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Verification of the Methodology for Forecasting the Ionosphere over Bulgaria in the Conditions of the Geomagnetic Storm on 27 February 2023

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Abstract.

A study of the behavior of the ionosphere over Bulgaria on 27 February 2023 ionospheric storm caused by the G2 (Moderate) geomagnetic storm is presented. The examined geomagnetic indices describing the behavior of geomagnetic storm (Dst and Kp) indicate that this event had a sudden onset. The variability of the ionospheric critical frequency is represented by the data of 10 ionospheric stations for vertical sounding. The selected European stations are between 35° and 55° latitude and between 6°E and 33°W longitude. Based on interpolation of the data from all ionosondes, the values for foF2 (characterizing the maximum electron density) for the territory of Bulgaria were obtained. At the National Institute of Geophysics, Geodesy and Geography, there is a developed and integrated methodology for forecasting the critical frequencies over the territory of our country. In order to make verification in real conditions, the values of the combined empirical model for short-term forecasting were compared with the interpolated data from the ionospheric stations. The results show an extremely good match between the two types of data. All these results play an essential role and can be used for practical purposes and more precisely in preparing predictions for the propagation of radio waves at a given distance of radio path.

Keywords: ionosphere, geomagnetic storm; critical frequency

Introduction

It is well known that the ionospheric storms are the result of geomagnetic disturbances caused by streams of solar energetic particles that interact with the Earth`s magnetic field. Ionospheric storms can cause both an increase in electron density (so-called positive storms) and a decrease in electron density (so-called negative storms) [Chukwuma, 2007; Horvath and Lovell, 2015]. The investigation of variations in ionospheric characteristics is related to the main practical application of the ionosphere, namely the radio waves propagation. In some cases, ionospheric storms can causestrong disturbances to radio communications, where in middle and high altitudes, radio communications are considered "ineffective" [Hill, 1963]. The impacts of disturbances related to radio communications can include temporary blackouts of signal to radio-wave based technology such as radio paths and navigation systems [Rama Rao2009; Klimenko, 2011; Blagoveshchenskii, 2013].

Everything described above shows the importance of investigating the ionosphere and its variability in the conditions of geomagnetic storms. At present, there are various ionospheric data bases from individual points on planet Earth for vertical sounding of the ionosphere, as well as GNSS data for Total Electron Content (TEC). For the territory of the Republic of Bulgaria there is no working ionospheric vertical sounding station. To solve this problem, a team from the National Institute of Geophysics, Geodesy and Geography has created an empirical model for calculating of the critical frequencies of the ionosphere over Bulgaria based on TEC data in the absence of data from ionospheric station [Bojilova and Mukhtarov,2020a; Bojilova and Mukhtarov, 2021]. Based on a known model of the electron density profile and the basic regularities of the reflection of radio waves from the ionosphere and through the obtained ionospheric parameters, it is possible to calculate specific radio paths (range of permissible radio communication frequencies) [Bojilova and Mukhtarov, 2020b].

In one of the latest studies related to the verification of the methodology for preparing daily forecasts for the propagation of radio waves on the territory of Bulgaria, a comparison was made between the measured values of the critical frequencies of the ionosphere (foF2 and MUF3000) for the San Vito station and the analogous ones obtained through the empirical model. The results show a very good coincidence between the model values and the measured ones in the conditions of the geomagnetic storm on 3-4November 2021 [Mukhtarov et al., 2021]. The obtained results confirm that the proposed dependency sufficiently accurately manages to solve the tasks set by the Ministry of Defense and the practical needs of environmental technologies [Ivanova et al., 2018].

The purpose of the present study is to reconstruct the state of the ionosphere over Sofia through a significant number of ionospheric stations. By interpolation between the values of foF2 in the ten points where the ionosondes are located, the value corresponding to the coordinates of the point of the city of Sofia is found.The data thus obtained should be compared with the data obtained by the created empirical model for short-term forecasting of the ionosphereat the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences. A future task is a comparison of more extensive statistical material to improve the quality of the developed methodology for the purposes of radio paths forecasting, which is also the main practical application related to Space Weather prediction and the tasks serving the interested institutions.

Data and Methods

In order to study in detail the behavior of the geomagnetic disturbance, the indices disturbance storm time (Dst) and planetary Kp index were used, which were obtained from Goddard Space Flight Center (https://omniweb.gsfc.nasa.gov/). It is well known that the Kp index is used to illustrated the magnitude of geomagnetic storms. Kp is an excellent indicator of disturbances in the Earth's magnetic field. Dst index gives information about the strength of the ring current around Earth caused by solar energetic particles [Masters, 2012].

