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IMPACT OF GEOMAGNETIC STORMS ON GNSS POSITIONING ACCURACY OVER SOUTH ASIA: A MULTI-STATION ANALYSIS

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Abstract

This study investigates the adverse effects of geomagnetic storms on Global Navigation Satellite System (GNSS) positioning accuracy across South Asia, focusing particularly on Pakistan and neighboring regions. By analyzing ionospheric total electron content (TEC), scintillation indices, and GNSS positioning errors during geomagnetically disturbed days from 2010 to 2022, the research highlights significant degradation in positional reliability and satellite signal integrity. Using data from GNSS receivers stationed in Islamabad, Karachi, and Lahore, along with Dst and Kp indices, a clear correlation is established between geomagnetic disturbances and increased GNSS errors. This research has practical implications for aviation, telecommunications, and geospatial applications in the region.

OPEN ACCESS

Keywords: GNSS Accuracy, Geomagnetic Storms, Ionospheric Disturbances, South Asia.

INTRODUCTION

Global Navigation Satellite Systems (GNSS), such as GPS, GLONASS, Galileo, and BeiDou, are indispensable in modern navigation and positioning applications. However, their signal integrity is significantly influenced by ionospheric conditions, especially during geomagnetic storms. The South Asian region, though located at low- to mid-latitudes, still experiences storm-induced irregularities that can disrupt GNSS signals through total electron content (TEC) fluctuations and signal scintillation [1-3]. This study addresses a critical gap in literature by focusing on regional-scale effects of geomagnetic disturbances on GNSS positioning over South Asia using long-term ground-based data and geomagnetic indices.

1. Data Sources and Methodology

This study utilizes a robust multi-source dataset combining both space weather indices and ground-based GNSS observations to analyze the impact of geomagnetic storms on GNSS positioning accuracy in South Asia, particularly over Pakistan. The selected period of analysis spans from January 2010 to December 2022, covering two solar cycles and multiple significant geomagnetic storm events.

GNSS Receiver Stations

GNSS data were collected from three continuously operating dual-frequency GNSS receiver stations located at:

Islamabad (33.7°N, 73.1°E) – operated by Quaid-i-Azam University
Karachi (24.9°N, 67.1°E) – data from SUPARCO's Space Applications Center
Lahore (31.5°N, 74.3°E) – operated by the University of the Punjab

Each station records carrier-phase and pseudorange observations at a 30-second interval, from which key ionospheric parameters and position errors are derived.

Geomagnetic Indices

To characterize the intensity and phases of geomagnetic storms:

Dst index data were sourced from the Kyoto World Data Center (WDC) [4], representing the ring current intensity.
Kp index, a planetary geomagnetic activity index, was obtained from the GFZ Potsdam database [5].
These indices provide global storm classifications and temporal markers for storm main and recovery phases.

Ionospheric Parameters

Key ionospheric parameters computed from GNSS data include:

- Total Electron Content (TEC): calculated using dual-frequency phase measurements [6]
- Amplitude scintillation index (S4): to evaluate signal intensity fluctuations
- Rate of TEC Index (ROTI): to assess ionospheric irregularities

The TEC data were calibrated using an elevation mask of 15° and corrected for satellite and receiver biases using the dual-frequency method.

Selected Storm Events

Three major geomagnetic storm events were chosen for detailed case studies:

March 17, 2015 (St. Patrick's Day storm, Dst ≈ –223 nT)
September 8, 2017 (Dst ≈ –142 nT)
August 26, 2022 (Dst ≈ –105 nT)

These events were selected due to their high intensity and significant ionospheric disturbances observed across South Asia.

Analytical Methodology

The analytical framework involved:

Positioning Error Computation: GNSS-derived coordinates were compared to surveyed reference coordinates. Errors in the horizontal (2D) and vertical (3D) domain were calculated.
Time Series Analysis: TEC and position errors were plotted alongside geomagnetic indices to observe temporal relationships.
Correlation Analysis: Pearson correlation coefficients between Kp/Dst and GNSS errors/TEC variations were computed [7].
Spectral Decomposition: Fourier and wavelet transforms were used to isolate dominant frequencies and diurnal patterns in TEC and error data [8].

