

KLOBUCHAR MODEL AND IGS GLOBAL IONOSPHERE MAPS PERFORMANCES IN GNSS SINGLE-POINT POSITIONING OVER BRAZIL

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ABSTRACT. Among the methods for mitigating the first-order effects of the ionosphere, the Klobuchar model and final Global Ionosphere Maps (GIM) produced by the International GNSS Service (IGS) are widely used. Previous studies have looked at their effectiveness in discrete periods and locations of Brazil, but this may have led to incomplete conclusions. Aiming to contribute to this discussion, this paper presents a more comprehensive evaluation of the Klobuchar model and IGS GIM performances in single-point positioning using data from the whole year of the solar cycle 24 peak from six stations of Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC). When compared to the solution without using correction for the ionosphere, improvements of approximately 39% and 52% were obtained with the Klobuchar model and the GIM, respectively. The results suggest that the lower intensity of solar cycle 24, the location of the GNSS station relative to the geomagnetic equator, and the occurrence of post-sunset ionospheric irregularities contribute to the worse performance of the assessed models when compared to research done with GNSS data from solar cycle 23.

Keywords: ionospheric correction; ionospheric irregularities; RBMC; solar cycle 24; positioning accuracy

INTRODUCTION

Brazil can be considered a favorable location to study events regarding the ionosphere due to its geographical position relative to the magnetic equator, where the highest free electron density gradients and irregularities, such as scintillation, are frequently observed (Aswathy and Manju, 2021; Yang et al., 2024). However, the ionosphere is the dominant source of error in GNSS positioning, and its correction is mandatory to obtain positioning with accuracy better than meter (Langley, 2017).

The ionosphere behaves like a dispersive medium in the frequency range of GNSS signals, allowing 99% of first-order effects to be eliminated with the linear combination of data from two frequencies called ion-free (Hauschild, 2017). However, the high cost of this kind of receiver restricts its use to applications that require centimeter accuracy. As a result, most users use lower-cost receivers, such as those installed in navigation systems, tablets, and smartphones. Thus, research on developing and evaluating different ways of reducing the effects of the ionosphere on single-frequency GNSS data is necessary.

The best-known ionospheric model is the Klobuchar model, whose coefficients are transmitted via Global Positioning System (GPS) satellite navigation messages (Klobuchar 1987). Research carried out in Brazil shows that this model can improve the quality of positioning by 16% to 70.4% (Matsuoka and Camargo 2002; Setti Júnior et al. (2019). Yang et al. (2020) evaluated the Klobuchar model over China and globally, with improvements of the order of 58% and 62%, respectively, results similar to those obtained by Wang et al. (2017), who found improvements of about 57%.

Final Global Ionosphere Maps (GIM) provided by the International GNSS Service (IGS) are a more accurate alternative for modeling the first-order ionosphere effects in single-frequency GNSS positioning. The IGS has been providing final GIM freely available since 1998 (Hernández-Pajares et al., 2009; Roma-Dollase et al., 2018). The IGS GIM was evaluated by Matsuoka and Camargo (2007) and Armendaris et al. (2009). The results showed improvements ranging from 72% to 77% in the altimetric component in Presidente Prudente/SP and Porto Alegre/RS, respectively.

It is important to note that the studies mentioned were carried out in a limited region of Brazil and that the data used in their analysis were from just a few days. Consequently, there is a need for a more thorough assessment of the performance of these methods, using data from stations located in different regions of Brazil observed continuously over a long period. Therefore, this research presents a more comprehensive analysis of the performance of these two methods, which considered data observed in six different regions of Brazil during the whole year of the solar cycle 24 peak occurred in 2014.

METHODS

Study Area

The study area was defined to cover the different regions of Brazil. Thus, six stations from the Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC) were selected: AMCO (Coari/AM), PITN (Teresina/PI), CUIB (Cuiabá/MT), BATF (Teixeira de Freitas/BA), SJSP (São José dos Campos/SP) and SMAR (Santa Maria/RS), whose location and geomagnetic latitude at the mid-year 2014 (epoch 2014.5) can be seen in Figure 1 and Table 1, respectively.

