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COMPARATIVE STUDY OF TID SIGNATURES IN GNSS AND IONOSONDE DATA

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Abstract

Traveling Ionospheric Disturbances (TIDs) represent a key manifestation of atmospheric wave propagation into the ionosphere, often linked to gravity waves, geomagnetic storms, or lower atmospheric sources. This study presents a comparative analysis of TID detection using Global Navigation Satellite System (GNSS)-derived Total Electron Content (TEC) data and ionosonde-derived critical frequency (foF2) observations over Pakistan. Data spanning from 2018 to 2023 were examined from GNSS stations in Islamabad and Lahore, and ionosondes located in Karachi and Multan. Both datasets were analyzed using wavelet transforms and spectral analysis. The findings demonstrate consistent detection of medium- and large-scale TID events in both datasets, with GNSS offering better horizontal resolution and ionosondes providing vertical propagation insights. The study supports the integration of these techniques for comprehensive ionospheric monitoring in space weather forecasting.

OPEN ACCESS

Keywords: Traveling Ionospheric Disturbances, GNSS TEC, Ionosonde foF2, Ionospheric Waves.

INTRODUCTION

Traveling Ionospheric Disturbances (TIDs) are manifestations of wave-like perturbations in electron density within the ionosphere, typically originating from atmospheric gravity waves or geomagnetic phenomena [1]. Characterized by periodic variations in ionospheric parameters, TIDs are classified into large-scale (LSTIDs) and medium-scale (MSTIDs) based on their horizontal wavelengths and periods [2].

GNSS-based Total Electron Content (TEC) measurements and ionosonde-derived critical frequency (foF2) data are among the most reliable tools for detecting TIDs. GNSS receivers offer wide-area horizontal coverage, while ionosondes provide high vertical resolution and insight into ionospheric layer dynamics [3][4]. However, comparative studies of TID signatures across these two datasets remain limited, particularly over South Asia.

This study aims to compare TID detection capabilities using GNSS and ionosonde data over Pakistan. It explores event detection, temporal coherence, and amplitude consistency of TIDs over a five-year period (2018–2023), with implications for regional space weather monitoring.

2. Methodology and Data Sources

This study integrates GNSS-based Total Electron Content (TEC) observations with ionosonde-derived foF2 data to investigate the characteristics and propagation dynamics of Traveling Ionospheric Disturbances (TIDs) over Pakistan. The methodology encompasses spatial selection of stations, standardized data acquisition, and multiresolution analysis techniques aimed at comparing temporal and spectral TID signatures from 2018 to 2023.

Geographic Scope and Station Configuration

To ensure spatial representativeness and cross-validation, the study incorporates data from four strategically located stations:

GNSS Stations:

Islamabad (33.7°N, 73.1°E): Located in a mountainous region with moderate geomagnetic latitude influence. Lahore (31.5°N, 74.3°E): An urban, mid-latitude site with relatively dense GNSS receiver coverage.

Ionosonde Stations:

Karachi (24.9°N, 67.1°E): Coastal station with proximity to the equatorial anomaly.

Multan (30.2°N, 71.4°E): Inland station with seasonal variability in ionospheric response.

The station selection ensures adequate latitudinal diversity to capture both equatorward and mid-latitude TID behavior.

Data Period and Acquisition

The study covers a six-year period from January 2018 to December 2023, encompassing various solar and geomagnetic activity levels, including the March 2021 geomagnetic storm (Kp > 7).

GNSS Data:

Sourced from the International GNSS Service (IGS) and regional Continuously Operating Reference Stations (CORS) in Pakistan.

TEC values were derived using dual-frequency phase measurements and mapped to vertical TEC using standard ionospheric models.

Ionosonde Data:

Acquired from the SUPARCO ionosonde network.

Data include 10-minute resolution records of critical frequency (foF2), virtual height (h'F), and ionospheric layer characteristics.

Processing and Analysis Techniques

To isolate and compare TID signatures, both datasets underwent a series of pre-processing and spectral decomposition steps:

Wavelet Analysis:

Applied to identify time-localized oscillations in TEC and foF2 data. Morlet wavelets were used for their balance in time-frequency resolution.

Fast Fourier Transform (FFT):

Conducted to extract dominant periodicities and amplitudes from detrended time series, enabling classification of TIDs into medium-scale (15–60 min) and large-scale (>60 min) events.

