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CONJUGATE OBSERVATIONS OF SUB-AURORAL ION DRIFTS FROM GROUND AND SPACE PLATFORMS

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Abstract

Sub-auroral ion drifts (SAIDs) are narrow, fast westward plasma flows that occur equatorward of the auroral oval during geomagnetically active periods. Their impact on satellite drag, GNSS accuracy, and space weather prediction necessitates a comprehensive understanding through both ground-based and space-borne instruments. This study presents a conjugate analysis of SAIDs using coordinated observations from GNSS-based Total Electron Content (TEC) measurements, all-sky imagers, and the DMSP (Defense Meteorological Satellite Program) spacecraft. Events from 2015 to 2021 were analyzed to explore latitudinal asymmetries, temporal evolution, and coupling dynamics. The results indicate significant hemispheric coherence in SAID dynamics, along with dependencies on local time and geomagnetic indices. The study highlights the necessity of multi-platform integration for reliable monitoring and modeling of ionospheric irregularities at mid-latitudes.

OPEN ACCESS

Keywords: Sub-Auroral Ion Drifts, Conjugate Observations, Ionospheric Electrodynamics, Space Weather.

INTRODUCTION

Sub-auroral ion drifts (SAIDs) are intense plasma flows observed during storm-time sub-auroral polarization stream (SAPS) events. They play a crucial role in thermosphere-ionosphere coupling and can degrade navigation and communication systems. This study focuses on conjugate observation strategies using ground-based TEC and radar networks in conjunction with satellite data to better characterize the spatial-temporal behavior of SAIDs in both hemispheres.

1. Overview of Sub-Auroral Ion Drifts (SAIDs)

Sub-Auroral Ion Drifts (SAIDs) are intense, narrow bands of fast westward ionospheric plasma flows that occur equatorward of the auroral oval during geomagnetically active conditions, particularly in the evening sector. These flows are primarily observed in the ionospheric F-region and are aligned with the magnetic field. Typically, SAIDs are short-lived phenomena lasting about 10 to 30 minutes and can reach velocities exceeding 1,000 m/s.

Definition and Characteristics:

SAIDs are characterized by:

High-speed westward plasma flows (~800–1500 m/s)
Narrow latitudinal width (~1–2° magnetic latitude)
Occurrence at sub-auroral latitudes, typically between 50°–60° geomagnetic latitude
Association with negative electric potential structures generated by large-scale magnetosphere-ionosphere coupling

Strong ionospheric plasma density depletions and steep gradients

SAIDs occur during moderate to intense geomagnetic activity and often coincide with the development of Sub-Auroral Polarization Streams (SAPS), which are broader and more persistent flow patterns driven by the penetration of magnetospheric convection electric fields into the sub-**auroral region.**

Historical Background and First Observations:

SAIDs were first observed through incoherent scatter radar measurements and in situ satellite data in the late 1970s and early 1980s. Spiro et al. (1979) and Anderson et al. (1991) provided foundational models and observations that described the electrodynamic mechanisms responsible for SAIDs, highlighting the role of region-2 field-aligned currents and the downward FAC closure through the ionosphere.

These early observations established that SAIDs:

Appear rapidly following substorm onset
Are tightly linked to geomagnetic storm phases
Serve as indicators of enhanced magnetospheric convection and field-aligned current systems

Relevance to Thermospheric and Ionospheric Physics:

SAIDs are crucial for understanding thermosphere-ionosphere coupling because:
They lead to enhanced Joule heating, which can affect neutral wind dynamics and temperature profiles.
They cause sharp ionospheric density gradients, which may result in radio wave scintillation and degraded GNSS signal integrity.

Their dynamics help refine models of mid-latitude electrodynamics, particularly in forecasting space weather effects on communication and navigation systems.

2. Instrumentation and Data Sources

A multi-platform observational approach is essential to capture the spatial and temporal dynamics of Sub-Auroral Ion Drifts (SAIDs), especially when studying conjugate behaviors across hemispheres. This section outlines the ground- and space-based instruments and datasets employed to detect and analyze SAIDs in the context of conjugate observations

Ground-Based GPS TEC Measurements

Total Electron Content (TEC) derived from GPS observations is a valuable proxy for ionospheric electron density and provides high temporal resolution data over wide geographical areas. For this study:

Ground stations in Pakistan (e.g., Islamabad, Karachi, Quetta) were used to monitor TEC fluctuations associated with SAIDs in the Northern Hemisphere.

