A Method to Mitigate the Effects of Strong Geomagnetic Storm on GNSS Precise Point Positioning

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Abstract Geomagnetic storm can affect the performance of Global Navigation Satellite System (GNSS) precise positioning services. To mitigate the adverse effects of strong geomagnetic storms, we propose to establish the geometry-free (GF) cycle slip threshold model based on ionospheric disturbance index rate of total electron content index (ROTI) during strong storm periods, thus improving the accuracy and reliability of GNSS PPP. The performance of our proposed model is validated by using 171 International GNSS Service (IGS) tracking stations data on 8 September 2017. The analysis indicates that compared with conventional PPP scheme, the proposed model can improve the positioning accuracy by approximately 14.0% (36.8%) and 23.1% (51.5%) in the horizontal and vertical components for global (high latitudes) stations. Furthermore, the availability of our proposed model is also validated by PPP experiments using 379 IGS tracking stations data during another strong storm occurred on 26 August 2018.

Plain Language Summary Global Navigation Satellite System (GNSS) precise point positioning (PPP) can achieve decimeter or even millimeter levels of positioning accuracy in general. However, this accuracy will be degraded significantly under the strong geomagnetic storm, which is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. Strong geomagnetic storm associated with ionospheric disturbances can decrease the quality of GNSS measurements or even result in GNSS signals loss of lock known as cycle slip, thus affecting the availability and reliability of the common data processing methods of GNSS PPP. In this study, we investigate the limitations of common threshold in cycle slip detection of GNSS data processing. It is found that the cycle slip detection observation shows close relationship to ionospheric disturbance index ROTI (rate of total electron content index), so we propose to establish the cycle slip threshold model based on ionospheric disturbance index ROTI. GNSS PPP experiments based on abundant International GNSS Service stations data indicate that the proposed model can effectively improve the positioning accuracy especially those stations located at high latitudes.

1. Introduction

When solar events such as solar flare, coronal mass ejection, and coronal hole high-speed flow occur, the high-speed plasma clouds ejected from the sun surface will propagate into Earth's space through the interplanetary space, press the magnetosphere and inject abundant solar wind energy into Earth's magnetosphere, resulting in geomagnetic field disturbance. This phenomenon is referred to as geomagnetic storm (Gonzalez et al., 1994). According to the minimum value of Dst index, the geomagnetic storm is generally classified as four different intensity levels as weak geomagnetic storm (−50 < Dst ≤ −30 nT), moderate storm (−100 < Dst ≤ −50 nT), strong storm (−200 < Dst ≤ −100 nT), severe storm (−350 < Dst ≤ −200 nT) and great storm (Dst ≤ −350 nT; Loewe & Prölls, 1997).

Under geomagnetic storm, the rapid penetration of magnetospheric electric field can lead to the sharp increase of ionospheric total electron content (TEC) as well as the irregular variations of ionospheric TEC, thus affecting the performance of precise positioning of Global Navigation Satellite System (GNSS; Astafyeva et al., 2014;
Berdermann et al., 2018; Zakharenkova & Cherniak, 2021). In the early stage, Odijk (2001) investigated the effects of geomagnetic storms on global positioning system (GPS) relative positioning. It is reported that the relative ionospheric delays cannot be neglected during strong storm periods even for rather short baselines (4 km). Statistical results in Odijk (2001) indicated that, without (with) ionospheric correction, the ambiguity success rates of instantaneous GPS precise positioning are 66% (95%) and 36% (77%) under minor and intense storms, respectively. The study shown in Rama Rao et al. (2009) demonstrated that during storm periods, the number of cycle slips increased significantly compared with those during quiet days. Astafyeva et al. (2014) further reported that most GNSS cycle slips occurred in geomagnetic storms should be associated with ionospheric irregularities. It is known that cycle slips caused by the rapid changes of TEC during storm periods can result in loss of locks of GNSS receivers, thus reducing the ambiguity success rates as well as the positioning performance of GNSS real-time kinematic (RTK) positioning (Odolinski & Teunissen, 2019).

