

A New Approach for Forecasting the Main Ionospheric Parameters over Bulgaria

Bojilova R., Mukhtarov P.

National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences,
Acad. G. Bonchev St, Bl. 3, 1113 Sofia, Bulgaria
E-mail: rbojilova@geophys.bas.bg

Abstract.

In order to build up a new reliable approach for forecasting the short-term variability of the main ionospheric parameters (foF2 and MUF3000) over Bulgaria the following two conditions have to be fulfilled: (i) a detailed study of the main physical processes defining the observed short-term ionospheric variability over the considered mid-latitude area, and (ii) the use of an appropriate mathematical apparatus enabling the observed relationships to be described correctly. The results of the regression and correlation analysis of ionospheric characteristics demonstrating how the external factors, as short-term solar anomalies and geomagnetic activity, affect the ionosphere over Bulgaria. The obtained results are used for justifying the functional dependence choice incorporated in the established empirical model for short-term forecast of foF2 and MUF3000 for the territory of our country, taking into account the variations in Kp and F10.7 indices. The proposed model is based on the data from the ionosonde station Sofia for the period of 1995-2014 and is designed to make prediction of the radio wave propagation up to three days ahead if the ionospheric reflection occurs over the territory of Bulgaria. The practical application of this model consists of its ability to predict the basic parameters of a particular radio path at a given distance determined by the user.

Introduction

The ionosphere is an extremely interesting one for scientists because of its scientific and practical significance. Ionization is the process by which neutral atoms break down into negatively charged free electrons and positively charged ions. Ions are the ones that give their name to the ionosphere, but much lighter and freer moving electrons are responsible for HF radio propagation. The A1 method used by the ionosondes allows the measurement of the virtual height of the reflection signal at a given frequency of the emitter. The obtained ionograms provide information about the main parameters of the ionosphere, such as the two values foF2 and MUF3000, which allow determining the operating frequencies of radio communication at a given distance of the radio path from the user. The variations of the Earth's geomagnetic field, are just one manifestation of a complex geophysical phenomenon of cosmic origin. The influence of the solar wind on the Earth's atmosphere is the change in the electron concentration of the ionosphere. These variations, called "ionospheric storms," are essential for long-range radio communications and satellite navigation systems. The study and modeling of the electron density anomalies under the influence of the solar wind are of practical importance for these communications and navigation [Bojilova and Mukhtarov, 2020].

This work presents the newest empirical model for forecasting the ionospheric critical frequencies, developed in the section “Physics of the ionosphere” at the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences.

Data

The geomagnetic activity, described by the planetary Kp-index, and solar activity, described by F10.7 is provided from: <https://omniweb.gsfc.nasa.gov/>. The foF2 and MUF3000 values are derived from the ionosonde station Sofia - SQ143 (42.4°N, 23.2°E) that belongs to

the National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences for the period of 1995-2014.

In order to create a working empirical model with sufficient accuracy for practice, it is necessary to find the relationships between the predicted quantities and the factors that determine them. For this purpose it is necessary to use correlation analysis, on the basis of which conclusions can be made about the existence of a causal relationship [Kutiev *et al.*, 1999; Muhtarov *et al.*, 1998]. If such a connection between the quantities is established, a regression analysis is performed, the results of which can also determine the type of the required dependence between the predicted quantities and the input parameters. The results of the correlation analysis performed by [Bojilova, 2019] show that there is a correlation as it is different in different months. It turns out that in general the reaction of the ionosphere from geomagnetic activity is negative except for the months of December and January. The need to separate day and night conditions of the response to critical frequencies is also substantiated. The result of the group regressions is that the relationship between foF2 and the short-term variations in solar activity represented by F10.7 is close to the linear one, but a second-degree polynomial is accepted in the model [Bojilova and Mukhtarov, 2020a]. The obtained results of the regression analysis reveal that during the winter months the response is weaker than that in the summer and equinoxes. The dependencies between both ionospheric characteristics and the geomagnetic activity turn out to be substantially nonlinear, requiring a third-degree polynomial approximation [Bojilova and Mukhtarov, 2020b].

