

COMPARISON OF SEVERE GEOMAGNETIC STORM EVENT AND LOW-LATITUDE TOTAL ELECTRON CONTENT ANOMALIES

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ABSTRACT

In this study, we examined the Total Electron Content (TEC) anomalies at different scales during geomagnetic storms using Global Positioning System (GPS) satellites at low latitudes, which contributed to the catastrophic geomagnetic storm that occurred on March 24th, 2023. SIET KMITL, Bangkok station (13.729°N, 100.780°E) and KMITL Chumphon station (10.724°N, 99.375°E), Thailand, are the low-latitude GPS stations. After comparing the two GPS TEC stations, we examined the connection between TEC anomalies in the ionosphere and geomagnetic storm sizes. The findings demonstrate that ionosphere anomalies detected by GPS TEC correlate with geomagnetic storm timing. The findings demonstrate that ionospheric TEC anomalies detected by GPS were noticed that the GPS TEC values at both stations increase in proportion to the strength of the geomagnetic storm on days when the storm's intensity is higher. TEC levels rise progressively during periods of high geomagnetic storm severity. Even after the storm passes, TEC stays raised for two to three days before gradually falling back to normal. The maximum value of TEC, about 35 TECU, was observed at the SIET KMITL, Bangkok station (13.729°N, 100.780°E), whereas TEC increased to about 25 TECU at the KMITL Chumphon station (10.724°N, 99.375°E). TEC is high and positively correlated with an increase in days with intense geomagnetic storms. A rise in the frequency of intense geomagnetic storms is positively connected with TEC. However, in typical circumstances, TECs do not decrease in a negative direction during the quiet period.

Keywords: Geomagnetic storm, GPS TEC, Low-latitude, Total electron content

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I. INTRODUCTION

A novel avenue for exploring natural dynamics sensing is the use of satellite applications for the Global Positioning Systems (GPS), which provide dependable guidelines. Thus, it is essential to keep enhancing GPS's accuracy and dependability. The quality of GPS satellite transmissions is correlated with the propagation status of the Earth's ionosphere. The ionosphere acts as a middleman to both speed up and slow down signal propagation. The identity of the ionosphere plasma density determines these variations. According to Nayak et al. (2016, pp. 7941-7960), the Total Electron Content (TEC) of the ionosphere influences the phase advance and group delay of GPS satellite signals. The positive ionospheric storms are associated with an enhancement in electron density caused by thermospheric winds, by compositional changes or by the transport of ionization or electric field changes, whereas the negative storms are primarily due to compositional changes of the ionosphere" (Nayak et al., 2016, pp. 7941-7960; Reddybattula et al., 2019, p. 283; Serafimov et al., 1982, pp. 397-399). The main causes of ionospheric anomalies at various latitudes are solar and geophysical-induced perturbations in Earth's space environment. The equatorial and low latitudes around the equator are where changes are most noticeable. An electromagnetic field over the magnetic equator typically has a significant impact on the variation of TEC at low latitudes. Electrical conductivity above the equator significantly increases as a result (Li et al., 2019, p. 9380).

