Anuário do Instituto de Geociências
Universidade Federal do Rio de Janeiro
https://revistas.ufrj.br/index.php/aigeo/

ISSN 0101-9759
e-ISSN 1982-3908

ENVIRONMENTAL SCIENCES

Multi-GNSS Data Processing and Analysis in Point Positioning for Brazilian Stations in Months of High and Low Ionospheric Activity

Processamento e Análise de Dados Multi-GNSS no Posicionamento Por Ponto em Estações Brasileiras para Meses de Alta e Baixa Atividade Ionosférica

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Abstract

The Global Navigation Satellite Systems (GNSS) have been increasingly used in positioning-related activities. The term GNSS includes the U.S. Global Positioning System (GPS), the Russian GLObal'naya NAvigationnaya Sputnikowaya Sistema (GLONASS), initially developed by the Soviet Union, the European Union's Galileo, the Chinese BeiDou, and Satellite and Ground Based Augmentation System (SBAS and GBAS). With the large number of satellites available, the trend today is to combine the systems at the user level, improving availability and positioning accuracy. The objective of this study is to process and analyze GNSS data from Brazilian monitoring stations using point positioning (PP), correlating with the ionosphere activity and the multipath around each station. Four systems were considered individually and combined, under different atmospheric conditions. The results were evaluated in terms of the Root Mean Square Error (RMSE), considering the horizontal and vertical bias, as well as the respective uncertainties, given by the Least Squares Method (LSM). The multi-GNSS positioning presented the best results, mainly due to the redundancy in the number of observations (average of 29 satellites per epoch), with a root-mean-square error of 1.5 m. GPS and Galileo showed the best performance among the individual results.

Keywords: Brazilian GNSS monitoring stations; Multipath; Scintillation

Resumo

Os Sistemas Globais de Navegação por Satélite (GNSS) têm sido cada vez mais utilizados em atividades relacionadas ao posicionamento. O termo GNSS inclui o Sistema de Posicionamento Global (GPS) dos Estados Unidos, o *GLObal'naya NAvigationnaya Sputnikowaya Sistema* (GLONASS) da Rússia, desenvolvido inicialmente pela União Soviética, o Galileo da União Europeia, o BeiDou da China e os Sistemas de Aumento Baseados em Satélites e em estações Terrestres (SBAS e GBAS). Com o grande número de satélites disponíveis, a tendência atual é combinar os sistemas a nível de usuário, melhorando a disponibilidade e a precisão do posicionamento. O objetivo deste estudo é processar e analisar dados GNSS de estações de monitoramento brasileiras usando o posicionamento por ponto (PP), correlacionando com a atividade ionosférica e o multicaminho obtido para o respectivo período. Foram considerados os 4 sistemas individualmente e integrados, sob diferentes condições atmosféricas. A avaliação dos resultados foi dada pela Raiz do Erro Quadrático Médio (REQM), considerando as discrepâncias horizontais e verticais, bem como as respectivas incertezas, dadas no ajustamento pelo Método dos Mínimos Quadrados (MMQ). O posicionamento multi-GNSS apresentou os melhores resultados, principalmente devido à redundância no número de observações (média de 29 satélites por época). GPS e Galileo mostraram o melhor desempenho entre os resultados individuais.

Palavras-chave: Estação Brasileira de Monitoramento GNSS; Multicaminho; Cintilação

Received: 15 Februrary 2024; Accepted: 15 October 2024

1 Introduction

The GNSS are used for position, velocity, and timing determination and have been widely applied in a wide range of activities. The four global systems are the GPS, operational since 1995 and with 29 operational satellites currently in orbit, (GPS 2024); the GLONASS with 26 satellites in orbit, initially developed with Frequency Division Multiple Access (FDMA) technology, with a recent addition of a third frequency with code division CDMA technology (IAC 2024); the Galileo system, with 28 satellites in orbit, expected to become operational in 2024 (ESA 2024); and the BeiDou system, with 31 satellites in Medium Earth Orbit (MEO), besides 12 more satellites in geosynchronous and 9 more in geostationary orbit (IAC 2024) for regional coverage. Additionally, Ground Based Augmentation System (GBAS) and Satellite Based Augmentation System (SBAS) are also part of the GNSS.

Currently, more than 100 GNSS satellites in MEO are available. Different studies have pointed out advantages in the use of combined systems (multiple constellations and frequencies), much on account of the greater redundancy of observations and on the improved satellites geometry, providing a better estimate of the user's position (Li et al. 2015a; Li et al. 2015b; Lou et al. 2015; Pan et al. 2017). Another advantage in the combination of constellations is the better coverage in areas of restricted visibility, allowing an increase in the elevation mask, avoiding possible signal obstructions (Bahadur and Nohutcu 2018; Montenbruck et al. 2017; Odijk 2017; Setti Jr. et al. 2020).

Different techniques can be used to determine the user's position with GNSS signals. Point Positioning (PP) consists of determining the position of a point of interest referenced to the geocenter using pseudorange observations measured by one receiver (Odijk 2017). Thence, it is necessary to simultaneously receive observations from at least four GNSS satellites, determining the three-dimensional position and the receiver clock error (Monico 2008). However, several errors affect the use of this technology, such as those related to the satellites (orbit, clock, and relativity), to the receivers (clock, centering, and channels), to the stations (polar motion, tides, ocean load, and coordinates), and errors related to the signal propagation, mainly the ionospheric refraction, scintillations, multipath, and the refraction caused by the neutral atmosphere (Montenbruck et al. 2017).

The ionospheric layer causes different types of effects and attenuation in the GNSS signals, including scintillation. The ionospheric scintillation corresponds to fluctuations in the amplitude or phase of radio waves as they propagate through regions of irregular electronic density. It causes weakening and in many cases loss of the signal tracked by the receiver (Conker et al. 2003). In equatorial regions, the ionosphere effects are associated with anomalies, with greater intensity at the local peak of the anomaly (Seeber 2003; Monico 2008). Another phenomenon that can be highlighted in the interference of GNSS signals is related to the South American Magnetic Anomaly (SAMA), with the point of the lowest geomagnetic field value located in southeastern Brazil (Duzellier 2005). This makes Brazil a privileged area to study the subject, since most of its territory is in the equatorial region, strongly influenced by these effects.

In this context, the main objective of this work is the processing and assessment of autonomous and combined (multi-GNSS) Point Positioning considering a set of GNSS stations in Brazil under the effect of different ionospheric conditions. The methodology section describes the use of in-house point positioning software, the input files used and the experiments that will be carried out. Subsequently the results, analyses and conclusions of the work will be presented.

2 Methodology

A C++ scientific software under development at the Study Group on Space Geodesy (GEGE – *Grupo de Estudo em Geodésia Espacial*), São Paulo State University (Unesp – *Universidade Estadual Paulista*) were used, which performs Point Positioning with the possibility of using different GNSS signal frequencies and constellations (Setti Jr. 2019). The software execution flowchart is illustrated in Figure 1.

Pseudorange observations were used at L1 GPS (1575.42 MHz), L1 GLONASS (1597~1617 MHz), E1 Galileo (1575.42 MHz), and B1 BeiDou (1561.098 MHz) frequencies. The Hopfield model and Niel's mapping function were selected for the correction of the neutral atmosphere delay and the Klobuchar model for the minimization of ionospheric effects (Klobuchar 1987; Seeber 2003). An elevation mask of 10° and PDOP limited to 6 were adopted. In the results, the impact of systematic effects on Point Positioning was assessed, including the influence of station location, multipath, ionospheric scintillations, and the number of tracked satellites. Quality control was carried out using the DIA (Detection, Identification and Adaptation) method (Monico 2008).

