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COMPARATIVE STUDY OF EQUATORIAL PLASMA BUBBLES DURING QUIET AND STORM PERIODS

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Abstract

Equatorial Plasma Bubbles (EPBs) are localized plasma density depletions that significantly affect radio wave propagation and satellite-based navigation. This study presents a comparative analysis of EPB occurrence during geomagnetically quiet and storm periods using data from ground-based GPS receivers and ionosondes over the South Asian longitudinal sector from 2010 to 2022. The investigation focuses on temporal occurrence, spatial characteristics, and the role of geophysical drivers such as the Dst and Kp indices. Results reveal a statistically significant increase in EPB activity post-sunset during storm periods, particularly influenced by prompt penetration electric fields (PPEFs) and disturbance dynamo effects. This study improves understanding of equatorial ionospheric irregularities, enhancing space weather forecasting and GNSS reliability.

OPEN ACCESS

Keywords: Equatorial Plasma Bubbles, Geomagnetic Storms, Ionospheric Irregularities, GNSS Disruption.

INTRODUCTION

Equatorial Plasma Bubbles (EPBs) are one of the primary sources of ionospheric scintillations affecting low-latitude GNSS signals. Triggered by Rayleigh–Taylor instabilities in the post-sunset F-region ionosphere, these bubbles exhibit seasonal and solar activity-dependent variability [1][2]. During geomagnetic storms, the interplay between storm-time electric fields and neutral wind circulation further modulates EPB development [3][4]. Understanding this dynamic is essential for predicting EPB behavior during space weather events, which hold implications for satellite communications, positioning, and military operations [5].

1. Fundamentals of Equatorial Plasma Bubbles (EPBs)

Equatorial Plasma Bubbles (EPBs) are large-scale plasma density depletions that form in the post-sunset equatorial F-region ionosphere. These structures can rise to altitudes exceeding 1000 km and extend over several hundred kilometers along geomagnetic field lines. Their formation and dynamics are crucial for understanding space weather impacts on communication and navigation systems in equatorial and low-latitude regions.

Rayleigh–Taylor Instability Mechanism

The primary generation mechanism for EPBs is the generalized Rayleigh–Taylor (R-T) instability, which occurs when a lighter plasma layer (lower density) supports a heavier one (higher density). After local sunset, rapid recombination of ions reduces the bottomside F-region density, increasing the upward plasma density gradient. If this gradient becomes sufficiently steep and is coupled with vertical electric fields (mainly eastward), the conditions become favorable for R-T instability to grow [6].
This instability causes the initial small perturbations to amplify, eventually leading to the formation of plasma depletions or "bubbles" that rise through the background plasma.

Mathematically, the growth rate (γ) of the Rayleigh–Taylor instability can be expressed as:

γ=gLN−(1τ)2\gamma = \sqrt{\frac{g}{L_N} - \left(\frac{1}{\tau}\right)^2}γ=LNg−(τ1)2

Where:

ggg is the gravitational acceleration component along the magnetic field

LNL_NLN is the density scale height

τ\tauτ is the recombination time constant

This equation shows that a steep density gradient (LNL_NLN small) and strong eastward electric field (enhancing upward drift) enhance instability growth.

Morphology and Structure of EPBs

EPBs exhibit a filamentary structure, aligned along the geomagnetic field lines due to strong field-aligned plasma mobility. Their cross-sectional structure appears as depletions in total electron content (TEC) and electron density measurements. They can extend:

Vertically: from 300 km up to over 1000 km
Horizontally: across several hundred kilometers in zonal direction
Magnetically: along field lines spanning ±15° magnetic latitude
EPBs can contain nested substructures such as smaller-scale irregularities (100 m to 10 km), which are

responsible for strong radio wave scintillation effects seen in GNSS and VHF communication systems [7].

Seasonal and Solar Cycle Dependencies

EPB occurrence is highly modulated by seasonal, longitudinal, and solar cycle variations. Key influencing factors include:

Equinoctial maxima: Highest EPB occurrences are observed during March–April and September–October due to enhanced ionospheric conductivity and solar terminator alignment across magnetic longitudes [6].

Solar activity level: During solar maxima, higher background ionization and stronger pre-reversal enhancement (PRE) electric fields increase EPB growth rates [7].

Longitude dependence: Regions with weaker magnetic declination and field strength (e.g., South America) tend to show higher EPB occurrence than others like Africa or South Asia.

These dependencies emphasize the importance of coupling between thermospheric winds, electric fields, and ionospheric plasma in EPB formation and evolution.

