Vol. 05, No. 1 (2023) 97-104, doi: 10.24874/PES05.01.009

Proceedings on Engineering Sciences

www.pesjournal.net

ACCOUNTING FOR SMALL-SCALE IRREGULARITIES IN THE PROPAGATION OF SHORT RADIO WAVES IN THE HIGH-LATITUDE IONOSPHERE

Gennadiy Zhbankov
Olga Maltseva [1]

Received 06.10.2022.
Accepted 11.01.2023.
UDC – 52-77:[004.942:537.877]

Keywords:

Small-Scale Irregularities, Short Radio-Waves, High-Latitude Ionosphere, Sounding, Ionogram, Modeling.

A B S T R A C T

In the modern world, the need for accurate knowledge of the state of the high-latitude ionosphere has increased, the modeling of which is difficult due to the presence of a large-scale structure. However, the empirical and theoretical models of the ionosphere developed in recent years have made significant progress in taking them into account. The situation with small-scale irregularities is more complicated. In this work, the comparison was performed between experimental ionograms of vertical, oblique, external and transionospheric sounding with ionograms, calculated by a computer simulation taking into account small-scale irregularities. The obtained conformity has allowed one to conclude that there is a range of parameters values of these irregularities which can be used in interpreting and predicting the propagation characteristics of short radio-waves in complicated conditions, especially during disturbances.

1. INTRODUCTION

Due to climate change and increased economic activity, the high-latitude zone has become an area of increased interest in terms of modeling the state of the ionosphere, which is necessary, first of all, to ensure the propagation of HF radio waves (Blagoveshchenskii, 2020; Mingalev et al. 2021). Waves of this particular range are mainly used on transpolar routes, the number of civil aviation flights on which is growing (Warring et al., 2017).
The polar ionosphere strongly differs, for example, from the mid-latitude ionosphere by a large spatial irregularity, the structure and statistics of which are not well understood, but at present it is possible to take into account such features as large-scale TIDs (Themens et al. 2017), patches (Carlson, 2012), and others. As for small-scale irregularities, the situation here is even more complicated.

The consequences of the presence of these irregularities are well known, but there are difficulties in directly measuring their sizes. From the point of view of HF wave propagation, these consequences are fading, frequency scattering in ionospheric communication channels, multipath, and the Fspr phenomenon (Szuszczewicz, 1987). In a higher frequency range, this leads to a deterioration in the accuracy of navigation and positioning systems (Zhbankov et al., 2022).

[1] Corresponding author: Olga Maltseva
Email: oamaltseva@sfedu.ru

For the experimental study of small-scale irregularities, the methods of ground-based vertical (VS) and oblique (OS) sounding are traditionally used (e.g., Booker & Wells, 1938; Bowman, 1990; Hunsucker & Hargreaves, 2003; Ossakow, 1981; Panchenko et al., 2018). Ivanov et al., 2019 showed the possibilities of using various types of satellite sounding to monitor the state of the high-latitude ionosphere, in particular, that low-flying satellite data can be used to track the response of the ionosphere to disturbances. This indicates a possible successful mission of small satellites, the use of which will become real in the near future (Chernyshov et al., 2020).

To simulate HF propagation, the latest version of the IRI model, IRI-2016 (Bilitza et al., 2017), is used. Such modeling showed a good agreement between the calculated and experimental characteristics of HF propagation not only under quiet conditions, but also during disturbances (Blagoveshchensky et al., 2018). Therefore, in this paper, the original IRI-2016 model is used as the base model and also the model IRI-2016 adapted to the parameters of the current diagnostics.

The aim of this work is to simulate the HF propagation in the high-latitude ionosphere in a model taking into account small-scale irregularities and to compare the model values with experimental characteristics in order to assess the possibility of a more accurate obtaining of the state of the ionosphere. In contrast to other works, such modeling and comparison are carried out not only for the terrestrial (VS and OS) sounding, but also for the satellite external (ESS) and transionospheric (TIS) sounding. The corresponding ionograms are used as experimental data.

2. EXPERIMENTAL CONFIRMATIONS OF THE EFFECT OF SMALL-SCALE IRREGULARITIES

Since the work is devoted to modeling the influence of small-scale irregularities in order to take them into account during the propagation of short radio waves, experimental examples are given along with the results of modeling, a detailed presentation of which is given in the next section. Examples are given for the main experimental methods of studying the ionosphere.

For vertical sounding, a typical case of Fspr was chosen as an example, which was observed on the ionogram obtained on May 14, 2013 by the DPS-4 ionosonde located in Tromsø (69.58º N, 19.12º E), UT=00:45 (Figure 1). Also on it, a thin black line shows the N(h)-profile of the ionosphere processing by the ARTIST-5 program, a thicker one is reconstructed using the method proposed by the authors. The result of modeling taking into account small-scale irregularities with relative amplitude $\Delta N/N = 4\%$ is shown in Figure 1 (the lower panel).