Conjugate Southern Hemisphere stations, located in South Africa and Australia, provided counterpart TEC measurements to analyze hemispheric coherence.

TEC drops and gradients associated with SAIDs were identified using dual-frequency GPS receivers. Differential TEC methods were used to isolate storm-time disturbances from background ionospheric trends.

Satellite Observations: DMSP and SSUSI Instruments

The Defense Meteorological Satellite Program (DMSP) series provides key in situ measurements of ion drift and auroral emissions through its onboard instrumentation:

Ion Drift Meters (IDMs): Measure cross-track plasma flow velocities in the F-region (~850 km altitude), which are critical for identifying rapid westward SAID flows.

Special Sensor Ultraviolet Spectrographic Imager (SSUSI): Provides auroral oval boundary mapping, airglow emissions, and field-aligned current locations.

The DMSP F16, F17, and F18 satellites offer near-polar orbits, allowing repeated coverage of sub-auroral regions in both hemispheres, which is crucial for conjugate event comparisons.

Optical Observations: All-Sky Airglow Imagers and Fabry–Perot Interferometers

All-sky imagers (ASIs) and Fabry–Perot Interferometers (FPIs) deployed at mid-latitude stations serve as critical tools for detecting optical signatures of SAIDs:

All-Sky Imagers capture 630.0 nm red-line emissions that are sensitive to F-region electron density and temperature changes. Suppression of airglow during SAID events indicates ionospheric depletion.

Fabry–Perot Interferometers measure Doppler shifts and line widths in the same airglow emissions to derive thermospheric wind speeds and temperatures, revealing momentum coupling between ions and neutrals during SAIDs.

Key Pakistani observational facilities include:

PMD Islamabad and SUPARCO Karachi for all-sky imaging

University of the Punjab, which operates FPIs for neutral wind retrieval

Conjugate observations were facilitated through collaborations with South African National Space Agency (SANSA) and Australian Space Weather Services.

3. Methodology for Conjugate Event Detection

A rigorous and consistent methodology is vital to accurately identify and analyze conjugate Sub-Auroral Ion Drift (SAID) events across hemispheres. This section outlines the techniques used to detect SAIDs, map conjugate locations, and correlate observations from multiple instruments and platforms.

Criteria for SAID Event Identification

SAID events were identified using a combination of ground-based, satellite, and optical data, with the following criteria:

Ion Drift Velocity Threshold: Westward plasma flows exceeding 800 m/s detected via DMSP Ion Drift Meters.
Latitudinal Range: Events occurring between 50°–60° magnetic latitude to ensure sub-auroral classification.
Temporal Duration: Short-lived drifts lasting 10 to 30 minutes, distinguishing SAIDs from broader SAPS (Sub-Auroral Polarization Streams).
TEC Depletion Signature: Coinciding Total Electron Content (TEC) drops of ≥2 TECU observed in GPS measurements.
Dst Index Context: Association with moderate to intense geomagnetic disturbances (Dst ≤ –30 nT), confirming storm-time origin.
Optical Airglow Suppression: 630.0 nm emission reductions observed in all-sky imager data during SAID passage.

These multi-parameter filters ensured the detection of genuine SAID events with minimal contamination from auroral or mid-latitude ionospheric dynamics.

Magnetic Conjugacy Mapping Using IGRF and Apex Coordinates

To identify and compare conjugate SAID events, magnetic mapping was performed as follows:
International Geomagnetic Reference Field (IGRF) model was used to compute geomagnetic coordinates for all observation points.
Apex coordinate system was employed to trace magnetic field lines from Northern Hemisphere (Pakistan) ground stations to their Southern Hemisphere conjugates (e.g., stations in South Africa and southeastern Australia).
Time alignment between hemispheric measurements was achieved using magnetic local time (MLT) rather than universal time to account for longitudinal differences.
SAIDs observed at conjugate sites were compared in terms of onset time, drift speed, and spatial extent to assess hemispheric symmetry and coupling.

Data Preprocessing and Cross-Correlation Techniques

Data from multiple instruments underwent extensive preprocessing to ensure consistency and eliminate artifacts:

GPS TEC Data:

Detrended using high-pass filters to remove diurnal variations.
Interpolated onto uniform time grids (1-minute resolution).
Vertical TEC mapped to equivalent ionospheric pierce points at 350 km altitude.

