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SHORT-TERM PREDICTION OF THE IONOSPHERIC CRITICAL FREQUENCIES OVER BULGARIA

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Abstract. An empirical model has been developed for short-term forecasting of ionospheric critical frequencies over Bulgaria, taking into account the variations in solar and geomagnetic activity. The model is based on data from the vertical sounding of the ionosphere over Bulgaria for the period 1995-2014 and designed to prepare real-time forecasts for the propagation of radio waves during ionospheric reflection on the territory of Bulgaria.

Key words: ionosphere, critical frequency, geomagnetic storm, solar activity.

Introduction

Forecasting of the critical frequencies of the ionosphere is a scientific and practical activity related to implementation of long-distance radio communications using ionospheric reflection of the radio waves. The critical frequencies of the ionosphere – *foF2* (maximum frequency at which the reflection from the ionosphere is observed in vertical propagation) and *MUF3000* (maximum frequency of reflection in oblique propagation at a distance of 3000km) are connected with the maximum value of the electron concentration in the ionosphere and the shape of its altitude profile.

Knowing these critical frequencies allows determining the operating frequencies of radio receivers and radio transmitters when making a radio communication at a given distance. The ionospheric electron concentration, respectively the critical frequencies depend on the diurnal time, the season, the level of the solar and geomagnetic activity.

The task of short-term prediction is to determine the most probable values of the critical frequencies for a future period of time of the interval 1-3 days, taking into account the forecast values of solar and geomagnetic activity, represented by heliophysics.

Short-term ionospheric prediction has been a priority topic of the section "Physics of the ionosphere" at the National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences since its creation.

A team from the section participates in the international scientific project COST 251 with a developed autocorrelation model for short-term prediction (Kutiev et all, 1999, Muhtarov et all, 1998). The tradition of providing ionospheric forecasts to the Ministry of Defense of the Republic of Bulgaria is long-standing.

This paper presents the newest empirical model for predicting of the ionospheric critical frequencies, developed in the section "Physics of the ionosphere".

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.

Detailed research (Mukhtarov et al, 2018) shows that for the purposes of short-term forecasting it is appropriate to use modified values of both the critical frequencies and the quantities characterizing the solar and geomagnetic activity. In this modification, the steady (undisturbed) state is removed from all quantities.

The task of prediction is to determine the deviation from this steady state. The steady state itself is determined on the basis of a sufficiently long time interval before the moment of forecasting, assuming that for this time interval there are measured values of the critical frequencies and the indices of solar and geomagnetic activity.

$$\begin{aligned} rfoF2(t) &= \frac{foF2(t) - foF2_{med}(UT)}{foF2_{med}(UT)}, \\ rMUF3000(t) &= \frac{MUF3000(t) - MUF3000_{med}(UT)}{MUF3000_{med}(UT)}. \end{aligned} \tag{1}$$

The relative values of the critical frequencies in (1) are calculated from the measured value at the given moment *t* and the median, calculated on the basis of the values during the same hour of the day in the 15 previous days.

The relative value of the index of solar activity (F10.7) is determined in a similar way:

$$rF10.7(t) = \frac{F10.7(t) - F10.7_m}{F10.7_m}. \tag{2}$$

With index *m* is denoted average value of 10.7 for the previous 15days.

The modification of the index of geomagnetic activity *Kp* is reduced to the subtraction of the average value of *Kp* for the previous 15 days:

$$Kp_f\left(t\right) = Kp\left(t\right) - Kp_m. \tag{3}$$

The modified index of geomagnetic activity is subjected to additional processing related to the fact that the ionosphere reacts to disturbances of geomagnetic origin as an inert system, due to the inertia of the processes of heating neutral gases in polar latitudes under the action of the solar wind (Andonov et al, 2011):

$$Kp_i\left(t_n\right) = \left(\exp\left(\frac{1}{T}\right) - 1\right)\sum_{k=0}^{n-1} Kp_f\left(t_k\right)\exp\left(-\frac{t_n - t_k}{T}\right). \tag{4}$$

The time constant of delay *T* depends on the season and is determined in the synthesis of the model.

Model functions

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

$$\Phi = \Phi_{UT}\left(UT\right)\Phi_{sol}\left(F10.7_{rel}\right)\Phi_g\left(K_{pi}\right). \tag{5}$$

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, Bojilova 2017).