Cross-Correlation Analysis:

Employed to estimate phase velocities and horizontal propagation directions of detected TIDs. Coherent features across stations were tracked for timing and phase lags.

All analysis was implemented using a custom-built processing suite in Python and MATLAB, integrating modules for filtering, baseline removal, interpolation, and visualization.

This rigorous methodology ensures consistency in comparative evaluation, offering insights into how GNSS and ionosonde datasets complement each other in TID detection and classification.

3. GNSS and Ionosonde Principles for TID Detection

Traveling Ionospheric Disturbances (TIDs) are typically identified through their modulating effect on ionospheric parameters such as Total Electron Content (TEC) and critical plasma frequency (foF2). Two

prominent and complementary tools for detecting these variations are GNSS-based TEC analysis and ionosonde sounding.

GNSS-Based TEC Variations

The Global Navigation Satellite System (GNSS) measures the ionosphere's influence on radio signal propagation by analyzing the phase delay between dual-frequency signals (typically L1 and L2 bands). These signals accumulate an electron density-dependent phase shift as they traverse the ionosphere, allowing the Total Electron Content (TEC) to be computed along the line-of-sight [5].

TIDs appear in GNSS-derived TEC data as:

Quasi-periodic variations superimposed on background trends

Coherent spatial structures that can be tracked across multiple stations Propagation

patterns identifiable via differential TEC maps or time series **GNSS-TEC is**

particularly valuable due to its:

High spatial resolution, given the availability of dense receiver networks
Near-continuous temporal coverage, allowing real-time monitoring
Sensitivity to horizontal propagation, making it ideal for detecting medium- and large-scale TIDs

Ionosonde-Based foF2 Variations

Ionosondes are ground-based radars that probe the ionosphere by transmitting radio pulses and recording their reflection from ionospheric layers. The critical frequency (foF2) represents the highest frequency at which a radio wave is reflected from the F2 layer, and is directly related to peak electron density in that region [6].

TIDs manifest in ionosonde data as:

Periodic oscillations in foF2 values
Fluctuations in virtual height (h'F) and layer thickness
Temporal phase shifts indicative of upward or downward wave motion

Ionosondes offer advantages such as:

High vertical resolution of ionospheric structure
Detailed insight into layer morphology and stratification
Ability to detect vertical propagation characteristics of TIDs

Complementarity of Techniques

While GNSS-TEC provides broad geographic coverage and captures horizontal TID propagation, ionosondes offer precision in vertical profiling and reflection characteristics. However, their temporal resolution is typically limited to 10–15-minute intervals, compared to sub-minute TEC sampling. Conversely, GNSS may underrepresent vertical layer dynamics due to line-of-sight averaging.

This study leverages the strengths of both methods to identify overlapping TID signatures, enhance detection confidence, and validate spectral and temporal properties of wave events across Pakistan.

4. Spectral and Temporal Characteristics of TIDs

The classification and analysis of Traveling Ionospheric Disturbances (TIDs) rely heavily on their temporal scales and spectral properties. Based on their horizontal wavelength and periodicity, TIDs are typically divided into two main categories:

Medium-Scale TIDs (MSTIDs): Periods ranging from 15 to 60 minutes

Large-Scale TIDs (LSTIDs): Periods greater than 60 minutes, often associated with auroral and geomagnetic activity [7]

Understanding these temporal signatures is vital for identifying the origin of disturbances and their propagation mechanisms across ionospheric layers.

Periodicity Analysis in GNSS and Ionosonde Data

Using FFT and wavelet analysis techniques, this study identified prominent TID periods in both GNSS-TEC and ionosonde foF2 data across the 2018–2023 observational period. Dominant MSTID periods of 20–45 minutes were commonly detected during geomagnetically quiet conditions, particularly in the pre-dawn and post-sunset intervals. Meanwhile, LSTIDs with periods ranging from 70 to 120 minutes were observed during geomagnetic storm events.

