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Total ionospheric electron content from GPS measurements over the Brazilian region

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RESUMEN

El principal propósito del sistema GPS es el de determinar la posición y la velocidad de un objeto fijo, o móvil, sobre la superficie terrestre o próximo de ella, utilizando señales de 24 satélites en órbita terrestre. Debido al efecto de la ionosfera en la propagación de las ondas electromagnéticas, transmitidas por los satélites GPS en 1575,42 y 1227,60 MHz, es posible deducir el contenido eletrónico total (TEC), utilizando los mismos datos de GPS que normalmente son utilizados en navegación.

El TEC es el número de electrones libres a lo largo de la trayectoria de la onda electromagnética, entre cada satélite y el receptor.

El TEC es un importante parámetro geofísico que tiene, también, aplicaciones en la corrección de medidas de navegación con receptores de frecuencia única.

Este trabajo presenta la metodología que fue utilizada para obtener las variaciones diurnas y latitudinales del TEC vertical, sobre la región brasileña, con el uso de datos de receptores de doble frecuencia del «Global Positioning System». También son mostrados algunos resultados preliminares y se propone un nuevo método de obtención del atraso instrumental.

PALABRAS CLAVE: Ionosfera, contenido electrónico, GPS.

ABSTRACT

Due to the effect of the ionosphere on the propagation of the electromagnetic waves transmitted by the GPS satellites, in 1575.42 and 1227.60 MHz, it is possible to obtain the total ionospheric electron content (TEC). We present the methodology used to obtain diurnal and latitudinal variations of vertical TEC over the Brazilian region with data from Global Positioning System (GPS) dual frequency receivers. Some preliminary results are presented and a new method to obtain instrumental delays is proposed.

KEY WORDS: Ionosphere, electronic content, GPS.

INTRODUCTION

The total electron content (TEC) is the amount of free electrons along the path of the electromagnetic wave between a satellite and a receiver, given by

$$TEC = \int_{receiver}^{satellite} N \cdot ds \qquad (1)$$

where N is the electron density.

TEC has been measured for decades using the Faraday rotation effect on a linear polarized propagating plane wave (Klobuchar, 1985 and 1996). Special transmitters in geostationary and non-geostationary satellites were used for this purpose. But today there is a complex constellation of 24 satellites distributed in 6 orbital planes, 4 satellites per plane, at 20 200 km altitude, with an orbit inclination of 55 degrees and an approximately 12 hour available period, which can provide up to 9 TEC values within 1000 km from a receiving station about every 30 seconds. There are a great number of GPS receiving stations able to provide TEC measurements. The International GPS Service has 196 stations as of 26 October 1998, including 2 in Brazil and 15 in South and Central America. There are also local GPS networks.

In the following we present the methodology utilized by the INPE group in Brazil to obtain diurnal and latitudinal variations of vertical TEC over the Brazilian region, using data from Global Positioning System (GPS) dual frequency receivers. A new method to obtain instrumental delays is proposed, and some preliminary results are provided.

GLOBAL POSITIONING SYSTEM (GPS)

Each satellite transmits two carrier electromagnetic waves with frequencies, L1, and L2, both in the L-band:

L1 = 1575.42 MHz (154 × 10.23 MHz) λ = 19 cm
L2 = 1227.60 MHz (120 × 10.23 MHz) λ = 24 cm

with code modulation. By comparing with a reference code it is possible to measure the travel time of the code and the carrier between the satellite and the receiver using the pseudoranges from the code travelling time

$$P_i = \rho + c \cdot (dT - dt) + \Delta i_i^{iono} + \Delta^{trop} + b_i^{P,r} + b_i^{P,s} + m_i^P + \varepsilon_i^P \qquad (2)$$

and the carrier phases

$$\Phi_i = \lambda_i \cdot \phi_i = \rho + c \cdot (dT - dt) + \lambda_i N_i - \Delta_i^{iono} + \Delta^{trop} + b_i^{\phi,r} + b_i^{\phi,s} + m_i^{\phi} + \varepsilon_i^{\phi} \quad (3)$$

where

i = 1,2 corresponding to carrier frequencies L1 and L2
P is the code pseudorange measurement in distance units
ρ is the geometrical range between satellite and receiver
c is the speed of light
dT, dt are the receiver and satellite clock offsets from GPS time
$\Delta_i^{iono} = 40.3\ TEC/f_i^2$ is the ionospheric delay
TEC is the Total Electron Content
f_i is the carrier frequency Li
Δ^{trop} is the tropospheric delay
b_i are the receiver and satellite instrumental delays on P and Φ
m_i are the multipath on P and Φ measurements
ε_i are the receiver noise on P and Φ
Φ_i are the carrier phase observations in distance units
ϕ_i are the carrier phase observations in cycles
λ = c/f is the wavelength
N_i are the unknown Li integer carrier phase ambiguities

Details can be found in Hoffmann-Wellenhof *et al*. (1994), Seeber (1993), Leick (1995) and Komjathy (1997).

