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## GPS Total Electron Content measurements at low latitudes in Brazil for low solar activity

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### RESUMEN

Se calcularon las variaciones del número total de electrones en la ionosfera (TEC) usando datos de GPS, obtenidos en la estación de baja latitud de Presidente Prudente, Brasil (22.1° S; 51.4° W) en 1997, un periodo de baja actividad solar. Se presentan dos promedios horarios durante este periodo. Se discuten las variaciones diarias, estacionales, debidas a la actividad solar y la Anomalia Ecuatorial. Los promedios diurnos de TEC se comparan con las predicciones del modelo IRI-95 para los meses de los equinoccios y los solsticios y se muestra que IRI-95 sistemáticamente sobreestima los valores observados. Los aumentos pre-nocturnos de TEC se observaron durante todo el año excepto en mayo y junio. Los valores de TEC medidos reproducen la misma tendencia general de los valores TEC observados en Cachoeira Paulista, Brasil (22.5° S; 45° W). El efecto "fuente" parece ser más efectivo en Presidente Prudente debido a su menor latitud magnética. La correlación entre los valores experimentales de TEC y el flujo solar durante la baja actividad ( $62 < F_{10.7} < 116$  unidades de flujo) enfatiza que el modelo IRI para bajas latitudes y periodos de baja actividad solar es inadecuado. Los resultados aquí presentados son los primeros obtenidos usando la técnica TEC-GPS sobre la parte suroeste de Brasil.

**PALABRAS CLAVE:** GPS, Número Total de Electrones, Anomalia Ecuatorial.

### ABSTRACT

Variations of ionospheric Total Electron Content (TEC) have been calculated using GPS data at station Presidente Prudente, Brazil (22.1° S; 51.4° W) in 1997, a period of low solar activity. Two hourly TEC averages are presented for the period. Diurnal, seasonal, solar activity variations and Equatorial Anomaly effects are discussed. TEC diurnal means compared with IRI 95 predictions for equinox and solstice months show that IRI-95 systematically overestimates the observed values. Pre-midnight TEC enhancements were observed all over the year, except in May and June. The TEC values reproduce the same general trend of TEC observations over Cachoeira Paulista, Brazil (22.5° S; 45° W). The "fountain" effect seems to be more effective at Presidente Prudente because of its lower magnetic dip latitude. A correlation between TEC experimental values and low solar flux ( $62 < F_{10.7} < 116$  flux units) emphasizes the inadequacy of IRI to model low latitude TEC values at low solar activity periods. These are the first results obtained using TEC-GPS technique for total electron content measurement in southwestern Brazil.

**KEY WORDS:** GPS, Total Electron Content, Equatorial Anomaly.

### INTRODUCTION

The ionosphere is a dispersive medium for electromagnetic waves. The regular refraction of a radio signals passing through the ionosphere can be calculated provided that the ionosphere has a symmetric distribution of electron density, the radio signal frequency is substantially above the F-layer's critical frequency and the layer thickness is substantially smaller than its radius of curvature. Refraction then will depend on the radio signals frequency, on the total electron content (TEC) of the ionosphere and on the angle of incidence of the radio wave on the ionospheric layer.

Since 1958 measurements of the electron content of the ionosphere have been made using Faraday rotation tech-

nique (see Titheridge, 1973 and the references cited). As a rule these measurements were restricted to the north hemisphere and to mid- to high latitudes. More recently, measurements have been extended to the south hemisphere and to low latitudes and a great variety of new results have been gathered (see for example: Ezquer and Adler, 1989; Balan *et al.*, 1994; Batista *et al.*, 1994; Huang and Cheng, 1995; Su *et al.*, 1995; Abdu *et al.*, 1996; Ganguly *et al.*, 2001; Sethi *et al.*, 2001).

Total electron content observations using Global Positioning System (GPS) satellites are becoming a very powerful and valuable tool for investigating global and local ionospheric structures (Davies and Hartmann, 1997; Breed *et al.*, 1998; Hernandez-Pajares, *et al.*, 1999) because the world-

wide coverage provided by the 27 satellites constellation and the increasing number of networks available such as the International Geodynamics Service (IGS) for global survey and local networks as the Geophysical Survey Institute in Japan (Saito *et al.*, 1998), the Australian Surveying and Land Information Group (AUSLIG) in Australia and the Brazilian Network for GPS Continuous Monitoring (RBMC) settled up and coordinated by the Brazilian Institute of Geography and Statistics (IBGE) in operation since 1996 (Fortes *et al.*, 1998).

