Development of improved ionospheric empirical model and software for HF ray tracing

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Abstract

We developed two new global empirical models of the F2 layer critical frequency that discribe the main features of high latitude ionosphere in details: (1) Main Ionospheric Trough (MIT) model based on satellite data of topside ionosphere sounding and in-situ measurements; (2) CHanged of the foF2 calculation in IRI model (Kaliningrad version) - CHIRIK model based on radio occultation measurements. Using radio occultation and ground-based ionosonde database with an archive of F10.7 values we obtained the F10.7-optimized index for better global reproduction of the foF2 dependence on solar activity for all temporal intervals. Another applied product of our team is the ray tracing technique in 3D weakly inhomogeneous ionosphere.

1. Introduction

The Earth's ionosphere plays a key role in the space radio communication, radiolocation, navigation, and operation of the satellite navigation systems GLONASS/GPS. Currently existing ionosphere empirical models, including the most used International Reference Ionosphere (IRI) [1], are not accurate enough to describe the media for precise ray tracing at high latitudes [2]. The increased interest for Arctic exploration and the progress in Arctic civil air flights makes the reliability of HF radio communication as critical issue. We developed two new global empirical models of the F2 layer critical frequency, which discribe high latitude ionosphere in details. In addition, we obtained the F10.7-related index, for the better global reproduction of foF2 dependence on solar activity for all temporal intervals.

Another applied product of our team is the ray tracing technique in 3D weakly inhomogeneous ionosphere. We have developed a technique and software to solve this problem. We modify all models existing in our group for solving radio wave propagation problems and create the software for calculation and visualization modeled ionograms of oblique and vertical sounding. Using the developed programs we can investigate the influence of magnetic field on ionogram traces.

2. Ionosphere empirical model development

2.1. Main Ionospheric Trough (MIT) model

Main Ionospheric Trough (MIT) model [3] describes foF2 climatology in high latitude ionosphere for winter season. This model has been created in two steps. First, the model of the trough minimum position was developed. Then with taking into account trough position the foF2 spatial distribution in MIT area was calculated. To obtain the absolute values of foF2, the normalization procedure was performed using either ground-based measurements or the results of the IRI model in the area of MIT equatorial wall. We modified MIT model that now can be used for local winter and quiet geomagnetic (Kp = 2) conditions at high latitudes in Northern and Southern hemispheres for all local times and solar activity levels. It is shown that the MIT model much more adequately reproduces the variations in the winter nighttime subauroral ionospheric structure, including the MIT position and shape variations, than the International Reference Ionosphere model. The online version of the MIT model is available on the IZMIRAN website: http://www.izmiran.ru/ionosphere/sm-mit/ for free using and more detailed testing.

2.2 CHanged of the foF2 calculation in IRI model (Kaliningrad version) - CHIRIK model

We collected the experimental data and prepared the database from satellite measurements of the ionospheric F2 layer peak electron density (critical frequency) that includes Radio Occultation (RO) data and topside sounding data of the ionosphere obtained onboard the IK-19 satellite. In this research, we used RO data from CHAMP, GRACE and COSMIC missions since 2001 to present. To statistical data analysis we created program software [4] which allows: 1) to sort the ionospheric data by solar activity index (F10.7), time (years, days, hours) and spatial distribution (by geographical latitudes and longitudes) with arbitrarily selected temporal and spatial sampling; 2) to find the mean and median values of ionospheric parameters in cells of preset spatial and temporal grid. The presence of device malfunctions and RO method simplifications suggest the possibility of the existence of data with a known high error, especially in the regions with large spatial gradients of electron density. To reject such data the program software was developed.

In a new global model that we called CHIRIK (CHanged of the foF2 calculation in IRI model (Kaliningrad version)) the monthly averaging foF2 values are functions on F10.7 index, geographic coordinates, date and hour. The CHIRIK model development included the following steps: 1) data sorting (spatial and temporal); 2) regression analysis for ionospheric parameter dependence on different F10.7-related indices of solar activity for each cell of spatial-temporal grid; 3) choice of optimal F10.7-related indices for global empirical model development.