It is necessary to notice, that phenomenon Fspr complicates reconstruction of the N(h)-profile, therefore it was necessary to apply specially developed procedure, allowing it to make. It can be characterized as a method of reconstruction of a profile on digitized ionogram. This method is based on numerical trajectory calculations in non-uniform magnetoactive environment. It allows calculating the N(h)-profile on digitized ionogram in several points to a trace of O-components. In areas where reflection is absent, the model IRI-2016 is used as zero approach.

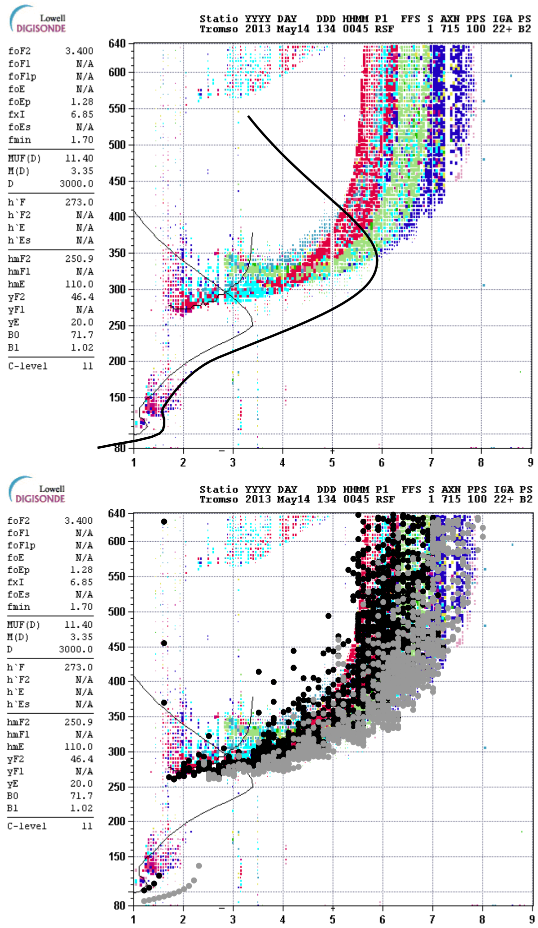

Figure 1. Real ionogram recorded on the DPS-4 ionosonde in Tromsø on 14.05.2013 (the upper panel) and the result of numerical simulation taking into account small-scale irregularities (the lower panel)

The next type is the oblique sounding which allows obtaining the major characteristic - the maximum used frequency MUF for the given path. This case is illustrated by the example of an oblique ionogram on the Moscow – Murmansk path 1486 km long in a quiet ionosphere and in the presence of small-scale irregularities at a frequency of 5.8 MHz in Figure 2. Ordinary rays are shown in red, extraordinary rays are shown in green.

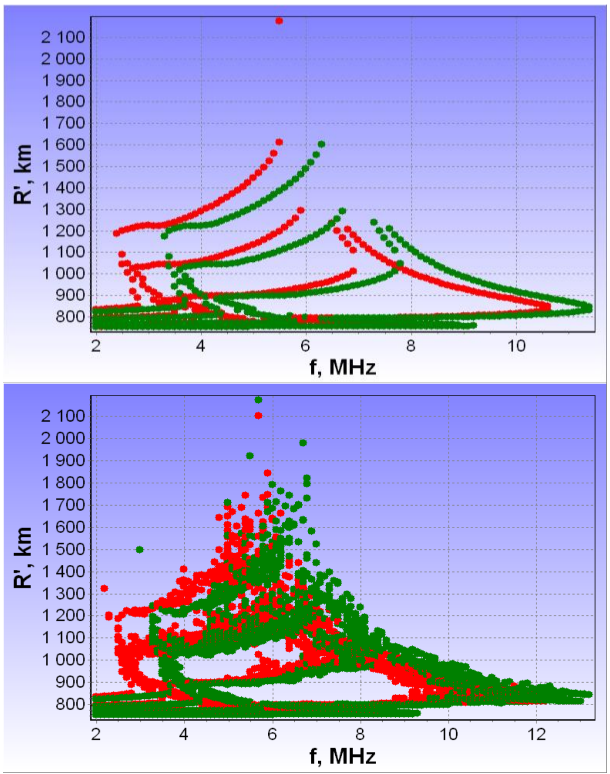

Figure 2. Background ionogram of oblique sounding (the upper panel) and the result of modeling taking into account small-scale irregularities (the lower panel)

Ionograms of external sounding are unique, giving the chance to investigate structure of the ionosphere above the height maximum of the F2 layer. The results of external sounding are illustrated by the example of an analog ionogram extracted from the huge data of the Interkosmos-19 satellite and presented in Figure 3. It was registered at the receiving point Moscow on April 9, 1981. The satellite was above the point with coordinates (26.80º N, 32.90º E) at an altitude of 939 km. The high quality of analog ionograms made it possible to record in detail a very interesting structure in the ionosphere. It consists of four diffuse clouds of a characteristic shape, strung like beads on the main trace of the reflected signal.