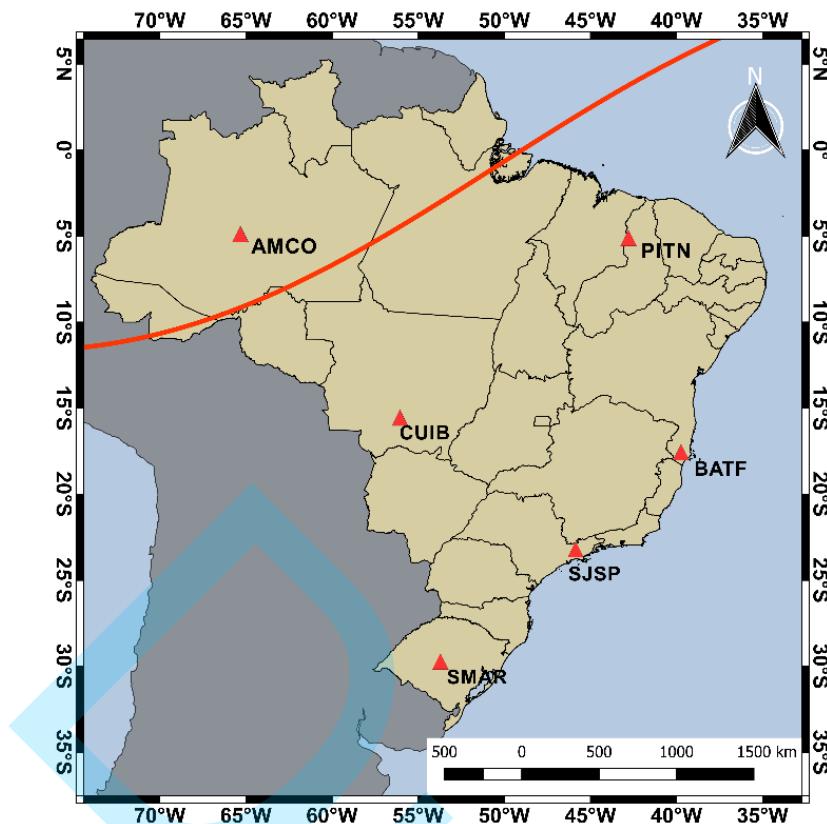


Figure 1: Location map showing the selected stations (red triangles) of the Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC) and their relative positions to the geomagnetic equator (red line).

Table 1: Geomagnetic latitude of the six selected GNSS stations.

Station	Dip Lat*	Station	Dip Lat*
AMCO	04,553400°	BATF	-20,280812°
PITN	-07,499240°	SJSP	-20,645256°
CUIB	-08,798191°	SMAR	-20,828738°

* Dip Lat: magnetic latitude computed from its relationship with the magnetic inclination (I), according to: $dip_lat = \arctan(0.5 \times \tan((I)))$

The six selected GNSS stations cover the five administrative regions of Brazil, providing a more robust spatial evaluation of the models. In addition, they are located at different distances from the geomagnetic equator to enable an analysis of the models performance under the different ionospheric conditions caused by the fountain effect, in which free electrons are moved from the geomagnetic equator to a distance close to $\pm 20^\circ$, creating two regions of higher density of free electrons, called Equatorial Ionization Anomaly (EIA) (Kelley, 2009). Furthermore, to avoid statistical dependence between the data used in producing the final IGS GIMs and the results obtained in this research, GNSS stations were selected that did not participate in the production of the GIMs.

Data

The GNSS observation and navigation files recorded during the whole year of 2014 by the six RBMC stations were downloaded from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística - IBGE) FTP server (IBGE 2024).

The Ionosphere Exchange format (IONEX) IGS final GIM files were downloaded from the National Agency for Space Administration Crustal Dynamics Data Information System HTTPS server (NASA/CDDIS 2024).

Data Processing

GNSS data were processed in the in-house program called PinPoint to compute the three-dimensional coordinates of the stations. This program processes GPS data by a batch non-linear least squares adjustment of the pseudo-ranges derived from the C/A code according to Subirana et al. (2013). Processing was carried out at a 5-minute interval with a 10° elevation cut-off to avoid multipath and other atmospheric disturbances.

The satellite coordinates and clock corrections, needed to estimate station coordinates, are computed from the broadcast ephemerides elements contained in the RINEX navigation files. Those files are also used to compute the Klobuchar model corrections from the eight coefficients contained in its header. The mathematical models used for both computations can be viewed at Klobuchar (1987) and Subirana et al. (2013).

Since the GIM is structured in a time-gridded vertical total electron content (VTEC) values, the computation of the ionosphere corrections requires a spatial-time interpolation and a projection of the VTEC to the satellite-receiver direction, called slant TEC. The spatial interpolation was computed by the bivariate method using the nearest four VTEC measurements, while the temporal interpolation took two consecutive rotate maps into account, as stated by Schaer et al. (1998). The slant TEC were computed using the standard geometric mapping function at 450 km high, i.e., the same setup adopted by IGS on the final GIM.

Three processing strategies regarding the ionosphere were adopted to provide a way to assess the performance of the Klobuchar model and GIM: no correction, applying the Klobuchar model, and applying the GIM.

Evaluation of the Ionosphere Correction Methods

The performance of the ionosphere correction methods was evaluated by analyzing the differences between the coordinates computed by the IBGE (taken from the header of the observation files), which were assumed as the ground truth, and the coordinates obtained from processing using the three aforementioned strategies.

The local geodetic coordinate system was adopted because the altimetric component is more affected by the ionospheric delay. This makes it possible to compare both the planimetric components (E and N) and the altimetric component (U) independently. Therefore, the

coordinate differences will be referred to as: DE and DN, for the planimetric components, and DU for the altimetric one. Finally, mean and root mean square error (RMSE) were computed from the coordinate differences.

