Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 76, No 12, 2023

SPACE SCIENCES

Space physics

PRELIMINARY RESULTS OF METHODOLOGY FOR FORECASTING THE MINIMUM VIRTUAL HEIGHT OF IONOSPHERIC F-REGION FOR SOFIA CITY

Rumiana Bojilova, Plamen Mukhtarov

Received on September 29, 2023
Presented by P. Velinov, Corresponding Member of BAS, on October 31, 2023

Abstract

Using the virtual height for the calculation of the minimum and maximum usable frequency of a given radio path is well known. The purpose of the present investigation is to illustrate a methodology for determining the values of the minimum virtual height (h′F) of the ionospheric F-region. The dependence of the entire ionosphere on the level of solar activity is one of the main factors in the empirical modelling of the ionosphere. Correlation analysis was used to assess the relationship between the quantities. The results show a significant correlation, confirming the well-known relationship between solar activity and its impact on the ionosphere. In order to analyze the most appropriate dependence between the solar activity represented by F107 and h′F, a regression analysis was performed by month. The results show that the optimal dependence is close to linear. As a result, an empirical median model for forecasting h′F for the territory of Sofia city, depending on solar activity and season, is proposed. In its concluding part, this study also presents examples of the model's performance in selected months. The resulting errors are ME = 0.000 km and RMS = 8.180 km, respectively, which is accurate enough for practical purposes.

Key words: virtual height, ionosphere, forecasting

This work was partially supported by the Bulgarian Ministry of Education and Science under the National Research Programme "Young scientists and postdoctoral students-2" approved by DCM 206/07.04.2022.

DOI:10.7546/CRABS.2023.12.08

Introduction. It is well known that the main practical importance of the ionosphere is related to the possibility of reflecting radio waves in a certain frequency range from the different ionospheric regions [1–5]. The method for vertical sounding of the ionosphere is widespread and allows a sufficiently detailed representation of the main ionospheric quantities. For this purpose, the so-called ionosonde is used. It is a high frequency radar, which sends very short impulses vertically upward into the upper atmosphere [6, 7]. The ionosonde records show the time delay between the the transmission and reception of impulses in a frequency range of 1.5–20 MHz. After the signal is emitted, reflections first appear from the lowest region (the ionospheric E-region) and subsequently with a longer delay from the regions F1 and F2. It is well known that the F2-region is the most important region for HF radio propagation because: a) it is present 24 hours of the day; b) its high altitude allows the longest communication paths; c) it reflects the highest frequencies in the HF range [8]. The A1 method is one of the main methods for studying movements in the ionosphere. When propagating in an ionized environment, radio waves are reflected from an area with a certain value of the electron density, which depends on the frequency of the radio waves. By using radio waves of different frequencies and measuring the time it takes for the radio signals to return, information is obtained about the height distribution of the electron density of the ionosphere. In ionospheric research, we work not with the time delay of the reflected signal, but with the height of the reflection obtained on the assumption that the speed of radio waves is equal to the speed of light in a vacuum. But the speed of radio waves in an ionized environment is lower than the speed of light and depends on the electron density. For this reason, the reflection height obtained by delaying the reflected signal is referred to as the "virtual" height h′ [km]. The graph showing the dependence of the virtual height of the signal reflection on the frequency of the emitted impulse is called an ionogram. Ionograms make it possible to directly determine the electron density of the maxima of individual ionospheric regions. In the area of maxima, the propagation speed of radio waves, which depends on the electron density and its height gradient, tends to zero, which causes the presence of an asymptotic curve in the ionogram. Those frequencies at which asymptotic behaviour occurs correspond to the maximum electron concentrations that can be determined by the following formula:

$$N_m[\mathrm{el/cm^3}] = 1.24 \cdot 10^4 f_{cr}^2[\mathrm{MHz}].$$

The frequencies corresponding to the maximum electron density are denoted as critical frequencies. By interpreting the ionograms, both the critical frequencies of the ionospheric regions and the approximate virtual heights of the individual layers can be determined [9–11]. Everything described so far shows the importance of ionospheric investigations for a better understanding of the processes in the upper atmosphere and for improving the established methodology for forecasting

the ionospheric parameters. The purpose of the present study is to propose a methodology by which to improve the quality of the existing models for predicting the frequency range for a given radio path in the territory of Bulgaria.

