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Impact of Geomagnetic Storms on the Earth's Ionosphere: A Multi-Latitude foF2 Study During Solar Cycle 25

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Abstract:
This study investigates the impact of geomagnetic storms (GSs) on the Earth's ionosphere during Solar Cycle 25 using the disturbance storm time (Dst) index and the critical frequency of the F2 layer (foF2). Four intense GS events occurring on 24 April 2023, 11 May 2024, 12 November 2025, and 20 January 2026 were analyzed. Ionosonde data from low-, mid-, and high-latitude stations were used to examine the latitudinal variation of ionospheric response. The results show that GSs produce significant and non-uniform changes in foF2 across different regions. High-latitude stations exhibit strong fluctuations and depletion due to particle precipitation and enhanced electrodynamic processes. Low-latitude regions generally show delayed responses, often characterized by an initial decrease followed by recovery or enhancement, associated with penetration electric fields and disturbance dynamo effects. Mid-latitude stations display mixed behavior with both positive and negative storm effects depending on the storm phase. The May 2024 event shows the strongest disturbance, highlighting the influence of storm intensity on ionospheric variability. Overall, the study confirms that ionospheric responses to GSs are highly dependent on latitude, local time, and thermosphere–ionosphere coupling processes. These findings contribute to a better understanding of space weather effects and are important for improving prediction models and mitigating impacts on communication and navigation systems.

Keywords: Geomagnetic storms (GS) , Ionosphere , F2-layer , foF2 variability , Dst index, Space weather, solar cycle 25

Introduction:

The Earth's ionosphere is a highly dynamic region that responds continuously to variations in solar and magnetospheric forcing. Its electron density is primarily controlled by solar extreme ultraviolet (EUV) and X-ray radiation, along with electric fields and thermospheric neutral winds. During GS conditions, enhanced coupling between the solar wind and Earth's magnetosphere leads to large-scale disturbances in ionospheric structure and dynamics. These disturbances significantly modify plasma distribution and electrodynamic processes across different latitudes, as discussed by [1]**.** GSs are mainly driven by solar transients such as coronal mass ejections and high-speed solar wind streams, which compress the magnetosphere and intensify magnetospheric convection. As a consequence, strong electric fields are generated at high latitudes and can penetrate to equatorial and mid-latitude regions, altering plasma motion through E × B drift mechanisms. The combined role of neutral composition changes and vertical plasma drift in controlling daytime F2-region storm effects has been emphasized in earlier studies such as[1] and related works on ionospheric variability. One of the most significant impacts of GSs is observed in the F2 layer of the ionosphere, which contains the maximum electron density. Variations in this layer are described using parameters such as the critical frequency (foF2) and peak electron density (NmF2). Depending on storm-time processes, ionospheric responses can be classified as positive (enhancement in electron density) or negative (depletion of electron density). These variations are strongly influenced by local time, latitude, and thermospheric circulation changes, as reported by [2-4]. The intensity of GSs is commonly characterized using the disturbance storm time (Dst) index, which reflects the strength of the ring current. Based on Dst values, storms are categorized into different levels of severity, as defined by[5]. Strong geos can significantly affect technological systems, including satellite communication, navigation systems, and ground-based power grids, due to ionospheric irregularities and signal degradation, as highlighted in recent studies such as [6] and other regional investigations. From a physical perspective, storm-time ionospheric variability is governed by a combination of prompt penetration electric fields and disturbance dynamo effects. These processes modify thermospheric winds, alter neutral composition, and influence ion production and recombination rates. The F2 layer, located near a constant pressure level in the thermosphere, is particularly sensitive to these changes. Variations in the peak height (hmF2) are largely controlled by vertical plasma drifts and neutral wind dynamics, as explained by [7] and [8]. Earlier studies have also examined seasonal and latitudinal dependencies of ionospheric response to GSs, showing that the thermosphere–ionosphere system behaves differently under varying background conditions, as demonstrated by [2,3]. In this context, the present study investigates the response of the ionospheric F2 region during GS events by analyzing variations in foF2 and their relationship with geomagnetic indices such as Dst. The objective is to improve the understanding of ionospheric dynamics under disturbed conditions and contribute to more accurate space weather prediction models.

Data and methodology:

Table 1: Summary of selected GS events during Solar Cycle 25, showing the case study number, date of minimum Dst, and corresponding Dst values used for ionospheric analysis.

