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SPACE WEATHER IMPACTS ON AVIATION AND SATELLITE SYSTEMS: CASE STUDIES FROM 2023–2024

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Abstract

Space weather, primarily driven by solar phenomena such as coronal mass ejections (CMEs) and solar flares, poses significant risks to modern aviation and satellite systems. This paper investigates key geomagnetic disturbances recorded during 2023–2024 and their measurable impacts on global navigation satellite systems (GNSS), aviation communication, and orbital satellite integrity. Using observational data from IGS GNSS receivers, aviation logs, and satellite telemetry, this study highlights specific case studies of disruptions over Pakistan and South Asia. The findings underscore the critical need for operational mitigation frameworks and real-time alert systems to safeguard technological infrastructure.

OPEN ACCESS

Keywords: Space weather, Aviation disruption, Satellite anomalies, GNSS errors.

INTRODUCTION

Modern aviation and satellite operations rely heavily on precise space-based services. Events such as solar flares and CMEs disturb the Earth's magnetosphere and ionosphere, leading to adverse effects such as radio blackouts, GPS inaccuracy, and satellite drag. With growing air traffic and space-based assets, especially in vulnerable regions like South Asia, understanding these disturbances is vital for resilience and preparedness [1–4].

2. Data Collection and Methodology

This study employs a multi-source, cross-disciplinary approach to analyze the impacts of space weather events on aviation and satellite systems across Pakistan during the years 2023–2024. The data sources and analysis techniques are outlined below:

Data Sources

Solar Activity and Geomagnetic Indices:

Hourly and daily data on solar flares, coronal mass ejections (CMEs), solar wind velocity, and interplanetary magnetic field (IMF Bz) were acquired from the NOAA Space Weather Prediction Center and NASA's OMNIWeb database [5]. This includes Kp, Dst, and AE indices essential for identifying storm intensity and duration.

Ionospheric Total Electron Content (TEC):

GNSS-derived TEC measurements were obtained from the International GNSS Service (IGS) ground-based receivers operating in Karachi, Lahore, and Islamabad [6]. These data were used to assess ionospheric fluctuations and their impact on GNSS signal accuracy.

Aviation HF Communication Logs:

Operational HF communication disruption records were accessed from the Civil Aviation Authority (CAA) Pakistan, specifically from the Karachi and Lahore Area Control Centers [7]. These logs provided empirical records of signal loss, frequency shifts, and re-routing decisions.

Satellite Telemetry and Anomalies:

Data logs from SUPARCO's geostationary platforms, including PAKSAT-1R and regional cubesats, were reviewed for telemetry anomalies, attitude control deviations, and power system fluctuations during storm periods [8].

Methodology

The analytical workflow followed these steps:

Time-Series Analysis:

Using Python libraries (pandas, matplotlib, scipy) and MATLAB, time-series plots were constructed for TEC, Kp, Dst, and satellite parameters to identify synchronized anomalies.

Event Correlation:

A correlation matrix was computed to evaluate the temporal alignment between space weather indices (Kp, IMF

Bz) and the incidence of GNSS signal degradation, HF communication blackouts, and telemetry faults.

GNSS Error Estimation:

Positioning errors were calculated by comparing known ground truth coordinates with the GNSS-derived positions during storm intervals. TEC variation thresholds ($\Delta TEC > 5$ TECU) were flagged as high-risk periods.

Anomaly Tracking in Satellite Systems:

Telemetry values such as battery voltage, onboard temperature, and magnetometer readings were statistically analyzed to detect deviations exceeding $\pm 2\sigma$ during solar events.

Spatial Analysis:

GNSS error heatmaps over Pakistan were generated using GIS tools (geopandas, matplotlib) to visualize regional vulnerability during the storm peaks.

3. Aviation Impacts During Major Events

Aviation systems are among the most vulnerable to space weather disturbances, especially due to their reliance on GNSS-based navigation and HF radio communication in transoceanic and polar routes. During 2023–2024, multiple solar events disrupted flight operations over South Asia, with the most significant being the March 2023 X1.2-class solar flare, which had observable effects on flights operating in and out of Pakistan.

GNSS Signal Degradation and Communication Loss

During the peak of the March 2023 event (March 23–25), increased ionization in the lower ionosphere (D and E regions) caused severe HF radio blackouts, particularly in the 3–30 MHz band used by high-altitude aircraft. The Karachi and Lahore FIRs (Flight Information Regions) reported multiple pilot position reports lost, forcing temporary reliance on VHF communication where possible [9].

Simultaneously, GNSS positioning accuracy degraded significantly, with horizontal errors rising above 20 meters, especially over western Pakistan and the Arabian Sea. This caused disruptions in approach procedures at Jinnah International Airport and emergency revisions of Standard Terminal Arrival Routes (STARs) [10].

