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COMBINING GPS MEASUREMENTS AND IRI MODEL VALUES FOR SPACE WEATHER SPECIFICATION

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ABSTRACT

We will discuss various ways in which the International Reference Ionosphere (IRI) model and ionospheric data deduced from GPS measurements can be combined to improve ionospheric determinations. A number of research groups are analyzing GPS data products and providing global maps of vertical Total Electron Content (TEC) on a regular basis. IRI predictions can guide the interpolation of regional TEC estimations, computed from GPS data, to obtain global TEC maps. GPS measurements, on the other hand, can be used to update the IRI monthly averages to actual conditions. This can be done by using the GPS-derived TEC maps or by using the actual GPS measurements of the electron content along the signal path from satellite to ground receiver. We will discuss the updating results using the actual GPS measurements.

INTRODUCTION

The free electrons distributed in the ionosphere (between one hundred and thousands of km in height) produce a frequency-dependent effect on Global Positioning System (GPS) signals: a delay in the pseudorange and an advance in the carrier phase. These effects are proportional to the columnar electron density between the satellite and receiver, i.e. the integrated electron density along the ray path.

To successfully estimate the electron density vertical profiles, it is necessary to combine ground and Low Earth Orbiter (LEO) GPS data in order to ensure enough ray geometry to solve the inverse problem (Hajj et al. 1994, Howe et al. 1998, Hernández-Pajares et al. 1998, 2000). When only ground data is used, the vertical profiles cannot be resolved. Nevertheless, a coarse tomographic model (voxel model) with only two layers (top and bottom) can be used to diminish the mismodeling -with regard the more classical one thin layer model- in the Total Electron Content (TEC) estimation (Juan et al. 1997, Hernández-Pajares et al. 1999).

Since June 1st 1998, our group is contributing, jointly with JPL, ESA, CODE and NRCAN, to an international project to define a common IGS ionospheric (TEC) product, where daily TEC maps in IONEX format are computed with data gathered from the permanent ground GPS receivers of the International GPS Service (IGS) (Feltens and Schaer, 1998, Mannucci et al. 1998).

These ionospheric maps are obtained in our group with a two layer tomographic (voxel) model solved for each ground IGS station independently, and the IRI model (Bilitza, 1990) is applied as a reference ionospheric model to carry out the interpolation for the global TEC map. The details of how the IRI helps this TEC global ionospheric determination will be explained in this paper. The performance of these ionospheric estimations as compared with TOPEX TEC direct estimations will be shown as an application.

By other hand, an exhaustive comparison of the Electron Content estimated with GPS and the IRI prediction on 23 geomagnetically quiet days distributed over 1991 to 1997, for most of the available IGS stations covering a wide range of geomagnetic latitudes, was made in Bilitza et al. (1999). We will extend this analysis, in the last part of this paper, with data sets close to the solar maximum.

MODEL

Geodetic dual frequency GPS receivers usually provide, for each epoch and for each of the tracked satellites –typically 6 or 7 simultaneously–, *codes* (P_1 and P_2) and *carrier phases* ($\mathcal{L}_1$ and $\mathcal{L}_2$) in two L-band frequencies, $f_1 \simeq 1575$ MHz and $f_2 \simeq 1227$ MHz, respectively. The codes are noisier than the carrier phases, with large multipath errors, but unambiguous; and, on the contrary, the carrier phases are much more precise with error noise of 0.002 m or smaller, but ambiguous (see for example Wells et al. 1986 for a general review of this problem).

As was mentioned in the introduction, when the GPS signals travel between the transmitter position $\vec{r}^T$ and the receiver position $\vec{r}_R$ they cross regions of the ionosphere with densities N_e. Then, if we avoid the code data due to their greater error noise, the main ionospheric quantity obtained from the dual frequency GPS receiver data is the ionospheric combination of carrier phases, $\mathcal{L}_I \equiv \mathcal{L}_1 - \mathcal{L}_2$, which can be written in terms of:

$$\mathcal{L}_I = \kappa \cdot \int_{\vec{r}^T(t^T)}^{\vec{r}_R(t_R)} N_e(\vec{r}, t)\, ds + Amb + \epsilon_I \qquad (1)$$

where $\kappa = K\left[1/f_2^2 - 1/f_1^2\right] \simeq 1.05$ m delay/10^{17} electrons/m^2 and where the error ϵ_I is assumed to be normally distributed with $\sigma_{\epsilon_I} \simeq 0.002m$.

The ambiguity term Amb is constant along each data arc of continuous phase for a given pair of satellite (T) and receiver (R), and can be canceled by taking differences of carrier phase referred to the first point of arc. Notice that, in this way, we avoid the estimation of the differential code biases, with the unique assumption that they do not change in an arc of continuous carrier phase (typically during less than 4 hours). More details can be found in Hernández-Pajares et al. (1999).