Case study	Dst minima date	Dst value
Case-1	April 24, 2023	-213
Case-2	May 11, 2024	-406
Case-3	November 12, 2025	-217
Case-4	January 20, 2026	-235

In this study, ionospheric and geomagnetic data were analyzed for selected intense storm events during Solar Cycle 25 (2023–2026). The critical frequency of the F2 layer (foF2) was obtained from the Global Ionosphere Radio Observatory database (https://giro.uml.edu/didbase/scaled.php), which provides global ionosonde measurements. The GS intensity was characterized using the disturbance storm time (Dst) index, acquired from the NASA Space Physics Data Facility https://omniweb.gsfc.nasa.gov/form/dx1.html). Hourly values of both foF2 and Dst were used to examine the ionospheric response during different phases of GSs. Four major GS events were selected based on their minimum Dst values: April 24, 2023 (−213 nT), May 11, 2024 (−406 nT), November 12, 2025 (−217 nT), and January 20, 2026 (−235 nT). These events represent intense to severe geomagnetic disturbances and were used as case studies to examine ionospheric variability. To examine ionospheric variability during GSs of Solar Cycle 25, digital ionosonde observations were analyzed from representative low-, mid-, and high-latitude stations. For the 2024 event, data were obtained from Ascension land (low latitude), Canberra (mid latitude), and Millstone Hill (high latitude). For the 2023 storm, Tromso was considered as the high-latitude station along with Ascension (low latitude) and Canberra (mid latitude). In the 2025 case, Canberra and Ascension were used for mid- and low-latitude observations, respectively, while Gakona represented high-latitude conditions. Similarly, for the 2026 event, Canberra (mid latitude), Ascension (low latitude), and Tromso (high latitude) stations were selected. These stations were chosen to ensure a comprehensive latitudinal coverage and to effectively investigate the ionospheric response under varying GS conditions.

Result and discussion:

Case1: April 24, 2023

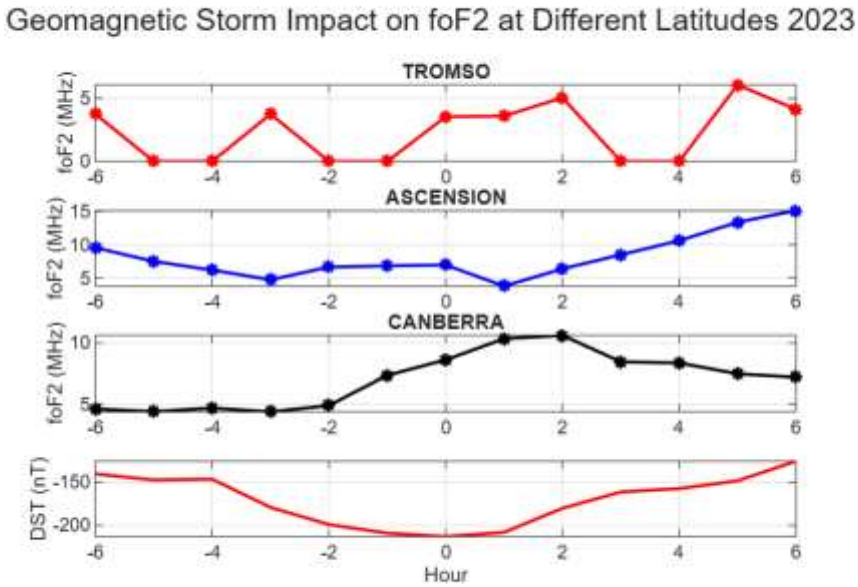

Figure1: Variation of foF2 at high-latitude (Tromsø), low-latitude (Ascension), and mid-latitude (Canberra) stations along with the Dst index during the GS event of 24 April 2023. The figure illustrates distinct latitudinal differences in ionospheric response relative to the storm's main and recovery phases.

