Peculiarities of the behavior of the Ionosphere and HF Propagation Parameters in September 2017

Donat V. Blagoveshchensky, Olga A. Maltseva, Tatyana V. Nikitenko, Gennady A. Zhbankov

Abstract**—** Due to increasing of economic and scientific activity in the high latitude regions interest to information tools has been raised. One of the basic ways of exchanging information is the propagation of high-frequency (HF) waves, which requires knowledge of the state of the ionosphere. One of the main ways to describe this state is to use models. In the present paper, the most widespread model IRI2016 is used, however it has not been adequately tested in the high latitude regions, especially from oblique sounding and during disturbances. Results of testing the state of the ionosphere and the characteristics of HF propagation are presented for the period of September 2017, the month with the strongest disturbance at the end of the year. Two methods: analytical and numerical modelling, based on ray tracing, were used to determine the maximum usable frequency MUF on the paths of Gorkovskaya-Lovozero and Cyprus-Lovozero. A special feature of the study is the use of vertical and oblique sounding data with a 15-minute resolution. It is shown, that during the period of September 6-8, the MUF experienced a positive disturbance. The model values corresponded to the experimental magnitudes rather well. The possibility of using the analytical method for obtaining the MUF is confirmed by ray tracing. It is shown, that for monitoring of ionospheric conditions along any path it is possible to use the total electron content measured by means of navigation satellites GPS, GLONASS.

Keywords**—** disturbance, hf propagation, ionosphere, maximum useable frequency.

I. Introduction

Knowledge of the behavior of ionospheric parameters is important for theoretical studies and technological applications, such as the functioning of telecommunications, broadcasting, and navigation systems [1]. Ionospheric models play a special role. This is especially true of the high latitude region, which is insufficiently provided with means of measurement. The most widely used here are the VOACAP, ICEPAC, ITUREC533 (e.g. [2-3]) models, but recently there has been interest in using the IRI model [4-5]. In the paper [6], the possibility of using the IRI model in the high-latitude region was shown. In papers [4, 7-8], examples of the use of this model in high latitudes are given, including during the disturbance March 17, 2015. To confirm this use, a comparison is made for model values of the parameters with experimental magnitudes. The parameters relating to the maximum of the F2 layer were studied most fully: the critical frequency foF2 and the height of the maximum hmF2. However, there is another parameter M3000F2, which can play an important role in monitoring and forecasting the state of the ionosphere as a medium for the propagation of radio waves, as it directly determines the maximum usable frequency MUF3000F2 = M3000F2 * foF2. Despite the creation of models [9-10], this parameter is not given sufficient attention, especially in high latitudes. The peculiarity is that like the parameters foF2 and hmF2, the parameter M3000F2 can be predicted using the model. All parameters depend on the levels of solar and geomagnetic activity therefore it is necessary to investigate the behavior of the ionosphere in each new time period to identify features that may not be described by models. For this, it is necessary to compare the model and experimental values of the parameters. In this paper, this is done for the least studied region of sufficiently high latitudes according to the data of vertical sounding at Moscow stations (55.5° N, 37.3° E), Gorkovskaya (60.27° N, 29.38° E), Lovozero (67.97° N, 35.02° E) and oblique sounding on the paths of Gorkovskaya-Lovozero (path length 900 km) and Cyprus-Lovozero (path length 3,600 km), provided by AARI on the site (http://geophys.aari.ru/). For the study period, September 2017 was selected - the month with the strongest disturbance (the minimum value is Dst = -142 nT) at the end of the year. IRI2016 was used as the IRI model [11]. A feature of this study is the use of vertical and oblique sounding data with a 15-minute resolution. Since such data may have more variability than sentinels, it is important to estimate the deviation of model values from experimental ones. In the first section, modelling methods are described. In the second section, results of modelling in the September 2017 including the strongest disturbance of the end of year are yielded.