Then, the final equation in the preprocessing stage is:

$$\mathcal{L}_I(t+\tau) - \mathcal{L}_I(t) = \kappa \cdot \left(\int_{\vec{r}^T(t^T+\tau)}^{\vec{r}_R(t_R+\tau)} N_e(\vec{r}, t+\tau)\, ds - \int_{\vec{r}^T(t^T)}^{\vec{r}_R(t_R)} N_e(\vec{r}, t)\, ds \right) + \epsilon_I \qquad (2)$$

where the time τ must be sufficient to provide enough geometry variation of the ray to allow solving for the free electron densities in the tomographic problem and small enough to suppose that the electron density does not change in a reference frame with the Sun fixed (for instance, for $\tau \geq 720$ seconds the method works well).

Tomographic model

The tomographic model adopted is spatially formed by a set of cells or volume elements (voxels) in a Sun fixed reference frame, (see Figure 1), especially suitable to detect local features, that cover all the ionosphere sampled by the GPS satellite/receiver rays. In these voxels the electron density is considered uniform at a given time. Although there are other possible distributions (for example, adapted to the data density as in Hernández-Pajares et al. (1997a)), the uniform distribution is adequate for describing a region sampled from an approximately homogeneously distributed network of ground stations or also from a single ground station, as is the case in the computation of the daily TEC maps.

These TEC maps, which computation strategy is described in this paper, are estimated using only ground GPS data (and the IRI reference model for interpolation) gathered from the IGS permanent ground stations. In this case, as mentioned in the introduction, the use of a coarse tomographic (voxel) model with two layers instead of the more classical one thin layer model allows a better determination of the TEC: in the thin layer model the ionospheric delays are only a function of the pierce point, while in the voxel model an implicit horizontal gradient is taken into account for each ray illuminating several cells (especially important for low elevations rays). Furthermore, the fixed height assumption of the one layer model is relaxed when a voxel model is used, where a variable effective height, data driven, is implicitly assumed. Notice that the height of maximum peak can change several kilometers between the day and night, and a clear missmodelling is introduced if the fixed height hypothesis is adopted. These variations can be absorbed by the voxel model, as a redistribution of the electron densities in the voxels. This is specially important when the ionospheric gradient is large, i.e. close to the solar maximum or close to the geomagnetic equator. A comparison and discussion of the ionospheric estimations for the one layer thin model and the voxel model can be found in Hernández-Pajares et al. (1999), where improvements up to 50%, regarding on the mean TEC values, are obtained close to the equator when the voxel model is used.

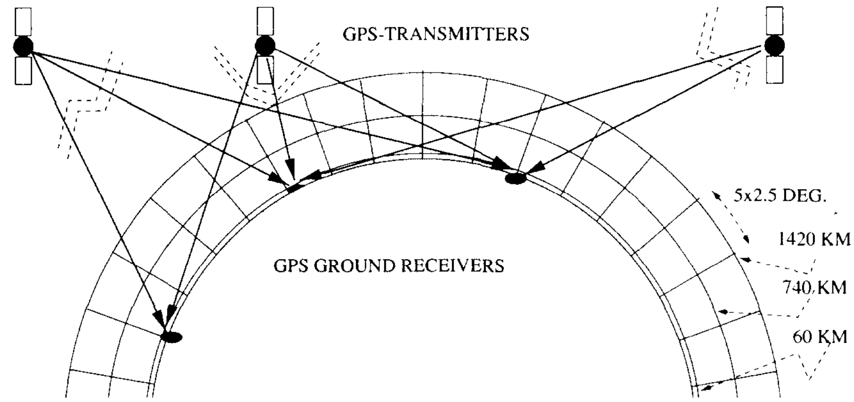

Fig. 1. Layout of the tomographic model of the ionosphere with voxels of 5×2.5 degrees in solar longitude and latitude, forming two layers with boundaries at 60-740-1420 km.

The distribution of the IGS permanent ground stations is not homogeneous, with the stations basically located on the continents, especially in northern latitudes, and very few in the oceans. For this reason, and also to reduce the computational load of the model, the following scheme has been adopted to estimate the global TEC (IONEX) maps:

- To compute, first, a **regional solution** of TEC for each ground station, processing each station independently with the voxel model.
- To obtain the global solution by **interpolating** the regional TEC with the help of the IRI model.

