Latitudinal response of the Ionosphere to geomagnetic disturbances in 2021

S. Singh(1)*, V. Chauhan#(1), Vishakha(1), R. Singh(2), V. Singh(3), O. P. Singh(4)
(1) Department of Physics, Graphic Era Hill University, Dehradun-248002
(2) Department of Petroleum Engineering, Graphic Era Deemed to be University, Dehradun-248002
(3) Department of Physics, St. John's College, Agra-282002
(4) Department of Applied Sciences & Humanities, Institute of Engineering & Technology, Lucknow-226021

Abstract

The study investigates the impact of geomagnetic disturbances on total electron content (TEC) across different latitudes. GPS satellite signals experience time delays when passing through the ionosphere which is quantified as TEC. This study utilized TEC data from three IGS stations—Bangalore (India), North Liberty (United States), and Saskatoon (Canada)—representing low, mid, and high latitudes respectively. The TEC variations were analyzed for two disturbed days in 2021: January 25 and August 27, which had ΣKp values of 22 and 26. Data from quiet days in the same month were used as a baseline to calculate percentage changes. Results show significant TEC increases during disturbed days, with maximum percentage changes ranging from 38% to 125%. These changes were more pronounced at mid and high latitudes, indicating a stronger geomagnetic impact in these regions. This research highlights the sensitivity of ionospheric TEC to geomagnetic disturbances and its spatial variability, providing insights into ionospheric behavior crucial for improving navigation and communication systems.

*Presenting author- shishupal_k2002@yahoo.com
#Corresponding author- vishalchauhan@gehu.ac.in

1. Introduction

When GPS satellite signals pass through ionosphere for the navigation and communication they suffer time delay due to refraction and reflection. This delay in time depends on density of the ionosphere. This time delay is used to measure the total electron content (TEC). Its standard unit is TECU (1 TECU= 10^{16} electron/m^2). As the solar radiations expose the atmosphere in day time, the value of TEC increases and in night time it decreases. Hence the study of TEC is very useful to understand the structure and ionization process of the ionosphere. The TEC values depend on various factors which include season, local time, latitude, longitude and latitude. Even the ionosphere changes with any disturbances whether it is natural or man-made [1, 2]. During a disturbed day the structure and density of ionosphere changes and consequently the TEC values are also changed. The TEC values can be measured from the positioning data provided by ground based GNSS receivers installed all around the globe. A disturbed day is defined as a day whenever there is any natural or man-made activity occurs and it perturb the ionization of the ionosphere. The natural phenomenon includes geomagnetic storms, earthquakes, volcanoes, solar flare, CME etc. The intensity of disturbed days may be measured in terms of many variables including Dst, Ap and Kp indices. The study of changes in ionosphere on the disturbed days helps to understand the structure of ionosphere as well as to improve the navigation and communication signals passing through the ionosphere. Nishimura et al. [3] defined short term disturbances or variations in ionosphere those depend on regional, local or global activities. These disturbances can impact the accuracy of navigation signals and can also affect the communication signals. These disturbances are more often observed at mid and high latitudes [4]. Jin et al. [5] studied GPS phase scintillations and their study suggests that the possible reason of GPS disturbances at high latitudes are due to polar cap patches. These patches are responsible for convecting clouds of higher plasma density. Wang et al. [6] studied the TEC variations at high latitudes and observed that the high density plasma was formed during ionospheric irregularities. Jacobsen et al. [7] conducted a study of St. Patrick's day storm occurred on 17-18 March, 2015 in Norway. They analyzed and measured very strong disturbances in GNSS signals using rate-of-TEC index. They also found co-variation between ionospheric currents and ionospheric density variations. Fabbro et al. [8] conducted study of effect of solar winds at high latitudes above 50^0 for the time period from 2007 to 2019. Their study revealed the errors in the TEC values during disturbed weather conditions and they proposed a model to predict the correct TEC values. In this study we are focusing on two cases of disturbed geomagnetic activity in year 2021 by using the data from three IGS stations locating at low, mid and high latitudes. The purpose is to understand the role of spatial variations in TEC during disturbed geomagnetic conditions.