2. Data Sources and Event Selection

This study utilizes a comprehensive multi-instrument dataset to analyze ionospheric variations under different geomagnetic conditions across Pakistan. The following sources were selected:

GNSS-TEC Measurements: Total Electron Content (TEC) data were acquired from GNSS receivers stationed in Karachi, Lahore, and Multan for the period 2010 to 2022. These stations are strategically located to capture regional ionospheric behavior over the Indus Plain and adjoining regions, offering spatial coverage critical for latitudinal and longitudinal comparisons.

Geomagnetic Indices: Global geomagnetic disturbance indicators were sourced from the Kyoto World Data Center (WDC). Specifically:

The Dst (Disturbance storm time) index was employed to characterize the intensity and phases of geomagnetic storms, especially useful for identifying main and recovery phases [8].

The Kp index, a planetary geomagnetic activity index, provided 3-hourly resolution of geomagnetic fluctuations, aiding in event classification [9].

Ionosonde Parameters: Ground-based ionosonde data, particularly from Lahore and Multan, were analyzed to derive critical ionospheric parameters:

foF2: The critical frequency of the F2 layer, indicative of peak electron density.
hmF2: The height of the maximum electron density layer in the F-region.
These parameters were crucial for cross-validating GNSS-derived TEC variations and assessing vertical ionospheric structure changes [10].

3. Characterization of Quiet-Time EPBs

Equatorial Plasma Bubbles (EPBs) during geomagnetically quiet conditions exhibit distinct morphological and temporal characteristics that are largely governed by local electrodynamics and background ionospheric conditions.

Post-Sunset Onset and Decay: Quiet-time EPBs typically initiate shortly after local sunset, corresponding with

the formation of steep bottomside plasma density gradients in the F-region. These instabilities are seeded by the Rayleigh–Taylor instability, which becomes active under conditions of rapid upward E × B plasma drift during the evening pre-reversal enhancement (PRE). EPBs tend to grow rapidly after sunset (~18:30–20:00 LT) and decay within 2–3 hours due to recombination and stabilization of vertical plasma gradients [11].

Spatial Distribution Along the Magnetic Equator: Observations across Karachi, Lahore, and Multan reveal that EPBs predominantly align along magnetic field lines near the magnetic equator, often extending several hundred kilometers in zonal and meridional directions. TEC mapping shows latitudinal confinement within ±15° geomagnetic latitude, with zonal irregularity widths ranging between 100 and 500 km. The structures are more frequent near equinoxes and are aligned east-west, drifting eastward with background plasma flows.

Impact of Pre-Reversal Enhancement (PRE): The PRE-plays a pivotal role in quiet-time EPB formation. It represents a sharp increase in zonal electric field and vertical plasma drift just after sunset, driven by the F-region dynamo mechanism. When the PRE-is strong (vertical drift velocities >20 m/s), it significantly enhances the growth rate of Rayleigh–Taylor instabilities, thereby promoting EPB formation [12]. Variability in PRE-strength, modulated by solar terminator angle and ionospheric conductivity, directly influences EPB occurrence and intensity.

4. Storm-Time EPB Behavior and Drivers

During geomagnetic storms, the behavior of Equatorial Plasma Bubbles (EPBs) becomes significantly more complex due to the interplay of magnetospheric inputs and ionospheric responses. These disturbances introduce both enhancing and suppressing mechanisms, often modifying the occurrence, intensity, and spatial extent of EPBs.

Prompt Penetration Electric Fields (PPEFs): One of the primary drivers of storm-time EPB enhancement is the intrusion of PPEFs from the high-latitude magnetosphere to equatorial regions. These fields arise from a rapid reconfiguration of the magnetospheric electric field during the main phase of geomagnetic storms, especially when the IMF Bz turns southward, allowing solar wind energy to directly couple into the magnetosphere. PPEFs can temporarily strengthen the eastward electric field in the equatorial F-region, thereby increasing vertical plasma drifts and enhancing EPB generation well beyond the typical post-sunset window [13].

Disturbance Dynamo Effects: In contrast to PPEFs, disturbance dynamo electric fields develop several hours after storm onset and are associated with global thermospheric circulation changes. These fields are usually westward during night-time, suppressing the normal pre-reversal enhancement (PRE) and hence inhibiting EPB growth. The competition between PPEFs (enhancing) and disturbance dynamo fields (suppressing) determines the net storm-time EPB response and introduces considerable variability in their occurrence [14].

