Pergamon
www.elsevier.com/locate/asr
Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
doi: 10.1016/S0273-1177(03)00026-7

VALIDATION OF THE GPS TEC MAPS WITH TOPEX DATA

R.Orús[1],M.Hernández-Pajares,J.M.Juan,J.Sanz,M.García-Fernández

[1] *Group of Astronomy and Geomatics/Universitat Politècnica de Catalunya (gAGE/UPC) Barcelona, Spain*

ABSTRACT

The existence of a worldwide IGS (Internacional GPS Service) permanent network of dual frequency receivers, makes feasible the computation of Global Ionospheric Maps (GIM's) of vertical Total Electron Content (TEC). The GIM's computed by the IGS Associate Analisys Centers (IAAC's) are being computed in a daily basis since 1998. The comparison with other kinds of forecast GIM's (computed from the International Reference Ionosphere (IRI) model and the GPS broadcast model) show that the GPS GIM's provide better accuracy and are useful for different applications such as navigation and time transfer. In this context, the performance of both kind of models are presented in this work in order to determine the accuracy of the different Global Ionospheric Maps. This is done by comparing with the TOPEX data that provides an indepentent and precise vertical TEC determination over the oceans (at the level of few TECU) which provides a way of validating the GIM's.

INTRODUCTION

The Navstar/GPS system provides the capability of positioning receivers with an accuracy of a few meters, if the code pseudorange is used, and few centimeters, if the carrier phases are used, wherever the user is. This precision is mainly due to the fact that at any time and at any location the user can lock 4 or more satellites to solve the four main unknowns: 3D position and user clock error, (there are at least 24 satellites distributed in six orbital planes, at 26000 km of radii, with an inclination of 55^o respect to the equator). These satellites broadcast two carrier phases at two frequencies in the L-band (L_1 at 1575.42 MHz and L_2 at 1227.60 MHz) modulated by several signals; the codes Pseudorandom noise (PRN) and the navigation message. Since electromagnetic signals are affected by ionized media, this system is useful to monitor the ionosphere not only on a regional but in a globlal scale as well.

As it is known, the vast majority of GNSS users are using single frequency receivers in their applications. These type of receivers are unable to eliminate one of the most important sources of error for the GPS applications: the delay produced by the ionosphere, with typical values of tens meters. To correct this error the users can rely on different kinds of models that predict the vertical Total Electron Content (TEC) at their location. The GPS signal broadcast an 8 parameters global model, that can correct about 50 % of the delay (see for instance Klobuchar, 1996). More accurate models, based on a multiparametric description of average data, can also be used (such as the International Reference Ionosphere (IRI), Bilitza, 1990). Finally, the existence of a worldwide network of GPS receivers allows the computation of more reliable Global Ionospheric Maps (GIM's) of TEC based directly on the actual data. There are five centers (IAAC's: CODE (University of Bern; Schaer 1999), EMR (Energy, Mines and Resources, NRCan; Gao et al), ESA (European Space Agency; Feltens, 1998), JPL (Jet Propulsion Laboratory; Ho et al, 1995) and UPC (Polytechnical University of Catalonia; Hernandez-Pajares et al, 1999)) computing global TEC maps on a daily basis, in the framework of the IGS ionospheric working group (see Feltens, 2002).

In order to evaluate these different kind of global ionospheric models, and the GPS GIM's produced by the differents IAAC's, an external and independent source of data will be used: the TOPEX/Poseidon TEC derived from the dual-frequency altimetric data.

Adv. Space Res. Vol. 31, No. 3, pp. 621–627, 2003

Printed in Great Britain
0273-1177/03 $30.00 + 0.00

UPC GIM MODEL

Data procesing

To compute the GIM's, the UPC uses a tomographic approach to describe the input data: the ionospheric (geometric-free) combination of carrier phases ($L_I = L1 - L2$).

