

IONOSPHERIC RESPONSE TO TWO GEOMAGNETIC STORMS ON 12–13 NOVEMBER 2025 OVER EUROPEAN REGION

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Abstract

The present research reveals the ionospheric response over Europe during two strong geomagnetic storms (class G5 and G3) on 12–13 November 2025. In the analysis of the manifestation of geomagnetic conditions and to describe in detail the selected geomagnetic disturbances, the Dst index was considered. The ionospheric response is represented by the variations in Total Electron Content (TEC) according to data from the vertical sounding of the ionosphere and GNSS data. Data from selected ionospheric stations located in the European region, were used, which were supplemented with analogous data from satellite measurements. This investigation used the separation of the ionospheric quantity TEC into three types: a) full TEC, which is the integral of the electron density for the entire ionosphere along a line vertical at a given point on the Earth's surface; b) bottom TEC – the electron density up to the maximum, and c) top TEC includes the electron density above the maximum region. In addition, the determination of the relative deviation of the quantity has been introduced, which allows an assessment of the influence of ionospheric anomalies resulting from the geomagnetic storm. The results of the analysis of the behaviour of the measured TEC values show a positive response in full TEC on 12 and 13 November, as well as in bottom TEC, with the least pronounced effect in top TEC. The analogous presentation of the relative deviation demonstrates the most significant influence of geomagnetic storms on top TEC. This analysis allows the response of each individual ionospheric region to be examined.

Key words: geomagnetic storm, ionospheric response, TEC

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Introduction. Solar processes that affect the Earth have been the subject of many studies in recent decades [1–3]. The coronal mass ejections (CMEs) and streams of charged particles from the sun lead to interplanetary shock waves and southward magnetic fields, which are the cause of the so-called geomagnetic storms [4–6]. Of particular interest are the dynamics and chemical interactions between the thermosphere and the ionosphere under conditions of geomagnetic disturbances, the effects of galactic cosmic rays, as well as relativistic and highly relativistic electrons [7, 8]. The processes operating in the upper layers of the atmosphere are caused by an increase in the convective electric field and particle precipitation, which lead to Joule heating, the main driver of global atmospheric changes [9–12]. Global Navigation Satellite System (GNSS) allows us to study the ionospheric response to variations in the solar wind, which are part of the magnetosphere-ionosphere-thermosphere system, which is important for accurate positioning and radio communications [12].

The aim of the present study is to present the ionospheric response of TEC over Europe in geomagnetic conditions on 12–13 November 2025. An attempt has been made to show the response of the ionosphere by separating it into top TEC, bottom TEC and full TEC. The relative deviation for the three types of TEC is also calculated and their behaviour under conditions of geomagnetic disturbance is again compared and assessed.

Data and methods of investigation. The Dst index, provided by the Goddard Space Flight Center (<https://omniweb.gsfc.nasa.gov/>) is used to describe geomagnetic activity.

Two types of TEC data are used in this study. The first type of global GNSS data by satellite measurements were obtained from the NASA JPL (Jet Propulsion Laboratory, California Institute of Technology, La Cañada Flintridge, CA, USA): <https://www.izmiran.ru/ionosphere/weather/grif/Maps/TEC/>. The time resolution of TEC data is one hour and the data have a grid spacing of 5° (in longitude) $\times$ 2.5° (in latitude).

The second type of TEC data is based on vertical sounding of the ionosphere by Digisondes providing their data to the Global Ionosphere Radio Observatory (GIRO) <https://giro.uml.edu/index.html>. Table 1 shows a list of the European stations as part of the GIRO used with their codes and location (by latitude and longitude).

The following formula

$$(1) \quad \text{rTEC}(t) = \sqrt[3]{\frac{\text{TEC}(t)}{\text{TEC}_{\text{med}}(\text{UT})}} - 1$$

illustrates the methodology for obtaining the relative deviation (rTEC) of its values from the hourly medians (TEC_{med}), which allows for the analysis of variations in TEC in quiet conditions.

