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ORIGINAL ARTICLE

Assessment of GPS positioning performance using different signals in the context of ionospheric scintillation: a month-long case study on São José dos Campos, Brazil

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Abstract:

The ionospheric scintillation associated to small-scale irregularities in the ionospheric layer can lead to performance degradation of Global Navigation Satellite Systems (GNSS) signals, and the reduction of positioning accuracy. The influence of the ionospheric layer on the GNSS systems is expected to be different for each signal since it is transmitted on different carrier frequencies. This paper presents the results of a quantitative analysis of the scintillation amplitude of GPS (Global Positioning System) signals at L1, L2 and L5 frequencies, aiming to evaluate the impact of the ionospheric scintillation effects on the GPS frequencies. As the ionospheric scintillation may impact positioning accuracy, we also present an assessment of GPS point positioning using those frequencies. The GPS sample data were collected for 30 days between November and December 2014 at SJCE station located in São José dos Campos (SP), Brazil. Such a region is subjected to the equatorial anomaly effects being characterized by the occurrence of strong ionosphere scintillation. Considering the quantitative analysis, during the different levels of ionospheric scintillation presented a similar behavior, the magnitude of scintillations is small for the L1 signal and larger for L5. In general, the results confirmed that lower frequencies (L2 and L5) suffer more impact from intense scintillation than L1. Regarding the positioning assessment, the multi-frequency positioning was more accurate than single frequency. Considering dual-frequency positioning, results with L1-L2 were more accurate than those with L1-L5 signals. With single-frequency positioning, the L1 signal was more accurate compared to the L2 frequency.

Keywords: GPS Positioning; Amplitude Scintillation; Ionospheric Scintillation; GPS frequencies.

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1. Introduction

The atmosphere has a great influence on Global Navigation Satellite Systems (GNSS) signal propagation. The GNSS signals that pass through the Earth's atmosphere are disrupted, especially due to events occurred in the ionospheric layer (Seeber, 2003; Zolesi and Cander 2014). This issue has garnered efforts from the scientific community over many years.

The error caused by the ionospheric layer is directly proportional to the Total Electron Content (TEC) and inversely proportional to the squared frequency. Therefore, higher frequencies are supposed to be less affected by the ionosphere when compared with lower frequencies (Zolesi and Cander 2014; Langley et al., 2017).

The spatial variation of electron density in the ionospheric layer can cause an effect called ionospheric scintillation. This effect is defined as rapid changes in phase and/or amplitude of a radio signal as it propagates through small-scale plasma density irregularities in the ionosphere (Conker et al., 2003). The scintillation is related to small-scale irregularities in the ionospheric layer, which is, in the Brazilian region, primarily associated to Equatorial Plasma Bubbles (EPBs) (de Paula et al.,2007; Moraes et al., 2017). The ionospheric scintillation in general occurs after sunset until midnight, sometimes also extending for a few hours in the post-midnight period (Conker et al., 2003; Seeber, 2003).

The occurrence and intensity of scintillations vary according to several factors, such as solar activity, the epoch of the year, geographic location and local time. Scintillation occurs dominantly at high and low latitude, and equatorial regions of the Earth, where the Brazilian territory is located (Walter et al., 2010; Vani et al., 2017). In this way, in Brazil, ionospheric scintillation is a serious threat to satellite navigation and communication. Under severe ionospheric scintillation, GNSS positioning can be affected by errors and losses of lock which can lead to performance degradation and unavailability of GNSS signals (Conker et al., 2003).

The scintillation effect can be measured by several indices, such as S4 and Sigma-phi. S4 is the scintillation intensity index, which measures the relative magnitude of amplitude fluctuations. The S4 index is the standard deviation of the signal strength, normalized by its mean. Sigma-phi is a phase scintillation index, which measures the magnitude of carrier phase fluctuations (Walter, 2010).

As previously mentioned, the ionospheric error is directly proportional to TEC and inversely proportional to the squared frequency, so it is expected that the severity of ionospheric effects (such as the ionospheric scintillation) follows the same relation considering the signal frequency, due to dispersive nature of the ionosphere. The GPS (Global Positioning System) modernization program introduced two new civil navigation signals, on L2 (L2C) and L5. In this case, the new navigation signals, which have lower frequencies, would be more susceptible to the ionospheric effects compared to L1 signal. The same performance from GPS L1 frequency can not directly be transferred to the new signals that use different frequencies, mainly in low latitudes due to scintillation.

