Error %**
CODE	2.8	8.8	24
EMR	3.2	12.7	34
ESA	2.4	10.9	30
JPL	-1.6	6.9	19
UPC	0.0	8.0	22

The results are shown in Table 3, where there are the global comparison for the years 2000 and 2001. This table shows the discrepances among the differents IAAC's. Thus, there are significant differences in Bias among the IAAC's: Centers with TEC determinations below TOPEX TEC, that they are not compatible with TOPEX observations. And, centers with TEC determinations above TOPEX TEC, that they are compatible with TOPEX observations.

These discrepances may be produced by the differences between the models used to computed the TEC.

4. REAL TIME IONOSPHERIC DETERMINATION

In this section the goal is to compute the UPC TEC maps in real-time, combining both ionospheric and geodetic computation, resolving and fixing the integer ambiguities common unknowns (see details in Hernández-Pajares et al. (2000)).

Thus, it has been performed an experiment to study the performance of the real-time technique (Hernández-Pajares et al. (2001a)). This experiment takes place in 4 consecutive weeks in March-April 2001, in Solar Maximum conditions, but with variable geomagnetic activity: quiet geomagnetic conditions during the first 2 weeks (Kp < 4) and high geomagnetic conditions during the last 2 weeks, with one day with Kp = 8.5. It has been used 12 IGS GPS sites between about -40° to 50° in latitude (see Figure 2), at very long distances, with baselines between 1000-3000 km. Part of these stations are affected by the equatorial anomalies.

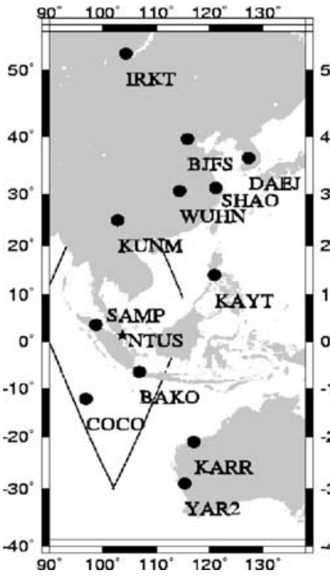

Figure 2 – IGS GPS sites used in the experiment of real-time ionospheric determination. The lines are the TOPEX footprint for the comparison for the doy 67 of the year 2001.

As an example of the results obtained, the vertical determination in real-time has been compared with the TOPEX observations and with the UPC GIM determination (see Figure 3 to see an example of the comparison).

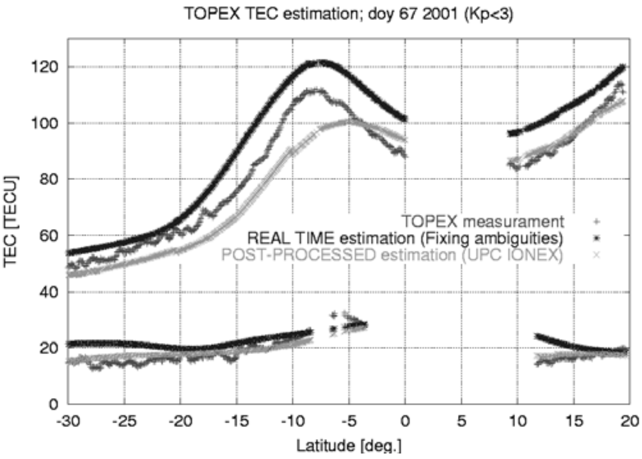

Figure 3 – Comparison of Real-time ionospheric determination with TOPEX data and UPC GIM for the doy 67 of the year 2001.

Looking at Figure 3, it is posible to see that there are two passes of the TOPEX satellite, the first one, corresponding to a day pass (the lines have TEC values between 40 – 120 TECU), and the night pass (the lines have TEC values close to 20 TECU). The most interesting for the study is the one corresponding to the day pass because the TEC values are higher. Then, there are significant differences of several TECU between the TOPEX TEC and the real-time ionospheric determination. This can be due to the plasmaspheric component (part of the ionosphere above 1350 km, that is the mean TOPEX height) that can reach up to 7 TECU (see Lunt et al. (1999)). Therefore, the real-time determination is compatible with TOPEX+Plasmaspheric TEC.

Additional comparisons have been performed to show that the accuracy of such real-time corrections is about 1 TECU in this difficult scenarios.

5. CONCLUSIONS

The study of the differents kind of models to provide ionospheric corrections to GNSS single frequency users has been done trying to lump together all representative models, and real time ionospheric determination as well.

Thus, the comparison between the different kind of models regarding to TOPEX data can be summarized, in terms of relative error, as: GPS Broadcast model (54%), Climatological model (41%), and GPS data driven model (21%).

But, when the different GPS TEC Models are studied comparing with the TOPEX TEC estimates, it is clear that there are significant biases of several TECU depending on vertical modelling. These discrepances are significant if it is desired to combine the different GPS data driven models in a common ionospheric product.

In the sense of real time ionospheric determination, a new technique has been improved to get precise real-time STEC's from reference GPS sites in long distances at low latitudes and Solar Maximum conditions. With this technique there are potencial applications such as: precise water vapor determination (see Hernández-Pajares et al. (2001b)) and precise (subdecimenter) navigation in WADGPS-like networks (see for details in Hernández-Pajares et al. (2000)).

6. ACKNOWLEGMENTS

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