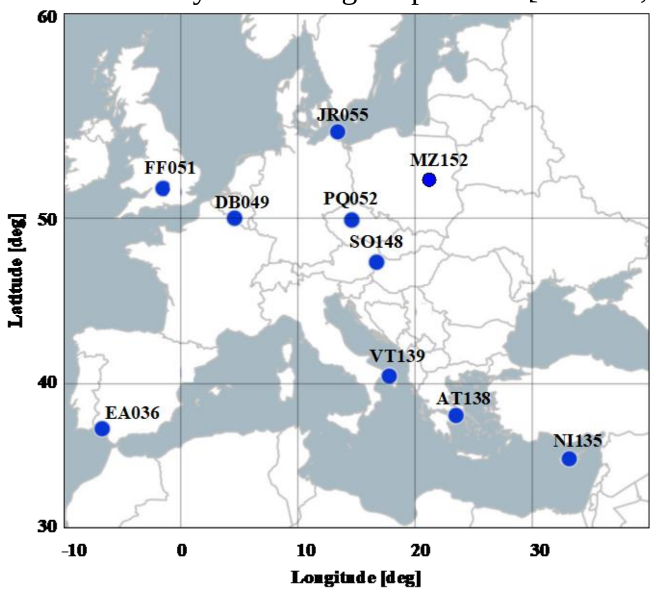

Figure 1. *Map of used European ionospheric stations*

Data on the F2-layer critical frequency obtained from ten ionospheric stations are available at the website of Global Ionosphere Radio Observatory (GIRO) https://giro.uml.edu/didbase/scaled.php. The data used for comparison of foF2 for the territory of Bulgaria are calculated by an empirical model from TEC data [Bojilova and Mukhtarov, 2020a; Bojilova and Mukhtarov, 2021]. The model allows predicting the values of foF2 and MUF3000 based on real (measured on every hour) TEC data from the global database the Center for Orbit Determination of Europe (CODE) - http://ftp.aiub.unibe.ch/CODE/.

Figure 1 show all used GIRO data base stations. The selected European stations are between 35° and 55° latitude and between 6°E and 33°W longitude. After the stations are selected, the foF2 data is interpolated for each point. The ionospheric response over Sofia is investigated by taking data for the point with the coordinates of the city of Sofia from all the interpolated values. The obtained values are compared with the model values.

Results

The influence of geomagnetic activity on the ionosphere has been the subject of long-term and detailed research by scientists working in this field [Bojilova and Mukhtarov, 2020c; Bojilova and Mukhtarov, 2020d; Mukhtarov and Bojilova, 2017]. In order to analyze the behavior of the geomagnetic disturbance in the present study the Kp and Dst indices shown in Figure 2. On the two graphs, the values of the two indices corresponding to disturbed conditions are marked in red. In the example of Dst, values below -30nT are moments of disturbance, while Kp values above 5 are considered as disturbed geomagnetic conditions.

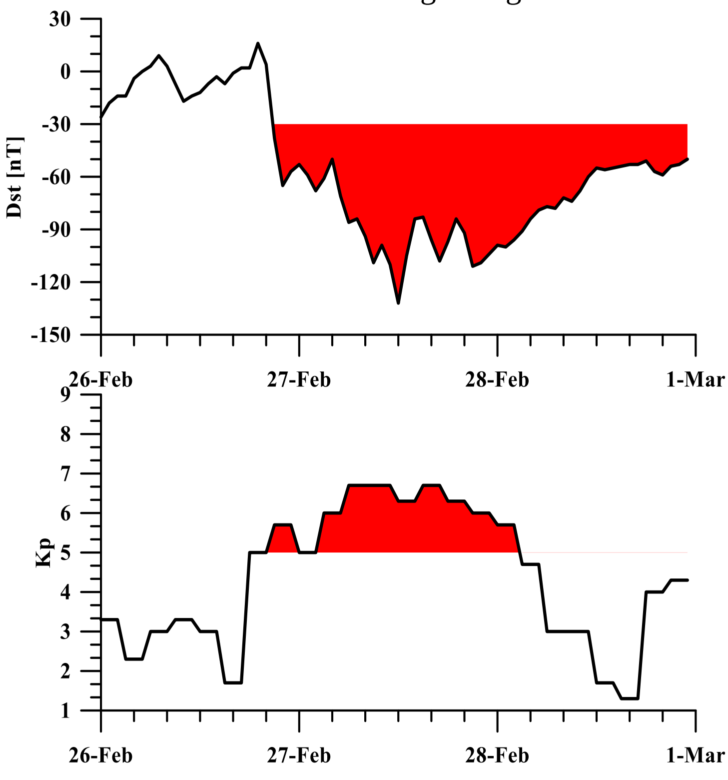

Figure 2. *Parameters describing geomagnetic storm- top panel Dst-index and bottom panel Kp-index*

From the graphs it is clear that the onset of the geomagnetic disturbance can be considered to be around 19:30UT on 26 February. The event under consideration has a sudden onset, which is clearly seen in the sharp rise of Kp to values around 5. The main phase of the storm occurs around noon (12UT) on 27 February when the Dst index reaches values -135nT. According to the accepted classifications for the magnitude of this index, the discussed geomagnetic storm is of the severe class (Dst ≤ -200 nT) [Loewe and Prölss, 1997]. The other considered index Kp has a maximum value of 6.66 at the same time. According to this index, the geomagnetic disturbance is of class G2 (Moderate).