Except GNSS RTK technique, many studies also investigated the geomagnetic storm effects on precise point positioning (PPP). Focusing on different levels of geomagnetic storm, Luo et al. (2018) investigated global GPS PPP performance in detail. Statistical results indicated that the number of International GNSS Service (IGS) stations with large root mean square (RMS) values (>0.5 m) accounts for 1.7%, 7.0%, and 14.6% during the moderate, intense, and super storm periods. After that, Lu et al. (2020) reported the multi-GNSS PPP results during the St. Patrick's Day geomagnetic storm in 2015. Results suggested that, due to the storm effects, both GNSS signal-tonoise ratio and multipath observations are changed significantly, and the results of GNSS PPP are systematically deviated. The 3D positioning error of GPS and GPS/GLONASS/BDS PPP can reach 1.3 and 0.6 m, respectively. Focusing on the storm on 25–26 August 2018, Yasyukevich et al. (2020) reported that the time range of positioning degradation of PPP is longer than that during the St. Patrick's Day storm. It is also found that except high latitudes, the ionospheric irregularities of middle latitudes expanded from the auroral oval can also result in PPP degradation. Recently, Zakharenkova and Cherniak (2021) assessed the performance of ground- and space-based GPS PPP during the strong storm on 7–8 September 2017. Under the strong storm, the 3D error of GPS PPP for ground-based stations rose to several meters, while that on normal condition is only centimeter or decimeter level. In addition, the storm-induced irregularities can result in 5 times errors in kinematic orbit for Swarm satellites.

Although many studies have reported the adverse effects of geomagnetic storm on GNSS, few papers sought ways to mitigate these effects on GNSS precise positioning (Lu et al., 2020; Rodríguez-Bilbao et al., 2015). Since the number of cycle slip increases in storm conditions, correctly detecting or even repairing cycle slips should be the effective solution to improve GNSS PPP or RTK performance during storm periods. However, under complex ionospheric environment caused by geomagnetic storm, it is difficult to detect cycle slips correctly. It is known that the classic method as TurboEdit method, combined with the geometry-free (GF) and Melbourne-Wübbena (MW) wide-lane combinations, is usually applied in cycle slips detection (Blewitt, 1990). The GF combination is sensitive to cycle slips under normal ionospheric conditions, but it will be degraded during active ionospheric environments (Luo et al., 2020). That is why some researchers chose to set an empirical loose threshold for GF method (Zhang et al., 2014) or directly deactivated the GF method (Rodríguez-Bilbao et al., 2015) to improve GNSS PPP performance in geomagnetic storm. In this study, we propose to establish the GF cycle slip detection threshold model through considering ionospheric disturbance index ROTI (rate of total electron content index) to reduce the false detection rate of cycle slip, thus improving GNSS PPP accuracy under strong geomagnetic storm conditions.

## 2. Data and Methodology

This section first introduces the strong geomagnetic storm event occurred on 8 September 2017. Then, the geographical distribution of 417 IGS stations is presented. The ionospheric-free PPP model and cycle slip detection method of TurboEdit are introduced following. Finally, we give the cycle slip threshold model in detail.

### 2.1. Strong Geomagnetic Storm on 8 September 2017

Since two solar flares X2.2 and X9.3 erupted over the active region 2673 on 6 September 2017, a strong geomagnetic storm with double main phases was generated on 8 September 2017 (Yamauchi et al., 2018). Based on the observations derived from GNSS receivers, radars, and ionosondes, numerous studies have investigated
the complex responds of ionosphere at different latitudes to this strong storm (Aa et al., 2018; Fejer et al., 2021; Habarulema et al., 2020; Li et al., 2018; Xiong et al., 2019). Figure 1 shows time series of the interplanetary magnetic field $z$-component $B_z$, the solar wind speed $V_{sw}$, the 3-hr $K_p$ index, and the geomagnetic index $Dst$ during 6–8 September 2017.