Regional TEC solutions

A regional TEC solution for each ground station is computed by processing its GPS data independently in the voxel model: The last equation (2), for each arc of continuous carrier phases between a transmitter T and receiver R, can be written as

$$\mathcal{L}_I(t+\tau) - \mathcal{L}_I(t) = \kappa \sum_i \sum_j \sum_k (N_e)_{i,j,k} \cdot \left[\Delta s_{i,j,k}^{t+\tau} - \Delta s_{i,j,k}^{t}\right] + \epsilon_I \qquad (3)$$

where i, j, k are the indices for each cell corresponding to local time, geodetic latitude and height ($k = 1, 2$); $(N_e)_{i,j,k}$ is the corresponding free electron density; and $\Delta s_{i,j,k}^t$ is the length of the ray path crossing the illuminated cells at time t ($\Delta s_{i,j,k}^t = 0$ for the "dark" cells). Voxels of 5×2.5 degrees in solar longitude and latitude, forming two layers with boundaries at 60-740-1420 km, have been adopted (see Figure 1). These values do not corresponds to any physical layer, instead they are selected in function of the rays-geometry to disminish the correlations in the inverse problem.

In this case (processing only one station at a time) the Least Mean Squares estimation is enough to solve the model[1], because each permanent receiver rotates continuously in the adopted Sun-fixed reference frame, and individual cells are illuminated for only a short period of time due to the Earth's rotation (see for instance, Hernández-Pajares et al. 1998).

In Figure 2a, an example of the regional solutions computed for 2000 June 16th is shown (in the overlapping areas, the mean value between the TEC regional estimations involved is given).

Interpolating the TEC

The regional solutions computed from the voxel model for each ground station are interpolated in order to fill the spatial and temporal gaps.

[1] In the general formulation, the model is solved with the Kalman filter, where the electron density is updated as a random walk parameter.

For the interpolation, the Gaussian radial basis function approach is used (Haykin, 1995, 269-274), where the weights are Gaussian functions of the distance between the data points (in solar longitude and latitude and UT coordinates) to the point where the interpolated value is desired. The scale parameters σ, or correlation radii, have been chosen corresponding to two voxels (10 deg in longitude, 5 deg in latitude and 4h in UT). Notice that the information comes from the closest estimations in space and time, and on the stationarity assumption in the solar fixed reference frame.

As regards the interpolation, two possible methods have been considered in this study: a) To interpolate (directly) the TEC_{GPS} regional solutions obtained in the voxel model. b) To interpolate the TEC_{GPS}/TEC_{IRI} ratios.

As is shown in Figure 2b, the interpolation over the TEC_{GPS} (without the help of the IRI) can produce flat estimations when the gaps are in regions with large gradients. This is especially important close to the equator, where the linear weighted (Gaussian) average of the TEC-GPS values of the neighborhood cannot follow the local patterns (equatorial anomaly). This problem is satisfactorily overcome when the interpolation is performed over the ratio (TEC_{GPS}/TEC_{IRI}), due to the smoother variations of these values (see Figures 2d and 3).