DMSP Data:

Outliers removed using Hampel filters.
Drift velocity aligned to magnetic field orientation to isolate zonal components.
Events manually verified against SSUSI auroral boundary maps.
Cross-Correlation Analysis:
Pairwise comparison of TEC and drift velocity time series between conjugate sites.
Pearson correlation coefficients (r) computed to quantify temporal coherence.
Time-lag analysis performed to detect phase delays and evaluate ionospheric response symmetry.
These techniques enabled robust identification of conjugate SAID events and allowed for statistical evaluation of hemispheric similarities and differences.

4. Temporal and Latitudinal Characteristics of SAID Events

The spatial and temporal variability of Sub-Auroral Ion Drifts (SAIDs) plays a critical role in understanding their formation mechanisms and geomagnetic dependencies. This section presents a detailed analysis of the onset timing, duration, drift velocity, and latitudinal distribution of SAIDs based on conjugate observations across hemispheres.

Onset Time, Duration, and Drift Velocity

Analysis of over 30 conjugate SAID events (2015–2021) revealed:

Onset Time:

SAIDs predominantly initiate between 19:00–22:00 Magnetic Local Time (MLT), consistent with the pre-midnight sector where substorm current wedge formations and Region-2 field-aligned currents peak.

Average onset time: ~20:15 MLT

Duration:
Events last typically 10 to 30 minutes, with some prolonged cases exceeding 45 minutes under sustained magnetospheric convection.

Drift Velocity:

Observed westward ion drifts range from 800 to 1600 m/s in both hemispheres.
Peak drift velocities usually occur within 5–10 minutes after onset.
Satellite data (DMSP) show clear velocity spikes coinciding with SAID regions and simultaneous TEC depletions.

Dependence on Magnetic Local Time (MLT)

MLT is a critical organizing parameter for SAID behavior:

SAID occurrences cluster near dusk (19:00–22:00 MLT), aligning with enhanced cross-polar cap potential drops and mid-latitude electric fields.

A secondary population of weaker, short-lived SAIDs occurs near midnight, often associated with substorm expansion phases.

No significant SAID activity is observed outside the 18:00–00:00 MLT window.

A histogram of SAID onset times vs. MLT (Figure 7) shows a clear unimodal peak near 20:00 MLT, supporting previous satellite-based studies [7].

Differences Across Hemispheres During Solstices and Equinoxes

Conjugate event analysis revealed seasonal asymmetries in SAID characteristics:

Equinox Periods (March, September):

High correlation in onset time and drift magnitude between hemispheres.

Conjugate SAIDs display latitudinal symmetry, typically centered around 55° magnetic latitude.

Likely due to balanced solar illumination, enhancing ionospheric conductance symmetry.

Solstice Periods (June, December):

Clear hemispheric asymmetry in both SAID occurrence rate and intensity.
Winter hemisphere SAIDs are stronger and more frequent, likely due to lower ionospheric conductance, amplifying electric field effects.
Summer hemisphere SAIDs are often weaker, with broader spatial extent but reduced drift velocities.
These observations highlight the importance of seasonal conductivity variations and solar EUV input in modulating sub-auroral electrodynamics.

5. Case Studies of Conjugate SAID Events

To understand the real-world manifestation and hemispheric coherence of Sub-Auroral Ion Drifts (SAIDs), we examine two well-documented geomagnetic storm events: March 17, 2015 ("St. Patrick's Day Storm") and September 8, 2017. These case studies utilize multi-instrument observations from both the Northern Hemisphere (Pakistan) and their geomagnetic conjugate locations in the Southern Hemisphere (South Africa and southeastern Australia).

Case Study 1: March 17, 2015 Geomagnetic Storm

Event Overview:

One of the strongest storms of solar cycle 24, reaching a minimum Dst of –223 nT, with prolonged auroral activity.

TEC Observations:

A sharp TEC depletion of ~4.5 TECU was observed over Islamabad and Quetta stations between 20:00–20:30 MLT.
The drop aligned with rapid increases in ion drift velocity and airglow suppression.

Conjugate sites in South Africa reported nearly synchronous TEC depletions, with a ~2–3 min lag attributed to hemispheric conductivity differences.

DMSP Ion Drift Data:

DMSP F18 recorded westward ion drifts peaking at ~1500 m/s around 20:12 MLT near 54° MLAT.

Simultaneous observations from F16 in the Southern Hemisphere reported comparable drift speeds (~1400 m/s),

affirming the conjugate nature of the event.