Data. The influence of solar activity on the ionosphere is well known. In order to study the dependencies of virtual height of ionospheric F-region, data from the vertical sounding of the ionosphere from ionospheric station Sofia SQ143 (42.4° N, 23.2° E), which is part of the National Institute of Geophysics, Geodesy and Geography at the Bulgarian Academy of Sciences, for the time period 1995–2014 are used. The values of short-term variations in solar activity represented by the solar radio flux F10.7 are received from: `https://omniweb.gsfc.nasa.gov/`. It is accepted that daily and seasonal variability of ionospheric quantities and their dependence on long-term changes in solar activity are given by the monthly median of hourly values. The advantage of using the median value over the average one is due to the elimination of the influence of several extreme values recorded during geomagnetic disturbances [12–15]. Traditionally to characterize the quiet in the geomagnetic sense conditions of the ionosphere at a given month the medians are used.

Comparison between two types of data. The main idea of the present investigation is to present a universal methodology for predicting the minimum virtual height of ionospheric F-layer depending on the level of solar activity. For this purpose, the variations of F10.7 and the median values of h′F for the entire period from 1995 to 2014 were examined. Comparing the two panels in Fig. 1 clearly shows the influence of solar activity on the minimum virtual height of ionospheric F-layer. It can be seen in Fig. 1 that the course of the median values of the minimum virtual height follows the variability of F10.7. The next step is to find the optimal relationship between the two quantities through regression analysis.

Correlation analysis between F107 and h′F. In order to determine whether there is any relationship between two quantities, it is most appropri-

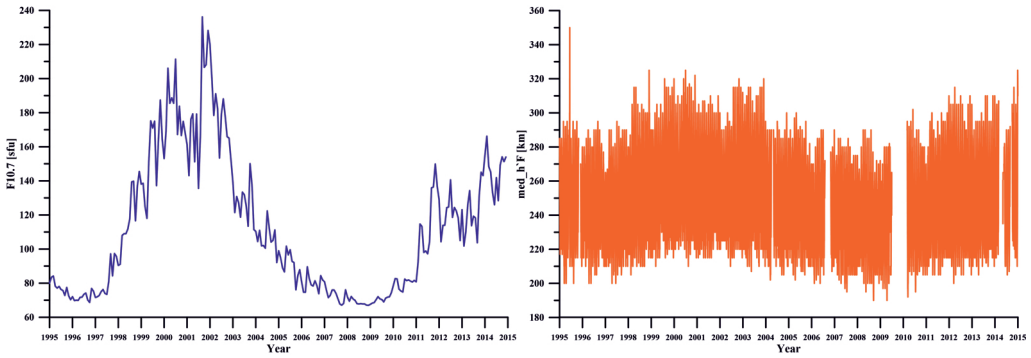


Fig. 1. Behaviour of the values of F10.7 by years for the entire considered period (left panel). Median values of h′F of ionospheric station Sofia for the period 1995–2014 (right panel)

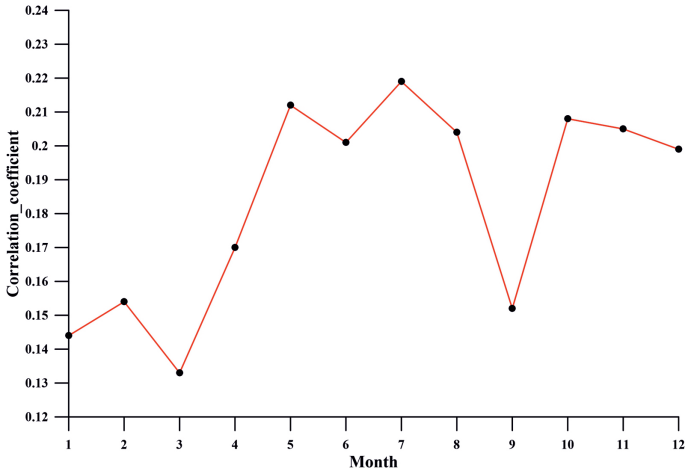


Fig. 2. Results of the correlation analysis between h′F and F10.7 by months

ate to apply a correlation analysis between the studied parameters [16]. In the present study, a correlation analysis was applied between the averaged h′F and F10.7 by month for the entire time interval. Figure 2 shows the course of the correlation coefficients for each month. The well-expressed seasonal course with minimums of the correlation coefficients in the equinox months are clearly seen. Figure 2 shows the well-defined seasonal course with minima of the correlation coefficients in the equinox months. The most significant correlations about 0.2–0.22 are observed in the summer months from May to August. Everything described so far together with the results of the correlation coefficients suggests the existence of the well-known dependence of the ionosphere on variations in solar activity. When applying correlation analysis, one should always take into account the possibility that the two considered processes represent two consequences of a third process, i.e. there should be no relationship between them regardless of the values of the correlation function between them.