It is clear that unusual traces are associated with the irregularities structure of the ionosphere. Since the "beads" are located at different heights (and, accordingly, at different frequencies), the irregularities are also located at different heights. Because all “beads” are densely filled with reflected signals, then there are many small-scale irregularities at different distances. They can be presented as four layers located at different heights.

The last type is transionospheric sounding. This type of sounding is now one of the most developing because of occurrence of a network of orbital satellites (as with the orbits close to circular, and with high apogee orbits). An example of a transionogram for the Satellite-Murmansk path in a quiet ionosphere and in the presence of small-scale irregularities is given in Figure 4 for 21.02.2014 at UT=03.00. Satellite with coordinates 47.11° N, 63.59° E is located at an altitude of 24260 km. An example is considered to assess the possibility of using satellites with high apogee orbits.

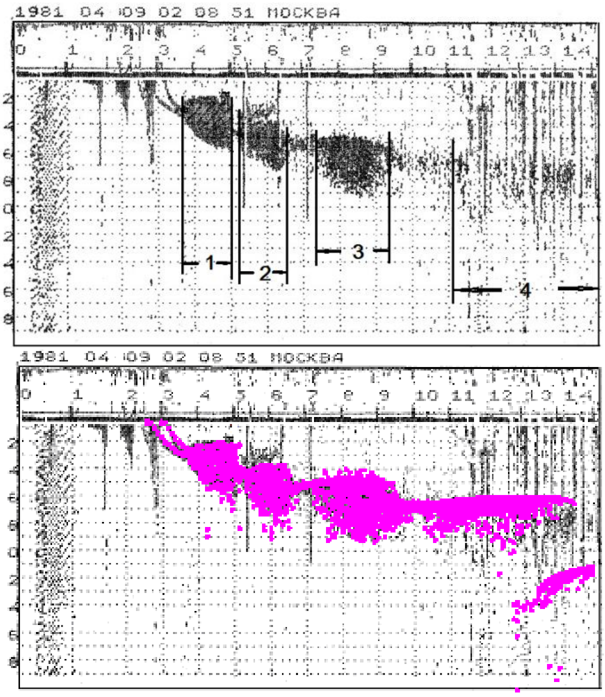

Figure 3. Ionogram of external (satellite) sounding (the upper panel) and the result of its modeling taking into account small-scale irregularities (the lower panel)

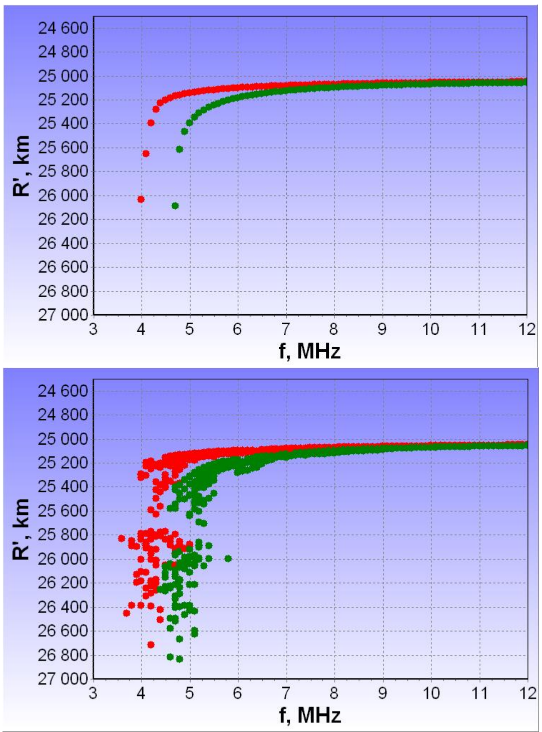

Figure 4. Simulation of the transionogram for the AES-Murmansk path in a quiet ionosphere (the upper panel) and in the presence of small-scale irregularities (the lower panel)

3. SIMULATION WITH ACCOUNT FOR SMALL-SCALE IRREGULARITIES AND ADDITIONAL EXAMPLES

As noted in the Introduction, the simulation was carried out using the IRI-2016 model. In this case, the data of the DIDBase system (foF2 and hmF2) processed by the ARTIST5 procedure (Galkin et al., 2008) were used to adapt the model.