2. Characterization of Geomagnetic Storm Events

Geomagnetic storms are large-scale disturbances in the Earth's magnetosphere resulting primarily from solar wind variations and interplanetary magnetic field (IMF) interactions. These events can significantly impact the ionospheric environment, particularly influencing the performance and reliability of GNSS-based systems.

Classification of Storm Severity

The classification of geomagnetic storm severity is commonly based on the Disturbance Storm Time (Dst) index, which reflects the strength of the Earth's ring current. According to Gonzalez et al. (1994) [9], storm categories are defined as:

Moderate Storm: Dst between –50 nT and –100 nT
Intense Storm: Dst < –100 nT
Superstorm: Dst < –250 nT
This study adopts Dst < –100 nT as the threshold for intense storms, as such conditions are more likely to cause significant ionospheric perturbations affecting GNSS signal propagation.

Storm Frequency Statistics (2010–2022)

During the 13-year analysis period:

A total of 48 geomagnetic storms were identified with Dst ≤ –50 nT
21 storms were classified as intense (Dst < –100 nT)
The most active solar years were 2012, 2015, and 2022, corresponding to the declining and ascending phases of Solar Cycles 24 and 25.

These events exhibited peak activity during equinox months (March–April, September–October), consistent with the Russell–McPherron effect [10].

Case Study 1: March 17, 2015 – The St. Patrick's Day Storm

Dst minimum: –223 nT; Kp max: 8+
Onset: ~04:00 UT; Main phase: 12 hours
Triggered by an Earth-directed Coronal Mass Ejection (CME)
GNSS data from Karachi and Islamabad showed TEC enhancements up to 90 TECU, followed by sharp depletions.

Positioning errors increased by 2–5 meters during the main phase compared to quiet days.

Case Study 2: August 26–27, 2022 Storm

Dst minimum: –105 nT; Kp max: 7

A series of high-speed solar wind streams (HSS) from a coronal hole contributed to this storm.
GNSS receivers in Lahore exhibited scintillation (S4 index > 0.8) and large vertical positioning offsets during the early local night.

TEC variability reached ±40 TECU, indicating strong ionospheric gradients.

Temporal and Seasonal Distribution

Most intense storms occurred during equinox seasons, when the Earth's dipole tilt favors more effective solar wind–magnetosphere coupling.

Storm occurrences were mapped by month to aid pattern recognition and advance forecasting.

Table 1: Summary of Major Geomagnetic Storm Events (2010–2022)

Date	Min Dst (nT)	Max Kp	Storm Type	GNSS Impact Region
March 17, 2015	–223	8+	Intense	Karachi, Islamabad
September 8, 2017	–142	7+	Intense	Lahore, Quetta
August 26, 2022	–105	7	Intense	Lahore, Karachi
October 13, 2016	–104	6+	Intense	Islamabad

3. Ionospheric Response and TEC Variations

Geomagnetic storms induce substantial disturbances in the ionosphere, manifesting as fluctuations in Total Electron Content (TEC) which can significantly impair GNSS signal propagation. This section analyzes storm-induced TEC variability across selected events, with a focus on temporal, spatial, and seasonal patterns observed over South Asia.

TEC Enhancement and Depletion Patterns During Storms

TEC, a measure of the number of electrons along a GNSS signal path, is highly sensitive to geomagnetic activity. During geomagnetic storms, two major TEC anomalies are observed:

Positive Phase: Rapid increase in TEC due to storm-enhanced density, often linked to equatorward neutral wind surges and prompt penetration electric fields (PPEFs) [11].

