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Ionospheric Gradients Estimates based on Brazilian Network Data

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Abstract

The ionosphere affects the propagation of GPS signals in the equatorial and low-latitude regions. Even auxiliary systems based on GPS such as the Ground Based Augmentation System (GBAS), are affected by ionospheric effects and large gradients due peaks of electron concentration may occur. This contribution will present results and analysis of ionospheric delays and vertical ionospheric gradients estimated from data of dual frequency receivers from Brazilian network located in different geomagnetic latitudes.

1 Introduction

The Global Positioning System (GPS) has an increasing role in Air Traffic Control. However, the ionosphere affects the propagation of GPS signals in the equatorial and low-latitude regions [1]. The ionospheric effects cause positioning error that degrades the accuracy, performance and availability to support the phases of approach, landing, departure and surface operations of the aircraft [2], [3].

Different techniques and Augmentation Systems have been developed to overcome the ionospheric effects, and to meet the safety requirements of aviation. For example, Ground Based Augmentation Systems (GBAS) provide differential corrections and integrity information to the aircrafts [3]. However, GBAS operations may also be severely affected by the equatorial and low-latitude ionosphere [4].

The ionospheric delay gradient is an important parameter for the correction of medium effect on GBAS. The objective of the study reported here is to estimate the ionospheric gradients. To analyze these effects, the GPS measurements of dual frequency receiver stations from the Brazilian network are extracted.

In addition, the present work determines the ionospheric delay estimated from Total Electron Content (TEC) and ionospheric vertical gradients using the time-step method [5] considering stations located in different geomagnetic latitudes.

2 Methodology

The propagation of the GNSS electromagnetic signals in the ionosphere depends on its electron density. The ionosphere is a dispersive medium, the apparent time delay contributed by the ionosphere depends on the frequency of the signal and the Total Electrons Content (TEC). The ionospheric delay I can be related to the TEC through

$$I = \frac{K}{2f^2} TEC \tag{1}$$

where K = 80.62 [m^2/s^2] represents the ionospheric refraction and f is the frequency of the system.

It is possible to compute the value of the slant TEC (TEC_s) from the satellite to the receiver using the GPS observables. The pseudoranges P and the carrier phase delays L corresponding to operation frequencies (f_1=1575.42 MHz and f_2=1227.60 MHz) are the observables extracted from the GPS receivers by cross-correlating both frequencies modulated carrier signal, which are generally assumed to travel along the same path through the ionosphere. By using the, the difference between the pseudo-ranges (P_1 and P_2) and the carrier phase measurements (L_1 and L_2) it is possible to compute the value of the slant TEC. The slant TEC (TEC_s) represents a measure of TEC of the ionosphere along a straight path from the satellite to the receiver [6], [7] and it is defined by

$$TEC_{slp} = \frac{2\,(f_1 f_2)^2}{K(f_1^2 - f_2^2)}(P_2 - P_1) - b_r^P - b_s^P \left[\frac{el}{m^2}\right] \quad (2)$$

$$TEC_{sll} = \frac{2\,(f_1 f_2)^2}{K(f_1^2 - f_2^2)}(L_1\lambda_1 - L_2\lambda_2) - b_r^P - b_s^P \left[\frac{el}{m^2}\right] \quad (3)$$

where K is the ionospheric refraction, 80.62 (m^2/s^2), λ_1 and λ_2 are the wavelength corresponding to f_1 and f_2, respectively.

The difference of the carrier phase between (L_1 and L_2) is precise and less noisy, not providing the absolute TEC. However, the ambiguity in the integer value of L, know as a cycle slip, often arises. The cycle slip correction can typically be made with the aid of pseudorange [7], [8]. To hold phase path accuracy for the slant path TEC_{sl}. TEC_{sll} is fitted to TEC_{slp}, adding a baseline B_{rs} for the difference phase TEC_{sll} [9]

$$TEC_{sl} = TEC_{sll} + B_{rs} \quad (4)$$

$$B_{rs} = \frac{\sum_{i=1}^{N} \langle TEC_{slp_i} - TEC_{sll_i} \rangle_{arc} \sin^2 \varepsilon_i}{\sum_{i=1}^{N} \sin^2 \varepsilon_i} \quad (5)$$

where N is the number of continuous measurements contained in the arc, and ε is the elevation angle. The notation $\langle\ \ \rangle_{arc}$ in (5) indicates an average taken over a phase connected arc (between successive cycle slips) [6].

After that, the relative TEC has been estimated, the subtraction of the satellite and receiver differential instrumental code biases results in the calibrated TEC, equal to the number of electrons encountered along the line of sight between the satellite and receiver, defined as

$$sTEC = (TEC_{sl} - B_i) \quad (6)$$

$$B_i = b_s + b_r \quad (7)$$

where b_s and b_r are the instrumental differential code biases of the satellite and receiver, respectively.