GPS has been used in many researches to display ionospheric abnormalities at different latitudes: high, middle, low, and equatorial. At Chumphon, Thailand, a near equatorial latitude station, Kenpankho et al. (2011, pp. 365-370) conducted a comparison between GPS TEC observations and IRI TEC prediction. Low-latitude TEC variability was investigated by Rao et al. (2013, pp. 1-6) from magnetically conjugate places along 73°E longitude. The 2015 St. Patrick's Day geomagnetic storm prompted studies of the middle-and low-latitude ionosphere reaction by Nava et al. (2016, pp. 3421-3438). By comparing the 28 days running median with the spectral whitening method, Chen et al. (2017, pp. 3632-3639) were able to derive the geomagnetic activity effect from TEC data. During moderate, strong, and extreme geomagnetic storms over the Indian subcontinent, analysis of ionospheric TEC using GPS, Global Ionosphere Map (GIM), and global ionosphere models was conducted (Reddybattula et al., 2019, pp. 283-292). The ionospheric irregularity behavior during the magnetic storm that occurred over the Brazilian equatorial-low latitudes on September 6th-10th, 2017, was examined by de Paula et al. (2019, pp. 1-15). Dugassa et al. (2019, pp. 1161-1180) looked at the connection between the presence of ionospheric abnormalities and the spatial gradient of TEC between two neighboring stations. In the high-latitude ionosphere, Chernyshov et al. (2020, pp. 1-13) reported on the connection between TEC jumps and aurora sub-storms. Ratovsky et al. (2022, pp. 1-15) looked into the relationship between meteorological and geomagnetic activity and extreme ionospheric phenomena. The morphology and processes of the foF2 and TEC disturbances during the geomagnetic storms on September 26th-30th, 2011, were compared and contrasted by Klimenko et al. (2017, pp. 923-938). A global and regional ionospheric response during two geomagnetic storms on February 3rd-4th, 2022, was compared and evaluated by Bojilova and Mukhtarov (2023, pp. 1-23).

In a related study, the response of the middle- and low-latitude ionosphere to the 2015 St. Patrick's Day geomagnetic storm was examined by Nava et al. (2016, pp. 3421-3438). They contrasted the low-latitude station, cusv (Northern Hemisphere), with two middle-latitude stations, Northern Hemisphere (wuhn) and Southern Hemisphere (yar2), for the Asian area. They found a significant decline in the TEC near the middle latitude many days following the storm. At the low latitude, they did discover a rise in TEC on the day of the storm and no decline in the days that followed. Chen et al. (2017, pp. 3632-3639) compared the 28-days running median with the spectrum whitening approach to examine the geomagnetic activity effect from TEC data. They discovered that both the Running Median Centered (RMC) and the Spectral Whitening Method (SWM) assess the ionospheric variations in both quiet and disturbed conditions. When comparing the RMC results to the SWM results, the RMC results overestimate the occurrence of disturbances by approximately 5-20% during geomagnetic storms and up to 35% during quiet periods.

We came up with the idea to gather and compare GPS TEC data from the GNSS receiver and compare the low-latitude TEC disturbances focused on over Bangkok and Chumphon, Thailand, during severe geomagnetic storms on March 24th, 2023. The purpose of the study is to compare TEC anomalies during severe geomagnetic storm event utilizing low-latitude GPS satellites.

II. METHODOLOGY

A. Geomagnetic storm data

The Kp index is a physical classification of geomagnetic storm event data. The Space Weather Prediction Center (SWPC), National Oceanic and Atmospheric Administration (NOAA) uses the Kp index to classify geomagnetic storms into five severity levels: G0 (None), G1 (Minor), G2 (Moderate), G3 (Strong), G4 (Severe), and G5 (Extreme). On March 24th, 2023, a severe (G4) geomagnetic storm was observed. Geomagnetic storm data was collected for nine days within the storm period from March 21st to March 29th, 2023, three days before peak of the storm and five days after. The Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio wave Propagation of the Russian Academy of Sciences (IZMIRAN) website, located at <https://www.izmiran.ru/ionosphere/weather/storm/>, was where we obtained the hourly geomagnetic storm data for March, 2023. Subsequently, the geomagnetic storm level average every three hours was examined (Kp index), and the data analysis was plotted during the following session.

B. GPS TEC data

In this investigation, low-latitude monitor stations for the Global Navigation Satellite System (GNSS) were located in Bangkok, at SIET KMITL (School of Industrial Education and Technology, King Mongkut's Institute of Technology Ladkrabang), station (13.729°N, 100.780°E) and KMITL Chumphon station (10.724°N, 99.375°E), Thailand. Following the significant geomagnetic storming that was recorded on March 24th, 2023, we collected GPS TEC data in addition to the geomagnetic storm events that occurred three days before and five days after the geomagnetic storm. The GPS TEC was ascertained using the Receiver Independent Exchange Format (RINEX) data obtained from the multi GNSS receiver. The multi GNSS receiver (BG2s GNSS ionospheric monitor model) was used in this work as the data collection tool for GPS TEC. The Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), provides support for the BG2s GNSS ionospheric monitor system. Figure 1 depicts the connection of the GNSS ionospheric monitor system.