Flight Path Deviations

The most affected air corridors were those extending southwest over the Arabian Sea, where HF propagation collapsed due to Sudden Ionospheric Disturbance (SID). Airlines including PIA, Emirates, and AirBlue filed deviation reports indicating manual rerouting and delays averaging 30–45 minutes.

These disruptions were particularly critical for long-haul flights traversing the Karachi FIR, especially during nighttime hours when HF dependency is higher due to lack of VHF coverage.

4. GNSS Signal Errors in South Asia

The accuracy and integrity of GNSS-based navigation systems are critically dependent on ionospheric stability. During 2023, increased solar activity induced pronounced ionospheric disturbances across South Asia, resulting in major navigation anomalies, particularly in Pakistan's urban airspace.

TEC Fluctuations and Error Magnitude

Total Electron Content (TEC) values recorded from IGS stations in Karachi and Lahore showed abrupt fluctuations exceeding 10 TECU, coinciding with solar flare and CME events during March, July, and November 2023. These fluctuations directly impacted GNSS signal propagation by altering the phase and group delay of L1 and L2 signals, leading to horizontal positioning errors surpassing 20 meters [11].

The peak disturbance occurred on March 24, 2023, when a sudden TEC drop (~15 TECU within 30 minutes) was followed by severe GNSS deviations lasting over 2 hours. Local positioning services recorded drift in flight trajectories and delayed waypoint crossings.

Impact on Navigation-Based Landing Systems

Airports relying on RNP (Required Navigation Performance) and GNSS-based ILS (Instrument Landing Systems) experienced degraded reliability. Karachi's Jinnah International Airport and Lahore's Allama Iqbal International Airport each reported delays in multiple GNSS-enabled approach procedures due to satellite position inconsistencies [12]. Flight logs indicated increased use of conventional ILS and visual approaches, especially under VFR (Visual Flight Rules) conditions at night.

5. Satellite System Disruptions

Satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) are directly affected by space weather phenomena, particularly geomagnetic storms that can induce surface charging, increase atmospheric drag, and degrade subsystem performance. The April 2024 CME event, one of the strongest in Solar Cycle 25, resulted in notable telemetry anomalies across satellites monitored by SUPARCO and international agencies.Thermal and Orbital Effects

During the geomagnetic storm of **April 19–22, 2024**, spaceborne instrumentation recorded significant enhancements in energetic particle fluxes, leading to thermal anomalies on multiple platforms. SUPARCO's thermal control system logs for PAKSAT-1R indicated a rise of 5.6°C in onboard temperature, exceeding operational thresholds temporarily [13]. Concurrently, increased orbital drag was detected on experimental cubesats in Low Earth Orbit (LEO), with deceleration corresponding to up to 12% more atmospheric density at 400 km altitude.

These effects were driven by storm-induced thermospheric expansion, which elevated air particle density, increasing friction against LEO satellites [13].

Data Loss and Communication Interruptions

During the main phase of the April 2024 storm, telemetry blackouts lasting up to 28 minutes were reported from PAKSAT-1R. These were attributed to temporary loss of lock on transponders and anomalous current spikes in attitude control modules [14]. Diagnostic logs highlighted corrupted data packets in downlinked telemetry, requiring post-event recovery protocols and redundant system fallback.

Geostationary operations were also affected by enhanced surface charging, increasing the risk of electrostatic discharge (ESD), a known cause of subsystem failures in satellite electronics.

6. Case Studies: March 2023 and April 2024 Storms

To provide a detailed view of how extreme space weather affects aviation and satellite systems, we examine two major events during Solar Cycle 25: the March 2023 X-class solar flare and the April 2024 coronal mass ejection (CME). These case studies illustrate the temporal correlation between solar and geomagnetic activity with terrestrial technological impacts.

March 2023 – Sudden Ionospheric Disturbance (SID)

On March 24, 2023, the Earth was struck by an X1.2-class solar flare, producing an immediate sudden ionospheric disturbance (SID). Observations from IGS stations in Karachi and Lahore recorded rapid TEC increases, while HF communication logs reported blackouts across 6 MHz and 8 MHz channels [9]. GNSS receivers recorded horizontal errors exceeding 20 m, and several airline flights were rerouted due to unreliable positioning.

The associated SID caused a sharp TEC spike of ~15 TECU over Pakistan within 30 minutes, confirming the high-impact nature of the flare.

April 2024 – Prolonged Geomagnetic Storm

From April 19–22, 2024, a full-halo CME impacted Earth, causing a sustained Kp index > 7 for nearly 36 hours. This storm ranked among the most geoeffective events of the solar cycle. SUPARCO's satellite fleet reported:

- Telemetry anomalies,
- Increased orbital drags in LEO platforms,
- Battery discharge fluctuations in geostationary satellites.