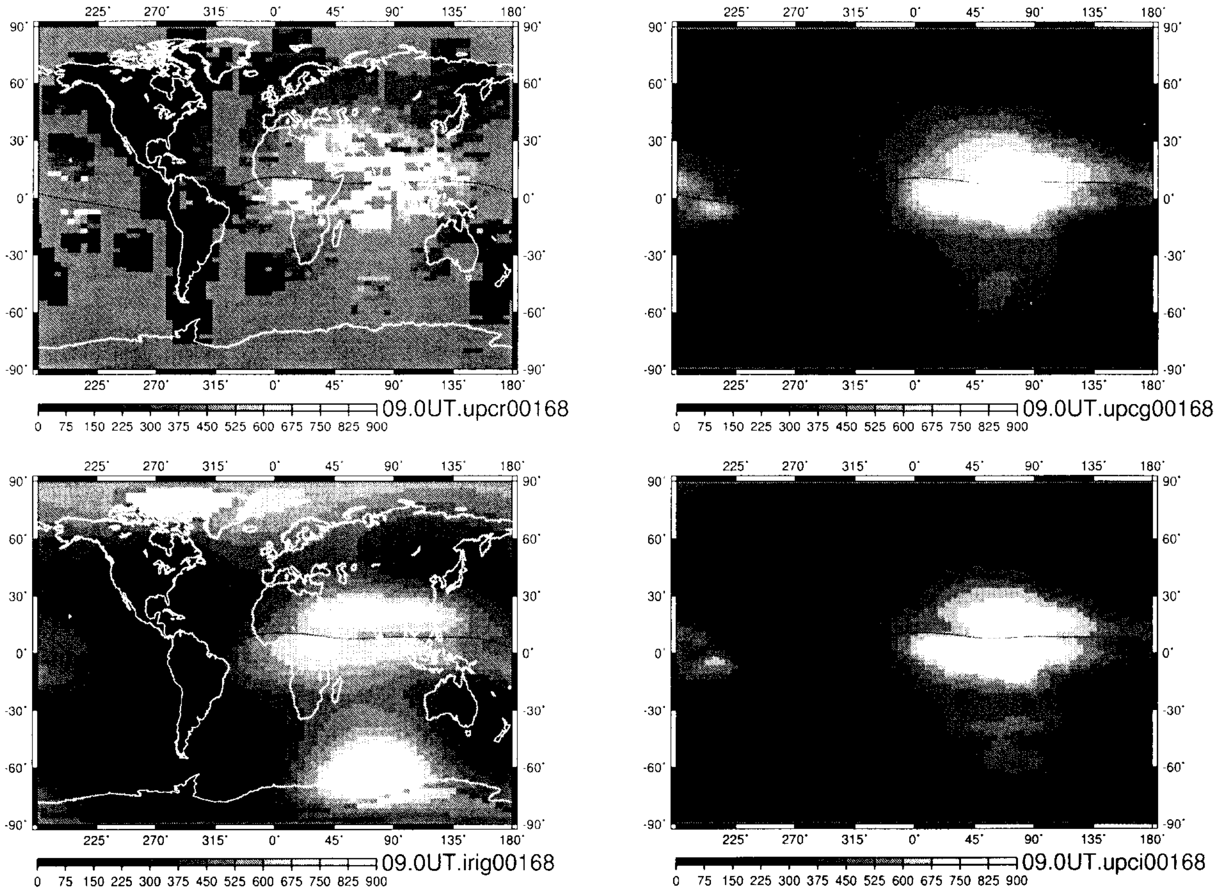

Fig. 2. a) (top left) TEC-GPS regional estimations from the voxel model. b) (top right) Interpolation of the regional TEC-GPS estimations *(only GPS data)* c) (bottom left) IRI TEC prediction d) (bottom right) Interpolation of the regional TEC estimations with IRI (*interpolation over* TEC_{GPS}/TEC_{IRI} *ratios*). The data set corresponds to June 16th 2000 at 9 UT. (The scale is in units of 0.1 TECU).

The interpolated values of the ratio $TEC_{GPS}/TEC_{IRI} \times 100$ used to compute the TEC map in Figure 2d, are shown in Figure 3. Notice that, according to this plot, in the middle latitudes this ratio is close to 1 (100%), with smooth patterns close to the equator. In extreme latitudes the the ratio can be below 50%.

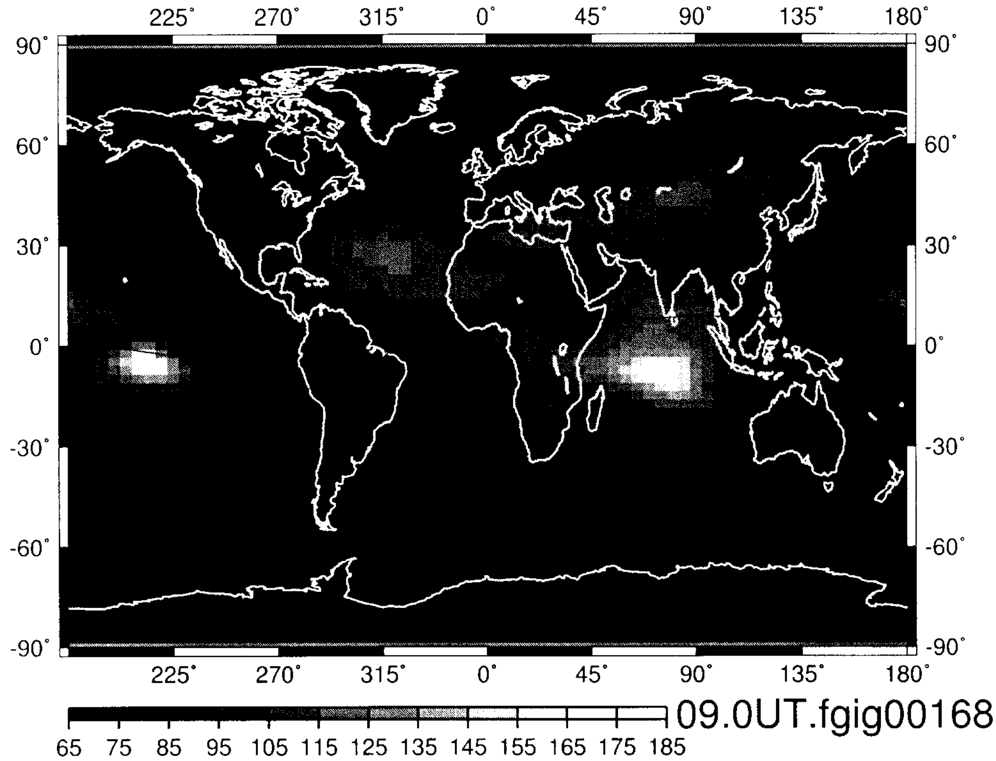

Fig. 3. Map of $TEC_{GPS}/TEC_{IRI} \times 100$ ratio values, interpolated with the radial basis functions, for 2000 June 16th at 9 UT.

Comparison with TOPEX data

Over the oceans few GPS data are available, and the comparison with TOPEX data becomes a good test to analyze the accuracy of the TEC estimations far from the ground stations, checking the goodness of the adopted interpolation scheme.