On 24 April 2023, a GS event is observed, characterized by a gradual decrease in the Dst index reaching a minimum of −213 nT, indicating an intense geomagnetic disturbance (Schunk & Nagy, 2000). The variation of Dst clearly shows the main phase around hour 0, followed by a recovery phase thereafter [8]. Such a strong negative excursion in Dst reflects enhanced ring current intensity and significant energy input from the solar wind into the magnetosphere–ionosphere system [9]. The response of the ionospheric critical frequency (foF2) to this storm exhibits clear latitudinal dependence [10]. At high latitude (Tromso), foF2 shows strong fluctuations with intermittent enhancements and sharp decreases, indicating unstable ionospheric conditions due to particle precipitation and enhanced electrodynamic processes [9]. At low latitude (Ascension), a gradual increase in foF2 is observed after the main phase, suggesting a positive ionospheric storm effect, likely driven by prompt penetration electric fields and disturbance dynamo effects [10]. In contrast, at mid latitude (Canberra), foF2 initially increases near the main phase and then decreases during recovery, indicating a transition from positive to negative storm effects [11]. Overall, the graph demonstrates that the GS produces both positive and negative ionospheric responses depending on latitude and local time [12]. This behavior is consistent with earlier studies, which report that ionospheric storm effects vary significantly with latitude due to changes in thermospheric composition, electric fields, and neutral winds [8]. The observed variability confirms that GSs do not produce uniform ionospheric responses, but rather a complex, location-dependent behavior of foF2 [13].

Case 2: May 11, 2024

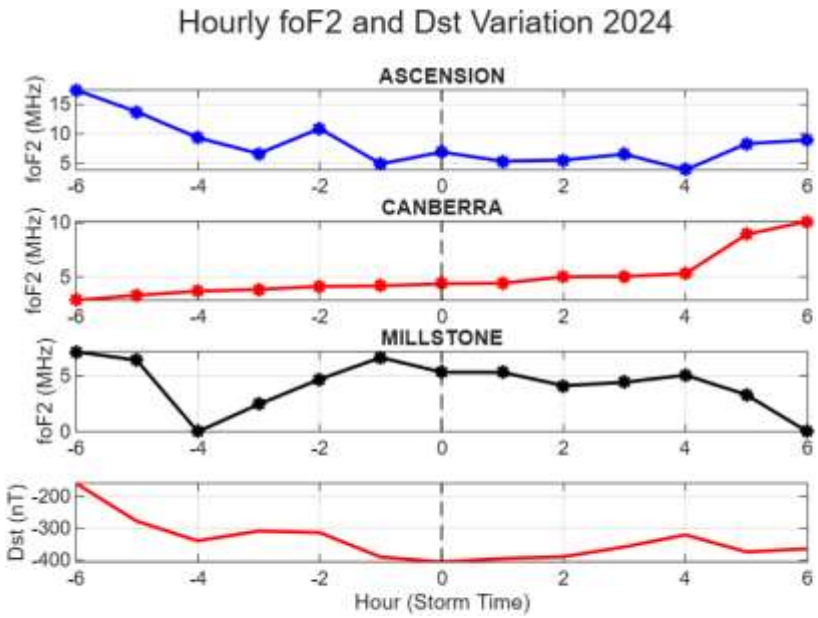

Figure 2: Hourly variation of foF2 at low-latitude (Ascension), mid-latitude (Canberra), and high-latitude (Millstone Hill) stations along with the Dst index during the GS event of 11 May 2024. The dashed line indicates the storm main phase (hour 0), showing distinct latitudinal ionospheric responses under severe geomagnetic disturbance conditions.

On 11 May 2024, a severe GS is observed, as indicated by the Dst index reaching a minimum value of -406 nT, representing an intense main phase around hour 0 [9]. The sharp decrease in Dst reflects strong magnetospheric disturbances caused by enhanced solar wind–magnetosphere coupling [8]. Following the main phase, a gradual recovery in Dst is evident, indicating the decay of the ring current system [13]. The ionospheric response, represented by foF2 variations, shows a clear latitude-dependent behavior. At the low latitude station (Ascension), foF2 initially decreases significantly before the main phase, followed by moderate fluctuations and slight recovery after hour 0, indicating a negative ionospheric storm effect [10]. This behavior is mainly attributed to thermospheric composition changes, particularly a decrease in the O/N_2 ratio, along with disturbance dynamo effects [8]. At the mid-latitude station (Canberra), foF2 exhibits a gradual increase throughout the storm period, especially during the recovery phase, suggesting a positive ionospheric storm effect [8]. This enhancement is likely driven by equatorward neutral winds and storm-time electrodynamic processes that increase plasma density [13]. At the high latitude station (Millstone Hill), foF2 shows strong variability with alternating decreases and recoveries, reflecting unstable ionospheric conditions [9]. This behavior is associated with auroral particle precipitation, Joule heating, and enhanced electric fields that dominate high-latitude ionospheric dynamics during GSs [10]. Overall, the results confirm that the 11 May 2024 GS produces mixed ionospheric responses, including negative effects at low latitudes, positive effects at mid latitudes, and highly variable conditions at high latitudes [8]. This demonstrates that ionospheric storm effects are strongly dependent on latitude, local time, and thermosphere-ionosphere coupling processes [13].