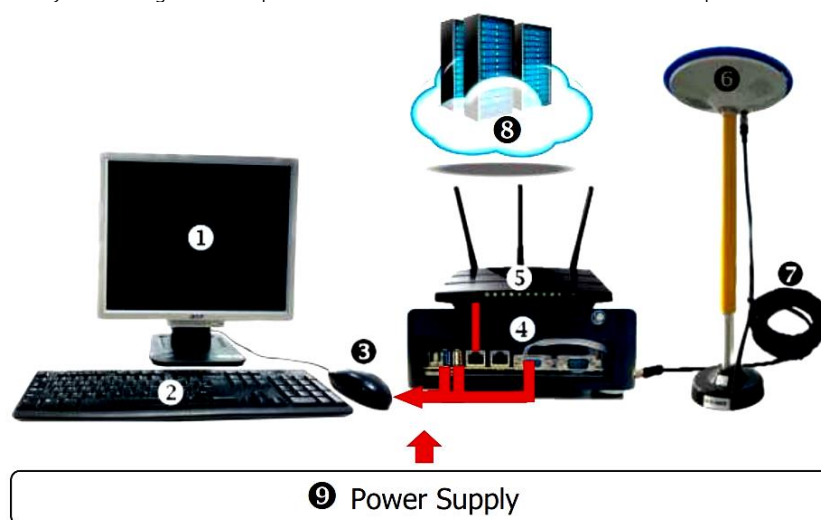


Figure 1 System of BG2s GNSS ionospheric monitor

The GPS system uses two frequencies for signal transmission: $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz. Four to twelve GPS signals are continuously received by the GPS receiver. For the GPS TEC computation, RINEX data from the GNSS receiver is utilized. The RINEX file contains pseudo-range (P_1 and P_2) and phase measurements (L_1 and L_2). The difference between the pseudo-ranges (P_1 and P_2) and the phases (L_1 and L_2) of the two frequencies GPS receiver can be used to determine the Slant Total Electron Content (STEC) (STEC_P and STEC_L) from a satellite to a receiver (Blewitt, 1990, pp. 199-202; Kenpankho et al., 2011, p. 366). This is the method for calculating values are calculated. The GPS TEC equations, denoted as (1) and (2), are STEC_P and STEC_L.

$$\text{STEC}_P = \frac{2(f_1 f_2)^2}{k(f_1^2 - f_2^2)} (P_2 - P_1), \quad (1)$$

$$\text{STEC}_L = \frac{2(f_1 f_2)^2}{k(f_1^2 - f_2^2)} (L_1 \lambda_1 - L_2 \lambda_2), \quad (2)$$

where the wavelengths corresponding to f_1 and f_2 are represented by λ_1 and λ_2 ($\lambda_1 = 0.1904$ m, $\lambda_2 = 0.2444$ m), respectively, and k , which is related to the ionosphere refraction, is $80.62 \text{ m}^3/\text{s}^2$.

In order to get the GPS TEC, we utilized Equation (2) and entered the parameters ($f_1, f_2, L_1, L_2, \lambda_1$, and λ_2) into the equation. Next, we computed Vertical Total Electron Content (VTEC) using Equation (3) and (4). The total electron in a vertical column with a cross-section of one meter is known as GPS TEC (Goodwin et al., 1995, pp. 1723-1732). TEC is measured in TECU unit. One TECU is equal to 10^{16} eV/m^2 . Equation (3) displays the VTEC, expressed in eV/m^2 , which may be calculated using the STEC (Kenpankho et al., 2011, p. 366; Ma & Maruyama, 2003, p. 2084).

$$\text{VTEC} = \text{STEC}_L \times \cos \chi, \quad (3)$$

where the zenith angle χ is expressed as

$$\chi = \arcsin \left(\frac{R_E \cos \alpha}{R_E + h} \right), \quad (4)$$

where R_E is the mean radius of the Earth $\approx 6,371$ km, α is the satellite's elevation angle, h as the height of the ionospheric layer, which is estimated to be 400 km (Kenpankho et al., 2011, p. 366; Ma & Maruyama, 2003, p. 2084).