The data P_i e ϕ_i and the corresponding satellite orbits were obtained from the Internet by anonymous ftp in gracie.grdl.noaa.gov/dist/cignet/ in RINEX and sp3 formats.

TEC CALCULATION

Combining the pseudoranges observations P_i, a TEC value is obtained as follows.

$$TEC_P = 9.52 \cdot (P_2 - P_1) + \textit{instrumental delays} + \textit{multipath} + \textit{noise} \quad (4)$$

which is very noisy.

After combination of carrier phase observations Φ_i we get

$$TEC_\phi = 9.52 \cdot [(\Phi_1 - \Phi_2) - (N_1\lambda_1 - N_2\lambda_2)] + \textit{instrumental delays} + \textit{multipath} + \textit{noise} \quad (5)$$

which is less noisy than TEC_P but ambiguous.

The ambiguity is removed by averaging (TEC_P - TEC_ϕ) over a satellite pass (phase connecting arc)

$$TEC_L = TEC_\phi - \left\langle TEC_\phi - TEC_P \right\rangle \quad (6)$$

This levels the TEC to the unambiguous TEC_P and contains the information of the less noisy TEC_ϕ, but includes instrumental delays, multipath and noise. The carrier phase observations may have a sudden jump that is removed ("cycle slip correction") by adjusting the continuity of (Φ_1 - Φ_2) .

The vertical TEC (TEC_V) depends only on geographical location and time, and not on a slant TEC function of the satellite and receiver locations. To relate these TEC's a mapping function M(E), where E is the satellite elevation angle at the receiver, is used. A simple function is M(E) = 1/cosχ, where χ is the zenith angle at the subionospheric point between the satellite and the receiver at a height given by the center of mass of the ionospheric profile, usually between 350 and 450 km (thin shell model).

ABSOLUTE TEC AND TEC MAPPING

To study perturbations in the ionosphere, the $TEC_V = TEC_L \cos\chi$ may be sufficient, but when the absolute value of the TEC is needed the satellite and receiver instrumental delays must be known, because they can be significant. To obtain the instrumental delays and to make regional or global maps of the ionospheric TEC an estimation strategy is applied. The TEC_L measurement $T^{rs}(t)$ between receiver *r* and satellite *s* at epoch *t* can be modeled by

$$T^{rs}(t) = M(E) \cdot I(\theta,\varphi,t) + b^r + b^s \quad (7)$$

where

M(E) is the mapping function for the elevation *E*
I(θ,φ,t) is an ionospheric TEC model
θ,φ are latitude and longitude
t is the measurement epoch
b^r, b^s are the differential instrumental delays of the receiver *r* and satellite *s.*

Given the satellite orbits, the values of *θ, φ* and *E* are determined. With TEC_L measurements, the b's and the parameters of the ionosphere TEC model *I(θ,φ,t)* can be determined by least-square fit or with a Kalman Filter (Lanyi and Roth, 1988; Coco *et al*., 1991; Gail *et al*.,1993; Mannucci *et al*., 1993; Wilson and Mannucci, 1993; Sardón *et al*., 1994; Komjathy and Langley, 1996). These methods can be quite complicated to apply.

Precalculated biases b's are available in the CDDIS (Crustal Dynamics Data Information System) in the Internet (Feltens,1998). For simplicity we may assume TEC to equal about 3-5 TECU at vertical nighttime data (about 4 AM local time), or to assume no TEC gradients (fixed zenith TEC value) over an arc of GPS data (Mannucci, 1998).

The following "similitude" method, here proposed, is still in development.

SIMILITUDE METHOD FOR OBTAINING SATELLITE INSTRUMENTAL DELAYS

For a receiving station and for each satellite, over an arc of data the measured vertical TEC (Figure 1) is

$$I^{r,s}(LT) = \left[T^{r,s}(LT) - (b^r + b^s)\right] \cdot \cos\chi^{r,s}(LT), \qquad (8)$$

where *LT* is the subionospheric local time. Varying the delays *b*'s in the above expression, the *I(LT)* curve will vary its shape from $\cap$ to $\cup$ (U-shape). This provides a range of possible values for $(b^r + b^s)$. Two data arcs for different satellites at similar local times should have similar shapes, but not a pronounced U-shape, otherwise they would intersect each other. The similarity is imposed by adding a "floating constant", α_S, to *I(LT)*, so that

$$\sum_{s,LT}\left[I^{r,s}(LT) - \alpha_S - \left\langle I^{r,s}(LT)\right\rangle_S\right]^2 \qquad (9)$$

is a minimum. Here $\langle\rangle_S$ denotes an average over all satellites. Satellite and receiver delays cannot be separated, and can be determined for each satellite, but if one assumes that the receiver delay is more significant than the satellite delays, the solution is simplified.

