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High resolution TEC monitoring method using permanent ground GPS receivers

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Abstract. In this paper we propose a new and simple method for obtaining the ionospheric Total Electron Content (TEC) variations from GPS permanent station data, in a very precise manner and with high temporal and spatial resolution.

The key idea is to use of the *resonant* period of 1 sidereal day between the Earth's rotation and the GPS satellite orbit periods, in order to obtain one TEC variation estimate directly from each ionospheric observation.

This new strategy can be applied on both global and local scales, for instance to one single station. Its capabilities are shown in the application performed with the data gathered on 17, 18 and 19 October 1995 from 95 GPS permanent stations and 9 and 10 January 1997 (180 stations), coinciding with two major geomagnetic storms.

Introduction

Usually, the ionospheric electron content estimated from dual frequency Global Positioning System (GPS) observations is modeled in *absolute terms*, taking as unknowns the instrumental delays jointly with the electron content (e.g., Wilson et al. 1995, Ho et al. 1997, Juan et al. 1997, Hernández-Pajares et al. 1997) or its gradients (for instance, Martinez et al. 1996), which are considered constant over certain regions or *pixels*. These approaches have the disadvantage of not using all the accuracy of the input data, the ionospheric combination, calculated from both the dual phase and code observations. One source of this *loss of accuracy* is the integration time interval needed to merge the observations in order to have enough data to perform electron content estimates. Other sources are the discretization error, in the case of pixel (*boxel* in 3-D) models (see Hajj et al. 1994), and the correlations between instrumental delays and electron content estimations under certain circumstances (Juan et al. 1997).

In order to overcome part of these limitations some authors have used as *input data* the consecutive differences in time (or equivalent) for the same station-satellite pair, which are useful for improving the temporal sensitivity of the model (Coco et al. 1995 applying the Fourier transform to the input ionospheric delays) and the spatial resolution (Martinez et al. 1996). Other approaches use Kalman filtering to improve the temporal resolution by *connecting* batches of *boxel* electron content models (Sardon et al. 1994 in an Earth-bounded coordinate system, Juan et al. 1997 with two layers in an inertial reference frame).

In this paper we propose a new strategy that simultaneously avoids the need to model with boxels and Kalman filtering the spatial and temporal variations of the Total Electron Content (TEC) respectively. It consists of using, in an inertial reference frame, the difference in the slant total electron content (STEC) experienced by GPS rays connecting the same transmitter–receiver pair separated in time by a whole number of sidereal days (hereinafter sd for one sidereal day). This is the *resonant* period of the Earth's rotation (1 sd) and of the GPS satellite orbit (1/2 sd). This means that the differences in the integrated electron density along the same geometrical path (in an *inertial* reference frame) can be easily obtained. In this way, the common bias terms such as the instrumental delays are canceled and we get one STEC variation/ray, which can easily be converted into radial total electron content (TEC) variation, assuming a one layer model, thus obtained with a high temporal and spatial resolution.

Model

The ionospheric combination $I_i^j(t)$ (see, for instance, Blewitt 1990 or Sardon et al. 1994) corresponding to the GPS satellite j placed at position $\vec{S}(t)$ at time t, observed from the GPS station i at position $\vec{R}(t)$, can be expressed as:

$$I_i^j(t) = \int_{\vec{R}(t)}^{\vec{S}(t)} N_e(\vec{r},t)\, ds + D_i + D^j \qquad (1)$$

where $N_e(\vec{r},t)$ is the electron density at position $\vec{r}$ and time t, D_i, and D^j are the instrumental delays corresponding to the receiver i and satellite j, which are very stable[1] and are assumed constant in this approach. The integral expresses the slant total electron content along the ray path.

[1]For instance, from DLR (1997) and during March 1997, the mean rms of the instrumental delays estimated daily are 0.13 ns ($\simeq$ 4 cm of delay) for the 25 GPS satellites and 0.55 ns ($\simeq$ 16 cm of delay) for the 18 European stations considered in the reference.

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From this expression, and taking into account that the Earth's rotation period is $\tau = 1$ sd, and the orbital period of a GPS satellite is $\frac{\tau}{2}$, and consequently $\vec{R}(t + k\tau) = \vec{R}(t)$ and $\vec{S}(t + k\tau) = \vec{S}(t)$:

$$\Delta I_i^j(t) = I_i^j(t + k\tau) - I_i^j(t) =$$

$$\int_{\vec{R}(t)}^{\vec{S}(t)} (N_e(\vec{r}, t + k\tau) - N_e(\vec{r}, t))\, ds =$$

$$= \int_{\vec{R}(t)}^{\vec{S}(t)} \Delta N_e(\vec{r}, t)\, ds = \Delta \mathrm{STEC}_i^j(t) \qquad (2)$$

where $\Delta \mathrm{STEC}_i^j(t)$ is the consecutive difference in slant TEC's separated by k integer sidereal days (between t and $t + k\tau$) along the same geometrical path. From this point, we can adopt, for instance, a simple model with one layer, with a mean electron density N_e:

$$\Delta I_i^j(t) \simeq \Delta N_e(\vec{r_0}, t) \cdot \Delta s = \Delta TEC(\vec{r_0}, t) \cdot M$$

