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Evaluating Ionospheric Responses to Geomagnetic Storms through IRNSS-Derived S4 Index and Total Electron Content

Nagesh B. Kothawale*(1), Shridhar N. Kamble(1), Karishma N. Maner(2), Supriya S. Kamble(2), Prashant P. Chikode(1), Rajiv S. Vhatkar(2), Ravindra D. Mane(1)
(1) Department of physics, Jaysingpur College, Jaysingpur, MS, India
(2) Department of physics, Shivaji University, Kolhapur, MS, India

1. Introduction

The most volatile region of the earth's upper atmosphere plays crucial role in radio communication and navigation system. However, its highly variable nature during geomagnetic disturbance, can leads to signal disturbance and mitigation of system performance [1]. India's indigenous navigation system called Indian Regional Navigation Satellite System (IRNSS), offers a valuable tool for investigating ionospheric variability [2]. Previous studied have reported the capability of IRNSS data to monitor and analyze ionospheric changes under both quiet and disturbed condition [3]. The occurrence of scintillation oftenally found at sunset time [4].

Preceding studied have been reported that the L5 frequency band of IRNSS suffers more scintillation than the S1 frequency band. The main impact of geomagnetic storm on the ionosphere is the significant growth in TEC and S4 index value. Particularly, past studies reported that TEC values fluctuations starts from the equatorial ionization anomaly (EIA) crest, were amplitude scintillation observed at same time [5]. This study focuses to validate of IRNSS signal during disturbed geomagnetic condition and impact of geomagnetic storm on ionosphere. Analysis of IRNSS-derived parameters like S4 index and total electron content (TEC), could provide a valuable insight into variable nature of ionosphere during geomagnetic storm period [2].

2. Methodology

2.1 Collection of data

This study uses the data of IRNSS to investigate the ionospheric response to geomagnetic storm. The IRNSS constellation has seven satellites, providing coverage over the Indian subcontinent and surrounding region. Mainly two types of service provided by IRNSS, one is the Standard Positioning Service (SPS) and second is the Restricted Service (RS) [6].

IRNSS-GPS-SBAS (IGS) receiver is deployed at Panhala (Kolhapur). Data is continuously logging at 1 Hz rate in raw format. Raw data is extracted in usable format by using dedicated software. Extracted data is in .csv format contains C/No ratio, Iono Delay, Tropo Delay, Elevation angle, azimuthal angle, Pseudo Range (PR), etc.

The signal scintillation is measured by S4 index which is calculated by using Carrier-to-noise ratio (C/No) data. And total electron content is derived from dual frequency IRNSS signal, providing variation into overall electron density of ionosphere..

2.2 S4 Index Calculation:

The S4 index, defined as the normalized standard S4 index is defined as the normalized standard deviation of the signal intensity, was calculated using 60 seconds of averaged signal intensity (SI) data. The formula is given as [6],

$$S4 = \sqrt{\frac{< Si^2 > - < Si >^2}{< Si >^2}}$$

where Si = $10^{0.1\times C/No}$

2.3 VTEC Calculation:

For the computation of total electron content (TEC) we used the pseudo range (PR) value. We obtain STEC using pseudo range values of L5 and S band from IRNSS extracted data. For the calculation of slant total electron content (STEC) and vertical total electron content (VTEC) we adopted equation from [7], equations is given as,

$$STEC = \frac{1}{40.3} \times \left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right)(P_2 - P_1)$$

$$= 4.4192 \times (P_2 - P_1) \quad electron/m^2$$

$$= 4.4192 \times (P_2 - P_1) \quad [TECU]$$

(1)

Where f_1 (L5) = 1176.46 MHz and f_2 (S1) = 2492.08 MHz

$$VTEC = STEC \times \cos\left\{arc\ sin\left(\frac{\cos\theta}{R_e + h_{max}}\right)\right\} \quad (2)$$

Where R_e (Radius of Earth) = 6378 km, h_{max}= 350 km, θ = elevation angle at the ground station.

3. Observational Results:

We have analyzed the two G-Class geomagnetic storms which occurred in ascending phase of the 25th solar cycle. First storm occurred on 23rd-24th April, 2023 and second is on 10th-11th May, 2024 respectively. The details of variation of geomagnetic parameters with derived parameter using IRNSS data is discussed in following subsections.