As input, the observation files of each GNSS station in RINEX (Receiver-Independent Exchange Format) format, version 3, which contain pseudorange information of the tracked systems and frequencies, were used. These files were obtained from the Brazilian Institute

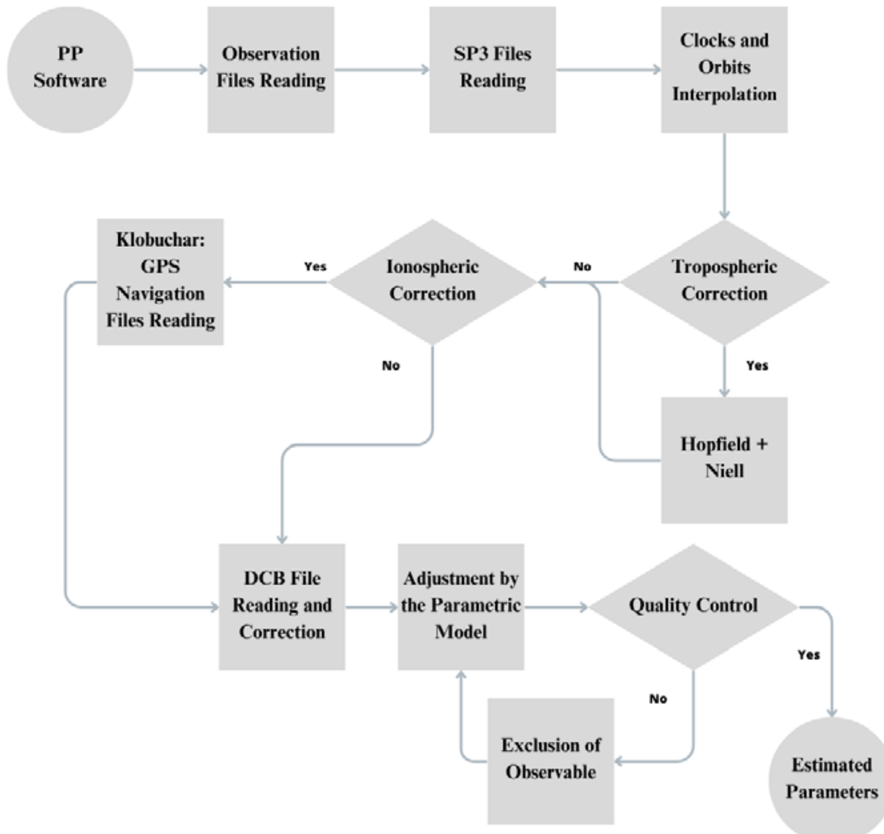

Figure 1 PP software flowchart. Adapted from Setti Jr. (2019).

of Geography and Statistics (IBGE) database. Each RINEX file contains 24 hours of observations, with a sampling rate of 15 seconds, from 00:00 to 23:59:45 Universal Time Coordinated (UTC). Data from 20 stations of the Brazilian Network of Continuous Monitoring of GNSS systems (RBMC), distributed across the Brazilian territory, were selected (Figure 2).

It is worth mentioning that all selected stations are equipped with multi-GNSS receivers (GPS, GLONASS, Galileo and BeiDou), but some did not track and/or registered BeiDou B2A observations (one side lobe of B2 signal: 1176,42MHz). The data were processed for the systems individually and in combination (GPS + Galileo and GPS + Galileo + BeiDou + GLONASS), considering the months of March and June 2022, which represent periods of high and low ionospheric activity, respectively.

The results are divided in two parts. The first experiment consists of a case study, in which one station was assessed in detail. Some of the analysis and conclusions taken from the case study will serve as justification for the general results in the second experiment.

2.1 First Experiment

For the first experiment, the PPTE station was selected, located in the city of Presidente Prudente – SP. Figure 3 shows the estimated Total Electron Content (TEC) for March and June 2022, derived from GPS measurements of a station also located in Presidente Prudente (about 280 m away from PPTE), named PRU2 and part of the INCT GNSS-NavAer (National Institute of Science and Technology - GNSS Technology in Support of Air Navigation) network. It is worth noting that the unit of measurement is TEC Unit (TECU), with 1 TECU = 10^{16} electron/m^2.

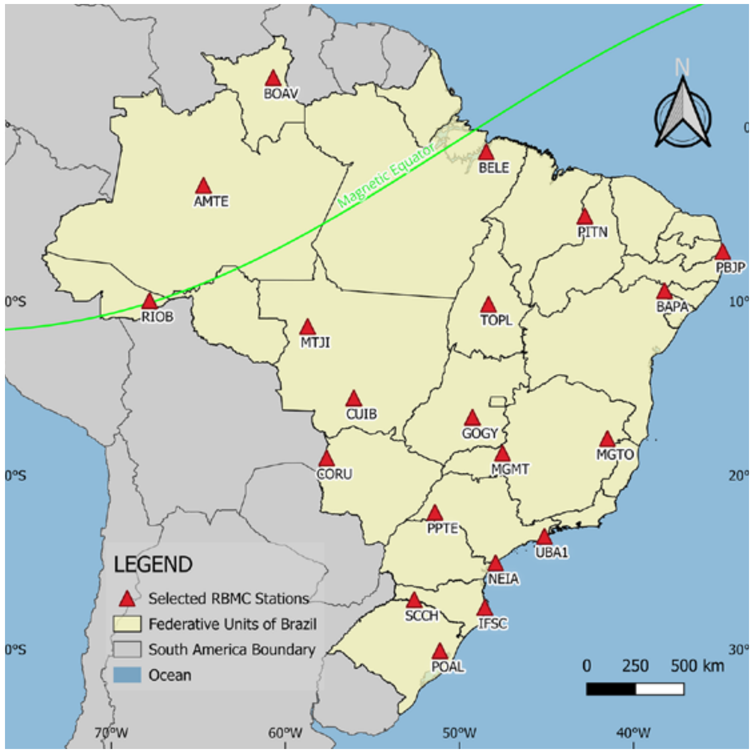

Figure 2 Distribution of selected stations.

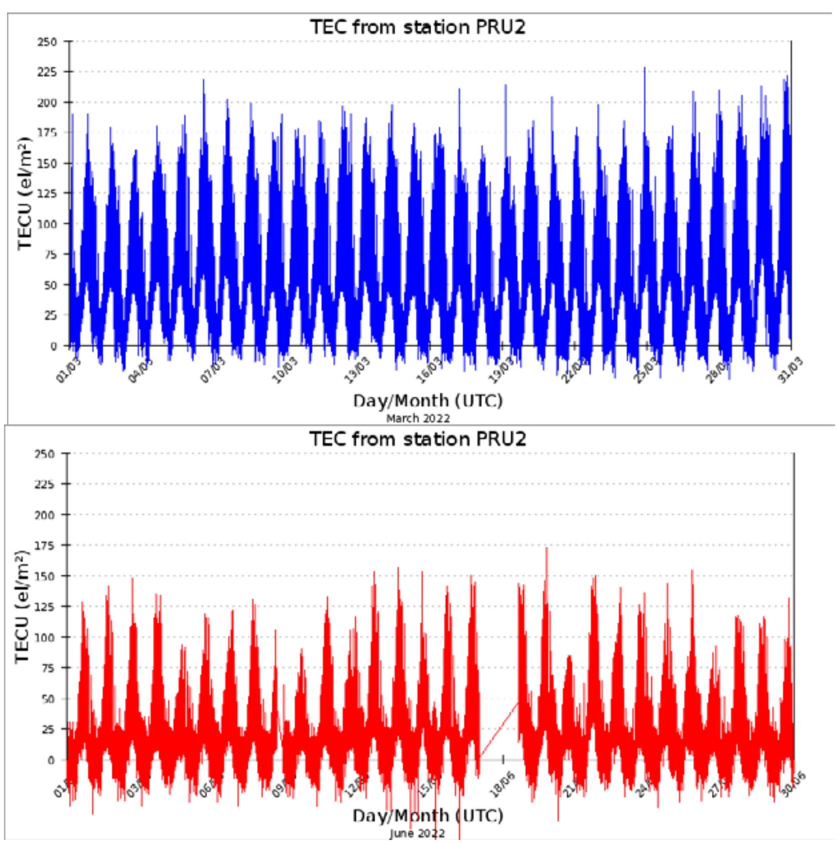

Figure 3 TEC at the PRU2 station for the months of March and June 2022, respectively. Source: ISMR n.d.