Much research has been conducted in this context. Usually, the S4 scintillation index is analyzed on the GNSS primary frequencies (for instance, the GPS L1 frequency). However, those indices can also be estimated on the other GNSS frequencies available. Hegarty et al. (2001) and Peng et al. (2011) defined some functions that allow the scintillation indices to be mapped from the L1 frequency to obtain an expected value at L2 and L5 frequencies. Delay et al. (2015) presented a statistical analysis on L1, L2 and L5 GPS tracking performance under ionospheric scintillation using the S4 index. The results indicated a larger probability of signal loss at lower frequencies than at higher ones. Moraes et al. (2017) performed a study to analyze the variability of low-latitude ionospheric amplitude and phase scintillation detected by a triple-frequency GPS receiver. Based on an empirical quantification, the results showed the frequency dependence of scintillation, that is, the lower frequencies L2 and L5 suffer more intense scintillation than L1 signal.

Taking into account the new GPS signals performance on the positioning, Engel (2008) evaluated the theoretical performance of GPS signals in terms of positioning accuracy. The author showed that the positioning accuracy, using single frequency, is almost the same for all satellite signals, with L2 and L5 signals leading to worse performance than L1 signal. Andrade and Alves (2016) analyzed static and kinematic positioning improvement obtained by the introduction the GPS new signals L2 and L5. The results showed that the use of new frequencies causes faster convergence on kinematic positioning. The improvement rate in the positioning using the three frequencies was about 61% compared to single frequency (L1).

Considering the current availability of the new signals, it is possible to perform a more detailed analysis of the dispersive behavior of the ionospheric layer. In addition, the new signals can be used to improve the positioning solution, so it is necessary to evaluate how they are influenced by scintillation and which signal is less affected under ionospheric conditions.

In this context, in this paper, we present a quantitative analysis of the ionospheric amplitude scintillation impact on GPS frequencies, aiming to evaluate the scintillation impact on GPS signals for different scintillation levels, taking into account a station located at low latitude. Furthermore, as the ionospheric scintillation may reduce positioning accuracy, we present an assessment of GPS point positioning at L1, L2 and L5 frequencies.

2. Methodology

The data used in this study are from the SJCE station (23.21°S, 45.95°W) of the GNSS – NavAer network <http://inct-gnss-navaer.fct.unesp.br/pt/>. Located in São José dos Campos (SP), Brazil, the station has a triple-frequency (L1, L2, and L5) receiver (Septentrio PolaRxS). The station region is characterized by the occurrence of strong amplitude scintillation, due to the influence of the equatorial anomaly. The data were continually collected over 30 days, between 03 November to 03 December 2014, the period associated to frequent scintillation occurrence due to higher ionospheric activity, influenced by the last solar cycle.

The parameter used in these analyses was the amplitude scintillation index – S_4, which is the main statistic for indicating the severity of the amplitude scintillations. In this paper, we considered the same limits used by Muella (2009) for the S_4 index classification: weak level $0.2 < S_4 \leq 0.4$; moderate level $0.4 < S_4 \leq 0.6$; strong level $0.6 < S_4 \leq 1.0$; and saturated level $1.0 < S_4 \leq 1.4$. According to Muella (2009), saturated levels can be attributed to the effects of multiple scattering and means that the S_4 is not due to a single scatter of the radio wave.

For the quantitative analysis, the S_4 index was obtained using the ISMR Query Tool (Vani et al., 2017). The S_4 was calculated from measurements performed at the three GPS frequencies: L1 (1575.42 MHz), L2 (1227.60 MHz), and L5 (1176.45 MHz). The values were limited to measurements from satellites with elevation angle higher than 20°, considered above the level of noise and multipath effects.

Considering the positioning, the data were applied to precise point positioning in kinematic and static modes using the online software CSRS-PPP (Canadian Spatial Reference System – Precise Point Positioning) developed by NRCan (Natural Resources Canada) available in <https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php>. We used Receiver Independent Exchange Format (RINEX v.2.11) files with 24 hours of data, GPS satellites, collected using 20° elevation mask, and 15 seconds sampling rate. For the positioning processing carrier phase and pseudorange were used. It is important to emphasize that there is a difference between the number of satellites that provide the new signals (L2C and L5), due to the different generations of GPS satellites currently available. Thus, during the period analyzed period, 31 satellites transmitted L1 signal, 15 transmitted L2C and 8 satellites transmitted L5. Considering the number of satellites tracked per epochs transmitting L2C signal (~5 satellites), and the ones transmitting L2P signal (~8 satellites), the L2P was used for the positioning assessment. The kinematic positioning processing was performed using 5 configurations: L1 signal (L1C), L2P signal (L2P), L1-L2P signals (L1C and L2P), L1-L5 signals (L1C and L5) and L1-L2P-L5 signals (L1C, L2P and L5). The static mode was processed with three frequencies and used as reference values. The editions of the RINEX files were performed using TEQC (Translation, Editing and Quality Checking) software from UNAVCO. The single-frequency positioning using L5 signal was not possible due to the small number of satellites transmitting L5 frequency or a limitation in the software used. Results from the kinematic positioning in each configuration were compared to the static positioning. With the discrepancies obtained from the results of the kinematic positioning and the reference values, the root mean square error (RMSE) was obtained.

