Ionospheric Gradients in Low-latitude Regions

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Abstract

The ionosphere affects the propagation of Global Positioning System signals. Due to their special features, the equatorial and low-latitude ionosphere may produce particularly severe effects on them. 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 vertical ionospheric gradients and σ_vig 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) located at airports provide differential corrections and integrity information to the aircrafts [3]. Differential corrections allow an aircraft approaching an airport to correct satellite navigation signals, removing spatially correlated errors between the ground station and the aircraft. Thus, the aircraft is able to improve the accuracy of its position estimation. In addition, integrity parameters allow the aircraft system to calculate the limits of residual position errors and ensure safe operation. 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 Station-Pair method [5] considering stations located in different geomagnetic latitudes.

The σ_vig is an integrity parameter transmitted by the ground station that guarantees safe operation only as long as the state of the ionosphere is nominal. This parameter will be estimated using statistical analysis.

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 procedures described in the Appendix of [6] have been applied to estimate the absolute slant Total Electron Content (TEC_s) and then it was converted to vertical TEC (vTEC).

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 Station-Pair method will be presented for the estimation of ionospheric gradients, which does not present a spatial correlation.

The Station-pair method considers simultaneous ionospheric delays (amount proportional to vTEC) observed in each pair of stations connected to the same satellite [7], as shown in Figure 1.

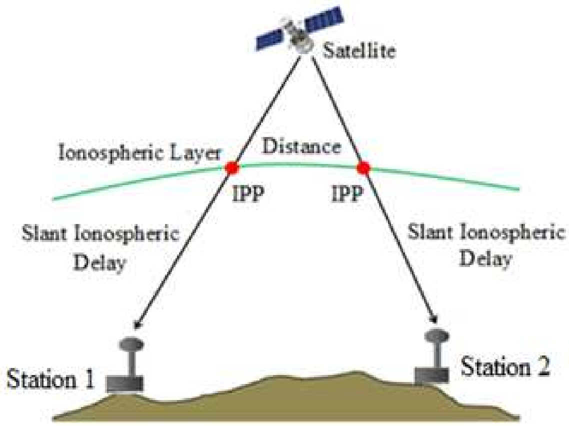

Figure 1. Station-Pair method.

For a given instant, the estimate of the ionospheric delay gradient using the station-pair method for a given satellite can be represented by the following equation:

$$g^s = \frac{|I_{s,r_1} - I_{s,r_2}|}{DIST_{IPP(s,r_1;s,r_2)}} \quad \left[\frac{mm}{km}\right] \qquad (2)$$

I_{s,r_1} and I_{s,r_2}: Vertical ionospheric delay values estimated in the IPSs corresponding to satellite s; receiver 1 and 2 respectively.
$DIST_{IPP(s,r_1;s,r_2)}$: Distance between two IPPs.

Note that the ionospheric delay I can be expressed as a function of vTEC using equation $I = K \cdot TEC/2f^2$
In the procedure described above we will often have the presence of outliners that are calibration errors, to validate the gradients of great extension a formulation using pseudodistance and carrier phase measurements [7].

3. Data

The vertical ionospheric delay, vertical ionospheric delay gradient and the σ_vig were estimated using observed GPS satellite measurements obtained every 15 seconds (sampling rate) from the Rede Brasileira de Monitoramento Continuo (RBMC) station pairs: SJSP-SJCE-SJCU, SSA1 - SAVO, ONRJ - RIOD, located at different magnetic latitudes, as shown in Figure 2 Additionally, for a precise representation, in Figure 2 the orientation of the station pairs (Blue lines) and the geomagnetic equator (Red line) can be observed. The measurements were extracted from data collected using an elevation cut-off angle of 20°, to avoid multipath.

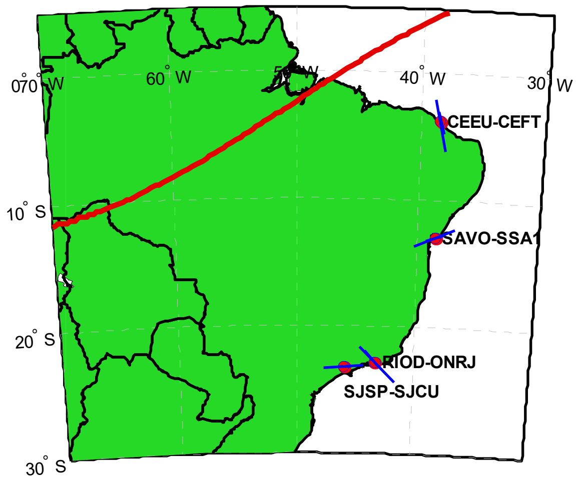

Figure 2. Positions of RBMC station pairs in 2014 (Red dots) and station pair orientations (Blue lines).