Case3: November 12, 2025

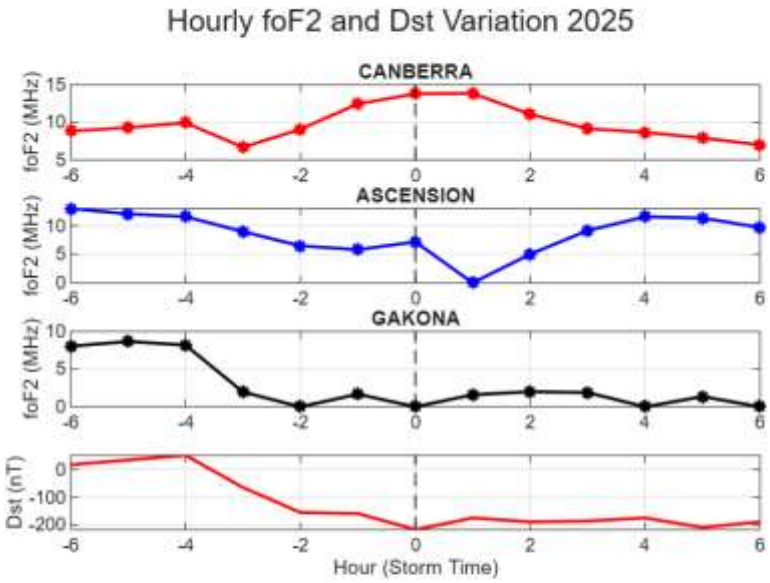

Figure 3: Hourly variation of foF2 at mid-latitude (Canberra), low-latitude (Ascension), and high-latitude (Gakona) stations along with the Dst index during the GS event of 12 November 2025. The dashed line indicates the storm main phase (hour 0), highlighting distinct latitudinal responses of the ionosphere during the storm evolution.

On 12 November 2025, a GS event is observed, with the Dst index decreasing to −217 nT, indicating a moderate to intense geomagnetic disturbance [13, 14]. The Dst profile shows a clear main phase around hour 0, followed by a recovery phase, representing the development and decay of the magnetospheric ring current [8]. Such a decrease in Dst reflects enhanced energy transfer from the solar wind into the magnetosphere–ionosphere system [9]. The ionospheric response in terms of foF2 shows significant latitudinal variation [10]. At the mid-latitude station (Canberra), foF2 increases steadily before the main phase and reaches peak values near hour 0, followed by a gradual decline, indicating a positive ionospheric storm effect during the main phase [15,16]. At the low latitude station (Ascension), foF2 shows a decreasing trend before the main phase and drops sharply to a minimum around hour 1, followed by a strong recovery and enhancement, indicating an initial negative storm phase followed by a positive phase due to disturbance dynamo effects and penetration electric fields [10,17]. At the high latitude station (Gakona), foF2 exhibits strong depletion, with values approaching near zero around the main phase and fluctuating at low levels throughout the storm period, indicating highly disturbed ionospheric conditions [9]. This behavior is mainly caused by auroral particle precipitation, Joule heating, and enhanced high-latitude electrodynamic processes [13]. Overall, the results indicate that the 12 November 2025 GS produces mixed ionospheric responses, including positive effects at mid latitudes, negative-to-positive transitions at low latitudes, and strong depletion at high latitudes [12].

These observations confirm that ionospheric storm effects depend strongly on latitude, local time, and thermospheric-electrodynamic coupling processes [8, 16].