Finally, we used GPS TEC data following geomagnetic storm events according to hourly Kp index levels using median statistic.

C. Correlation coefficient

The correlation coefficient can be analyzed from Equation (5) (Mukaka, 2012, p. 69) following as

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left[\sum_{i=1}^n (x_i - \bar{x})^2 \right] \left[\sum_{i=1}^n (y_i - \bar{y})^2 \right]}} \quad (5)$$

where, r is the correlation coefficient of the linear relationship between the variables x and y , x_i is the value of the scale of geomagnetic storm in a sample, $\bar{x}$ is the average of the scale of geomagnetic storm value, y_i is the values of the TEC in a sample, and $\bar{y}$ is the median of the TEC value. The correlation coefficient meaning is in Table 1 as follows.

Table 1 Size interpretation of a correlation coefficient.

Size of correlation	Interpretation
0.90 to 1.00 (–0.90 to –1.00)	Very high positive (negative) correlation
0.70 to 0.90 (–0.70 to –0.90)	High positive (negative) correlation
0.50 to 0.70 (–0.50 to –0.70)	Moderate positive (negative) correlation
0.30 to 0.50 (–0.30 to –0.50)	Low positive (negative) correlation
0.00 to 0.30 (0.00 to –0.30)	Negligible correlation

The datasets were used to calculate the correlation between geomagnetic storm levels and TEC anomalies in low-latitude regions. In this study, we utilized the Kp index levels as an indicator of geomagnetic storm intensity from March 21st to 29th. The GPS TEC values for hourly intervals from the SIET KMITL station (13.729°N, 100.780°E) and KMITL Chumphon station (10.724°N, 99.375°E) were computed to determine the correlation corresponding to each geomagnetic storm day with the Kp index levels. The datasets covered the period from 00:00 to 24:00 UT for each day, spanning March 21st to 29th, 2023.

III. RESULTS

A. Geomagnetic storm levels

Geomagnetic storm level data were acquired for the March 21st, 2023, to March 29th, 2023, timeframe. Figure 2 displays the average hourly geomagnetic storm.

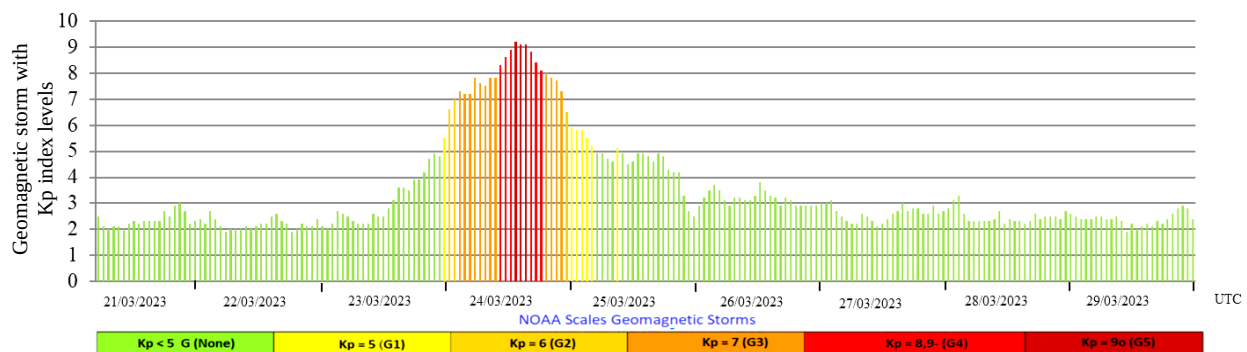


Figure 2 Geomagnetic storm levels that occurred during March 21st, 2023 to March 29th, 2023.