3. Results and Discussion

3.1 Quantitative analysis of the ionospheric scintillation impact on GPS frequencies

For the chosen period, just three satellites had data collected on the L5 frequency with a higher number of epochs (PRN 24, PRN25 and PRN 27). This way, the data were acquired for those satellites on the three frequencies (L1, L2 and L5). Figure 1 illustrates the S_4 index from PRN 24, PRN 25 and PRN 27; on November 27, 2014.

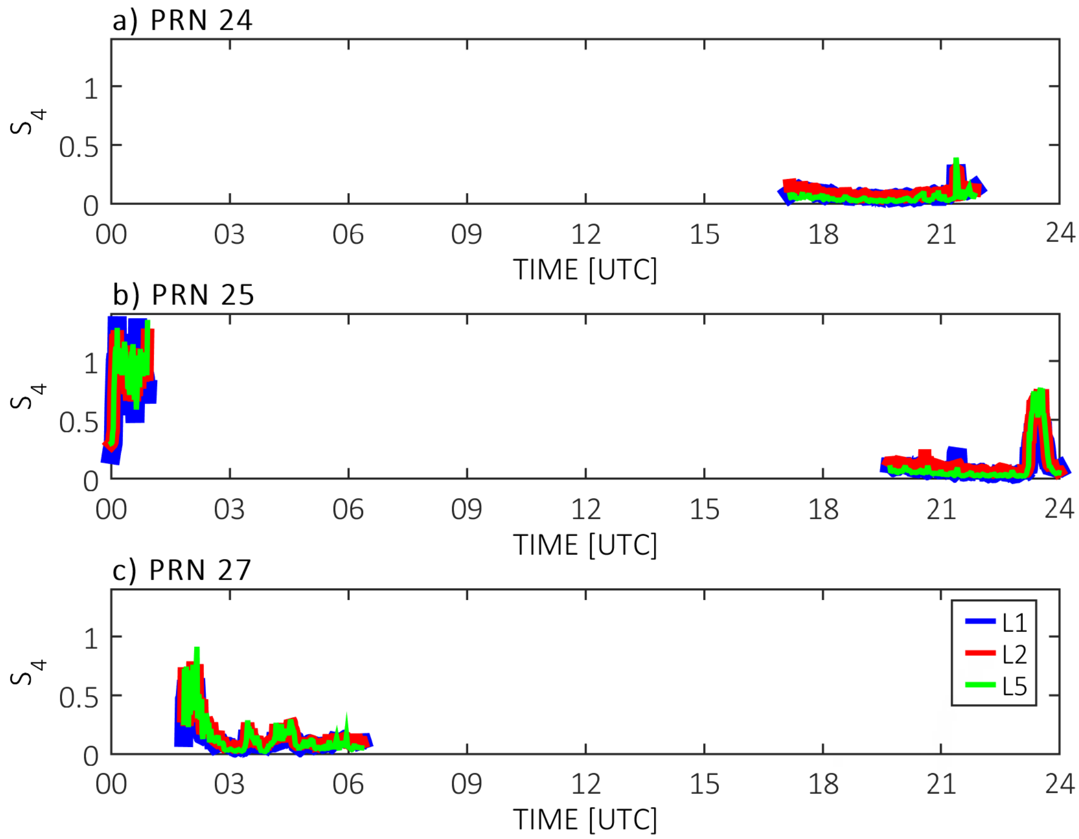

Figure 1: S_4 index at L1, L2 and L5 signals on November 27, 2014 for a) PRN 24; b) PRN 25; and c) PRN 27.

According to Figure 1, in all satellites, the difference between L1, L2 and L5 signals is small during the undisturbed conditions. However, at the peak of the scintillation events, the difference between the three signals becomes larger. Considering the PRN 24, the data were collected from 17:10 to 21:51 UT, in which no scintillation level could be classified, with S_4 values lower than 0.2. The PRN 25 presented two periods of collected data (00:00 – 00:50 UT and 19:42 – 23:59 UT), in the first period the scintillation level can be classified as moderated to saturated level, the S_4 index varied from 0.6 to 1.4. The second period could be classified as undisturbed conditions until 23:13 UT, with values smaller than 0.2, after this period, the values increased, leading to a moderated scintillation level classification, considering the L1 signal and strong scintillation level for L5 signal. In PRN 27, the data were collected from period 01:50 – 06:20 UT, the scintillation level can be considered weak to strong, the values with index values were between 0.2 and 0.8, until the values decrease to undisturbed level.