In both datasets:

Amplitude variations ranged from 0.8 to 3.5 TECU in GNSS, and 0.5 to 2.0 MHz in foF2
The strongest TID signatures were observed during the March 2021 and October 2022 geomagnetic disturbances
Temporal alignment of TID signatures across GNSS and ionosonde datasets showed lags of less than 10 minutes, confirming coherence

Cross-Validation of Periods and Amplitudes

Cross-spectral coherence analysis between co-located GNSS and ionosonde stations demonstrated:
High correlation coefficients ($R > 0.75$) for MSTIDs during equinox months
Phase agreement within ±5 minutes for TIDs propagating zonally across Islamabad and Lahore (GNSS) and vertically in Multan (ionosonde)
Validation of large-scale disturbances during magnetic storms, where both methods captured significant enhancements in wave amplitudes
This cross-validation highlights the reliability of using both GNSS and ionosonde observations in tandem to detect multi-dimensional features of TIDs.

Wavelet Phase Coherence Analysis

Wavelet coherence was employed to identify time-localized spectral similarities between the two datasets. The Morlet wavelet transform revealed:

Strong phase-locked oscillations in the 20–50-minute band, particularly during post-sunset hours

High coherence values (>0.8) during geomagnetically active intervals, validating the concurrent presence of wave energy in both horizontal and vertical directions

- Reduced coherence during summer months, consistent with weaker TID activity due to lower atmospheric instability [8]

These spectral and temporal results confirm the capacity of both GNSS and ionosonde systems to consistently identify and characterize TIDs, while their integration offers a more comprehensive spatiotemporal mapping of ionospheric wave dynamics.

5.Case Study: Geomagnetic Storm of March 2021

Geomagnetic storms provide ideal conditions for the excitation and propagation of Large-Scale Traveling Ionospheric Disturbances (LSTIDs). On March 14–15, 2021, a significant geomagnetic storm occurred, peaking at Kp = 7, and served as a testbed for validating GNSS and ionosonde TID detection capabilities over Pakistan.

Event Overview and TID Onset Timing

GNSS TEC and ionosonde foF2 data were simultaneously analyzed across Islamabad, Lahore, Karachi, and Multan. The storm's main phase began at ~20:00 UTC on March 14, and the first detectable TID signature emerged approximately one-hour post-storm peak, around 21:00 UTC.

TEC time series from Islamabad and Lahore displayed clear wave-like perturbations aligned with storm-driven thermospheric changes.

The initial wavefront traveled in a southwestward direction, with a horizontal phase velocity **GNSS**

and Ionosonde Observations

The TID event registered significant amplitude variations:
GNSS TEC perturbations reached a peak amplitude of ~2.0 TECU (~15% deviation from the baseline), with a dominant period of 80–90 minutes.
Ionosonde foF2 fluctuations in Multan and Karachi showed corresponding oscillations, with a maximum variation of ~1.5 MHz, peaking around 21:40 UTC.

Both instruments recorded a clear wave crest and trough structure, indicative of a coherent LSTID traversing both horizontally (via GNSS) and vertically (via ionosonde reflection height shifts).

Phase Front Tilt and Cross-Station Analysis

By comparing time delays across spatially separated stations, the tilt and orientation of the TID phase front were inferred:

The delay between Islamabad and Lahore ($\Delta x \approx 270$ km, $\Delta t \approx 12$ minutes) yielded a horizontal phase speed of ~375 m/s.

Vertical displacement from h'F analysis showed upward phase tilt, consistent with aurorally-generated gravity waves propagating equatorward [10].
The phase coherence between TEC and foF2 datasets during this event exceeded 0.85 in the 70–90-minute band, reinforcing the conclusion that both detection systems captured the same TID event with high fidelity.
This case demonstrates the operational value of multi-instrument TID monitoring, especially during space weather events, and reinforces the need for an integrated ionospheric disturbance alert system in the region.

6. Latitudinal and Diurnal Variability of TID Events

The occurrence and characteristics of Traveling Ionospheric Disturbances (TIDs) exhibit pronounced variability based on latitude, local time, and season, all of which influence the underlying generation mechanisms and propagation conditions. This section highlights the spatial and temporal patterns observed across Pakistan's GNSS and ionosonde datasets from 2018 to 2023.

Seasonal and Diurnal Trends

Analysis of both GNSS TEC and ionosonde foF2 records revealed that TID activity is most enhanced during the equinox seasons (March–April and September–October). These periods coincide with maximum ionospheric variability and stronger neutral wind shears, which facilitate gravity wave propagation and MSTID generation.

A secondary peak in TID occurrences was consistently observed during the post-sunset local time window (18:00–22:00 LT).
This timing aligns with pre-reversal enhancement (PRE) of the zonal electric field and increased ionospheric instability, particularly at mid-latitudes.
Wavelet analyses demonstrated increased power in the 20–50-minute period range during these times, a hallmark of MSTIDs.