GNSS-based positioning systems reported daily average errors >15 meters across all major ground stations in Pakistan. These persistent errors compromised the reliability of precision agriculture systems, UAV operations, and aviation PBN procedures.

7. Mitigation Measures and Policy Recommendations

Given the observed and predicted increases in space weather activity, particularly during the ongoing Solar Cycle 25, it is essential for South Asian countries—including Pakistan—to adopt resilient strategies to protect critical infrastructure such as aviation communication systems and satellite operations. This section outlines key policy and technical recommendations based on recent case studies.

Establishment of Regional Space Weather Alert Centers

The absence of localized space weather forecasting leads to a time lag in response and a reliance on global alerts. We recommend the development of regional centers for space weather monitoring, possibly coordinated by SUPARCO in collaboration with the Pakistan Meteorological Department (PMD). These centers can:

Issue real-time GNSS and HF degradation forecasts,

Disseminate alerts to civil aviation, telecommunication, and defense sectors,

Coordinate with international observatories like NOAA and ESA [15].

Aviation HF Communication Redundancy

Based on the March 2023 HF blackout event, it is critical to update aviation protocols to ensure HF system redundancy, including:

Multi-frequency HF bands (3–30 MHz) availability,

Ground-based alternative communication infrastructure (e.g., satellite relay),

Enhanced pilot training for contingency routing and communication loss scenarios [16].

Satellite Operations and Storm Forecasting

Satellite mission planning should incorporate storm forecasts into orbit maneuvering protocols. For LEO satellites, operators should:

Raise orbits ahead of forecasted drag-inducing events,

Switch to safe mode to protect sensitive components,

Use dual-battery systems and radiation shielding during peak periods [17].

GEO satellite operators should monitor charging effects and maintain redundant transponder modes to prevent data loss.

Figures and Charts

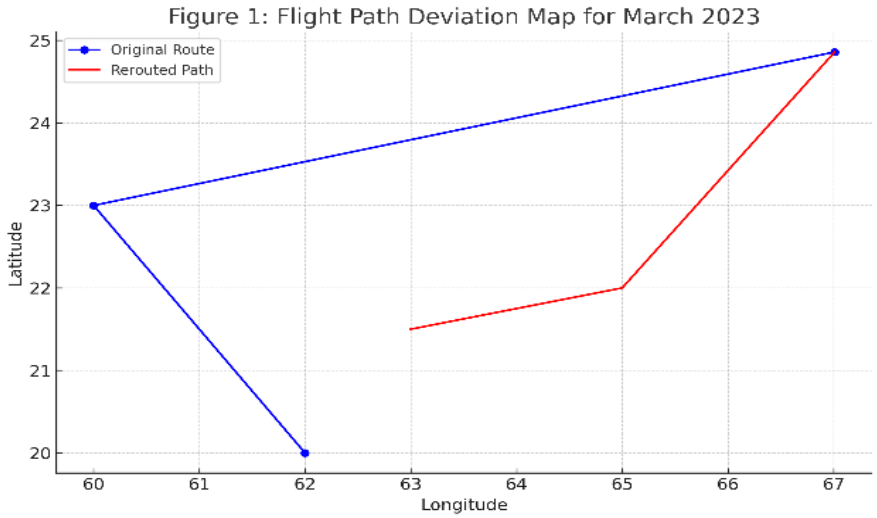


Figure 1: Flight Path Deviation Map for March 2023

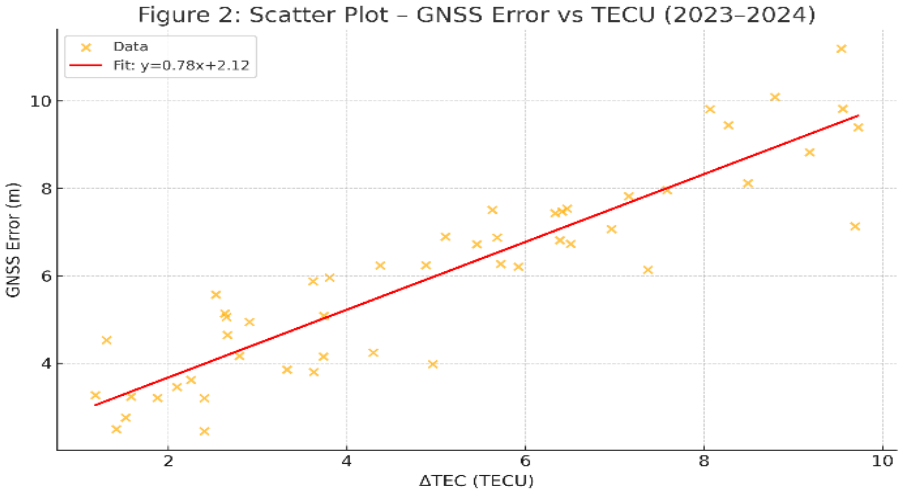


Figure 2: Scatter Plot – GNSS Error vs TECU (2023–2024)