T a b l e 1

List of used data from selected ionospheric stations over Europe

Station code	Station name	Lat [deg]	Lon [deg]
JR055	JULIUSRUH	54.60	13.40
FF051	FAIRFORD	51.70	358.50
DB049	DOURBES	50.10	4.60
PQ052	PRUHONICE	50.00	14.60
SO148	SOPRON	47.63	16.72
EB040	ROQUETES	40.80	0.50
VT139	SAN VITO	40.60	17.80
AT138	ATHENS	38.00	23.50

Another calculation is related to the determination of the individual TEC types. For the purposes of this study, full TEC was obtained from GNSS data for points with coordinates coincidence with those of the ionospheric stations described in Table 1. The bottom TEC data were obtained from GIRO for each station. The top TEC results were obtained by the difference between full TEC and bottom TEC. A relative deviation procedure based on formula (1) was applied to each of these TEC data types.

Data analysis and results. The geomagnetic index that characterizes the behaviour of the equatorial ring current, namely Dst, is shown in Fig. 1. The figure shows that before midnight on 12 November there is an increase in the Dst index, after which a specific negative reaction is observed, reaching about -225 nT in the

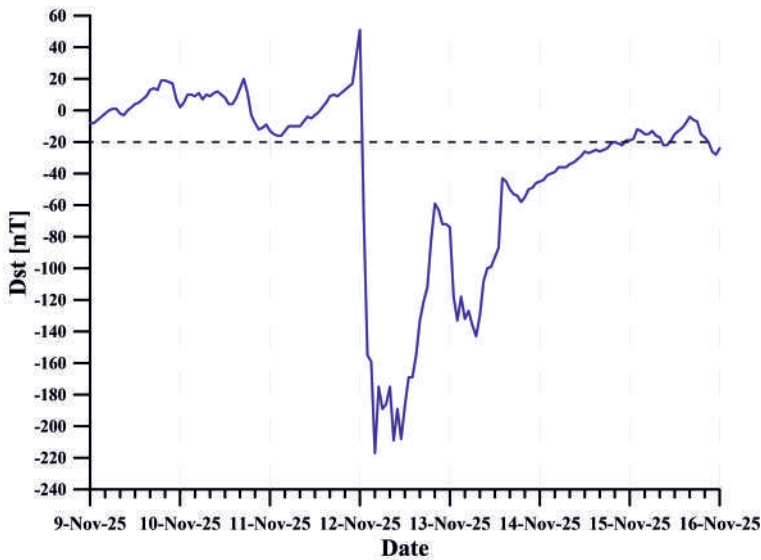


Fig. 1. Behaviour of Dst index

hours around 04 UT. According to the accepted classification for the Dst index, this geomagnetic storm is of the Severe (class G4) (Dst index between -200 nT to -350 nT) [13–15]. The described minimum of the Dst index coincides with the maximum of the Kp index. In the following hours, there is an increase in the index, which does not change to values characteristic of quiet conditions. In the early hours on 13 November, a second decrease in the Dst index was observed, which was most pronounced around 08 UT on November 13 and had values up to about -140 nT. This geomagnetic storm is classified as G3 – Strong (Dst index between -100 nT to -200 nT). After this moment, the recovery phase of the second storm begins, which lasts until 15 November 2025.

The relationship between geomagnetic activity and variations in the electron density of the ionosphere is well known. Therefore, in the following examples, the behaviour of the TEC and its relative deviation for each of the ionospheric stations in the European region is presented. In addition, in order to examine in detail the ionospheric response at different levels, a division of the TEC into top, bottom and full is made. Figure 2 presents the behaviour of the measured TEC values for eight ionospheric stations, described in detail in Table 1. The black colour in Fig. 2 shows the full TEC, the data for which are obtained from satellite measurements. The red colour illustrates the bottom TEC, the values for which are taken from direct measurements for each station. The top TEC, marked with blue colour, demonstrates the difference between full TEC and bottom TEC.

