Intense Geomagnetic Storm effect on the Ionosphere using Ionosonde observation over the 24th Solar Cycle

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Abstract

The ionosphere is significantly impacted by disturbed and unfavorable geomagnetic conditions. Geomagnetic disturbances cause changes in the ionosphere, which is the most prominent effects of space weather on the near-earth environment. In October 2011, March 2012, and July 2012, there were three intense geomagnetic storms (Dst index ≤ 100 nT). Over 24 solar cycles, we examined how they affected the ionosphere at low, mid, and high latitude stations in the northern hemisphere. We examined changes in the critical frequency (foF2) of the ionosphere's F2-region. During the storms. In these case studies, we investigated the behavior of the ionospheric foF2 delay during each of these geomagnetic storms. We obtained very persuasive results in three cases. An analysis of the previously reported results shows that strong geomagnetic storms primarily negatively impact the ionospheric foF2 at low, mid, and high latitudes in the northern hemisphere.

1 Introduction

The Earth's ionosphere is subject to a variety of solar and magnetospheric conditions. The electron density in the ionosphere is influenced by solar EUV and X-ray fluxes, electric fields, and neutral breezes' dynamic effects. In the event of a geomagnetic storm, the solar wind compresses Earth's magnetosphere, causing electric fields to appear along the geomagnetic field lines in the high-latitude ionosphere. These electric fields are able to reach low latitudes, and at high latitudes, they may even impact neutral winds via collisions and accelerate plasma convection. Convection increases ionospheric conductivity, expands the auroral zone, and discharges energetic particles into the lower thermosphere and below. Geomagnetic storms, associated with space weather phenomena and strong cyclones, can affect the entire ionosphere on Earth [1]-[3]. Intense geomagnetic disturbances can lead to significant problems for satellite communication, navigation systems, and ground-based systems, such as radio outages, power grid failures, and scintillations. The geomagnetic storm disturbs the ionosphere's F2 layer. This is a large ionospheric storm, often known as space weather. The ionospheric storm is caused by changes in either the critical frequency (foF2) or the ionospheric electron density (N_e). These changes determine whether the storm is positive (foF2 or N_e goes up) or negative (ionospheric electron density goes down, mostly in the F2 region). These storms change the background electron density over time in high, middle, and equatorial latitudes [4]-[9]. The primary indicators often used to characterize geomagnetic storms are the disturbance storm time (Dst) index, which quantifies the strength of the ring current as well as the magnetic field. The Dst index and the Bz of the Interplanetary magnetic field can classify geomagnetic storms into several categories. These categories include light or minor storms (Dst ≥ -30 nT), moderate storms (Dst ≥ -50 nT), intense storms (Dst ≥ -100 nT), and severe storms (Dst ≥ -200 nT) [10]. F-layer factors reduce positional accuracy and satellite tracking capability. The strong electric currents related to these processes connect the ionosphere at high latitudes with the magnetosphere, causing significant heating of neutral and ionized molecules. Along magnetic field lines, the perturbed thermospheric circulation shifts the neutral composition and transports plasma up and down, which changes the rates at which ionized gases are made and recombined. During this phenomenon, disturbed neutral winds create electric field of polarization via the dynamo effect caused by collisions with plasma in the Earth's magnetic field.

In terms of temporal scale, solar transients have two distinct impacts on Earth: prompt and delayed. The ejection of particles from the sun leads to delayed geomagnetic storm impacts. High latitudes have extensively studied the impact of geomagnetic storms on the Earth's atmosphere, particularly in the E region [11]. Geomagnetic storms have a large impact on the E region at high latitudes. This is because particle precipitation in the cusp and aurora regions results in a considerable amount of ionization. The ionosphere's F2 layer, typically located near a constant pressure level in the thermosphere, contains the majority of the ionospheric electron content [12]. Solar winds raise or reduce the height of the F2 peak (hmF2). Equator-ward winds can cause enhance in the F2 peak height, reaching regions of reduced loss, which results in an increase in the electron density of the F2 region (NmF2). Local time variations of winds and changes in neutral composition at middle latitudes often observe negative ionospheric storm effects in the morning, while positive storm effects are more prevalent in the afternoon and evening. This paper presents the current perspectives on ionospheric storms in the F region. This study explores current perspectives on ionospheric storms in the F region. Some researchers published additional information regarding the response of the lower ionospheric layers [13], [14] and their corresponding references