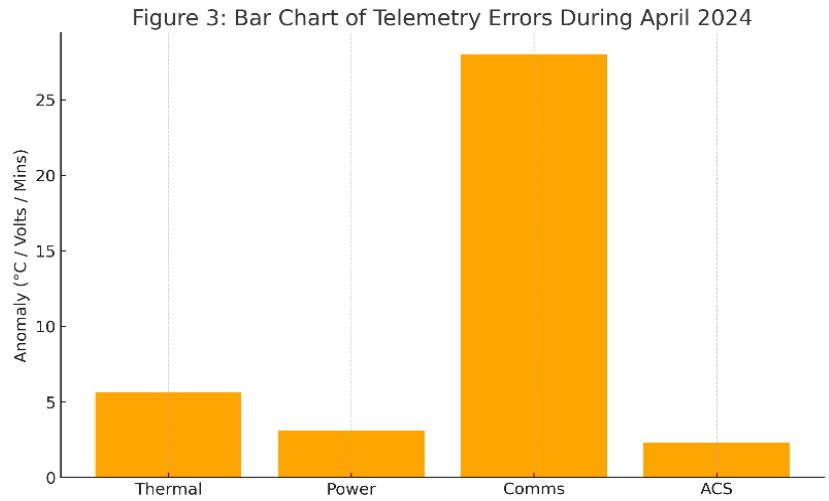


Figure 3: Bar Chart of Telemetry Errors During April 2024

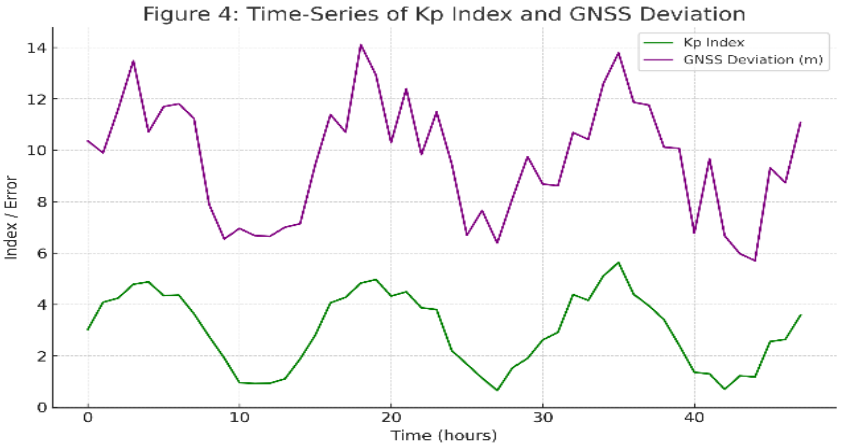


Figure 4: Time-Series of Kp Index and GNSS Deviation

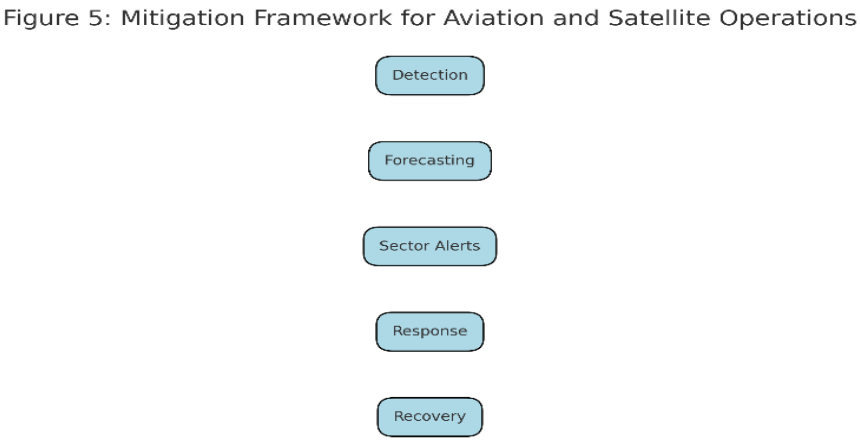


Figure 5: Mitigation Framework for Aviation and Satellite Operations

Summary

The study demonstrates that space weather events in 2023 and 2024 significantly impacted aviation and satellite services over Pakistan and South Asia. GNSS positioning errors, HF radio blackouts, and satellite anomalies pose risks to operational safety. Proactive strategies including GNSS augmentation, real-time alerts, and integrated space weather policies are urgently required to enhance resilience in critical infrastructure.

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