The percentage improvement of the three-dimensional component was computed to carry out a relative analysis of the Klobuchar model and GIM performances compared to the no correction solution. It considers two situations: one when the result applying ionosphere correction performs better and the other when the no correction solution performs better. In the first case, the percentage improvement was computed from the ratio between the solution applying ionosphere correction and the no correction solution. In the second case, the computation was based on the ratio between the No and Cor solutions, multiplying the result by -1 so that the percentage improvement resulted in a negative number (equation 1):

$$\Omega = \begin{cases} 100 - (|Cor/No|)100 & \text{if } |Cor| < |No| \\ \text{or} \\ [100 - (|No/Cor|)100](-1) & \text{if } |Cor| > |No| \end{cases} \quad (1)$$

where Cor represents the values of the differences in the three-dimensional component using the Klobuchar model or the IGS GIM, and No is related to the differences obtained from the no ionosphere correction processing. In this way, individual improvement is obtained for each correction model.

RESULTS

Figure 2 shows the behavior of the coordinate differences in the planimetric and altimetric components throughout 2014 for each selected RBMC station. The Y-axis shows the differences in the planimetric components (DE and DN) on a scale ranging from 20 m to -20 m and the altimetric component (DU) on a scale ranging from 80 m to -80 m. The scale of the altimetric component is larger because it is the component most affected by the ionosphere, as shown particularly at the BATF station, where several irregularities can also be seen near the equinoxes, showing differences of more than 70 m in the altimetric component at various epochs. Besides, there is a predominance of random error in the planimetric components, whose mean difference values are close to 0 m, unlike the altimetric component. In addition, the ionosphere's effect is most significant in the equinoxes, mainly because of the higher ionization of the Earth's atmosphere, and least at the June solstice. These observations align with the specialized literature on the subject (Choy et al., 2008; Venkata Ratnam et al., 2017).

The graphs of the AMCO, PITN and CUIB stations, located closer to the geomagnetic equator, show that they were less affected by the ionosphere, especially near the fall and spring equinoxes. On the other hand, the stations located near the crest of EIA, i.e., BATF, SJSP, and SMAR, showed differences with irregular variation mainly during the equinoxes, when there are high peaks in the coordinate differences for all the components. Besides being associated with the EIA, post-sunset ionospheric irregularities such as scintillation may negatively affect the positioning in this region.

