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Performance of different TEC models to provide GPS ionospheric corrections

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Abstract

The existence of a worldwide international GPS service (IGS) permanent network of dual-frequency receivers makes the computation of global ionospheric maps (GIMs) of total electron content (TEC) feasible. The GIMs computed by the IGS Associate Analysis Centers on a daily basis and by other kinds of forecast GIMs, which can be computed from, for instance, the international reference ionosphere (IRI) model, and the GPS broadcast models in the navigation message, can be applied to a broad diversity of fields, for instance as, navigation and time transfer.

In this context, the performance of different kinds of models are presented in order to determine the accuracy of the different GIM. This is carried out by comparison with the TOPEX data that provides an independent and precise (at the level of few TECU) vertical TEC determination over the oceans and seas. Thus, the obtained accuracies, in terms of global relative error, ranging from 54% corresponding to the GPS broadcast model, to about 41% corresponding to IRI climatological model, and to less than 30% corresponding to GPS data driven models.

Keywords: TOPEX; Total electron content (TEC); Global ionospheric maps (GIMs); GPS; Comparison; Ionosphere

1. Introduction

As is known GPS signals are affected by the atmosphere of the Earth. For a single-frequency receiver, the main source of error is due to the portion over 60 km above the surface of the Earth, that is the ionosphere. In this region, the carriers and codes have, respectively, advances and delays for the pseudorange values. Thus, as a first approximation, we can consider that these effects are produced by the free electrons of the ionosphere (see Davies, 1990) and more than 99% of this advance delay can be explained by a term proportional to the integrated free electron density along the GPS ray (slant total electron content, STEC) and inversely proportional to the squared frequency of the signal. This first approximation allows the correction of this term by using simultaneous measurements in both frequencies (f_1=1574 MHz and f_2= 1227 MHz) computing the ionosphere free combination L_C for precise positioning. But for a GNSS single-frequency receiver, the STEC correction must be provided to users. In this context, there are several models that can be used to take into account this ionospheric term.

Broadcast models, such as the GPS broadcast model, see for example Klobuchar (1987), the Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS) ionospheric models for civil aviation, see for example, El-Arini et al. (1995).

Theoretical models, such as the International reference ionosphere (IRI) Model (Bilitza, 1990), the Bent model (Bent et al., 1976) and the NeQuick Model (Hochegger et al., 2000), that mainly provide a *climatological* prediction.

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GPS data driven models, like the Global Ionospheric Maps (GIMs) provided by different centers, see for example Feltens and Schaer (1998).

Thus, with the availability of these different models, it is necessary to determine which model gives the best performance in correcting the ionospheric delay.

One approach is to compare the model predictions with the TOPEX TEC derived from the dual-frequency altimeter (see Ho et al., 1995). On June 1, 1998, the IGS Associate Analysis Centers (IAACs)[1] started to compute GIMs on a daily basis with the aim to define a common IGS ionospheric product combining the different GIMs (Feltens and Schaer, 1998). In this way, there is a large database of different GIMs computed by the IAACs (about 60,000 maps) that opens the possibility to conduct an accurate study for a significant period of time (more than 3 years) in order to determine the performance of each GIM by comparing them with the TOPEX data in the whole period.

In this context, a study with TOPEX data is presented, where we compute the performance of the different kinds of models that a GNSS single-frequency user can use in order to correct the ionospheric delay: the GPS broadcast model computed from eight parameters in the GPS navigation message, the IRI model, and the GIMs computed from GPS data, provided by the 5 IAACs. On the other hand, the GIMs obtained from GPS data can show significant differences that have to be taken into account if it is desired to combine them in a common IGS product. These discrepancies are also studied using TOPEX data.

2. Comparison with TOPEX data

As it is mentioned above, the aim of this work is to show the main differences in performance among the different kinds of models available for a GNSS single-frequency users, including the GIMs computed from GPS data by the different IAACs. The reference consists of the TOPEX/Poseidon data in the period between June 1998 and August 2001 (about 45,000,000 observations). As is already known, these data come from an altimetric satellite, at a mean height of about 1330 km. Among other sensors, it has a dual transmitter–receiver in C-band (5.5 GHz) and Ku-band (13.6 GHz), that provide total electron content (TEC) with accuracies, including systematic biases, of about 2–3 TECU (Ho et al., 1995).