3.1. 23rd – 24th, April 2023 Geomagnetic Storm:

A large CME from sun's active region 13283 triggered a strong geomagnetic storm during ascending phase of 25th solar cycle on 21 April,2023. This storm particularly with high plasma speed 700 Km/s and flow pressure beyond 10 nPa by 23 April, resulting in a high Kp index of 8. This storm impacted both high and low latitudes of the ionosphere.
Figure 1 highlights the geomagnetic indices and IMF Bz variations on 23-24. The IMF Bz turned southward at 17 UT on 23 April, hitting -21 nT at 19 UT, with corresponding minimum Dst and SYM-H indices of -165 nT and -175 nT. Despite a brief northward shift to 11 nT, it again turned southward, reaching minimum Dst and SYM-H indices of -212 nT and -233 nT by 24 April at 6 UT. The recovery phase begins from 6 UT , and ending at 00 UT on 25 April.

Figure 2 shows VTEC variations from 22-24 April. On 22, VTEC peaked at 100 TECU around 11 UT, then fluctuated between 15 and 18 UT. On 23 April, VTEC increased sharply between 6 and 12 UT, with particular fluctuations around 15 UT due to plasma pressure. On 24 April, lowest Dst and SYM-H were recorded at 6 UT, indicating strong disturbed condition, and data loss occurred around this time.

Figure 3 analyzes S4 index data from 23-25 April, for L5 and S band. Strong scintillation were found in the L5 band on 23 April around 15 UT for three hours, while the S band suffers weaker but longer scintillation for about 19 hours. On 24 April, minimum scintillation were observed with data gap appearing during the main phase of storm. On 25 April, weak scintillation observed in L5 frequency band, with severe scintillation shows IRNSS 1B for two hours and weak and moderate scintillation in the S band lasting approximately 9.5 hours.

3.2. 10th – 12th May, 2024 Geomagnetic Storm:

In the period of 7-10 May, 2024, several X-class solar flares and at least five earthward CMEs were observed, erupted from active region AR3664, a large bunch of sunspots. This events leads a CME plasma speed to 700 Km/s and flow pressure to 55 nPa, leading increased geomagnetic activity, with the Kp index exceeding 8 after 15 UT. The IMF Bz is southward at 16 UT on 7 May, causing a sudden storm commencement (SSC) around 17 UT. a severe geomagnetic storm is identified by a Dst index of -412 nT and SYM-H index of -518 nT around 3 UT. The recovery phase of storm began after 3 UT.

On 10 May, VTEC values attains its highest value of 100 TECU between 8-9 UT, decreased after 12 UT, and fluctuated between 15-18 UT. On 11 May, VTEC values peaked up to 105 TECU around 10-11 UT, with data loss happened from 17.30 UT until 2.30 UT on 12 May. Severe VTEC values fluctuations were noted on 12 May between 18-20 UT.

The S4 index analysis shows no scintillation in the L5 band on 10-11 May, but moderate scintillation in the S band from 12-20 UT. on 12 May, strong scintillation occurred between 18-20 UT, highlighting the significant impact of geomagnetic storm on IRNSS signal.

