Enhancing GNSS Positioning resilience against strong ionospheric scintillation

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Abstract

The Global Navigation Satellite System (GNSS) has become an integral component in various applications, offering differing levels of accuracy that span from several dozen meters to mere millimeters. While achieving high precision in positioning is essential, an equally important aspect that must be taken into consideration is the reliability of these results, particularly for applications that demand real-time data processing. Various environments can negatively impact the quality of positioning signals, highlighting the necessity for users to be cognizant of these challenging conditions. In particular, low-latitude regions experience significant interference due to the ionosphere, which plays a pivotal role in determining the effectiveness of GNSS signals. This interference is predominantly attributed to the occurrence of plasma bubbles, which induce scintillation, leading to a noticeable degradation in the quality of GNSS signals. Such conditions can hinder the capability to track certain satellites, potentially resulting in multiple cycle slips that compromise positional accuracy. Therefore, it is crucial to develop and implement strategies that ensure robust GNSS positioning in these affected environments. This paper aims to present a comprehensive analysis of several GNSS Real-Time Kinematic (RTK) evaluations conducted in Brazil, where the impact of scintillation will be systematically assessed alongside positioning results. The study relies on data gathered in both static and kinematic modes to draw conclusions. Furthermore, it will discuss various strategies aimed at mitigating these issues, focusing on enhancing the reliability of GNSS results, which typically involve modifications to the underlying stochastic model used in positioning calculations.

1. Introduction

1.1 GNSS and Earth Plasma Bubble

As electromagnetic waves propagate through the ionosphere, they encounter significant variations in both direction and velocity, primarily due to processes such as signal refraction and diffraction. These variations are intricately linked to the density of free electrons present along the signal's travel path, a measurement that is quantified by the Total Electron Content (TEC). Notably, these variations are directly proportional to TEC and inversely proportional to the frequency of the signal being transmitted (Monico, 2008).

The ionosphere is characterized by irregularities that can lead to abrupt fluctuations in TEC, often caused by the formation of Earth Plasma Bubbles (EPBs). Such irregularities induce ionospheric scintillation, a phenomenon that not only compromises the accuracy of GNSS (Global Navigation Satellite System) positioning but also impacts a variety of other critical services that depend on reliable electromagnetic wave propagation. The scintillation effect results in fluctuations across several parameters of the received signal, including amplitude, phase, angle, and polarization, substantially degrading the overall quality of positioning outcomes (Klobuchar, 1996; Conker, 2003; Souza, 2015).

For instance, Figure 1 illustrates an occurrence of an EPB over Brazilian territory, captured on November 28, 2014, at precisely 00:25:00. This figure vividly portrays the pronounced variations in TEC values, indicative of the EPB's presence and activity in the region EPB.

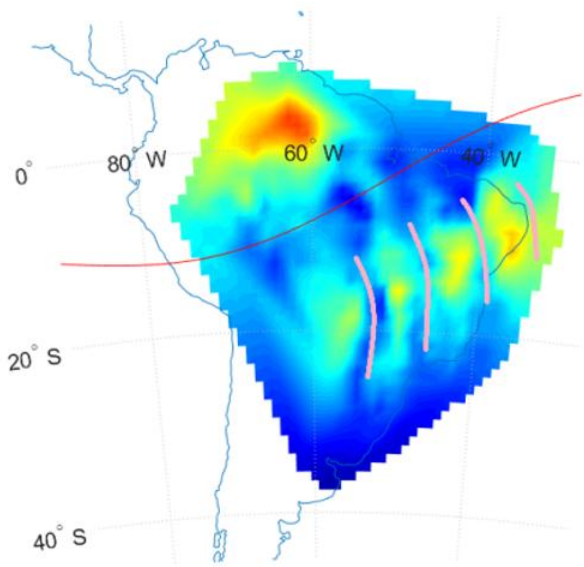

Figure 1. TEC maps showing EPBs occurrences

This significant phenomenon occurs with greater frequency and intensity in equatorial regions situated at low geomagnetic latitudes, such as Brazil. The country experiences higher electron densities in the ionosphere along with stronger spatiotemporal variations in TEC (Davies, 1990). Such unique characteristics render Brazilian territory particularly susceptible to various forms of ionospheric interference, making it an excellent location for conducting experimental research on these effects. For readers who are interested in obtaining a thorough understanding of EPBs and their occurrences specifically in low-latitude regions like Brazil, a comprehensive discussion can be found in the work of De Paula et al. (2000).