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D. V. B. is with Saint-Petersburg State University of Aerospace Instrumentation, 67, Bolshaya Morskaya street, Saint-Petersburg 190000, Russia (e-mail: donatbl@mail.ru)

O. A. M. is with Institute for Physics, Southern Federal University, Stachki, 194, Rostov-on-Don 344090, Russia (corresponding author to provide phone: +7-918-577-25-33, e-mail: mal@ip.rsu.ru)

T. V. N. is with Institute for Physics, Southern Federal University, Stachki, 194, Rostov-on-Don 344090, Russia (e-mail: niki-ta1952@mail.ru)

G. A. Z. is with Institute for Physics, Southern Federal University, Stachki, 194, Rostov-on-Don 344090, Russia (e-mail: zhbankov@ip.rsu.ru)

Despite the increase in the number of ionosondes in this zone in recent years, their number is not sufficient for detailed monitoring. Additionally, we can use receivers of signals from navigation satellites of systems such as GPS, GLONASS providing information about the total electronic content TEC. In the paper [12], the possibility of using TEC to obtain critical frequencies has shown. In the end of the second section, the possibility to use TEC to estimate the ionospheric state is shown in the large number of points in a considered zone. The last section includes the conclusion.

II. Methods of Modeling

To calculate the maximum usable frequency MUF(F2), two methods were used: analytical and numerical modelling. The analytical method consists in using the product of the propagation coefficient M3000F2 to the critical frequency foF2. For comparison with the experimental values of MOF(F2) on the Gorkovskaya-Lovozero path, the coefficient M3000F2 was recalculated to the MD coefficient for the corresponding path length D = 900 km in accordance with the algorithm [13]. The method of numerical modelling is briefly as follows. In general, the calculation of trajectories follows the classical ray tracing procedure [14]. Since the ionosphere is an inhomogeneous medium, it is impossible to find a trajectory in it by analytical methods. The most consistent and effective problem of finding the trajectory and energy characteristics of HF radio waves is realized within the framework of the geometric optic approximation on the basis of the method of characteristics [15-16] consisting of a numerical solution of the local dispersion equation

$$F(\mathbf{r},\mathbf{k},\omega) = \kappa^2 - \kappa_0^2 \cdot n^2(\omega,\mathbf{r},\mathbf{k},\mathbf{H})$$

by transforming it to a system of differential characteristic equations with respect to spatial and ray coordinates. A system of characteristic equations for finding trajectories in canonical form can be written as follows:

$$\begin{cases} \dfrac{d\mathbf{r}}{d\tau} = \dfrac{\partial F}{\partial \mathbf{p}} = \mathbf{p} - \dfrac{1}{2}\dfrac{\partial n^2}{\partial \mathbf{p}} \\ \dfrac{d\mathbf{p}}{d\tau} = -\dfrac{\partial F}{\partial \mathbf{r}} = \dfrac{1}{2}\dfrac{\partial n^2}{\partial \mathbf{r}} \end{cases}$$

where $n(\omega,\mathbf{r},\mathbf{k},\mathbf{H}) = \mu + i\chi$ is the complex refractive index of Appleton, $\mathbf{H}$ is the vector of the external geomagnetic field, $\mathbf{r} = r\{\theta,\varphi\}$ is the radius vector in the spherical coordinate system, $\mathbf{p} = \dfrac{\mathbf{k}}{|\mathbf{k}_0|} = n\{\}$ is the normalized wave vector, and τ is an independent auxiliary variable. Since the allowance for the collision in the ionospheric plasma has little effect on the trajectory of the ray, n can be replaced by its real part μ.

The calculations use a two-dimensional inhomogeneous model for the distribution of electron concentration in the ionosphere. The distribution of Ne along the plane of propagation of radio waves is given as the sum of the basic unperturbed part and an additional perturbation: $N_e = N_0 \cdot (1 + \delta_L + \delta_T)$ where N_0 is the unperturbed "base" part described by the international model IRI-2016 with allowance for the possibility of correction in the presence of vertical sounding data [17], δ_L is a perturbation created by single large-scale inhomogeneities with the relative amplitude of the perturbation ΔN_L, δ_T is a perturbation created by inhomogeneities with a wave-like structure (TID) with amplitudes ΔN_T.To construct the ionization distribution according to the IRI-2016 model, taking into account the correction, an electron concentration is calculated at the nodes of a given grid plane at a given time. Subsequently, the values of the concentration at an arbitrary point are found using, for interpolation, cubic splines satisfying the requirements of the continuity of the function and its derivative.