For our comparisons, we have computed the bias and rms of the models regarding the TOPEX data as

$$BIAS = \langle TEC_{TOPEX} - TEC_{GIM} \rangle,$$

$$RMS = \sqrt{\langle (TEC_{TOPEX} - TEC_{GIM})^2 \rangle},$$

where TEC_{TOPEX} is the TOPEX TEC, and TEC_{GIM} is the GIM vertical TEC. When the IAACs GIMs are used, the GIM TEC predictions are interpolated to the TOPEX footprint location, using bivariate spatial interpolation scheme in a solar-fixed reference frame, and linear time interpolation between two consecutive GIM maps following Feltens and Schaer (1998).

For this study, we do not consider the TOPEX observational errors and the plasmaspheric electron content, that can be neglected at high latitudes but can reach several TECUs in the equator (see Lunt et al., 1999). An example of the mean plasmaspheric electron content can be seen in Fig. 2: This figure represents TEC above TOPEX, that has been computed using data from the dual-frequency TOPEX GPS receiver for 1 week in 1993.

In conclusion, a comparison with TOPEX data will provide an evaluation of the different model predictions, being the ideal case: small standard deviation that would include TOPEX measurement error, and several TECU of negative Bias at low latitudes, corresponding to the plasmaspheric component.

In order to determine how well a single-frequency user can correct the ionospheric delay, the IRI, the GPS broadcast model, and GIMs computed from IAACs have been compared for the year 2000. In the GIMs computation, there are several aspects that can limit the accuracy of the TEC estimation: The use of a fixed height layer to represent the vertical electron densities distributions and the lack of data in wide areas, such as ocean and southern hemisphere. In our framework, we independently compute the TEC station by station (about 100 stations) with a coarse tomographic description of the ionosphere sounded by the GPS rays; the ionosphere is divided into voxels distributed in two layers, and with a resolution of 2^h in UT, 5° in local time and 2.5° in latitude. Once these regional solutions are obtained, one has to fill the gaps in order to have a GIM. This is done by combining and interpolating in time and space with the help of the IRI model. It is done by computing the ratio between the TEC_{GPS} and TEC_{IRI} (TEC_{GPS}/TEC_{IRI}) where there are TEC_{GPS} data. Afterwards, this ratio is interpolated with radial basis functions to regions where there are no TEC_{GPS} data. This ratio multiplied by IRI predictions provides the final UPC GIM (Hernández-Pajares et al., 1999). It helps especially in regions with few GPS stations, like oceans (where there are the most part of TOPEX data), and important TEC gradients, as for instance, the equator.

Thus, in order to perform the comparison with the TOPEX TEC, we have chosen several TOPEX/GPS overlapped areas (see Fig. 1) to try to diminish the effect of the interpolation scheme on GIMs. In these areas, the portion of sea/ocean is relatively close to GPS stations. Then, with this good coverage of GPS stations, the degradation in the TEC estimation, due to the interpolation, is expected to be small. These selected areas are: the Baltic Sea, the Mediterranean, and Indonesia, for high, medium, and low latitudes,

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[1] (CODE) University of Bern, Energy, Mines and Resources (EMR, NRCan), European Space Agency (ESA), Jet Propulsion Laboratory (JPL) and Polytechnical University of Catalonia (UPC).