Model functions

The main dependences of the relative deviation (formally denoted by Φ) of the critical frequencies of the day time, solar and geomagnetic activity can be represented as:

$$\Phi = \Phi_{UT}(UT)\Phi_{sol}(F10.7_{rel})\Phi_g(K_{pi}) \quad (1)$$

Each of the three unknown functions is assumed to be continuous, so it can be represented by the partial sum of its decomposition in order. Obviously, the periodic dependence on the diurnal time is represented by its Fourier decomposition, and the aperiodic dependences on the solar and geomagnetic activity are presented by Taylor decomposition. The study of the functional dependence of the relative deviations from the geomagnetic activity shows that it is expedient to use a third degree polynomial, which means that the partial sum of the Taylor order can be limited to the third degree. The dependence on solar activity turned out to be close to the linear one, but a second degree polynomial will be accepted [Mukhtarov and Bojilova, 2017; Bojilova and Mukhtarov, 2020b].

Under these assumptions, the three functions take the following form:

$$\begin{aligned} \Phi_{UT} = & a_0 + a_1 \cos\left(\frac{2\pi}{24}UT\right) + a_2 \sin\left(\frac{2\pi}{24}UT\right) + \\ & a_3 \cos\left(\frac{2\pi}{12}UT\right) + a_4 \sin\left(\frac{2\pi}{12}UT\right) \end{aligned} \quad (2)$$

$$\Phi_s = b_0 + b_1 F10.7_{rel}(t - t_s) + b_2 F10.7_{rel}^2(t - t_s) \quad (3)$$

$$\begin{aligned} \Phi_g = & c_0 + c_1 K_{piT1}(t) + c_2 K_{piT1}^2(t) + c_3 K_{piT1}^3(t) + \\ & c_4 K_{piT2}(t - t_{g2}) + c_5 K_{piT2}^2(t - t_{g2}) + c_6 K_{piT2}^3(t - t_{g2}) \end{aligned} \quad (4)$$

In accordance with the study of the global ionosphere response [Mukhtarov *et al.*, 2013], it is assumed that there are two types of ionosphere responses to geomagnetic disturbances with two different time constants denoted by T1 and T2, respectively. Two additional time delays have been introduced. The delay t_s reflect the delay of variations in the electron concentration with variations in solar activity. The delay $tg2$ reflects the additional delay of the negative reactions of the electron concentration during geomagnetic disturbances, related to the time required to transport the heated air from polar to mid latitudes.

The model is described by a total of 193 constants, which are different for rfoF2 and rMUF3000 and for each calendar month of the year. Separately calculated the constants of the model for day and night conditions. They are determined by the method of least squares, which minimizes the standard deviation of the model values from the data.

Results

In order to demonstrate the results of the created empirical model in the conditions of geomagnetic disturbances, examples from the real-time forecasting simulation of some selected storms at different levels of solar activity as well as for different seasons are presented. For this purpose, each figure shows the course of the index Kp (green), the measured values from Sofia station, marked in red for both critical frequencies (left panel shows foF2, right MUF3000) and model values plotted in blue and for both parameters. For the considered time interval of each individual storm, the respective ME and RMSE errors for the two critical ones are calculated and presented in tables in order to illustrate the comparative analysis between the generated empirical model and the data obtained from the ionospheric station Sofia.