2 Datasets and Methodology

To investigate the fluctuations in the ionosphere during the 24th solar cycle's intense geomagnetic storms. We used digital ionosonde observations collected at low, mid, and high-latitude stations in the northern hemisphere. In this analysis, there are three stations at low, mid, and high latitudes. We have considered the stations Ramey, PRJ18 (18.5° N, 67.91° W), Millstone Hill, MHJ45 (42.4° N, 71.95° W), and Greenland, NDA81 (81.4° N, 17.5° W), respectively. We selected Sondrestorm, SMJ67 (66.98° N, 50.94° W) as a high-latitude station to analyze the July 15, 2012 event, as Greenland did not provide the necessary data. We also ensured that various datasets were available, removing events with incomplete or unreliable data from our analysis. We used two sets of data to conduct this study: (a) the Storm Intensity Index (Dst) and (b) the critical frequency (foF2) of the ionosphere, measured using a ground-based radio sounding system called Ionosonde. For our study, we obtained the Dst index data from the Space Physics Data Facility OMNI website http://omniweb.gsfc.nasa.gov/. For our investigation, we specifically used the Dst index's hourly values. We downloaded the critical frequency (foF2) data from the Global Ionosphere Radio Observatory's (GIRO) archives at https://giro.uml.edu/didbase/scaled.php GIRO is an open-access source that provides auto-scaled data on the ionospheric electron density profile over the globe.

Table 1. Detail of intense Dst events in the 24th solar cycle

Case Study	Event Date	Dst (min) nT
Case-I	25 Oct 2011	-147 nT
Case-II	9 March 2012	-145 nT
Case-III	15 July 2012	-139 nT

3 Analysis and Results

Geomagnetic disturbances and adverse circumstances have a significant impact on the ionosphere. To investigate the changes in the critical frequency of the ionosphere during these disturbed conditions, we specifically chose three intense geomagnetic storms from 2011 and 2012. The following subsections sequentially discuss these three cases, focusing on the behavior of ionospheric foF2 delay during each of these geomagnetic storms.

Case I: 25 October 2011

On October 25, 2011, one of the most intense geomagnetic storms characterized by a sudden commencement phase followed by the initial and main phases. The storm's intensity index, Dst, reached its minimum or peak value of -147 nT. Along with changes in the storm intensity index Dst, Figure 1.1 shows how the geomagnetic storm that occurred on October 25, 2011, affected the ionospheric foF2. As shown in the figure, the ionospheric foF2 exhibits a distinct decrement at low, mid, and high latitude stations, Ramey, Millstone Hill, and Greenland, respectively. As a result, the geomagnetic storm's impact on the low, mid, and high latitude ionospheric foF2 is clearly negative.

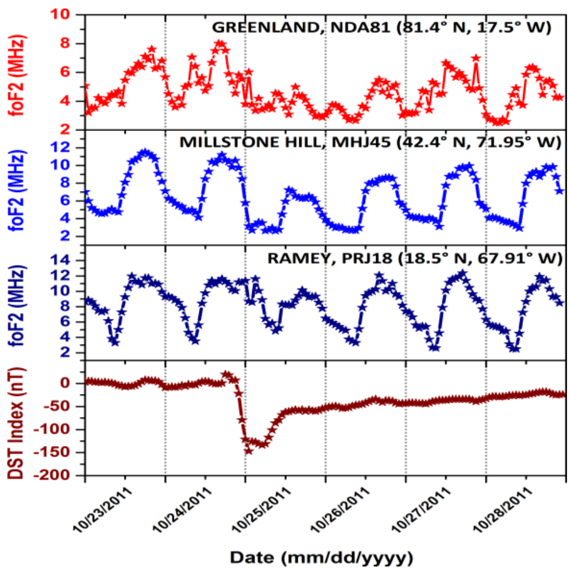

Figure 1.1: foF2 Variation over low-latitude station Ramey, mid-latitude station Millstone Hill, and high-latitude station Greenland with Dst index during the geomagnetic storm of October 25, 2011.