The algorithm for constructing trajectories is based on the geometric-optical approximation by solving an extended system of characteristic equations (method of characteristics) and is presented in detail in the paper (Zhbankov et al., 2022). Since a distinguishing feature of the algorithm is the inclusion in the model of a factor describing small-scale irregularities, it is necessary to determine at what sizes of irregularities this approximation can be applied. Simplification of the initial wave equations is achieved in cases where the problem has a small parameter:

$$\mu = \max\left(\frac{\lambda}{L_0}, \frac{1}{\omega T}\right) << 1. \qquad (1)$$

where λ is the wavelength of oscillations in the direction of the plasma irregularity, ω is the average frequency of the radio wave, L_0 is the characteristic size of the irregularity, and T is the characteristic time of change in the parameters of the medium. A similar inequality is proposed by (Kravtsov and Orlov, 1980): the parameters of the medium, as well as the parameters of the wave, should not change noticeably in the cross section of the Fresnel volume

$$a_f \left|\frac{\nabla_{\perp} n}{n}\right| << 1 \qquad (2)$$

where a_f is the section of the Fresnel volume, n is the refractive index. Analyzing these conditions, it can be argued that both inequalities are satisfied for irregularities larger than 1 km. This size was taken as the lower limit of the irregularity scale.

Specifically, small-scale irregularities were specified by the sum of 25 components described by formula (3),

$$\Delta N_2 = \sum_i \delta_i(r,\theta,\varphi)\cos\left[-\frac{2\pi}{T_i}t + p_{ri}(r-R_0) + p_{\theta i}R_0\theta + p_{\varphi i}R_0\varphi + \Phi_{0i}\right]. \qquad (3)$$

with relative amplitude $\Delta N/N = 3\%$, wavelength Λ, randomly distributed in the range from 2 to 20 km, random values of initial phases Φ_0 and guiding angles η and ξ. The qualitative correspondence of the obtained inhomogeneous structure to small-scale irregularities was checked visually in the course of calculations and is shown in the Figures below. Particular attention in the study was paid to the number of rays arriving at the receiving point at a fixed frequency, the possibility of determining the key parameters of the ionosphere from such ionograms, and the energy of the incoming signals.

To exclude possible random effects of the appearance of sufficiently large inhomogeneous structures associated with the method of specifying irregularities, a large number of model experiments were carried out.

The distributions of the electron density in the plane of the magnetic meridian and the trajectory of rays of ordinary polarization are given below for the cases presented in the Figures in the previous section. Figure 5 shows this distribution for beams reflected at a frequency of 6.0 MHz in the presence of irregularities for conditions corresponding to Figure 1 (the lower panel). It can be seen that the received signal does not consist of a single beam (as it would be in ideal conditions), but of a set of a large number of beams propagating along independent trajectories with a sufficient spread over the effective height.

Another example for May 05, 2016 is shown in Figure 6.

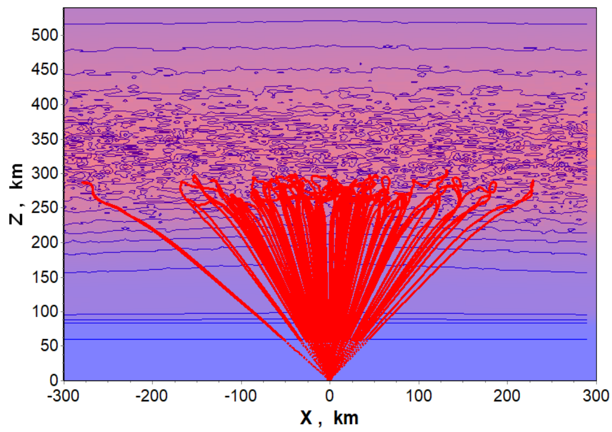

Figure 5. Two-dimensional distribution of the electron density in the plane of the magnetic meridian and the trajectory of a part of the rays of ordinary polarization reflected at a frequency of 6.0 MHz

The comparison of two ionograms with the simulation results shows that the agreement is almost complete.

Thus, the results of comparing real ionograms with model ones allow one to conclude that our assumptions about the mechanism of the influence of small-scale inhomogeneous structures on the propagation of vertical sounding radio waves, as well as the proposed methods for their modeling, are correct.

In the process of numerical modeling, it was found that the ionogram is most affected by the relative amplitude of irregularities (degree of ionospheric disturbance) and the approximate height of the onset of turbulence development. Thus, by varying these parameters and achieving visual correspondence of the obtained model ionogram with the experiment, it is possible to approximately obtain the value and height of the onset of turbulence development.

