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FIRST RESULTS FOR THE INFLUENCE OF TWO GEOMAGNETIC STORMS DURING 10–12 MAY 2024 ON MID-LATITUDE IONOSPHERE

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Abstract

The main idea of this study is to analyze the ionospheric anomalies in selected points related to the extreme geomagnetic storm which occurred during the period 10–12 May 2024. In the present research, data of the critical frequency of the F2 region (foF2) from the vertical sounding of ionospheric station Rome (Italy) and foF2 data for the territory of Sofia (Bulgaria) obtained by empirical modelling were used. The selection of Rome ionospheric station is related to the fact that this ionosonde is located at the geographic latitude coinciding with the latitude of Sofia, which suggests similar characteristics of the ionosphere. In order to evaluate the type of response (positive or negative), the relative deviation of the values was used, taking into account the influence of the local time for the individual points (1 hour). The results of the of the ionospheric response analysis show a well expressed negative response, more significant at Rome station. Another interesting result related to the inertia of the ionosphere is expressed in the observed response delay depending on the

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onset of the geomagnetic storm. From the comparison of the measured data and those obtained through the empirical model it can be seen that for the purposes of ionospheric forecasting, the model is able to describe the behaviour of the ionosphere with sufficient accuracy. The ionospheric response is supported by an additional study of the behaviour of the Total Electron Content (TEC), which response is similar to that of foF2.

Key words: ionospheric response, geomagnetic storm, critical frequency

Introduction. The relationship between the processes of the Sun and geomagnetic activity is well known, which in turn has a significant impact on the ionospheric electron density, causing in some cases the so-called "ionospheric storm". Ionospheric storms are associated with magnetic storms and can lead to significant problems and inaccuracies of radio-wave propagation and related radio communications and positioning of objects, especially at high latitudes. It has been found that the manifestation of individual geomagnetic disturbances depends on geomagnetic latitude, season, and local time. During ionospheric storms, two phases are observed: a) an initial increase in electron density (positive phase), which has a duration of a few hours, and b) a subsequent decrease in electron density lasting a few days (negative phase). An interesting fact related to the Equatorial Ionization Anomaly (EIA) is that at low latitudes only the positive phase is observed. The effects that can cause negative ionospheric storms are related to blackouts both in high-frequency (HF) radio communications and in the positioning of transionospheric Global Navigation Satellite Systems, while positive ionospheric storms can significantly delay and scintillate radio signals [1–3]. The physical explanation for obtaining negative ionospheric storms is related to the chemical effect of the (upwelling) storm time equatorward neutral wind [4], which leads to enrichment of the thermosphere with molecular nitrogen concentration and reduction of atomic oxygen concentration [5]. Due to the fact that negative ionospheric storms are caused by changes in the neutral gas composition, they are the dominant characteristic in ionospheric response to geomagnetic activity, especially in summer conditions.

The idea of this study is to investigate the variability of the ionosphere in the conditions of the two geomagnetic storms in May 2024. A comparison of the behaviour of the ionosphere based on data from the vertical sounding for the territory of Rome (Italy) and data from an empirical model for forecasting the ionosphere for the territory of Sofia (Bulgaria) is proposed [9,10]. The results of the comparison are used for additional verification of the working of the created model in the conditions of significant geomagnetic disturbances such as the considered example. In addition, the ionospheric response was analyzed based on TEC data for the points closest to Rome and Sofia. The results are compared with the behaviour of foF2 and the similarity in the manifestation of the variations in the two ionospheric quantities is shown.

Data and methods. In order to proceed to an analysis of the influence of geomagnetic disturbances on ionospheric variability, it is necessary to consider the behaviour of the geomagnetic Kp index and the foF2 variability. Data on the Kp index, which characterize the variations of the Earth's magnetic field, were used, which are freely available from the databases of the GFZ Helmholtz-Zentrum Potsdam at the following link: `https://kp.gfz-potsdam.de/en/data`.