The perturbed part of the electron concentration δ is generally given in the form of a sum of ellipsoids:

$$\delta_L = \Delta N_S = \sum_i dN_i \cdot \exp\left\{-\left(\frac{x - x_{0i}}{Lx_i}\right)^2 - \left(\frac{y - y_{0i}}{Ly_i}\right)^2 - \left(\frac{z - z_{0i}}{Lz_i}\right)^2\right\}$$

where $dN_i(r,\theta)$ is the relative amplitude of the wave inhomogeneities with a period depending on the coordinates; Φ_0 - the initial phase, Λ - the wavelength, R_0 = 3670 km - the radius of the Earth.

The output of auxiliary information is provided: 1) N(h) profiles above the transmitter and receiver and at the middle point of the path, what is especially important to see when adapting the model, 2) the ionization distribution contour representing the position of inhomogeneities, for example, the Es layer or traveling ionospheric disturbances (TID), and 3) patterns of trajectories that make it possible to identify the type of trajectory. Fig. 1 gives an example of the presentation of this information.

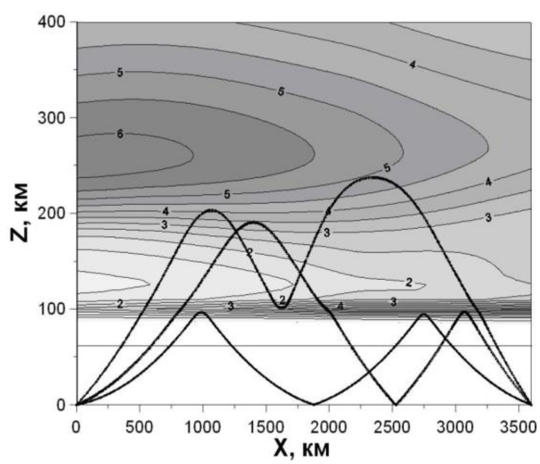


Fig. 1 an example of information that makes it possible to understand the nature of wave propagation in the model ionosphere

III. Results of the Ionospheric State Assessment in September 2017

Fig. 2 shows the behavior of the indices of solar F10.7 and geomagnetic Dst activity in September 2017. The Dst index is represented by the period including the disturbance under study.

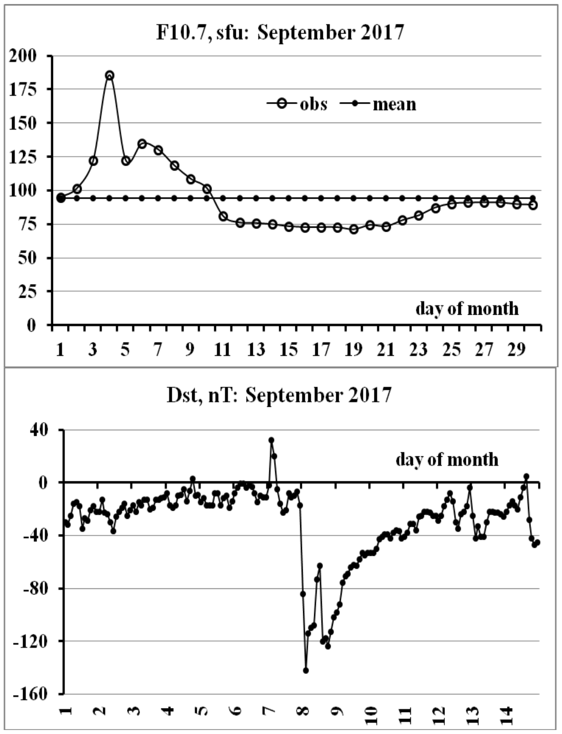


Fig 2 solar F10.7 and geomagnetic Dst indices in September 2017

It can be seen that this month stands out by a burst of solar activity, and a strong geomagnetic disturbance. The behavior of the parameters foF2 and hmF2 is shown in Fig. 3 for the station Moscow, located in the middle point of the path Cyprus-Lovozero. On the left, the curves for the monthly medians are shown, on the right - for the selected days, including the disturbance. Based on these data, the model was corrected in calculating the trajectories.