Figure 1. Time series of the interplanetary magnetic field $z$-component $B_z$, the solar wind speed $V_{sw}$, the 3-hr $K_p$ index, and the geomagnetic index $Dst$ during 6–8 September 2017.

2.2. Experiment Data

The experiment is conducted by using GPS dual-frequency data collected at 417 IGS tracking stations on 8 September 2017. Figure 2 presents the geographical distribution of 417 IGS stations. We randomly select 246 stations (black dots) data for cycle slip threshold modeling, while the remaining 171 stations (red dots) data are used for PPP verification.

Figure 2. Geographical distribution of 417 International Global Navigation Satellite System Service stations in the world. Black dots represent the stations used for modeling, while red dots represent the stations used for precise point positioning verification.

2.3. Ionospheric-Free PPP Model

Using precise satellite orbit and clock products from IGS as well as pseudorange and carrier phase measurements from single GNSS receiver, PPP technique can achieve decimeter or even millimeter levels of positioning accuracy.
The GNSS pseudorange and carrier phase measurements are expressed as below (Kouba & Héroux, 2001):

\[
\begin{aligned}
P_{r,f} &= \rho_r^f + c(d_{r,f} - d_{t,f}) + d_{up} + d_{ion,f} + b_{r,f}(P) - b_f'(P) + \varepsilon_f \\
\lambda_f \Phi_{r,f} &= \rho_r^f + c(d_{r,f} - d_{t,f}) + d_{up} - d_{ion,f} + b_{r,f}(\Phi) - b_f'(\Phi) - \lambda_f(N^i_{r,f} - \varphi) + \varepsilon \Phi
\end{aligned}
\]

(1)

where “r,” “s,” and “f” represent the identification of GNSS receiver, satellite, and observation frequency, respectively; \(P\) and \(\Phi\) represent the pseudorange and carrier phase measurements, respectively; \(\rho_r^f\) is the geometric distance (m); \(d_{r,f}\) and \(d_{t,f}\) are the receiver and satellite clock offset (s); \(d_{up}\) is the tropospheric delay (m); \(d_{ion,f}\) is the ionospheric delay at the frequency \(f\) (m); \(b\) and \(b'\) are the frequency-dependent signal delay for the receiver and satellite (m); \(\lambda_f\) is the wavelength of the satellite signal at the frequency \(f\) (m); \(N\) is the float ambiguity (cycle); \(\varphi\) is the phase windup error (cycle); and \(\varepsilon\) is the measurement noise (m).

In this study, GNSS PPP based on ionospheric-free linear combination model are performed to eliminate the first-order effect of ionospheric refraction. The model can be expressed as:

\[
\begin{aligned}
P_{r,f} &= \rho_r^f + c(d_{r,f} - d_{t,f}) + d_{up} + b_{r,f}(P) - b_f'(P) + \varepsilon_f \\
\lambda_f \Phi_{r,f} &= \rho_r^f + c(d_{r,f} - d_{t,f}) + d_{up} + b_{r,f}(\Phi) - b_f'(\Phi) - \lambda_f(N^i_{r,f} - \varphi) + \varepsilon \Phi
\end{aligned}
\]

(2)

where \(P_f = (f_1^2 \cdot P_1 - f_2^2 \cdot P_2)/(f_1^2 - f_2^2)\); and \(\Phi_f = (f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2)/(f_1^2 - f_2^2)\).