Data from the months of January, February and March of 2014 (Bubbles period) were used for the estimation of the σ_vig (High activity), due to the fact that they present daily average values of the S4 index greater than 0.1, as shown in the ISMR Query Tools developed by [8]

4. Results

In this section, results of the temporal and spatial characteristics of the ionospheric gradients that could possibly affect the operational integrity of the GBAS CAT-I will be presented, as well as the estimation of the σ_vig for different airports located in the Brazilian region, such as: São José dos Campos Airport (São José dos Campos), Galeão Airport (Rio de Janeiro) and Luís Eduardo Magalhães Airport (Salvador) using receivers close to them.

Results of SJCE, SJCU and SJSP stations (Near of São José dos Campos Airport - São José dos Campos)

In this section, results obtained from the estimated spatial gradients near the São José dos Campos Airport based on the SJCE, SJCU and SJSP stations will be presented. The azimuth between the SJSP and SJCE stations is 268°.

Firstly, in the top panel of Figure 3, we can observe the difference of the ionospheric delay in relation to the distance of the IPPs. In the bottom panel of Figure 3, the probability density function (pdfs) of the estimated gradients to estimate and verify the Sigma VIG σ_vig and the Sigma VIG overbounding σ_vig overbound are presented, for a period of high solar activity.

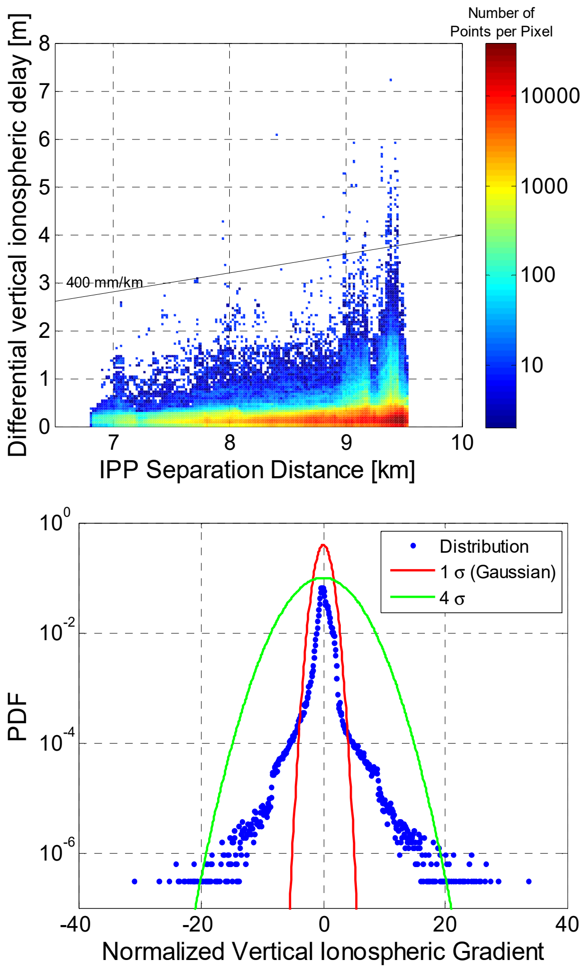

Figure 3. Vertical ionospheric delay difference (Top) and probability density function of the ionospheric gradients (Bottom) estimated using GPS observables from the SJSP, SJCE and SJCU stations in a period of high solar activity.

In Figure 3 (Top), can be observed the gradients do not that exceed 400 mm/km during a period of high solar activity. The estimated value of σ_vig in the bubbles period is σ_vig=20.2 mm/km and σ_vig overbound=80.8 mm/km represented by the red line in Figure 3 (Bottom).

Results of RIOD - ONRJ stations (Near of Galeão Airport - Rio de Janeiro)

Results obtained from the estimated spatial gradients in the proximity of Rio de Janeiro Airport based on the RIOD and ONRJ stations will be presented, as is shown in Figure 4. The azimuth between stations is 135.72°.

In the top panel of Figure 4, we can observe the difference of the ionospheric delay in relation to the distance of the IPPs. In the bottom panel of Figure 4, the probability density function (pdfs) of the estimated gradients to estimate and verify the Sigma VIG σ_vig and the Sigma VIG overbounding σ_vig overbound are presented, for a period of high solar activity.