Since the Sun is the main source of ionization, it has been chosen a Sun fixed reference frame to process the data, because in this reference frame the electron content varies slowly and the unknowns update can be done less frequently. In this scenario, the ionosphere is divided into a set of cells or volume elements (voxels) in which the electron density is considered constant (see Figure 1). Then, in a given time for a given satellite-receiver ray, the ionospheric carrier phase can be expressed as (see the details of the model in Hernández-Pajares et al, 1999):

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

Where i,j,k are the indices for each cell corresponding to local time, geodetic latitude and height; $(N_e)_{i,j,k}$ is the electron density for the i,j,k cell; $\Delta s_{i,j,k}$ is the length of the ray path crossing the illuminated cells; and b_I is the arch bias, that changes when a cycle-slip happens.

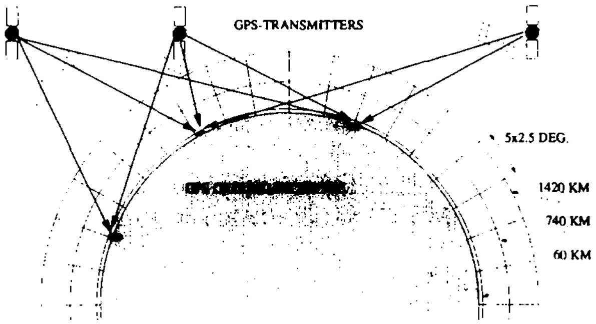

Fig. 1. Model scheme where there are depicted the voxel structure, and the size of the voxels.

GIM's construction

First of all, the TEC is computed independently for each one of the about 100 worldwide distributed stations. In this way, a 2-layer tomographic model is solved with temporal resolution of 2^h in UT, and spatial resolution of 5^o in local time and 2.5^o in latitude, with the layers limits (see Figure 1) set to 60 Km - 740 Km, for the lower layer, and 740 Km - 1420 Km, for the upper layer; notice that these altitudes have been chosen heuristically in order to minimize the mismodelling, (see for instance, Hernández-Pajares et al, 1999). Secondly, these regional solutions (see an example in left plot in Figure 2) are combined on time and space with the help of the TEC gradients predicted by the IRI, to provide interpolated values in the regions where there are no available GPS data: oceans, south hemisphere and equatorial regions with high TEC gradients (see details in Hernández-Pajares et al, 1999)

COMPARISON WITH TOPEX DATA

One way to evaluate the performance of the GIM's is to compare the predicted TEC values with those direct vertical TEC observations provided by the dual frequency TOPEX altimeter over the oceans. However, the TOPEX altimeter only accounts for the TEC below 1350 km (aproximately the average orbital altitude of the TOPEX-Poseidon satellite) with an accuracy about 2-3 TECU[1] (see Ho et al, 1995). Another difficulty is the lack of collocation between the TOPEX and GPS observations, which are not available in most parts of the ocean.

[1]Note that 1 $TECU = 10^{16} \ e^-/m^2$

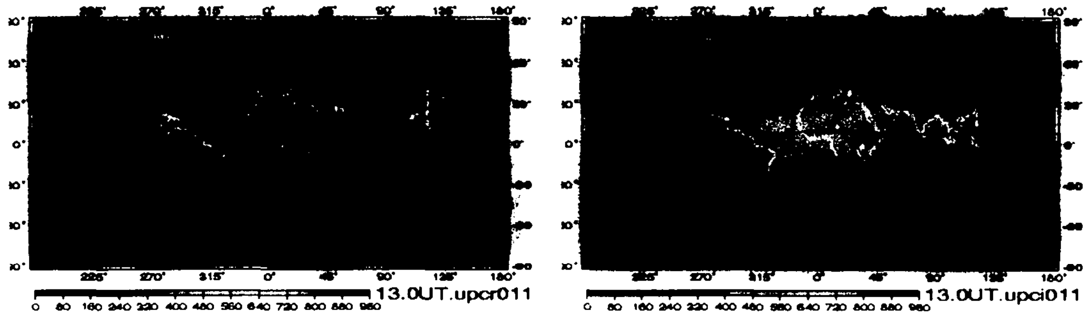

Fig. 2. Example of the interpolation result. The figure on the left depicts the raw map (before the interpolation), while the figure on the right depicts the final UPC GIM (after interpolation) corresponding to doy 154 of the year 2001, at 13 UT.