The other type of data is the ionospheric F2-region critical frequency values obtained from ground-based measurements by ionosondes for vertical sounding of the ionosphere part of the Global Ionosphere Radio Observatory (GIRO) and available at: `https://giro.uml.edu/index.html`. The data on the ionospheric variability are subjected to additional mathematical calculations of the relative deviation of the quantity, which removes quiet conditions (median) and allows the analysis of variations on the electron density due to the influence of geomagnetic activity [11–14].

In the additional analysis of the ionospheric response, global TEC data provided freely by the Center for Orbit Determination of Europe (CODE) on `http://ftp.aiub.unibe.ch/CODE/` were used. Based on the global TEC data with a grid spacing of $5^\circ \times 2.5^\circ$ in longitude and latitude and a time resolution of 1 hour it is possible to obtain values at the closest points by coordinates to Sofia and Rome.

Results. This section presents the results related to the behaviour of the Kp index, which characterizes the geomagnetic conditions, as well as the response of the ionosphere to the considered storms in the period 10–12 May 2024, described by the variations in the critical frequency of the ionospheric F2 region and TEC. The proposed comparison of the behaviour of foF2 for two points located at mid-latitudes in the European region allows to analyze the type of response, and also to evaluate the accuracy of the created and incorporated methodology for forecasting the ionospheric characteristics for the territory of Bulgaria. As confirmation of the type of ionospheric response from data and model, an analysis of the response of the ionospheric TEC for the same points, Sofia and Rome, is also proposed.

Geomagnetic conditions. The general level of geomagnetic activity is given by the Kp index, which is a series of measurements dated from 1932 to the present [15]. This index is mainly formed by the auroral electrojet and the equatorial ring current, and the data for it are at the 3 hour time interval. It is given in relative units, which are ranged between 0 and 9, depending on the level of the field perturbation.

In the shown example of the behaviour of the Kp index for the period 8–14 May 2024, the sudden onset of the storm on 10 May around 12UT is clearly visible. Figure 1 shows that in the hours after 12UT the Kp index values reach a maximum value of 9, which according to the accepted classifications of the NOAA Space Weather Scales corresponds to a geomagnetic storm of class G5 "Extreme" [16]. The index has a maximum value until the afternoon of 11 May (around 15 UT),

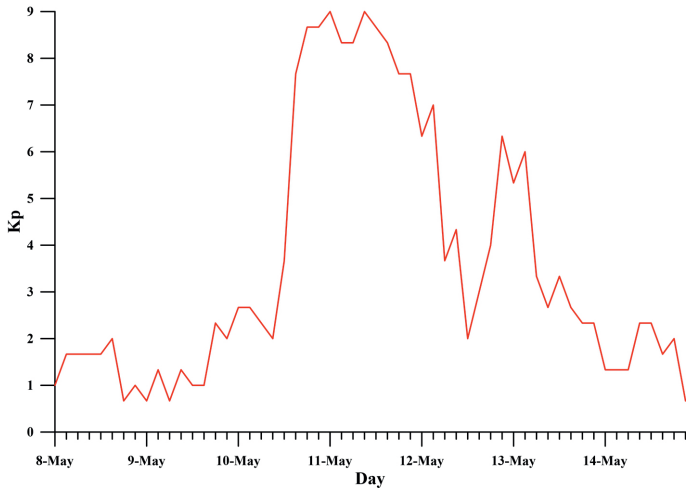


Fig. 1. Behaviour of the Kp index

after which it begins to decrease. In the early hours on 12 May, the Kp index values are below 5 (i.e., quiet conditions). In the hours around 21UT on 12 May to 06UT on 13 May the second geomagnetic storm was registered, which is of class G2 "Moderate". In this time interval the Kp index reaches values above 6. According to Fig. 1 a normalization of the index to quiet conditions is observed after 6UT on 13 May 2024.

Ionospheric response. In order to analyze the ionospheric response, this sub-section presents comparisons of the behaviour of foF2 from measurements and modelled values of the quantity for points with coordinates of the Rome ionospheric station (RO041, 41.9°N, 12.5°E) and the nearest point to Sofia (42.5°N, 25°E). Two examples are given for the period 8–14 May 2024, which illustrate both quiet conditions and the days in which the extreme geomagnetic storm and the second moderate geomagnetic storm occur. A comparison of the variability of foF2 (measured and modelled values) and their relative deviation for the two selected points is subsequently presented (see Fig. 2 and Fig. 3).