The geomagnetic storm data in Figure 2, which was gathered between March 21st and March 29th, 2023, indicated that there were geomagnetic storm watches in place from March 23rd to March 25th. As the storm continued throughout the late hours of March 23rd, it became stronger into G1, G2, and G3. Furthermore, a G3 episode was observed in the afternoon on March 23rd and strengthened to extreme storm (G5) levels at 12:04 UTC on the 24th. On March 24th, the geomagnetic storms had an average strength that was at the severe storm (G4) category. Following that, on March 25th, the storm's intensity dropped, and the following day, it was back to normal.

B. TEC anomalies compare with geomagnetic storm levels

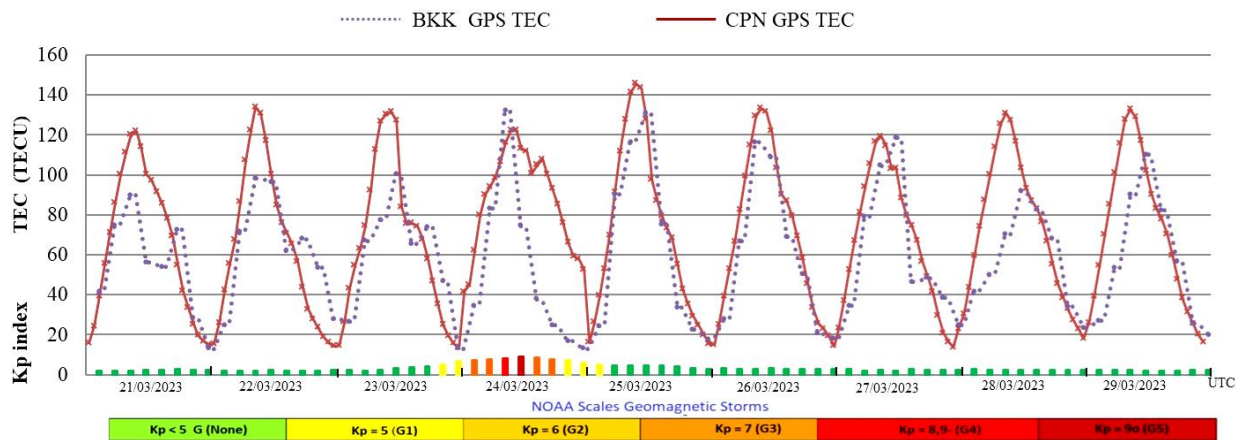


Figure 3 GPS TEC anomalies compare with geomagnetic storm levels at SIET KMITL station (13.729°N, 100.780°E) and KMITL Chumphon station (10.724°N, 99.375°E).

In Figure 3, it can be observed that on days with higher levels of geomagnetic storms, both CPS TEC values at the two stations increase in accordance with the intensity of the geomagnetic storm. The TEC values gradually rise during periods of increased geomagnetic storm intensity, and even when the storm subsides, TEC remains elevated for approximately 2-3 days before gradually decreasing to normal conditions. It was found that at the SIET KMITL, Bangkok station (13.729°N, 100.780°E), TEC reached its highest value, approximately 35 TECU, while at the KMITL Chumphon station (10.724°N, 99.375°E), TEC increased to around 25 TECU. It is clear that the KMITL Chumphon station has greater TEC values than the SIET KMITL, Bangkok station when comparing the TEC values at low-latitude zones between the two stations.