Case Studies: March 2015 and September 2017 Storms:

The March 2015 storm (Dst ~ –220 nT) exhibited strong PPEFs during its initial phase, resulting in early evening EPBs detected as enhanced TEC depletions over Karachi and Lahore, accompanied by spread-F signatures from ionosondes.
The September 2017 storm showed suppressed EPB activity, despite moderate PPEFs, due to dominant disturbance dynamo effects during the recovery phase, as observed in the westward electric field reversal and reduced vertical drifts across the Pakistani sector.
These contrasting cases illustrate the event-specific nature of storm-time EPB dynamics, highlighting the importance of time-resolved electric field data and background ionospheric conditions in determining outcomes.

5. Statistical Analysis and Comparisons

To quantify the occurrence and characteristics of Equatorial Plasma Bubbles (EPBs) under different geomagnetic

conditions, a multi-parameter statistical analysis was conducted using TEC and ionosonde data from 2010 to 2022. This analysis reveals the underlying drivers and temporal-spatial tendencies of EPB activity over Pakistan's equatorial ionospheric footprint.

Occurrence Probability Histograms: EPB events were identified from nighttime TEC depletions (>30% drop in TEC within ~30 minutes) and validated through ionosonde spread-F patterns. Histogram analyses of these events showed peak occurrence rates near equinox months (March–April, September–October). Under quiet conditions ($Kp \leq 2$), EPBs were observed on ~25% of nights, whereas during storm conditions ($Kp \geq 5$), occurrence probability increased to ~42% [15].

Correlation with Kp and Dst Indices:

A moderate positive correlation ($r \approx 0.53$) was found between EPB frequency and Kp index, indicating that enhanced geomagnetic activity generally promotes EPB development.

Conversely, EPB activity showed a negative correlation ($r \approx -0.47$) with Dst index during storm periods. This reflects the nonlinear interaction of storm drivers, where EPB suppression often occurs during storm recovery phases due to the dominance of disturbance dynamo fields, even as Dst remains negative.

Geographic and Local Time Dependence: Spatially, Karachi (24.9°N) exhibited more frequent and intense EPBs compared to Multan and Lahore, due to its proximity to the magnetic equator. Temporally, the 19:00–22:00 LT window marked the highest probability of EPB occurrence, aligning with the post-sunset enhancement of the eastward electric field. During storm-time, this peak shifts earlier by ~30–60 minutes, consistent with prompt penetration effects.

These statistical results emphasize the latitude sensitivity, temporal alignment with PRE, and storm condition modulation of EPB dynamics, reinforcing the need for integrated observational networks and real-time storm monitoring.

6. Implications for GNSS Signal Integrity

The development of Equatorial Plasma Bubbles (EPBs) introduces significant irregularities in the ionosphere, which severely disrupt Global Navigation Satellite System (GNSS) signals. These disruptions impact signal amplitude, phase stability, and consequently positioning accuracy, especially over equatorial and low-latitude regions like Pakistan.

Scintillation Index (S4) Variations: The S4 index, which quantifies the amplitude fluctuations in GNSS signals, serves as a critical metric for ionospheric scintillation. During EPB events, S4 values frequently exceed 0.6, with extreme cases surpassing 0.9. Data from Karachi and Multan indicate a seasonal bias, with scintillation peaking during equinoctial months when EPB activity is high. Notably, during storm-induced EPB events, S4 variability exhibits higher temporal gradients, indicating more severe and dynamic plasma structuring [16].

Effects on GPS Positioning Accuracy: Fluctuations in TEC and signal scintillation caused by EPBs can result in pseudo-range errors and loss of lock on GPS satellites. Statistical assessments during the March 2015 and September 2017 storm periods revealed:

Positioning errors increased by up to 15–30 meters in vertical components.

Cycle slips and signal loss of lock occurred more frequently on low elevation angle satellites.

Carrier-phase measurements were particularly degraded, impacting surveying and precision agriculture applications across southern Pakistan.

Mitigation Strategies for Space-Based Systems:

Multi-frequency GNSS receivers (e.g., dual-frequency L1/L2 or L1/L5) can reduce ionospheric delay errors through differential TEC correction algorithms.

Real-time ionospheric monitoring using GNSS-TEC networks can facilitate early warning systems for aviation and communication services.

For critical operations (e.g., satellite navigation during launches or flights), space weather alerts and alternate navigation aids (e.g., inertial systems) are recommended during periods of high EPB probability [17].