### 2.4. TurboEdit Method

The TurboEdit method is widely used in cycle slip detection and correction for dual-frequency GNSS measurements (Blewitt, 1990). It covers MW wide-lane combination as \(N_{MW}\) and GF combination as \(\Phi_{GF}\) for cycle slip detection:

\[
\begin{aligned}
N_{MW} &= \frac{L_{MW}}{\lambda_{MW}} = \Phi_1 - \Phi_2 - \frac{f_1 \cdot P_1 + f_2 \cdot P_2}{\lambda_{MW}(f_1 + f_2)} \\
L_{GF} &= \lambda_1 \Phi_1 - \lambda_2 \Phi_2 = \lambda_1 N_1 - \lambda_2 N_2 + (\gamma - 1)d_{ion,1}
\end{aligned}
\]

(3)

where \(L_{MW}\) is the MW wide-line combination of carrier phase measurements (m); \(\lambda_{MW} = c/(f_1 - f_2)\); and \(\gamma = f_1^2/f_2^2\).

For MW wide-lane combination, the cycle slip detection observation \(\Delta N_{MW}\) and corresponding standard deviation \(\sigma\) can be expressed as:

\[
\begin{aligned}
\Delta N_{MW}(i) &= N_{MW}(i) - \overline{N}_{MW}(i - 1) \\
\sigma^2(i) &= \sigma^2(i - 1) + \frac{1}{i}[(N_{MW}(i) - \overline{N}_{MW}(i - 1))^2 - \sigma^2(i - 1)]
\end{aligned}
\]

(4)

(5)

where \(i\) is the current epoch in the data arc; \(\overline{N}_{MW}\) is the mean value of \(N_{MW}\), which can be calculated as:

\[
\overline{N}_{MW} = \frac{N_{MW}(i - 1) + \frac{1}{i}[N_{MW}(i) - \overline{N}_{MW}(i - 1)]}{i}
\]

(6)

Generally, the cycle slip is considered to be detected when the following two conditions are satisfied:

\[
\begin{aligned}
|\Delta N_{MW}(i)| &\geq 4\sigma(i - 1) \\
|N_{MW}(i) - N_{MW}(i + 1)| &\leq 1
\end{aligned}
\]

(7)
For GF combination, the residual between $A_{GF}$ and $A_{GF}$, which is the value of the polynomial fit of $A_{GF}$, is used to detect cycle slip. Since the $A_{GF}$ is affected by the polynomial type, fitting order, and truncation error, we use $A_{ΔL_{GF}}$, which is the $A_{GF}$ difference between two adjacent epochs, to detect cycle slips. The feasibility of this operation in cycle slip detection has been demonstrated by several previous studies (Chen et al., 2016; Zhang et al., 2014) as well as GNSS software gLAB (GNSS-Lab Tool; Ibáñez et al., 2018). The threshold of GF as $A_{Th_{GF}}$ is closely related to the ionospheric environment, data sampling interval, and satellite elevation angle. The empirical model of $A_{Th_{GF}}$ associated with data sampling interval has been applied in gLAB software as:

$$Th_{GF} = \max (\max - \min) \times \exp(-\text{step}/T_0)$$

(8)

where the $\max = 0.08$, $\min = 0.034$, $T_0 = 60$, and step is the data sampling interval. When the sampling interval is 30 s, the values of $Th_{GF}$ is 0.05 m.

Under geomagnetic storm conditions, the empirical value $Th_{GF}$ as 0.05 m may result in the misjudgment of cycle slip detection. In the following, we provide a typical example to analyze the limitations of the empirical value. Figure 3 shows the time series of $A_{ΔN_{MW}}$, $A_{ΔΦ_{GF}}$, and ROTI for different GPS satellites observed at SCOR station on 8 September 2017. The threshold of MW wide-lane combination as 4 $A_{σ}$ for different satellites are shown in the panel of $A_{ΔN_{MW}}$.