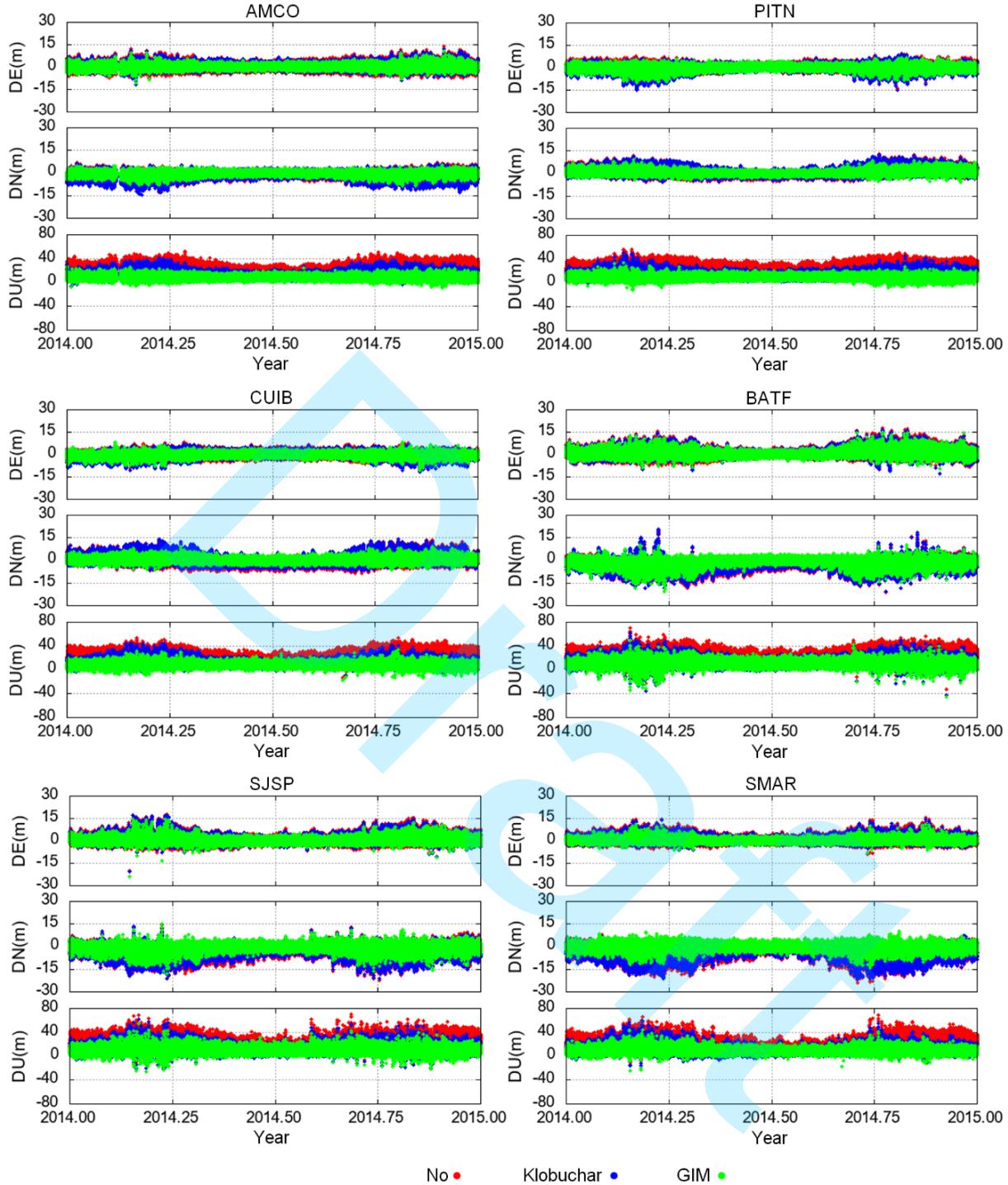


Figure 2: Coordinate differences time-series at East, North, and Up components for the six selected RBMC stations (red – no correction; blue – Klobuchar model; green – GIM).

Accuracy Evaluation

Figure 3 shows the RMSE of the three coordinate components (East, North, and Up) for all the stations applying the three strategies. The solution applying the Klobuchar model improved the accuracy of all the components of the six stations, with a more marked improvement in the

altimetric component and a more subtle improvement in the planimetric components, especially in the DN component of the AMCO station. As expected, the use of GIM produced even better results than the other solutions at all six stations, mainly in the altimetric component. The BATF, SJSP, and SMAR stations have the highest RMSE values for the planimetric components, justified by their location closest to the EIA crest region.

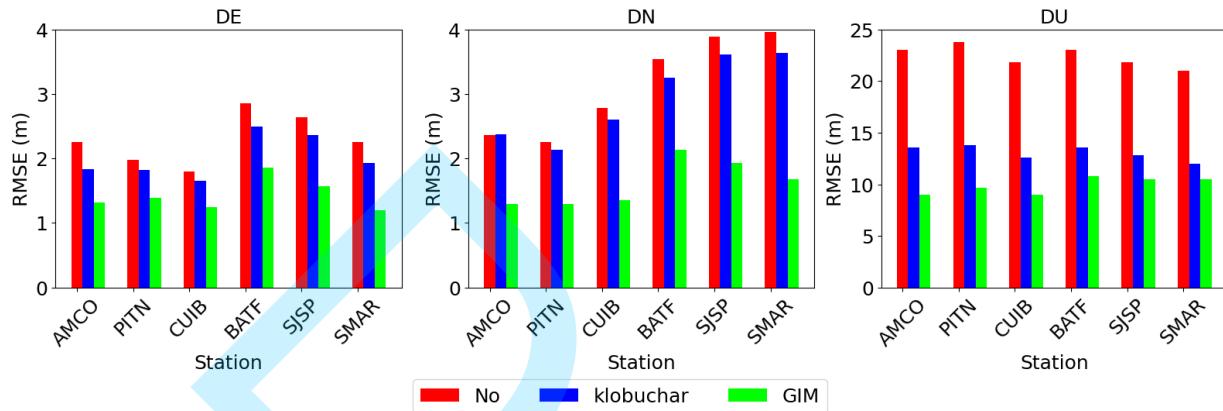


Figure 3: Coordinates accuracy at East, North, and Up components for the six selected RBMC stations (red – no correction; blue – Klobuchar model; green – GIM).

Three-dimensional Relative Evaluation

Figure 4 shows the behavior of the percentage improvement in the three-dimensional component for each of the six RBMC stations throughout the experiment period, a crucial timeline in our research. The bars with negative values indicate that the solutions applying the Klobuchar model or GIM showed worse results than the no correction solution. Most of the time, especially near the equinoxes, the solution using the GIM showed better relative performance when compared to the Klobuchar model. For CUIB, BATF, SJSP, and SMAR stations, the relative performance of the Klobuchar model was better during the period close to the June solstice.