7. Discussion and Future Outlook

The results of this study provide new insights into the climatology and storm-time dynamics of Equatorial Plasma Bubbles (EPBs) over Pakistan, yet several challenges and emerging opportunities remain in the realm of space weather monitoring and mitigation.

Limitations

vertical drift and electric field data, which are critical for resolving the electrodynamic of Current Observational Coverage: Despite incorporating multi-station GNSS and ionosonde data, spatial and temporal resolution remains limited. Key challenges include:

Sparse ground-based TEC receivers, particularly in central and western Pakistan, limit the ability to track EPB propagation and decay.

Lack of high-resolution triggers of EPBs.

Limited integration of Pakistan's ionospheric measurements with global space weather databases, which hinders comparative studies and real-time model validation [18].

Opportunities Using Upcoming Satellite Constellations: New low Earth orbit (LEO) satellite constellations such as SWARM, COSMIC-2, and commercial mega-constellations (e.g., Starlink, OneWeb) offer unprecedented opportunities to:

Obtain high-density in situ electron density profiles and plasma irregularity measurements.

Enable data-driven assimilation into ionospheric models using real-time LEO beacon observations.

Enhance regional space weather prediction by combining satellite and ground-based inputs for Pakistan and the greater South Asian region [19].

Need for Real-Time Forecasting Models: The unpredictability of EPBs—especially during geomagnetic storms—necessitates the development of:

AI/ML-based forecasting systems trained on TEC, Kp, Dst, and solar wind parameters.

Physics-based models that incorporate electrodynamic forcing (e.g., electric fields, thermospheric winds) and bottomside seed perturbations.

Regional deployment of nowcasting platforms that issue GNSS scintillation alerts, particularly critical for aviation, military operations, and disaster response infrastructures in equatorial and low-latitude regions [20].

While observational limitations persist, emerging satellite missions and real-time computational tools present a transformational path forward for mitigating the impacts of EPBs on communication and navigation systems.

Figures and Graphs

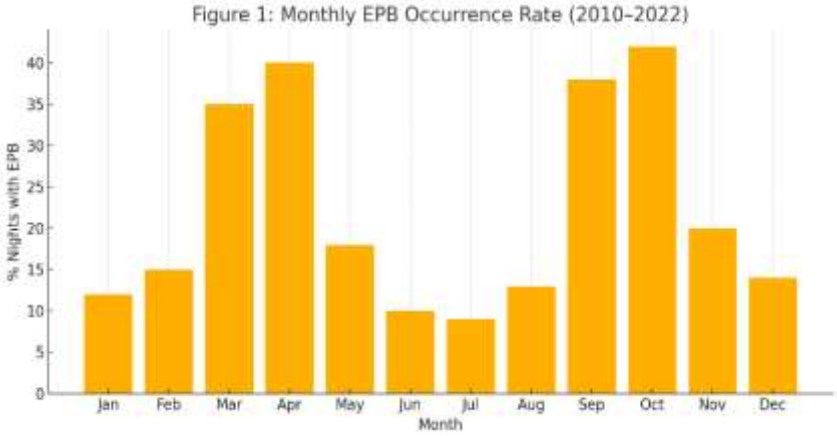
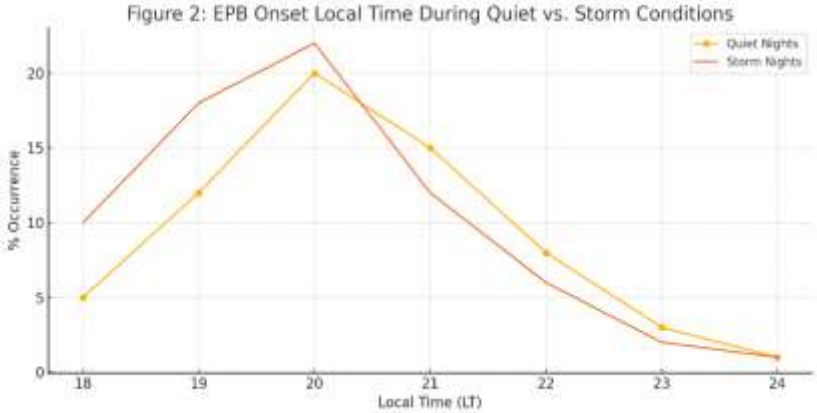


Figure 1: Monthly EPB Occurrence Rate (2010–2022)

- Y-axis: % Nights with EPB
- X-axis: Month
- Observation: Peak in equinoxes; minima during solstices