Considering the behavior of satellite frequencies, especially when the scintillation is classified as weak to strong levels, the data from L1 frequency are less affected when compared to the other GPS frequencies. This behavior is especially observed when there are long continuous data and the ionospheric scintillation is classified as weak to strong levels. This behavior is shown in Figure 1b in the second period of data, the L5 signal was classified as strong while the L1 was classified moderated level. Thus, considering all the days selected, indices presented similar behavior under ionospheric scintillation, data from L1 frequency was less affected, when compared to L2 and L5 frequencies.

In order to show the influence of the scintillation in the S_4 values, Figure 2 shows one example of the slant TEC estimated and the S_4 values at the L1, L2 and L5 signals for PRN 25 on November 27, 2014 (DOY 331). The slant TEC was obtained using calibration procedures such as Ciraolo et al. (2007) and Prol et al. (2018). The technique is based on the code-delay to the carrier-phase by the so-called levelling process, applied to reduce carrier-phase ambiguities from the data.

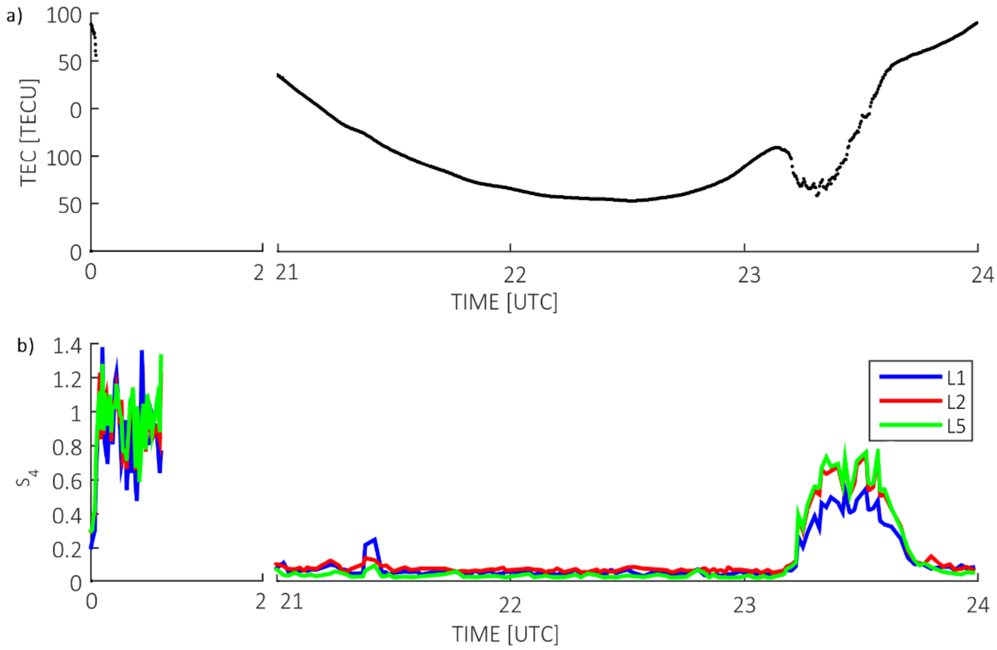

Figure 2: a) Slant TEC estimated for PRN 25 on November 27, 2014; b) The corresponding S_4 values for L1, L2 and L5 signals.

Analysing the TEC values, it is possible to note the strong gradients during the period of scintillation occurrence. It is worth mentioning that, the presence of two data periods is due to the period of satellite visibility. Considering the first period of data collected, due to the intense scintillation, the receiver was unable to estimate TEC as shown in Figure 2a, with a loss of lock. In the second period of data collected, near 23:00 – 24:00 UT, where the S_4 values were classified as moderated to strong levels, it is possible to verify that the TEC estimated passed through a short maximum and minimum between the same period of time, this reveals that the signals received are crossing an irregularity structure. And the slant TEC depletions indicate that the ionosphere is disturbed by ionospheric plasma bubble.

Furthermore, we investigate the occurrence rate for each intensity level of scintillation. In this analysis, all the available S_4 values were taken into account during the days analysed. The percentages of occurrence for each frequency considering the S_4 classification levels are summarized in Table 1.

The highest percentages of occurrence were observed in the undisturbed level, due to the ionospheric scintillations occurrence at specific times of the day (after the sunset up to midnight, sometimes extending for a few hours). It is important to consider that the scintillation occurrence, especially in strong scintillation levels, may lead to loss of lock between satellite and receiver, reducing the precision in positioning applications. Considering undisturbed and moderated scintillation levels, the three signals presented a similar behavior, i.e. between the different signals no statistical differences were observed. Considering weak, strong and saturated scintillations levels, the percentages increase as GPS frequencies decrease. In addition, for the strong and saturated levels, the percentage of occurrences observed at the L1 frequency (0.6%) was approximately half the values observed for the frequencies L2 and L5.