The International Reference Ionosphere (IRI) is the international standard for the specification of ionospheric densities and temperatures. It was developed and is being improved-updated by a joint working group of the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR) (Bilitza, 1997; Bilitza, 2001). For a given location, time and date, IRI describes the electron density, electron temperature, ion temperature, ion composition, and the electron content in the altitude range from 60 km to 2000 km. It provides monthly averages in the non-auroral ionosphere for magnetically quiet conditions.

The highest TEC in the world occurs in the equatorial region. The maximum TEC values are not found at the equator, but rather in the so-called Equatorial Anomaly region located at approximately  $\pm 17^\circ$  from the magnetic equator. Several authors have reported the ionospheric instabilities observed in the TEC measurements in this region, associated to scintillations (Kumar and Gwal, 2000), nighttime enhancements (Balan *et al.*, 1994), solar cycle dependence (Huang and Cheng, 1995) and for the Brazilian region (Abdu *et al.*, 1996).

The purpose of this work is to describe the local ionospheric conditions for a low latitude station in Brazil, using a dual frequency GPS receiver to calculate the ionospheric total electron content during a period of low solar activity, 1997. GPS data received at Presidente Prudente (Brazil) ( $22.1^\circ$  S;  $51.4^\circ$  W), were converted to vertical TEC values and compared to IRI-95 model for equinox, summer and winter months. Diurnal, seasonal, and solar cycle dependences of TEC are clearly seen. The resulting plots were compared to TEC measurements obtained in Cachoeira Paulista - CP (Souza *et al.*, 2002) and in Australia (Goodwin *et al.*, 1995). An extensive search in the literature has revealed that these are the first results obtained to describe the ionosphere over the southwestern part of Brazil (Presidente Prudente), using GPS signals.

The solar radio flux (F10.7) values used in this study were taken from Internet site NASA/NOAA. The minimum and maximum flux values recorded for 1997 were 62 and  $116 \text{ W/m}^2/\text{Hz}$  respectively.

## EXPERIMENTAL DATA AND ANALYSIS

The RBMC network includes thirteen receivers, two of them (Brasília and Fortaleza) are part of the IGS. TEC measurements presented in this study were obtained from GPS signals received in Presidente Prudente (dip latitude  $12.3^\circ$  S) during 1997. This RBMC-GPS station started to operate in 1996 and these were the first long term GPS data continuously recorded. Figure 1 shows the location of the GPS stations in Brazil. Presidente Prudente is indicated as PP and the magnetic dip equator is shown in the figure as a reference.



Fig. 1. GPS location of dual-frequency receiver sites of the RBMC in Brazil. GPS signals analyzed in this study were received at Presidente Prudente (PP in the map). The approximate position of the magnetic dipole equator is also indicated.

Although 1997 was at the beginning of the ascending phase of the 23<sup>rd</sup> solar cycle, there were only four severe magnetic storms (Dst index  $< -100$  nT) reported in the period (April 22, May 15, October 11 and November 8). Because of the magnetically quiet conditions all over the year the data were indistinctly analyzed without any further correction for the four periods mentioned.

### TEC Measurements

The vertical total electron content at a certain receiving station is assumed to be mainly a function of the spherical distance to the Sun, which depends on both the incident solar radiation flux and the time, and the magnetic latitude of the station.

The differential time delay technique allows the calculation of the slant TEC (Horvarth and Essex, 2000) of the

combined ionosphere and plasmasphere up to 20,000 km. The measured slant TEC for each “visible” satellite at a given point and time is then converted to vertical TEC following a similar procedure given in details by Horvath and Essex (2000) and Breed *et al.* (1998). In the present study a single thin shell of infinitesimal thickness situated at a median ionospheric height of 400 km above the earth surface was assumed.

Values of TEC were obtained using differential phase measurements combined with the absolute differential time delay measurements in order to improve the accuracy of the resulting values. Although differential phase measurements are nonabsolute, they are much more precise than differential time delay measurements which can carry inaccuracies arising from the signal that contains pseudorandom noise code and multipath reception (Breed *et al.*, 1998).

#### Local ionospheric model

The ionospheric local model applied to the vicinities of the GPS station operating with dual frequency receiver (Schaer *et al.*, 1995) can be represented by

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} E_{nm} (\beta - \beta_o)^n (s - s_o)^m, \quad \text{where}$$

$n_{\max}$  and  $m_{\max}$  represents the maximum degree of a bidimensional expansion of Taylor series.  $E_{nm}$  are unknown coefficients of TEC (local model parameters to be estimated),  $\beta_o$  and  $s_o$  are the receiver coordinates and  $\beta$  and  $s$  stand respectively for the latitude and longitude of the subionospheric points for a median ionospheric height of 400 km. (The subionospheric point is the projection on the ground immediately below the point where the line of sight from satellite to receiver intersects the 400 km shell).