It is observed that the TEC for the month of June does not exceed 190 TECU (30.4 m of error at L1 GPS frequency), where 1 TECU is equivalent to 16 cm at L1 GPS (Klobuchar 1996). According to Figure 3, the electron density in the ionospheric layer in the month of March is elevated, with a peak higher than 241 TECU (38.6-m error at L1 GPS). On June 18 there was a lack of data, due to the station being out of operation. One also identifies the presence of negative TEC values, which occur due to problems in the calibration of the receiver Differential Code Bias (DCB) at the station. Figure 4 depicts the estimated ionospheric scintillation at the same station by means of the S4 index obtained for the GPS satellites.

It is observed that the highest values of S4 occur in March 2022, month of higher ionospheric activity. According to Tiwari et al. (2011), the threshold for considering the ionospheric scintillations as strong is when the S4 index is above 1, moderate between 0.5 and 1 and weak when it is less than 0.5. For the month of June, the S4 values are mostly below 1, representing a moderate to low disturbance in the electron density, thus less affecting the signals compared to the month of March.

2.2 Second Experiment

As in the previous experiment, the performance of the different systems in the autonomous and combined PP was evaluated using 20 stations of the RBMC network. In addition, the correlation between multipath and positional accuracy was computed aiming to justify the obtained results. By observing the 99.7% percentile of the parametric adjustment a posteriori sigma of the different systems (GPS - 0.27 m; Galileo - 0.34 m; GLONASS - 0.42 m and BeiDou - 0.56 m), obtained in Experiment I, lower values were observed for GPS and Galileo compared to GLONASS and BeiDou, meaning that in general GPS and Galileo position estimates are more accurate when considering the systems individually. Consequently, the adjustment stochastic model was adapted to assign half the weight to GLONASS and BeiDou observations compared to GPS and Galileo.

The location where the receiver is placed can also affect the results due to the possible occurrence of multipath caused by the surrounding environment. In this sense, Figure 5 shows the average multipath index (Alves et al. 2013) of the selected stations, considering the average of 3 days in March and June. Pearson's correlation coefficient was computed to investigate the influence of multipath on the PP results.

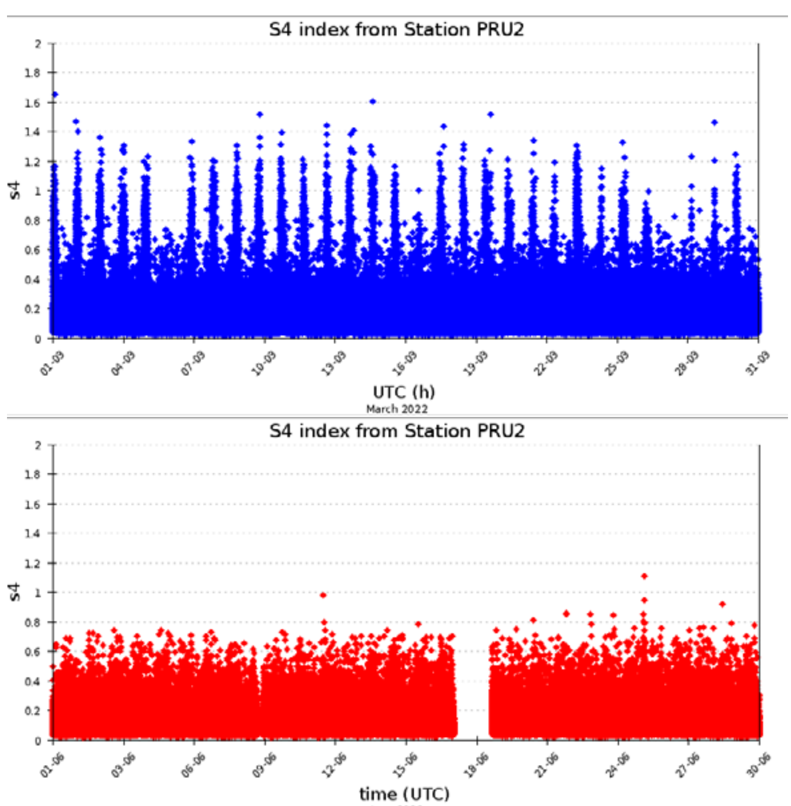

Figure 4 S4 at the PRU2 station for the months of March and June, respectively. Source: ISMR n.d.