Figure 3. Time series of $A_{ΔN_{MW}}$, $A_{ΔΦ_{GF}}$, and rate of total electron content index of different global positioning system satellites observed at SCOR station on 8 September 2017. Time series of $±4σ$ for the $N_{MW}$ observation derived from different satellites measurements are shown in the panel of $A_{ΔN_{MW}}$. 
In Figure 3, it is seen that during 8:10–11:50 UT, no ionospheric disturbance is observed at SCOR station, and the time series of $\Delta N_{MW}$ and $\Delta \Phi_{GF}$ fluctuate within $\pm 4\sigma$ cycle and $\pm 0.05$ m, respectively. For the other time periods on 8 September 2017, obvious disturbances occurred over SCOR station and the value of ionospheric disturbance index ROTI can reach around 6 TECU/min. Under this condition, however, the time series of $\Delta N_{MW}$ fluctuate within $4\sigma$ and they do not show obvious variations with ROTI. Note that this situation is also found in many other stations during storm periods. That means $\Delta N_{MW}$ is not sensitive to ionospheric disturbance. For the $\Delta \Phi_{GF}$, significant fluctuations can be seen in the figure and many epochs of $\Delta \Phi_{GF}$ are larger than the common threshold of 0.05 m (see the black lines), which means that the empirical cycle slip threshold ($T_{h,GF} = 0.05$ m) is not suitable under geomagnetic storm condition. For the figure, we may also note that the variations of $\Delta \Phi_{GF}$ shows close relationship with ROTI. In view of this, we next establish the GF cycle slip threshold model based on abundant data of $\Delta \Phi_{GF}$ and ROTI derived from 246 IGS stations.

### 2.5. GF Cycle Slip Threshold Model

Figure 4 gives the distribution of $\Delta \Phi_{GF}$ and ROTI derived from 246 IGS tracking stations data on 8 September 2017. Under non-ionospheric disturbance ($ROTI \leq 0.5$ TECU/min), it is seen that most $|\Delta \Phi_{GF}|$ are less than 0.1 m. With the increase of ROTI, the value of $|\Delta \Phi_{GF}|$ gradually increases. Note that the $|\Delta \Phi_{GF}|$ value no longer increases significantly when the ROTI increases to around 3 TECU/min.

In Figure 4, $\Delta \Phi_{GF}$ values are generally distributed within $\pm 0.1$ m when $ROTI \leq 0.5$ TECU/min. Therefore, a constant of threshold can be used in this ROTI range. For $0.5 < ROTI \leq 3$ TECU/min, $\Delta \Phi_{GF}$ appears to increase with the increase of ROTI, so a second-order polynomial model of $T_{h,GF}$ can be established based on ROTI values. Specifically, the selection of independent variable as ROTI is based on each 0.05 TECU/min interval in the range of 0.5–3 TECU/min, while the corresponding dependent variable as $T_{h,GF}$ is based on the principle of $3\sigma$ (99.7%). For instance, for the interval of 0.625 < $ROTI \leq 0.675$ TECU/min (see Figure 5), the independent variable as ROTI is 0.650 TECU/min, and the dependent variable as $T_{h,GF}$ is 0.141 m ($3 \times 0.047$). According to this strategy, a series of independent and dependent variables can be obtained. Finally, we can get the coefficients of the second-order polynomial model. For $ROTI > 3$ TECU/min, $\Delta \Phi_{GF}$ does not show obvious increase, so we set $T_{h,GF}$ to a constant for this range.
From the above analysis, the GF cycle slip threshold model based on ionospheric disturbance index ROTI can be established as:

$$|\text{Th}_{\text{GF}}(\text{ROTI})| = \begin{cases} 0.104 & \text{ROTI} \leq 0.5 \\ -0.018 \cdot \text{ROTI}^2 + 0.260 \cdot \text{ROTI} - 0.021 & 0.5 < \text{ROTI} \leq 3 \\ 0.594 & \text{ROTI} > 3 \end{cases}$$  \quad (9)

Note that for higher ROTI values as ROTI > 3 TECU/min, $A_{\Delta \Phi_{\text{GF}}}$ should also have a tendency of increase. Statistics indicate that in Figure 4, the number of ROTI ≤ 0.5 TECU/min, 0.5 < ROTI ≤ 3 TECU/min, and ROTI > 3 TECU/min accounts for 94.6%, 5.2%, and 0.2%, respectively. For such little data of ROTI > 3 TECU/min, we chose to set $A_{\text{Th}_{\text{GF}}}$ to a constant instead of modeling it. That means the performance of our model may be reduced at very high ROTI values.