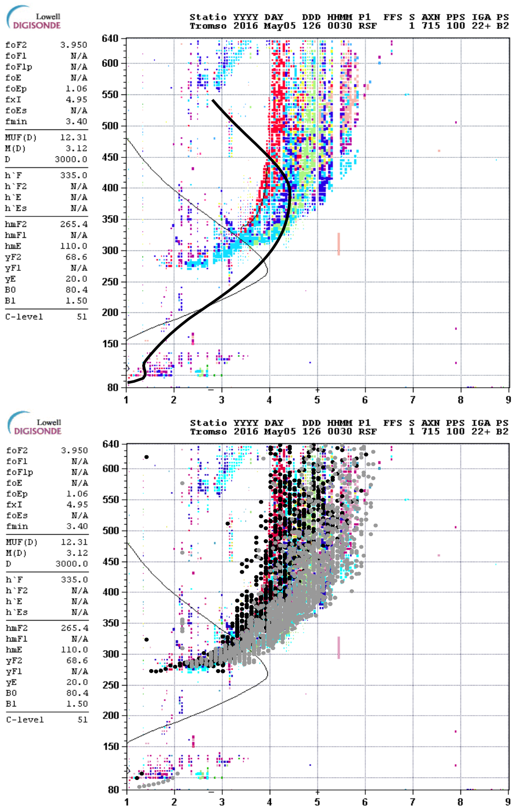

Figure 6. Real ionogram recorded on the DPS-4 ionosonde in Tromsø on May 14, 2013 (the upper panel) and the result of numerical simulation taking into account small-scale irregularities (the lower panel)

These examples allow one to make two additional important remarks about the use of experimental data and models. In recent years, a discussion about the methods of processing ionograms has flared up with renewed vigor. The use of new processing methods can lead to significant differences in N(h) profiles, especially when the ionograms are very noisy, as in these examples. The results of comparing the N(h)-profiles obtained by the ARTIST5 and Autoscala methods (Galkin et al., 2008; Pezzopane and Scotto, 2004) showed (on a large statistics) advantage of Autoscala by comparison of automatic and manual processing. A program Autoscala was developed for the automatic scaling of f0F2 and MUF(3000)F2 in the National Institute of Geophysics and Vulcanology (INGV). The INGV software is based on an image recognition technique and can operate without polarization information. Krasheninnikov and Leshchenko, 2021 also compared these two methods according to the data of the Moscow station (55.5° E, 37.3° N) for four months of 2018 and found that the processing of ionograms by the ARTIST procedure systematically underestimates the hmF2 height. The second remark concerns the use of the IRI model. If there is at least one ionosonde along the HF propagation path, then the model can be adapted to the parameters of the current diagnostics. In these examples, this is done for one station. It is appropriate to add that the IRTAM model has been developed (Galkin et al., 2012), in which the IRI model is adapted to the global foF2 map. Pignalberi et al., 2021 compared the accuracies of the IRI model and the IRTAM procedure on a vast amount of statistical material. Among the 5 selected stations from different latitude zones, for which the comparison was carried out in more detail, two stations Sondrestrom and Thule belong to the high latitude zones. It is shown that for all levels of solar activity, there is a significant improvement in accuracy of foF2 for IRTAM compared to IRI. This improvement is especially significant in the equinoctial and winter months.

For the oblique sounding, Figure 7 gives a picture of the rays leading to oblique ionograms of Figure 2.

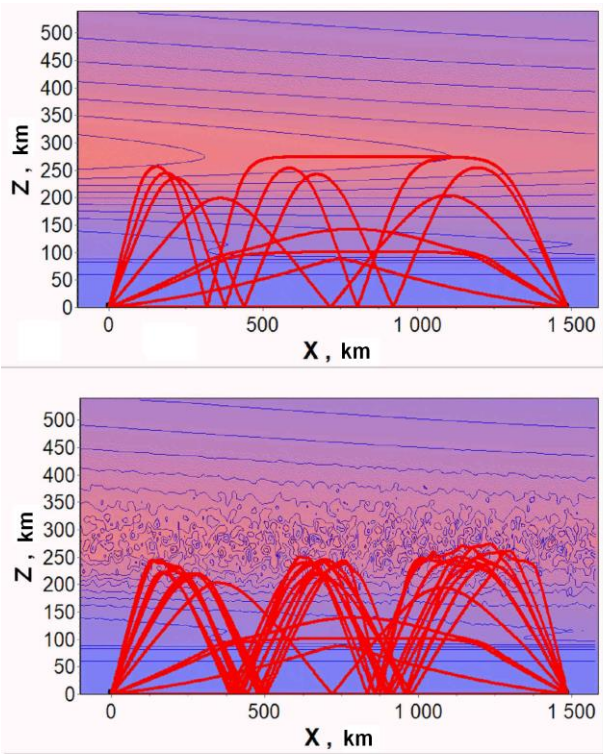

Figure 7. An example of modeling an oblique ionogram on the Moscow-Murmansk path in a quiet ionosphere (the upper panel) and in the presence of small-scale irregularities (the lower panel)

It can be seen that the presence of small-scale irregularities leads to smearing of traces in which there are rays passing through the F2 layer of the ionosphere. The value of such an important parameter as the maximum usable frequency (MUF) is also noticeably increasing. This parameter determines the most favorable radio frequencies. Another consequence is an increase in the number of beams with different delay times, which leads to an additional deterioration in the quality of radio communications.