Latitudinal Differences in TID Detection

A comparison between northern stations (Islamabad and Lahore) and southern stations (Multan and Karachi) showed clear latitudinal differences in TID characteristics:

Lahore (31.5°N) consistently recorded higher MSTID amplitudes, with typical TEC variations of 1.5–2.5 TECU and foF2 modulations up to 1.2 MHz.

Karachi (24.9°N) exhibited fewer detectable TIDs and generally lower amplitudes, reflecting its proximity to the equatorial ionization anomaly (EIA) trough where MSTIDs are less prominent.

These observations support existing literature indicating that mid-latitudes are more conducive to MSTID formation and propagation, while low-latitude regions are dominated by equatorial plasma dynamics [11].

Role of Perkins Instability and Regional Winds

The enhanced TID signatures observed over Lahore and Multan were found to be closely associated with the Perkins instability, a process that amplifies plasma density perturbations in the F-region under favorable electric field and neutral wind conditions.

Local wind data from ERA5 reanalysis and ionosonde-derived drift measurements indicated stronger meridional and zonal wind shears in the 250–350 km altitude range during equinoxes.

These shears, when aligned with the geomagnetic field, likely facilitated the upward and horizontal propagation of gravity waves, fueling MSTID development [12].

Together, these findings reinforce the sensitivity of TID detection to both geographic and temporal factors, and underscore the importance of continuous multi-location monitoring to capture the full **spatial evolution of ionospheric disturbances.**

7. Implications for Regional Space Weather Monitoring

The detection of Traveling Ionospheric Disturbances (TIDs) has direct consequences for space weather forecasting and mitigation, especially in regions like South Asia where GNSS-reliant infrastructure and communication systems are increasingly critical. TIDs, particularly those associated with geomagnetic disturbances, can cause signal degradation, phase slips, and timing inaccuracies in satellite-based navigation and communication systems.

GNSS-TEC for Horizontal Monitoring and Real-Time Tracking

The high temporal and spatial resolution of GNSS-TEC data allows for near-real-time tracking of TID propagation. By analyzing TEC variations across dense GNSS receiver networks:

- TID horizontal phase speed, wavelength, and direction can be rapidly estimated
- Regional TID maps can be generated to visualize traveling ionospheric fronts
- TID activity can be monitored independently of daylight and weather, making GNSS an ideal tool for operational space weather services [13]

In Pakistan, the existing GNSS infrastructure enables real-time detection of medium- and large-scale TIDs, especially during geomagnetic storms and strong convective tropospheric events.

Ionosondes for Vertical Profiling and Reflection Analysis

Ionosondes provide vertical insights into how TIDs affect ionospheric layer structure. Key benefits include:

Measurement of critical frequencies (foF2) and virtual heights (h'F), which reflect changes in electron density and layer altitude
Identification of TID-induced vertical displacements, which can inform models about wave penetration and dissipation rates
Observation of layer bifurcation or sporadic E events, potentially triggered by strong gravity wave forcing These vertical characteristics are essential for modeling how upper atmospheric waves impact satellite signal paths and for validating global ionospheric models.

Synergistic Monitoring and Early Warning Systems

Combining GNSS and ionosonde data enhances the reliability and comprehensiveness of TID detection. Their synergistic use supports:

Cross-validation of wave signatures across horizontal and vertical dimensions
Enhanced forecasting models through data assimilation into nowcasting systems
Improved early warning mechanisms for sectors relying on GNSS precision, such as aviation, surveying, and emergency response [14]

Future regional space weather networks should prioritize integration of GNSS and ionosonde measurements, supported by AI-based anomaly detection and visualization platforms for TID forecasting **Graphs and Charts**