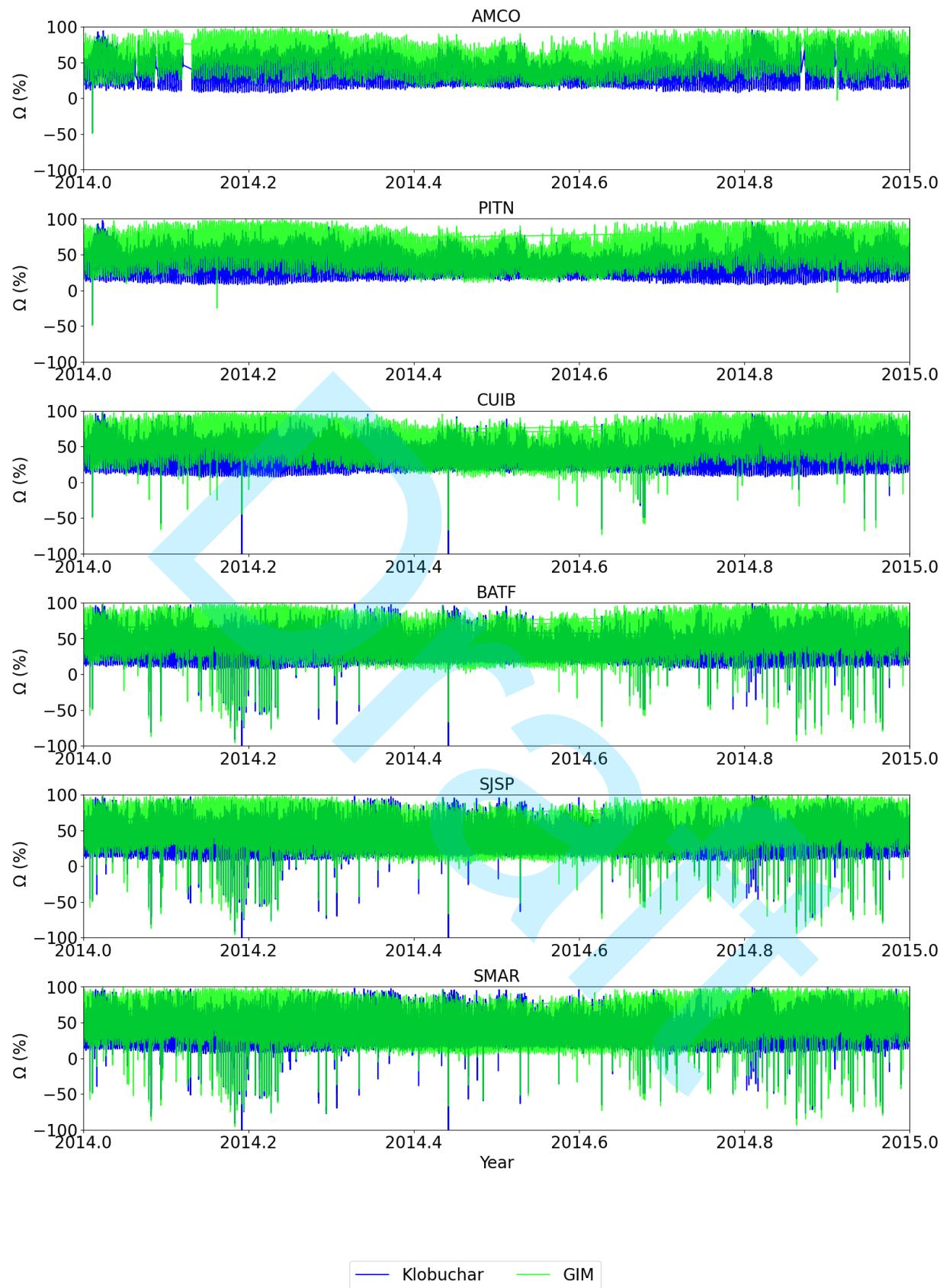


Figure 4: Three-dimensional Klobuchar model (blue) and GIM (green) relative performances for the six RBMC stations.

Figure 5 shows the mean relative performance of the three-dimensional component resulting from the Klobuchar model and the IGS GIM solutions for each RBMC station during 2014. The GIM solution produced better results at all the stations, with the most significant improvements observed at stations closer to the geomagnetic equator. These improvements can be explained by the fountain effect. The BATF, SJSP, and SMAR stations showed the worst percentages improvement, as their location is more susceptible to ionospheric irregularities associated to EIA.

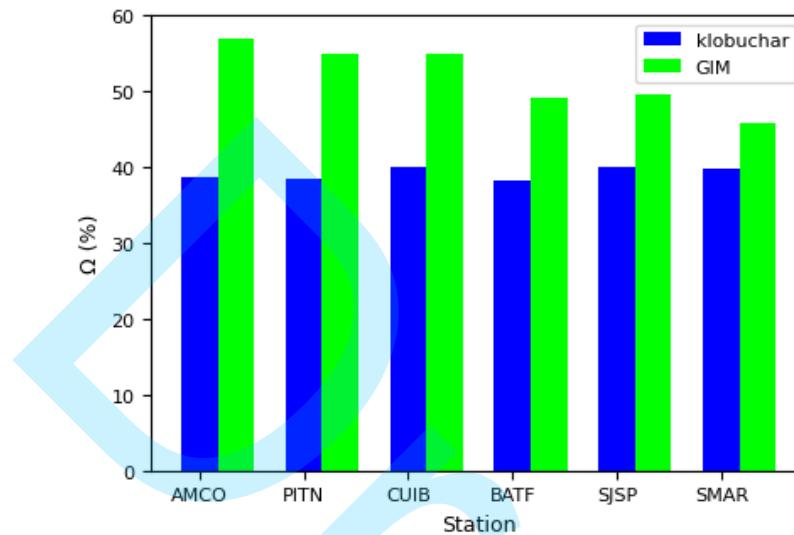


Figure 5: Three-dimensional relative performance for the six RBMC stations (blue – Klobuchar model; green – GIM).