Taking into account these considerations, two different subsets of comparisons are going to be presented: First, a global comparison, showing mostly the accuracy of the TEC interpolation in the case of GPS GIM's. This is due to the fact that the TOPEX observations are over oceans and seas where there are few GPS stations, then in these zones the GPS GIM's are mainly an interpolation products. Second, regional comparisons (both at mid latitudes -Mediterranean Sea- and equatorial latitudes -Indonesia-) close to available GPS receivers, that show the accuracy of the GPS models without interpolation.

This comparison is done by means of computing the Bias and RMS of the "Observation" (TOPEX TEC) minus "Computation" (GIM TEC). In such a way that a 0 or an sligtly negative bias (less than few TECU, see Lunt et al. 1999), and a low RMS indicate compatibility with the TOPEX+Plasmaspheric TEC.

Several kind of ionospheric models are considered in the comparison with TOPEX:

- The broadcast GPS model, climatological models (such as IRI) and the GPS data driven ionospheric models (such as UPC GIM's).
- The different GPS GIM's provided by the five IAAC's (CODE, ESA, EMR, JPL, UPC) will be compared among them.

RESULTS

Different types of models

As it has been mentioned before, different kinds of models are compared in order to estimate their accuracy. This comparison has been done with all the data available for the year 2000. Table 1 summarizes the results in two regions with close GPS receivers, as mentioned above: The Mediterranean Sea, [5W,40E]x[30N,45N], and for Indonesia, [92E,110E]x[15S,7N]. This table shows that in the Indonesia region the absolute RMS of all models increase by a factor greater than 2 compared to the RMS values in the Mediterranean Sea. This is related to the TEC gradients present in the equator, which are very large compared to those at mid latitudes. However, the UPC GIM bias is still compatible with TOPEX data whereas for the other kinds of models the bias increases regarding to the mid latitude values (specially for the GPS broadcast model).

The comparison at global scale, determined by the interpolation performance for the GPS GIM's, is shown in the histograms of the TOPEX-GIM TEC (Figure 3) and in Table 1 containing the corresponding bias, absolute and relative RMS. This interpolation performance is computed taking into account all the latitudes and longitudes where there are TOPEX data during the year 2000 as well.

Looking at Table 1 and Figure 3, and as it could be expected, the best performance is for the GPS data driven model. For the GPS broadcast model, the relative error regarding to TOPEX data (54%) is compatible with previous studies (Klobuchar et al, 1996). These results can be understood in the context that the GPS broadcast model only uses 8 parameters (due to the requirements on the GPS navigation message) which make it difficult to take into account complex structures, like the equatorial anomalies (see

	Mediterranean (101,000 obs.)		
	BIAS IN TECU	RMS 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 IN TECU	RMS IN TECU	Error %
Br.GPS	24.9	32.3	60
IRI	11.6	22.2	41
UPC GIM	-1.0	9.1	17

	Global (15,600,000 obs.)		
	BIAS IN TECU	RMS IN TECU	Error %
Br.GPS	12.2	19.9	54
IRI	1.1	15.1	41
UPC GIM	-0.2	9.0	24

Table 1. Results for the two selected areas (top tables) and for the global comparison (bottom table), where the GPS Broadcast model, IRI, and UPC GIM's are compared. The Bias and Rms are in TECU and the relative error in %. Notice that the relative error has been computed as $(Err = RMS_{GIM}/TEC_{TOPEX})$.

Figure 4). Then, for the IRI model, the results are better, but with a significant global relative error[2] (41%). The improvement is not as important as could be expected since the GPS broadcast model uses 8 parameters while IRI uses hundreds. With this superior number of parameters the error is still high. Thus, the high IRI error budget may be produced for the overestimation of the IRI TEC prediction on high latitudes (see Figure 4). The GPS data driven model presents a negative bias (close to zero) and the lowest relative error (24%). This fact makes this model one of the most compatible with TOPEX by the moment.