TEC data have been processed using a software known as Bernese GPS Software, version 4.2, developed at Bern University (Switzerland) for geodetic purposes, allowing a high accuracy for positioning calculations (Rothacher *et al.*, 1996). In the processing sequence the software checks the integrity of daily files, splits the 24 hours Rinex format files in two files of 12 hours each and converts the files to Bernese format. The observing masking angle is then chosen ( $15^\circ$ ) and the TEC is calculated at two hours intervals to assure small rms ( $< 0.5$  TECU). The TEC is computed in TEC units (TECU) where  $1 \text{ TECU} = 1 \times 10^{16} \text{ electrons. m}^{-16}$ .

#### Diurnal variations

Two hourly diurnal means of TEC have been determined as a function of time of day for Presidente Prudente, cen-

tered on 1200 and 2400 LT, i.e., (UT – 3) hours from January to December, 1997. Figure 2 shows the daytime (upper plot) and nighttime (lower plot) daily means for 1997. The thick lines represent the corresponding running mean of the points. Diurnal peak values varied from a minimum of 10 TECU (July 12 - 17) to a maximum of 43 TECU (Nov. 25 – Dec. 5). In the plots, missing points due to technical problems, power failure or cycleslips due to loss of tracking signal represent less than 10% of the days in 1997.

Diurnal TEC peaks occurrence varied slightly from month to month from 1700 to 1900 UT. In some summer days, the peaks were displaced to 21 UT. After a previous visualization of the diurnal dispersion taken from plots superposition each fifteen days, the peak to peak daytime variation for a fortnight was obtained and this values used to define the daytime interval of the TEC “plateau”. The same criteria have been used to define the nighttime stable intervals. Figure 3 shows an example of the daytime variations (diurnal plots superposed) for 28 days in September, 1997, when the dispersion range from peak to peak reached a maximum value of 10 TECU. In Figure 3 it can also be seen that the dispersion of diurnal plots shows a minimum just after local sunrise.

Double peaked maximum of TEC values were observed in some days of equinoctial months or close to them (February, March, April, October) and also in winter (June).

Nighttime minimum values rarely overcome 5 TECU, ranging as a rule from zero or very close to zero to 3 TECU all over the year. Minimum diurnal values in general occurred between 0700 and 0900 UT. Nighttime means are less reliable because their magnitudes of approximately 5 TECU are comparable with the limit accuracy of GPS-TEC, a few TECU, after Davis and Harmann, 1997.

Pre-midnight enhancements have been observed systematically all over the year (at least in 80% of the available days), with maximum amplitude of 10 TECU in September/October and minimum amplitude by the end of January and August (3-5 TECU). They are practically absent in May and June.

#### Seasonal variations

March, June, September and December were taken as representative months for autumn equinox, winter, spring equinox and summer respectively. Monthly TEC means have been calculated using the data available for each month: 25, 14, 28 and 21 days respectively for March, June, September and December.

Estimated values have been plotted together with IRI-95 predictions (data available from Internet NSSDC