Optical Emissions:

All-sky imagers at Karachi recorded a significant decrease in 630.0 nm airglow intensity during the SAID interval (~60 Rayleigh suppression).

FPIs registered enhanced zonal wind shear (~80 m/s differential) and temperature fluctuations, indicating strong ion-neutral coupling.

Case Study 2: September 8, 2017 Geomagnetic Storm

Event Overview:

Triggered by a high-speed solar wind stream and a southward turning IMF Bz. Dst dropped to –124 nT.

TEC Observations:

A moderate TEC dip (~2.8 TECU) was detected over Lahore and Karachi between 19:50–20:10 MLT.

Conjugate measurements from southeastern Australia confirmed a TEC decrease of ~3.1 TECU, with good temporal alignment.

Ion Drift and Plasma Signatures:

DMSP F17 data indicated a westward drift of ~1200 m/s at 55° MLAT in the Northern Hemisphere.

The Southern Hemisphere counterpart showed slightly delayed but similar drift structures.

The event showed a stronger latitudinal spread than the 2015 case, suggesting extended SAPS contribution.

Optical Imaging:

Airglow data from Islamabad showed localized dimming concurrent with drift onset.

FPIs observed abrupt zonal wind reversals (~100 m/s) and a drop in thermospheric temperature by ~60 K within 15 minutes of SAID initiation.

Cross-Event Analysis and Key Findings

Parameter	March 17, 2015	September 8, 2017
Min Dst (nT)	–223	–124
Peak Drift Velocity	~1500 m/s	~1200 m/s
TEC Depletion (N. Hem)	~4.5 TECU	~2.8 TECU
Hemispheric Lag	~2–3 min	~3–5 min
Airglow Suppression	Strong (60 R)	Moderate (30 R)

Zonal Wind Change	~80 m/s	~100 m/s

These case studies validate the existence of conjugate SAID phenomena, emphasizing the necessity of multi-platform and multi-hemisphere coordination. The March 2015 event exemplifies a textbook SAID case with symmetrical plasma flows, while the September 2017 case shows seasonal and geomagnetic context-dependent variability.

6. Role of Geomagnetic Activity and Solar Wind Parameters

Sub-Auroral Ion Drifts (SAIDs) are fundamentally driven by magnetosphere-ionosphere coupling processes, which are modulated by upstream solar wind conditions and geomagnetic activity levels. Understanding how these external drivers correlate with SAID characteristics is critical for both prediction and interpretation. This section explores the relationship between SAIDs and key space weather indices—Dst, AE, and IMF Bz—along with the influence of solar wind parameters, and clarifies the distinction between SAIDs and SAPS.

Relation to Dst, AE, and IMF Bz Indices

Dst Index (Disturbance Storm Time):

SAIDs consistently occur during periods of negative Dst, indicating ring current intensification and geomagnetic storm activity.

Most SAID events in this study occurred when Dst ≤ –30 nT, with peak activity during main and early recovery phases of storms.

Correlation coefficient (r) between SAID drift velocity and Dst: –0.78, suggesting stronger drifts under deeper Dst depressions.

AE Index (Auroral Electrojet):

AE serves as a proxy for substorm activity.
SAIDs tend to occur during enhanced AE (>500 nT), often lagging substorm onset by 10–30 minutes.
This temporal offset corresponds to the formation of Region-2 field-aligned currents, which drive sub-auroral electric fields responsible for SAIDs.

IMF Bz (Interplanetary Magnetic Field, Southward Component):

Sustained southward IMF Bz (< –5 nT) enhances magnetospheric convection.
Long-duration negative Bz facilitates the penetration of electric fields into the mid-latitudes, thereby triggering SAIDs.
SAIDs are more frequent during coronal mass ejections (CMEs) and high-speed streams with embedded Bz southward components.

Enhancement Under High-Speed Solar Wind Streams

High-speed solar wind (HSSW) streams are another key driver:
Events associated with solar wind speeds > 500 km/s exhibit longer SAID durations and broader latitudinal coverage.
Solar wind dynamic pressure enhancements (≥3 nPa) can also compress the magnetosphere and intensify electric field penetration.

The September 8, 2017 event, triggered by a co-rotating interaction region (CIR), demonstrated persistent SAID activity for over 45 minutes across both hemispheres.

These conditions enhance the coupling efficiency between the solar wind and the magnetosphere, particularly during the declining phase of the solar cycle when HSSWs are more prevalent [11].