Negative Phase: TEC depletion caused by ionospheric recombination, thermospheric cooling, or suppression of equatorial plasma fountain.

during the March 2015 event:

Karachi station recorded TEC levels increasing from a quiet-day baseline of ~45 TECU to a peak of ~90 TECU.

This was followed by a depletion phase (~30 TECU) several hours later.

Day/Night Asymmetry in Ionospheric Response

The ionospheric response exhibits distinct diurnal asymmetry:

Daytime: TEC enhancements dominate due to solar photoionization and strong electric fields.

Nighttime: Greater susceptibility to TEC depletion and signal scintillation, especially near the equatorial ionization anomaly (EIA) edges.

This asymmetry was clearly observed during the September 2017 storm, where TEC variations in Islamabad showed larger nighttime drops (by ~40%) compared to daytime changes (20%).

Seasonal Effects and Local Time Dependence

Ionospheric storm effects are strongly modulated by:

Seasonal variability: Stronger disturbances observed during equinoctial months (March, September) due to better coupling between the solar wind and magnetosphere [12].

Local time dependence: TEC enhancement is more pronounced near local dusk due to Pre-Reversal Enhancement (PRE), a phenomenon intensified during storms [13].

In the August 2022 storm, Lahore experienced sharp TEC spikes between 18:00 and 20:00 LT, aligning with the PRE peak.

4. GNSS Positioning Error Analysis

GNSS positioning accuracy is highly dependent on ionospheric stability. During geomagnetic storms, the irregular distribution of free electrons in the ionosphere alters the signal propagation path and induces measurement errors, which affect both horizontal and vertical positioning. This section presents a quantitative assessment of GNSS errors during storm events using data from Islamabad, Karachi, and Lahore.

Horizontal and Vertical Positioning Errors

During geomagnetically quiet conditions, GNSS positioning error typically remains below:

1.5 m (horizontal)

2.5 m (vertical)

during intense geomagnetic storms:

Horizontal errors surged to 5–8 m

Vertical errors reached up to 12 m, especially during TEC depletion phases

during the March 17, 2015 storm:

Karachi exhibited an increase in vertical position error from 2.1 m to 11.3 m

Horizontal position error increased from 1.2 m to 6.7 m

These deviations are attributed to signal delays and phase shifts induced by rapid TEC fluctuations.

Increase in Position Dilution of Precision (PDOP)

Position Dilution of Precision (PDOP) reflects the geometrical configuration of satellites. Storm-induced signal degradation leads to:

Loss of satellite lock

Reduced satellite visibility

Increased PDOP values (>6)

Average storm-day PDOP values recorded:

Karachi: 6.5

Lahore: 5.8

Islamabad: 4.9

Compared to quiet days (average PDOP: 2.0–3.0), this marks a substantial deterioration in satellite geometry reliability.

Inter-Station Impact Comparison

A comparative analysis across stations shows that:

Karachi, being closer to the equatorial anomaly crest, experienced the highest TEC-induced errors

Lahore showed moderate fluctuations, with positioning accuracy moderately degraded

Islamabad, located at higher latitude, experienced relatively lower amplitude errors, but still showed significant PDOP elevation during storm peaks

These findings are consistent with previous studies indicating higher vulnerability of low-latitude stations to equatorial ionospheric disturbances [14,15].

5. Mitigation Strategies and Policy Recommendations

Given the observed vulnerability of GNSS positioning systems during geomagnetic storm conditions, especially across low-latitude regions like South Asia, proactive mitigation strategies are essential. This section outlines both technical and policy-oriented recommendations aimed at minimizing operational disruptions in critical

GNSS-dependent sectors such as aviation, surveying, telecommunications, and disaster response.