2. Data and Methodology

The TEC data used in this study are obtained from the web source of IGS stations (https://igs.org/data/) for three stations namely IISC, Bangalore (India), NLIB, North Liberty (United States) and SKTN, Saskatoon (Canada).

The coordinates of these stations are given in Table 1 and their positions on global map are shown in Figure 1. These stations are selected to represent spatial variations for low, mid and high latitudes**.** In this study we considered two cases of disturbed days from year 2021. This period of study is the part of present increasing solar activity cycle. The obtained data from above mentioned IGS stations are positioning data in RINEX format which is further used for measuring vertical TEC data. The VTEC measuring process is accomplished with the help of open software developed by Dr. Gopi Seemala. The detailed information about it can be traced at the following web source; seemala.blogspot.in.

Table 1. List of GPS stations and their locations taken into consideration for study

Sr No	Name of Station	Geographic latitude	Geographic longitude
1	IISC (Bangalore, India)	13.021	77.570
2	NLIB (North Liberty, United States)	41.772	-91.575
3	SKTN (Saskatoon, Canada)	52.196	-106.398

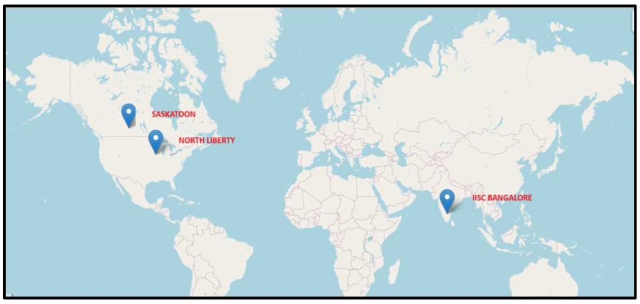

Figure 1: Locations of considered IGS stations (SKTN, NLIB, and IISC) on the globe.

Further, to investigate the relationship of disturbed days and TEC, we get the list of disturbed days from the web source of World data center, Kyoto (https://wdc.kugi.kyoto-u.ac.jp/qddays/index.html.) It has classified five disturb days for every month of the year. These days are named as D_1, D_2, D_3, D_4 and D_5. These days are arranged as per reducing intensities of disturbed condition. These days are classified on the basis of geomagnetic activity indices like Dst, K_p or ΣK_p.

To identify any anomalous variation in VTEC data, first we calculated average VTEC of ten quietest days of same month, listed on web source by world data center. Further, we calculated the percentage change between VTEC values and average VTEC of quietest days. The VTEC data used for this purpose is hourly sampled.

3. Results and discussion

In this paper, we are presenting two cases of disturb days for all three stations. These two cases are for Jan 25, 2021 and Aug 27, 2021. The values of ΣK_p on these two days are 22 and 26 respectively. In general, it is considered that when $\Sigma K_p < 30$, it is a weak disturbed day, $\Sigma K_p = 30$ is a moderate disturbed day while $\Sigma K_p > 30$, may be considered as a strong disturbed day. But these values indicative only, sometimes the disturbed geomagnetic condition can be identified by other factors too like the values of Dst-index and three hourly Kp-index values. The values of Kp-index vary on the scale of 0 to 9 and the values above 5 may represent disturbed geomagnetic condition.

3.1 Variation of VTEC on January 25, 2021

This case is the D_1 day of January 2021 which was observed on January 25, 2021. On this day, the ΣK_p value is 22, and it is considered a weak activity disturbed day. The quarterly values of K_p index are 2, 2, 3, 3, 2, 3, 2 and 5. The maximum value of K_p index was observed at 2100-2400 hrs UT. To see any change in VTEC on this day we plotted VTEC data for five days from January 23 to January 27, 2021 in Figure 2. The VTEC data on event day (January 25, 2021) is kept at the center while other four curves are representing the VTEC variations for two days before (January 23 and 24, 2021) and two days after (January 26 and 27, 2021) the event. There are six panels in this figure in which first and second panels are for IISC, third and fourth panels are for NLIB, and fifth and sixth panels are for SKTN station. In every two panels for each station, the first panel show variation of VTEC by red lines and average VTEC of quietest days is shown by black line while the percentage change variation is shown in the second panel.