Figure 2 shows that in all stations the full TEC has the highest values and on 12 and 13 November there is a positive response (especially well expressed in the ionospheric stations at lower latitudes, namely VT139, AT138, EB040). The other value bottom TEC at almost all stations except AT138 again reacts positively, especially on 12 November. The last considered quantity, related to the sub-maximum manifestation of the ionospheric response (bottom TEC), shows a positive response associated with an increase in electron density, more pronounced and significant on 12 November at all considered stations. For the second day on which a geomagnetic event was registered, namely 13 November 2025, a positive anomaly is observed in the data of stations (SO148, VT139, EB040). The less pronounced anomaly is probably due to the fact that this event occurs in the conditions of a disturbed ionosphere as a result of the geomagnetic storm of the previous day. A similar study presents the ionospheric response to three events from January 2005 and different ionospheric response in top TEC, full TEC and bottom TEC [16]. The positive ionospheric response obtained for the two geomagnetic storms considered in the present study is a specific manifestation of the anomalies in winter conditions in the European sector. The comparison between top and bottom TEC over Sofia shows that the bottom TEC response is significantly larger than that of the top TEC for all three geomagnetic storms.

Figure 3 demonstrates the behaviour of relative TEC, which is obtained by applying formula 1 to the data in Fig. 2. Based on the relative deviation, an