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

$$\begin{gathered}\Phi_{UT} = a_0 + a_1\cos\left(\frac{2\pi}{24}UT\right) + a_2\sin\left(\frac{2\pi}{24}UT\right) + \\ + a_3\cos\left(\frac{2\pi}{12}UT\right) + a_4\sin\left(\frac{2\pi}{12}UT\right)\end{gathered} \tag{6}$$

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

$$\begin{aligned}\Phi_g &= c_0 + c_1 K_{piT1}(t) + c_2 K_{piT1}^2(t) + c_3 K_{piT1}^3(t) + \\ & c_4 K_{piT2}(t-t_{g2}) + c_5 K_{piT2}^2(t-t_{g2}) + c_6 K_{piT2}^3(t-t_{g2}) .\end{aligned} \tag{8}$$

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 t_{g2} 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

Fig. 1 shows the seasonal course of root mean square errors (RMSE) of the model relative deviations of *foF2* and *MUF3000* separately in day and night conditions. The error in daytime conditions for both critical frequencies is about 11%. For nighttime condition varies from 11% to 16%. Under nighttime conditions, larger deviations of the model from the data are obtained, which is due to the greater instability of the night ionosphere, which is dominated by recombination processes related to the dynamics of neutral gases, which is determined by internally atmospheric processes. Deviations increase during the winter season compared to the summer season due to the greater instability of the neutral atmosphere during the winter season.

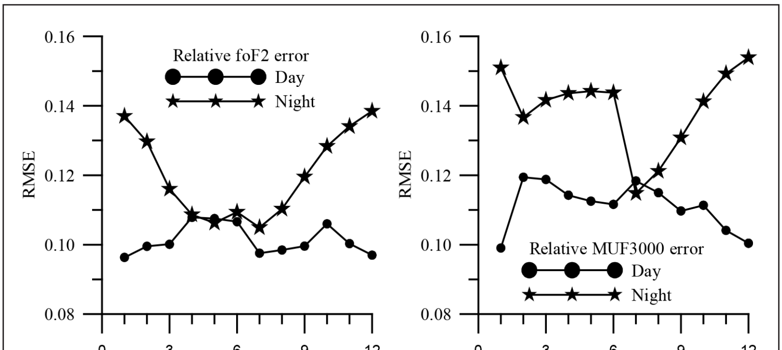

Fig. 1. Seasonal course of RMSE of the model relative foF2 and MUF3000 presented separately for day (circles) and night (stars) conditions.

In real prediction mode, the critical frequency values are calculated as follows from (1):

$$\begin{aligned} &foF2(t) = foF2_{med}(UT)\left(1 + foF2_{rel}(t)\right), \\ &MUF3000(t) = MUF3000_{med}(UT)\left(1 + MUF3000(t)\right). \end{aligned} \tag{9}$$

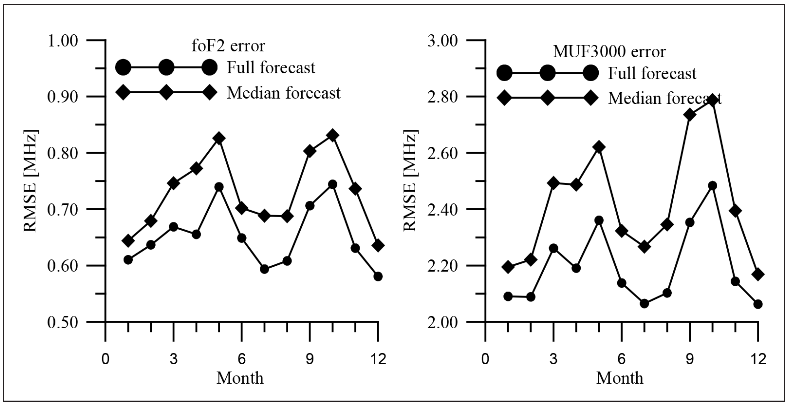

Fig. 2. Seasonal course of RMSE of the model for foF2 and MUF3000 values when forecasting only by the medians (circles) and by the full model (diamonds).