The first two panels are showing results for IISC station. It can be observed from these panels that the peak value of TEC on the studied disturbed day is observed at 0800 hrs UT equal to 27.09 TECU and its varies by 4.13 TECU from quietest day average which is equal to 17.97% rise. Whereas maximum percentage change in TECU was observed 41.86% at 0100 hrs. The third and fourth panels of the figure are showing the results for NLIB station. Here the peak value of TEC on the studied disturbed day is observed at 1900 hrs equal to 17.99 TECU and its varies by 8.93 TECU, equal to 98.62% from quietest day average. Whereas maximum percentage change in TECU was observed 124.43% at 2400 hrs. The fifth and sixth panels are showing the results for SKTN station. It can be seen that **t**he peak value of TEC on the studied disturbed day is observed at 2300 hrs equal to 14.00 TECU and its varies by 7.33 TECU from quietest day average, it is equal to 110.07% change. Whereas maximum percentage change in TECU was observed 125.55% at 2400 hrs. These results are clearly indicating that the increased geomagnetic activity between 2100-2400 hrs UT is affect TEC variations dominantly. However, the corresponding changes in TEC are larger at mid and high latitudes as compared to low latitude station.

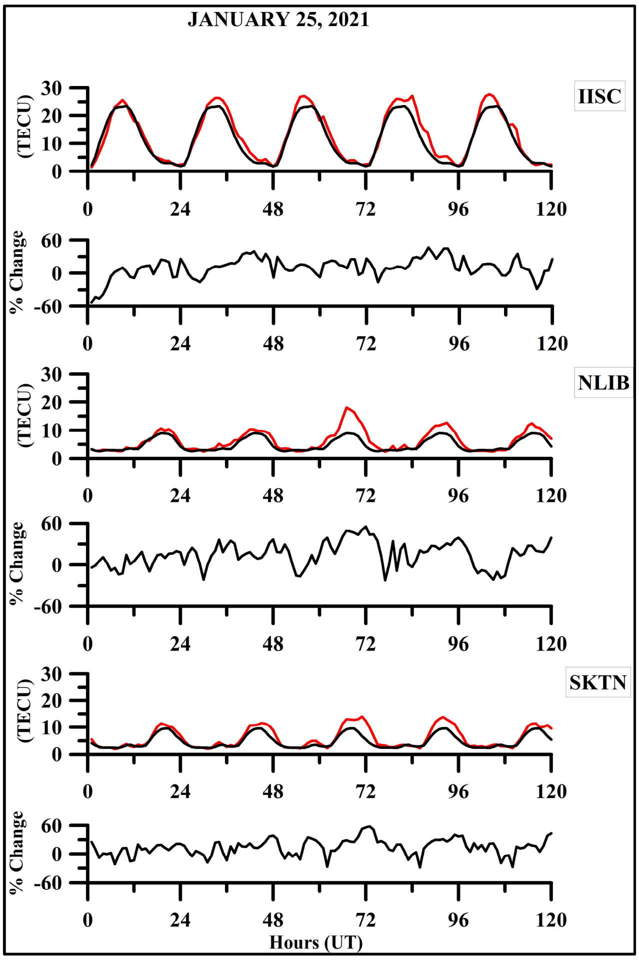

Figure 2.Variations of VTEC from January 23 to January 27, 2021 corresponding to the case of January 25, 2021. The event day is placed at the center. The variation of VTEC for IISC station is shown by red curves, and average VTEC of ten quietest days of January 2021 are shown by black curves (top panel), plot of corresponding percentage change between VTEC and average VTEC of quietest days for IISC station (second panel), same as top and second panel but all variations are for NLIB station (third and fourth panel), same as above but all variations are for SKTN station (fifth and sixth panel).