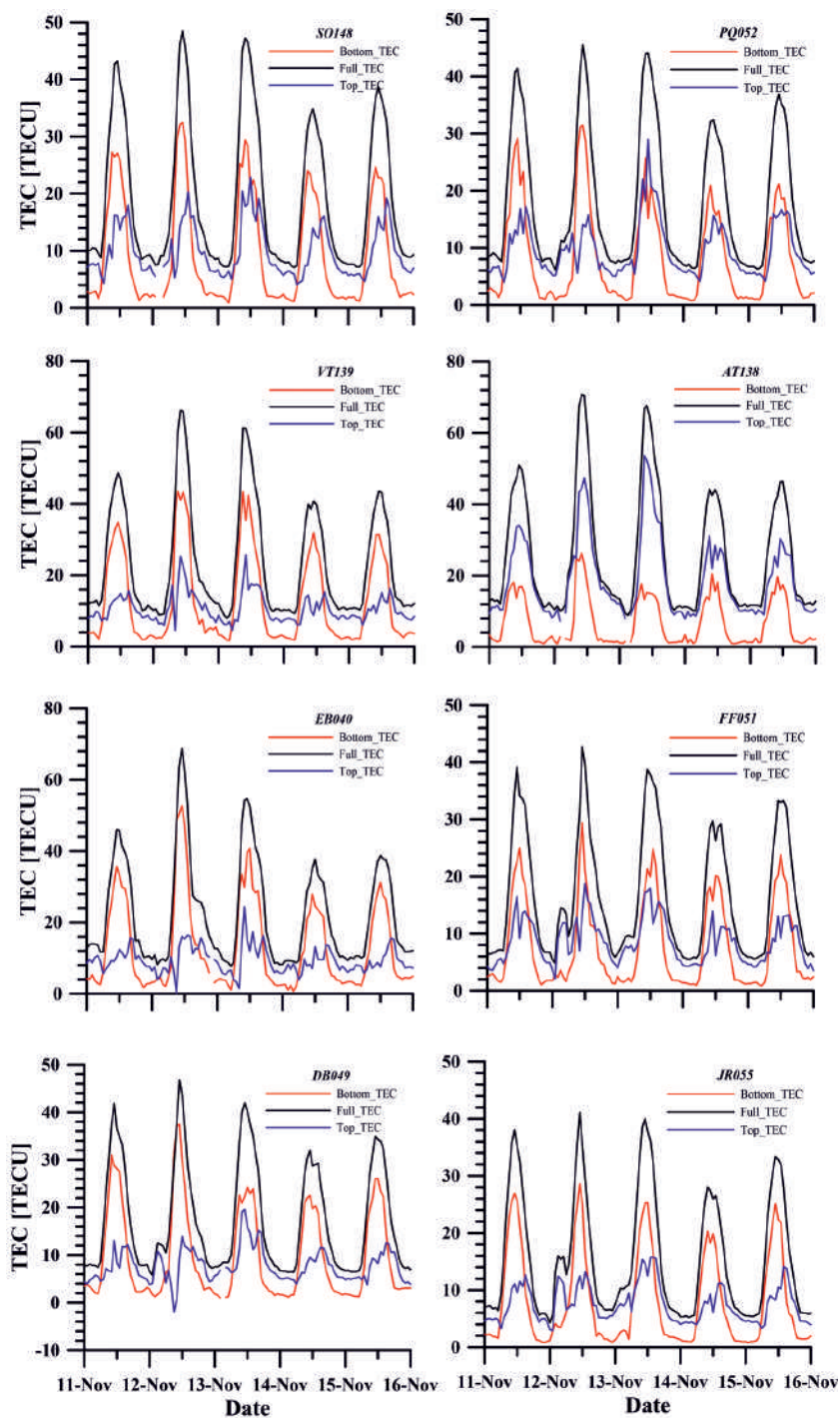


Fig. 2. Variations in measured data for: a) top TEC (blue line),
b) bottom TEC (red line), and c) full TEC (black line)