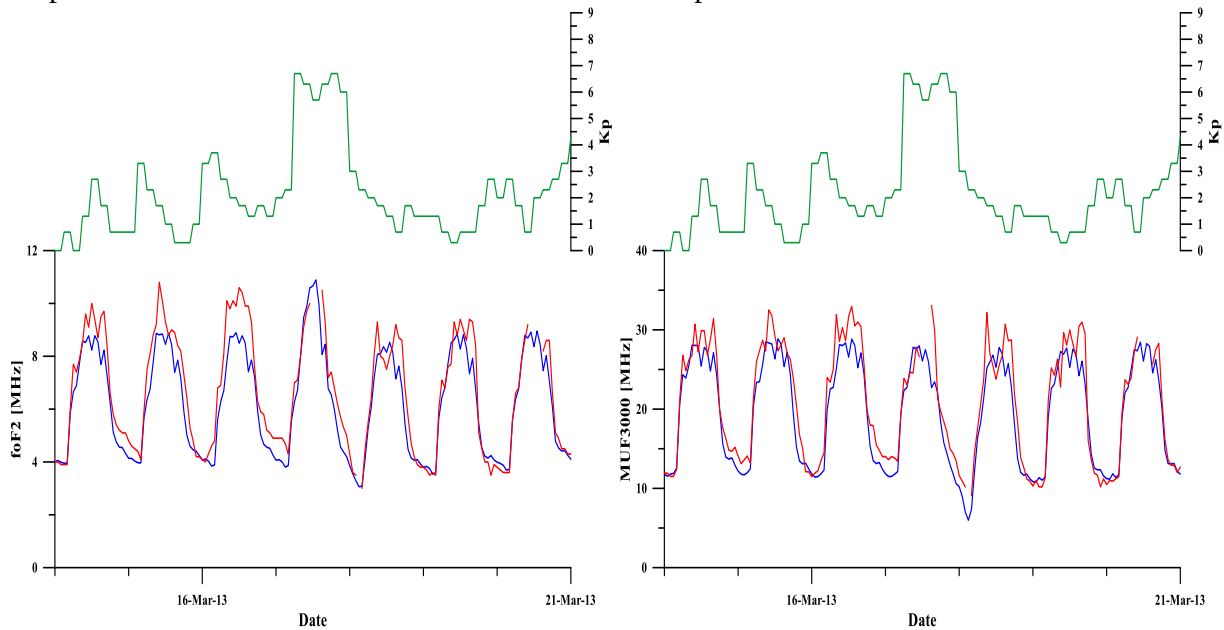


Fig.1. Comparison between the predicted foF2 by the model (left lower panel; line in blue) and MUF3000 (right lower panel; line in blue) with the same quantities received from Sofia station again for foF2 (left lower panel; line in red) and MUF3000 lower right panel; red line) during the geomagnetic storm of 17.03.2013, represented by Kp (upper panel; green line)

Fig. 1 shows an example of a geomagnetic storm in the spring season that occurred on March 17, 2013 with a maximum Kp index of 7. The shown storm has a sudden onset and duration of about one day, the initial phase being at night. The reaction of the critical frequencies (foF2 left lower panel and MUF3000 right lower panel of Fig. 1) is positive in daytime conditions, and the next night on 18.03, after the storm subsides, the response turns negative, which can be seen in the station data (red line) and the values obtained from the model

(blue line). Due to the fact that the storm is clearly separated from the previous and next quiet periods, the presence of a positive reaction with a small delay relative to the maximum of Kp and a negative response with a significant delay, again relative to the same index, can be seen.

If we consider only the two disturbed days, March 16 and 17, 2013, foF2 shows that the model very well describes the positive reaction during the day of the storm and the negative one on the night of March 16/17, while with MUF3000 the model underestimated the positive reaction and overestimated the negative one. During the rest of the quiet days, it can be seen that on average both the day and night model values are slightly lower than the measured ones. The mean error (ME) and the root mean square error (RMSE) for the both critical frequencies are presented in the table below:

ME_{foF2}	-0.55 MHz	$RMSE_{foF2}$	0.87 MHz
$ME_{MUF3000}$	-1.53 MHz	$RMSE_{MUF3000}$	2.69 MHz

Table 1. The mean error and the root mean square error for both critical frequencies for the period March 14-20, 2013