Finally, Figure 6 shows the mean relative performance obtained with the two models and considering all the six stations. The GIM solution improved the quality of three-dimensional positioning by approximately 52%, while for the Klobuchar model, this percentage drops to 39%. Thus, GIM solution was around 31% more accurate than the Klobuchar model.

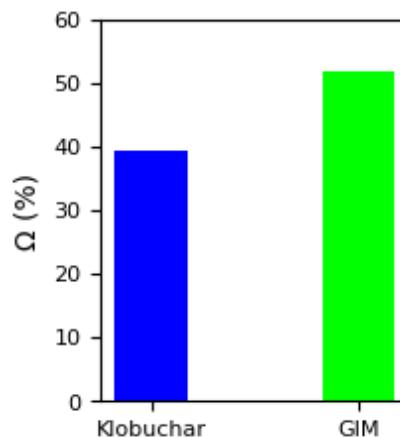


Figure 6: Brazil mean relative performance considering the six selected stations.

DISCUSSION

The ionization level of the Earth's atmosphere varies according to solar activity, which is related to the number of sunspots. While the results of this research were obtained with GPS data observed during the period of high solar activity of solar cycle 24, the research carried out previously used data observed in periods involving different levels of the solar cycles 23 and 24 activity. To provide subsidies for the analyses considering the differences in solar activity, Figure 7 shows the behavior of the number of sunspots observed in such solar cycles, showing that solar cycle 23 was more intense than its successor.

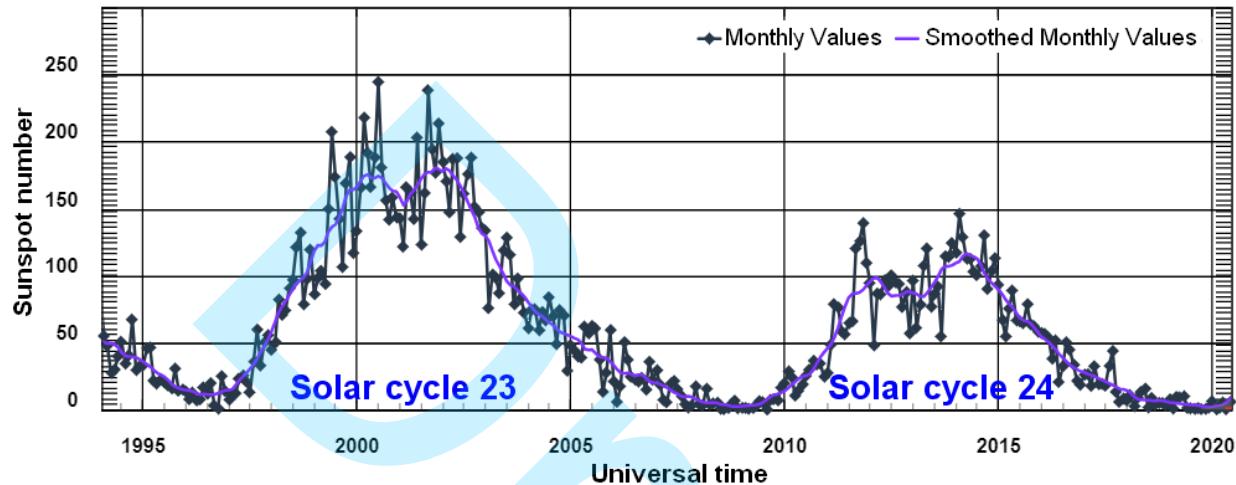


Figure 7: Solar cycles 23 and 24 sunspot number monthly averages. Adapted from NOAA (2024).

The evaluation of the Klobuchar model presented in this paper revealed an improvement of about 32% in the three-dimensional component. Improvements of approximately 70% in the average accuracy of the estimated positions using such model were observed using data from the Presidente Prudente/SP station (UEPP), which is located near the EIA crest (Matsuoka and Camargo 2002), while Aguiar et al. (2003) showed that Klobuchar's model decreased the effects of the ionosphere on the L1 pseudo-ranges at the UEPP station by around 53%, both using data surveyed during the solar cycle 23 high activity periods. In addition to considering two locations, these two experiments were conducted in a discrete way by using data from one week of each season (winter - July/2000, spring - October/2000, summer - January/2001, and autumn - April/2001). On the other hand, Setti Júnior et al. (2019) showed that the Klobuchar model improved three-dimensional positioning by 16% to 50% when the analyses were done with data from six years (2013-2018) from the POAL and PRU2 stations, located in Porto Alegre/RS and Presidente Prudente/SP, respectively. Apart from the experiment conducted by Aguiar et al. (2003), which assessed the error in pseudo-ranges, the other authors employed the same positioning method to determine the three-dimensional coordinates for this research. However, the number of satellites used in each experiment varies, which means that the comparisons are not made under identical conditions. Nevertheless, this variation does not significantly impact the results, as the ionosphere remains the primary source of error in this type of positioning.