Results of the regression analysis to determine the relationship between F107 and monthly median of virtual height of ionospheric F-region for selected months and hours. After the results of the correlation analysis show the existence of a relationship between the considered quantities, it is necessary to investigate in more detail how exactly virtual height of ionospheric F-region depends on the variations of solar activity. For the purposes of empirical modelling, it is very important to establish the most appropriate relationship between the studied quantities. To solve this problem, this section presents the results of the regression analysis between the hourly values of h′F and F10.7 [17]. In this type of analysis, a division is made into separate intervals for which the average values of the quantity "cause" and its corresponding time values of the quantity "consequence" are determined. The least-squares regression is calculated

based on these group means. The advantage of this approach in this particular case is because the solar activity data have many values in near-quiet conditions and too few values in disturbed conditions. The advantage of this approach is that if the regressions are calculated on the basis not of the group but of the output values, the dependencies acquire the character of the dependencies in conditions close to quiet conditions and some features in disturbed conditions may not be taken into account and be lost. Figure 3 presents the results of the described regression analysis for several selected months – January (winter), March (equinox month), and June (summer). The considered hours of the day are 00UT (midnight), 06UT (sunrise), and 12UT (noon), respectively. From the obtained results, it can be seen that for the purposes of empirical modelling, it is appropriate to use a linear relationship between the quantities, to be introduced during the synthesis of the model.

In the synthesis of the model, the function modelling the influence of the time of the day is a periodic function with a period of 24 hours and it is accepted to present it with its expansion in the Fourier series. The decomposition of the

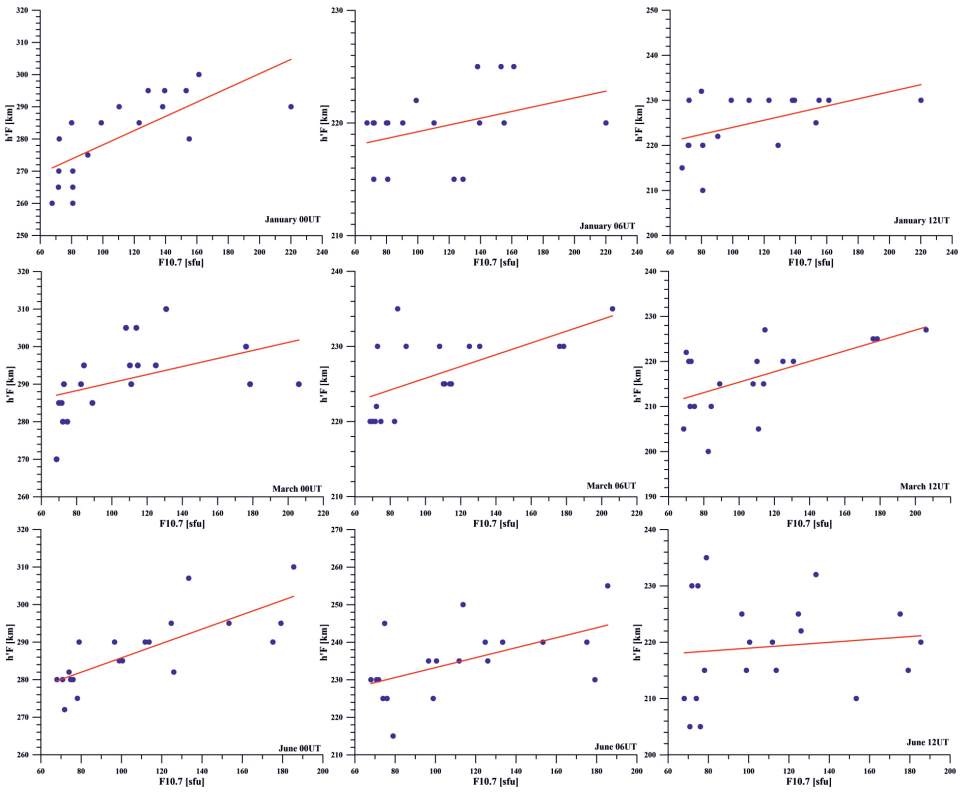


Fig. 3. Results of the regression analysis between h′F and F10.7 for the months: January (top row of panels), March (middle row of panels) and June (bottom row of panels) at given hours of the day