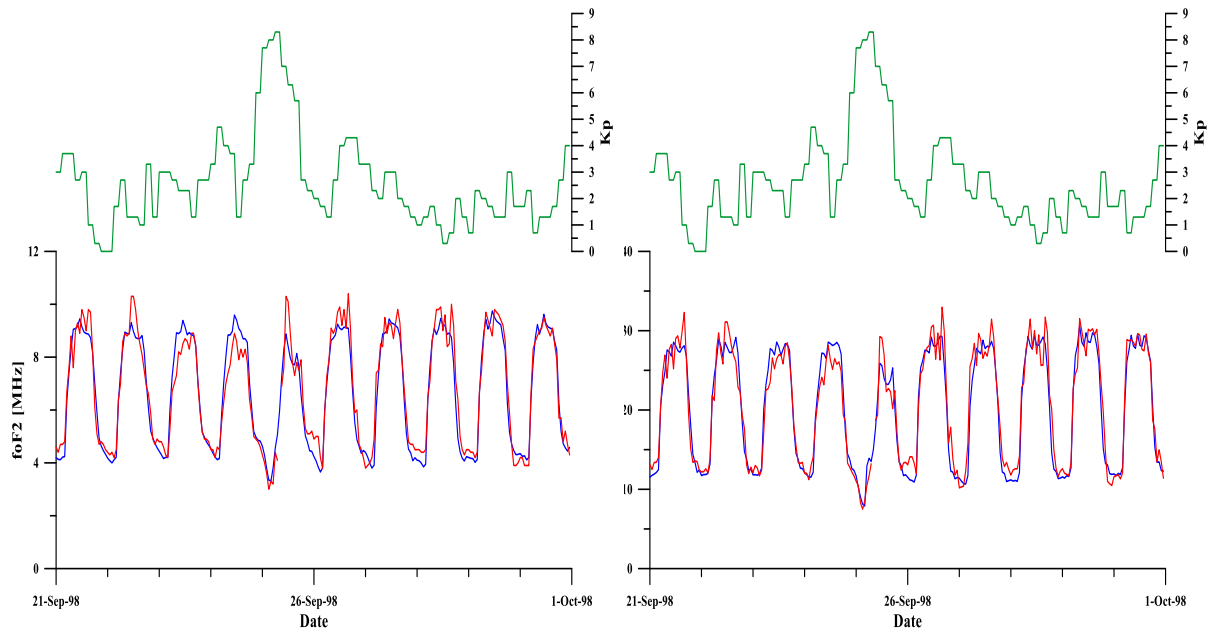


Fig. 2. Comparison between the predicted foF2 by the model (left lower panel; line in blue) and MUF3000 (right lower panel; line in blue) with the same quantities received from Sofia station again for foF2 (left lower panel; line in red) and MUF3000 lower right panel; red line) during the geomagnetic storm on September 24-25, 1998, represented by Kp (upper panel; green line)

Fig. 2 shows a geomagnetic storm with a maximum Kp index of almost 9 and a duration of about one day in the autumnal equinox. The geomagnetic storm has a sudden onset. The increase in Kp values on 25 September (upper left and right panel; green line) was initially accompanied by a weak negative reaction in the critical frequencies of the ionosphere in the early hours of 25 September, followed by a weak positive reaction (more pronounced in foF2; lower left panel; red line) shortly before reaching the maximum of the Kp index. Characteristic of this typically autumn storm is the relatively weak response to critical frequencies. Confirmation of the good similarity between model and data is shown in Table 2, containing the mean and root mean square error for the two critical frequencies for the period 21-30 September 1998. And in this example we have a good match between data and model, with

minor average (systematic) errors for both parameters, as well as completely satisfactory for the practical application of the model values of RMSE (Table 2).

ME_{foF2}	-0.08 MHz	$RMSE_{foF2}$	0.57 MHz
$ME_{MUF3000}$	- 0.26 MHz	$RMSE_{MUF3000}$	1.90 MHz

Table 2. The mean error and the root mean square error for both critical frequencies for the period September 21-30, 1998