Given the growing demand for high-precision and reliable GNSS applications across numerous sectors, it has become increasingly essential to undertake studies focused on mitigating the adverse effects of ionospheric scintillation on GNSS signals. This is particularly critical in regions such as Brazil, where the impact of these atmospheric phenomena can be quite severe and detrimental to signal integrity.

1.2 Objectives and paper organization

This study aims to conduct a thorough analysis of the effects of ionospheric scintillation on both post-processed kinematic relative positioning and Real-Time Kinematic (RTK) positioning systems. Additionally, it seeks to develop an innovative stochastic modelling approach designed to effectively mitigate these negative effects. Ultimately, this research aims to achieve enhanced accuracy in GNSS positioning, ensuring that users can rely on these systems in the face of challenging atmospheric conditions.

The organization of this paper is structured to facilitate a comprehensive understanding of the research conducted. It begins with a thorough introduction to the study area and the dataset utilized, providing essential contextual information that sets the stage for the analysis that follows. After establishing the background, the paper delves into the methodology applied throughout the research process, detailing the specific approaches and techniques employed to gather and analyse the data. In the sequence, the paper presents a selection of preliminary results, which are crucial for understanding the initial findings of the study. Additionally, this concluding section will also lay out prospects for future work, identifying areas that warrant further exploration and potential advancements in the field.

2. Study area and data set

The study area selected for this research is situated in the southeast region of Brazil, which incorporates multiple stations from the INCT (Instituto Nacional de Ciência e Tecnologia) GNSS NavAer network, as highlighted in the work by Monico et al. (2022). These stations are strategically positioned to capture valuable GNSS data that is critical for our analysis. Figure 2 shows the exact locations of these stations. In addition to the INCT stations, the study also includes the PPTE station, which is part of the Brazilian Continuous GNSS network - RBMC, as maintained by the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2024). The inclusion of the PPTE station is essential as it provides complementary data that enhances the robustness of the overall dataset utilized in this research. The GNSS stations used in the study are visually represented in Figure 3, allowing for a comprehensive understanding of the spatial distribution of the data collection points across the study area. This geographical context is vital for analyzing the potential effects of ionospheric conditions on GNSS signal quality and positioning accuracy in this specific region.

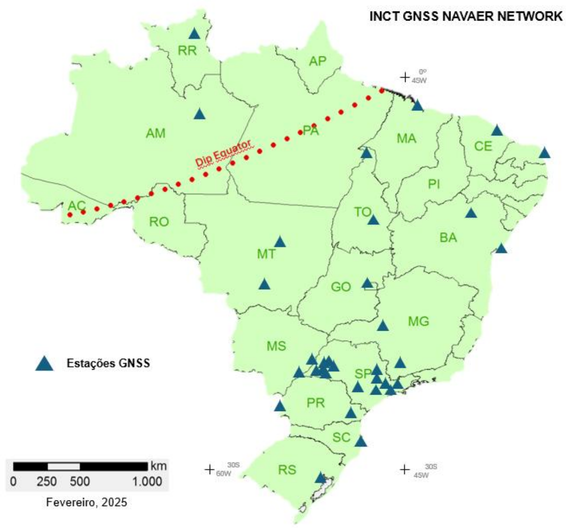

Figure 2. INCT GNSS NavAer Network (February 2025).

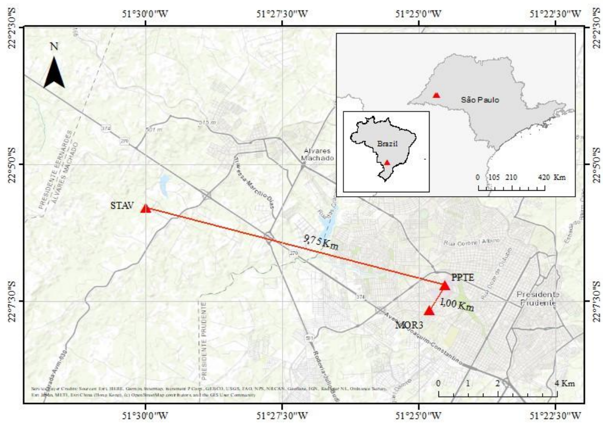

Figure 3. Location of the study area inside Brazil.