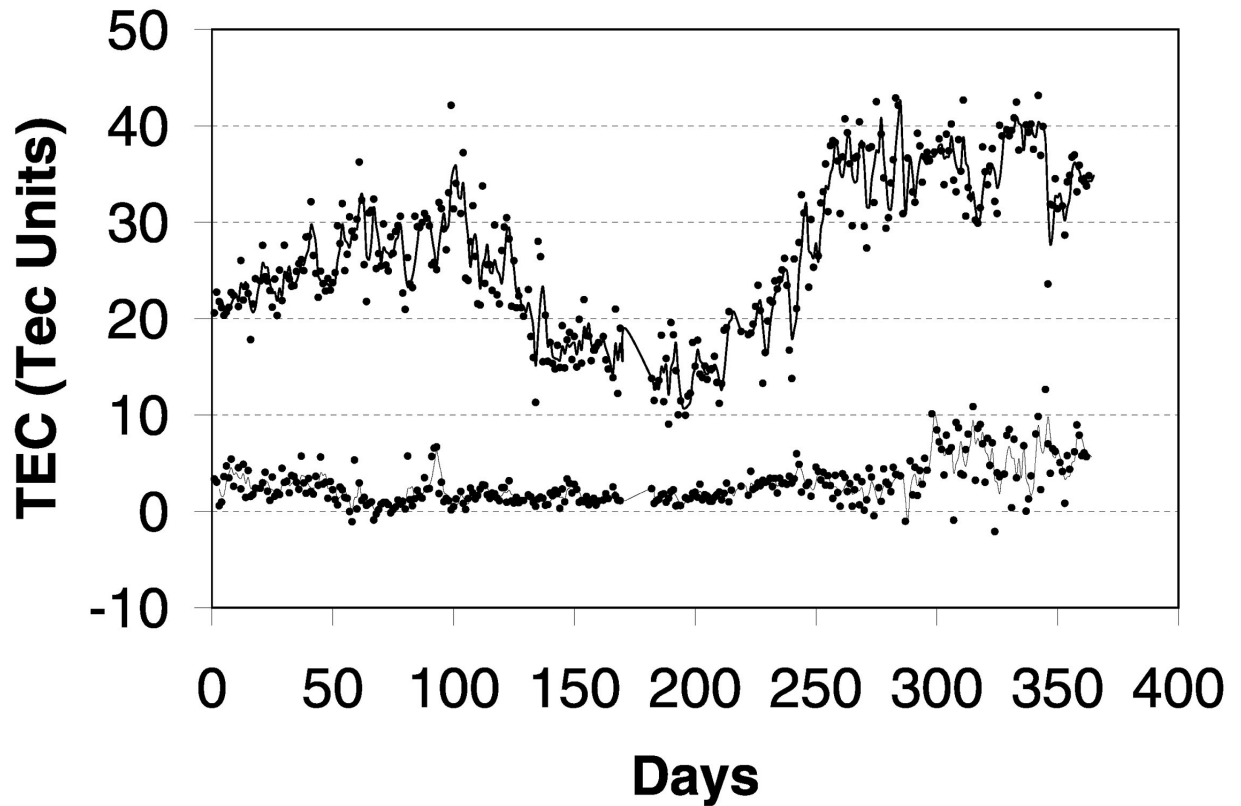


Fig. 2. Daytime (upper plot) and nighttime (lower plot) means for successive days in 1997. The thick lines in the plots show the corresponding running mean of the experimental points.

homepage) in Figure 4 for comparison purposes. Maximum standard deviations for the observed values are shown as vertical bars. The maximum discrepancies between IRI-95 predictions and the estimated TEC are observed in May and June. Smaller divergences are observed for minimum TEC values at nighttime for all the months in 1997. In all seasons IRI predictions overestimates measured TEC values over PP.

#### Solar cycle variations

A sixth order polynomial curve has been adjusted to the TEC diurnal means for the totality of days in 1997 within a fitting coefficient ( $R^2$ ) of 0.78. The solar radio flux measured at 2800 MHz (10.7 cm) (data output available at the Internet site of NASA/NOOA) was also averaged and a similar adjustment has been made, showing a fitting coefficient ( $R^2$ ) of 0.66. The fitted curves show a very similar trend as can be seen in Figure 5. The dependence of the TEC diurnal peak on the F10.7 is presented for 1997 in Figure 6.

### RESULTS AND DISCUSSIONS

The equatorial region ( $\pm 20^\circ$ ) is characterized by interactive processes involving eastwards electric fields, horizon-

tal magnetic field lines and changing neutral winds which results in local important effects such as the equatorial anomaly and scintillations.

The equatorial anomaly results from the east-west electric field at the equator giving rise to an upward  $E \times B$  plasma drift across the horizontal magnetic field lines, during daytime. The  $F_2$  region plasma, after being lifted to higher altitudes, diffuses downwards. The overall process results in the formation of the equatorial anomaly characterized by a trough at the magnetic equator and two crests at about  $\pm 17^\circ$  magnetic latitudes. The effects of neutral winds can cause north – south asymmetries that arises from the offset between the magnetic and geographic equators and from the magnetic declination angle (Su *et al.*, 1995; Horvath and Essex, 2000).

Pre-midnight enhancements are frequent at latitudes near the dip equator ( $\pm 17^\circ$  dip latitude), a region known as the Equatorial Anomaly (Su *et al.*, 1995).

The TEC increases interpreted as pre-midnight enhancements at PP overcome by two or three times the amplitudes and frequencies reported by Balan *et al.*, 1994, for a