4. Figures and Tables

4.1 Figures

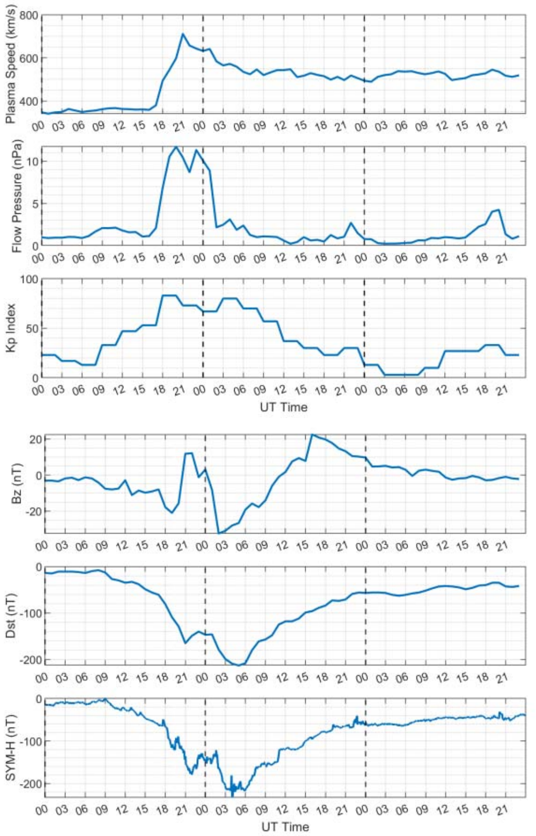
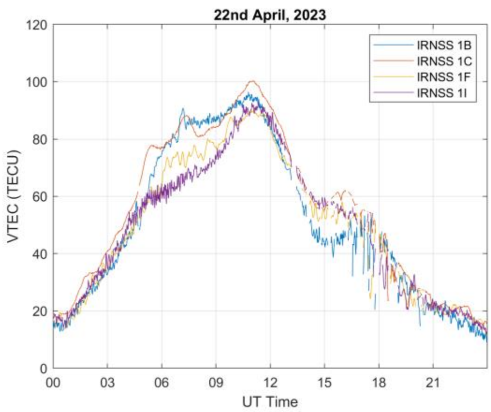
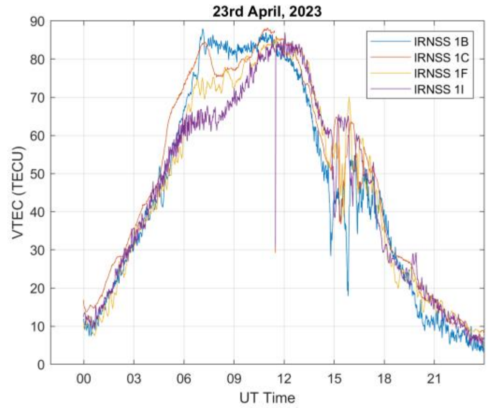


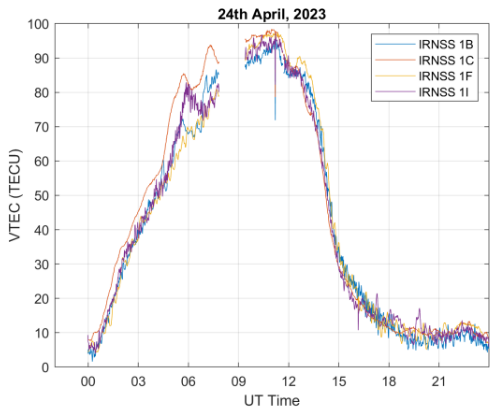
Figure 1. Shows the variation of geomagnetic parameters and interplanetary magnetic field (IMF Bz) during 23-25 April, 2023



(a)



(b)



(c)

Figure 2. Variation of VTEC during 22-24 April, 2023

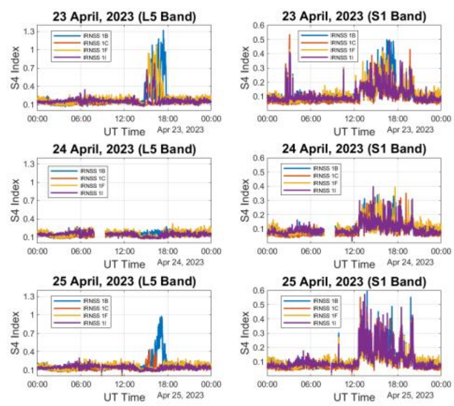


Figure 3. Shows the S4 Index values during 23-24 April, 2023 geomagnetic storm condition.