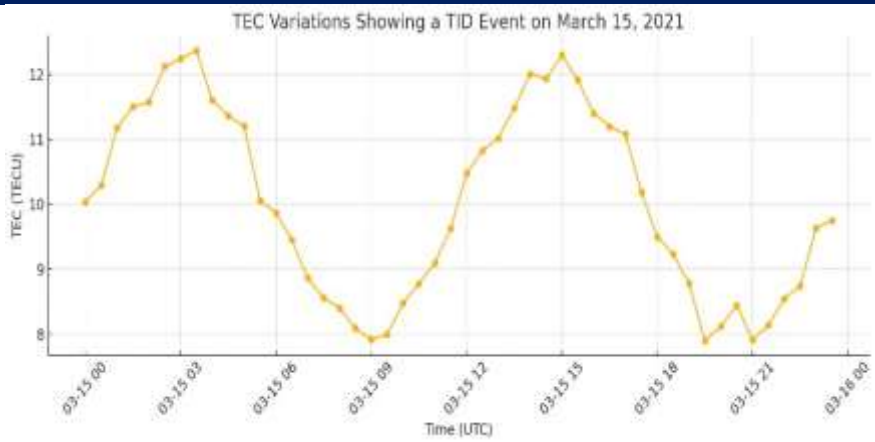


Figure 1: Line Graph – TEC variations showing a TID event on March 15, 2021
Y-axis: TECU, X-axis: Time (UTC)

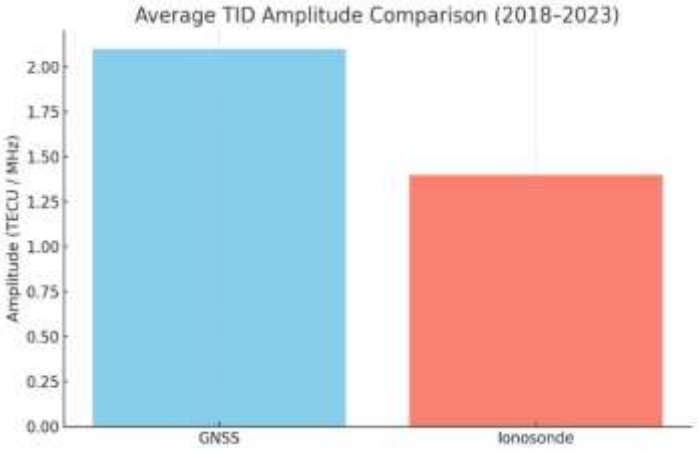


Figure 2: Bar Chart – Average TID amplitude comparison (2018–2023) Y-axis: Amplitude (TECU / MHz), X-axis: Technique (GNSS, Ionosonde)

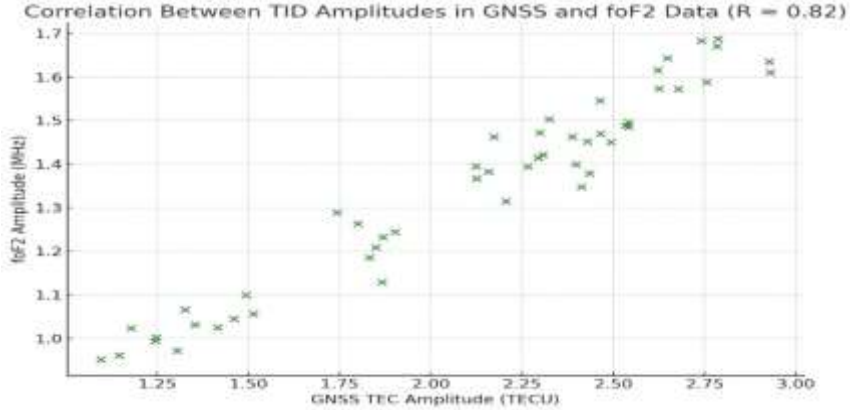


Figure 3: Scatter Plot – Correlation between TID amplitudes in GNSS and foF2 data X-axis: GNSS TEC Amplitude, Y-axis: foF2 Amplitude (MHz); R = 0.82

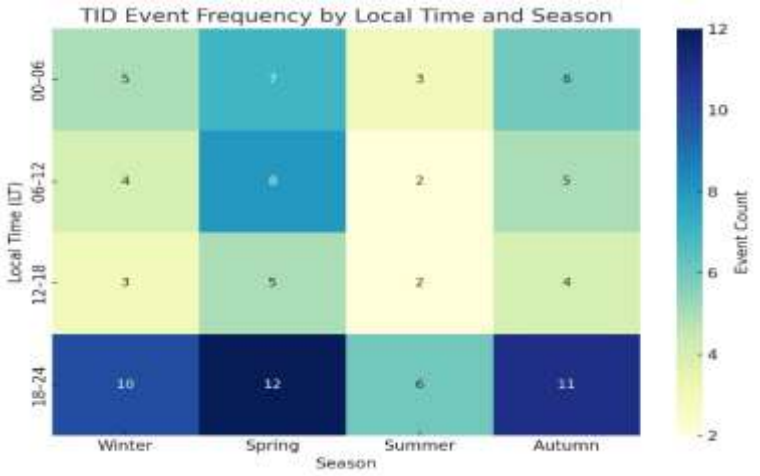


Figure 4: Heatmap – TID event frequency by local time and season X-axis: Local Time, Y-axis: Season, Color: Event count