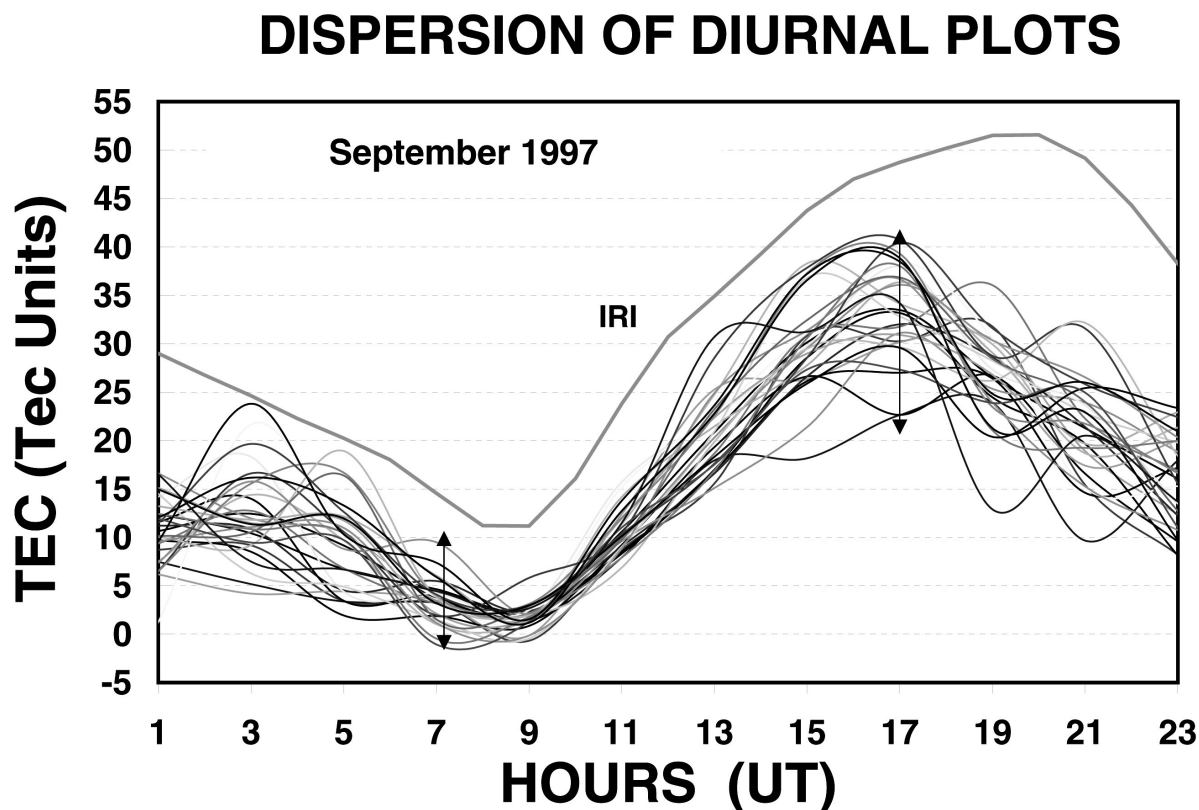


Fig. 3. Superposition of the diurnal plots obtained in September, 1997 (28 days available). The maximum dispersion of plots is shown as a bar at diurnal TEC peak.

south hemisphere location in the equatorial anomaly ( $20^{\circ}$  S) for a period of moderate solar activity. The authors also mention that enhancements are more frequent and stronger in the south hemisphere and that they occur mostly during September to March. In PP, nighttime TEC enhancements are observed all over the year, but May and June. On the other hand, the nighttime enhancements observed in PP are of about the same amplitude of those reported by Horvath and Essex (2000) for Guam (dip latitude  $8^{\circ}$  N) for low solar activity conditions.

Diurnal TEC values have been compared to measurements obtained at Cachoeira Paulista (CP) in Brazil (Souza *et al.*, 2002). The TEC values at PP show a slightly higher amplitude in all seasons for low solar activity. This behavior may be a consequence of the particular location of CP (magnetic dip latitude  $12^{\circ}$ ). The latitudinal position of the anomaly crest depends on the magnitude of the upward vertical drift at the magnetic equator. During low solar activity the anomaly crest may be displaced northwards affecting more PP than CP.

The same seasonal asymmetry in the TEC diurnal peak values reported by Abdu *et al.* (1996) for CP is found in the

TEC observations at PP. The spring equinox shows larger values than the autumn equinox, as can be seen from Figure 4.

Although the protonospheric contribution to TEC is mostly noticeable at mid latitudes and during solar maximum, it is worthwhile to mention that a small amount of the TEC estimated for PP may have built in a protonospheric contribution not present in the ionospheric electron content (IEC). MacPherson *et al.* (2000) found a remarkable plasmaspheric contribution over Arecibo on a magnetically disturbed period (Jan. 9-10, 1997, Dst index of  $-78$  nT). On the other hand, Makela *et al.* (2000) argue that for summer conditions, the plasmaspheric contribution to the TEC is of the order of 20%. MacPherson *et al.* (2000) believe that the reason for such differences in plasmaspheric contributions is a seasonal effect driven by the relative changes in the topside ion densities which are reversed from winter to summer.