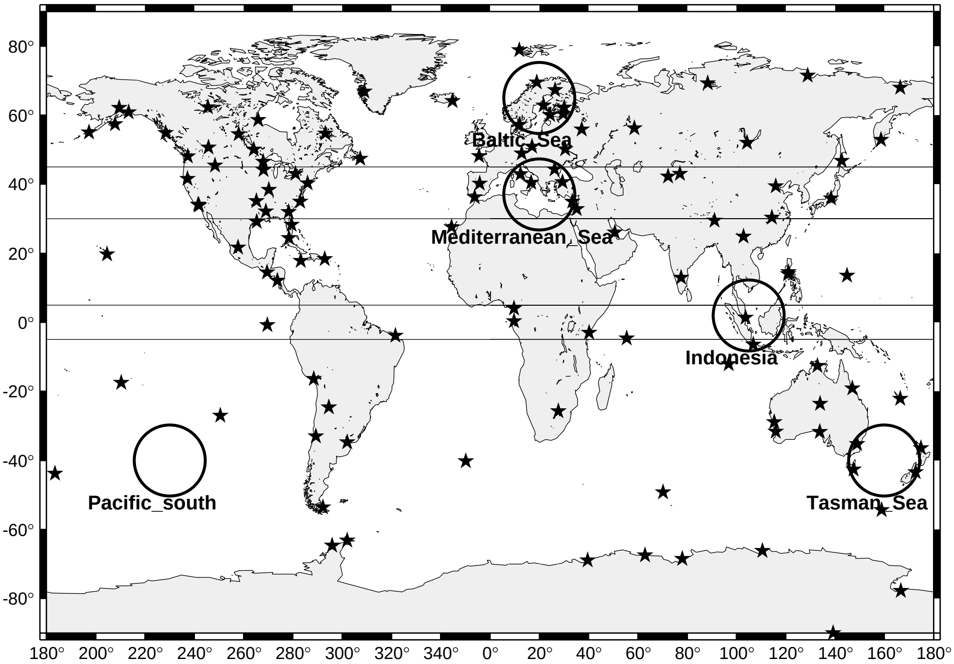

Fig. 1. Example of the distribution of selected IGS GPS stations (about 110 in the example) used to compute the UPC GIM. Circles limit the selected areas. The regions between lines are the latitude bands: [−5° to 5°] and [30–45°] that are discussed, jointly with the selected areas, in the paper.

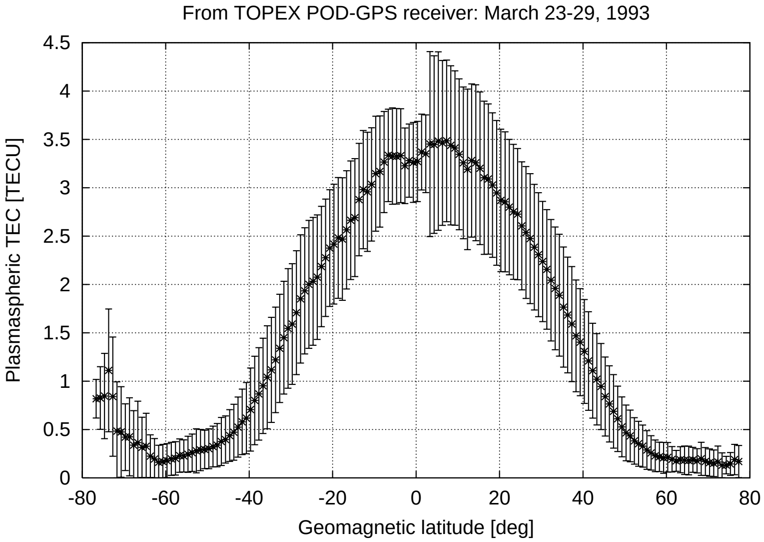

Fig. 2. Mean plasmaspheric electron content (between the TOPEX at 1350 km height, and the GPS transmitters, at 20,200 km height) as a function of the geomagnetic latitude. It was directly observed from the TOPEX GPS receiver for 1 week (March 23–29, 1993).

respectively. Moreover, we have chosen two areas with similar size and latitude in order to see the influence of the interpolation scheme in the IAACs TEC computation. These areas are: The South Pacific zone and Tasman sea area (see Fig. 1). The main difference between these two zones is the presence of GPS receivers. The South Pacific zone is not surrounded by GPS stations while Tasman Sea zone is surrounded by GPS stations and the determination of the TEC predictions are not so affected by the interpolation scheme.