3.2 Variation of VTEC on August 27, 2021

This case is the D_1 day of August 2021 which was observed on August 27, 2021. The value of ΣK_p on this day is 26 and it is considered a weak activity disturbed day. However, the quarterly values of K_p index are 3, 1, 2, 4, 4, 4, 4 and 4. From 0900 hrs UT K_p index is constantly 4 which is a moderately active value. To see any change in VTEC on this day we plotted VTEC data for five days from August 25 to August 29, 2021 in Figure 3. As similar to Figure 2, the VTEC data on event day (August 27, 2021) is kept at the center while other four curves are representing the VTEC variations for two days before (August 25 and 26, 2021) and two days after (August 28 and 29, 2021) the event. All other details of this figure are similar to Figure 2.

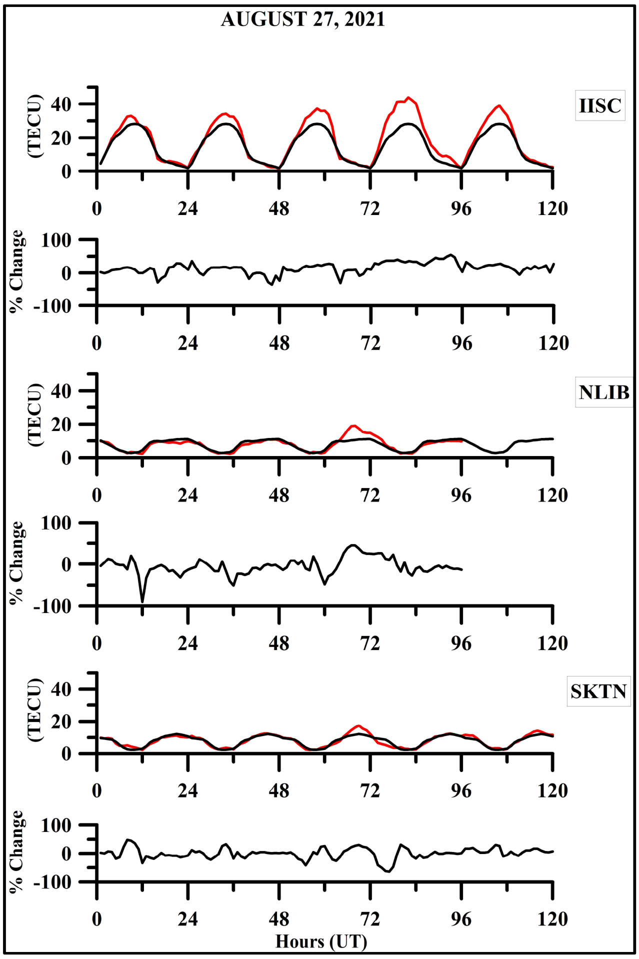

Figure 3.Same as figure 2 but for the case of August 27, 2021.

As similar to Figure 2, the first two panels in this Figure 3 are showing results for IISC station. The peak value of TEC on the studied disturbed day is observed at 1000 hrs equal to 37.23 TECU and it varies by 9.03 TECU from quietest day average which is equal to 32.03% rise. Whereas maximum percentage change in TECU was observed 38.27% at 1300 hrs. The third and fourth panels of this figure are showing the results for NLIB station. It can be seen from these panels that the peak value of TEC on the studied disturbed day is observed at 2000 hrs equal to 19.03 TECU and its varies by 8.55 TECU from quietest day average. Whereas maximum percentage change in TECU was observed 81.56% at 1900 hrs. The fifth and sixth panels of the figure are showing the results for SKTN station. Here, the peak value of TEC on the studied disturbed day is observed at 2100 hrs equal to 17.40 TECU and it varies by 5.26 TECU from quietest day average. It is the maximum value of percentage change too which is equal to 43.28%.