Fig. 3 shows three examples of storms occurring in typical winter conditions. The time interval shown (from 16 to 25 January) includes two separate storms, studied in detail by [Bojilova and Mukhtarov, 2019]. The first storm (January 17-19) has a very smooth onset and a significant duration of more than two days, and the index of geomagnetic activity Kp in this period is between 6 and 8. The second storm (the night hours of 21 to the night of January 22) has a sudden onset and it is brief with a duration of one day, with a maximum value of Kp of about 8 (upper left and right panel; green line). The model did not evaluate the positive responses of the critical frequencies (foF2 left bottom panel; blue line and MUF3000 right bottom panel; blue line) in daytime conditions (from 17 and 18 January), but successfully represented the negative reaction on 19 January (attenuation of storm) at both critical frequencies. In the second storm presented in Fig. 3 (January 21-22) we have a good match of the model data (lower left and right panel; blue line) with the measured ones (lower left and right panel; red line) for both critical frequencies: foF2 (left lower panel) and MUF3000 right bottom panel).

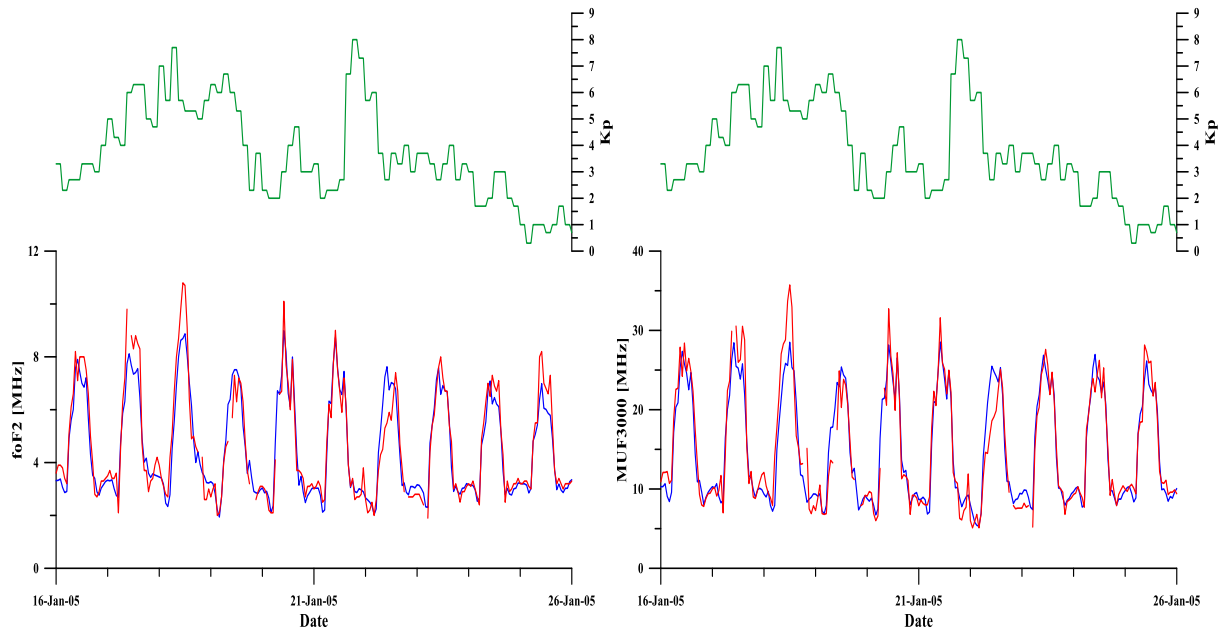


Fig. 3. Analogous to previous figures, but for two geomagnetic events in January 2005.

ME_{foF2}	-0.12 MHz	$RMSE_{foF2}$	0.67 MHz
ME_{MUF300}	-0.20 MHz	$RMSE_{MUF3000}$	2.31 MHz

Table 3. The mean error and the root mean square error for both critical frequencies for the period September 16-25, 2005

Table 3 shows the mean error and the root mean square error, again in order to show whether the model performed well or not and as can be seen the results are sufficiently satisfactory for the purposes of radio forecasting.

Conclusions

The model for short-term prediction of the ionospheric critical frequencies foF2 and MUF3000 presented in this study is designed for automatic and in real-time preparation of forecasts for the propagation of radio waves over Bulgaria to be used in the implementation of radio communication through ionospheric reflection. The model is based on measured values of the critical frequencies for a 15-days period before the current day and on forecasts of solar and geomagnetic activity indices.