$\Delta TEC(\vec{r_0}, t)$ being the variation in TEC at the crossing point of the ray with the mean height of the layer under consideration $\vec{r_0}$ -the *sub-ionospheric point*- between the epochs t and $t + k\tau$. $M = \Delta s / \Delta h$ is the projection factor or *mapping function*, changing from slant to radial in the *one-layer* model adopted (Δh is the thickness of the layer). We must emphasize that the main contribution to this variation is (from equation 2) due to the areas of the ionosphere sounded by the ray with greater variations of electron density. This can exclude regions where we can assume a more stationary electron distribution, such as the protonosphere.

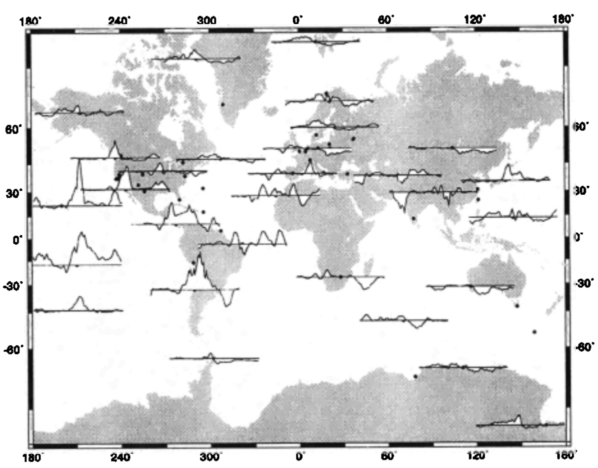

Figure 1. Permanent GPS stations used in the computations with data for 17, 18 and 19 October 1995 (bullets). They belong to the *International GPS Service for Geodynamics* or IGS. For a set of representative stations, the differences in TEC referred to the same *inertial* ray on 17 October is plotted, using the method described in the paper. The vertical range reaches 4 meters of delay on TEC variation for the Hawaiian station (KOKB). The horizontal axis ranges from 0 to 48 hours UT referred to the 18 October 0h UT (this figure was produced with the software package GMT, of Wessel & Smith, 1995).

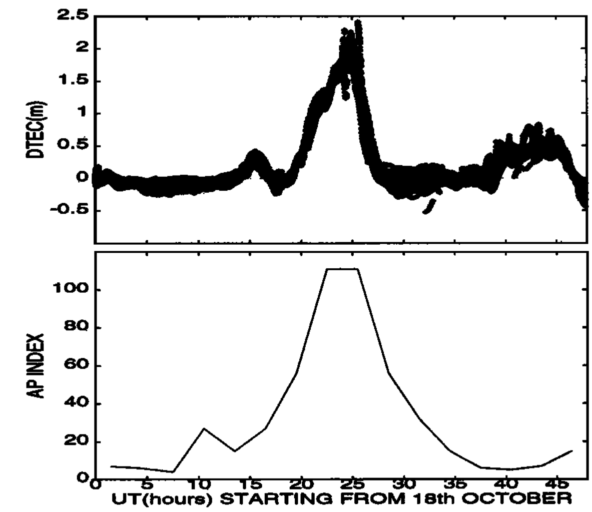

Figure 2. In the first figure (a), the TEC variation (in meters) is plotted after one and two sidereal days for the days 18 and 19 October referred to the 17th October 1995 (time is expressed in hours from 0 h UT on 18 October). The data considered come from 11 very close permanent GPS stations in California (contained in 1 degree^2), belonging to the IGS network. The ray elevations considered are greater than 25 degrees. In the second figure (b), the Ap geomagnetic index corresponding to the same period is plotted in the same time scale as Figure (a).

Hence, from these relationships, we can directly obtain the variation in TEC for each ray within an interval of $k\tau$=k sd=$k{\cdot}23^h56^m$ approximately, without estimating instrumental delays or *mean TEC* values i.e., in a pixel model by *Least Squares*. We could say that in this way, we get one *parameter* (ΔTEC) from one *datum* (ΔI).