C. The relationship between TEC anomalies and geomagnetic storm levels

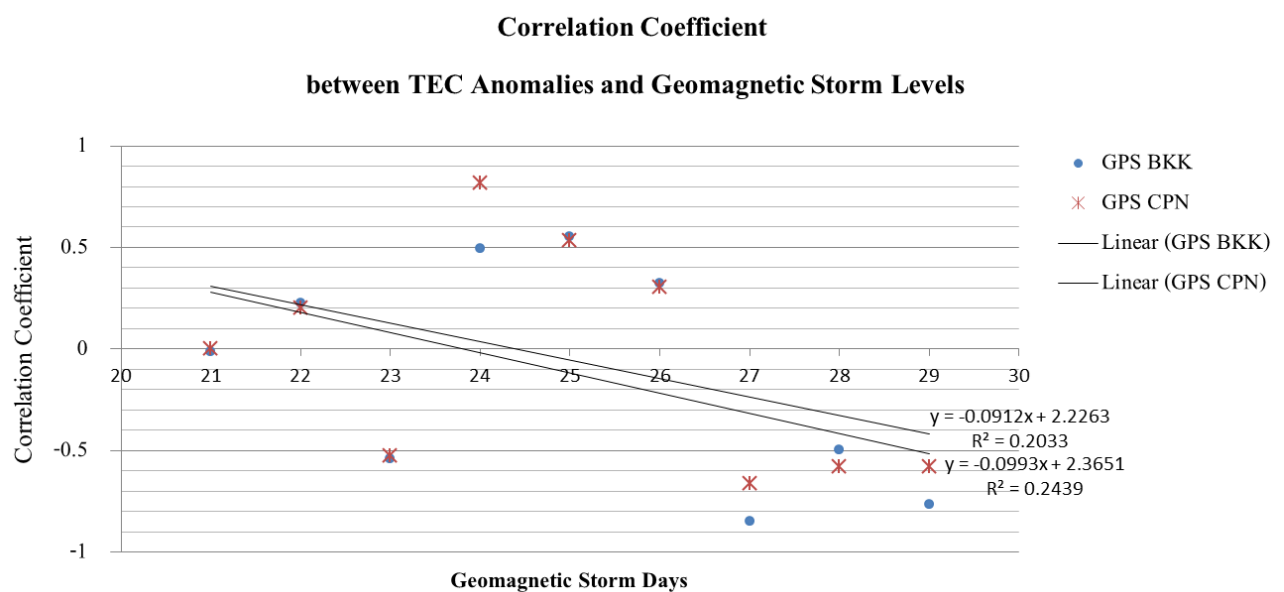


Figure 4 Correlation between TEC anomalies is significantly related to the level of geomagnetic storms.

Figure 4 shows that there is a considerable association between the level of geomagnetic storms and TEC abnormalities. For an increase in strong geomagnetic storms days, TEC is high in a positive direction correlation. TEC is highly correlated in a positive direction with a rise strong geomagnetic storms days. However, during the quiet period, TECs do not drop under normal conditions in a negative direction correlation.

IV. CONCLUSION AND DISCUSSION

In conclusion, we observed the behavior of the TEC at different scales during geomagnetic storms using low-latitude GPS satellites. Ionosphere anomalies detected by GPS TEC two stations at SIET KMITL, Bangkok station (13.729°N, 100.780°E), and KMITL Chumphon station (10.724°N, 99.375°E) correlate with geomagnetic storm-time. A few days after a geomagnetic storm, TECs tend to constantly increase before declining to normal. The degree of geomagnetic storm activity is strongly correlated with TEC abnormalities. When there is a rise in powerful geomagnetic storms, there is a high positive association between TECs. However, under typical circumstances, TECs do not decrease during the quiet period.

In discussion, our research backs up the findings of Chen, et al. (2017, pp. 3632-3639), who examined the geomagnetic activity effect from TEC data and compared the 28-days running median with the spectrum whitening approach. Ionospheric changes in quiet and disturbed settings exaggerate the occurrence of disturbances in tranquil periods and during geomagnetic storms. This study shows that the geomagnetic storm and TEC behavior are similar at low latitudes to those where middle- and low-latitude ionosphere reaction to geomagnetic storm was investigated by Nava et al. (2016, pp. 3421-3438). The study demonstrates a strong association between the storm's aftermath at the middle latitude and a notable decline in the TEC over a few days. At low latitudes, there is an increase in TEC on the day of the storm and no drop in the days that follow. The TEC is confined to low latitudes close to the equator in the days following the storm, and it nearly vanishes in middle latitudes.

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