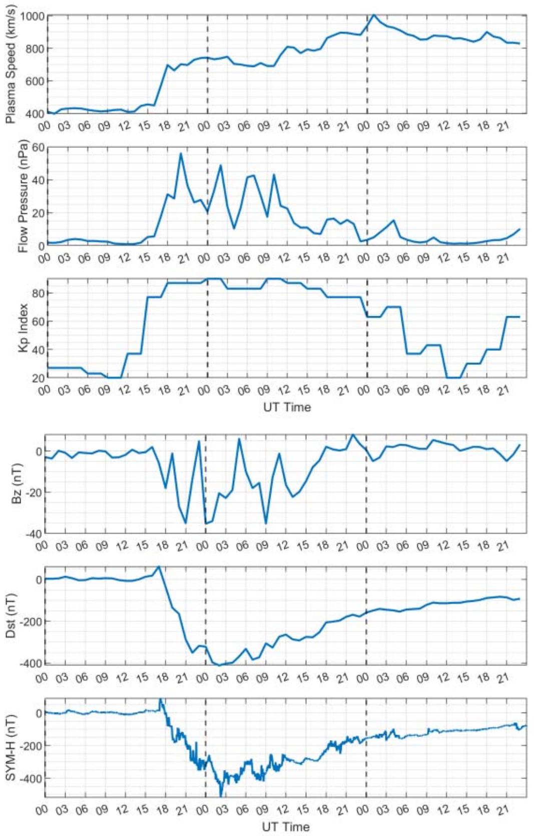
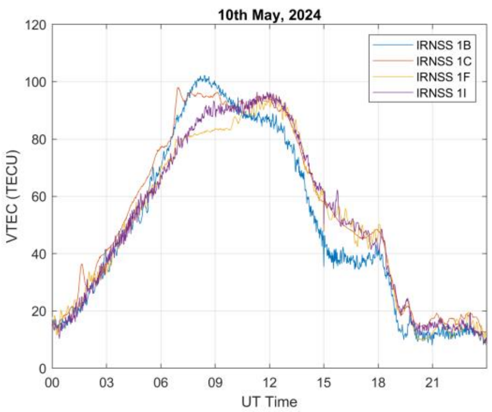


Figure 4. Shows the variation of geomagnetic parameters and interplanetary magnetic field (IMF Bz) during 10-12 May, 2024



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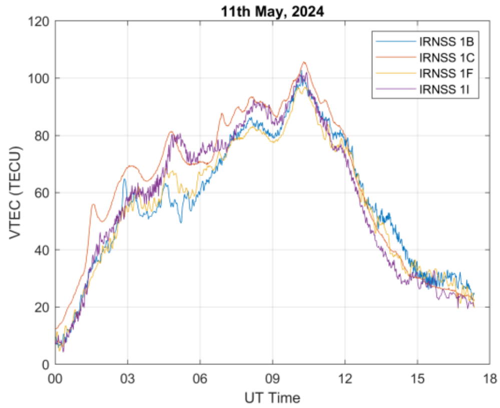

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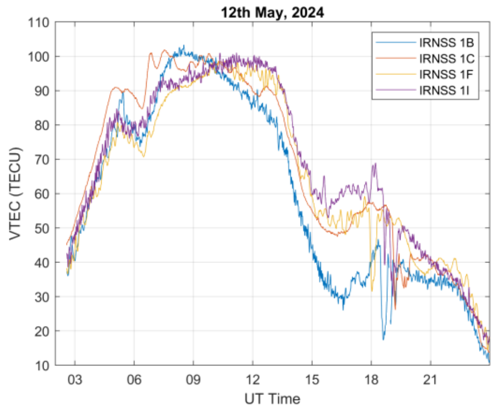

(c)

Figure 5. Variation of VTEC during 10-12 may, 2024

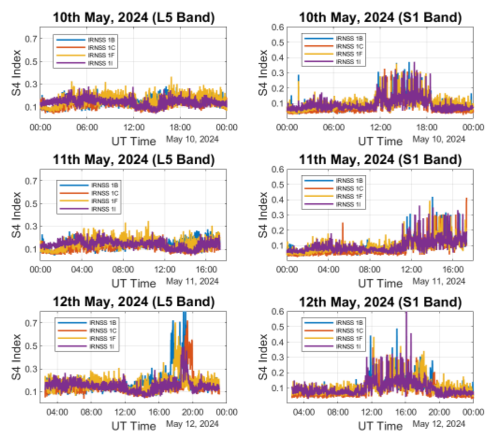

Figure 6. Shows the S4 Index values during 10^{th} -12^{th} May, 2024 geomagnetic storm condition.

5. Acknowledgements

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6. References

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