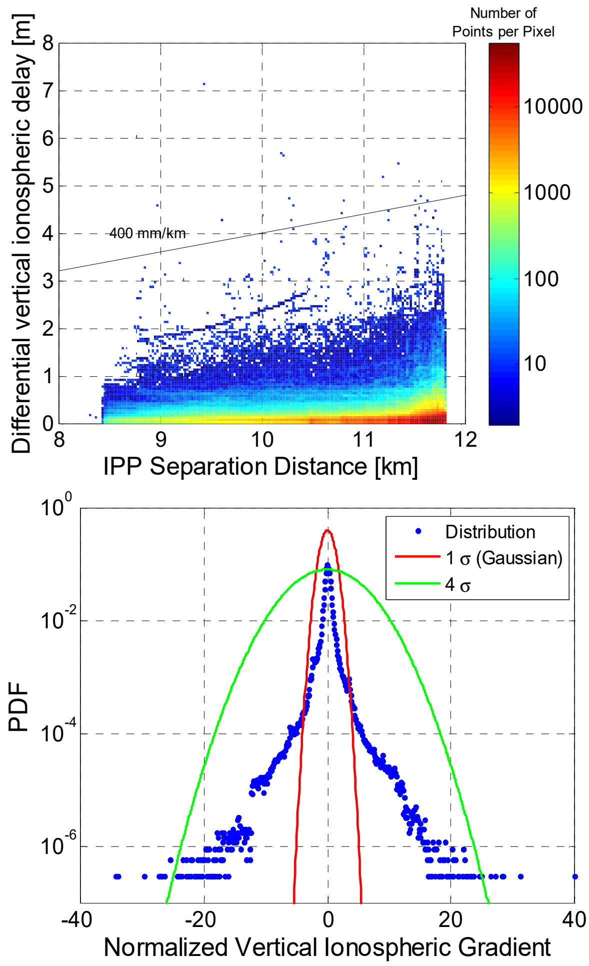

Figure 4. Vertical ionospheric delay difference (Top) and probability density function of the ionospheric gradients (Bottom) estimated using GPS observables from the RIOD-ONRJ stations in a period of high solar activity.

In Figure 4 (Top), can be observed the gradients exceed 400 mm/km during a period of high solar activity, limit value of the CONUS. The estimated value of σ_vig in the bubbles period is σ_vig= 16.2 mm/km and σ_vig overbound=64.8 mm/km represented by the red line in Figure 4 (Bottom).

Results for SSA1 – SAVO stations (Near of Luís Eduardo Magalhães Airport- Salvador)

Results obtained in the proximity of Salvador airport based on the SAVO and SSA1 stations will be presented, as can be observed in Figure 5. The azimuth between SAVO and SSA1 stations is approximately 66.52°.

In Figure 5 (Top), can be observed the gradients exceed 400 mm/km during a period of high solar activity, limit value of the CONUS. The estimated value of σ_vig in the bubbles period is σ_vig= 21.0 mm/km and σ_vig overbound=84 mm/km represented by the red line in Figure 5 (Bottom).

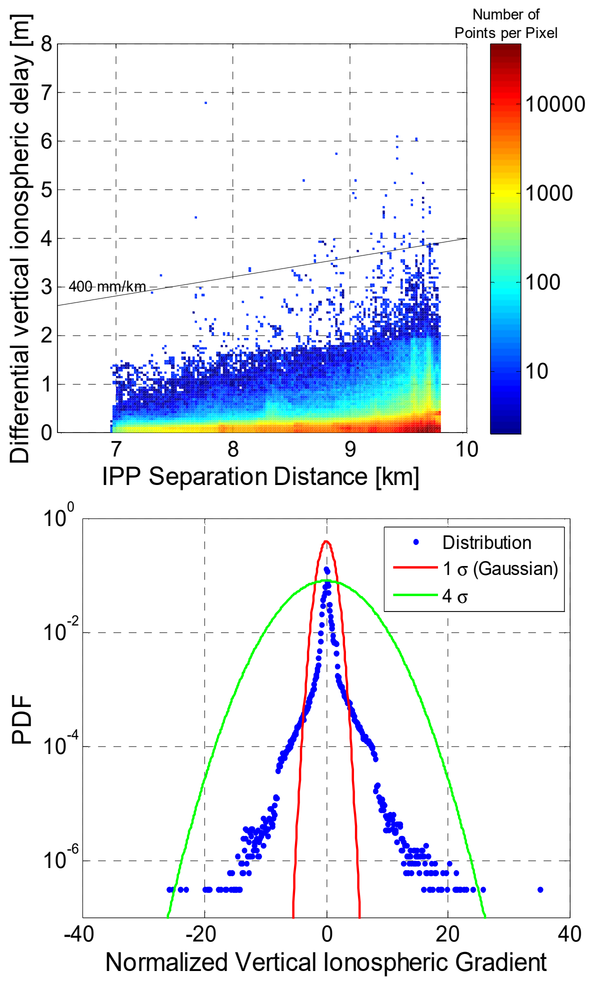

Figure 5. Vertical ionospheric delay difference (Top) and probability density function of the ionospheric gradients (Bottom) estimated using GPS observables from the SAVO – SSA1stations in a period of high solar activity.

5. Conclusions

This research presented the methodology used to estimate the vertical ionospheric gradients and σ_vig estimated from RBMC data. The results shows that the gradients exceed 400 mm/km during a period of high solar activity (January to March, covering the summer months of the southern hemisphere), as expected.

In this work statistical distributions of ionospheric gradients and σ_vig were estimated based on the Station Pair, using the vTEC results. All of the detected threatening gradients occurred between the post-sunset and early post-midnight hours. The values of σ_vig in the bubble period are σ_vig=20.2 mm/km, σ_vig= 16.2 mm/km and σ_vig= 21.0 mm/km for (SJSP - SJCE and SJCU, RIOD - ONRJ, SSA1 – SAVO), respectively.

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