Table 1: Fraction of occurrences (in percent) for each carrier frequency considering the S_4 classification levels, for 24 hours of data.

S_4 classification	**L1**	**L2**	**L5**
<0.2	89.8%	87.5%	87.1%
$0.2 < S_4 \le 0.4$	4.2%	4.7%	5.0%
$0.2 < S_4 \le 0.6$	2.4%	2.3%	2.2%
$0.6 < S_4 \le 1.0$	2.9%	4.2%	4.3%
$1.0 < S_4 \le 1.4$	0.6%	1.3%	1.4%

To perform a quantitative analysis, we considered the S_4 data classified in each scintillation level to identify which frequencies suffer the greatest and the least impact. In other words, greatest and least impact means that signal presents the highest and least S_4 values compared to the other signals. Figure 3 presents the percentage of the epochs in which each frequency suffered the greatest and the least impact, the sum for each frequency must be 100%.

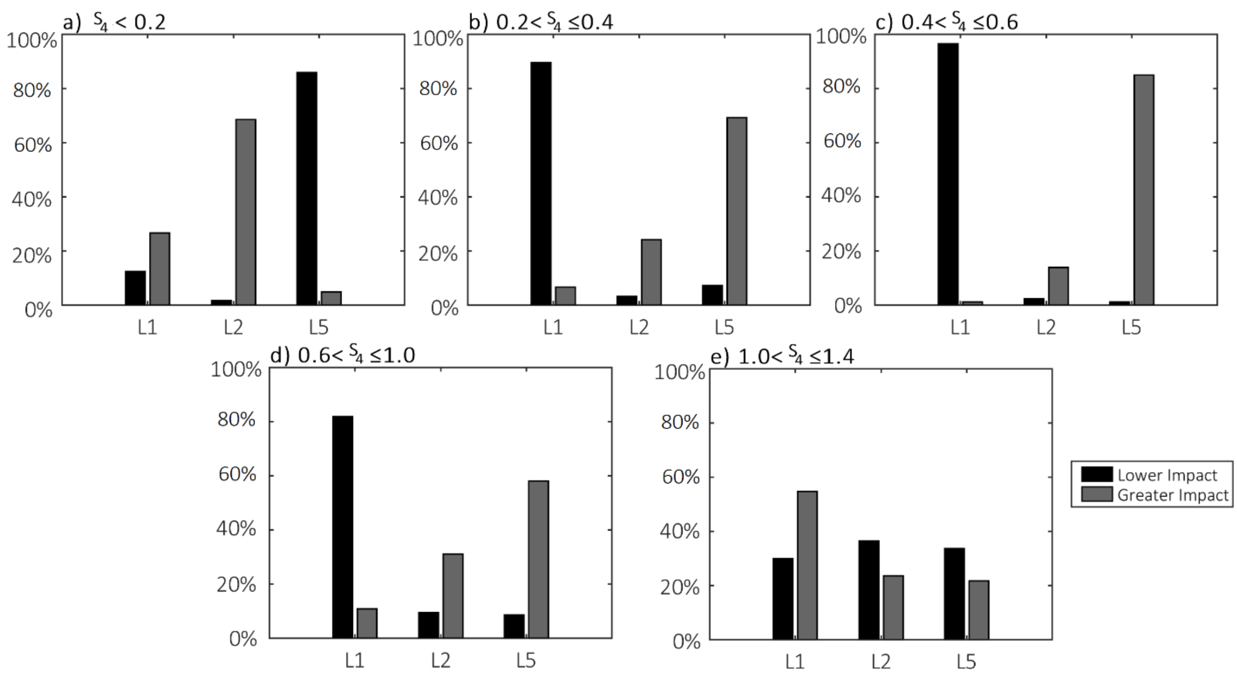

Figure 3: Percentage of epochs in which the GPS frequencies suffered least and highest impact considering S_4 classification level (a) undisturbed level; (b) weak level; (c) moderated level; (d) strong level; and (e) saturated level.

In general, the graphs considering the weak level (Figure 3b), the moderated level (Figure 3c), and the strong level (Figure 3d) showed similar behavior. L1 signal suffered the least impact while the L5 frequency suffered the greatest impact, that is, in most of the epochs, L1 signal presented the least S_4 values compared to the other signals, while L5 signals presented the highest values. This behavior indicates that during scintillation presence, the L1 signal is less affected by the ionospheric layer. The undisturbed level (Figure 3a) presented a different behavior, L5 signal suffered the least impact, while the L2 frequency suffered the greatest impact. With the saturated level (Figure 3e), considering the least impact, the three frequencies showed a similar percentage. Taking into account the greatest impact, the L1 frequency was more affected than the other frequencies. In order to summarize the analysis, we estimated the mean S_4 values and corresponding standard deviation, considering the S_4 classification levels, presented in Table 2.