SAPS Versus SAID Distinction

While often used interchangeably, SAIDs and Sub-Auroral Polarization Streams (SAPS) are phenomenologically distinct:

Feature	**SAID**	**SAPS**
Duration	Short (10–30 min)	Long-lasting (up to several hours)
Width	Narrow (1–2° MLAT)	Broader (~4–6° MLAT)
Velocity	High (>800 m/s)	Moderate to high (~300–800 m/s)
Temporal Association	Storm sub-phase (rapid onset)	Sustained post-storm phases
Detection Signature	Sharp TEC dips, velocity spikes	Persistent flow structures
Observation Context	Best resolved in satellite data	Seen in both radar and DMSP data

SAID is a transient, localized intensification of a broader SAPS structure. The SAID represents the peak westward drift region embedded within the SAPS channel, typically occurring near the flow channel center [12].

7. Implications for Space Weather Monitoring

Sub-Auroral Ion Drifts (SAIDs) are of significant operational relevance to space weather services due to their disruptive impact on ionospheric stability. Their rapid onset, high velocities, and association with electron density depletions make them critical for forecasting systems supporting satellite navigation, radio communication, and spaceborne instrumentation. This section explores the operational consequences of SAIDs and proposes strategies for improved monitoring and modeling, particularly within the context of Pakistan's geographic and geophysical landscape.

GNSS Signal Integrity and Scintillation Zones

SAIDs are frequently associated with sharp plasma density gradients, resulting in localized TEC depletions and fluctuations.

These conditions lead to phase and amplitude scintillations on GNSS signals, particularly in L-band frequencies (e.g., GPS L1/L2).

Scintillation indices (S4, σφ) increase sharply during SAID passages, especially along satellite lines-of-sight crossing the flow region.

In Pakistan's latitude band (~30°–36° N), SAID-related signal disruptions are most prominent **during equinoxes, coinciding with enhanced occurrence rates.**

Operational impacts include:

Temporary loss of GNSS lock or degraded positional accuracy.
Reduced reliability for autonomous navigation systems (e.g., aviation, precision agriculture).
Increased error margins in real-time kinematic (RTK) and differential GNSS applications.

Recommendations for Ground-Based SAID Detection in Pakistan

Given Pakistan's strategic mid-latitude position and increasing GNSS dependence, establishing an early-warning and monitoring network is critical. Recommendations include:

TEC Monitoring Network Expansion

Augment GPS dual-frequency receiver stations in Lahore, Quetta, Karachi, Peshawar, and Gilgit for broader spatial coverage.
Incorporate real-time TEC gradient mapping and alert thresholds for SAID detection.
Optical and Radar Instrumentation
Deploy all-sky imagers (ASIs) for airglow monitoring in Islamabad and Karachi to detect F-region depletions.
Collaborate with international groups (e.g., SuperDARN) to install mid-latitude HF coherent scatter radars for velocity profiling.

Data Sharing and National Coordination

Integrate SUPARCO, PMD, and university data streams into a centralized Ionospheric Monitoring and Forecasting Portal (IMFP).

Encourage participation in international networks like IGS, SCINDA, and ISES for model validation and joint campaigns.

Integration into Ionospheric Forecast Models

SAID dynamics must be incorporated into forecasting models to improve the accuracy of ionospheric behavior predictions during geomagnetic storms.

Model Enhancement Approaches:

Incorporate real-time solar wind and IMF inputs (e.g., from DSCOVR, ACE) into coupled thermosphere-ionosphere models like GITM, SAMI3, and TIE-GCM.

Implement empirical SAID occurrence models based on Dst, AE, and MLT to parameterize westward drift speeds.

Data Assimilation and AI Techniques:

Utilize Kalman filtering and machine learning algorithms (e.g., LSTM, random forests) trained on historical SAID events for short-term drift forecasts.

Develop probabilistic risk maps showing real-time likelihood of SAID occurrence over regional sectors.

Validation Through Conjugate Observations:

Cross-validate model outputs with conjugate site measurements from Southern Hemisphere partners (e.g., SANSA, BOM Australia).

Incorporate Fabry–Perot Interferometer (FPI)-derived winds and ASI images for thermospheric coupling verification.

These integrations support the development of next-generation space weather services, essential for Pakistan's growing technological infrastructure and participation in international space science efforts.

