Studies of TEC in Ecuador using Global Positioning System (GPS) data

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Abstract. The ionosphere is a region of the atmosphere formed by electrons and ions, which is located between 300 and 500 km of altitude. The ion concentration in this layer is affected by interactions with particles arising from the solar activity. Parameters such as latitude, longitude, time, solar cycle, ground stations and others, influence the content of electrons/ions present in this region. The ionosphere disturbs the electromagnetic signals due to its conductivity and high variability. In this research, signals from Global Positioning System (GPS) were used to estimate the total electron content (TEC) of the equatorial ionosphere, with data from the IGS network, based on dual-frequency receivers. Furthermore, we discuss a model that we employed to estimate the TEC, considering the variations experienced by signals as they propagate through the atmosphere and the instrumental systematic errors.

Keywords: Total electron content; Ionospheric delay; Pseudorange.

Introduction.

The ionosphere has fundamental importance for long-distance communication of radio signals. But besides, the ionosphere is as a disturbing medium for electromagnetic waves that pass through it, and this effect should be eliminated from the observations. A major space geodetic positioning technique currently uses, is the Global Positioning System (GPS). The ionosphere acts as a scattering medium, being this effect directly proportional to the total electron content (TEC) and inversely proportional to the square of the frequency. This is a major source of error in the GPS signals.

The Global Positioning System (GPS) consists of 21 satellites in six orbital planes. The orbits with eccentricities between 10^{-4} and 10^{-2} have a major axis of about 26,500 km and an orbital period of 12 hours sidereal time. These satellites broadcast two carrier signals with frequencies of 1575.42 MHz (L1) and 1227.60 MHz (L2), modulated by two codes (C / A and P) and a navigation message. The use of these codes, which are in binary language 0 and 1, allows distinguishing signals from different satellites. The navigation message contains information about the status of the satellites, their ephemerides, their watches and GPS time. They usually updates several times a day.

There are two observables in GPS which are: the **pseudorange** and the **carrier phase**. In the receivers known as code correlation or with code, a replica is generated by the code C / A, P or both. The code received from the satellite is correlated with that generated by the receiver, so that the latter is displaced in time until the maximum correlation occurs. That state is easily identifiable and corresponds to the case where the two copies of the Code are aligned in time.

The displacement done by the receiver copy to match the code from the satellite, multiplied by the speed of light is known as pseudorange. It is not the actual distance between the satellite and receiver because the signal propagation has been affected by the effects of the troposphere and ionosphere, among others agents, and also because the code is generated on the satellite from its clock and the replica of this code in the receiver is based on the receiver's clock, even these clocks may not be perfectly synchronized.

The second observable GPS is the phase of the signal obtained multiplying the signal from the satellite by the signal generated in the receiver. By measuring phases, there is an ambiguity of an integer number of cycles associated with each measurement that cannot be known. This problem, which appears only in the first step, because from here it is performed a continuous monitoring of the signal, known as initial ambiguity. If for any reason there is a momentary loss of signal, ambiguity reappears in the first phase as it once recovered. The difference between this new and previous ambiguity is known as ambiguity cycle, and corresponds to an integer number of cycles. There is an initial ambiguity for each satellite – receiver. This number is not forced to be integer, because there are instrumental delays on satellites and receivers that can overlap with this term. These terms are grouped in what it will be called as initialization constants.

Materials and methods.

GPS measurements are affected by a number of errors introduced by the difference between the time given by the clocks on the satellites and receivers with an ideal time period known as GPS time, tropospheric delay, ionospheric delay, ambiguities, cycle ambiguities, multi-path interference (which occurs in the antenna when the signal reaches it by various ways, e.g. due to reflections on metal structures close to the receiver), delays introduced by the equipment which must pass through GPS signals (both in satellites and receivers).