Table 2: Mean and standard deviation for the GPS satellites PRN 24, 25 and 27, for 03 November to 03 December 2014, considering the S_4 classification levels.

S_4 classification	Frequencies	Mean of S_4	Std. dev. of S_4
$S_4 \leq 0.2$	L1	0.076	0.038
	L2	0.091	0.046
	L5	0.052	0.029
$0.2 < S_4 \leq 0.4$	L1	0.275	0.138
	L2	0.342	0.187
	L5	0.344	0.194
$0.4 < S_4 \leq 0.6$	L1	0.369	0.246
	L2	0.490	0.329
	L5	0.516	0.346
$0.6 < S_4 \leq 1.0$	L1	0.778	0.395
	L2	0.907	0.456
	L5	0.930	0.466
$1.0 < S_4 \leq 1.4$	L1	1.104	0.011
	L2	1.025	0.025
	L5	1.042	0.023

The mean values and standard deviation confirm the analysis of Figure 3. For the undisturbed level, the L2 frequency presented the highest mean value and standard deviation, indicating to be more disturbed. Considering weak, moderated and strong levels, the mean values and standard deviation show that the L1 signal is less impacted by ionospheric scintillation followed by L2 and L5 respectively. In addition, the mean values and corresponding standard deviation for the L2 and L5 signals are very close. Thus, these results also indicate that during ionospheric scintillation presence both signals behave in a similar way. Due to the dispersive behavior of the ionospheric layer, it was expected that losses of lock could affect L1, L2 and L5 signals differently. Thus, those results confirm the expected behavior. The severity of ionospheric effects follows the same relation considering the signal frequency. The L2 and L5 signal are more likely to suffer by loss of lock. This performance also can be explained by deep power fades associated with scintillation presence. Considering the saturated level, the L2 signal is less impacted followed by L5 and L1 signals.

In general, during ionospheric scintillation, we observed that the magnitude of scintillations is smaller for L1 signal and larger for L5. Despite L5 signal being dedicated to safety-of-life applications, the results reveal a significant problem for this application type, considering disturbed ionospheric scenarios. Since the L5 signal is the most affected under ionospheric scintillation, this signal can suffer more than other signals, causing positioning errors, losses of lock, and consequently performance degradation and unavailability of service in receivers.

3.2 Assessment of GPS point positioning at different frequencies

Considering the positioning domain, we present the RMSE obtained by the comparison between the static and kinematic considering the GPS signals and their combinations, with the aim of assessing each frequency performance during the precise point position. Regarding the satellites available by epoch, on average, there were 10 satellites transmitting the L1 signal, 8 transmitting L2P and 2 satellites transmitting L5 signals. Figure 4 presents the RMSE results in 5 different configurations using the three GPS frequencies, considering all epochs of the day.