Computations and Conclusions

The main computations, presented as an application of this new strategy, were done using the GPS data collected from 95 dual frequency ground receivers of the International GPS Service for Geodynamics -IGS- network (Figure 1, see Zumberge et al. 1994 for details) over three consecutive days, 17, 18 and 19 October 1995 (hereinafter days 1, 2 and 3), coinciding with a major geomagnetic storm. This event reached the Earth toward the end of day 2 (see Figure 2b, representing the *Ap geomagnetic indices* published by NOAA, 1996; see Davies 1990 for definitions). The data sampling rate adopted is 1 observation every 120 seconds for each station-satellite pair. Then the sub-ionospheric points are separated by approximately half a degree, considering a one-layer model defined with shells at 60 and 600 km (mean height 330 km).

In Figure 2a ΔTEC is shown in relation to the corresponding ray on day 1, as a function of time for each ray (starting at day 2) collected from nine very closely spaced stations contained in a one-square-degree region in California. The method clearly presents the good

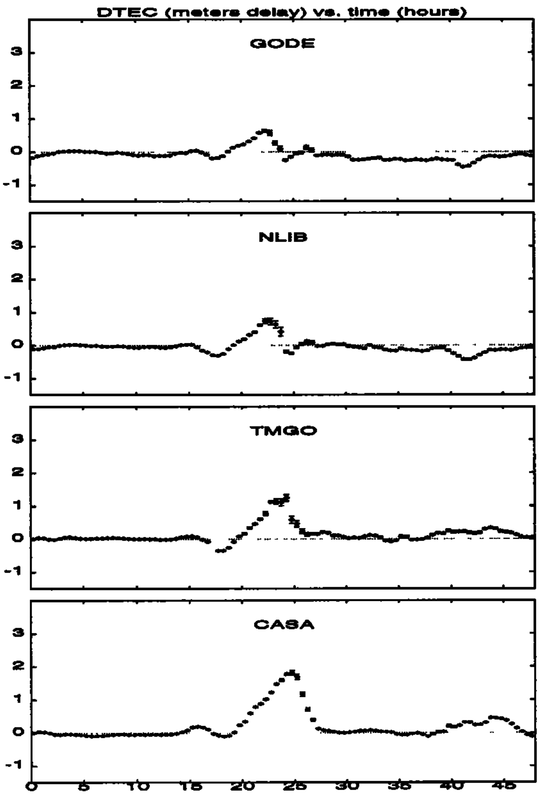

Figure 3. Mean TEC variation at 30-minute intervals are plotted for four permanent GPS stations in North America which are distributed along similar declinations (40 deg. approximately) and with longitudes separated by ≃10-15 deg.: GODE at 283 deg., NLIB at 268 deg., TMGO at 255 deg. and CASA at 241 deg. The data were also collected on 17, 18 and 19 October 1995 and the variation has been calculated referred to 17 October 1995 in meters of delay. The horizontal axis is the time from 18 October 0h UT in hours.

concordance and low noise between the independent estimates of ΔTEC. The noise is, in general, $\leq$ 15 cm, due basically to differences in the alignment process of the phase with regard to the code[2] (see Blewitt 1990). Also, there is a sharp rise in the TEC observed from these stations between 0.8 and 1.2 days, coinciding with a strong Ap geomagnetic index variation (Figure 2b).

In Figure 3 the TEC variations are shown as a function of time for three stations in North-America at similar latitudes but different longitudes. The different —consecutive— arrival times with respect to the storm scenario could qualitatively explain the difference in the epoch and value of the maximum variation in STEC. These considerations might be taken into account to interpret these kinds of results for a representative subset of IGS stations distributed worldwide, as in Figure 1. Again, although this time on a global scale, there is a clear increase in the TEC, in certain regions, especially in the Pacific area, near America.

[2]This result can be obtained by plotting differences in STEC for rays with high elevations only, thus avoiding the error due to the one-layer model.

In order to show the spatial and temporal extent of the storm, viewed by means of the total electron content variation, we have represented in Figure 4 the mean of variation in TEC along bins of 5 deg.×5 deg. in an inertial system (right ascension/declination)[3], within four consecutive *frames* of 3 hours: 18-21, 21-24, 24-27 and 27-30 h UT beginning at 18 October 0 UT. With the data we have, the maximum TEC increase occurs during 24-27 UT near the Sun, at around 240-300 deg.