Figure 4 plots the RMS of the discrepancies between the TOPEX TEC and the TEC values computed from GPS data and interpolating *with* (diamonds) or *without* (crosses) the help of the IRI model. This comparison has been made for eight days (between August 28th and September 4th 1998), involving 174 TOPEX passes and 2513 individual TOPEX observations, 138 GPS stations and more than 21,000,000 individual GPS observations. Each point in the plot accounts for 2 hours of TOPEX track data.

As can be seen, most of the time, the RMS is reduced by approximately 1 TECU when the IRI model is used to drive the interpolation as a reference model. On the other hand, the large RMS values over the days 240 to 241 could be associated with the greater ionospheric activity of this period (see Kp index in Figure 4d).

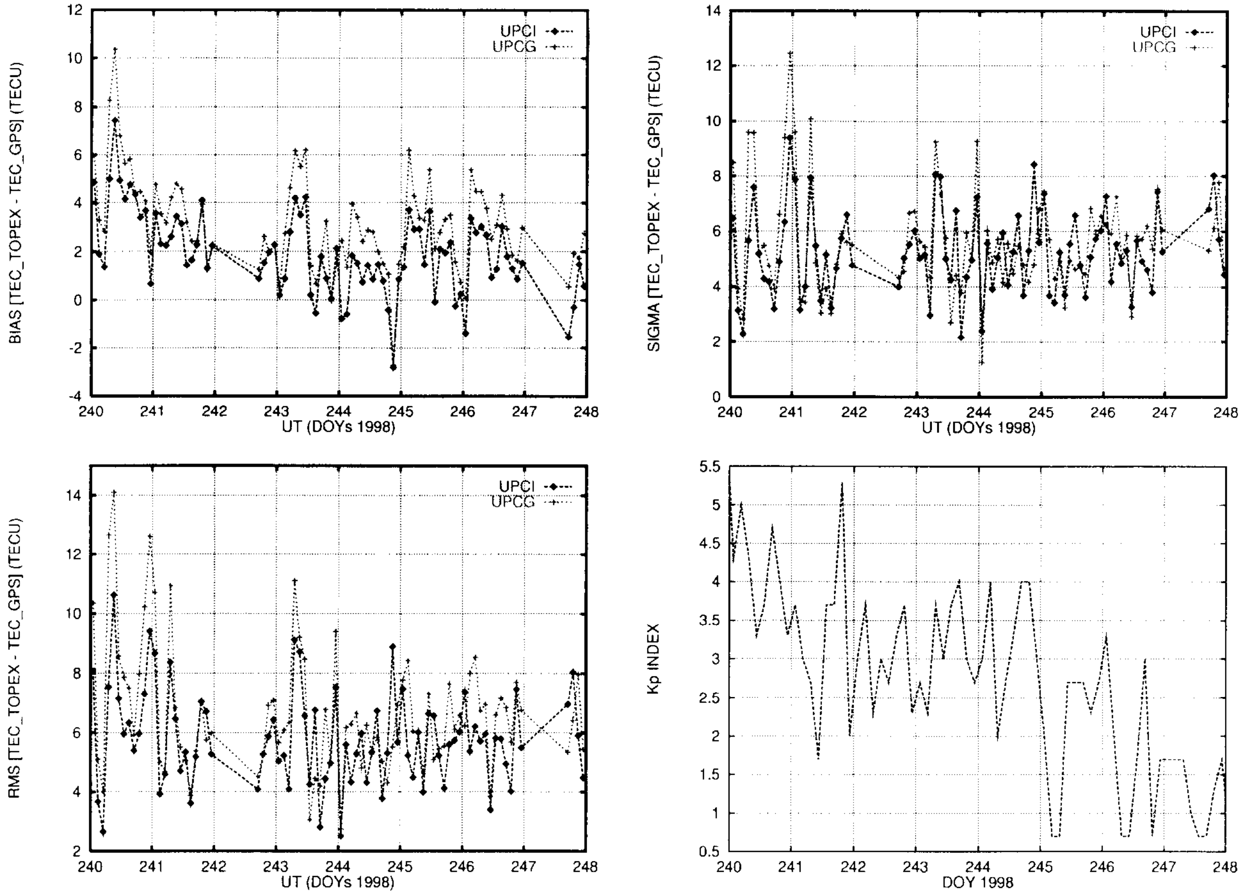

Fig. 4. Discrepancies between TOPEX and GPS TEC interpolating without IRI (UPCG) and interpolating with IRI (UPCI): bias (top left), standard deviation (top right), RMS (bottom left), Kp index (bottom right).