The instrumental bias (B_i) of each pair (receiver and satellite) are obtained by comparing the hourly averages of uncalibrated TEC values from all of the satellite and single receiver combinations using the weighted least mean square fitting method [10].

The slant TEC (sTEC) depends on the ray path geometry through the ionosphere. To estimate a version of this parameter that does not depend on the elevation angle of the ray path, the equivalent vertical (vTEC) is determined [6]. Each slant TEC value will be transformed into a vTEC one, by using the simple mapping function, represented by

$$vTEC = \frac{sTEC}{S(\varepsilon)} \quad (8)$$

where vTEC is measured in TEC units (1 TECU $=10^{16}$ (electrons/m^2) and $S(\varepsilon)$ is the slant factor, defined as

$$S(\varepsilon) = \frac{1}{\cos\left[\arcsin\left(\frac{R_E \cos\varepsilon}{R_E + H}\right)\right]} \quad (9)$$

where ε is the elevation angle, R_E is the radius of the earth, and H is the height of the ionospheric layer; which is assumed to be 400 km.

The ionospheric delay gradient is a non-uniform ionospheric structure that can cause errors in differential corrections broadcast to the aircraft using Ground-Based Augmentation Systems (GBAS). The present study determines the vertical ionospheric delay gradients using the time-step method g^t(mm/km) [11]. The method involves a single satellite and a single station, as well as ionospheric delays (associated to vTEC) at consecutive time instants, as shown in Figure 1.

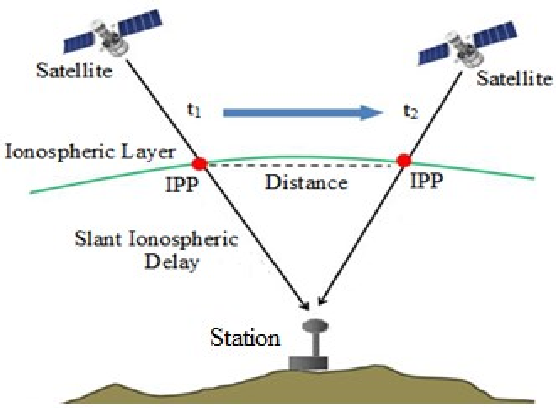

Figure 1. Time-Step method

The time-step ionospheric delay between the satellite and the receiver station at a time t_2 is subtracted from the delay of the same pair at time t_1. The gradient is then represented by the following equation

$$g^t = \frac{|I_{rt_1} - I_{rt_2}|}{DIST_{IPP(rt_1, rt_2)}}\left[\frac{mm}{km}\right] \quad (10)$$

where I_{rt_1} and I_{rt_2} are vertical ionospheric delay values for the receiving station and the satellite at time instants t_1 and t_2, respectively. $DIST_{IPP(rt_1, rt_2)}$ is the distance between the two IPPs referring to satellite positions at these instants of time.

3 Data

Data from the RBMC Brazilian network were obtained to estimate the variation of the vertical TEC as a function of position, local time, season and solar activity over the Brazilian region. The data were stored in the Receiver Independent Exchange format (RINEX) format with 15-

second sampling rate. The measurements were extracted from data collected using an elevation cut-off angle of 20°, to avoid multipath. RBMC RINEX files were used from January to December corresponding to the year 2013.
For this analysis we consider three receiver stations over the Brazilian territory used to estimate the vTEC. The geodetic position of each receiver are listed in Table 1 and shown by red triangles in Figure 2. These stations were selected because are located in different geomagnetic latitudes.

Table 1. Description of receiver stations

Station	Location	Geographic Coordinates	Dip Latitude
IMPZ	Imperatriz, Brazil	05.48° S 47.48° W	03.60° S
BRAZ	Brasília, Brazil	15.93° S 47.82° W	12.10° S
RIOD	Rio de Janeiro Brazil	22.82° S 43.30° W	20.83° S

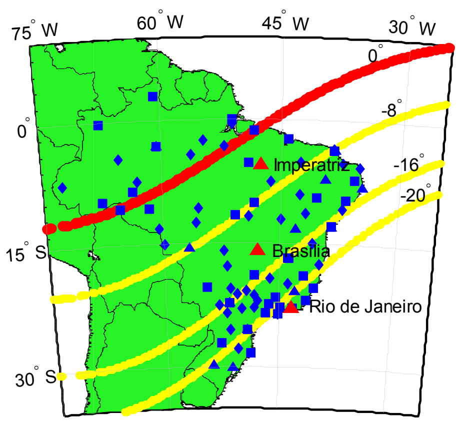

Figure 2. Positions of the ground-based RBMC stations

4 Results

The maximum vTEC can be used as an indication of the maximum delay that GPS signals may experiment due to ionospheric effects. Additionally, it also displays the ionospheric seasonal dependence. Figure 3 shows the maximum daily value of vTEC for the IMPZ (red), BRAZ (blue) and RIOD (green) stations for the year 2013.