The ionosphere reflects electromagnetic signals with frequencies below 30 MHz and for higher frequencies introduce a delay. The ionospheric delay is determined from the optical ray by using the ionospheric first order refraction index (Budden, 1961), which is given by the following expression:

$$\mu = \sqrt{1 - {f_p}^2 / f^2} \tag{1}$$

Then, the delay time as a function of this refraction index is given by:

$$I = \int (1-\mu) \frac{ds}{c} \tag{2}$$

Considering that for the GPS frequencies ${f_p}/{f} \ll 1$, we have the following expression:

$$\sqrt{1 - {f_p}^2 / f^2} = 1 - {f_p}^2 / 2f^2 \tag{3}$$

where f_p is the plasma frequency:

$$f_p = \frac{e^2 n}{4\pi^2 \varepsilon_0 m_e} \tag{4}$$

Thus, for the time delay we have:

$$I = \int (1-\mu)\frac{ds}{c} \approx \frac{e^2}{8\pi^2 c \varepsilon_0 m_e} \frac{1}{f^2} \int n ds$$

$$\approx \frac{1.345 \times 10^{-7}}{f^2} sTEC \quad , \tag{5}$$

where sTEC is the total electron content. Furthermore, if expression (5) is multiplied for the speed of light in both sides of the equation, it gives the delay distance signal, thus the expression (5) takes the following form:

$$d_{ion} = \frac{40.3}{f^2} sTEC \tag{6}$$

A dual frequency GPS receiver measure pseudoranges and carrier phase L1 and L2. These observables are used to calculate sTEC for each satellite and for every period of observation. To calculate even more precisely the sTEC, instrumental errors of the satellite-receiver must be removed. The pseudoranges $P_{k_j}^i$ and carrier phases $L_{k_j}^i$ for two frequencies k = 1,2 can be expressed as follows:

$$P_{1_j}^i = \rho_0^i + d_{ion1_j}^i + c\left(\tau^i - \tau_j\right) + b_{q1}^i + b_{q1_j} + b_{res_j}^i \quad \text{(7-a)}$$

$$P_{2_j}^i = \rho_0^i + d_{ion2_j}^i + c\left(\tau^i - \tau_j\right) + b_{q2}^i + b_{q2_j} + b_{res_j}^i \quad \text{(7-a)}$$

$$L_{1_j}^i = \rho_{0_j}^i - d_{ion1_j}^i + c\left(\tau^i - \tau_j\right) - \lambda_1 N_{1_j}^i + B_{q1_j} + B_{res_j}^i \quad \text{(7-a)}$$

$$L_{2_j}^i = \rho_{0_j}^i - d_{ion2_j}^i + c\left(\tau^i - \tau_j\right) - \lambda_2 N_{2_j}^i + B_{q2_j} + B_{res_j}^i \quad \text{(7-a)}$$

Where the phases $L_{1_j}^i = \lambda_1 \emptyset_{1_j}^i$ and $L_{2_j}^i = \lambda_2 \emptyset_{2_j}^i$ are expressed in distance. The observables depend on satellite-receiver distance, tropospheric and ionospheric effects, de-synchronization satellite clocks and the receiver phase ambiguities, multi-paths and other noise. The indices i and j in equation (7) represent the GPS satellite transmitter and the satellite receiver, respectively. ρ_0, represents the actual distance between the receiver and the satellite, d_{ion}, represents the ionospheric delay; τ is the difference between clocks, b_q y B_q represent instrument biases from GPS transmitter and receiver; b_{res} y B_{res}, are other errors such as noise and multi-path; λ is the wavelength signal; $\emptyset$ is the carrier phase of the signal between transmitter and receiver in a number of cycles, and N is the integer of the carrier phase.

As it was demonstrated above, the ionospheric effects on the GPS signal, dependent on the signal frequency f. Then, combining the equation (6) with the equations (7-a) and (7-b), also with the equations (7-c) and (7-d), respectively, we obtain the following expressions:

$$sTEC = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left(P_{2_j}^i - P_{1_j}^i - b^i - b_j + \varepsilon_p\right) \tag{8}$$

$$sTEC = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left(L_{1_j}^i - L_{2_j}^i - B^i - B_j + \lambda_1 N_{1_j}^i - \lambda_2 N_{2_j}^i + \varepsilon_L\right)_{arc} \tag{9}$$

where , $b_j = b_{q2_j} + b_{q1_j}$, y $B_j = B_{q2_j} - B_{q1_j}$

Whereby the pseudoranges and carrier phases of a GPS receiver are combined to obtain the sTEC as a function of the ionospheric observables. The sTEC is measured in TEC units (TECU) which is equivalent to 1 TECU = 10^{16} e/m^2.