Index	Average correlation coefficient				
	All months and LT	Mar 12 LT	Jun 12 LT	Sep 12 LT	Dec 12 LT
$F10.7_A$	0.71	0.79	0.78	0.76	0.80
$F10.7_6$	0.72	0.79	0.79	0.76	0.81
$F10.7_7$	0.72	0.79	0.79	0.76	0.81
$F10.7_p$	0.70	0.78	0.77	0.75	0.80
$F10.7_Y$	0.44	0.43	0.43	0.46	0.49
	Mean error (10^5 cm^{-3})				
$F10.7_A$	1.35	2.01	1.22	1.90	1.75
$F10.7_6$	1.33	1.99	1.20	1.89	1.63
$F10.7_7$	1.33	2.00	1.21	1.89	1.63
$F10.7_p$	1.37	2.06	1.26	1.93	1.70
$F10.7_Y$	1.85	3.04	1.84	2.70	2.55

As zero approximation we expect that foF2 dependence from F10.7-related index is close to linear. But still not clear which F10.7-related index is optimal for linear foF2 dependence from solar activity. We developed the CHIRIK model using the least square method for each cell in grid with spatial interval ±15° in longitude, ±5° in latitude, for each hour of day with interval ± 1 hour, for each month (the 22 day of the month ± 27 days). Also we used different F10.7-related indices: 1) classical: $F10.7_p$, $F10.7_A$; 2) averaging F10.7 indices for different numbers of previous days. As a result we obtain the tables which include longitude, latitude and linear regression coefficients for each hour and month. Using these tables we calculate foF2 values for different F10.7-related indices in each cell of spatial-temporal grid. We compared the correlation coefficients (R) and root mean square errors (RMSE) averaged by all months, hours and geographic coordinates, obtained for different F10.7-related indices. We found (see Table 1) that averaging F10.7 indices by 6 and 7 previous days (include the current day) are optimal for foF2 linear dependence on solar activity. This result was proofed by the similar data analysis of Kaliningrad ionosonde. So, based on radio occultation data the global empirical model of foF2 was developed. It is important to note that the used F10.7-related index have a significant advantage in comparison to previous ones, since we use only the prehistory of the F10.7 variations, which makes it possible to predict the foF2 values without the need to predict the F10.7 variations.

3. Ray tracing techniques

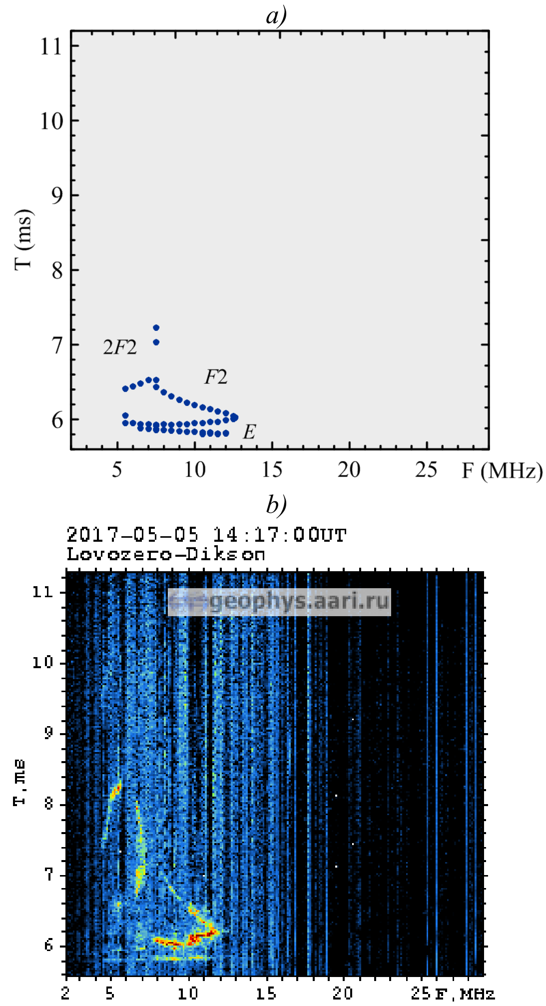

Figure 1. Oblique sounding ionograms obtained by the numerical solutions (a) and experimental data (b) between Lovozero (68ºN, 35ºE) and Dikson (73ºN, 80ºE) for 14:17 UT on May 5, 2017.