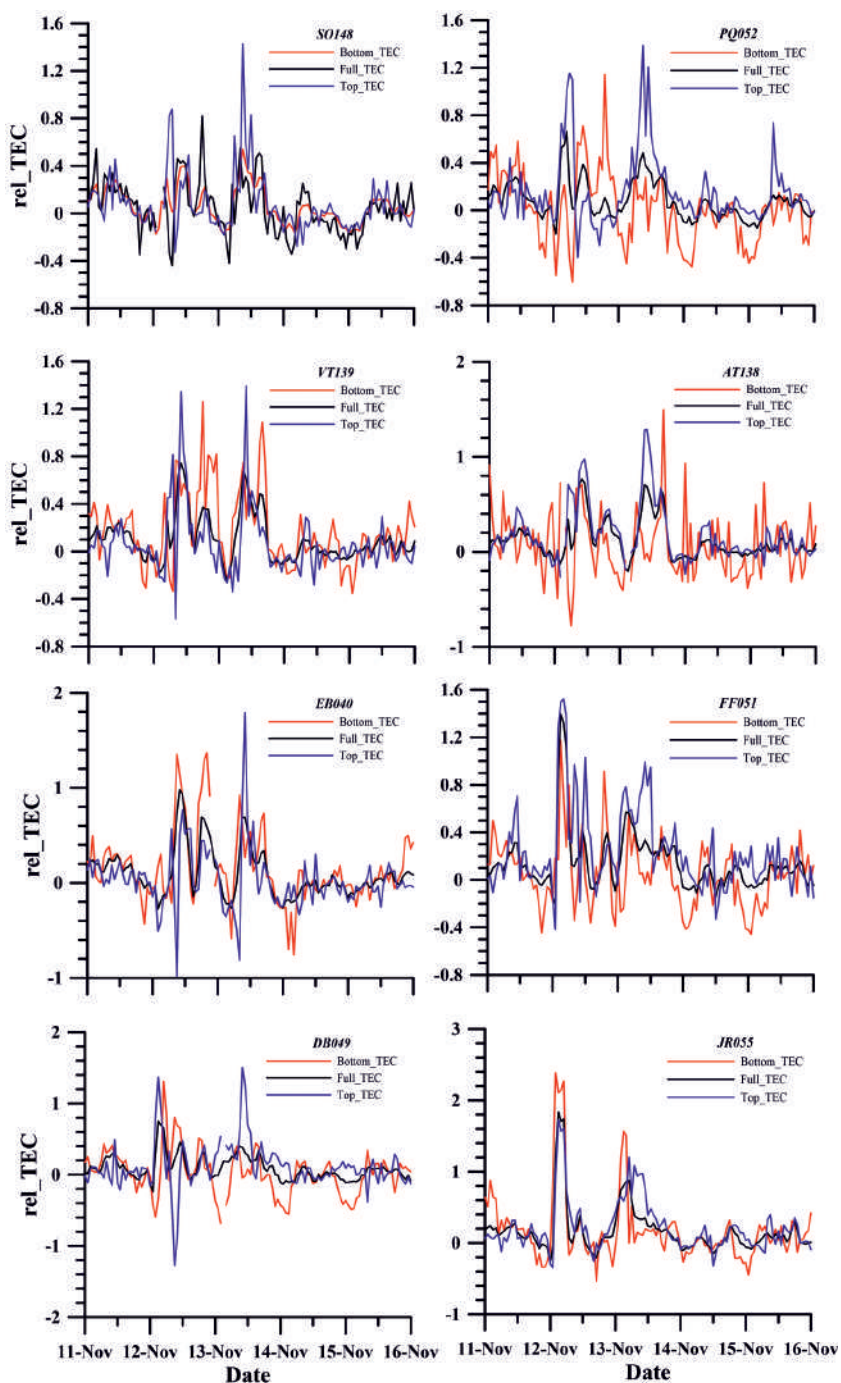


Fig. 3. Variations in relative deviation of: a) top TEC (blue line), b) bottom TEC (red line), and c) full TEC (black line) for each of the selected ionospheric stations

estimate can be made of the type (positive or negative) and significance of the ionospheric response [17, 18]. Figure 3 shows that the most significant anomalies are observed in relative top TEC at all selected stations. A positive anomaly in relative Top TEC is observed in the early hours on 12 November at all stations, with a maximum value of magnitude around 1.6–1.8. For the second geomagnetic storm, there is again a positive anomaly in the hours after midnight on 13 November, in which case the response is even more significant than that of the previous day (see stations SO143, PQ143, AT138, EB040). The behaviour of relative deviation of bottom TEC is not well expressed due to the poor quality of data from the vertical ionospheric sounding stations. The most clearly visible in Fig. 2 is the positive anomaly for both geomagnetic storms for the data of stations SO143 and JR055, which has maxima 0.4 and 2.2, respectively. The variations in the full TEC show weaker positive anomalies for both events compared to the other two quantities, which have a maximum of about 1.8 for the first storm and 1 for the second.

Conclusion. In this research, a methodology is proposed for studying the response of the ionospheric TEC over the European region based on satellite and ground-based measurements under the conditions of the geomagnetic storm on 12–13 November 2025. For this purpose, the ionosphere has been divided into separate regions, namely: a) total integral of the electron density for the entire ionosphere (full TEC); b) bottom TEC – the electron density up to the maximum, and c) top TEC includes the electron density above the maximum region. In addition, the relative deviations of each of the quantities are presented to provide an assessment of the type of ionospheric response and the impact on each region, and the main conclusions can be summarized as follows:

a) From the comparison and analysis of the measured TEC values, it is seen that a positive anomaly is observed in all three quantities full TEC, top TEC and bottom TEC on 12 and 13 November, but on the second day it is weaker. The less pronounced anomaly on the second day is probably due to the fact that this event occurs in the conditions of a disturbed ionosphere as a result of the geomagnetic storm of the previous day.

b) From the comparison and analysis of the relative TEC values, the most significant anomalies are observed in the relative top TEC in the early hours on 12 November at all stations (maximum 1.7–1.8). For the second geomagnetic disturbance there is again a positive anomaly in the hours after midnight on 13 November, in this case the response is even more significant than that of the previous day in some stations. The behaviour of the relative deviation of bottom TEC is not well expressed due to the poor quality of the data from the stations, but the positive anomaly is visible for both geomagnetic storms for the data of SO143 and JR055, which are 0.4 and 2.2, respectively. The variations in the full TEC show weaker positive anomalies for both events compared to the other two quantities with a maximum of about 1.8 for the first storm and 1 for the second.

All these results are contributions to solar-terrestrial and space physics and space weather [19, 20].