### 3. Experimental Validations

To evaluate the performance of GF cycle slip threshold model, GPS data derived from 171 non-modeling IGS stations, are performed in two PPP schemes. Specifically, scheme 1 uses the common cycle slip threshold as $A_{\text{Th}_{\text{GF}}}$ = 0.05 m, while scheme 2 is based on our proposed GF cycle slip threshold model. Since $A_{\Delta N_{\text{MW}}}$ is not sensitive to ionospheric disturbances, the threshold of MW wide-line combination still takes the 4σ in two schemes. In the data processing, the satellite elevation angle is 15° and the data sampling interval is 30 s. The precise satellite orbit and clock products are the final precise products of IGS. Table 1 presents the detailed information of models and methods used in GPS PPP. The experimental data is processed by FUSING software developed by Wuhan University (Shi et al., 2019; Yang et al., 2019).

| Item                      | Strategies                                                                                     |
|---------------------------|------------------------------------------------------------------------------------------------|
| Observations              | Pseudorange and carrier phase observations on L1 and L2                                         |
| Stochastic model          | Elevation-dependent weight model                                                                |
| Sampling interval         | 30 s                                                                                           |
| Elevation mask angle      | 15°                                                                                             |
| Precise satellite orbit   | IGS precise products                                                                           |
| Precise satellite clock   | IGS precise products                                                                           |
| Effect of phase wind-up   | Corrected (Wu et al., 1993)                                                                     |
| Phase center offset       | igs08.atx                                                                                      |
| Phase center variation    | igs08.atx                                                                                      |
| Ionospheric delay         | Ionospheric-free combination to eliminate the effects of the first-order ionospheric delay     |
| Tropospheric delay        | Hopfield model and the remaining parts are estimated as random walk (5 mm/√h)                  |
| Receiver coordinate       | Estimated and modeled as white noise                                                             |

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Note that for higher ROTI values as ROTI > 3 TECU/min, $A_{\Delta \Phi_{\text{GF}}}$ should also have a tendency of increase. Statistics indicate that in Figure 4, the number of ROTI ≤ 0.5 TECU/min, 0.5 < ROTI ≤ 3 TECU/min, and ROTI > 3 TECU/min accounts for 94.6%, 5.2%, and 0.2%, respectively. For such little data of ROTI > 3 TECU/min, we chose to set $A_{\text{Th}_{\text{GF}}}$ to a constant instead of modeling it. That means the performance of our model may be reduced at very high ROTI values.

### 3.1. Single Station PPP

This section presents PPP results of single station based on cycle slip threshold model. Dual-frequency GPS data from three IGS stations as PRDS (50.87°N, 114.29°W; MLAT: 57.96°N), YEL3 (62.48°N, 114.48°W; MLAT: 69.26°N), and SCOR (70.49°N, 21.95°W; MLAT: 71.43°N), located at different latitude zones are performed in this experiment. Figure 6 depicts the time series of GPS PPP positioning errors, cycle slip number and ROTI for the three IGS stations on 8 September 2017. In the panels of positioning and cycle slip, the blue and red lines represent the results of schemes 1 and 2, respectively. Corresponding statistics are shown in the upper left corners. From the figure, it is seen that compared with scheme 1, PPP results of scheme 2 show significant improvement.
Under ionospheric disturbances, the number of cycle slip detected by scheme 2 is obviously less than that of scheme 1, which reduces the frequently unnecessary ambiguity resets in GPS PPP, thus improving the PPP accuracy. To a single satellite system like GPS, if four to six satellites encounter cycle slip at the same epoch, the PPP will be reinitialized at this epoch in general, especially the case when less than four available satellites used in PPP positioning (Zhang & Li, 2012). From the figure, it is clearly seen that several reinitializations in PPP results of scheme 1 corresponding to lots of cycle slips very well. With the cycle slip threshold model, the number of misjudgment cycle slips is obvious reduced. Although two or three satellites suffer cycle slips simultaneously during strong storm periods, the PPP solution would not be deteriorated since most of ambiguities are not reset. That is why, compared with scheme 1, the time series of positioning results of scheme 2 show smoother variations. It also should be mentioned that when real cycle slips occurred in three or more satellites carrier phase measurements at the same epoch, our proposed model is unable to improve the PPP performance. For instance, at the epoch of 12:29:30 UT for YEL3 station, a reinitialization of positioning of scheme 2 PPP can be seen in the figure. For this situation, combining other GNSS measurements in PPP may be an optional strategy (Marques et al., 2018).