When modeling the external sounding ionogram shown in Figure 3, its other feature was also taken into account, namely, a highly developed non-uniform structure that creates separate “beads”. Some fairly weak small-scale irregularities are unable to describe such a phenomenon. We assumed that there may be a case here when such irregularities are the result of the appearance of powerful disturbances with dimensions of 100 km or more and $\Delta N/N \geq 20\%$. The numerical simulation of this ionogram was carried out under this assumption of the joint existence of large- and small-scale irregularities. Figure7 (the upper panel) shows a good agreement between the experimental and model ionograms. For a more visual representation of the nature of the ionospheric conditions in this case, Figure 8 displays the two-dimensional distribution of the electron density and the trajectories of some rays of ordinary polarization reflected at a frequency of 14 MHz.

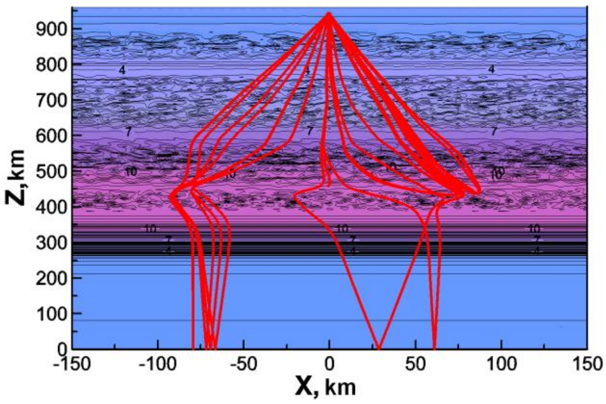

Figure 8. Two-dimensional electron density distribution with several layers of small-scale irregularities and trajectories of a part of rays of ordinary polarization reflected at a frequency of 14 MHz

Another example shown in Figure 9 concerns the high-latitude zone. It represents the ionogram obtained on the satellite "Kosmos-1809" on May 17, 1987 UT=22:36 in the northern hemisphere from a height of 937 km.

At frequencies above 2.5 MHz, a blurring of the main trace is observed, apparently associated with small-scale irregularities. The simulation results support this assumption well. The absence of scattering at lower frequencies indicates that the inhomogeneous structures are located quite compactly in a limited height range.

Thus, the proposed scheme for modeling the effect of small-scale irregularities on external sounding ionograms does not contradict the experimental data and can be used in the process of interpreting the results of HF propagation in the upper ionosphere.

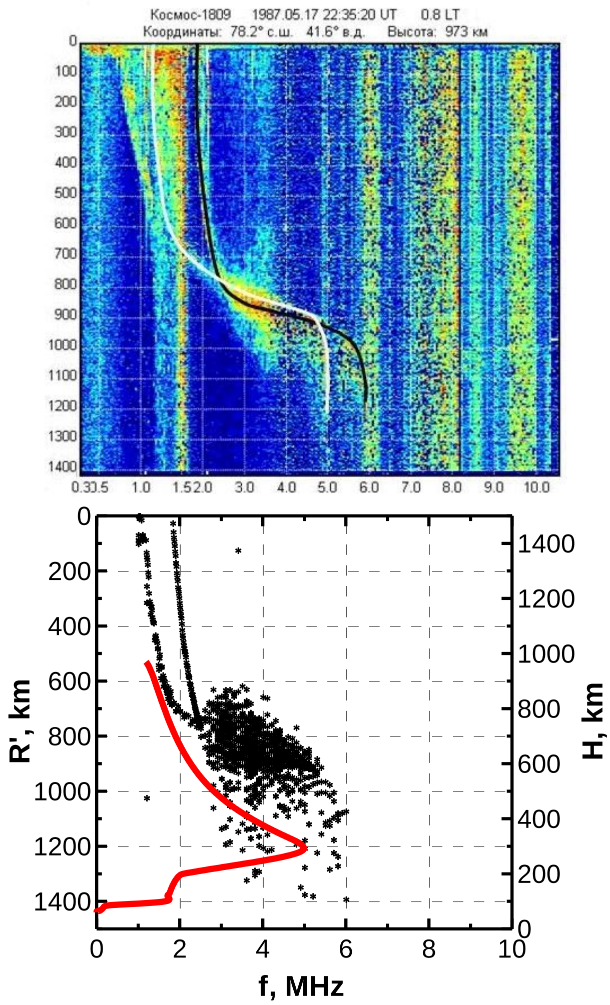

Figure 9. Ionogram obtained on the satellite "Kosmos-1809" 17.05.1987 UT=22:36 (the upper panel) and the result of numerical simulation (the lower panel). The gray color shows the digitized O-component trace and the N(h)-profile of the ionosphere reconstructed from it

Figure 10 shows the low-altitude pattern of transionospheric sounding beams, leading to the ionograms of Figure 4. The red color shows the trajectories of direct rays, the lighter color shows the two-hop, previously reflected from the Earth.