Another applied product of our scientific group is the ray tracing technique in 3D weakly inhomogeneous ionosphere. We developed the technique and software for this problem solution. One of the perspective approach, is the direct variational method for the point-to-point ionospheric ray tracing. The statement of the problem of the new ray tracing method (based on variational principle) is universal and can be applicable to a wide range of scientific problems (seismic wave propagation, ultrasound tomography, etc.) in geometric optics approximation. Therefore the finding solutions of various kinds using a new ray tracing technique have the fundamental importance. Also we modify all existing in our group ionosphere models for solving radio wave propagation problems and create the software for calculation of oblique sounding ionogram, their visualization and analysis.

3.1. Point-to-point ray tracing tool for oblique sounding ionogram simulation

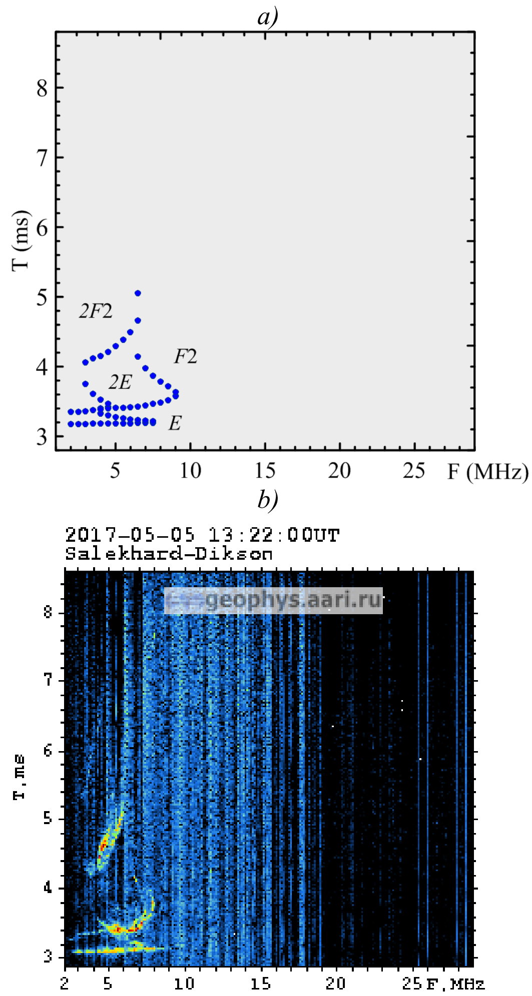

Figure 2. Oblique ionograms obtained by the numerical solutions (a) and experimental data (b) between Salekhard (66ºN, 66E) and Dikson (73ºN, 80ºE) for 13:22 UT on May 5, 2017.

In current work we present the version of oblique ionogram simulation based on direct variational method for ionospheric ray tracing. Previously, the direct variational method was proposed for high and low ionospheric rays in isotropic modeled ionosphere [5]. Direct variational method proved to be efficient tool for identification high as well as low ionospheric rays [6].

In order to present the possibility of our experience the several experimental ionograms of oblique sounding have been chosen. The both experimental and modeled ionograms between Lovozero – Dikson and Salekhard – Dikson, where the electron density is given by IRI-2007 model for the day time on May 5, 2017 are shown in Figures 1 and 2. Comparison with experimental ionogram of oblique sounding shows the applicability of the direct variational method for problem solution of the ionogram simulation. It should be noted the qualitative agreement between experimental and numerical results. Nevertheless in order to get higher agreement the improvement of ionospheric model is necessary.