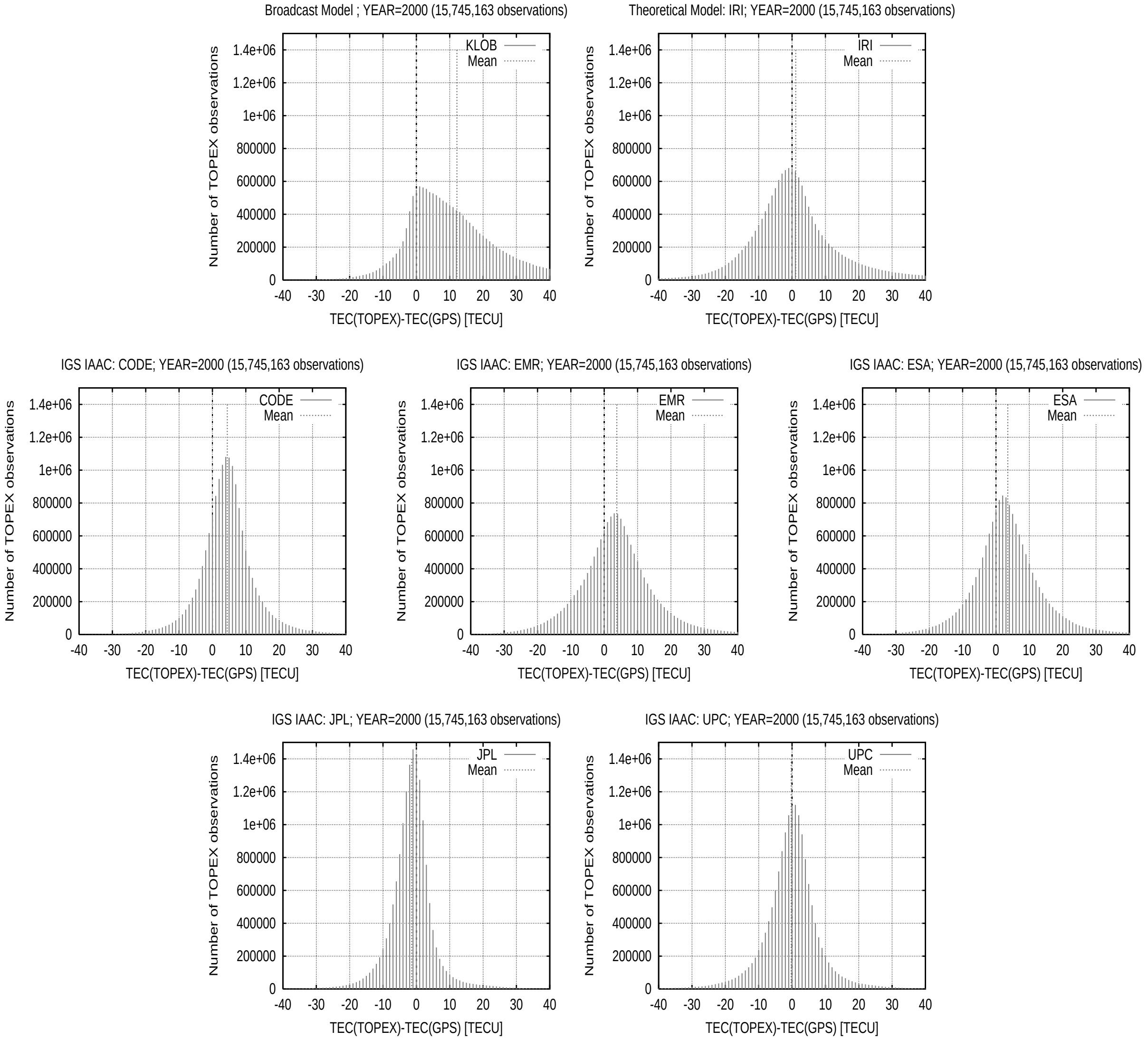

Fig. 3. Histograms for Broadcast model, IRI and GIMs provided by IAACs for the year 2000.

As will be detailed in the next subsection, looking at the results for all latitudes presented in Fig. 3 and Table 1 (bias, rms and the relative error, defined as $RMS_{GIM}/\langle TEC_{TOPEX}\rangle$), the order of performance is GPS GIMs, IRI and the Broadcast model, as it could be expected.