Forecasts of solar and geomagnetic activity are available online from Space Weather Prediction Center, National Oceanic and Atmospheric Administration (<https://www.swpc.noaa.gov/>) [Gadzhev, 2020; Gadzhev et al., 2015]. The presented model is developed on the basis of data from vertical sounding of the ionosphere over Bulgaria for the period 1995-2014. The errors obtained in the examples above allow calculating with sufficient accuracy a specific radio path for the territory of Bulgaria [Bojilova and Mukhtarov, 2020].

Acknowledgment

This work was partially supported by the Bulgarian Ministry of Education and Science under the National Research Programme “Young scientists and postdoctoral students” approved by DCM № 577 / 17.08.2018 and by project № КП-06-H44/2 from 27.11.2020.

References

- Bojilova, R., & Mukhtarov, P. (2020). LOCAL TIME DEPENDENCE OF THE IONOSPHERIC RESPONSE TO GEOMAGNETIC DISTURBANCES OVER BULGARIA. International Multidisciplinary Scientific GeoConference: SGEM, 20(1.2), 615-622, DOI:10.5593/sgem2020/1.2/s05.078, 2020.
- Kutiev, I., Muhtarov, P., Cander, L. R., & Levy, M. F. (1999). Short-term prediction of ionospheric parameters based on auto-correlation analysis. Annals of Geophysics, 42(1), 1999.
- Muhtarov, P., Cander, L., Levy, M., & Kutiev, I. (1998, March). Application of the geomagnetically correlated statistical model to short-term forecast of foF2. In 2nd COST 251 Workshop, European Cooperation in the field of Science and Technological Research (COST), Side, Turkey, pp. 30-31, 1998.
- Bojilova, R. (2019). Influence of geomagnetic activity on electron concentration of the ionosphere. In 10th Congress of the Balkan Geophysical Society .Vol. 2019, No. 1, pp. 1-5, DOI:10.3997/2214-4609.201902636, 2019.
- Bojilova, R., & Mukhtarov, P. (2020)a. Relationship between short-term variations of solar activity and critical frequencies of the ionosphere represented by FoF2 and MUF3000. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, 73(10), 1416 – 1424, 2020.
- Bojilova, R., & Mukhtarov, P. (2020)b. Relationship between the Critical Frequencies of the Ionosphere over Bulgaria and Geomagnetic Activity. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, 73(8), 1113-1122, DOI: 10.7546/CRABS.2020.08.10, 2020.
- Mukhtarov, P., & Bojilova, R. (2017). Influence of solar and geomagnetic activity on the ionosphere over Bulgaria. Comptes rendus de l'Académie bulgare des Sciences, 70(9), 1289-1297, 2017.
- Mukhtarov, P., Andonov, B., & Pancheva, D. (2013). Global empirical model of TEC response to geomagnetic activity. Journal of Geophysical Research: Space Physics, 118(10), 6666-6685, 2013.
- Bojilova, R., & Mukhtarov, P. (2019). Response of the electron density profiles to geomagnetic disturbances in January 2005. Studia Geophysica et Geodaetica, 63(3), 436-454, DOI: 10.1007/s11200-019-0510-6 2019.
- Gadzhev, G. (2020). The Seasonal Recurrence of Air Quality Index for the Period 2008–2019 Over the Territory of Sofia City. In International conference on Environmental protection and disaster RISks (pp. 161-170). Springer, Cham, 2020.
- Gadzhev, G., Ganev, K., & Miloshev, N. (2015). Numerical study of the atmospheric composition climate of Bulgaria-Validation of the computer simulation results. International Journal of Environment and Pollution, 57(3-4), 189-201, 2015.
- Bojilova, R., & Mukhtarov, P. (2020). Forecasting the Propagation of HF Radio Waves Over Bulgaria. In International conference on Environmental protection and disaster RISks (pp. 309-324). Springer, Cham, DOI: 10.1007/978-3-030-70190-1_21, 2020.