3.2. 3D shooting method with allowance for geomagnetic field

Software for the construction of oblique sounding ionograms was created. Three-dimensional consistent algorithm of numerical experiments was described with the use of the medium models and radio wave propagation model [7]. This algorithm was implemented using the shooting method. The developed program was used for creating the modeled sounding ionograms at the high-latitude trace between Lovozero and Gorkovskaya for quiet conditions and during geomagnetic storm on March 17 and 18, 2015. Since the geomagnetic storm sudden commencement began on March 17 at ~05 UT from the fall of the Dst index to -223 nT at ~ 23 UT, the time 0:02 UT on March 17 was selected as quiet conditions, and 0:02 UT on March 18 as disturbed conditions. We used the parameters of the ionosphere and neutral atmosphere at altitudes from 80 km to 800 km obtained using GSM TIP model [8]. At considered time (~00:00 UT) a model/data qualitative and quantitative agreement of the ionospheric response to geomagnetic storm was obtained for the high-latitude region [8]. We study the influence of the Earth's magnetic field on the HF radio wave propagation. For this reason we consider the ordinary mode of a wave, since in the absence of a magnetic field there is no splitting into components of wave mode.

Figure 3 shows a comparison of experimental and modeled ionograms of oblique sounding obtained with and without taking into account the geomagnetic field. A good agreement between the modeled and experimental ionograms confirms that the GSM TIP model reproduces the high-latitude ionospheric response to geomagnetic storm. We observe the reflection from the *E* and *F* layers under quiet conditions. The observed maximum usable frequency (MUF) reaches 5 MHz (Fig. 3, *e*), while the modeled MUF does not exceed 3.5 MHz (Fig. 3, *a*). During geomagnetic storm a strong *E*-layer appears. The *E*-layer shields the sounding signal, so we do not observe the reflection from the *F*-region There is strong absorption of the signal at 0:02 UT, so an ionogram for 0:47 UT (Fig. 3, *f*) is shown for comparison, because the MUF value near 17 MHz is clearly visible. The modeled MUF corresponds to the observed (Fig. 3, *b*). It can be noted that up to 7 MHz the signal is absent both in the experiment and in the model calculations results.

It can be noted that the accounting of magnetic field in the model of HF radio wave propagation is important for signals reflected from the *F* region and is not so important for signals reflected from *E*-layer. For March 18, the reflection is observed at frequency range 3-16 MHz.