At latitudes closer to the magnetic equator, scintillations can also occur during nighttime. The scintillation is basically associated with spread-F occurrences. After local sunset, the bottom side of the F-region over the magnetic equator is subjected to gravitational Rayleigh-Taylor mechanisms. As a

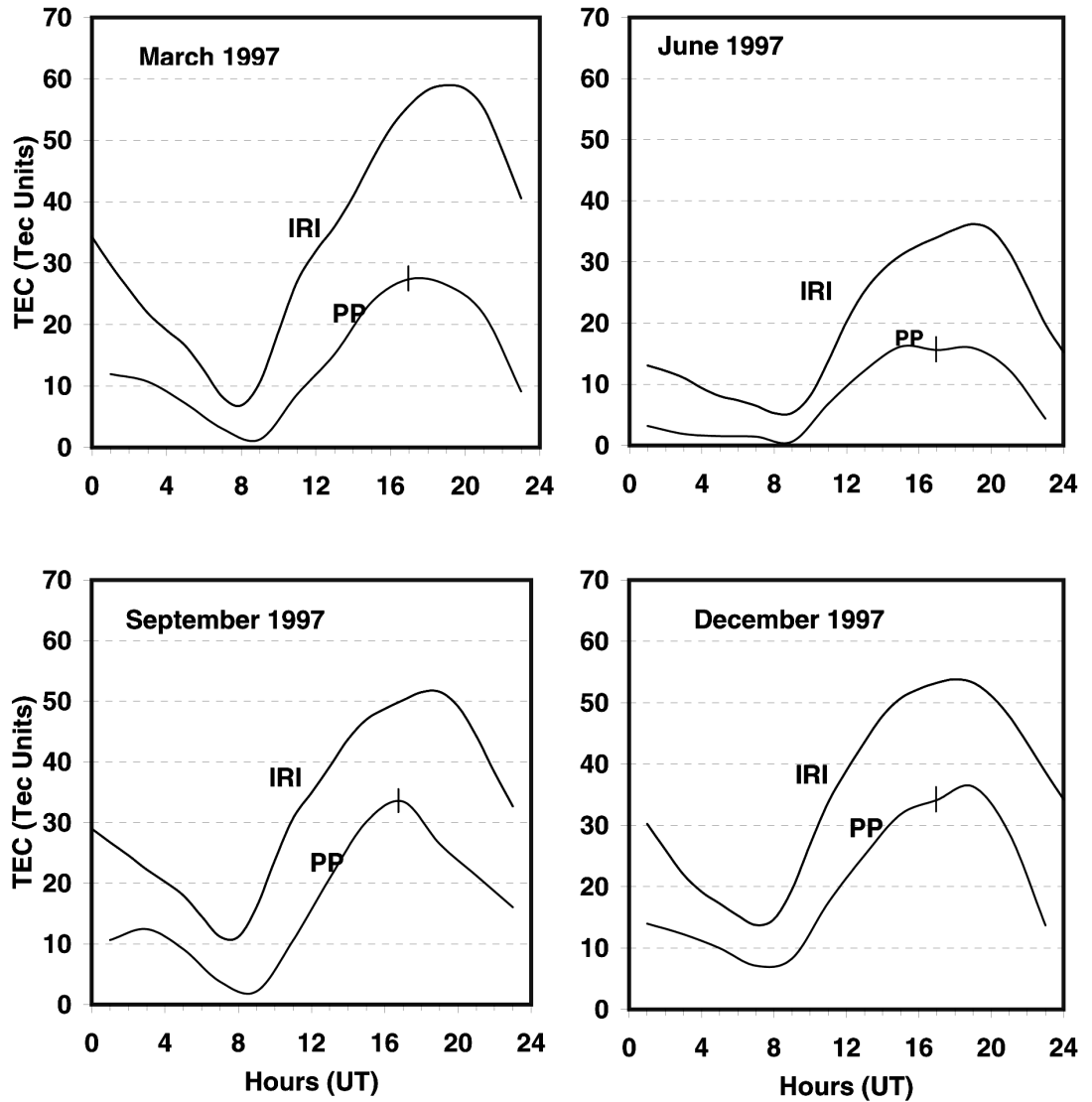


Fig. 4. March (autumn equinox), June (winter), September (spring equinox) and December (summer) means for Presidente Prudente (PP) in 1997 and IRI-95 model predictions for comparison.

result, irregularities known as plasma bubbles are generated which rise to the topside ionosphere due to non-linear evolution of the instability and produce scintillations in discrete patches (Kumar and Gwal, 2000; Abdu *et al.*, 1991). Although the scintillation frequency can be less during low solar activity more effects seem to occur at low latitudes mainly at equinoxes with a peak at 2200 LT (Kumar and Gwal, 2000).