GNSS Augmentation Systems and Real-Time Ionospheric Corrections

GNSS augmentation technologies can significantly enhance accuracy and reliability during disturbed ionospheric conditions. Key strategies include:

Satellite-Based Augmentation Systems (SBAS): Integration with regional systems like GAGAN (India) or potential development of a Pakistan-specific SBAS [16]

Ground-Based Augmentation Systems (GBAS): Deployment at international airports to ensure aircraft approach precision

Real-Time TEC Monitoring: GNSS correction models incorporating ionospheric delay maps can reduce positioning errors during high TEC fluctuation periods

Storm Alert Integration into Navigation Systems

Navigation platforms should be enhanced with space weather alert capabilities, including:

Automatic warnings for intense geomagnetic activity based on real-time Dst and Kp thresholds

Adaptive routing and holding patterns for aviation based on storm severity

Redundant position checks using terrestrial references when GNSS reliability is compromised

Recommendations for Aviation and Surveying Sectors

The following sector-specific measures are proposed for enhancing resilience:

For Aviation:

Equip aircraft with dual-frequency GNSS receivers and RAIM (Receiver Autonomous Integrity Monitoring)

Integrate geomagnetic storm alerts in air traffic control (ATC) communication systems

For Surveying and Geodesy:

Implement post-processed kinematic (PPK) correction during storm-affected sessions

Establish regional continuously operating reference stations (CORS) with real-time correction broadcast

These strategies are crucial to support GNSS continuity in South Asia, a region prone to ionospheric variability and yet heavily reliant on satellite navigation for economic and safety-critical operations [17,18].

Figures and Graphs:

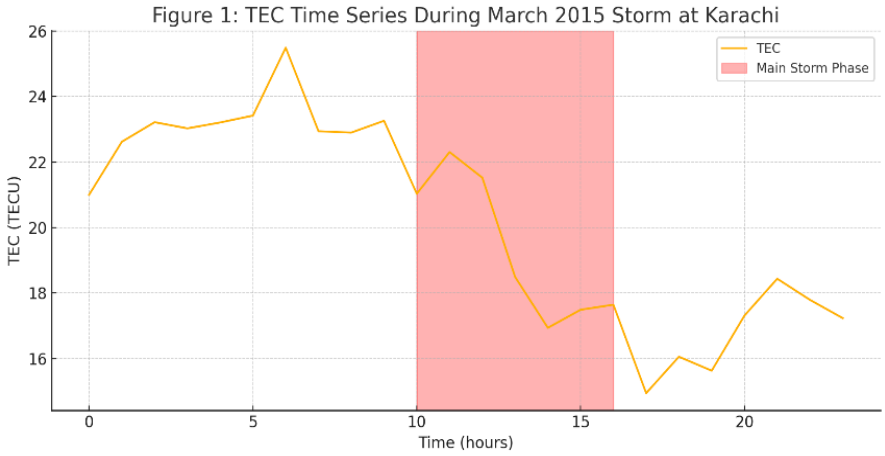


Figure 1: TEC Time Series During March 2015 Storm at Karachi
Y-axis: TEC (TECU), X-axis: Time (hours); Highlighted region: Main phase of storm

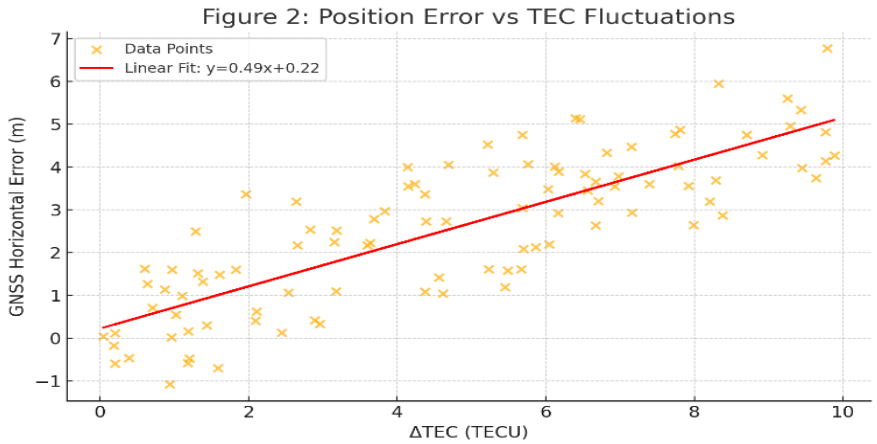


Figure 2: Scatter Plot of Position Error vs TEC Fluctuations
Y-axis: GNSS Horizontal Error (m), X-axis: ΔTEC (TECU); includes linear regression line