Case 4 January 20, 2026

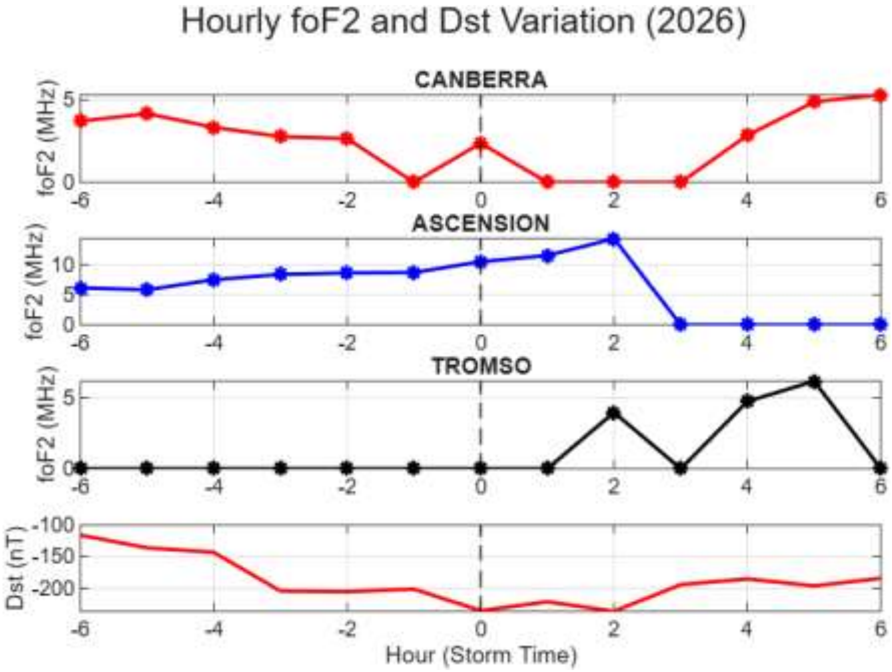

Figure 4: Hourly variation of foF2 at mid-latitude (Canberra), low-latitude (Ascension), and high-latitude (Tromsø) stations along with the Dst index during the GS event of 20 January 2026. The dashed line represents the storm main phase (hour 0), illustrating distinct latitudinal ionospheric responses during the storm evolution.

On 20 January 2026, a GS event is observed, with the Dst index decreasing to −235 nT, indicating a moderate geomagnetic disturbance [13, 14]. The Dst profile shows a gradual decrease leading to the main phase near hour 0, followed by a recovery phase, reflecting the development and decay of the magnetospheric ring current [8]. Such variations indicate enhanced coupling between the solar wind and the magnetosphere-ionosphere system [9]. The ionospheric response in terms of foF2 shows a clear latitudinal variation [10]. At the mid-latitude station (Canberra), foF2 exhibits an increase before and around the main phase, reaching peak values near hour 0, followed by a gradual decrease, indicating a positive ionospheric storm effect transitioning into recovery [15,16]. At the low latitude station (Ascension), foF2 shows a decreasing trend prior to the main phase, reaching a minimum shortly after hour 0, followed by a recovery and enhancement phase, indicating an initial negative ionospheric storm effect followed by a positive phase due to disturbance dynamo and penetration electric fields [10,17]. At the high latitude station (Gakona), foF2 displays strong depletion with near-zero values around the main phase along with minor intermittent recoveries, indicating highly disturbed ionospheric conditions [9]. This is mainly due to auroral particle precipitation, Joule heating, and enhanced electric fields dominating high-latitude ionospheric dynamics during GSs [13]. Overall, the results indicate that the 20 January 2026 GS produces mixed ionospheric effects, including positive responses at mid latitudes, negative-to-positive transitions at low latitudes, and strong depletion at high latitudes [12]. These observations confirm that ionospheric storm effects are strongly dependent on latitude, local time, and thermospheric-electrodynamic coupling processes [8, 16].

Discussion and Conclusion:

The analysis of four GS events during Solar Cycle 25 demonstrates that ionospheric response is strongly dependent on latitude, storm intensity, and temporal phase. The Dst index variations clearly indicate the main and recovery phases of each storm, reflecting enhanced solar wind–magnetosphere coupling and increased ring current intensity. The ionospheric parameter foF2 exhibits significant latitudinal variability, confirming the complex nature of storm-time ionospheric dynamics. High-latitude regions show strong fluctuations and depletion in foF2 due to auroral particle precipitation, Joule heating, and enhanced electric fields, leading to highly disturbed conditions. In contrast, low-latitude regions generally exhibit delayed responses, often characterized by an initial decrease followed by recovery or enhancement, driven by prompt penetration electric fields and disturbance dynamo effects. Mid-latitude regions display mixed behavior, including both positive and negative storm effects depending on storm phase and background conditions. Among the studied events, the May 2024 storm produces the most significant ionospheric disturbance, highlighting the role of storm intensity; however, the results also indicate that ionospheric response is not solely governed by Dst magnitude but is influenced by local time and thermosphere–ionosphere coupling processes. Overall, the study confirms that GSs produce non-uniform and location-dependent ionospheric effects, emphasizing the importance of multi-latitude analysis. These findings contribute to a better understanding of ionospheric dynamics during disturbed conditions and are important for improving space weather prediction and minimizing impacts on communication and navigation systems.

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