REFERENCES

- [1] BAKER D. N. (2000) Effects of the Sun on the Earth's environment, *J. Atmos. Solar-Terr. Phys.*, **62**(17–18), 1669–1681.
- [2] LEAN J. (1997) The Sun's variable radiation and its relevance for Earth, *Annual Rev. Astron. Astrophys.*, **35**(1), 33–67.
- [3] TSAGOURI I., A. BELEHAKI, N. BERGEOT et al. (2013) Progress in space weather modeling in an operational environment, *J. Space Weath. & Space Clim.*, **3**, A17, 1–72, <https://doi.org/10.1051/swsc/2013037>.
- [4] GONZALEZ W. D., J. A. JOSELYN, Y. KAMIDE et al. (1994) What is a geomagnetic storm?, *J. Geophys. Res., Space Physics*, **99**(A4), 5771–5792.
- [5] PERREAULT P., S. I. AKASOFU (1978) A study of geomagnetic storms, *Geophys. J.*, **54**(3), 547–573.
- [6] TASSEV Y. (2017) Analysis of extreme solar activity in early September 2017: G4 – Severe geomagnetic storm (07–08.09) and GLE72 (10.09) in solar minimum, *C. R. Acad. Bulg. Sci.*, **70**(10), 1437–1444.
- [7] VELINOV P. (1968) On ionization of the ionospheric *D*-region by galactic and solar cosmic rays, *J. Atmos. Terr. Phys.*, **30**(11), 1891–1905.
- [8] VELINOV P. I. Y., S. ASENOVSKI., K. KUDELA et al. (2013) Impact of cosmic rays and solar energetic particles on the Earth's ionosphere and atmosphere, *J. Space Weath. & Space Clim.*, **3**, A14, 1–17, <http://doi.org/10.1051/swsc/2013036>.
- [9] DANILOV A. D., A. V. KONSTANTINOVA (2019) Ionospheric precursors of geomagnetic storms. 1. A review of the problem, *Geomagn. Aeronomy*, **59**(5), 554–566.
- [10] DANILOV A. D., J. LAŠTOVIČKA (2001) Effects of geomagnetic storms on the ionosphere and atmosphere, *Int. J. Geomagn. Aeron.*, **2**(3), 209–224.
- [11] FULLER-ROWELL T. J., M. V. CODRESCU, R. G. ROBLE et al. (2013) How does the thermosphere and ionosphere react to a geomagnetic storm?, *Geophysical Monograph*, **98**, 203–225.
- [12] VELINOV P. I. Y., G. NESTOROV, L. I. DORMAN (1974) *Cosmic Ray Influence on the Ionosphere and on Radiowave Propagation*, 314, BAS Publishers, Sofia.
- [13] LOEWE C. A., G. W. PRÖLSS (1997) Classification and mean behavior of magnetic storms, *J. Geophys. Res., Space Physics*, **102**(A7), 14209–14213.
- [14] RATHORE B., S. C. KAUSHIK, D. C. GUPTA (2011) Classification and study of geomagnetic storms during year 1996–2010, *Int. J. Pure Appl. Phys.*, **7**(3), 199–202.
- [15] SIERRA-PORTA D., J. D. PETRO-RAMOS, D. J. RUIZ-MORALES et al. (2024) Machine learning models for predicting geomagnetic storms across five solar cycles using Dst index and heliospheric variables, *Adv. Space Res.*, **74**(8), 3483–3495.
- [16] BOJLOVA R., P. MUKHTAROV (2019) Response of the electron density profiles to geomagnetic disturbances in January 2005, *Stud. Geophys. Geod.*, **63**(3), 436–454.
- [17] JIN S., R. JIN, H. KUTOGLU (2017) Positive and negative ionospheric responses to the March 2015 geomagnetic storm from BDS observations, *J. of Geodesy*, **91**(6), 613–626.

- [18] MOŠNA Z., I. EDEMSKIY, J. LAŠTOVIČKA et al. (2021) Observation of the ionosphere in middle latitudes during 2009, 2018 and 2018/2019 sudden stratospheric warming events, *Atmosphere*, **12**(5), 602.
- [19] USOSKIN I., L. DESORGHER, P. VELINOV et al. (2009) Ionization of the earth's atmosphere by solar and galactic cosmic rays, *Acta Geophys.*, **57**(1), 88–101.
- [20] USOSKIN I., L. DESORGHER, P. VELINOV et al. (2008) Solar and galactic cosmic rays in the Earth's atmosphere. In: *Developing the scientific basis for monitoring, modelling and predicting Space Weather*, COST 724 final report, 124–132.

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