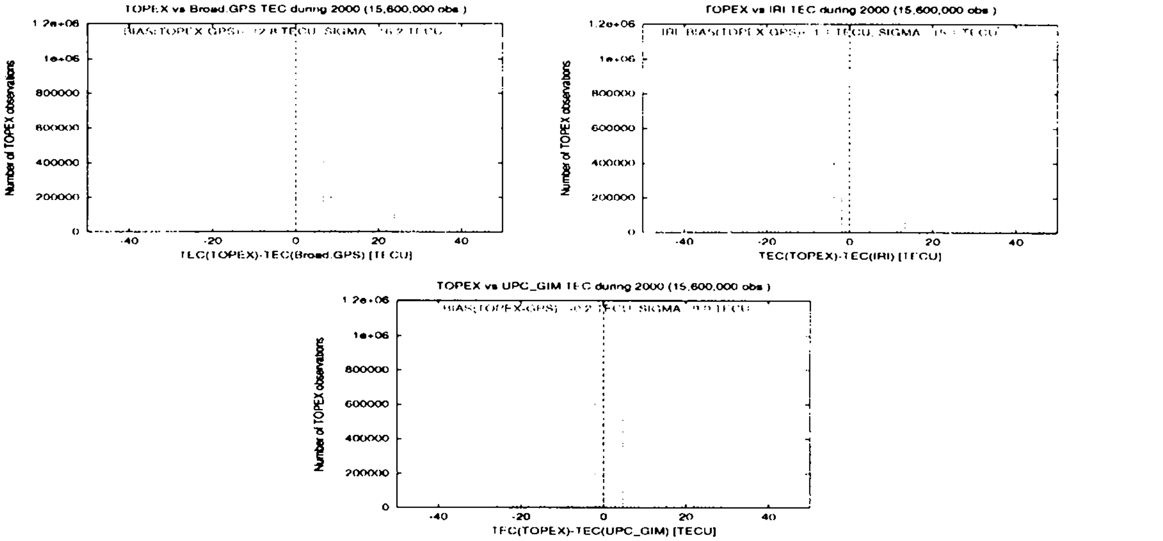

Fig. 3. Histograms corresponding to the global comparison among the differents kinds of models for the year 2000

[2]Notice that the IRI TEC has been computed until the TOPEX height

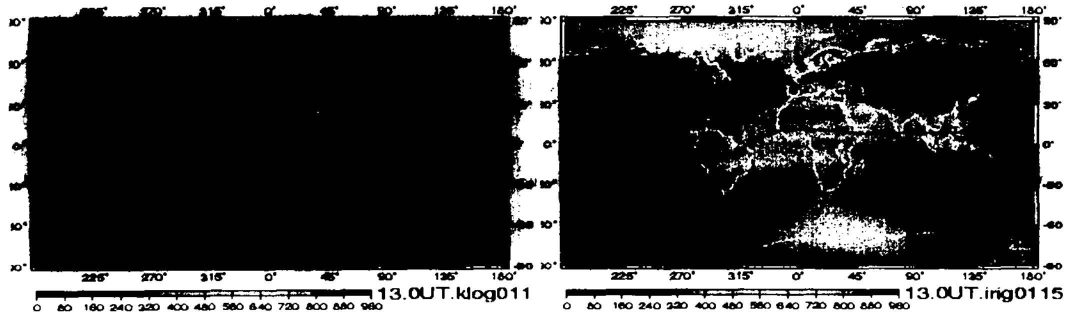

Fig. 4. Example of differents kinds of models. In the left hand side the GPS broadcast model is depicted. In the right hand side the IRI is depicted. Both for the same day and Universal Time (UT), that the GPS TEC map represented in Figure 2.

Comparison among GPS GIM's

It has been shown in previous section that the GPS GIM model, based on actual data, is more precise, as could be expected, than the GPS Broadcast and IRI models. But there can be significant differences among the GPS GIM's computed by different centers, in different manners. To study this, and in the same way that in the previous section, a similar study can be done with the GPS GIM's computed by the differents IAAC's. To do this, the GIM's TEC, originally provided by the computation centers in IONEX format, are interpolated (following Feltens and Schaer, 1998) in time and space where there are TOPEX observations.

The results in Table 2 show that the RMS of the differents IAAC's in the equator (Indonesia) are higher that those obtained at mid latitudes (Mediterranean). This is related to, as it has been mentioned above, the large TEC gradients in low latitudes. Besides, the study (during year 2000) takes place during the Solar maximum peak. Moreover, the TEC maps in the equator can be biased, among centers, up to 8 TECU. An example of TOPEX path over the equator can be seen in Figure 5; which also shows the direct TEC comparison between TOPEX and GIM's, where the bias among centers can be directly observed. In particular, the differences at mid latitudes (Mediterranean) are lower that the ones in the equator.