It can be seen that the experimental medians and model values correspond to each other quite well. For foF2, the mean monthly deviation was 0.064 MHz, which indicates that model values exceed the experimental medians. As can be seen from Fig. 3, this refers to the evening hours. The average absolute deviation was 0.22 MHz, RMS = 0.25 MHz, the relative deviation is equal to 6.24%. For the parameter hmF2, these values are 18.87 km (strong excess throughout the day), 19.51 km, 26.67 km and 10.37%. Perhaps such figures are associated with low level of solar activity (IRI index Rz12 = 16.3).

During the selected days, the increased values of foF2 took place. On September 6, these values were increased due to increased values of F10.7, as can be seen from Fig. 2. On September 7, the transition from positive values of the Dst-index to negative values has happened. The foF2 curve for the model shows that it describes the variations during the negative phase very well and does not feel the positive phase.

For the Gorkovskaya-Lovozero path, according to the data of vertical sounding, the experimental values of the M3000F2 coefficient were obtained and the corresponding model IRI values were calculated. The values of the MUF recalculated for the length of the path are shown in Fig. 4. The symbols GRK and LOZ mean the station (Gorkovskaya and Lovozero), the data of which were used in the calculation of the MUF. On the left panel, the experimental medians ("med" icon) are compared with the model values (the "IRI" icon). Since Gorkovskaya station is located at the southern point of the path, its foF2 is higher and it gives the upper limit of the MUF. Lovozero station is located at the northern point of the path, its foF2 is lower and it gives the lower limit of the MUF.

The average absolute deviations are 0.75 MHz for Gorkovskaya station and 0.56 MHz for Lovozero station, what leads to relative deviations of 15.4% and 11.2%. These estimates can be considered satisfactory, what is confirmed by the results of the right-hand panel, which gives a comparison of the values measured directly on the path with model values calculated in accordance with two options: 1) for the initial IRI model; 2) for the model adapted to the experimental values of foF2.

The moments of observation were for the period UT = 7-13, i.e. values lie within the limits of the left panel. For the right-hand panel, the absolute deviations are 0.52 MHz and 0.62 MHz, the relative deviations are 6.63% and 8.32%. This indicates that the analytical method can be fully used in high latitudes.

The MUF values for the 1st and 2nd hops on the Cyprus-Lovozero path are shown in Fig. 5, together with a 5-fold decrease in the values of the Dst-index. The values have gaps, and on the evening of September 8 they seem to be below the minimum measurement frequency of 8 MHz.

The left panel shows that the MUF follows the foF2 values of the station Moscow and experience the same variations. The right panel shows the values of the MUF of the first hop (triangles) and the model values of the MUF calculated for the initial model (dots) and for the model corrected for the experimental foF2 values (circles) of the station Moscow. Two points can be emphasized: 1) adaptation of the model significantly improves the correspondence between the experimental and model values of the MUF during the positive phase of the disturbance, 2) the values of one station located even near the midpoint of the path during the negative phase of the disturbance are insufficient. This can be seen from the example of the September 8 disturbance, when the behavior of the ionosphere at one point does not reflect the behavior along the path. For illustration, Fig. 6 shows the latitudinal variation of the total electron content TEC at the meridian 30°, near which the path passes, for September 6-8, 2017 at the moments UT = 10 and 18 together with the monthly median.

It can be seen that during the day the positive disturbance covers the entire region on September 6 and 7, including Moscow. On September 8, the ionosphere over Moscow is close to the average condition and the correction yielded a correspondence with the MUF. At the time UT = 18, Moscow was in the center of the shifted trough with a minimal value of the TEC, hence, a minimal value of the foF2, but this value does not correspond to the state of the ionosphere along the path and the MUF value seemed to be greatly underestimated.