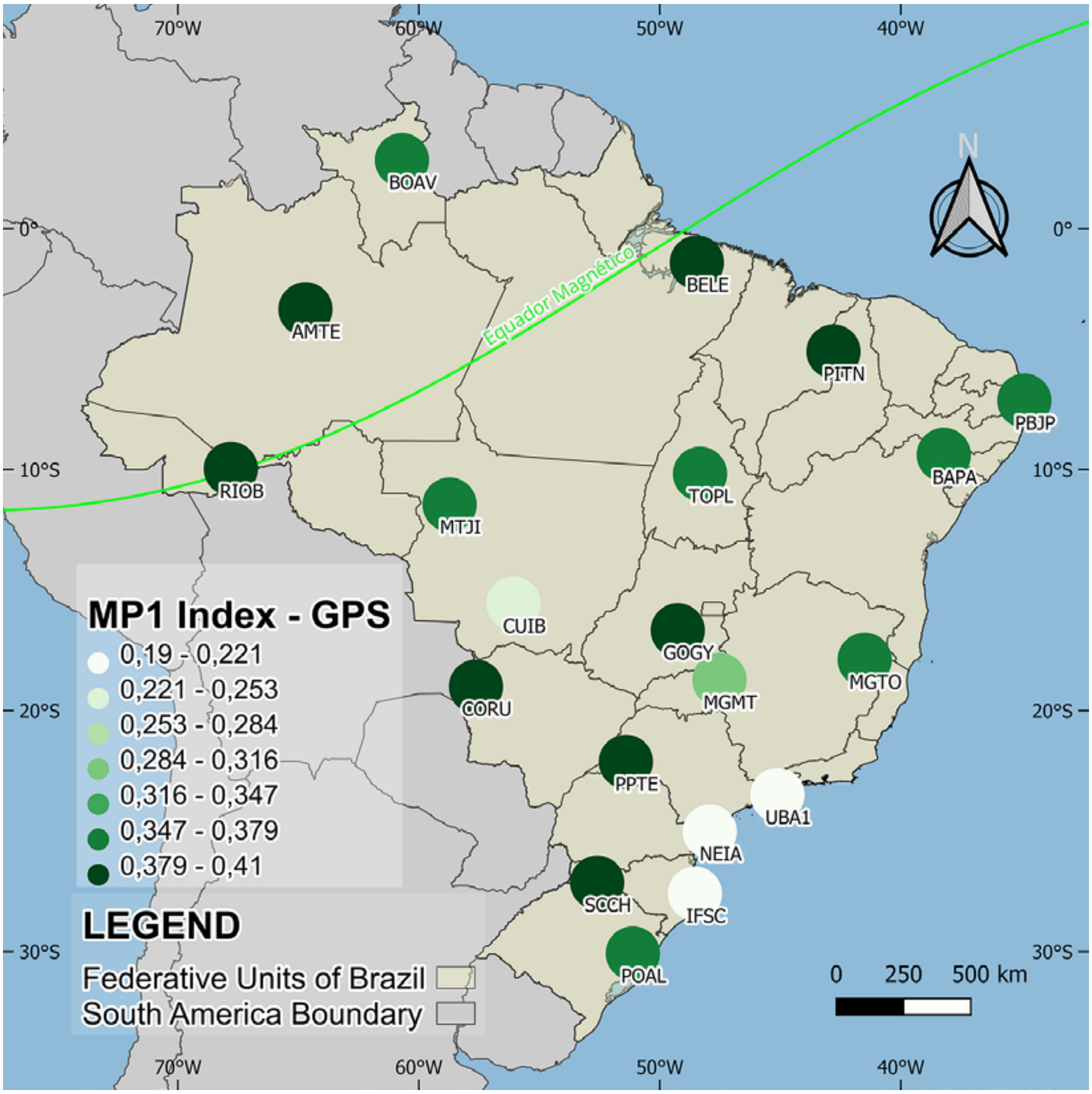

Figure 5 Multipath average (MP1 GPS) at different stations in the country.

3 Results

This section presents the results obtained in both experiments performed in this work, subdivided into two subsections.

3.1 Results of the First Experiment

In this subsection the results obtained in the first experiment using PPTE station are presented and discussed in three parts. In the first part, the results of the autonomous and multi-GNSS PP for the month of March are presented; in the second part the results of the autonomous PP only for March 11 (day of strong scintillation in the month of March) are detailed; finally, the multi-GNSS processing for the same mentioned day are shown and discussed.

3.1.1. High Ionospheric Activity Period (March/2022)

As shown in Figures 3 and 4, the month of March showed high ionospheric activity with the occurrence of scintillation. Considering the analyzed period, Figure 6 presents the mean number of satellites during the 31 days of the month, as well as the obtained Position Dilution of Position (PDOP), horizontal, vertical, and three-dimensional discrepancies (H, V and 3D Error), and three-dimensional standard deviation (σ_{3D}).

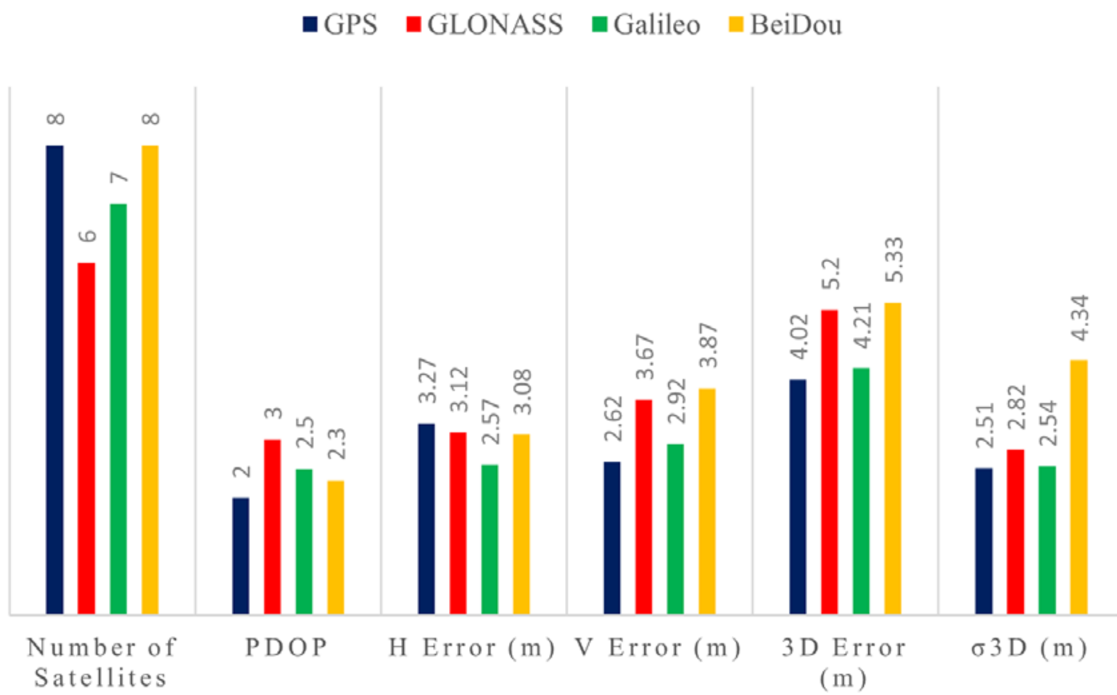

Figure 6 Average number of satellites, PDOP, H, V and 3D Error and 3D standard deviation for autonomous PP, for the 31 days of March.

Figure 6 shows that the GPS and BeiDou constellations have a greater number of satellites in view, with an average of 8 simultaneously tracked satellites; Beidou ranged from 5 to 12 and GPS ranged from 7 to 10. Galileo and GLONASS presented an average of 6 and 5 satellites, respectively. GPS presents the best mean PDOP, with the lowest average between the systems (2), followed by BeiDou (2.3), due to the massive launch of new satellites, and Galileo (2.5). For GLONASS, an effect that causes many epochs to be discarded in the PP processing is the large PDOP value, which in many cases exceeded the limit of 6 (24% of the time), obtaining the highest average between the systems (3).

Regarding the receiver estimated position, it can be observed that the system that presented the largest horizontal error was GPS, with an average of 3.27 m, followed by GLONASS with a 3.12 m error. When analyzing the vertical error, it is observed that the BeiDou system presented the worst results, with 3.87 m of average error, being 48%, 6% and 26% worse in relation to the vertical discrepancy obtained in the GPS, GLONASS and Galileo estimates, respectively. From that, the best results were obtained when using the GPS and Galileo systems in the vertical and horizontal components, respectively. GPS was the system that obtained the best three-dimensional accuracy overall (Table 1), with a 3D mean discrepancy of 4.02 m and an average 3D standard deviation of 2.51 m, thus resulting in a 3D root-mean-square error (RMSE) of 4.74 m.

It is observed that the Galileo system showed the lowest a posteriori sigma value. The low value of GLONASS is caused by the exclusion of several epochs due to the high PDOP. If we consider all the results presented, it can be concluded that GPS and Galileo obtained the best results at PPTE station.

Table 1 3D RMSE, percentage of degradation compared to GPS system in relation to the other systems and sigma a posteriori obtained for autonomous PP, for March.

	3D RMSE (m)	Degradation compared to GPS (%)	95% percentiles of the a Posteriori Sigma (m)
GPS	4.74	x	0.28
GLONASS	5.91	25%	0.33
Galileo	4.92	4%	0.30
BeiDou	6.88	45%	0.48

3.1.2. Analysis of the Autonomous PP for March 11

In this subsection we analyzed the positioning behavior over a day (March 11, 2022) of high TEC and strong S4. Figure 7 shows the ionospheric indices at PRU2 station. A high concentration of electrons is observed in the period from 3 p.m. (12 p.m. local time), decreasing only with sunset (6 p.m. local time, 9 p.m. UTC). In relation to the S4 index, a peak occurs after sunset, reducing only at midnight local time.