Both these effects can be responsible for the perturbations observed at nighttime before and/or after local midnight in the diurnal TEC values for PP in comparison to CP.

IRI-95 predictions for north hemisphere TEC values, in general are a good representation of the observational data

for all seasons and solar cycle periods (Hernandez-Pajares, 1999; Breed *et al.*, 1998; Goodwin and Breed, 2001).

It can be seen from Figure 4, that for all seasons IRI-95 overestimates TEC values at PP, as has already been observed by Abdu *et al.* (1996) over CP. Maximum discrepancies to IRI-95 model are observed in May and June when IRI diurnal peaks exceed the calculated means by more than 100%. The smaller discrepancies occur in September when the IRI diurnal peak is 25% above the calculated mean values.

The best agreement between IRI-95 model and experimental values occur at the nighttime in June, when the two values coincide within 2 TECU. This last result is consistent

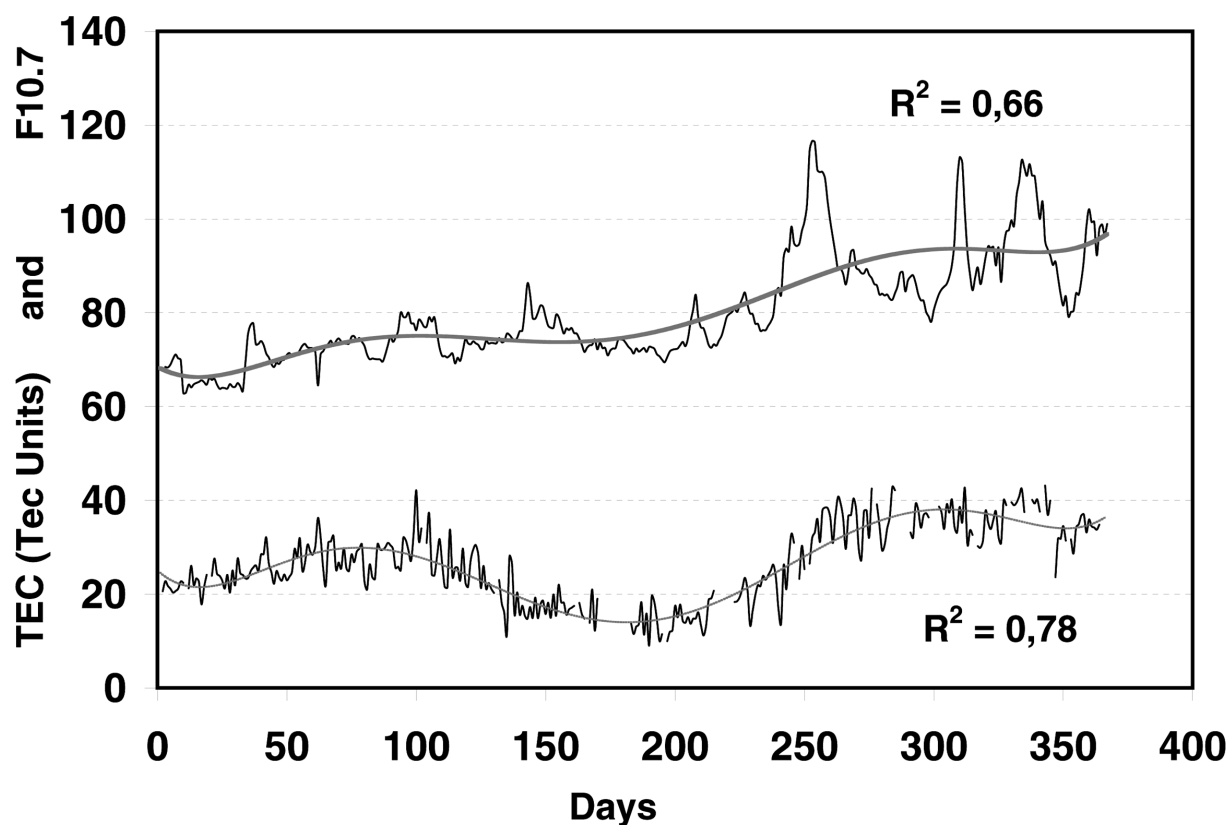


Fig. 5. Solar flux (F10.7) daily means and TEC daily means adjustments by polynomial curves. Fitting coefficients ( $R^2$ ) are 0.66 and 0.78 respectively. Note the general trend of the fits.

with observations reported by Abdu *et al.* (1996) over CP. Similar discrepancies have also been observed by Sethi *et al.* (2001) for observations over Arecibo.