We are currently comparing the delays obtained by similarity with other methods.

PRELIMINARY RESULTS

Figures 2 and 3 show some preliminary results for Fortaleza Station on January 13, 1997. TEC is given in TECU.

Figure 2 shows a TEC(magnetic latitude, LT) plot. The longitude of the subionospheric point was substituted by a local time variation (fixed sun system). Latitude is divided in 5° intervals and local time in 30 minutes intervals. Data is averaged in these interval cells, and later smoothed.

Figure 3 shows the daily variation of TEC using data with latitudes ± 2.5° from Fortaleza. Error bars represent the standard deviation of the data.

FUTURE WORK

Several studies have been conducted on TEC behavior at high and mid-latitude. There are few equatorial and low-latitude TEC stations and modeling is difficult in these regions. Studies will be conducted to describe and understand better TEC in the Brazilian region, and to develop a regional model of TEC over Brazil.

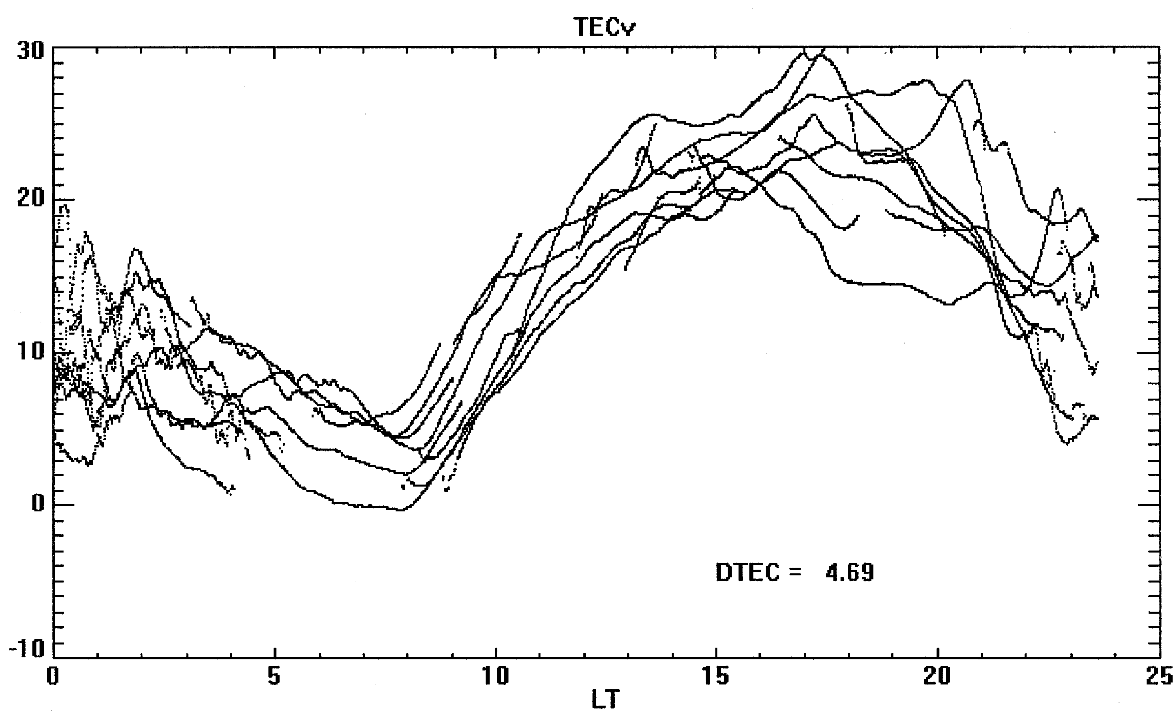

Fig. 1. Plot of $I^{r,s}(LT)$ for several satellites.