The sTEC information derived from pseudorange measurements has a large uncertainty due to high noise levels. The noise level of the phase measurements, are significantly lower than those obtained in the pseudorange measurements, but these have the problem of ambiguity of an integer. Therefore to remove these ambiguities it is defined the following expressions.

$$L_I = L_1 - L_2 \quad (10)$$

$$P_I = P_2 - P_1 \quad (11)$$

Then, combining equations (8) and (9), with the equations (10) and (11), and using the mean operator over an arc, the following expression isobtained:

$$\langle L_{I,arc} - P_I \rangle_{arc} = \lambda_1 N^i_{1_j} - \lambda_2 N^i_{2_j} + B_j - b_j + B^i - b^i - \langle \varepsilon_p \rangle_{arc} \quad (12)$$

Also, it is obtained the average value of the differences between the two direct measurements by calculating their difference for each continuous arc from the following expression:

$$\langle L_{I,arc} - P_I \rangle_{arc} = \frac{1}{N}\sum_{i=1}^{N}(L_I - P_I)_i \quad , \quad (13)$$

where N is the number of continuous measurements contained in the arc. The effect of additional noise and multi-path in carrier phase observations was neglected because it is very small in comparison with the effect of the code delay observations.

Extracting the equation (12) from L_I in the same arc, we can eliminate the term of the ambiguity of an integer. $\tilde{L}_{I,arc}$, is the observable ionospheric carrier phase, which has been corrected from the code delay observable. Then, we have the following expression:

$$\tilde{L}_{I,arc} = L_{I,arc} - \langle L_{I,arc} - P_I \rangle_{arc} \quad (14)$$

Finally, with this correction, we obtain an accurate measure of the total electron content:

$$sTEC = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left(\tilde{L}_{I,arc} - b_j - b^i - \langle \varepsilon_p \rangle_{arc} + \varepsilon_L\right) \quad (15)$$

For accurate monitoring of the ionosphere it is required to know the value of the total electron content in the vertical receiver, so mapping functions associated with the latitude and longitude of the ionospheric point (IPP), which is the point at which the signal path, between the receiver and the satellite, intercepts the Effective ionospheric layer, which is between 300 km and 500 km. Generally, the ionosphere can be divided into some altitude ranges according to the electron density, which reaches its peak value around 350 km altitude.

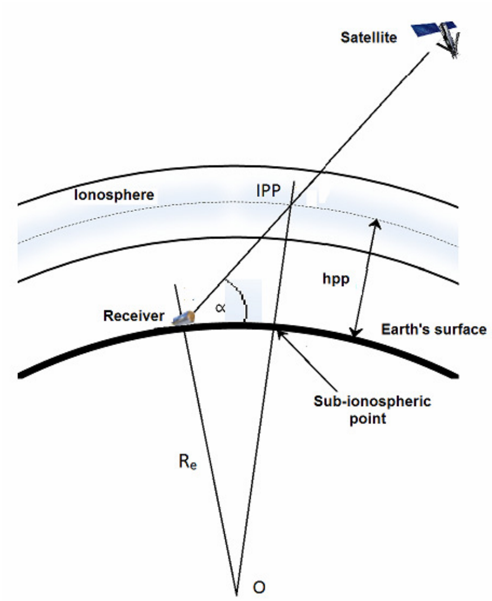

Figure 1. Outline of the GPS signal path, with the respective parameters for calculating the total content of electrons in the vertical region.