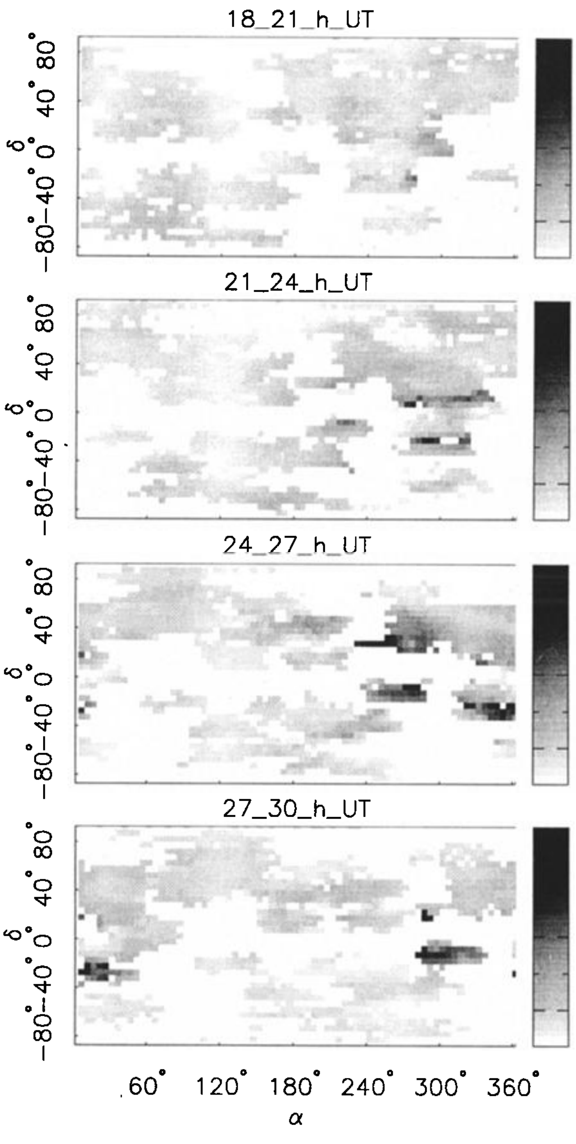

Figure 4. Four consecutive *frames* of the TEC variation *movie* between 18 and 30 h UT beginning at 18 October. The x-axis represents the right ascension and the y-axis the declination in degrees. The variations in TEC are expressed in meters of delay (in approximately 10 TECU units). The darker cells do not contain data.

[3]This is the Earth Centered pseudo-Inertial reference system (ECI), where the X-Axis points towards the Vernal Equinox and the Z-Axis points towards the Geographic North Pole; the XY plane is the celestial equator. In the ECI the Sun is only *moving* at 1 degree/day. The associated spherical coordinates are the right ascension α (*azimuthal* angle) and the declination δ (angle referred to the equator).

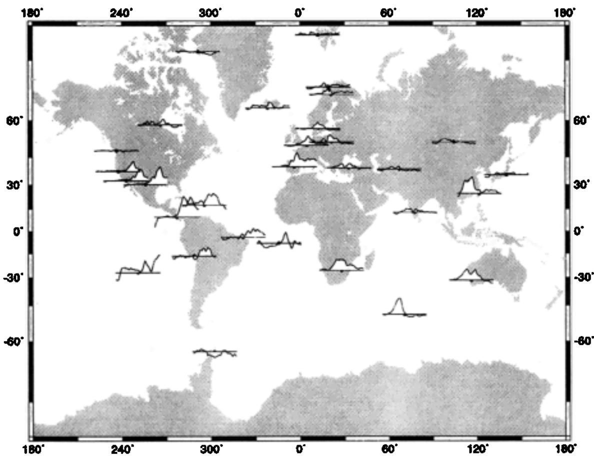

Figure 5. TEC variation during the 10 January 1997 referred to the 9 January is presented, coinciding with another major geomagnetic storm. A subset of representative IGS stations are shown: the vertical scale is the same as in Figure 1 (similar figure but for 17, 18 and 19th October), and the horizontal axis ranges from 0 to 24 h UT of 10 January.

in right ascension. Some details of the evolution can also be viewed with this representation.

Finally, the new strategy was also applied to a recent major geomagnetic storm that occurred on 10 January 1997 (see ISTP 1997), referred to the estimations for 9 January and using more than 180 IGS stations. The temporal evolution of the TEC can be viewed in Figure 5 for a representative subset of stations. A broader temporal extent of the TEC variation, compared to the October 1995 storm (Figure 1), and mainly concentrated in the southern hemisphere, can be observed.

Concluding, we can say that the new proposed model, which uses the resonant period of 1 sd between the Earth's rotation and the GPS satellite orbit, allows a precise and very detailed description of the TEC variations, referred to a (quiet) reference day from GPS data gathered at permanent ground receivers. It has been tested during a major geomagnetic storm (17, 18 and 19 October 1995) and also applied to the recent storm of 10 January 1997. One of the potential applications that can take advantage of the benefits of this new technique is TEC monitoring for long intervals on a global, regional or local[4] scale. It could also be used at near real time, providing a broad coverage in longitude, latitude and time.

[4] It can also be applied with data gathered by only one GPS receiver.

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