It can be seen that the presence of inhomogeneous structures in the region of the maximum of the F2 layer leads to multiple beams, including two-hop ones, and smearing of traces on the transionogram in the region located not far from the “breakdown frequency”. However, the very value of this important parameter, which determines the critical frequency foF2, practically does not change.

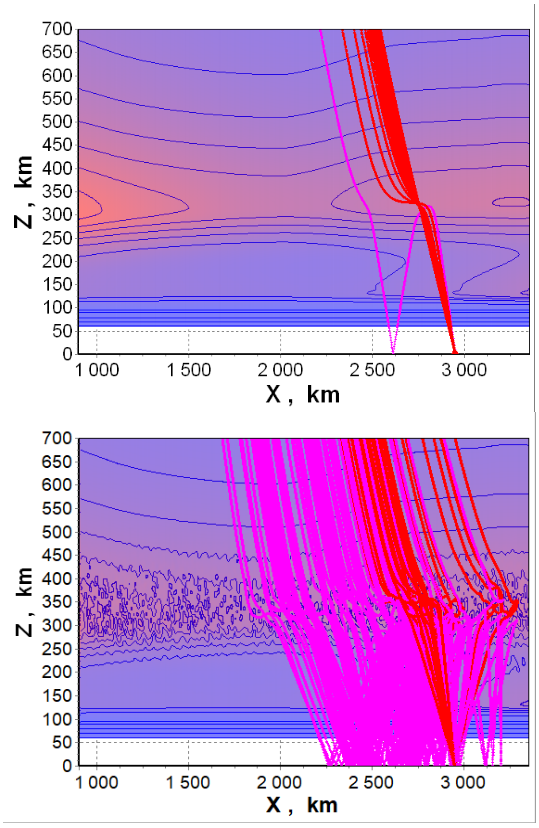

Figure 10. Profiles of the ionosphere along the path and trajectory of the rays for the transionograms of Figure 4.

4. CONCLUSION

Modeling the process of propagation of short radio waves in the high-latitude ionosphere is an important means of interpreting observations and predicting them. Modern models of the ionosphere allow one to take into account many large-scale structures at high latitudes. However, there are experimental facts that can only be explained by the influence of small-scale irregularities. The paper considers the main sounding methods associated with HF propagation (vertical, oblique, external, and transionospheric), and simulates propagation in a model with small-scale irregularities (with dimensions greater than 1 km). The choice of the parameters of these irregularities made it possible to obtain a correspondence between the model and experimental ionograms for all considered types of sounding. This allows one to conclude that small-scale irregularities can cause noticeable distortions of traces on ionograms. The choice of the parameters of these irregularities made it possible to obtain a correspondence between the model and experimental ionograms for all considered types of sounding.

Acknowledgement: The research was financially supported by Southern Federal University, 2020 Project VnGr/2020-03-IF.

References:

Bilitza, D., Altadill, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., & Huang, X. (2017). International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. *Space Weather*, *15*, 418-429. doi: 10.1002/2016SW001593

Blagoveshchenskii, D. V. (2020). Features of High-Frequency Radio Wave Propagation on Auroral Paths at Different Geomagnetic Activity. *Geomagnetism and Aeronomy*, *60*(3), 335-344. doi: 10.1134/S0016793220030020

Blagoveshchensky, D. V., Zhbankov, G. A., & Maltseva, O. A. (2019). Observed and calculated ionograms of oblique ionospheric sounding on HF radio paths during a magnetic storm of september 7-8, 2017. *Radiophysics and Quantum Electronics*, *61*(12), 881-892. doi: 10.1007/s11141-019-09944-3

Booker, H. G., & Wells, H. G. (1938). Scattering of radio waves by the F-region of ionosphere. *Journal of Geophysical Research*, *43*, 249-256.

Bowman, G. G. (1990). A review of some recent work on midlatitude spread-F occurrence as detected by ionosondes. *Journal Geomagnetism and Geoelectricity*, *42*, 109-138.