Figure 8 shows the number of satellites and PDOP obtained in each epoch in the autonomous PP for the four GNSS. It is worth noting the high PDOP of GLONASS system, caused by the low number of satellites in view.

Figure 9 shows the errors in the horizontal and vertical components obtained in the autonomous processing. Galileo presented the best results in terms of horizontal discrepancy and the GPS system was better vertically. There is also an increase in discrepancies in periods of high electron concentration and ionospheric scintillation, caused by the imperfect ionospheric correction of the Klobuchar broadcast model. The overall three-dimensional discrepancy and standard deviation are described in Table 2.

3.1.3. Analysis of the PP Multi-GNSS

The systems were combined in the multi-GNSS PP following two approaches: applying the same weighting for all four systems and adopting half the weight for GLONASS and BeiDou observations compared to GPS and Galileo. The results for the horizontal, vertical, and three-dimensional RMSE obtained for March 11 and for the month of March 2022 are shown in Table 3.

It is observed that when using different weights, the accuracy obtained in the multi-GNSS PP for March results has an improvement of 13 cm, with a 16 cm improved standard deviation. In Table 3 it is also possible to see an improvement of up to 3 cm in the three-dimensional accuracy for March 11, where the component that showed the greatest improvement was the horizontal one (9 cm).

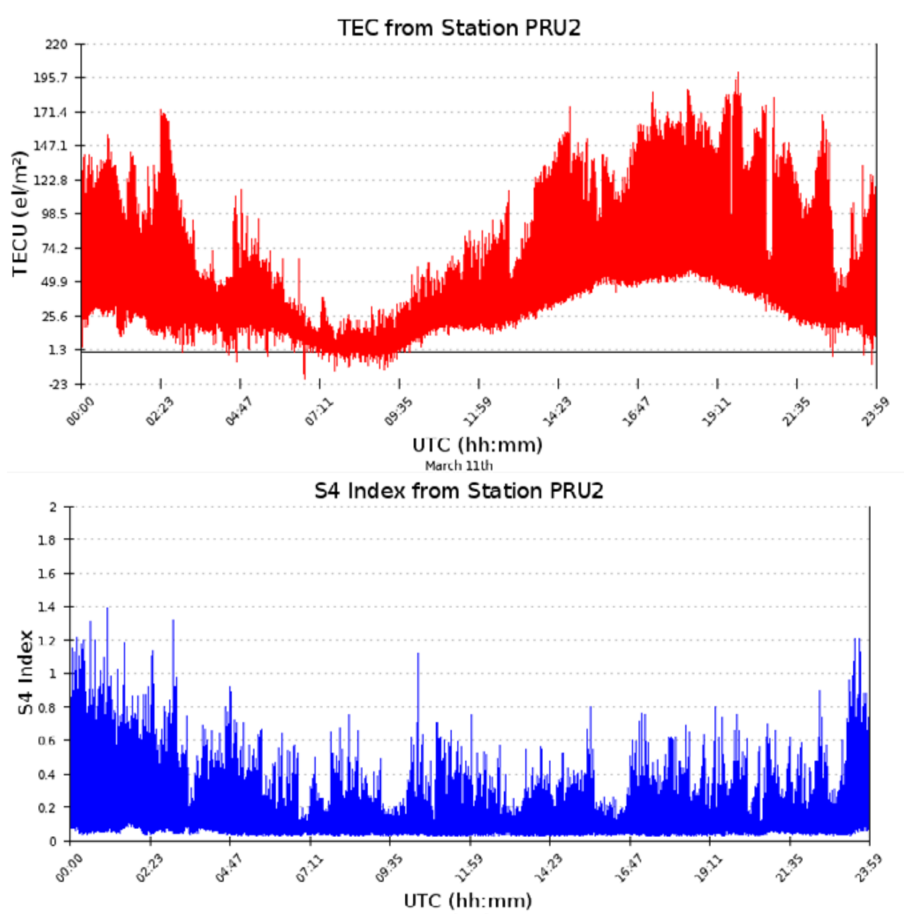

Figure 7 TEC and S4 Index at the PRU2 station for March 11, respectively. ISMR n.d.

Table 2 3D Error, standard deviation and RMSE, and percentage of improvement of the GPS system in relation to the other, obtained for autonomous PP, for March 11.

	3D Error (m)	σ_{3D}(m)	3D RMSE (m)	GPS Improvement (%)
GPS	3.82	2.69	4.67	x
GLONASS	5.44	3.38	6.4	37%
Galileo	3.94	2.74	4.8	3%
BeiDou	6.46	5.34	8.39	80%

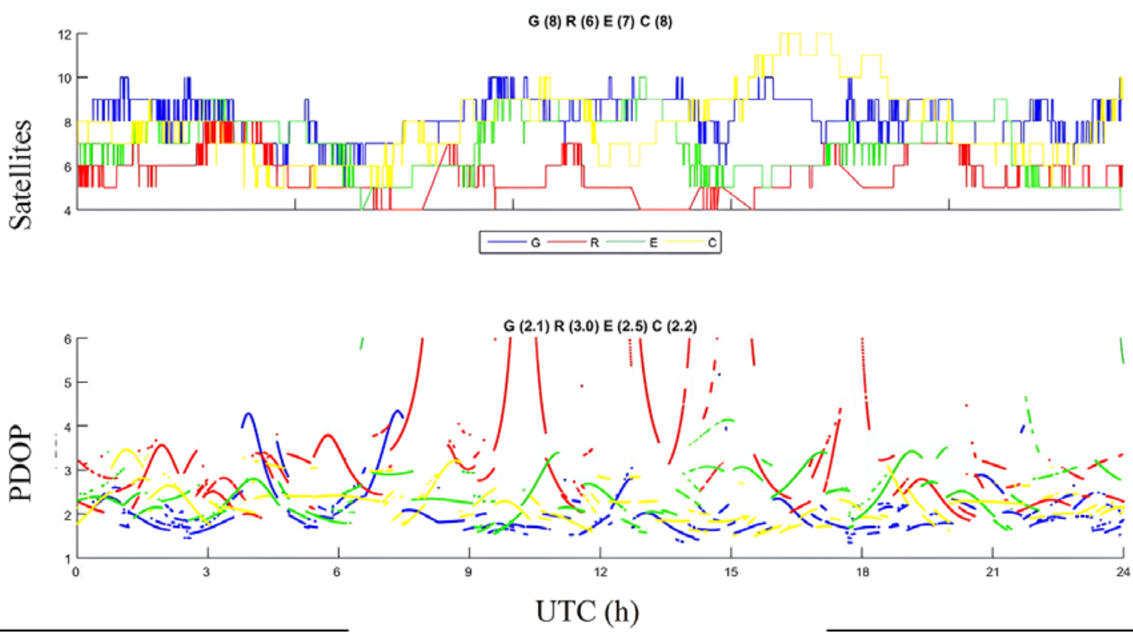

Figure 8 Number of satellites and PDOP at PPTE for autonomous PP, for March 11.