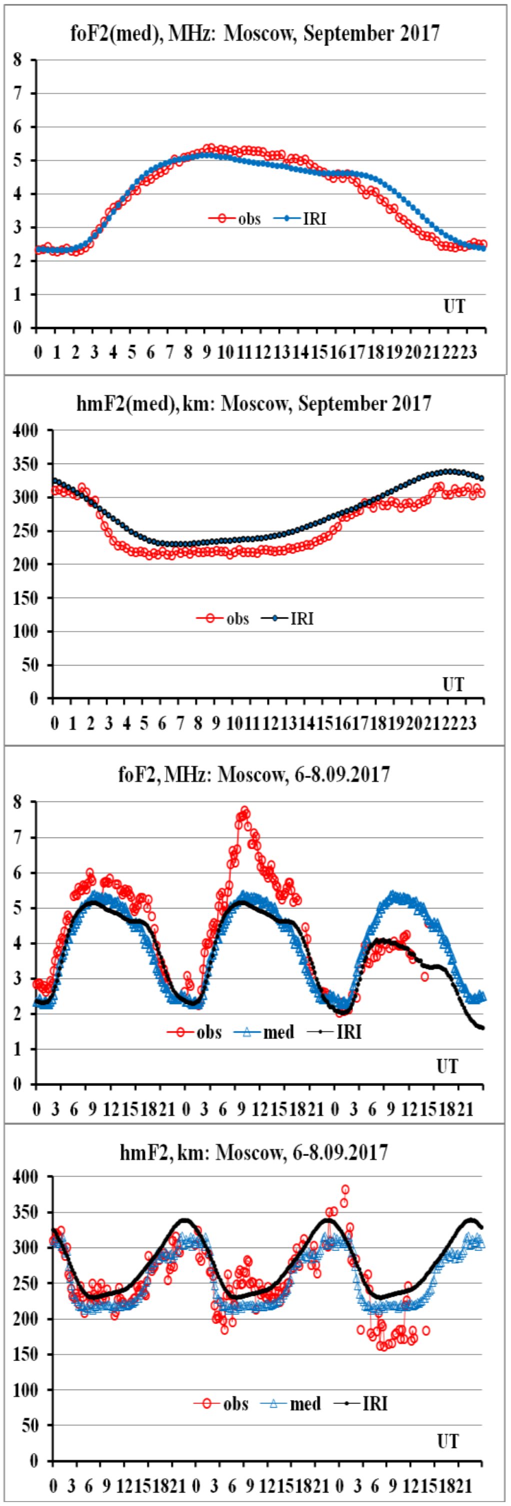


Fig. 3 behavior of the ionospheric parameters in September 2017 according to the station Moscow data

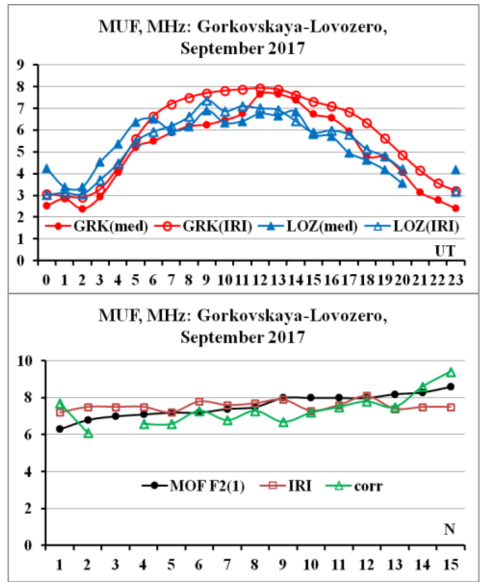


Fig. 4 the behavior of the MUF of the Gorkovskaya-Lovozero path in September 2017