Thus, the results shown in this paper are within the range obtained by the latter authors.

Concerning the IGS GIM, this paper showed an improvement of approximately 53% on the three-dimensional component. Matsuoka and Camargo (2007) presented an improvement of 26% and 72% in the accuracy of the planimetric and altimetric components, respectively, using data from the UEPP station on four days of all the months of 2001 while Armendaris et al. (2009) found improvements of 44% in the planimetric component and 77% in the altimetric component using data from the POAL station.

According to the results presented in this paper, the IGS GIM's performance in three-dimensional positioning is approximately 31% better than that of the Klobuchar model. Su et al. (2019) evaluated the performance of the Klobuchar model and the CODE's GIM in multi-constellation single-point positioning (SPP) using data observed at ten stations distributed between the geodetic latitudes 65°N and 40°S during September 2018 (solar cycle 24 low activity). They found that GIM improvements on the three-dimensional component with L1 frequency data overcome the Klobuchar model by about 22%.

The percentages improvement presented in this paper are lower than those obtained during periods of more intense solar cycle activity and higher otherwise. Therefore, it is possible to conclude that the level of improvement is proportional to the solar cycle intensity. This is because the assessment method is based on relative error. Even though the models' absolute errors are larger during periods of high solar activity, the greater ionization level causes the relative error to be proportionally smaller than in periods of lower solar activity.

The occurrence of negative improvements at the stations closer to the EIA crest (CUIB, BATF, SJSP, and SMAR) (Figure 4) stands out, especially near the equinoxes. This prompted a thorough investigation, where the values of the three-dimensional discrepancies were compared with the relative performance values. It was found that this situation occurred sporadically in post-sunset time, which is possibly related to irregularities in the ionosphere, such as Equatorial Spread F (ESF) or scintillation (Aswathy and Manju 2021). Figure 8 shows a typical case of this analysis, showing the discrepancies between the coordinates obtained in the processing and the coordinates computed by IBGE (a) and the percentage improvement (b) for the BATF station on two consecutive days, November 11 and 12. These days were chosen because there was no negative improvement on the 11th, unlike on the 12th. During the period between 1 a.m. and 2 a.m. and around midnight on 12 UT (Universal Time), the values of the three-dimensional discrepancies without using correction for the ionosphere were drastically reduced, reaching values very close to zero and lower than that using the Klobuchar and GIM models. At the same time, the percentage improvement is negative. Once such events are not influenced by the different methods of computing positions, it can be concluded that the ionosphere's behavior is not uniform during those periods, characterizing the occurrence of irregularities.