Despite the availability of a substantial volume of data and the successful processing of this information, this paper will focus on presenting one of the most representative results from the study. For this analysis, RINEX data files from the STAV station, located in Alvares Machado, São Paulo, were utilized as the rover station. In addition, data from the PPTE station, situated in Presidente Prudente, São Paulo, played the role of the base station. This configuration created a baseline of approximately 9.75 kilometres, strategically positioned within the network of the INCT NavAer ionospheric scintillation monitoring stations, as depicted in Figure 2.

To ensure a comprehensive evaluation, tests were conducted both in post-processing mode and in real-time scenarios. The n.primary parameter considered during these analyses was the amplitude scintillation index, denoted as S4. This index is the principal statistic used for quantifying the severity of amplitude scintillations, providing critical insights into the fluctuations and quality of the GNSS signals experienced at the respective stations. By focusing on this specific index, the study aims to highlight the impact of ionospheric conditions on signal integrity and the reliability of GNSS positioning in the region.

According to the classification established by Muella et al. (2009), the S4 index is categorized into several distinct levels that indicate the severity of scintillation. These classifications are as follows: a weak level, defined by the range ($0.2 < S4 \leq 0.4$); a moderate level, indicated by the range ($0.4 < S4 \leq 0.6$); a strong level, represented by the range ($0.6 < S4 \leq 1.0$); and a saturated level, which encompasses the range ($1.0 < S4 \leq 1.4$). It is noteworthy that saturated levels can generally be attributed to the effects of multiple scattering, which significantly affects the reliability of GNSS signals.

For the post-processing tests conducted in this research, the analyzed period encompassed a specific timeframe from 21:00 UTC on November 13, 2023, to 09:00 UTC on November 14, 2023. This interval was selected due to its occurrence of intense ionospheric activity, which is crucial for assessing the performance and reliability of GNSS signals under varying scintillation conditions. Figure 4 illustrates the S4 index values derived from the ISMR Query Tool, as researched by Vani, Shimabukuro, and Monico (2017), specifically at the STAV station. This figure effectively represents the varying levels of scintillation that were recorded during this time. Remarkably, it can be noted that the S4 index peaked at an impressive value of 1.9 for a specific satellite on the selected day. Such a high S4 index signifies severe scintillation effects, which can greatly compromise GNSS positioning accuracy and reliability. This observation highlights the importance of understanding ionospheric phenomena, as they play a pivotal role in influencing the quality of navigation solutions derived from GNSS technology.

In addition to the post-processing analyses, real-time tests were conducted to further assess the impact of ionospheric scintillation on GNSS signals, as previously mentioned. For this phase of the study, data from November 23, 2024, were utilized, during which the level of scintillation for a specific satellite was observed to reach an S4 value on the order of 1.5, indicating again significant scintillation activity. This level of scintillation can have substantial implications for the integrity and accuracy of GNSS positioning solutions. Figure 5 provides a visual representation of the scintillation levels recorded.

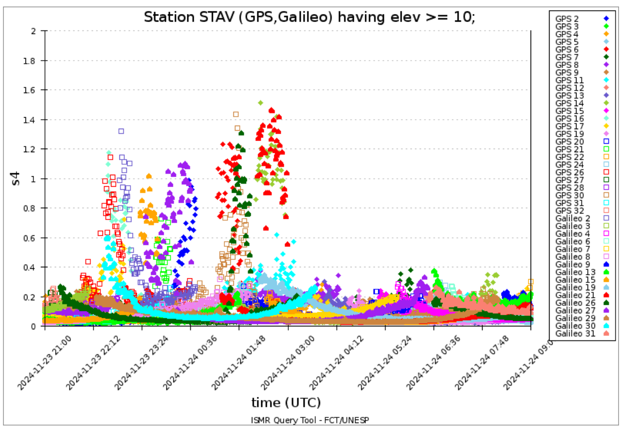

Figure 4. S4 index from the STAV station on November 2023 from 13th 21:00 to 14th 09:00