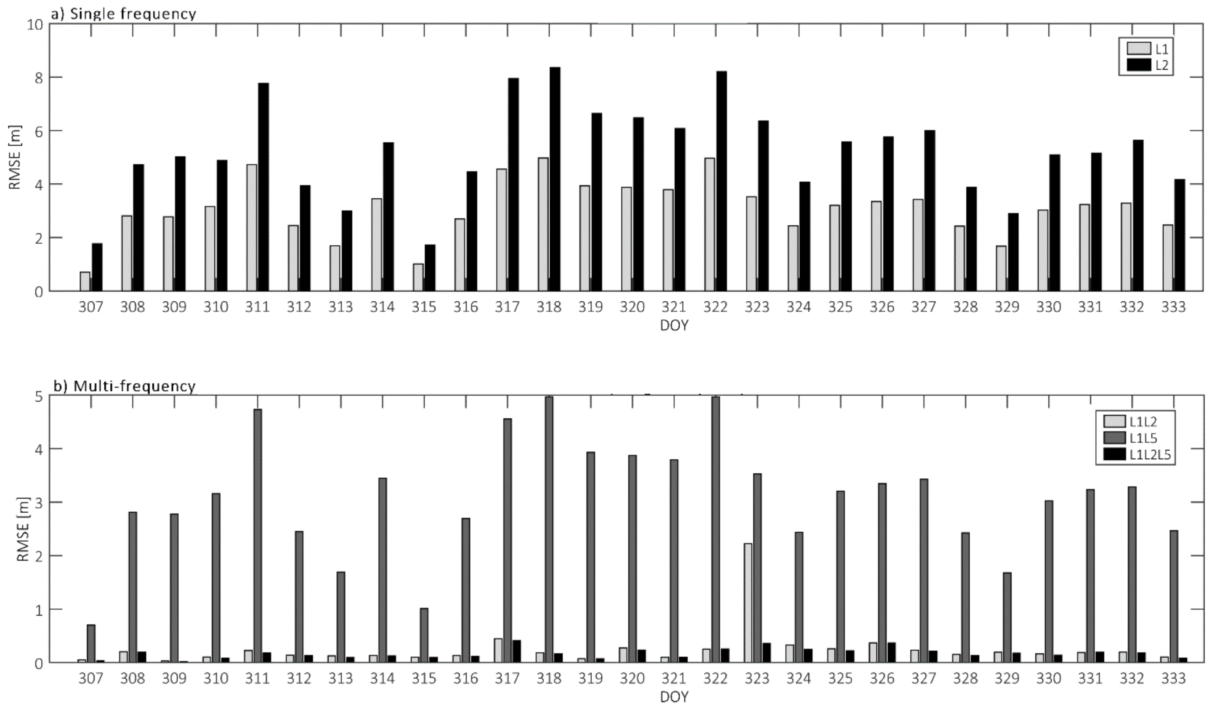

Figure 4: RMSE results for PPP processing considering different configurations, for SJCE station level (a) single frequency: L1 (light grey color) and L2 (dark color); (b) multi-frequency: L1-L2(light grey color), L1-L5 (dark grey color) an d L1-L2-L5 (black color).

The influence of the use of single or multi-frequency data in the positioning can be noticed in all obtained results. The RMSE values considering single frequency positioning are twice the RMSE values considering the dual frequency positioning. Concerning the single frequency positioning the RMSE obtained from L2P signal (dark color) presented larger errors compared to L1 signal (light grey color). This behavior can be explained due to the ionospheric error is inversely proportional to the squared frequency. Considering the multi-frequency positioning the RMSE obtained from L1-L5 (dark grey color) presented larger errors compared to L1-L2P (light grey color) and L1-L2P-L5. This can be explained due to the use of the linear combination of multi-frequency observables, which mitigates the ionospheric first order influence. In addition, the RMSE obtained by the L1-L2P and L1-L2P-L5 presented similar values, except for DOY 323. In order to summarize the results, we estimated the mean of RMSE considering the different GPS frequencies. The results are present in Table 3.

Table 3: Mean of RMSE, in meters, considering the GPS frequencies combinations.

GPS frequencies combinations	Mean of RMSE [m]
L1	3.576
L2P	6.037
L1-L2P	0.258
L1-L5	3.580
L1-L2P-L5	0.250

From Table 3, concerning the single frequency positioning, in all cases considered, the RMSE values for the positioning using only L1 signal are lower when compared with the RMSE value using L2P frequency. In this way and considering the similar number of satellites transmitting both frequencies, the results indicate that L1 frequency is more accurate when compared with L2P frequency. As previously mentioned, this behavior was expected, due to the dispersive nature of the ionospheric layer. Thus, L2 signal is more susceptible to loss of lock, resulting in a loss of performance for precision applications. Considering the multi-frequency positioning, it can be noted that RMSE values of L1-L5 signals positioning are similar to a single frequency (L1) positioning. Furthermore, it is noted that the RMSE values of L1-L2P signals positioning are also similar when using the three frequencies positioning (L1-L2P-L5). This behavior can be explained by the small number of satellites that transmits the L5 signal for the period when the experiment was performed.

On November 19, 2014 (DOY 323) the multi-frequency positioning (L1-L2P and L1-L2P-L5) presented higher RMSE values when compared with the other days. The reason for this behavior can be explained by the ionospheric influence, the S_4 index behavior over this day is presented in Figure 5.