From Fig. 2 it can be seen that in the hours before 18UT on 10 May a sharp decrease in foF2 is observed both in the Rome station (to about 2 MHz) and in the model for Sofia (to about 4.5 MHz). This type of decrease in electron density shows that a negative response is particularly unfavourable for radio communications and GNSS navigation systems. The observed delay of the ionospheric response from the beginning of the geomagnetic storm is related to the inertia of the processes in the upper atmosphere. Smaller values comparable to the quiet conditions of the previous two days (8 and 9 May) were observed in the early hours on 12 May, but were followed by a new anomaly related to the second moderate geomagnetic storm. In the hours between 06UT on 12 May and 06UT on 14 May, the figure shows that the ionosphere remains disturbed as a result of the second geomagnetic

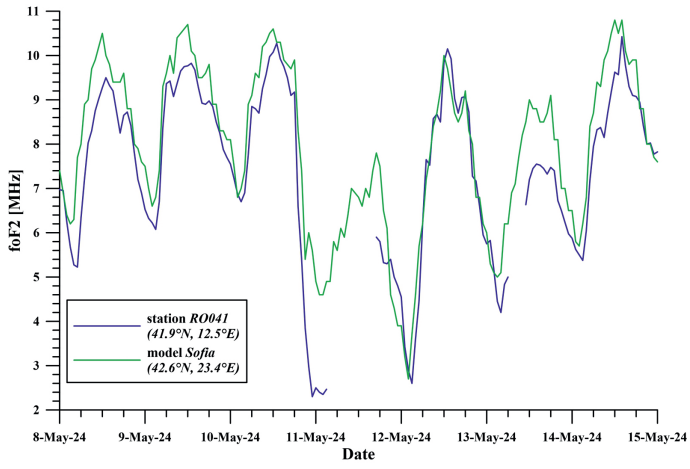


Fig. 2. Behaviour of foF2 for Rome and Sofia

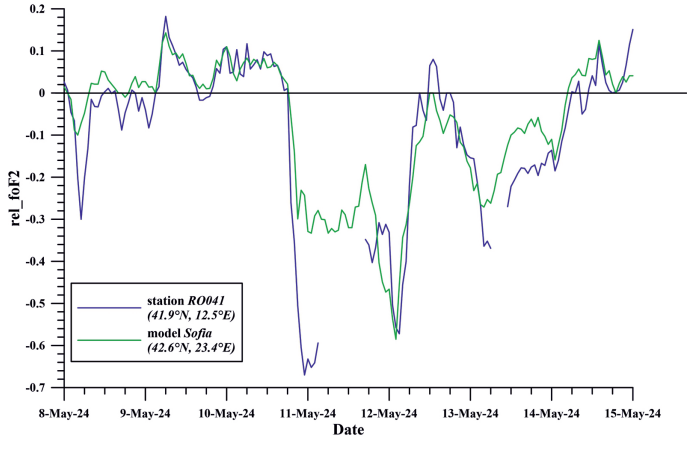


Fig. 3. Relative deviation of foF2 for Rome and Sofia

storm and the values are smaller compared to the two days (8 and 9 May) where there is no geomagnetic disturbance.

The main results are presented in Fig. 3, which illustrates a comparison of the variability of the relative deviation of foF2 for the two selected points. The black line is an indication of quiet (median) ionospheric conditions. Therefore, values above this line indicate a positive response, while those below it indicate a negative response. The behaviour of the two points is analogous to that presented in Fig. 2, but in this case it is clearly seen how strong the negative response is in both points compared to quiet conditions. It is particularly distinct and reaches about -0.7 for Rome station and -0.34 for Sofia in the hours around 00UT on 11 May. Another result seen in Fig. 2 and Fig. 3 is the delays in the ionospheric response as a result of the impact of the solar wind on the magnetosphere-thermosphere-