	Mediterranean (101,000 obs.)		
	BIAS IN TECU	RMS IN TECU	Error %
CODE	3.3	4.7	14
EMR	3.4	7.8	23
ESA	4.6	7.1	21
JPL	-2.1	4.0	11
UPC	0.7	4.0	12

	Indonesia (656,000 obs.)		
	BIAS IN TECU	RMS IN TECU	Error %
CODE	6.7	12.7	23
EMR	11.0	19.2	35
ESA	7.8	16.2	30
JPL	-2.5	10.1	19
UPC	-1.0	9.1	17

	Global (15,600,000 obs.)		
	BIAS IN TECU	RMS 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

Table 2. Results for the selected areas (top tables) and the global comparison (bottom table), where the differents IAAC's are compared for the year 2000. The Bias and Rms are in TECU and the relative error in %

In this point, it is important to notice that the differences existing among the centers (see Table 2) are not smoothed when the global comparison is done. Thus, the maximum differences among the centers are up to 6 TECU (in bias), which is a significant difference if one desires to combine these GIM's in a common IGS ionospheric product. These differences among the centers may be produced by the different methods of computation (i.e. vertical structure considered for the TEC determination, using or not vertical structure in the model like UPC) and the differences between the mappings functions used in the TEC computation.

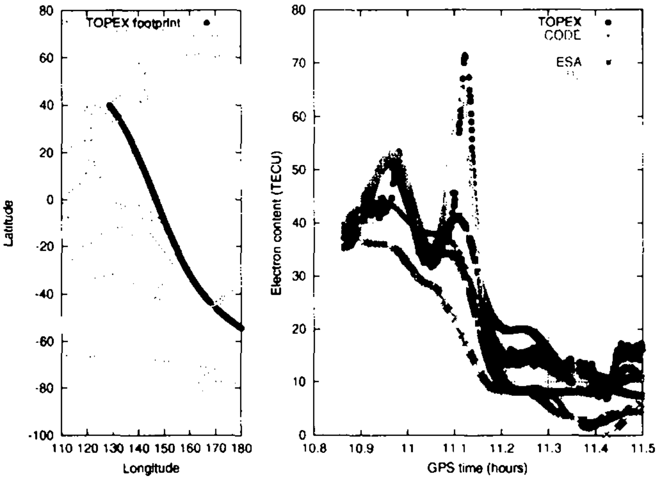

Fig. 5. A typical TOPEX path for the day 23rd March 2000 (DOY 175) (left hand side). And the vertical TEC of the different GIM's versus the TOPEX determination (right hand side).

UPC GIM in the equator

The UPC model has been studied with the full TOPEX data set since June 1st 1998 (about 40,000,000 obs). To do this, the bias and RMS relating to the TOPEX has been computed in bands of about 5° in latitude, covering all longitudes. Then, looking at the obtained results, the UPC GIM shows a significant improvement (see Figure 6) in the year 2000 coinciding with the use of the IRI model in the interpolation scheme. This improvement is especially strong in the equator. The improvement is 2.3 TECU (in bias) and 7 % in relative error. Notice that in the equator both difficult conditions, few GPS stations and large TEC gradients, happen simultaneously.

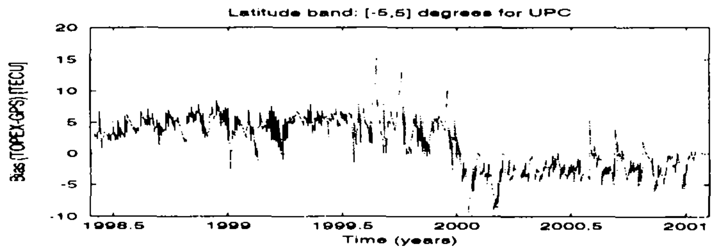

Fig. 6. Bias as a function of time (years) for the UPC GIM since June 1998 until January 2001, in the latitude band centered in the equator

SUMMARY AND CONCLUSIONS

Several kind of models available for a GNSS single frequency users have been compared with an external TEC data source provided by the TOPEX altimeter, trying to cover all representative models such as GPS Broadcast model, theoretical or empirical models (like IRI) and GPS data driven models. In this last group, the performance of the differents IAAC's have been computed in order to show discrepancies among them.