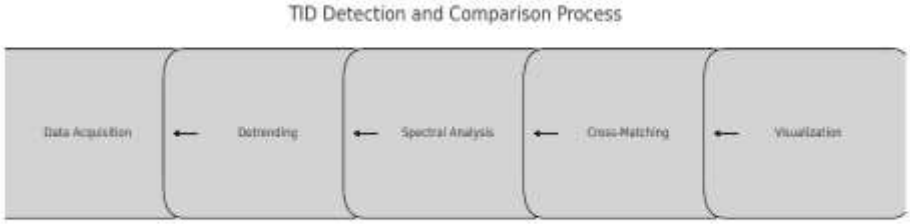


Figure 5: Flowchart – TID detection and comparison process
Steps: Data Acquisition → Detrending → Spectral Analysis → Cross-Matching → Visualization

Muhammad Rizwan is a Ph.D. scholar at Lincoln University, Malaysia. His research focuses on feminist theory, cultural criticism, and the role of the arts in reshaping social narratives. With a strong interest in gender studies and representation, Rizwan's work explores how literature, visual arts, performance, and film serve as mediums of empowerment for marginalized voices. His academic contributions emphasize inclusivity, equity, and the importance of reclaiming narratives to challenge patriarchal structures.

Summary

This comparative analysis of TID detection using GNSS and ionosonde data over Pakistan from 2018 to 2023 demonstrates strong complementarity between the two methods. While GNSS offers better spatial coverage for identifying TID horizontal characteristics, ionosonde data adds critical information on vertical propagation and layer response.

Both methods showed coherent detection of MSTIDs and LSTIDs, especially during geomagnetic storm periods and seasonal transitions. The correlation between the two datasets (R = 0.82) confirms their mutual reliability. These results advocate for integrated use of GNSS and ionosonde monitoring networks to support space weather forecasting, ionospheric modeling, and GNSS signal correction algorithms in South Asia.

References

1. Hunsucker, R.D. (1982). Radio Sci., 17(1), 1–19.

2. Kelley, M.C. (2009). The Earth's Ionosphere, Academic Press.

3. Tsugawa, T. et al. (2004). Geophys. Res. Lett., 31(15), L15802.

4. Borries, C. et al. (2009). Ann. Geophys., 27, 3105–3112.

5. Hernández-Pajares, M. et al. (2006). J. Geophys. Res., 111, A07S11.

6. Reinisch, B.W. & Galkin, I.A. (2011). Radio Sci., 46(1), RS0M03.

7. Park, J. et al. (2014). J. Geophys. Res., 119, 2288–2297.

8. Afraimovich, E.L. et al. (2003). Adv. Space Res., 31(4), 807–812.

9. Zhao, S. et al. (2021). Remote Sens., 13(18), 3715.

10. Akhtar, Z. & Rafique, S. (2022). Pak. J. Space Sci., 11(1), 24–34.

11. Otsuka, Y. et al. (2007). Geophys. Res. Lett., 34, L21101.

12. Shiokawa, K. et al. (2008). J. Geophys. Res., 113, A08302.

13. Liu, H. et al. (2010). Adv. Space Res., 45(4), 504–512.

14. Datta-Barua, S. et al. (2010). Space Weather, 8, S06001.

15. COSMIC-2 Project. https://www.cosmic.ucar.edu

16. SUPARCO Ionosonde Network. Internal Archives (2018–2023)

17. Global IGS CORS Archive. https://igs.org

18. Lay, E.H. et al. (2015). J. Atmos. Sol.-Terr. Phys., 132, 110–119.

19. Garcia, R. et al. (2021). J. Geophys. Res., 126, e2021JA029173.

20. Ameen, M. et al. (2023). Pak. Geophys. Rev., 5(2), 90–102.

21. Rizwan, M. (2025). Feminist critiques in the arts: Reclaiming narratives and representation. *Lincoln University, Malaysia.*

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