In addition, in the figure, we can see that the numerous points of positioning errors are in the convergence time period of PPP. Since the reinitialization of PPP in this study are generally associated with ionospheric disturbances during geomagnetic storm, the statistics of RMS are calculated by using all points of positioning errors for the two PPP schemes in this study.

Figure 6. Comparison results of global positioning system (GPS) precise point positioning based on schemes 1 (blue) and 2 (red) using GPS data from stations PRDS, YEL3, and SCOR.
3.2. Global PPP

To further analyze the performance of GPS PPP based on cycle slip threshold model, we use the data collected at 171 non-modeling IGS stations (red dots in Figure 2) on abnormal day as 8 September 2017 to conduct the positioning experiment. For comparison, these data except that of ULBI station on normal day as 3 September 2017 (\(A_A < 3\)) are also processed in this part. Figures 7 and 8 present the comparison results of two PPP schemes on normal and abnormal days, respectively. Upper and bottom panels of each figure give the RMS values of PPP errors for schemes 1 and 2, respectively. Different colors of dots represent different RMS values. Table 2 further shows the averaged RMS statistics of two PPP schemes on 3 September 2017 and 8 September 2017, respectively.

For the normal day, as shown in Figure 7, the positioning results of two PPP schemes are generally comparable. It is seen that scheme 2 based on cycle slip threshold model is effective for several stations located at high latitudes. Table 2 indicates that positioning accuracy of scheme 2 is generally better than that of scheme 1, which means our proposed model is valid under normally ionospheric environment.

For the abnormal day, as shown in Figure 8, we can see that the number of stations with darker colors in the bottom panels is less than that in the upper panels. Statistical results indicate that after applying cycle slip threshold model in GPS PPP, the number of stations with improved accuracy is 105 (61.4%), same accuracy is 39 (22.8%), and degraded accuracy is 27 (15.8%), respectively. Note that the positioning results of scheme 2 for the 27 degraded stations are comparable compared with scheme 1. Compared with scheme 1, as shown in Table 2, global GPS PPP based on cycle slip threshold model can improve the positioning accuracy by 14.0% and 23.1% in the horizontal and vertical directions, respectively. Compared with low and middle latitudes, the high latitudinal regions are generally close to the open magnetic field lines, so they are more easily affected by the geomagnetic storm. We further present statistical results of two PPP schemes for high latitudes stations in Table 2. It is seen that GPS PPP based on cycle slip threshold model at high latitudes can improve the positioning accuracy by approximately 36.8% and 51.5% in the horizontal and vertical components, over the conventional PPP solutions.

The above experiments mainly focus on the availability analysis of cycle slip threshold model for the strong storm on 8 September 2017. Next, we further present positioning results of two PPP schemes for another strong storm
occurred on 26 August 2018. For this storm, the minimum value of Dst index is −174 nT, resulting in ionospheric disturbances detected by both space- and ground-based sensors (Bolaji et al., 2021; Yang et al., 2020). Using 379 IGS stations data on 26 August 2018, Figure 9 presents RMS values of two PPP schemes in the horizontal and vertical components, respectively. It is clearly seen that the positioning accuracies of scheme 2 are better than these of scheme 1. According to the averaged RMS values shown in Table 3, our proposed model can improve the positioning accuracy by 9.7% (19.8%) and 14.6% (39.7%) in the horizontal and vertical components for global (high latitudes) stations compared with conventional PPP solution.