An additional comparison with TOPEX data, between February 21th and May 10th 2000, in a main window of 40x10 degrees around the station **chat** (Chatham) in New Zealand at coordinates ($\lambda = 183deg, \phi = -44deg$), is given in Figure 5. The graph on the left shows a good agreement between the GPS TEC and the TOPEX TEC in this region. The corresponding results with the IRI predictions are shown on the right as a reference.

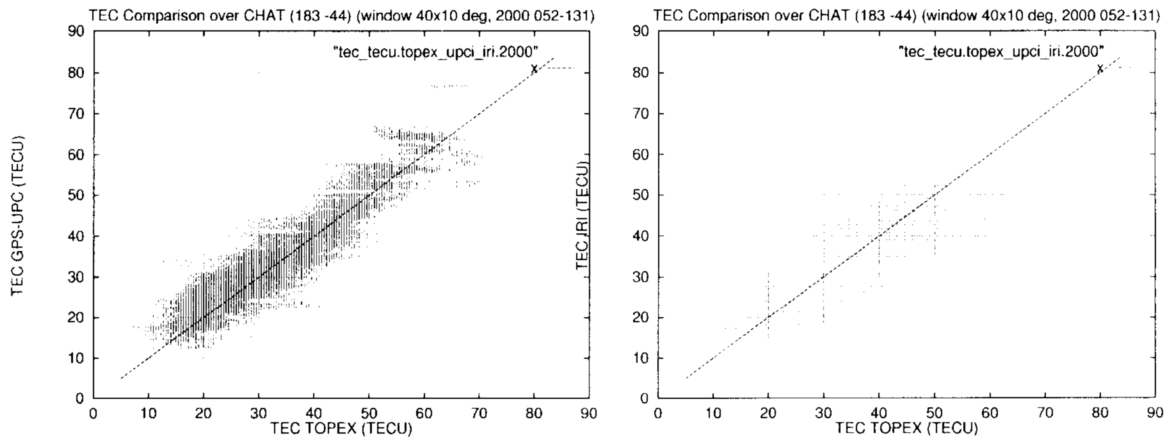

Fig. 5. TEC comparison between GPS and TOPEX data (left), and between IRI and TOPEX data (right). Data set: from February 21th to May 10th 2000.

USING GPS FOR MONITORING IRI PREDICTIONS

An analysis of the IRI predictions compared with the GPS estimations between 1991 and 1997 was made in Bilitza et al. (1999) using most of the available IGS stations in this period, the number which increased from 7 stations in 1991 to 240 in 1997. At present there are about 500 IGS stations distributed worldwide (see Figure 6), which allows a global and continuous TEC monitoring of IRI predictions with GPS.

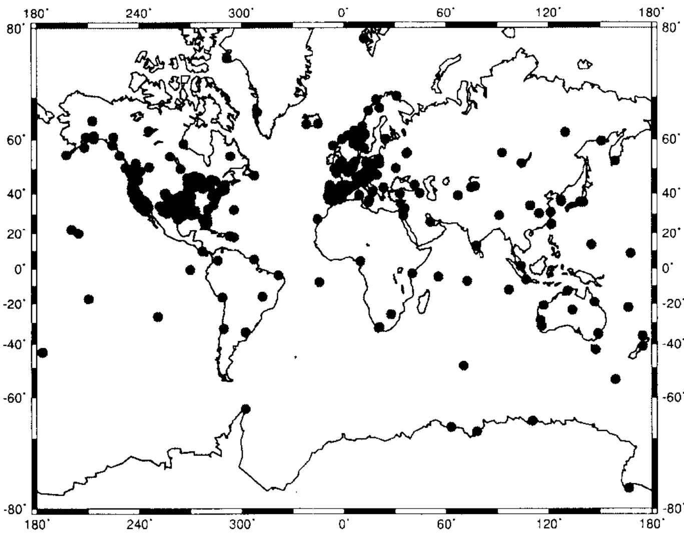

Fig. 6. IGS permanent ground stations at the beginning of 2000.

A comparison between the TEC estimations and the IRI predictions, at noon and at midnight for a three month period, close to the Solar Maximum, are given in Figure 7. Each plot corresponds to one different station whose name and coordinates (longitude, latitude) are given at the top. The Kp index is also given in the plots.

From the GPS estimations it is possible to observe a common maximum for all the stations in the plots, in the first week of April 2000.

Furthermore, the TEC IRI predictions are in good agreement with the GPS estimations for middle latitudes. Nevertheless, in the station `thul` (Thule, Greenland) at 76 deg. latitude the climatological IRI values are two times higher than the GPS estimations (these differences are clearly higher than the expected error (few TECUs) in the TEC estimations with GPS estimations in the voxel model (Hernández-Pajares et al. 1999)).

Local fit of IRI with the Sun Spot Number

With GPS data it is possible to perform a local fit of the IRI model by tuning the Sun Spot Number (SSN), which is one of the parameters that mainly drives the IRI model. This local fit can be done by using the STEC values obtained directly after removing the instrumental delays to the ionospheric combination of carrier phase data, aligned with the code. This provides an alternative way to update the IRI with GPS data with regards to the approach indicated in the above section, but without solving the tomographic model.