Case II: 09 March 2012

On March 9, 2012, another intense geomagnetic storm occurred, with a minimum recorded Dst value of -145 nT. Figure 1.2 depicts the influence of the geomagnetic storm on March 9, 2012, on the ionospheric foF2, accompanied by variations in the storm intensity index Dst. The ionospheric foF2 exhibits a distinct decrease at both low-latitude and mid-latitude stations, as shown in the figure. As a result, the geomagnetic storm's impact on the low-latitude and mid-latitude ionospheric foF2 is clearly negative. At the high-latitude station in Greenland, there is not enough data available for the effects of this geomagnetic storm.

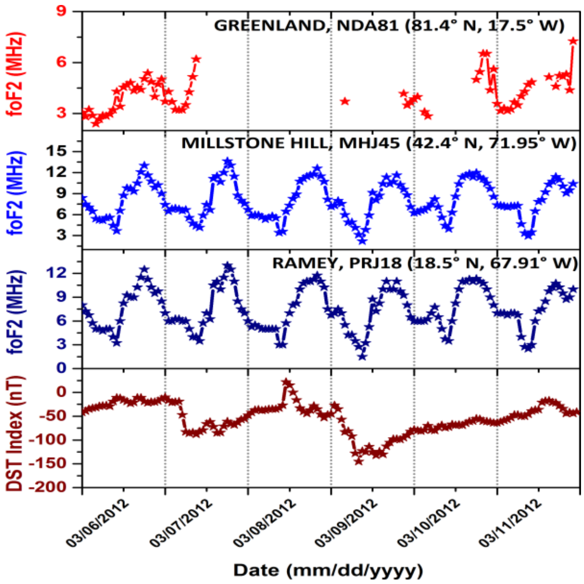

Figure 1.2: foF2 variation over low latitude station Ramey, mid latitude station Millstone Hill, and high latitude station Greenland with Dst during the geomagnetic storm on March 9, 2012.

Case III: 15 July 2012

Figure 1.3 depicts the influence of the geomagnetic storm on July 15, 2012, on the ionospheric foF2, accompanied by variations in the storm intensity index Dst. The minimum Dst recorded during this geomagnetic storm was -139 nT. As shown in Figure 1.3, the ionospheric foF2 exhibits a distinct enhancement at low latitude during the storm's recovery phase and a decrement at mid-latitude station, Millstone Hill, during the storm. As a result, the geomagnetic storm's impact on the low-latitude and mid-latitude ionospheric foF2 is clearly negative.

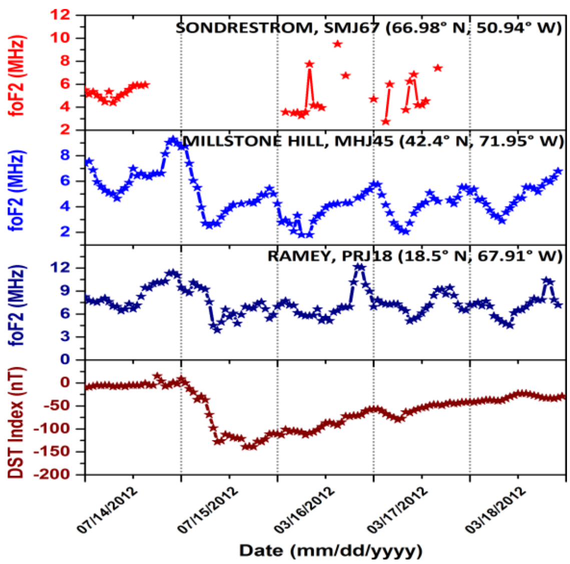

Figure 1.3: foF2 Variation over low latitude station Ramey, mid latitude station Millstone Hill, and high latitude station Greenland with Dst during the geomagnetic storm of July 15, 2012.

4 Discussion and Conclusion

In all three cases, we observed intense geomagnetic storms have a negative impact on the ionospheric foF2 at low, mid, and high latitudes in the northern hemisphere. We believe that changes in neutral winds, primarily generated by Joule heating in the auroral zone, cause the concurrent decrease in foF2 at these regions, indicating a depletion in plasma density within the F2 region. Furthermore, this study revealed that a specific geomagnetic storm consistently produces the same effect on the ionospheric foF2 across all latitudes in the northern hemisphere.

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