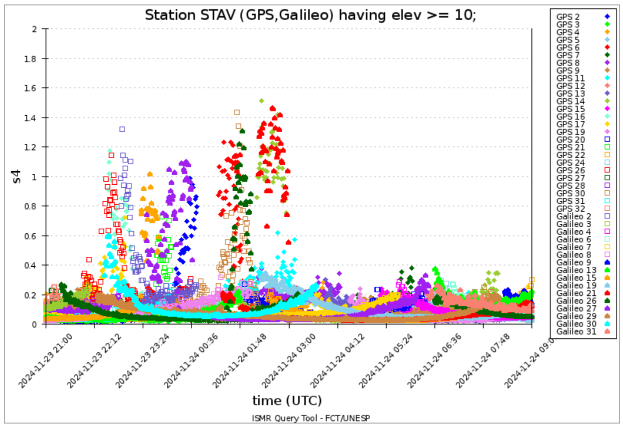

Figure 5. S4 index from the STAV station on November 2024 from 23th 21:00 to 24th 09:00

3. Methodology

In this paper, two distinct methodological approaches were adopted to analyse the effects of ionospheric scintillation on GNSS positioning: one utilizing the standard RTKLib interface (Takasu, 2009) without any modifications to the source code, and the other involving code modifications that allow for changes to the stochastic model—specifically, the weighting parameters informed by the dispersion of the double difference (DD) observation residuals.

In the first approach, two trials were conducted to establish a baseline for comparison. The initial trial employed the standard RTKLib interface, specifically the demo5 b34h version, utilizing the default configuration parameters for the stochastic model. In this context, the data processing was executed with a configuration, as illustrated in Figure 6. The precision of the carrier phase observations was set to 4 mm, while the code observations were deemed significantly less reliable, with a precision considered to be 100 times worse, translating to a value of 40 cm. Other values were also tested, but will not be discussed here.

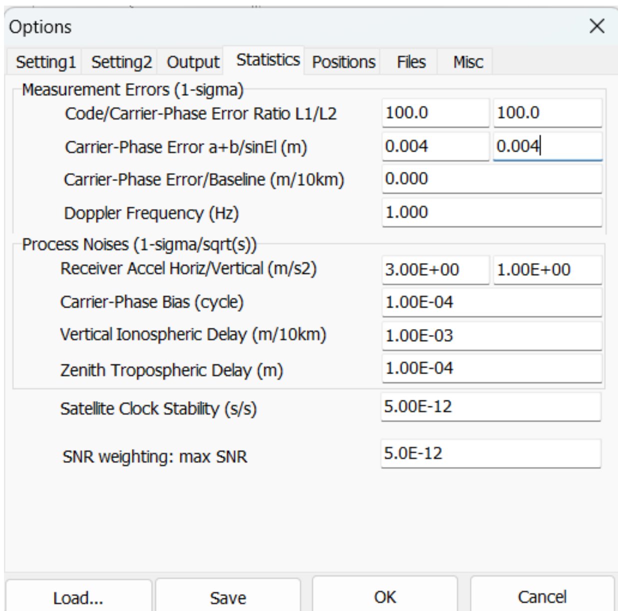

Figure 6. RTKLib statistic interface with default configuration

In the second trial of the first approach, modifications were made to the stochastic model by leveraging statistical insights gained from analysing the DD of the residuals. This adjustment aimed to enhance the accuracy and reliability of the positioning results by better accounting for the observed variability in the data. Such parameters were recomputed at the end of the first data processing, and based on the DD residuals new parameters were applied and the data were reprocessed with these new set of parameters.

The data processing was conducted in kinematic relative mode, considering only L1 observations from GPS and Galileo constellations, 1 second sample rate interval, a 10° elevation mask and the broadcasted ephemerides. No models for troposphere and ionosphere were considered, due to the short values of the baseline length (9.75km). In the first step, as stated before, the precision (a) of the carrier phase was considered 4 mm, while the pseudorange precision was considered 100 times worse (Rr). This is called solution "Without modification". The stochastic model was adjusted using the "Statistics" tab in RTKLib, where the Code/Carrier-Phase Error Ratio (*Rr*) and Carrier-Phase Error: a + b/sin(El) parameters were manually recomputed based on the ratio between the Root Mean Square (RMS) of the DD residuals of pseudorange and carrier phase measurements. A new set of precision parameters was specified to the carrier phase, also based in the DD residuals of the first step. This is called solution with stochastic model modification (With manual modification).

In the second methodological approach, an adjusted stochastic model was implemented directly within the RTKLib code, enabling the automatic adjustment of the pseudorange precision parameter ((Rr)) and the carrier phase error parameter (a). This dynamic adjustment is based on the RMS residuals of GNSS observations throughout the data processing cycle.