diurnal dependence in Fourier series is limited to the fourth harmonic (period of 12 hours). The dependence of h′F on solar activity turned out to be close to linear, and therefore the same dependence was introduced in the synthesis of the model.

The synthesis of the model is represented by the following formula:

$$\begin{aligned}\mathrm{h'F} &= (a_0 + a_1 \mathrm{F107}) \\ &\times \left(b_0 + \sum_{k=1}^{4} \left(b_{ck} \cos\left(k \frac{2\pi}{12} (\mathrm{month} - 1) \right) + b_{sk} \sin\left(k \frac{2\pi}{12} (\mathrm{month} - 1) \right) \right) \right) \\ &\times \left(c_0 + \sum_{k=1}^{4} \left(c_{ck} \cos\left(k \frac{2\pi}{24} ut \right) + c_{sk} \sin\left(k \frac{2\pi}{24} ut \right) \right) \right).\end{aligned}$$

The model results – comparison between model and data. Figure 4 shows a comparison between the medians, derived from measurements in ionospheric station Sofia (SQ143) and the obtained analogous values according to the proposed methodology for two years of high (bottom panel) and low solar activity (top panel). The plots show that there is a satisfactory fit between data and model. Seasonal changes are clearly visible, as well as the influence of solar activity. In addition to Fig. 4, for the purpose of a more detailed assessment of the accuracy, the errors for the entire considered time period were obtained. The resulting errors are ME = 0.000 km and RMS = 8.180 km, respectively, which is accurate enough for practical purposes such as radio path prediction. From the presented results, it can be concluded that the virtual height of ionospheric F-region can be predicted by the proposed methodology even in the conditions of a non-working ionospheric station on the territory of the Republic of Bulgaria.

Conclusion. In the present investigation, the dependence of the monthly median values of the virtual height of ionospheric F-region for the city of Sofia

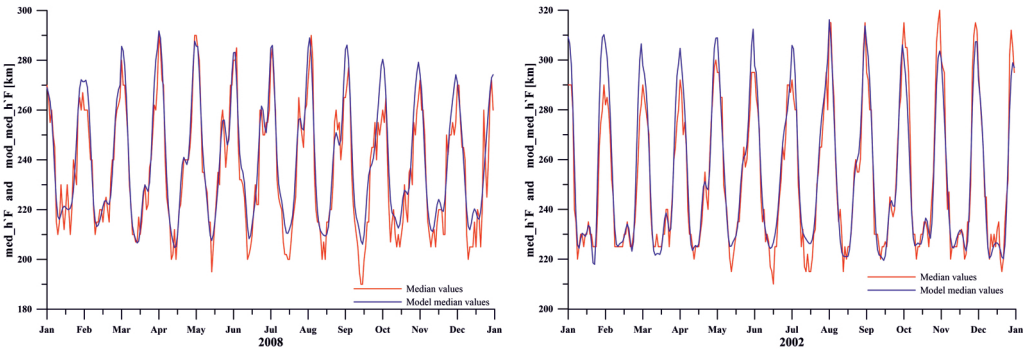


Fig. 4. Comparison between measured median values of h′F (red colour) and those obtained by the model (blue colour) for two specific years: a) low solar activity 2008 (left panel), and b) high solar activity 2002 (right panel)

on the level of solar activity represented by F10.7 over a period of almost two solar cycles is examined in detail. Tracking the variations of the solar activity and the behaviour of the monthly medians gives reason to look for a relationship between the two quantities. For this purpose, a correlation analysis, which shows in addition a well-expressed seasonal trend, a high correlation, which confirms the well-known influence of F10.7 on the ionospheric electron density, is presented. After confirming a relationship between the quantities, it is necessary to determine the most appropriate relationship to be implemented into the forecasting model. It was found based on regression analysis that the most appropriate dependence determining the relationship between the parameters is close to linear. Based on the results of the regression, a methodology for forecasting h′F is proposed depending on the season/time of day and variations in solar activity for the territory of our country. The obtained errors show that the methodology allows prediction of virtual height of ionospheric F-region with sufficient accuracy for practical purposes. From the presented examples and the received estimations for the quality of forecast, it is concluded that the thus synthesized empirical median model is able to forecast h′F for Sofia even in the conditions of a non-working ionospheric station. Everything described in this study demonstrates the importance of ionospheric research and prediction of ionospheric parameters for determining the usable frequencies of specific radio paths at a given radio distance [18–20].