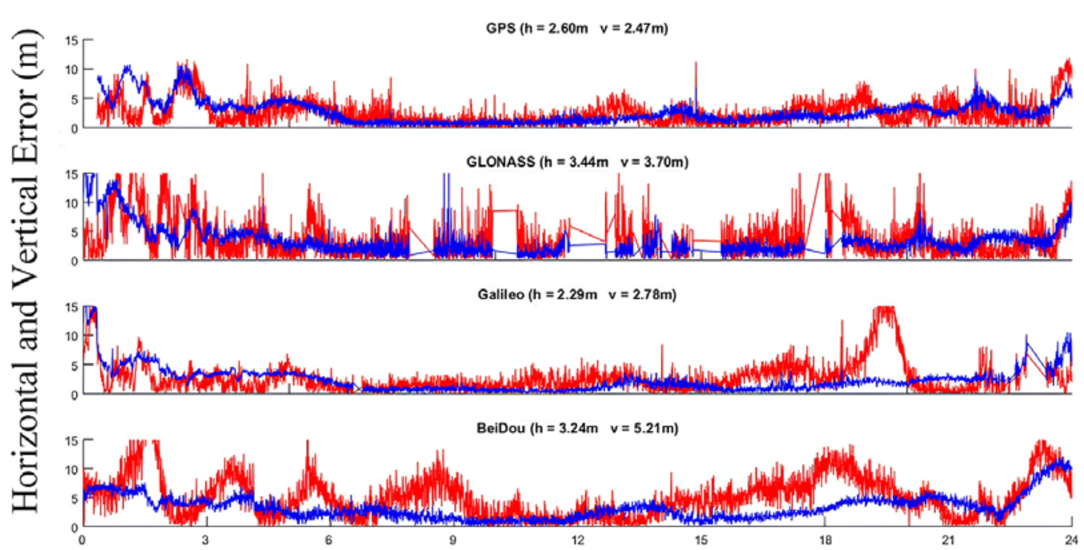

Figure 9 Horizontal (blue) and vertical (red) discrepancy obtained in PP, for March 11.

Table 3 H, V, and 3D RMS; and 3D Error, standard deviation and RMS obtained for combined PP, for March 11 and month of March.

	PP Multi-GNSS March 11		
	Same Weight	**Different Weight**	**Different weight Improvement**
H RMSE (m)	2.85	2.76	3%
V RMSE (m)	1.97	1.95	1%
3D RMSE (m)	3.59	3.56	1%
	PP Multi-GNSS March		
	Same Weight	Different Weight	Improvement
3D Error (m)	3.73	3.65	2%
(m)	1.52	1.36	12%
3D RMSE (m)	4.03	3.9	3%

3.2 Results of the Second Experiment

This section is subdivided into four parts. In the first one, we describe the results obtained in the standalone PP, considering all 20 stations. Then the accuracy results obtained in the combined multi-GNSS PP are shown and are correlated to the multipath index of each station. After that, the accuracy obtained in the GPS autonomous PP is compared to the combined multi-GNSS and GPS + Galileo (G + E). Finally, an average of the results obtained at the 20 stations is performed.

3.2.1. Analysis of the Autonomous PP for March 11

First the average number of satellites obtained in the 2 months of study is presented, demonstrating the difference in the number of satellites tracked at each station, as shown in Figure 10.

It can be seen in Figure 10 that at some stations about 7 to 8 BeiDou satellites were tracked per epoch, while in others an average of 5 was obtained. This is due to some receivers not tracking observables from satellites with the B2A signal, thus containing a smaller maximum number of available satellites than the full operational constellation. There is a larger number of tracked GPS satellites (9), followed by Galileo (8), BeiDou (7) and GLONASS (5), respectively, when averaging the 20 stations.

Figure 11 presents an average of the positional results obtained for March and June. In each month, it is possible to observe a significant change (in the order of decimeters) in positional accuracy when compared to each station and each month.

As shown in Figure 11.A, for the month of high ionospheric activity (March), GPS at most stations showed the most accurate result (3.64 m), followed by Galileo (3.79 m), GLONASS (4.56 m) and BeiDou (5.8 m), respectively. That month Galileo performed better than GPS at AMTE (4.12 m), CORU (3.81 m), MTJI (3.48 m), and PBJP (3.97 m) stations. Figure 11.B shows the results obtained for the month of June; taking the average of the 20 stations, the Galileo system showed the best accuracy, being approximately 3%, 41%, and 103% more accurate than the GPS, GLONASS, and BeiDou systems, respectively.

3.2.2. Results Obtained in the Combined PP

Figure 12 maps the average positional accuracy obtained in the multi-GNSS PP for the months of March and June 2022. An RMSE range was identified for March and June, varying from 1.50 to 3.75 m. The higher RMSE values obtained at stations located in the magnetic latitude region near 15° (CORU, MGMT, MGTO, NEIA, and PPTE) can be caused by the fountain effect (Matsuoka 2007).

The map depicted in Figure 5 shows that the stations that suffer the least with the multipath effect are IFSC, NEIA and UBA1. In most of the stations, the index is greater than 35 cm. Comparing Figure 5 with Figure 12, we note that there is a correlation between the stations with the highest errors and the stations with the highest multipath values; the Pearson's correlation found between positioning and multipath in March was 44%. The moderate correlation could be because of the ionosphere in its high activity period, hiding the multipath influence. In relation to the values of June, as it is a month of low activity'Ionospheric, we obtained a correlation coefficient of 62%.

Figure 13 shows the horizontal and vertical errors and their respective standard deviations for multi-GNSS and GPS+Galileo positioning in March and June 2022. The difference between the results is that the standard deviation is lower in multi-GNSS due to the redundancy of the observations, containing a larger average of the satellites per epoch, resulting in a lower RMSE.

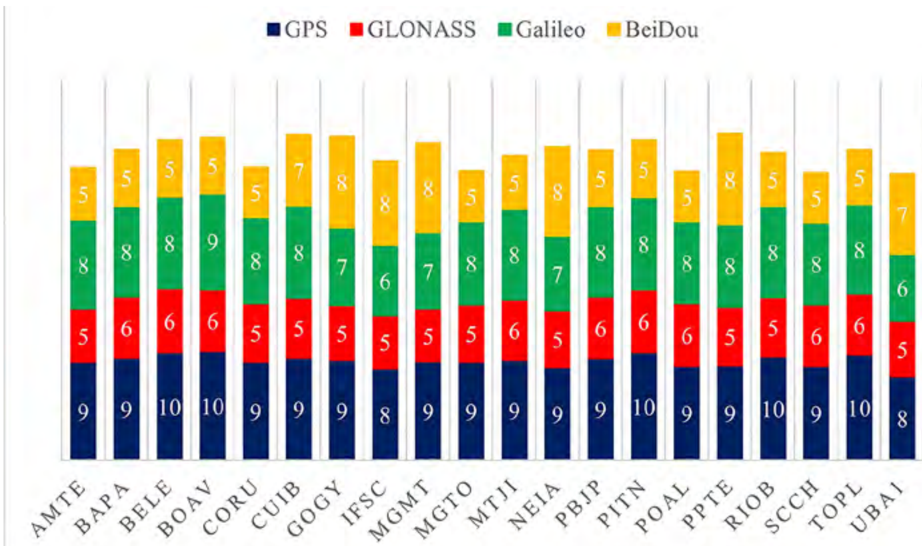

Figure 10 Number of satellites obtained in the standalone PP.