The maximum values of vTEC for 2013 (year with high solar activity of cycle 24) vary between approximately 25 TECUs and 135 TECUs for the RIOD station; and 40 TECUs and 105 TECUs for the IMPZ and BRAZ stations as shows Figure 3.

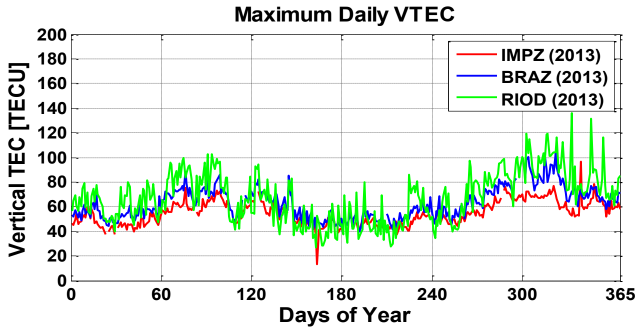

Figure 3. Maximum daily values of vTEC for the IMPZ (red), BRAZ (blue), and RIOD (green) stations in 2013

This contribution presents the statistical distributions of vertical ionospheric delay gradients estimated using the time-step method estimated every 15 seconds (sampling rate) based on data from Imperatriz (IMPZ), Brasília (BRAZ) and Rio de Janeiro (RIOD) receiver stations during the year 2013 as is shown in Figure 4.

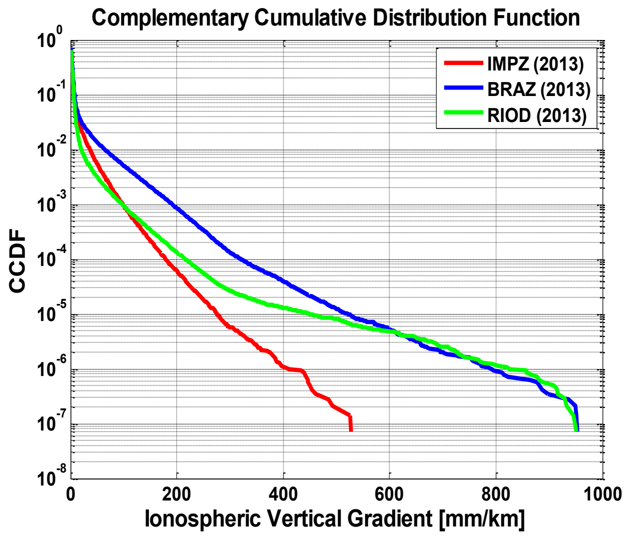

Figure 4. CCDF of the vertical ionospheric delay gradient

Figure 4 shows that the results estimated for IMPZ station present low percentages of large vertical gradients in comparison to those associated with the BRAZ and RIOD stations. Also, the results of BRAZ station reveal higher percentages of large vertical gradients than the other stations from in the range 0 mm/km to 600 mm/km. However, the BRAZ and RIOD stations present similar percentages of vertical gradients from 600 mm/km to their respective maximum values. For example, the probability to get a gradient corresponding to 400 mm/km is $1.2x10^{-6}$ (IMPZ), $1.4\ x\ 10^{-5}$ (RIOD) and $3.9\ x\ 10^{-5}$ (BRAZ).

The ionospheric gradient can cause errors in differential corrections broadcast to the aircraft using Ground-Based Augmentation Systems (GBAS) due the irregularities in the ionosphere. Consequently, the minimum requirements of a GBAS system are limited for the use of GNSS satellites ranging sources.

5 Conclusions

This research presented the methodology used to estimate the vertical TEC and the maximum values of vTEC estimated from RBMC data. The results shows that the smallest values of daily maximum vTEC occur between the days 100 and 240 (April to August, covering the winter months of the southern hemisphere), as expected.

In this work statistical distributions of ionospheric gradients were estimated based on the time-step, using the vTEC results. The gradients frequently exceeded 400 mm/km in periods of high solar activity. Occasionally, they even exceeded 600 mm/km. All of the detected threatening gradients occurred between the post-sunset and early post-midnight hours. The maximum estimated gradients are equal to 588.79 mm/km, 974.23 mm/km and 970.71 mm/km, for IMPZ, BRAZ and RIOD station, respectively, obtained from the application of the time-step method to 2013 RBMC data (year of high solar activity, with periods of equally intense geomagnetic activity).

6 Acknowledgements

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