In particular, the results for the year 2000 comparing differents kinds of models and TOPEX data can be summarized (in terms of relative error): GPS Broadcast model (54%), Climatological model (41%) and GPS data driven model (24%). These results point out the feasability of computing TEC maps with GPS data.

When the comparison is done with the IAAC's, it is possible to see that there are significant discrepancies among these centers. The most significant point is related to the bias regarding to TOPEX data. Thus, these centers can be separated in two groups: The first one includes the centers that have their bias about 2-0 TECU above TOPEX (more compatible with TOPEX), these biases could be related to the plasmaspheric component, as it has been explained before. And the second one includes the centers that have their bias about 3-5 TECU below TOPEX (less compatible TOPEX). Then, it is clear that there are significant biases of several TECU. Mainly, these biases may be dependent on the vertical modelling used to computed the TEC by each IAAC.This situation made it difficult to combine differents IAAC's GIM's in a common IGS ionospheric product. Nowadays, several centers have improved their TEC maps: in particular, CODE has reduced several TECU the bias regarding the TOPEX, and UPC is introducing a real-time modelling of the inosphere (see Hernández-Pajares et al., 2002).

ACKNOWLEDGEMENTS

The IRI model has been provided by Dr. Bilitza. The CODE, EMR, ESA and JPL GIM's were obtained from IGS. The maps have been generated with the GMT package. This work has been partially supported by the Spanish projects TIC-2000-0104-P4-03, TIC-2001-2356-C02-02 and the Spanish-USA project Fulbright 2000-001.

REFERENCES

Bilitza, D., International Reference Ionosphere 1990. *URSI / COSPAR*, NSSDC/WDC-A-R&S 90-22, 1990.

Feltens, J. and Schaer, S., *IGS products for the ionosphere, proceedings of the IGS Analysis Center Workshop*, ESA/ESOC Darmstadt, Germany, 225-232, 1998.

Feltens, J., Chapman Profile Approach for 3-d Global TEC Representation, *IGS Presentation, in Proceedings of the 1998 IGS Analysis Centers Workshop*, ESOC, Darmstadt, Germany, 1998, pp 285-297.

Feltens, J. Session: Ground-Based GPS Ionospheric Estimation, *IGS Analysis Center Workshop, NRCan, Ottawa, Ontario, Canada.* 2002. http://www2.geod.nrcan.gc.ca/~pierre/position_papers.htm

Gao, Y., P. Heroux and J. Kouba,*Estimation of GPS Receiver and Satellite L1/L2 Signal Delay Biases using Data from CACS*, 10 pages.

Hernández-Pajares, M., Juan, J.M., Sanz, J. New approaches in global ionospheric determination using ground GPS data. *Journal of Atmospheric and Solar-Terrestrial Physics*, 61, 1237-1247, 1999

Hernández-Pajares, M., J. M. Juan, J. Sanz., O.L. Colombo, Improving the real-time ionospheric determination from GPS sites at Very Long Distances over the Equator, *Journal of Geophysical Research*, in press, 2002.

Ho, C.M., Wilson, B.D., Mannucci, A.J., Lindqwister, U.J., Yuan, D.N., 1995. A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model. *Radio Science* 32, 1499-1512, 1995.

Klobuchar, J.A, Ionospheric Effects on GPS. *Global Positioning System: Theory and Applications*, Volume I, B.W. Parkinson and J.J.Spilker, Chapter 12, 485-515, 1996.

Lunt, N., L.Kersley, G.J. Bailey, The influence of the protonosphere on GPS observations: Model simulations. *Radio Science* 34, 3, pp.725-732, 1999.

Schaer, S. Mapping the Earth's Ionosphere Using the Global Positioning System Dissertation,*Astronomical Institute, University of Berne*, Berne, Switzerland, 1999.