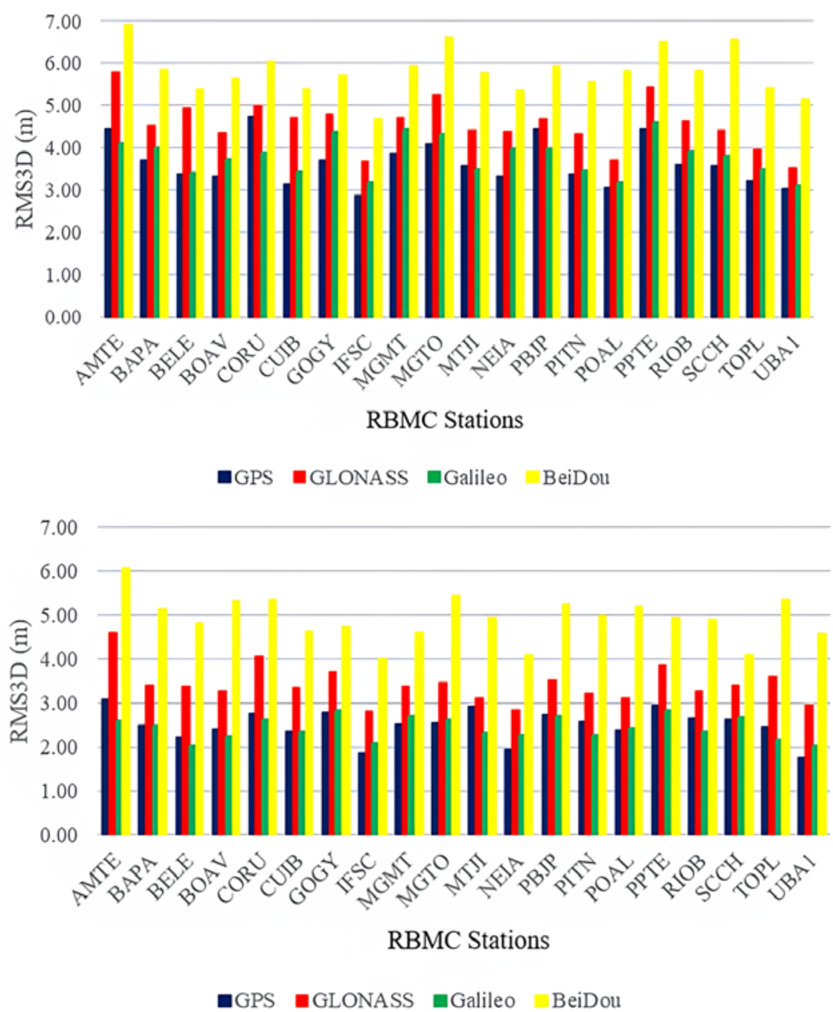

Figure 11 RMS3D obtained in the standalone PP at the 20 stations analyzed for the months of: A. March; and B. June.

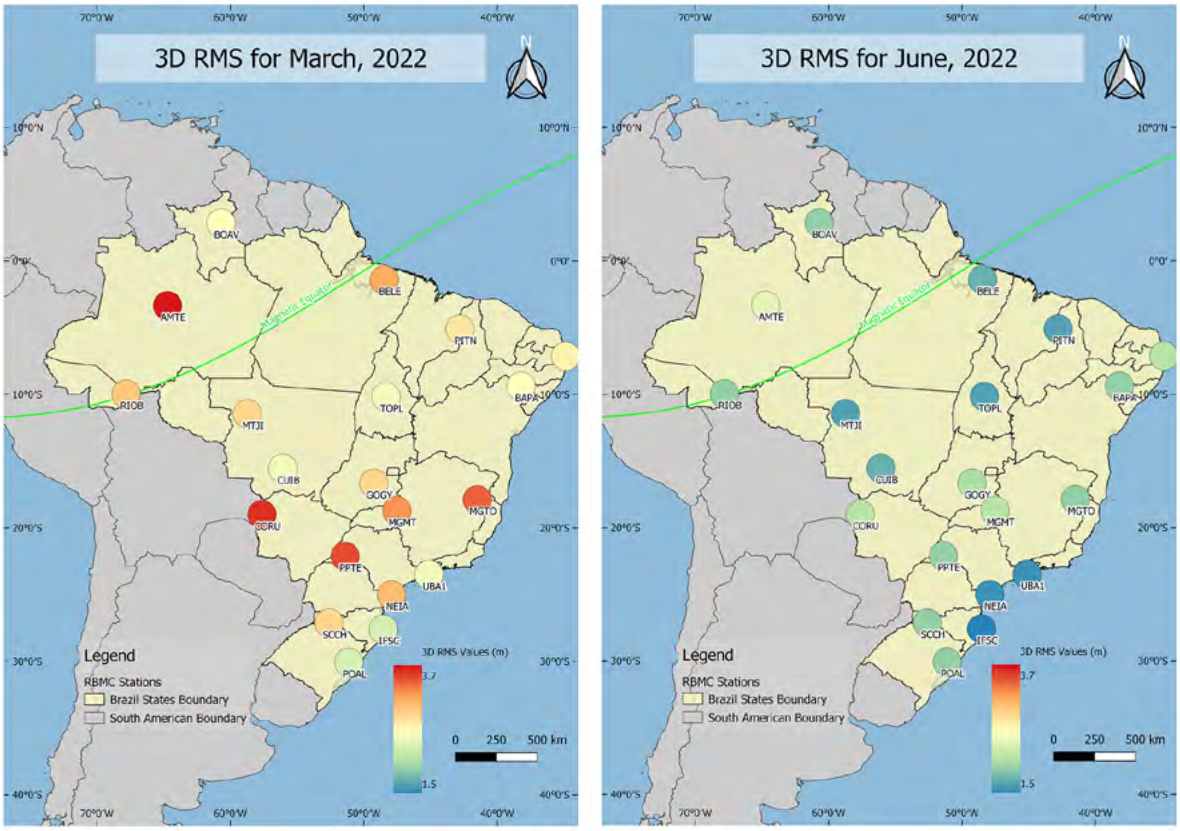

Figure 12 Positional accuracy (3D RMSE) obtained in the multi-GNSS PP at different stations for the months of March and June 2022.

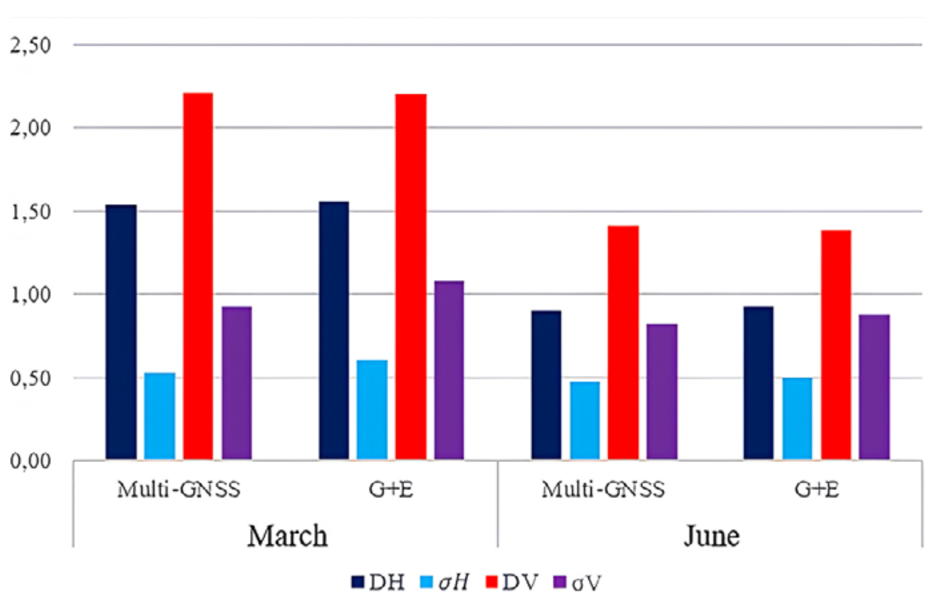

Figure 13 Horizontal and vertical errors and their respective standard deviations obtained in the multi-GNSS and GPS+Galileo (G+E) PP at different stations for the months of March and June 2022.