Figures 8 (a) and (b), top, show the observed STEC (solid line) between station `cagl` (Italy) and the satellite PRN01, as a function of UT time, and the STECs computed from the IRI model with different SSN. Figure 8 (a), left, is for a night-time, and Figure 8 (b), right, is for a day-time. As can be seen, an optimum SSN between 50 and 60 can be fitted from these data arcs. The reference value at this time was 49.

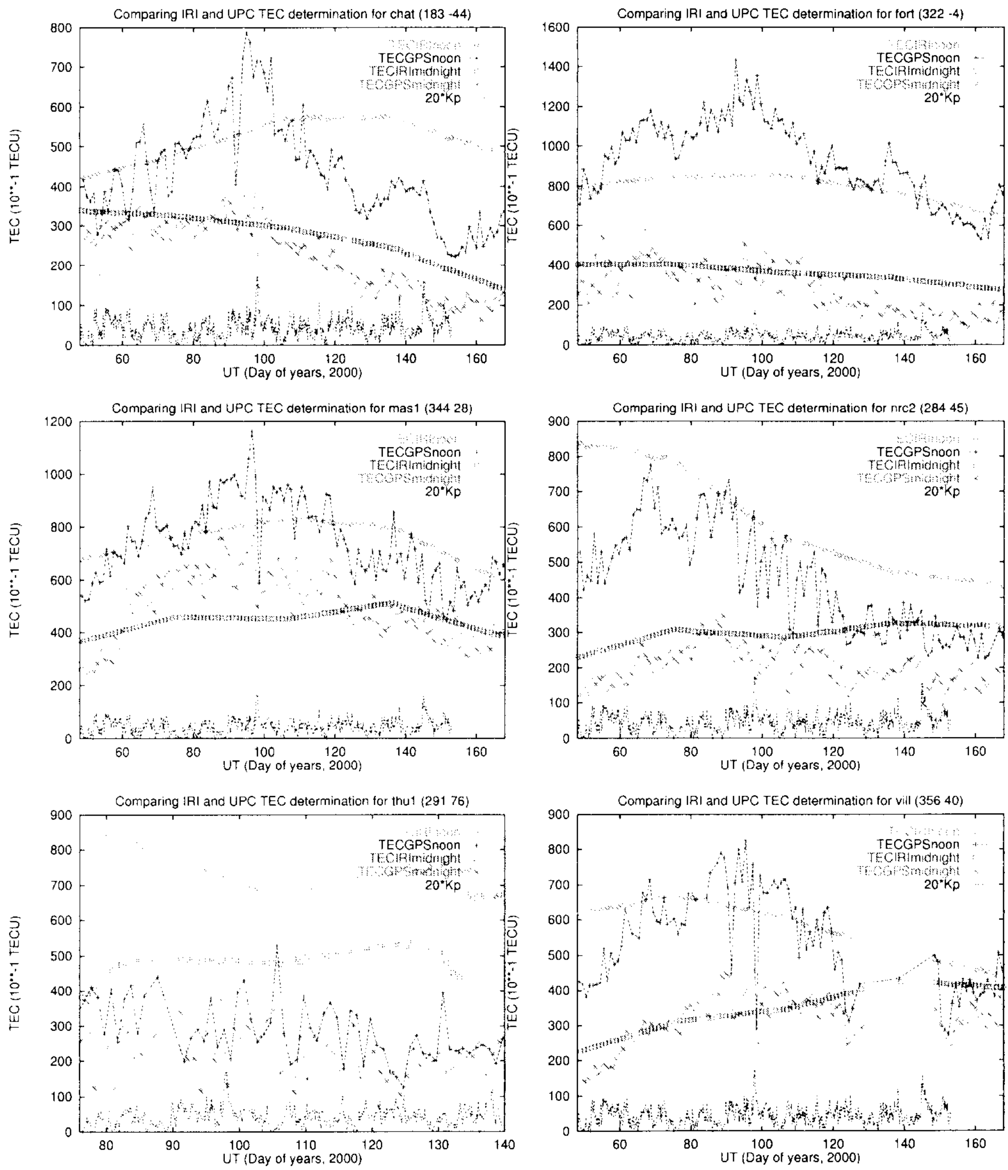

Fig. 7. Comparison between GPS TEC estimations and the IRI predictions (in 0.1 TECUs units) for six different stations; see the name and the latitude and longitude coordinates over each plot. The values are given at noon and midnight, over three consecutive months. The ratio Kp index is also given in the plots.