REFERENCES

[1] Belrose J. S. (1970) Radio wave probing of the ionosphere by the partial reflection of radio waves (from heights below 100 km), J. Atmos. Terr. Phys., **32**(4), 567–596.

[2] Miller K. L., L. G. Smith (1977) Reflection of radio waves by sporadic-E layers, J. Atmos. Terr. Phys., **39**(8), 899–911.

[3] Beynon W. J. G., J. O. Thomas (1956) The calculation of the true heights of reflection of radio waves in the ionosphere, J. Atmos. Terr. Phys., **9**(4), 184–200.

[4] Murray F. H., J. B. Hoag (1937) Heights of reflection of radio waves in the ionosphere, Phys. Rev., **51**(5), 333.

[5] Lundborg B., B. Thidé (1985) Standing wave pattern of HF radio waves in the ionospheric reflection region, 1. General Formulas, Radio Sci., **20**(4), 947–958.

[6] Bibl K., B. W. Reinisch (1978) The universal digital ionosonde, Radio Sci., **13**(3), 519–530.

[7] Bibl K. (1998) Evolution of the ionosonde, Annali Di Geofisica, **41**(5–6), 667–680.

[8] Davies K., D. M. Baker (1966) On frequency variations of ionospherically propagated HF radio signals, Radio Sci., **1**(5), 545–556.

[9] Titheridge J. E. (1959) The calculation of real and virtual heights of reflection in the ionosphere, J. Atmos. Terr. Phys., **17**(1–2), 96–109.

[10] Smith N. (1939) The relation of radio sky-wave transmission to ionosphere measurements, Proc. IRE, **27**(5), 332–347.

[11] King G. A. M. (1957) Relation between virtual and actual heights in the ionosphere, J. Atmos. Terr. Phys., **11**(3), 209–222.

[12] Bojilova R., P. Mukhtarov (2023) Comparative Analysis of Global and Regional Ionospheric Responses during Two Geomagnetic Storms on 3 and 4 February 2022, Remote Sens., **15**(7), 1739.
[13] 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.
[14] Bojilova R., P. Mukhtarov (2019) Response of the electron density profiles to geomagnetic disturbances in January 2005, Studia Geophysica et Geodaetica, **63**(3), 436–454.
[15] Danilov A. D., J. Lastovicka (2001) Effects of geomagnetic storms on the ionosphere and atmosphere, Int. J. Geomagn. Aeron., **2**(3), 209–224.
[16] Kintner P. M., B. M. Ledvina (2005) The ionosphere, radio navigation, and global navigation satellite systems, Adv. Space Res., **35**(5), 788–811.
[17] Forbes J. M., S. E. Palo, X. Zhang (2000) Variability of the ionosphere, J. Atmos. Sol. Terr. Phys., **62**(8), 685–693.
[18] Bojilova R., P. Mukhtarov (2020) Forecasting the propagation of HF radio waves over Bulgaria. In: International Conference on Environmental Protection and Disaster Risks, Springer, Cham, 309–324.
[19] Krasheninnikov I. V., I. B. Egorov, N. M. Pavlova (2008) Effectiveness of predicting radiowave propagation in the ionosphere based on the IRI-2001 ionospheric model, Geomagn. Aeron., **48**, 504–510.
[20] Bojilova R., P. Mukhtarov (2020) Methodology for Calculating the Parameters of Radio Paths with Ionospheric Reflection. In: Proc. 1st Int. Conf. on Environmental Protection and Disaster Risks, 241–248.

National Institute of Geophysics,
Geodesy and Geography
Bulgarian Academy of Sciences
Akad. G. Bonchev St, Bl. 3
1113 Sofia, Bulgaria
e-mails: rbojilova@geophys.bas.bg
engpjm@abv.bg