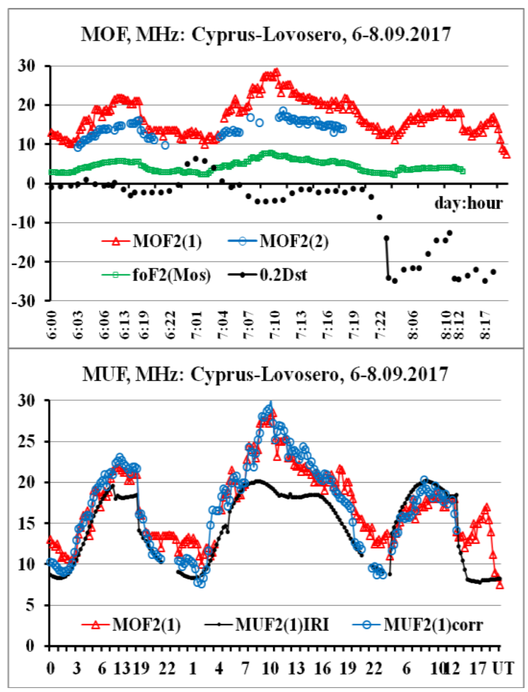
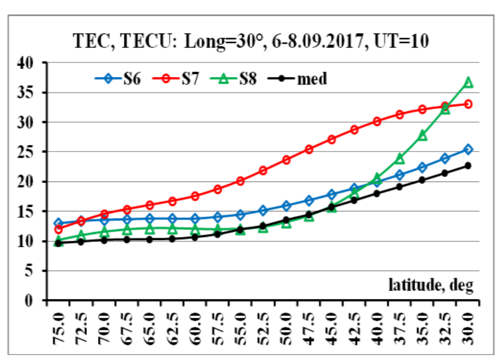


Fig. 5 measured and model values of MUF during the period September 6-8 on the path Cyprus-Lovozero



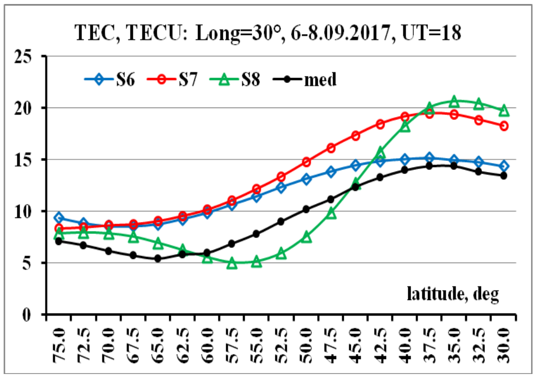


Fig. 6 latitudinal sections of the behavior of TEC on September 6-8, 2017 at the moments UT = 10 and 18

Peculiarity of the ionospheric behaviour during this period is that positive disturbance took place on September, 7th, before the main phase of a magnetic storm with the minimum value Dst =-142 nT on September, 8th. To show role TEC more clearly, we will notice, that relative deviations TEC from a median δTEC were 50 % in the afternoon and 80 % at night for the station Lovozero, 65 % and 135 % accordingly for the station Gorkovskaya and 72 % and 50 % for the station Moscow. Thereupon, it is necessary to notice, that in September 2017 one more magnetic storm 27-29.09 took place with the minimum value Dst =-100 nT on September, 28th, and the positive disturbance on September, 27th took place. This disturbance is characterized by the following δTEC: 80 % at day and night for the station Lovozero, 80 % in the afternoon and 40 % at night for the station Gorkovskaya and 70 % in the afternoon for the station Moscow. As well as in the previous case, behaviour of an AE index was absolutely quiet in previous days 24-26.09, and on September, 27th there were strong disturbances.

IV. Conclusion

The high latitude region is a problem area as from the point of view of experimental researches, and modelling. In the given paper, the most widespread model IRI was used. Comparison of model and experimental values of parameters foF2 and hmF2 has shown good enough conformity. Now in the paper [18], the new model of parameters foF2 and hmF2 is described specially for the high latitude region instead of, probably, IRI. Its testing according to data of Russian ionosondes can be the purpose of the future work as soon as it will be available on a corresponding site. Comparison of parameters of HF propagation testifies that the model IRI can be used as yet, especially at adaptation to data of the current diagnostics, allowing consider even 15-minute fluctuations of MUF. It was shown that in the period of September 6-8, the MUF on the Cyprus-Lovozero path experienced a positive disturbance. The possibility of using an analytical method for obtaining the maximum usable frequency MUF is confirmed by ray tracing. Use of the total electron content allows us to describe a state of the ionosphere with the larger spatial resolution, than use of a rare network of ionosondes. Processing and use of data of future network of GPS receivers are supposed.

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