Carlson, H. C. (2012). Sharpening our thinking about polar cap ionospheric patch morphology, research, and mitigation techniques. *Radio Science*, *47*(4), RS0L21. doi: 10.1029/2011RS004946

Chernyshov, A. A., Chugunin, D. V., Mogilevsky, M., & Petrukovich, A. (2020). Studies of the ionosphere using radiophysical methods on ultra-small spacecrafts. *Acta Astronautica*, *167*, 455-459. https://doi.org/10.1016/j.actaastro.2019.11.031

Galkin, I. A., Khmyrov, G. M., Kozlov A. V. et al. (2008). The ARTIST 5. *Radio Sounding and Plasma Physics. AIP Proceedings*, *974*, 150-159. doi: 10.1063/1.2885024

Galkin, I. A., Reinisch, B. W., Huang, X., Bilitza, D. (2012). Assimilation of GIRO data into a real-time IRI. *Radio Science*, *47*, RS0L07. doi: 10.1029/2011RS004952

Hunsucker, R. D., & Hargreaves, J. K. (2003). *The High-Latitude Ionosphere and Its Effects on Radio Propagation*. Cambridge, UK: Cambridge University Press.

Ivanov, I., Maltseva, O., Sotskii, V., Tertyshnikov, A., & Zhbankov, G. (2019). Reverse Satellite Transionospheric Sounding: Advantages and Prospects. *Satellite Information Classification and Interpretation* (pp. 1-20). London, UK: IntechOpen. http://dx.doi.org/10.5772/intechopen.80240

Kravtsov, Yu. A., & Orlov, Yu. I. (1980). *Geometric optics of inhomogeneous media*. (Moscow, Russia: Nauka).

Krasheninnikov, I. V., & Leshchenko, L. N. (2021). Errors in Estimating of the F 2-Layer Peak Parameters in Automatic Systems for Processing the Ionograms in the Vertical Radio Sounding of the Ionosphere under Low Solar Activity Conditions. *Geomagnetism and Aeronomy*, *61*(5), 703-712. doi: 10.1134/S0016793221050078

Mingalev, I. V., Suvorova, Z. V., Shubin, V. N., Merzly, A. M., Tikhonov, V. V., Talalaev, A. B., & Mingalev, V. S. (2021). Differences in the Predicted Conditions of Shortwave Radio Communication between a Medium-Latitude Transmitter and a Receiver in the Arctic Region with the Use of Different Empirical Ionospheric Models. *Geomagnetism and Aeronomy*, *61*(4), 565-577. doi: 10.31857/S001679402104009X

Ossakow, S. L. (1981). Spread F theories - a review. *Journal of Atmospheric and Solar-Terrestrial Physics*, *43*, 437-452.

Panchenko, V. A., Telegin, V. A., Vorob'ev, V. G., Zhbankov, G. A., Yagodkina, O. I., & Rozhdestvenskaya, V. I. (2018). Spread F in the Midlatitude Ionosphere According to DPS-4 Ionosonde Data. *Geomagnetism and Aeronomy*, *58*(2), 229-236. doi: 10.1134/S0016793218020160

Pezzopane, M. (2004). Software for the automatic scaling of critical frequency foF2 and MUF (3000) F2 from ionograms applied at the Ionospheric Observatory of Gibilmanna. *Annals of Geophysics*. *47*(6), 1783-1790. doi: 10.4401/ag-3375

Pignalberi, A., Pietrella, M., & Pezzopane, M. (2021). Towards a Real-Time Description of the Ionosphere: A Comparison between International Reference Ionosphere (IRI) and IRI Real-Time Assimilative Mapping (IRTAM) Models. *Atmosphere*, *12*, 1003. https://doi.org/10.3390/atmos12081003

Szuszczewicz, E.P. (1987). Morphology and phenomenology of ionospheric F-region irregularities and implication to users application: a review. *Artifitial satellites*, *22*(1), 143–166.

Themens, D. R., Jayachandran, P. T., Galkin, I., & Hall, C. (2017). The Empirical Canadian High Arctic Ionospheric Model (E-CHAIM): NmF2 and hmF2. *Journal of Geophysical Research Space Physics*, *122*, 9015-9031. doi:10.1002/2017JA024398

Warrington, E. M., Rogers, N. C., Stocker, A. J., Siddle, D. R., Al-Behadili, H. A. H., Honary, F., ... & Zaalov, N. Y. (2017, May). Developments in HF propagation predictions to support communications with aircraft on trans-polar routes. In *2017 Progress In Electromagnetics Research Symposium-Spring (PIERS)* (pp. 1953-1959). doi: 10.1109/PIERS.2017.8262070

Zhbankov, G. A., Danilkin, N. P., & Maltseva, O. A. (2022.) Influence of the ionosphere on the accuracy of the satellite navigation system. *Acta Astronautica*, *190*, 194-201. doi: 10.1016/j.actaastro.2021.10.004

Gennadiy Zhbankov
Institute for Physics
Southern Federal University,
Rostov-on-Don,
Russia
gzhbankov@sfedu.ru
ORCID 0000-0000-6154-1917

Olga Maltseva
Institute for Physics
Southern Federal University,
Rostov-on-Don,
Russia
oamaltseva@sfedu.ru
ORCID 0000-0001-5679-8849