The recovery phase begins in the night hours (after midnight) on 28 February when the Kp index recovers values in quiet conditions. Unlike this index, Dst index does not go into a quiet conditions even until the beginning of March.

After the behavior of the geomagnetic activity has been examined in detail, the next task is to analyze the behavior of the ionosphere in the conditions of the geomagnetic disturbance on 27 February 2023. For this purpose, the values of foF2 for the interval from 26 to 28 February were used. Based on the values obtained from the ten European ionospheric stations, the data is interpolated by determining the values of the point with coordinates coinciding with those of the city of Sofia. This type of data is shown in Figure 3 with black color. The other type of data is obtained by the empirical model for the same point - marked in red color. The figure shows a good match of the two types of data.

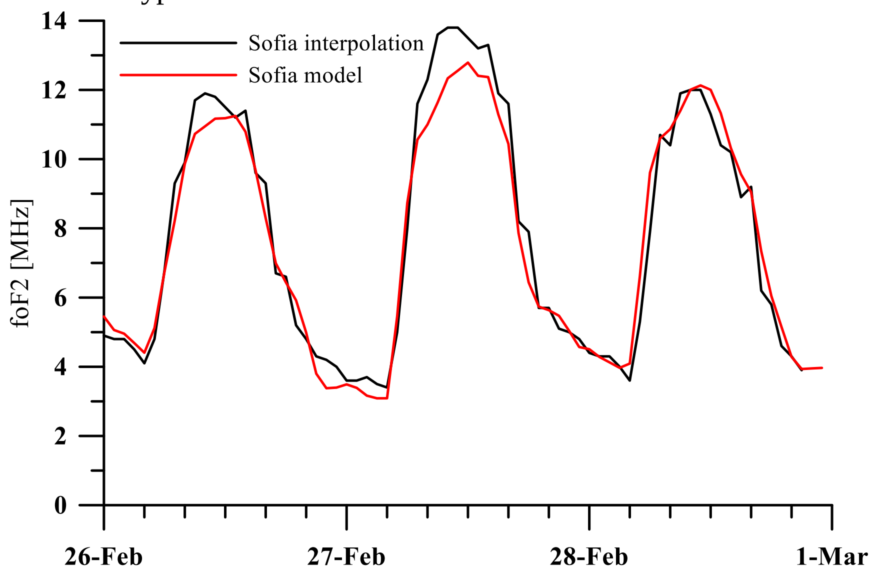

Figure 3.*Comparison between the data obtained from the interpolation of the stations and the data from the empirical model for Sofia*

The presented behavior of the critical frequency of the F2 layer in Figure 3 shows the reaction of the ionosphere for a mid-latitude region where Sofia is located according to coordinates. It can be seen from the graph that both types of data show an initial slightly negative reaction of the ionosphere at the onset of the storm in the hours after 20UT on 26 February 2023. The delay in response is due to the well-known fact of the inertness of the ionosphere. On 27 February around midday (which is also the main phase according to the geomagnetic activity indices, see Figure 2) an increase in foF2 of about 2MHz above the quiet condition values on 26 February is observed. The most probable explanation of the physical mechanism of the observed positive response of the ionosphere in the conditions of the geomagnetic storm under consideration is related to the changes of the ratio of atomic oxygen (O) to molecular nitrogen (N_2). It is well known that thermospheric composition (O/N_2) in winter is greater at high latitudes and decreases with distance from it, which is the reason for ionospheric winter anomaly and semiannual variation [Torr and Torr, 1973; Rishbeth, 1998;Millward, 1996]. Joule heating over the auroral region leads to longitudinal variations of thermospheric downwelling locations, which also causes changes in O/N_2 [Luan et al., 2017]. Effects such as Sudden Stratospheric Warming (SSW) have an additional influence in the period under consideration. SSW is a significant disruption of the stratospheric polar vortex that begins with large-scale atmosphere Rossby waves getting pushed higher into the atmosphere. SSW effects extend into the upper atmosphere (i.e. the ionosphere), producing changes in the thermospheric circulation and ionospheric disturbances [Yiğit et al., 2016].

Conclusions

The present study presents a comparison of two types of data characterizing the ionospheric response during the 27 February 2023 geomagnetic storm. In order to trace the manifestation of the particular disturbance- the changes in the geomagnetic activity represented by Dst and Kp were studied. In the analysis of the response of the ionosphere over Sofia, two types of data were used: a) from the interpolation of ten ionosondes, using the values for the point matching with the coordinates of Sofia and b) ionospheric data for Sofia obtained from the empirical model created in the National Institute of Geophysics, Geodesy and Geography. The comparison results show a good coincidence between the two types of data. All this shows the good work of the created model. In addition, the physical impact mechanisms related to the observed ionospheric reaction are presented, namely: a) changes in the O/N_2 ratio, and b) the influence of SSW. A future task is a comparison of more extensive statistical material to improve the quality of the developed methodology for the purposes of radio paths forecasting, which is also the main practical application related to Space Weather prediction and the tasks serving the interested institutions.

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