The summary of maximum percentage change observed at all three stations corresponding to both the considered cases is given in Table 2. The results show lower TEC changes at low latitude station while larger changes are observed at mid and high latitude stations, particularly mid latitude station experienced much higher change in TEC values. Similar kind of results were also observed by Paziewski et al. [4] and Jin et al. [5] in their studies. The possible reason of these results might be the convecting clouds of higher plasma density arise due to polar cap patches.

Table 2: The maximum percentage at different stations during disturbed days of 2021.

S. No	Date	ΣK_p	Maximum percentage change between VTEC and average VTEC (%)		
			IISC	NLIB	SKTN
1	25 Jan 2021	22	41.86	124.43	125.55
2	27 Aug 2021	26	38.27	81.56	43.28

4. Conclusion

The study of disturbed days and its effect on VTEC values over year 2021 gives very useful information and about the response of ionosphere during disturbed activity. This study consist three different stations situated at low, mid and high latitudes. It observed that there is sudden rise in VTEC values during disturbed days. The maximum percentage change in VTEC values found to be varied between 38% and 125% from averaged quiet condition VTEC measurements. These results show that there is a close relation between disturbed weather and ionospheric behaviour. This study further reveals that the behaviour of ionosphere is different at different latitudes. At different intensity of disturbed day the ionosphere behaves differently. The effect is better observed at mid and high latitudes, this might be due to cusp (characteristic U-shaped traces) auroral processes. A delay is also observed in peak VTEC variations.

5. Acknowledgements

The authors are thankful to Hon'ble Vice Chancellors of the Graphic Era Hill University, Dehradun and Graphic Era Deemed to be University, Dehradun, for their encouragement and for providing all the facilities to carry out this research work.

6. References

1. J. Park, R.R. Von Frese, D.A. Grejner-Brzezinska, Y. Morton andL.R. Gaya-Pique,"Ionospheric detection of the 25 May 2009 North Korean underground nuclear test," Geophysical Research Letters, **38**, 22, November 2011.

2. G. Savastano, A. Komjathy, E. Shume, P. Vergados, M. Ravanelli, O. Verkhoglyadova, X. Meng and M. Crespi, "Advantages of geostationary satellites for ionospheric anomaly studies: Ionospheric plasma depletion following a rocket launch," Remote Sensing, **11,** 14,July 2019 pp. 1734.

3. Y. Nishimura, O. Verkhoglyadova, Y. Deng and S.R. Zhang(Eds.), "Cross-scale Coupling and Energy Transfer in the Magnetosphere-ionosphere-thermosphere System," Elsevier, December 2021

4. J. Paziewski, P. Høeg, R. Sieradzki, Y. Jin, W. Jarmolowski, M. M. Hoque, J. Berdermann, M. Hernandez-Pajares, P. Wielgosz, H. Lyu, and W.J. Miloch,"The implications of ionospheric disturbances for precise GNSS positioning in Greenland,"Journal of Space Weather and Space Climate, **12**, 2022, p.33.

5. Y. Jin, J. I. Moen, and W. J. Miloch, "On the collocation of the cusp aurora and the GPS phase scintillation: A statistical study," *Journal of Geophysical Research: Space Physics* **120**, 10 , October 2015, pp. 9176-9191.

6. Y. Wang, Q. H. Zhang, P. T. Jayachandran, M. Lockwood, S. R. Zhang, J. Moen, Z. Y. .Xing, Y. Z. Ma, and M. Lester, "A comparison between large-scale irregularities and scintillations in the polar ionosphere," Geophysical Research Letters **43**, 10, May 2016, pp.4790-4798.

7. K. S. Jacobsen, and Y. L. Andalsvik, "Overview of the 2015 St. Patrick's day storm and its consequences for RTK and PPP positioning in Norway," *Journal of Space Weather and Space Climate* **6**, 2016, A9.

8. V. Fabbro, K. S. Jacobsen, Y. L. Andalsvik and S. Rougerie, "GNSS positioning error forecasting in the Arctic: ROTI and Precise Point Positioning error forecasting from solar wind measurements." Journal of Space Weather and Space Climate**11**, 2021, p.43.