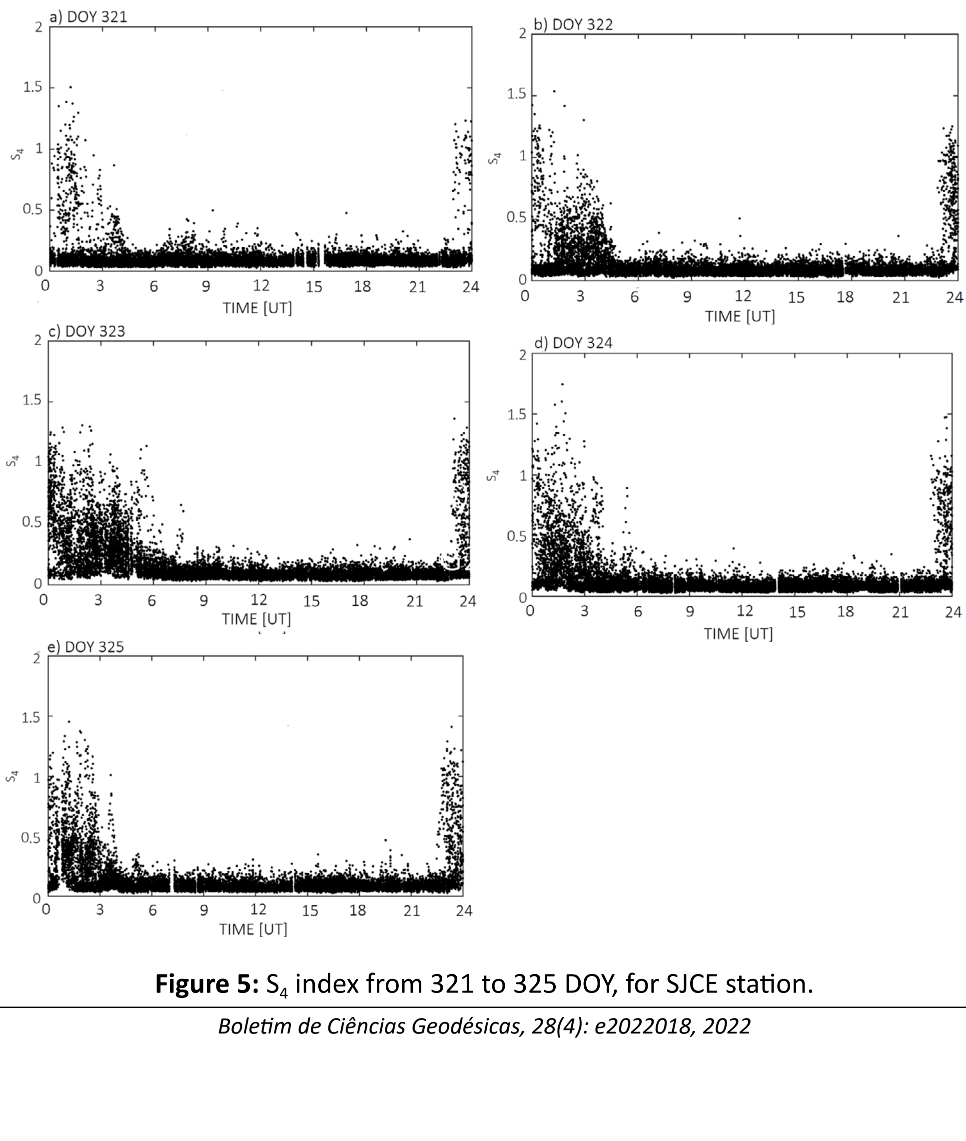

Figure 5: S_4 index from 321 to 325 DOY, for SJCE station.

4. Conclusion

This paper presented a quantitative analysis of the scintillation amplitude and the performance evaluation of the point positioning taking into account the GPS L1, L2, and L5 frequencies. Data used were collected over 30 days, for the SJCE station, located in a region characterized by scintillation occurrence, near the southern crest of the equatorial ionization anomaly.

A case of slant TEC depletion event, marking an EPB passage, was examined with the associated with S_4 index in each frequency. It showed that scintillation occurred at the strong gradient region of the depletion, and it appeared more intense at the L2-L5 signals. We investigated the occurrence rate for each intensity of scintillation, the results showed that there are a greatest number of occurrences for undisturbed scintillation levels at L1 signal when compared to the other frequencies and there is a bigger number of occurrences with strong and saturated scintillation levels for the L2 and L5 signals.

Considering the quantitative analysis, the S_4 data was classified in scintillation levels to identify which frequency suffers the greatest and the least impact. In general, the weak, moderated, and strong levels presented a similar behavior, the magnitude of scintillations is small for the L1 signal and larger for L5. For the undisturbed scintillation level, the L5 signal suffered the least impact and L2 signal the greatest impact. In the saturated level, the three frequencies suffered a similar impact for the least impact. Therefore, the results confirmed that lower frequencies (L2-L5) suffer more impact of intense scintillation than L1.

Considering the positioning, we observed that multi-frequency is more accurate than single positioning. For the multi-frequency positioning, the lower RMSE values were obtained using the three frequencies. With dual-frequency, it was observed that the positioning using L1-L2P is more accurate when compared with L1-L5. Furthermore, it was noted that similar RMSE values were obtained with three frequencies and with the L1-L2P positioning. This behavior can be explained by the small number of satellites that transmitted the L5 signal (~ 2 satellites) in the period used. Concerning the single positioning, the lower RMSE values were obtained with L1 signal when compared with L2P frequency. Therefore, the results indicate that the L1 signal frequency is more robust than the other frequencies, even under ionospheric scintillation. Thus, not only the highest frequency seems to be less affected by the ionosphere delay, but also by ionospheric anomalies, such as ionospheric scintillation.

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AUTHOR´S CONTRIBUTION

All authors contribute equally.

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