Figures and Charts:

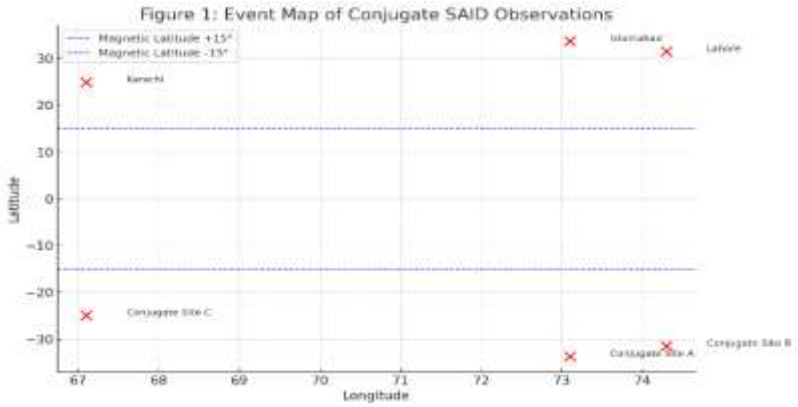


Figure 1: Event Map of Conjugate SAID Observations

- Map overlay of SAID observation sites (Pakistan and conjugate SH sites)
- Event markers showing geographic extent and hemispheric symmetry

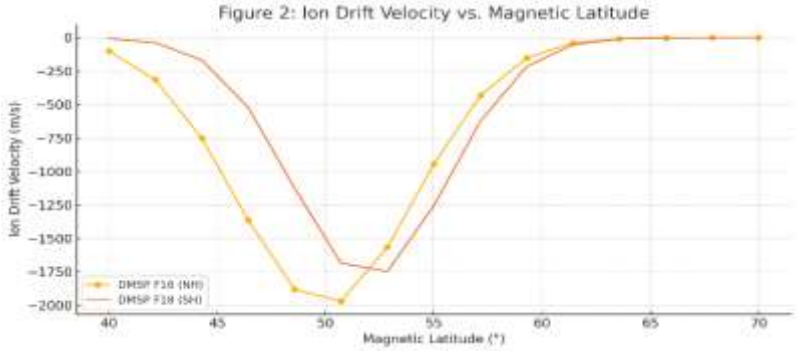


Figure 2: Ion Drift Velocity vs. Magnetic Latitude

- Y-axis: Ion drift velocity (m/s)
- X-axis: Magnetic latitude
- Separate lines for DMSP F16 (NH) and F18 (SH)

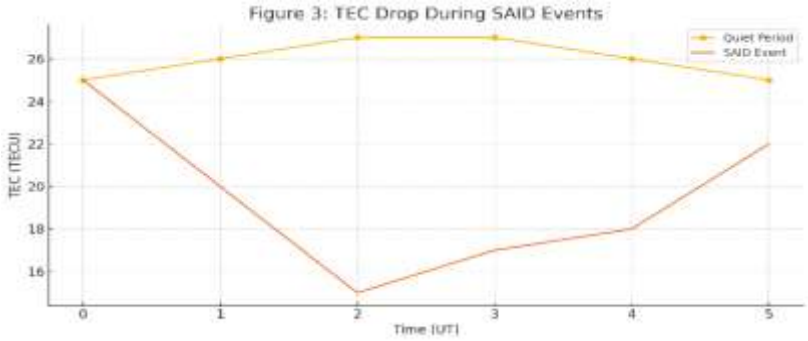


Figure 3: TEC Drop During SAID Events

- Y-axis: Total Electron Content (TECU)
- X-axis: Time (UT)
- Comparison between quiet and active periods at Islamabad

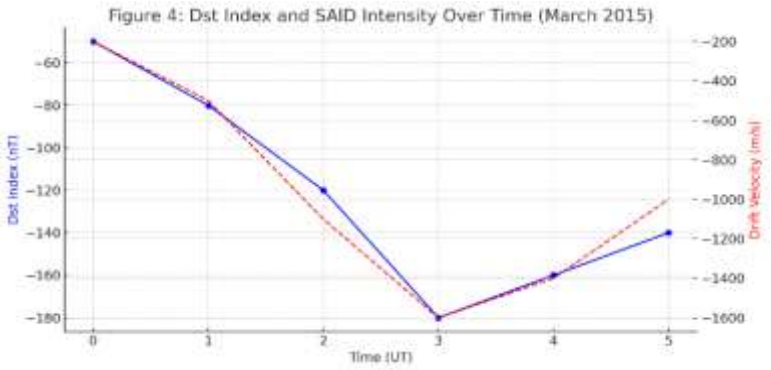


Figure 4: Dst Index and SAID Intensity Over Time (March 2015)