4 Conclusions

In this work, single-frequency standalone and combined multi-constellation data was processed using the four global GNSS systems. Through the results in the autonomous PP, a weighting for the multi-GNSS PP was defined. The work relied on 61 days of data from 20 RBMC stations, from March and June 2022. The two experiments were presented and described, the first being an analysis of a selected station, seeking to justify the results obtained in the second experiment.

The results show that the GPS system obtained the lowest PDOP, positional error, positional standard deviation, and three-dimensional accuracy compared to the other systems in the autonomous PP, both for the month of June and for the month of March, on most days. These results may be due to the system being in the market for a longer time, allowing a longer period of study on the emitted signals, as well as the development of models for error mitigation and orbits and clocks estimation. For the month of June, month of lower ionospheric activity compared to March, the Galileo system presented the best results in 11 out of the 20 selected stations. Thus, the system obtained good results compared to the others, being 3% more accurate than GPS for the month of June. GLONASS results were worse compared to Galileo and GPS, with poor values of PDOP in several epochs, presenting a "bad" geometry in the period and in the locations where the positioning was performed. BeiDou presented the worst results.

As expected, the combined multi-GNSS PP showed the best results in terms of three-dimensional accuracy at most stations, with the smallest horizontal error (1.22 m). When analyzing the three-dimensional standard deviation, due to the high redundancy of observations, the multi-GNSS presented the lowest result (1.01 m), remaining regular even in periods with the occurrence of strong ionospheric scintillations. In terms of vertical error, the combination GPS + Galileo presented the best results, being 2% better than the multi-GNSS.

For future studies, it is recommended to use a longer period of data, a larger number of stations, apply different weightings in the multi-GNSS PP and different combinations in the PP, also using multi-frequency data.

5 Acknowledgments

The authors would like to thank the São Paulo State University (Unesp), the National Council for Scientific and Technological Development (CNPq), files 304038/2020-2, and 130339/2023-7, and the São Paulo Research Foundation (FAPESP) files 2019/26669-0 and 2021/12377-8. The authors would also like to acknowledge the National Institute of Science and Technology (INCT) GNSS Technology for Supporting Air Navigation (GNSS-NavAer), funded by CNPq file 465648/2014-2, FAPESP file 2017/01550-0 and Coordination of Superior Level Staff Improvement (CAPES) file 88887.137186/2017-00. We also acknowledge the IGS Analysis Center (AC), for providing the navigation data, and IBGE for providing the GNSS observation data.

6 References

Alves, D.M., De Souza, E.M., Kaneshiro, V. Y. & Souza, J.S. 2013, *Análise de Séries Temporais de Multicaminho*, Boletim de Ciências Geodésicas, Curitiba.

Bahadur, B., Nohutcu, M. 2018, 'PPPH: A MATLAB-based software for multi-GNSS precise point positioning analysis', *GPS Solutions*, vol. 22, no. 4.

Conker, R.S., El-Arini, M.B. Hegarty, C.J., Hsiao, T. 2003, 'Modeling the Effects of Ionospheric Scintillation on GPS/Satellite-Based Augmentation System Availability', *Radio Science*, vol. 38.

Duzellier, S. 2005, 'Radiation effects on electronic devices in space', *Aerospace Science and Technology*, no. 9, 9399.

ESA - EUROPEAN SPACE AGENCY 2024, *Galileo Space Segment*, <https://www.gsc-europa.eu/system-service-status/constellation-information>.

GPS - The Global Positioning System 2024, *Space segment*, <https://www.gps.gov/systems/gps/space/#generations/>.

IAC - Information and analysis center for positioning, navigation and timing 2024, *GLONASS*, <https://www.glonass-iac.ru/en/GLONASS/>.

ISMR n.d., *Query Tool*, <https://ismrquerytool.fct.unesp.br/is/index.php>.

Klobuchar, J.A. 1987, 'Ionospheric time-delay algorithm for single-frequency GPS users', *IEEE Transactions on Aerospace and Electronic Systems*, vol. 23, no. 3, pp. 325-31.

Klobuchar, J.A. 1996, 'Ionospheric effects on GPS', in IGlobal Positioning System: Theory and Applications, *American Institute of Aeronautics and Astronautics*, pp .485-515.

Li, X., Zhang, X., Ren, X., Fritsche, M., Wickert, J. & Schuh, H. 2015a, 'Precise positioning with current multi-constellation global navigation satellite systems: GPS, GLONASS, Galileo and BeiDou', *Science Reports*, vol. 5, 8328.

Li, X., Zhang, X., Ren, X., Fritsche, M., Wickert, J. & Schuh, H. 2015b, 'Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo', *Journal of Geodesy,* vol. 89, no. 6.

Lou, Y., Zheng, F., Gu, S., Wang, C., Guo, H. & Feng, Y. 2015, 'Multi-GNSS precise point positioning with raw single-frequency and dual-frequency measurement models', *GPS Solutions*, vol. 20, no. 4, 84962.

Matsuoka, M.T. 2007, 'Influência de diferentes condições da ionosfera no posicionamento por ponto com GPS: Avaliação na região brasileira', PhD thesis, Universidade Estadual Paulista, Presidente Prudente.

Monico, J.F.G. 2008, *Posicionamento pelo GNSS: descrição, fundamentos e aplicações*, 2nd edn, UNESP, São Paulo.

Montenbruck, O., Steigenberger, P., Prange, L., Deng, Z., Zhao, Q., Perosanz, F., Romero, I., Noll, C., Sturze, A., Weber, G., Schmid, R., Macleod, K. & Schaer, S. 2017, 'The multi-GNSS experiment (MGEX) of the International GNSS Service (IGS) – achievements, prospects and challenges', *Advances in Space Research*, vol. 59, no. 7, pp. 1671-97.

Odijk, D. 2017, 'Positioning Model', in P.J.G. Teunissen & O. Montenbruck (eds), *Springer Handbook of Global Navigation Satellite Systems*, Springer, Berlin.

Pan, L., Cai, C., Santerre, R. & Zhang, X. 2017, 'Performance evaluation of single-frequency point positioning with GPS, GLONASS, BeiDou and Galileo', *Survey Review*, vol. 49, 354, pp. 197-205.

Seeber, G. 2003, *Satellite Geodesy: Foundations, Methods, and Applications*, Walter de Gruyter, Berlin/New York.

Setti Jr., P.T. 2019, 'Posicionamento por Ponto multi-GNSS: análise dos sistemas, sinais e modelos ionosféricos', MSc dissertation, Universidade Estadual Paulista.

Setti Jr., P.T., Silva, C.M., Oliveira Júnior, P.S., Alves, D.B.M. & Monico, J.F.G. 2020, 'Posicionamento multi-GNSS', *Revista Brasileira Cartografia*, vol. 72, pp. 1200-24.

Tiwari, R., Skone, S., Tiwari, S., Strangeways, H.J. 2011, '3WBMod Assisted PLL GPS Software Receiver for Mitigating Scintillation Affect in High Latitude Region', *Proceedings of IEEE*.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

All data included in this study are publicly available in the literature.

Funding information

CNPq, Process Nº 304038/2020-2.
CNPq, Process Nº 130340/2023-5.
CNPq, Process Nº 130339/2023-7.
FAPESP, Process N° 2019/26669-0.
FAPESP, Process N° 2021/12377-8.

How to cite:

Souza, F. T. L., Zaupa, J.P.V., Silva, J. L. F., Stafocher, M. A., Setti Jr., P.T. & Alves, D.B.M. 2025, 'Multi-GNSS Data Processing and Analysis in Point Positioning for Brazilian Stations in Months of High and Low Ionospheric Activity',, *Anuário do Instituto de Geociências,* 48:62882. https://doi.org/10.11137/1982-3908_2025_48_62882