Converting vTEC to sTEC, large errors are introduced for low heights where the electron density is low, while for high altitudes, where the electron density is higher, errors less than 1 TECU (1016 e/m2) are obtained. The highest electron density concentrations were found at heights from 350 km to 450 km above the surface of the earth. Then, starting from Figure 1, we obtain the following expression:

$$TEC_V = TEC_S(\cos\chi') \quad (16)$$

Where χ' is the difference between 90° and zenith angle (90°-χ). Now a result to the value of χ' is obtained by the following relationship:

$$\sin\chi' = \frac{R_e}{R_e + h_m}\sin\chi \quad (17)$$

where Re is the earth radius and hm is the height in which the highest electron density is found. Typical values of R_e y h_m are 6371 and 450 km. A more accurate mapping function is given according to Schaer et al. (1996), which is given by the expression:

$$\sin\chi' = \frac{R_e}{R_e + h_m}\sin a\chi, \quad (18)$$

where a, is close to unity with a value of 0.9782, R_e and h_m, are 6371 km and 506.7 km respectively.

Results.

The calculation of the total electron content (TEC) was based on RINEX observation files and satellite navigation. The dual frequency receiver RIOP, from which the information was obtained to calculate the

TEC in the equatorial region, is located in Riobamba, Ecuador and belongs to the IGS network.

Table 1. Location of the GPS receiver.

Riobamba Permanent	
Riobamba, Chimborazo, Ecuador	
GPS Network	IGS
Latitude	-1.65
Longitude	-78.65
Height	2817.2 m
Logging Interval	30s

As it can be seen in Figures 2, the total electron content depends on the time of day. This is because the sun's radiation does not interact with the Earth's atmosphere in the same way for different times of day.

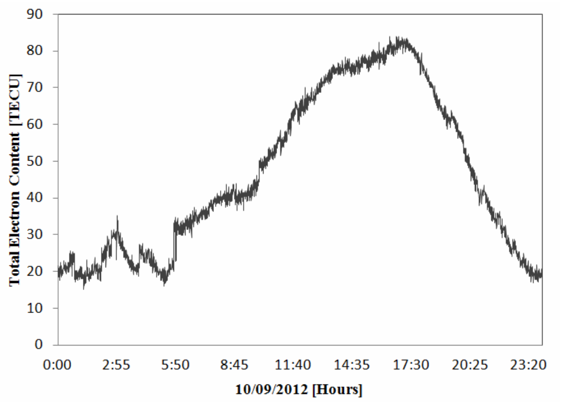

Figure 2.1. This figure shows the vTEC in TECU units for the day 10/09/2012

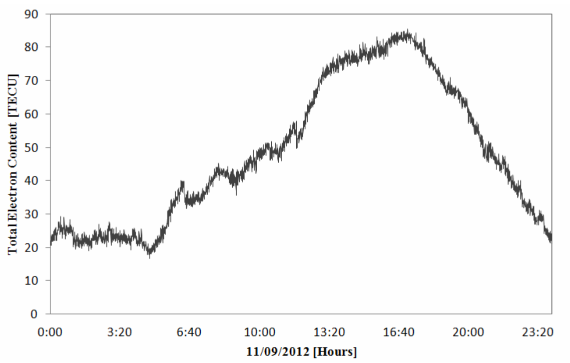

Figure 2.2. This figure shows the vTEC in TECU units for the day 11/09/2012

In Figures 2, it can be appreciated that the TEC at morning hours is low, due to the absence of electromagnetic radiation. The behavior of low TEC is noticeable until around 7:00 and starts increasing until it peaks around 16:40 and then decrease.

Discussion.

In order to calculate the total electron content (TEC) of equatorial ionosphere, data from a dual-frequency GPS receiver located in Riobamba, Ecuador have been employed. The Total Electron Content (TEC) in the equatorial region reaches high values with a maximum of 85.532 TECU, this is explained by the high solar activity in the epoch of the observations. We observe that the TEC changes very quickly, with a difference of 1.555 TECU ; 40 minutes 30 seconds and 1.528 TECU; 4 hours 30 minutes for the maximum and minimum values, respectively.

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