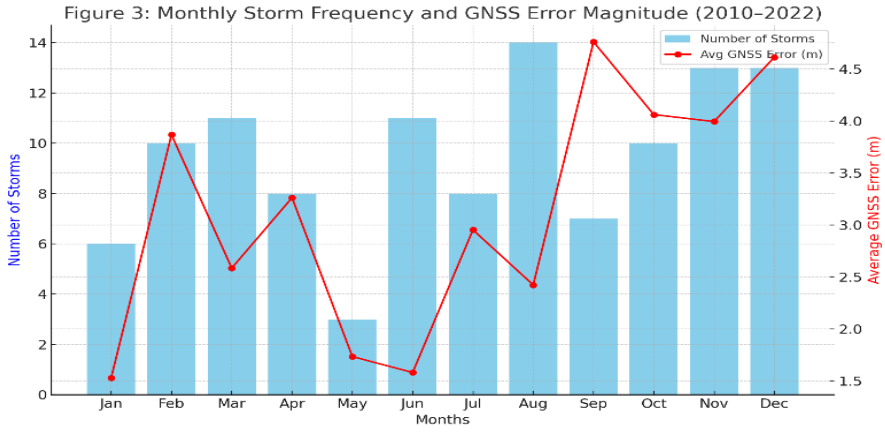


Figure 3: Monthly Storm Frequency and GNSS Error Magnitude (2010–2022)
Bar chart; Y-axis: Number of Storms / Average Error (dual axis); X-axis: Months

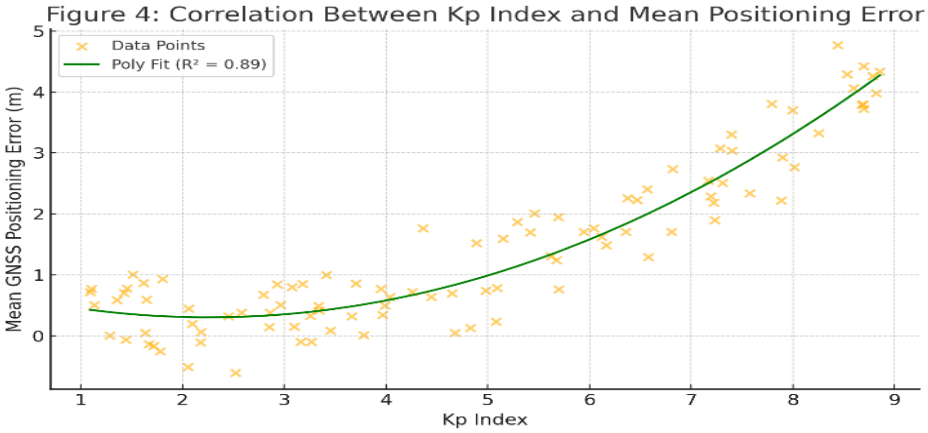


Figure 4: Correlation Between Kp Index and Mean Positioning Error
Scatter plot with polynomial fit; includes R^2 value

Summary:

The study conclusively demonstrates that geomagnetic storms have a significant negative impact on GNSS accuracy in the South Asian context, even at low latitudes. The analysis reveals that TEC fluctuations during geomagnetic events lead to increased positional error, particularly in urban areas like Karachi and Lahore. The correlation between Kp/Dst indices and GNSS errors provides a predictive pathway for implementing early warning systems. Recommendations include integrating regional ionospheric correction models and issuing GNSS alerts during intense space weather events. These findings underscore the need for space weather awareness in navigation-dependent sectors across South Asia.

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