2.1. *The models vs. TOPEX*

Looking at the selected areas (Table 1), we can see different behaviors of each model:

For the GPS broadcast model, it is possible to see that it has better agreement with TOPEX at high and middle latitudes than in the equatorial zone. It should be noted that GPS broadcast model has only eight parameters to describe the ionosphere (previous studies, such Klobuchar, 1996, limit its ionospheric error to 40–50%) and it cannot take into account complex structures like equatorial anomalies, this can explain its important bias in the equatorial zone (see Table 1, Indonesia).

For the IRI model, the matches are much better. This is due to the fact that IRI uses many more parameters than the GPS broadcast model. However, it has a bad performance at high latitudes and during solar maximum, overestimating the TEC in this zone. We can see this effect on the large negative bias for the Baltic Sea (see Table 1, Baltic Sea). Note that we have computed the TEC for IRI until TOPEX height, and in this case, the bias should be close to zero.

Table 1
Bias, rms and relative error (RMS_{GIM}/TEC_{TOPEX}) regarding the TOPEX TEC, for the year 2000, for the different kinds of models

	BIAS (TECU)	rms (TECU)	Error (%)	BIAS (TECU)	rms (TECU)	Error (%)
	Global (15,700,000 *obs.*)			*Baltic Sea* (14,000 *obs.*)		
Br.GPS	12.2	19.9	54	3.7	9.2	36
IRI	1.1	15.1	41	−5.5	12.4	49
CODE	4.5	9.7	26	6.1	6.8	27
EMR	3.8	12.7	34	4.8	8.1	32
ESA	3.5	11.6	31	5.3	8.0	32
JPL	−1.4	7.2	20	1.3	3.0	13
UPC	−0.3	9.0	24	2.0	3.7	16
	Mediterranean (101,000 *obs.*)			*Indonesia* (122,000 *obs.*)		
Br.GPS	6.3	12.0	35	24.9	32.3	60
IRI	2.6	8.9	26	11.6	22.2	41
CODE	3.3	4.7	14	6.7	12.7	23
EMR	3.4	7.8	23	11.0	19.2	35
ESA	4.6	7.1	21	7.8	16.2	30
JPL	−2.1	4.0	11	−2.5	10.1	19
UPC	0.7	4.0	12	−1.0	9.1	17
	Tasman Sea (661,000 *obs.*)			*South Pacific* (528,000 *obs.*)		
Br.GPS	10.0	14.1	46	8.5	13.0	42
IRI	−2.5	10.1	33	0.3	9.4	30
CODE	6.6	8.3	27	6.3	9.6	31
EMR	4.7	10.5	34	3.2	11.2	36
ESA	4.5	8.6	28	4.5	10.0	32
JPL	−1.3	4.8	16	−1.2	5.6	18
UPC	−0.9	6.3	20	2.7	7.1	23

For GIMs computed by the IAACs from GPS data, we can see that they have very good matching with TOPEX, their rms is the lowest in most cases. Note that in the equatorial zone the error is close to 20%, worse than the one obtained at mid latitudes (about 10%). These major errors are possibly due to large ionospheric gradients in this zone. Another source of error in the equator is the plasmaspheric component that can reach several TECU (see Fig. 2). Hence, if we take into account this component, the centers which have positive bias should still have higher rms.

In the last zone (see Table 1, South Pacific), without GPS stations close to the zone, we observe that the rms of all IAACs are higher than in the Tasman sea (see Table 1), it can also be seen that UPC bias is higher than in the other zone. All of these effects are due to the interpolation scheme. This may explain the differences among the bias in the selected areas and at global scale, the UPC bias is highly penalized in zones where there are no GPS stations, still maintaining a relatively low rms. For GPS broadcast model and IRI, we do not expect any significant change because these models do not use these GPS station data in their TEC determinations.

2.2. *Different GPS models vs. TOPEX*

Once we have seen that the GIMs computed from GPS data have the best performance, the accuracies of the different IAAC models are investigated as below.