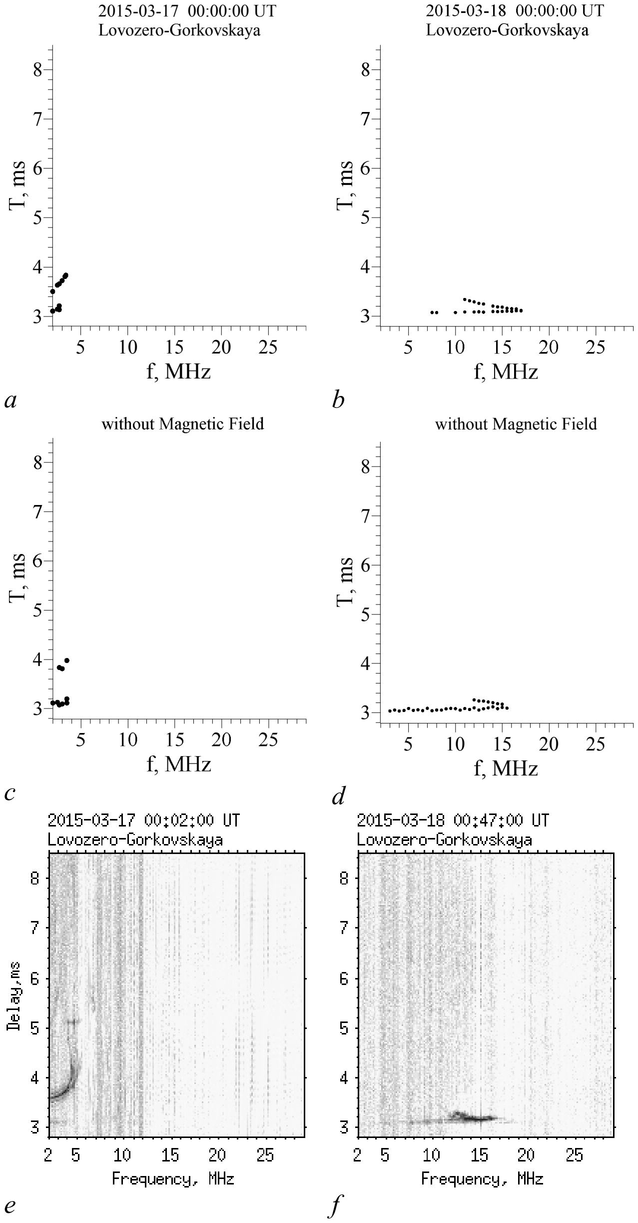

Figure 3. Modeled (*a, b, c, d*) and observed (*e, f*) oblique sounding ionograms at the high-latitude trace between Lovozero and Gorkovskaya on March 17, 2015 (*a, c, e*) and March 18, 2015 (*b, d, f*). (*a, b*) and (*c, d*) present the model results obtained with and without taking into account the magnetic field.

4. Conclusion

We developed new global empirical models of the F2 layer critical frequency, which describe high latitude ionosphere in details. We found that averaging F10.7 indices by 6 and 7 previous days (include the current day) are optimal for foF2 linear dependence on solar activity. We developed the technique and software for point-to-point ray tracing in 3D weakly inhomogeneous ionosphere using variational and shouting methods. We created the program for calculation of ionograms of oblique sounding, their visualization and analysis.

5. Acknowledgements

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6. References

1. D. Bilitza, D. Altadill, Y. Zhang, C. Mertens, V. Truhlik, P. Richards, L.-A. McKinnell and B. Reinisch, "The International Reference Ionosphere 2012 – a model of international collaboration," *Journal of Space Weather and Space Climate*, **4**, A07, February 2014, doi:10.1051/swsc/2014004.

2. D. R. Themens, P. T. Jayachandran, I. Galkin and C. Hall, "The Empirical Canadian High Arctic Ionospheric Model (E-CHAIM): N_mF_2 and h_mF2_2," *Journal of Geophysical Research: Space Physics*, **122**, 8, August 2017, pp. 9015-9031, doi:10.1002/2017JA024398.

3. A. T. Karpachev, M. V. Klimenko, V. V. Klimenko and L. V. Pustovalova, "Empirical model of the main ionospheric trough for the nighttime winter conditions," *Journal of Atmospheric and Solar-Terrestrial Physics*. **146**, May 2016, p. 149–159, doi:10.1016/j.jastp.2016.05.008.

4. N. V. Chirik, M. V. Klimenko, V. V. Klimenko, A. T. Karpachev, K. G. Ratovsky and N. A. Korenkova, "Principles for scaling and sorting of radio occultation observation data for ionospheric F2-layer investigations," *Russian Journal of Physical Chemistry B*, **36**, 12. 2017, p. 66–74.

5. C. J. Coleman, "Point-to-point Ionospheric Ray Tracing by a Direct Variational Method," *Radio Science*, **46**, 5, October 2011, RS5016, doi: 10.1029/2011RS004748.

6. I. A. Nosikov, M. V. Klimenko, P. F., Bessarab and G. A. Zhbankov "Application of the Nudged Elastic Band Method to the Point-to-Point Radio Wave Ray Tracing in IRI Modeled Ionosphere," *Advances in Space Research*, **60**, 2, July 2017, pp. 491-497, doi: 10.1016/j.asr.2016.12.003.

7. D. S. Kotova, M. V. Klimenko, V. V. Klimenko and V. E. Zakharov, "Influence of Geomagnetic Storms of September 26–30, 2011, on the Ionosphere and HF Radiowave Propagation. II. Radiowave Propagation," *Geomagnetism and Aeronomy*, **57**, November 2017, pp. 288-300, doi: 10.1134/S0016793217030100.

8. M. V. Klimenko, V. V. Klimenko, I. V. Despirak, I. E. Zakharenkova, B. V. Kozelov, S. M. Cherniakov, E. S. Andreeva, E. D. Tereshchenko, A. M. Vesnin, N. A. Korenkova, A. D. Gomonov, E. B. Vasiliev and K. G. Ratovsky, "Disturbances of the thermosphere-ionosphere-plasmasphere system and auroral electrojet at 30º E longitude during the St. Patrick's Day geomagnetic storm on 17–23 March 2015," *Journal of Atmospheric and Solar-Terrestrial Physics*, January 2018, doi:10.1016/j.jastp.2017.12.017.