Figure 8 (c), bottom left, shows the discrepancies between the optimum (fit) SSN and the reference SSN, computed for all the tracked satellites in 24 hours, for a worldwide distributed set of stations during June 1st 1998. It appears an under estimation of the TEC for several stations mainly in the north of America and Europe, with mean SSN-optimum above the reference value, and an over estimation of the TEC in the other stations. Figure 8 (d), bottom right, shows the standard deviation of the SSN values fitted from the STEC of the different satellites in view from each station.

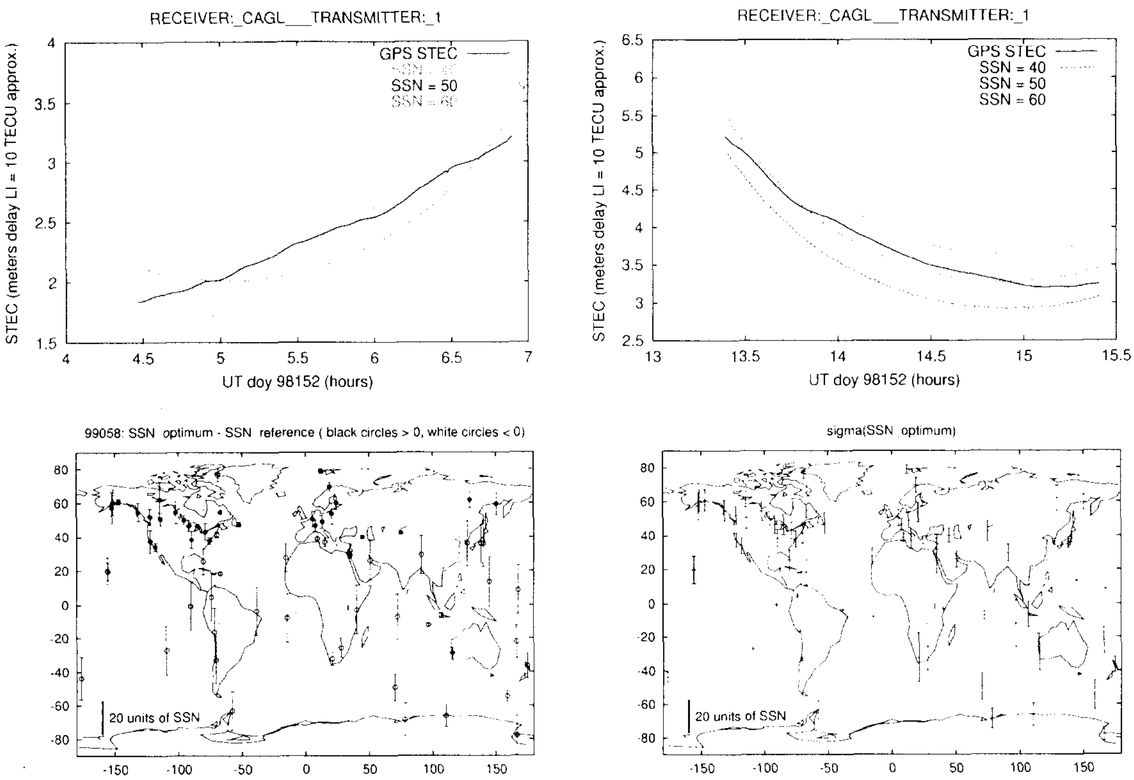

Fig. 8. (a) (top left) STEC computed from the IRI model with different SSN, dashed lines, and observed STEC between station cagl (Italy) and the satellite PRN01 (solid line). These values are computed for a night-time (between 4 and 7 UT). (b) (top right) *Id.* for a day-time data (between 13 and 15.5 UT). (c) (bottom left) discrepancies between the SSN optimum (fitted with GPS data) and the reference SSN, for 24 hours and a set of worldwide distributed ground stations for June 1st 1998. (d) (bottom right) standard deviations of the SSN optimum values.

CONCLUSIONS

Global ionospheric TEC maps can be obtained with GPS data from a network of ground IGS reference stations with an accuracy of few TEC units. The use of the IRI as a reference model for interpolating the global TEC maps (computed with GPS data) improve the accuracy, in general, by 1 TECU or more.

The comparison with the TOPEX TEC, mainly measured over the oceans far from the IGS stations, shows a mean bias and standard deviation of about 2 and 5 TECUs respectively. The discrepancies between the STEC predictions and the observed values show an RMS typically below 5 TECUs (which also includes the alignment code noise).

The existence of a growing database 2-hourly global TEC maps and with resolution of 5x2.5 degrees in longitude and latitude can be used to improve the IRI prediction capability of the TEC. When the IRI predictions and the GPS estimations are compared for a Three month period around the Solar Maximum, they are in good agreement for middle latitudes. An overdetermination of IRI TEC has been found at the extreme latitudes, the IRI predictions being, typically two times higher than the GPS estimations.

Finally, local fits of the IRI model can be done by tuning the SSN from STEC GPS observations.

ACKNOWLEDGMENTS

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