One of the points that can justify, in part, the differences among the groups is the vertical structure modelling. Thus, centers that take into account a certain vertical structure, such as UPC, can better model the ionospheric gradients. In fact, the point is that if only one thin layer is used, then the mapping function has a constant effective height producing a significant TEC mismodelling. However, if a certain vertical structure is considered, then the TEC mismodelling is reduced, for example, a model with two layers that can be understood as a model with a variable height driven by the data (Hernández-Pajares et al., 1999).

A summary of the results for the year 2000 and for each center is plotted as histograms of the residual between each TOPEX TEC observation and its model prediction (see Fig. 3), where the bias, as a deviation of the peak to zero, and the standard deviation, as the width of the histogram, can also be seen. Thus, CODE, EMR and ESA have their TEC determination significally smaller than TOPEX; and JPL and

Table 2
Bias in TECU, rms in TECU and relative error (RMS_{GIM}/TEC_{TOPEX}) from June 1, 1998 to August 18, 2001 for the different IAACs

	1998 (7,800,000 obs.)			1999 (12,900,000 obs.)			2000 (15,600,000 obs.)			2001 (9,400,000 obs.)		
	Bias	rms	Error (%)	Bias	rms	Error (%)	Bias	rms	Error (%)	Bias	rms	Error (%)
CODE	4.1	8.0	32	3.8	9.1	31	4.5	9.7	26	4.0	8.8	26
EMR	3.5	8.9	35	2.6	10.6	36	3.8	12.7	34	4.2	12.1	36
ESA	4.4	9.1	36	4.1	10.6	36	3.5	11.6	31	2.6	10.4	31
JPL	−0.3	6.0	21	−1.1	6.5	22	−1.4	7.2	20	−1.3	6.5	20
UPC	2.4	7.8	32	2.0	9.2	31	−0.3	9.0	24	0.5	7.4	22