To establish a reliable starting point, the model began with fixed configured values of (Rr = 100.0) and (a = 0.004) for the first 2000 epochs of data. This initial phase was designed to ensure a stable dataset prior to the onset of scintillation events, providing a solid foundation for the estimation filter—such as the Kalman filter or an alternative method—that follows. By maintaining these fixed values for the initial epochs, the model could effectively account for baseline noise and variability, thereby enhancing the reliability of observable statistics.

Starting from epoch 2001 and onward, the parameters (Rr) and (a) were then recalculated automatically at each new epoch (t). This recalibration utilized the accumulated residuals from the preceding epoch (t−1) to refine the accuracy of the stochastic model. The implementation of this automatic adjustment process is governed by specific equations, referred to as equations 1 and 2, which guide how the adjustments are computed based on the accumulated data. This approach is expected to yield more precise and reliable estimates of observable statistics, significantly improving the robustness of the GNSS positioning solutions in the face of varying ionospheric conditions

$$Rr = \frac{RMSpseudo^{(t-1)}}{RMScarrier^{(t-1)}/2}, \quad (1)$$

$$a = \frac{RMScarrier^{(t-1)}}{2}, \quad (2)$$

In the equation (1), (RMSpseudo) and (RMScarrier) represent the RMS residuals of the DD observations for pseudorange and carrier phase measurements, respectively, derived from the data processing phase. This framework allows for continuous recalibration of the stochastic model, ensuring it can adaptively respond to varying observation conditions. This adaptability is crucial, as it better reflects the inherent uncertainties present within GNSS measurements over time, thereby enhancing the model's overall reliability.

This approach is referred to as the solution with automatic modification of the stochastic model, or "With automatic modification." By implementing this automatic strategy, the model is not only more responsive to changing conditions but also more representative of real-time fluctuations in measurement accuracy, especially in environments subjected to significant ionospheric variability. Other range of epochs can be explored as results of this research.

The comparative analysis among the different methodological approaches facilitates a comprehensive assessment of the impacts associated with both ordinary and automatic to the stochastic model. By evaluating these two strategies, the study aims to discern how each approach influences the stability and accuracy of GNSS positioning solutions, particularly under conditions characterized by high levels of ionospheric variability, as observed in the context of this study. Understanding these impacts is vital for advancing the reliability of GNSS technology in fluctuating atmospheric environments.

3. Preliminary Results

To analyse the impact of stochastic model modifications on post-processed kinematic relative positioning, a series of comparative results were generated, focusing on key metrics such as precision, discrepancies, and 3D positional error. The analysis considered three distinct sets of results: the original outputs obtained without any modifications, the results achieved with manual modifications to the stochastic model, and the outputs resulting from the automatic modification approach.

For the assessment of discrepancies and 3D errors, the post-processed and real-time coordinates were compared against reference coordinates that were estimated using static relative positioning techniques during periods of low ionospheric activity. This particular condition is deemed to represent the ground truth, as it reflects a more stable environment less influenced by atmospheric disturbances. The comparison of these various approaches provides insights into how adjustments to the stochastic model can affect the accuracy and reliability of GNSS positioning solutions, particularly in environments characterized by variable ionospheric conditions

The results presented in Table 1, derived from the post-processed approach during the period of November 13, 2023, 21:00 UTC to November 14, 2023, 09:00 UTC, demonstrate that modifying the stochastic model led to a significant improvement in positioning accuracy. Key performance indicators, including mean positional accuracy, standard deviation, and 3D error metrics, were notably lower following the modification.

Specifically, the overall accuracy improved dramatically from 3.420 meters in the scenario without modification to just 0.799 meters with the implementation of the stochastic model modification, resulting in an impressive 76.6% reduction in positional error. Furthermore, the maximum 3D error also saw a substantial decrease, falling from 25.369 meters to 7.736 meters, which equates to a 69.5% reduction. These findings underscore the effectiveness of adjusting the stochastic model in enhancing the accuracy and reliability of GNSS positioning solutions, particularly under conditions influenced by ionospheric variability. But even applying such approach, the final results, although better, still require improvement.

Also in the post processing, with automatic modification, accuracy remained at the level of 0.793 m, showing a similar improvement. However, the maximum 3D error was further reduced to 3.69 m, demonstrating the benefits of modifying the stochastic model during events of ionospheric scintillation.