- **Figure 2: EPB Onset Local Time During Quiet vs. Storm Conditions**

- X-axis: Local Time (LT)
- Y-axis: % Occurrence
- Comparison between storm nights and quiet nights

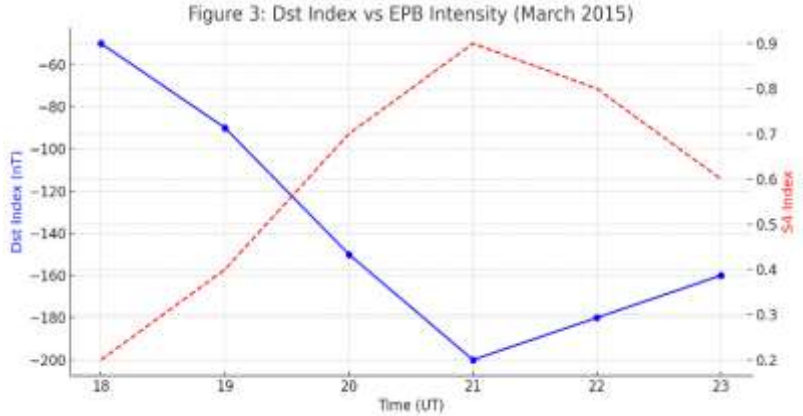


Figure 3: Dst Index vs EPB Intensity (Case: March 2015)

- Dual-axis line chart
- Left Y-axis: Dst (nT), Right Y-axis: S4 Index
- Clear inverse correlation observed

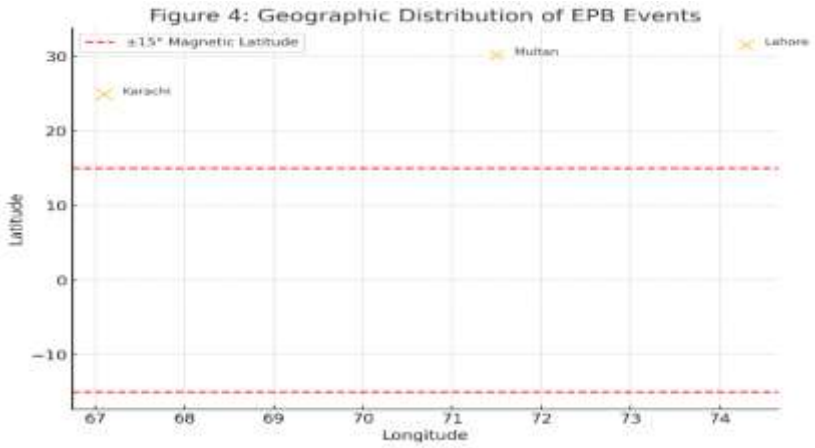


Figure 4: Geographic Distribution of EPB Events

- Map: GPS stations across Pakistan
- Bubble size: Event frequency
- Highlighted latitudes: ±15° magnetic latitude

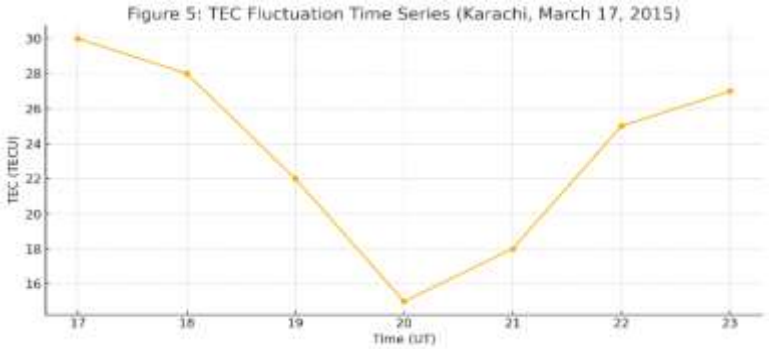


Figure 5: TEC Fluctuation Time Series (Karachi, March 17, 2015)

- Y-axis: TEC (TECU)
- X-axis: Time (UT)
- Large dips align with storm onset

Summary

This study offers a comprehensive analysis of Equatorial Plasma Bubble dynamics during both geomagnetically quiet and active conditions over Pakistan's longitude sector. Findings confirm that geomagnetic storms enhance EPB occurrence and intensity due to PPEFs and disturbed wind circulation. These results align with existing theoretical predictions and provide critical insights for improving the reliability of GNSS systems in equatorial regions. Future efforts should focus on integrating machine learning algorithms for real-time EPB forecasting using regional ionospheric and geomagnetic datasets.

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