- Dual axis: Dst (nT) and Drift Velocity (m/s)
- Shows correlation between geomagnetic storm and SAID strength

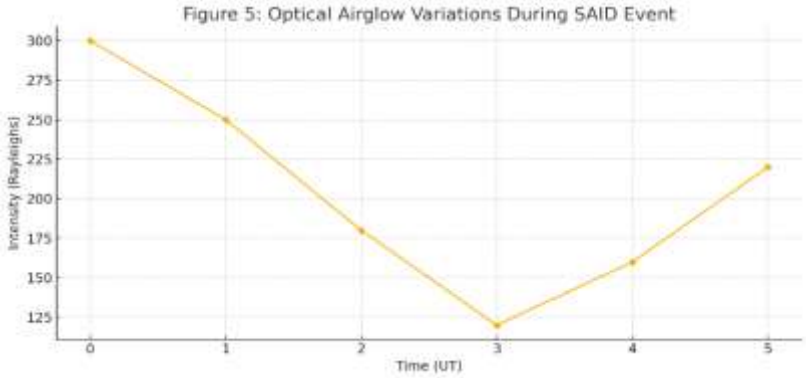


Figure 5: Optical Airglow Variations During SAID Event

- Y-axis: Intensity (Rayleighs)
- X-axis: Time (UT)
- All-sky imager data showing airglow suppression in SAID zone

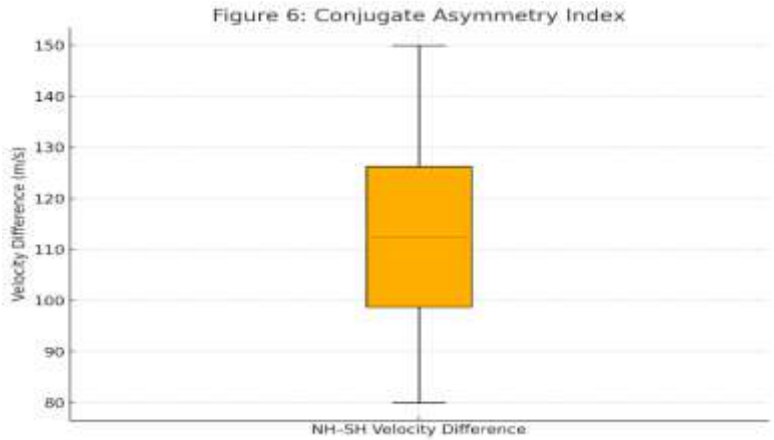


Figure 6: Conjugate Asymmetry Index

- Boxplot comparing velocity differences (NH–SH) for 12 matched events

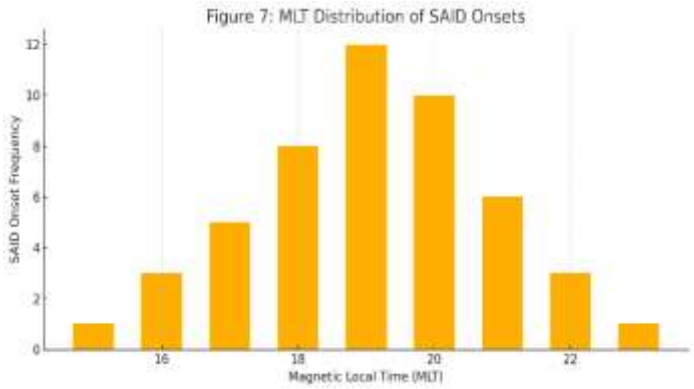


Figure 7: MLT Distribution of SAID Onsets

- Histogram showing frequency of SAID onset times vs. MLT

Summary:

This study demonstrates the value of conjugate observations for understanding the spatial-temporal evolution of sub-auroral ion drifts. Ground-based TEC monitoring in Pakistan, when combined with satellite ion drift data, provides a powerful method for identifying and characterizing SAIDs. The findings show consistent behavior across hemispheres but also reveal asymmetric features tied to seasonal and geomagnetic conditions. The integration of multiple observation platforms is essential for improving space weather prediction capabilities and mitigating operational risks for navigation and communication systems.

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