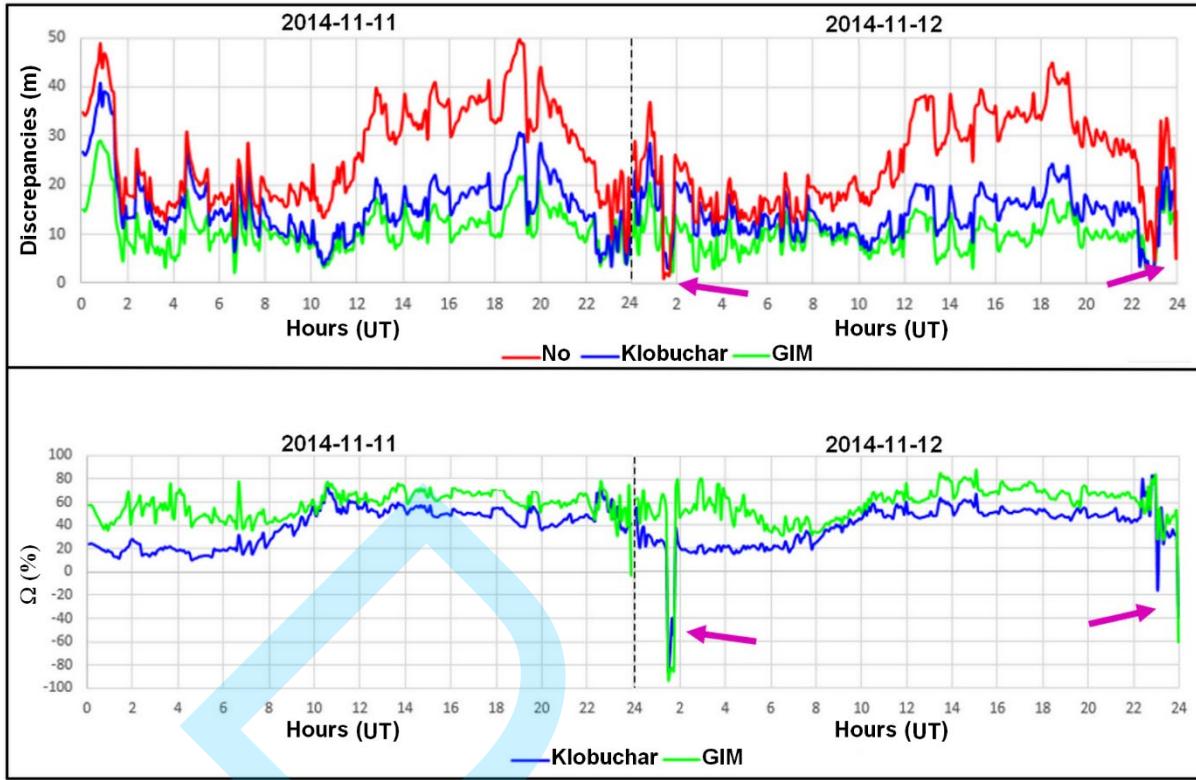


Figure 8: Three-dimensional coordinates discrepancies (a) and relative performance (b) on november 11th and 12th, 2014. The magenta arrows point to the time intervals of irregularities in both variables.

The ISMR Query Tool (Vani et al., 2017) was used to obtain the S4 index time series on November 11th and 12th at the station UFBA (Dip Lat = -17.445731°), which is near 530 km away from the station BATF (Figure 9). The S4 index values were consistently below 0.8 during both days, except for the nighttime between the two days and the end of November 12th, when the S4 index increased to more than 1. Despite the distance between the two stations, the negative improvements in Figure 8 can be associated with these periods of high S4 values, indicating a clear relationship to ionospheric irregularities.

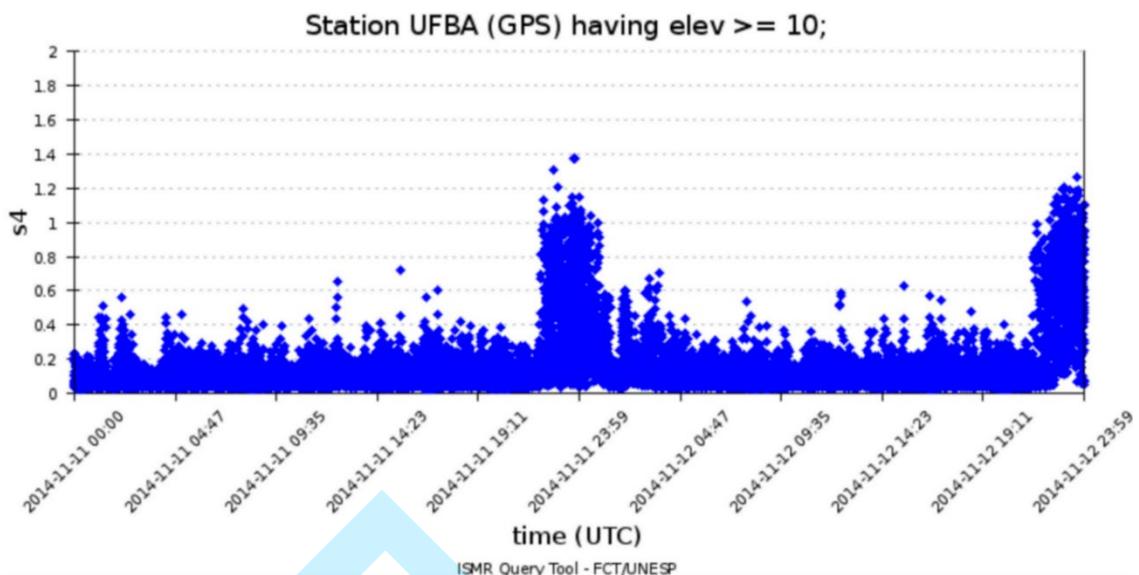


Figure 9: S4 time series at station UFBA on November 11th and 12th, 2014. (Figure created in the ISMR Query Tool - FCT/Unesp).

It is important to note that the present study in Brazil departed from the norm of considering discrete periods and single-site locations. Instead, continuous data for a whole year was analyzed, a unique approach that allowed the identification of irregularities in the ionosphere. These irregularities, as found here, significantly impact the performance of the models evaluated (Figures 4 and 8). The GIM's percentage improvement in relation to the Klobuchar model, as presented by Su et al. (2019), shows that the GIM produced less improvement than that obtained in our study. This difference may be attributed to Su et al. (2019) conducting their experiment during a period of low solar activity and considering data from different ionosphere regions, including the low and medium latitude regions.

CONCLUSIONS

An evaluation of the Klobuchar model and IGS final GIM performances on GPS single-point positioning during the year 2014 of solar cycle 24 peak was presented. Data from six stations located in different regions of Brazil were also taken into account to provide a better characterization of the performance of both ionosphere correction models over the country.

GIM's performance is around 31% better than the Klobuchar model. The average improvement values obtained are approximately 39% and 52% for the Klobuchar model and GIM, respectively.

Compared to previous research, this paper reveals that the relative performances of both ionosphere models are lower in some cases and higher otherwise. The results suggest three main reasons: the variation in the intensity of the solar cycle, where the more intense, the better the performance, the location of the GNSS station relative to the geomagnetic equator, and the occurrence of negative improvements caused by post-sunset ionospheric irregularities.

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