Approach	Mean (m)	Standard Deviation (m)	Accuracy (m)	Maximum error (m)
Without modification	1.341	3.146	3.420	25.369
With manual modification	0.452	0.659	0.799	7.736
With automatic modification	0.578	0.543	0.793	3.69

Table 1. Quality indication for solutions without, with and automatic stochastic model modification for post-processed kinematic relative positioning.

To facilitate a clearer understanding of the results, Figures 7, 8, and 9 illustrate the discrepancies observed in the three coordinate components (dE, dN, and dU) across each of the scenarios analysed. These figures visually represent the variations in positional accuracy and help to highlight the effectiveness of the different stochastic model approaches in mitigating errors.

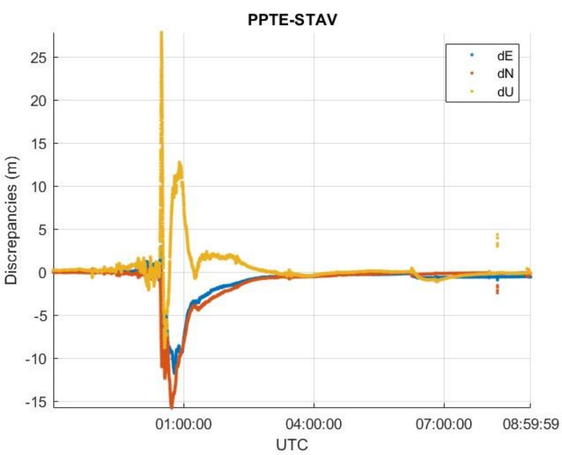

Figure 7. Discrepancies for solution "Without modification" for post-processed kinematic relative positioning.

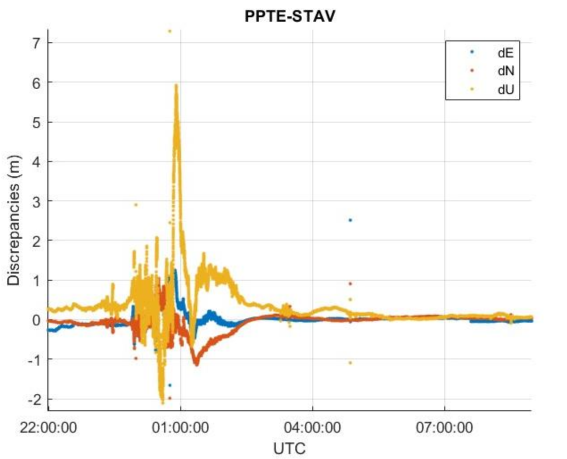

Figure 8. Discrepancies for solution "With manual modification" for post-processed kinematic relative positioning.

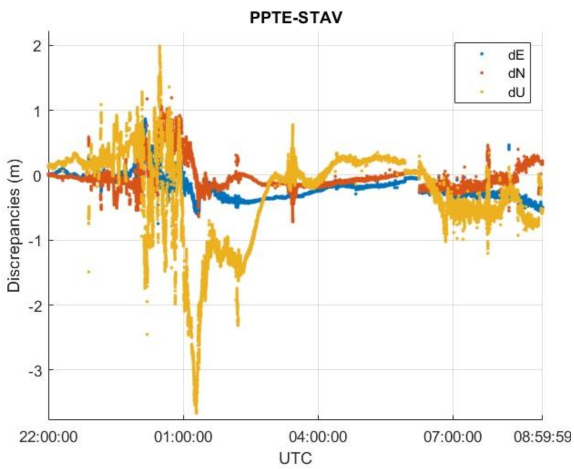

Figure 9. Discrepancies for solution "With automatic modification" for post-processed kinematic relative positioning.

Next, the approach was also tested for real-time applications using a different dataset. This analysis was conducted on November 22, 2024, where the level of scintillation reached an S4 value on the order of 1.5. The results were again analyzed in a manner consistent with the previous experiment; however, this time, they were compared solely against the outcomes obtained from the solution without modification.

The quality indicators for this analysis are presented in Table 2. Upon examination, we observe a substantial improvement in both the mean error and overall precision of the positioning results. This enhancement contributes to an impressive accuracy improvement of approximately 80%.

Approach	Mean (m)	Standard Deviation (m)	Accuracy (m)	Maximum error (m)
Without modification	0.802	0.873	1.185	3.074
With automatic modification	0.179	0.167	0.245	1.926

Table 2. Quality indication for solutions without modification and with automatic stochastic model modification for real time RTK positioning.