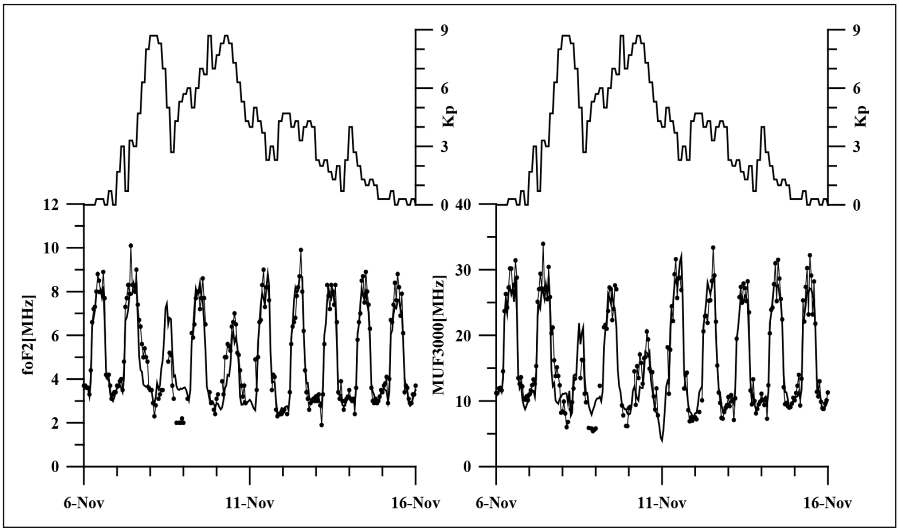

Fig. 3. Comparison between data (marked with circles) and the model in conditions of strong geomagnetic storm in November 2004.

Fig. 2 shows the seasonal course of RMSE of the model for *foF2* and *MUF3000*. For comparison, the prediction error is shown only on the basis of medians (relative values depending on the variations of solar and geomagnetic activity take zero values). The seasonal course in both types of forecasting has peaks during the equinox months. The fact that these increases also exist when predicted only by medians shows that they are due to the unstable course of the critical frequencies during the seasonal edistribution of the ionosphere in the equinox months.

Fig. 3 shows comparison of the hourly values of the data and the model during a strong geomagnetic disturbance in November 2004. For comparison, Fig. 4 presents a completely quiet period in May 2008.

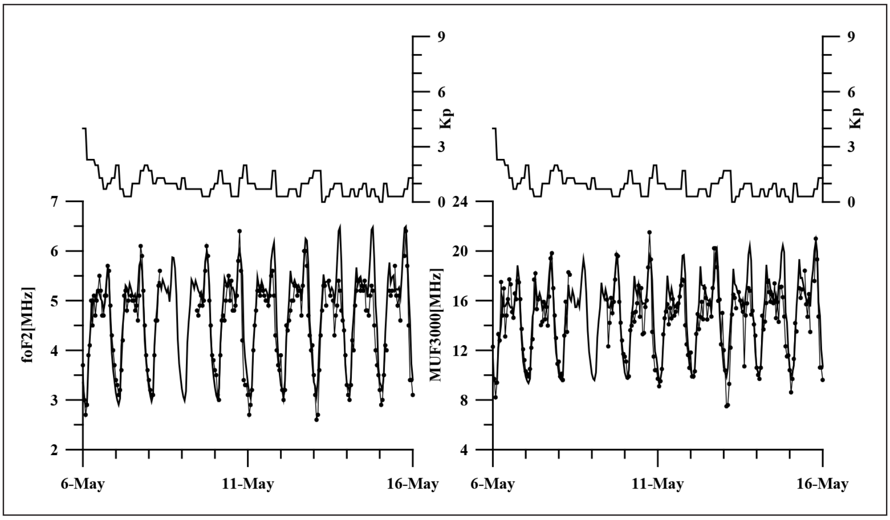

Fig. 4. Comparison between data (marked with circles) and the model during in quiet conditions in May 2008.

Conclusions

The model for short-term prediction of the ionospheric critical frequencies *foF2* and *MUF3000* presented in the 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.

The measured values of the critical frequencies can be data from the vertical sounding of the ionosphere or from their reconstruction according to the data of Total Electron Content TEC data (Rumiana Bojilova and Plamen Mukhtarov, article in press).

Forecasts of solar and geomagnetic activity are available online from Space Weather Prediction Center, National Oceanic and Atmospheric Administration (https://www.swpc.noaa.gov/).

The presented model is developed on the basis of data from vertical sounding of the ionosphere over Bulgaria for the period 1995-2014. The root mean square error (RMSE) when forecasting *foF2* is 0.65 MHz and when predicting *MUF3000* is 2.2 MHz, which allows calculation of specific radio paths in the territory of Bulgaria with sufficient accuracy.

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Краткосрочно прогнозиране на йоносферните критични честоти над България

Р. Божилова, П. Мухтаров

Резюме: Разработен е емпиричен модел за краткосрочно прогнозиране на йоносферните критични честоти над България с отчитане на вариациите в слънчевата и геомагнитна активност. Моделът се базира на данни от вертикалния сондаж на йоносферата над България за периода 1995-2014 г. и е предназначен за изготвяне в реално време на прогнози за разпространението на радиовълните при йоносферно отражение в границите на България.