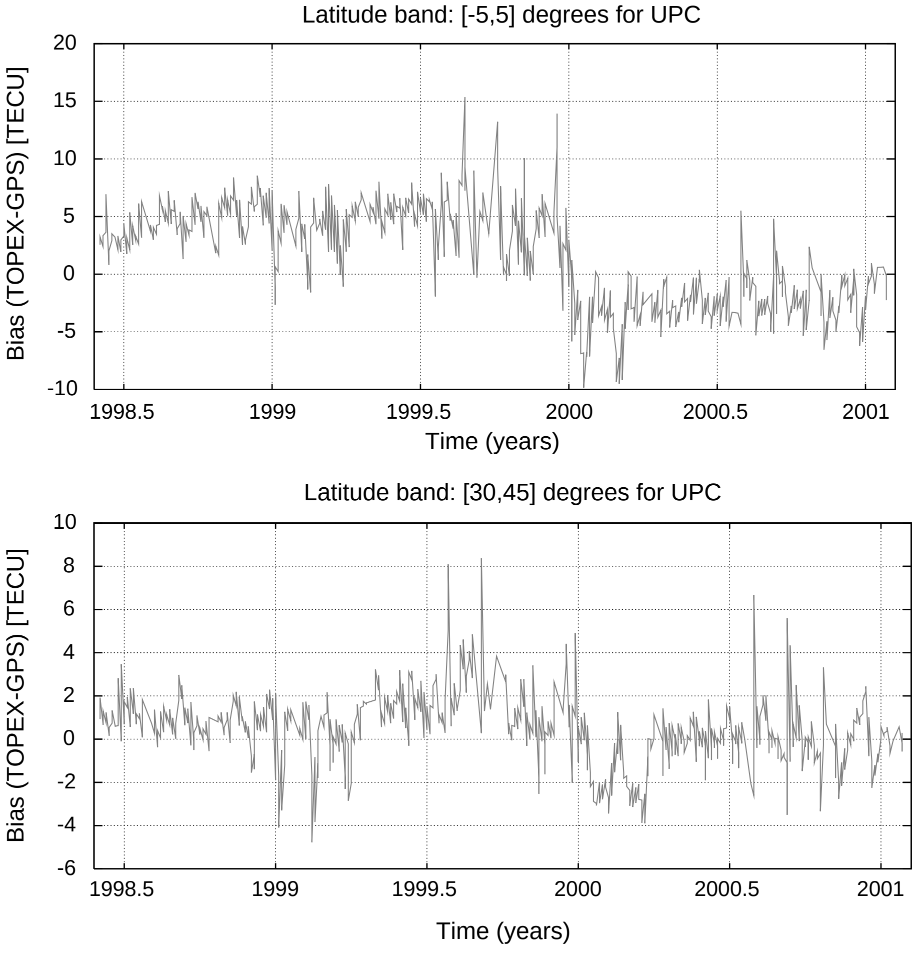

Fig. 4. Bias TOPEX-GPS in two latitude bands for UPC from June 1, 1998.

UPC have their mean TEC determination greater or similar to TOPEX, being compatible with the presence of the plasmaspheric component.

Next, and as a complementary study, we will consider the evolution of the different GIMs provided by IAACs from the beginning that GIMs were computed (June 1, 1998) until the pass of the solar maximum peak (August 18, 2001). With this huge amount of data, we can see the behavior for the last 3 years.

From the results of Table 2, we observe that UPC has a significant improvement in bias and relative error in the period between the years 1999 and 2000. Among other points of the TEC modelling (as the vertical structure modelling explained previously), it is necessary to have a realistic interpolation scheme in order to avoid adding new errors in the GIMs computation. Indeed, the most significant improvement, in particular, in bias, is in respect of the UPC in the year 2000 (about 2 TECU). This improvement coincides with the use of the IRI to help in the interpolation procedure, as it was explained above.

In order to explain the performance differences in the UPC model, we have conducted a special test from June 1, 1998 until December 31, 2000 in two latitude bands (see Fig. 1), the first one close to the equator (between −5° and 5°), and the second one at middle latitudes (between 30° and 40°). The results of this comparison can be seen in Fig. 4, where the bias of the UPC GIMs has been computed as was explained previously. Note that in the equatorial region, the UPC bias has experimented an important decrease in the year 2000. This decrease, which makes the results more compatible with TOPEX, is mainly due to the use of IRI in the interpolation scheme. In the middle latitudes, this effect is not so strong as in the equator, however, the bias is close to 0.

3. Conclusions

The performance of different kinds of models available for a GNSS single-frequency users has been explored in this paper. Thus, we can summarize that the best performance is for GPS data driven models that at global scale present an error of 24% of the rms with respect to TOPEX TEC, instead of the 41% of error of IRI climatological model, and an error of 54% using the GPS broadcast model.

From the point of view of the performance of the different GPS data driven models provided by the IAACs, the importance of the computing strategy has been studied, looking at both, the vertical structure in the models and the interpolation scheme. It is obvious that significant differences between the IAACs centers exist, being these differences, mainly, produced by the computing strategy. It depends, for instance, if the center uses either vertical structure modelling or does not use it in the TEC computation. The intercenter biases present, at the moment of writing this paper, differences that reach 6 TECU at global scale. These discrepancies are significant if it is desired to combine the different maps in a common IGS product, but such error is less important in a GNSS single-frequency user using the STEC corrections. At the moment of the publication of this paper (2002) several centers have improved the TEC maps: in particular, CODE has reduced several TECU the bias regarding to the TOPEX, and UPC is introducing a real-time modelling of the ionosphere helped by a simultaneous geodetic computation (see Hernández-Pajares et al., 2002), reducing the "error" compared to TOPEX to less than 20%.

The plasmaspheric component has been neglected in the computations, and therefore the existence of negative bias in certain GIMs is compatible with the existence of a plasmaspheric component, as has been shown with a direct plasmaspheric estimation with GPS data. In the near future, it could be interesting to contrast these values with plasmaspheric models such as the Global Core Plasma Model (GCPM, Gallagher et al., 2000); La Trobe Electron Density Model (Webb and Essex, 2001); and The Sheffield University Plasmasphere Ionosphere Model (SUPIM, Lunt et al., 1999).

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