To further illustrate these results, Figures 10 and 11 depict the discrepancies observed individually in the three coordinate components for the scenarios "Without modification" and "With automatic modification," respectively. Again, these figures provide a visual representation of how each approach influences the positional accuracy, allowing for a more nuanced understanding of the impact that automatic modifications to the stochastic model have on the overall performance of GNSS positioning solutions.

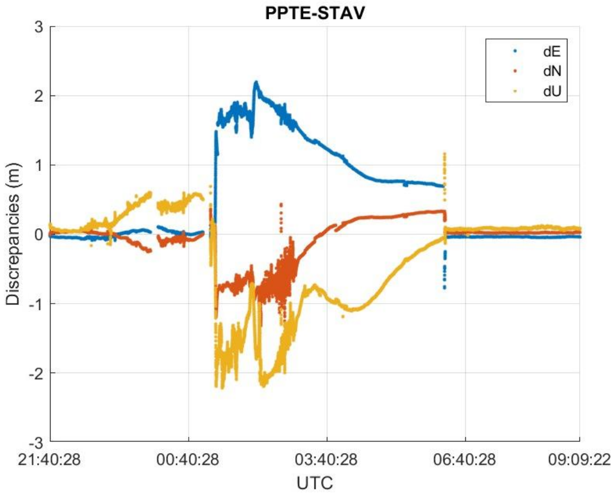

Figure 10. Discrepancies for solution without modification for real time RTK positioning.

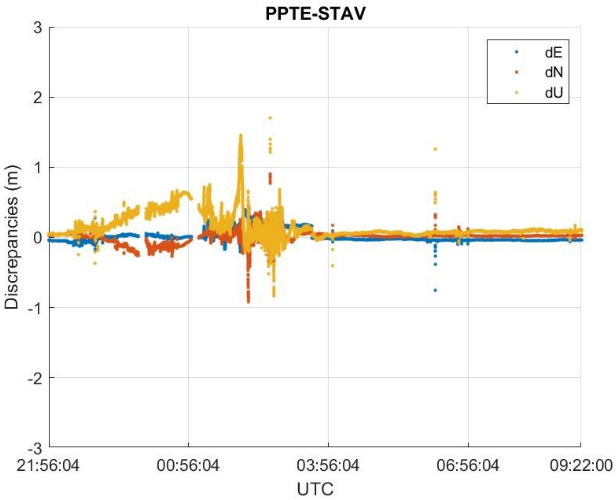

Figure 11. Discrepancies for solution with automatic stochastic model modification for real time RTK positioning.

It is evident that a significant level of improvement was achieved once the stochastic model was modified. However, the quality of the final results still falls short of the expectations typically associated with relative positioning in kinematic mode. Most applications demand an accuracy level within just a few centimetres to be effective. Therefore, there remains a critical area of research focused on further reducing the impact of ionospheric scintillation on post-processed real-time applications.

4. Conclusions and Prospects

In this paper, we presented preliminary results aimed at mitigating the effects of ionospheric scintillation in kinematic relative positioning and RTK. The findings demonstrate that modifying the stochastic model significantly enhances the accuracy of post-processed kinematic relative positioning. Notably, the automatic modification approach further reduced the 3D error from 3.420 meters (without modification) to 0.793 meters (with automatic modification), resulting in an impressive 76.8% improvement in accuracy. Additionally, the maximum 3D error decreased markedly from 25.369 meters to 3.69 meters, underscoring the advantages of adaptive weighting in mitigating the effects of ionospheric scintillation.

In the context of real-time RTK applications, the automatic model also proved effective, reducing the 3D error from 1.185 meters to 0.245 meters, reflecting an approximate 80% improvement. These findings highlight the effectiveness of the stochastic model modification technique for GNSS positioning, particularly under challenging ionospheric conditions.

Despite the improvements achieved through the methodologies presented, there remains room for further enhancement to reach the expected level of accuracy in RTK applications, specifically targeting an accuracy within just a few centimeters.

Looking ahead, future work will extend the analysis to encompass different ionospheric conditions and varying observation periods and implement new strategies. Additionally, evaluating performance across multi-frequency and multi-GNSS solutions will provide valuable insights into the broader applicability of this approach, paving the way for more robust and reliable GNSS solution.

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