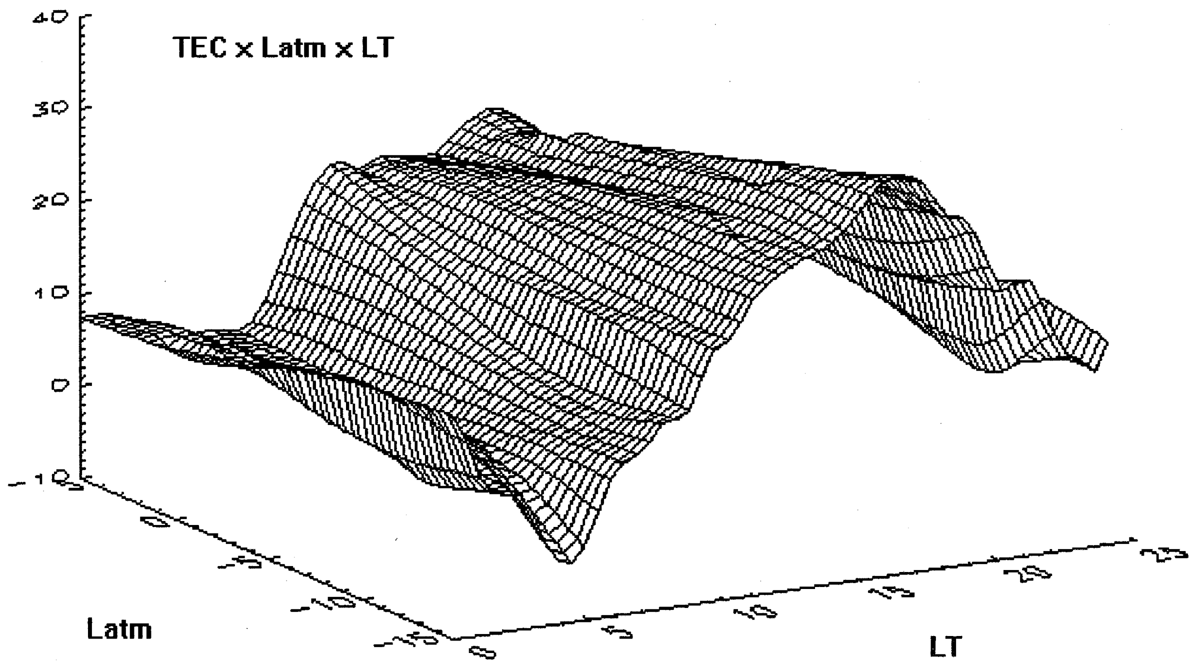

Figure 2 - Plot of TEC(magnetic latitude, local time) around Fortaleza (13 January 1997).

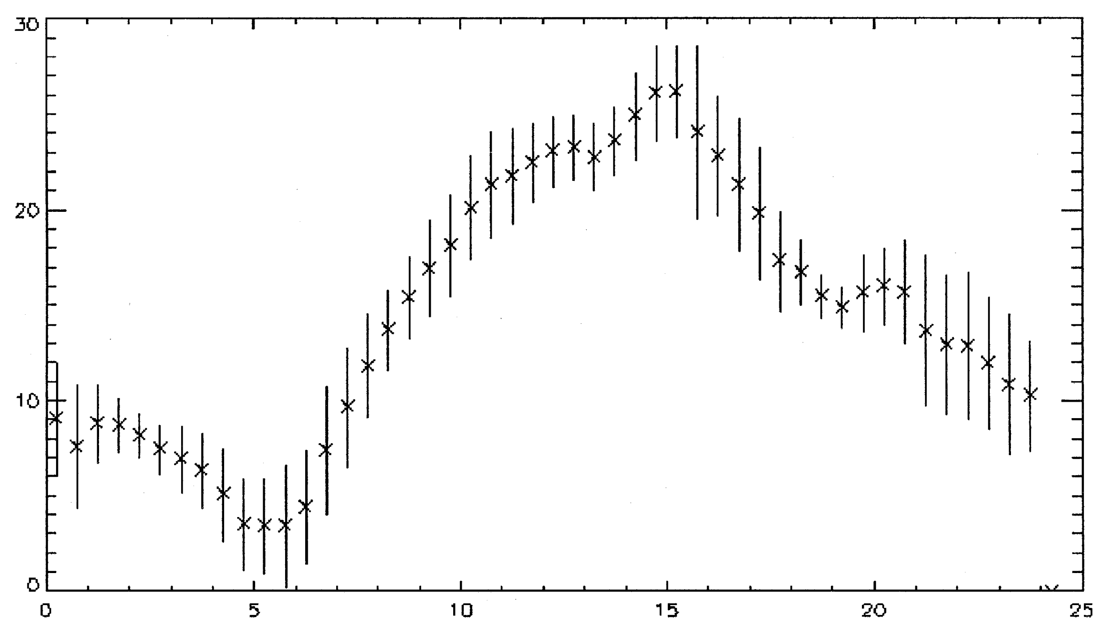

Figure 3 - Daily variation of TEC with local time at Fortaleza (13 January 1997).

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