In Figure 5, the regularity in the general trend of the fitted curves is an indication of the sensibility of TEC to modulations in the solar flux. Nevertheless, the relatively large and intense increases in solar flux that occurred on September 9, November 4 and 28 did not show any additional variation in the corresponding total ionospheric electron content. On November 8 a severe magnetic storm was reported (Dst index of - 110 nT at 0500 UT).

The TEC dependence on solar flux from 62 to 116 flux units, at 1700 UT, is shown in Figure 6, for 1997. In this case it was not necessary to split the experimental points seasonally because of the low solar fluxes range. Corresponding IRI-95 predictions, adjusted by the upper straight line, highlight an overestimation of about 20 TECU during all seasons in 1997. These results show consistency with those presented by Abdu *et al.* (1996) and expand largely the range for low solar fluxes.

## FINAL REMARKS

- Estimated TEC values over PP during a low solar activity period are very similar to those measured over Cachoeira Paulista. Nevertheless, because of Presidente Prudente lower dip latitude, the diurnal averages over Presidente Prudente seem to be more disturbed than over Cachoeira Paulista.
- Nighttime enhancements associated to the equatorial anomaly crest have been observed all over 1997, except in May and June.
- IRI-95 predictions overestimate TEC values at Presidente Prudente by 20 TECU in all seasons. The biggest discrepancies occur on winter months.
- IRI-95 seems to be inadequate to model the low latitude ionosphere at low solar activity.
- TEC behavior is a good indicator of the long term trend of the solar flux variability, for low solar activity periods.



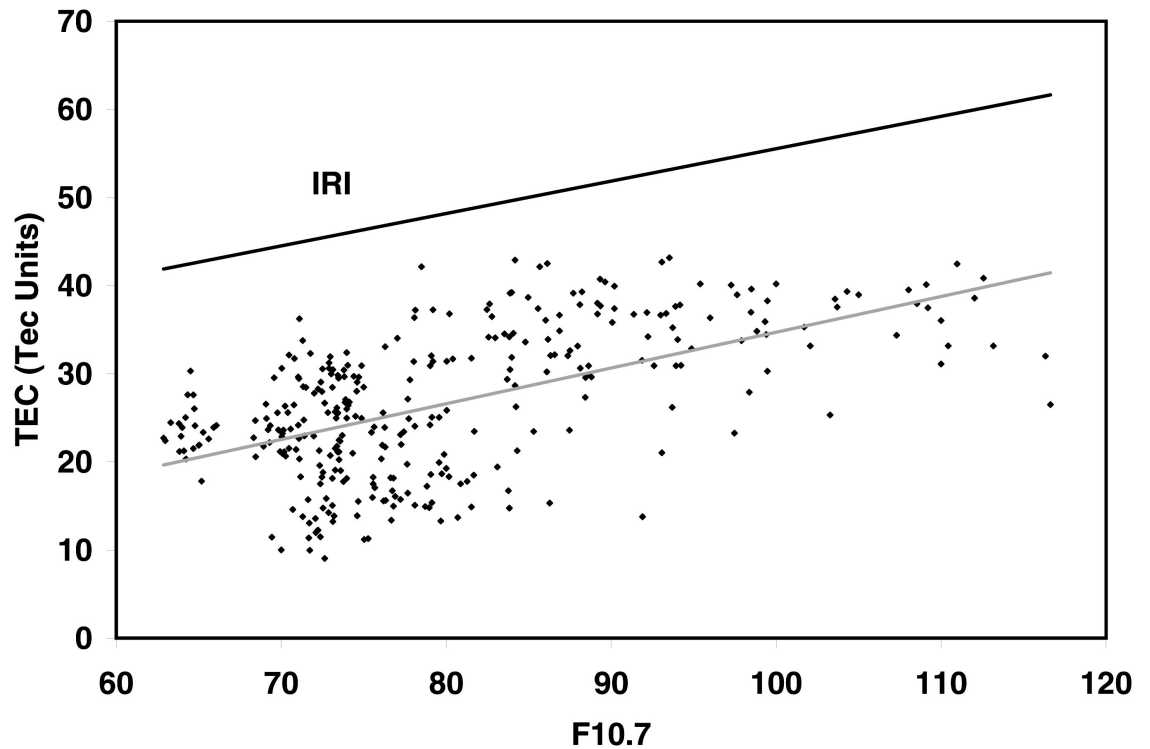


Fig. 6. TEC dependence on solar flux ( $62 < F10.7 < 116$  flux units), at 1700 UT, maximum diurnal peak, for 1997. The upper straight line represents IRI-95 predictions.

These are the first results obtained using TEC-GPS technique for total electron content measurement over the southwestern part of Brazil (Presidente Prudente). In future works different receivers will be included and higher solar activity conditions will be investigated.

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