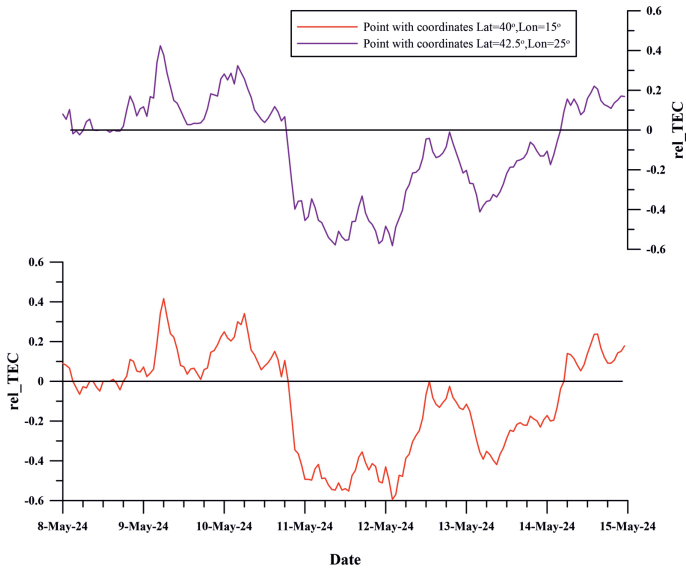


Fig. 4. Variability of relative TEC obtained for the nearest points to Rome and Sofia

atmosphere system. A similar study of the ionospheric response resulting from a great geomagnetic storm that occurred on 13 March 1989 shows similar results, namely long-lasting significant negative response at mid- and high latitudes, observed since the main phase [17].

Figure 4 shows the behaviour of the relative deviation of TEC for two selected points coinciding in coordinates with Rome and Sofia for the period 8–14 May 2024. It can be seen that in the hours after 18UT on 10 May the TEC in both points shows a negative response. The observed negative response persists until the early hours on 14 May. The presented comparison of the behaviour of the relative TEC for the two selected points shows an analogous response to that obtained by foF2 (see Fig. 3). This result is an additional confirmation of the reliability of the ionospheric characteristics obtained by empirical modelling.

Conclusion. The main goal of this research is a preliminary analysis of the ionospheric response to geomagnetic storms in the period 10–12 May 2024. For this purpose the foF2 variability by measurements from station Rome (Italy) and data, obtained by an empirical modelling for the territory of Sofia (Bulgaria) are presented. For this purpose, foF2 variabilities based on measurements from the Rome station (Italy) and data obtained by empirical modelling for the territory of Sofia (Bulgaria) are presented. The reason for the selection of these two points is that their coordinates coincide in geographic latitude, which suggests similar ionospheric responses. The analysis is based on a comparison of the behaviour of both the measured and modelled values of foF2 for the two points, as well as their relative deviation, which represents the anomalies compared to the median

condition in the period 8–14 May 2024. The results show a significant negative response for both selected points, with a stronger negative response in the relative deviation (about −0.68) at Rome station. The explanation for the obtained negative values of the relative deviation (negative ionospheric response) is related to the physical mechanisms and processes of changing the electron density in close to summer conditions (the month of May for the Northern Hemisphere), namely: a) chemical effect of the (upwelling) storm time equatorward neutral wind, and b) composition changes (neutral gas composition changes).

Another interesting effect observed during the analysis is the delay in the ionospheric response of about 6 h compared to the onset of the geomagnetic disturbance. This type of response delay has been well studied and described [18–20].

In addition, a comparison of the behaviour of foF2 and the variability of TEC for the studied time interval is also presented. The purpose of this analysis is to show that the ionospheric reaction obtained from the model and the data from measurements have a similar manifestation as the Total Electron Content for the territory of Rome and Sofia. The obtained results show a similarity in the response of the selected ionospheric parameters. The results of the comparison for the two points and the obtained similarity in the behaviour of the ionosphere can be used to confirm the quality and accuracy of the created empirical model for forecasting the ionospheric characteristics for the territory of Bulgaria.