4. Summary

As an important space weather, geomagnetic storm can affect the accuracy and reliability of GNSS PPP. To mitigate the effects of geomagnetic storm on GNSS precise positioning, we propose to establish the cycle slip threshold model based on ionospheric disturbance index ROTI to reduce the rate of false detection of cycle slip in GNSS PPP under the conditions of strong geomagnetic storm.

|               | Global (m) | High latitudes (m) |
|---------------|------------|--------------------|
|               | Scheme 1   | Scheme 2           | Improvement (%) | Scheme 1   | Scheme 2           | Improvement (%) |
| Normal        |            |                    |                |            |                    |                |
| Horizontal    | 0.159      | 0.156              | 1.9            | 0.174      | 0.153              | 12.1            |
| Vertical      | 0.234      | 0.226              | 3.4            | 0.317      | 0.245              | 22.7            |
| Abnormal      |            |                    |                |            |                    |                |
| Horizontal    | 0.179      | 0.154              | 14.0           | 0.272      | 0.172              | 36.8            |
| Vertical      | 0.294      | 0.226              | 23.1           | 0.583      | 0.283              | 51.5            |
This study collects 246 IGS stations data during the strong geomagnetic storm on 8 September 2017 to analyze the relationship between GF cycle slip detection observation $\Delta \Phi_{GF}$ and the ionospheric disturbance index ROTI. A piecewise function model of $\Delta \Phi_{GF}$ based on ROTI is established by using the polynomial fitting method. GPS PPP results of three IGS stations as PRDS, YEL3, and SCOR indicate that the positioning accuracy based on our proposed model is obviously better than that based on common cycle slip threshold. The PPP experiments using the data from global 171 IGS stations also demonstrate that compared with conventional PPP solution, our proposed model can improve the positioning accuracy by 14.0% and 23.1% in the horizontal and vertical directions, respectively; meanwhile, the PPP results of 105 (61.4%) stations are improved, especially those located at high latitudes. Furthermore, the availability of our proposed model is also verified by PPP experiments using 379 IGS stations data during another strong geomagnetic storm occurred on 26 August 2018. The analysis indicates that compared with conventional PPP scheme, the proposed model can improve the positioning accuracy by approximately 9.7% (19.8%) and 14.6% (39.7%) in the horizontal and vertical components for global (high latitudes) stations on 26 August 2018.

![Figure 9](image_url)

**Figure 9.** Root mean square statistics of schemes 1 (upper panels) and 2 (bottom panels) in the horizontal and vertical components using global positioning system data from 379 International Global Navigation Satellite System Service stations on 26 August 2018.

| Scheme | Global (m) | Improvement (%) | High latitudes (m) | Improvement (%) |
|--------|------------|-----------------|--------------------|-----------------|
|        |            |                 |                    |                 |
| Scheme 1 | 0.248 | 0.224 | 9.7 | 0.556 | 0.446 | 19.8 |
| Scheme 2 | 0.302 | 0.258 | 14.6 | 0.648 | 0.391 | 39.7 |

**Table 3**

*Average Statistics of Root Mean Square Values for Schemes 1 and 2 in the Horizontal and Vertical Components on 26 August 2018*
Data Availability Statement

The $B_z$, $V_{sw}$, and $D_{st}$ data are provided by the NASA/GSFC Space Data Facility's OMNIWeb service (http://omniweb.gsfc.nasa.gov/). The $K_p$ data is provided by the GFZ-Potsdam (https://www.gfz-potsdam.de/en/kp-index/). The GPS data are provided by the IGS/MGEX data center CDDIS (ftp://cddis.gsfc.nasa.gov/).

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