REFERENCES

[1] Horvath I., B. C. Lovell (2015) Positive and negative ionospheric storms occurring during the 15 May 2005 geomagnetic superstorm, J. Geophys. Res.: Space Physics, **120**(9), 7822–7837.

[2] Basu S., E. MacKenzie, C. Bridgwood et al. (2010) Specification of the occurrence of equatorial ionospheric scintillations during the main phase of large magnetic storms within solar cycle 23, Radio Sci., **45**(5), 1–15.

[3] Kintner P. M., B. M. Ledvina, E. R. De Paula (2007) GPS and ionospheric scintillations, Space Weather, **5**(9), S09003.

[4] Fuller-Rowell T. J., M. V. Codrescu, R. J. Moffett, S. Quegan (1994) Response of the thermosphere and ionosphere to geomagnetic storms, J. Geophys. Res., **99**(A3), 3893–3914.

[5] Balan N., K. Shiokawa, Y. Otsuka et al. (2010) A physical mechanism of positive ionospheric storms at low latitudes and midlatitudes, J. Geophys. Res.: Space Physics, **115**(A2), A02304.

[6] Szuszczewicz E. P., M. Lester, P. Wilkinson et al. (1998) A comparative study of global ionospheric responses to intense magnetic storm conditions, J. Geophys. Res.: Space Physics, **103**(A6), 11665–11684.

[7] Prölss G. W., M. Roemer, J. W. Slowey (1988) Dissipation of solar wind energy in the Earth's upper atmosphere: The geomagnetic activity effect, Adv. Space Res., **8**(5–6), 215–261.

[8] Rishbeth H. (1997) Long-term changes in the ionosphere, Adv. Space Res., **20**(11), 2149–2155.
[9] Bojilova R., P. Mukhtarov (2021) Construction of ionospheric critical frequencies based on the total electron content over Bulgaria, C. R. Acad. Bulg. Sci., **74**(1), 110–119.
[10] Mukhtarov P., R. Bojilova (2021) Accuracy assessment of the ionospheric critical frequencies reconstructed by TEC over Bulgaria, C. R. Acad. Bulg. Sci., **74**(2), 250–259.
[11] Bojilova R., P. Mukhtarov (2023) Comparative analysis of global and regional ionospheric responses during two geomagnetic storms on 3 and 4 February 2022, Remote Sensing, **15**(7), 1739.
[12] Bojilova R., P. Mukhtarov (2023) Analysis of the ionospheric response to sudden stratospheric warming and geomagnetic forcing over Europe during February and March 2023, Universe, **9**(8), 351.
[13] Bojilova R., P. Mukhtarov (2024) Seasonal features of the ionospheric total electron content response at low latitudes during three selected geomagnetic storms, Atmosphere, **15**(3), 278.
[14] Tassev Y., P. I. Velinov, D. Tomova, L. Mateev (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.
[15] Echer E., W. D. Gonzalez, M. V. Alves (2006) On the geomagnetic effects of solar wind interplanetary magnetic structures, Space Weather, **4**(6), S06001.
[16] NOAA Space Weather Scales: `https://www.swpc.noaa.gov/noaa-scales-explanation`.
[17] Mansilla G. A. (2004) Mid-latitude ionospheric effects of a great geomagnetic storm, J. Atmos. Sol.-Terr. Phys., **66**(12), 1085–1091.
[18] Mukhtarov P., D. Pancheva, P. Trifonova (2011) Geomagnetic and ionospheric response to recurrent geomagnetic activity at middle latitudes, C. R. Acad. Bulg. Sci., **64**(10), 1469–1478.
[19] Danilov A. D., J. Lastovicka (2001) Effects of geomagnetic storms on the ionosphere and atmosphere, Int. J. Geomag. Aeron., **2**(3), 209–224.
[20] Velinov P. I., Y. Tassev (2018) Long term decrease of stratospheric ionization near the 24-th solar cycle minimum after G4–Severe geomagnetic storm and GLE72 on September 8–10, 2017, C. R. Acad. Bulg. Sci., **71**(8), 1086–1094.

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