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ANALYZING EXISTING APPLIED MODELS OF THE IONOSPHERE TO CALCULATE RADIO WAVE PROPAGATION AND A POSSIBILITY OF THEIR USE FOR RADAR-TRACKING SYSTEMS. II. DOMESTIC MODELS

V.V. Alpatov
Fedorov Institute of Applied Geophysics, Moscow, Russia, v_alpatov@mail.ru

S.Z. Bekker
Sadovsky Institute of Geospheres Dynamics RAS, Moscow, Russia, susanna.bekker@gmail.com

S.I. Kozlov
Sadovsky Institute of Geospheres Dynamics RAS, Moscow, Russia, s_kozlov@inbox.ru
Research Testing Center, Central Research Institute, Aerospace Defense Forces, Moscow, Russia

A.N. Lyakhov
Sadovsky Institute of Geospheres Dynamics RAS, Moscow, Russia, alyakhov@idg.chph.ras.ru

V.V. Yakim
Sadovsky Institute of Geospheres Dynamics RAS, Moscow, Russia, 12-220@list.ru
Research Testing Center, Central Research Institute, Aerospace Defense Forces, Moscow, Russia

S.V. Yakubovsky
Research Testing Center, Central Research Institute, Aerospace Defense Forces, Moscow, Russia, syakubovskiy@mail.ru

Abstract. We consider the ionospheric models that are suitable for over-the-horizon HF and UHF band radars. Namely, there are three such models: the numerical model developed by IZMIRAN and Fedorov Institute of Applied Geophysics, the numerical model designed by ISTP SB RAS and IDG RAS, and the probabilistic model worked out by IDG RAS. We briefly describe these models and report the results of the analysis of their compliance with radar requirements. Probabilistic models are shown to be most promising; hence, they must be placed at the frontier of ionosphere simulation.

Keywords: radar means, ionospheric models.

INTRODUCTION

The first part of the paper by Aksenov et al. [2019] presents a detailed classification of ionospheric models, briefly describes existing methods of considering ionospheric conditions in modern SHF-, UHF-, VHF-, HF-band radars, formulates requirements for ionospheric models to use them in radar, which significantly improves radar performance. The purpose of the second part of the research is to analyze domestic models for compliance with these requirements.

The main difficulty in the study is to select ionospheric models to be included in the analysis. The fact is that by now the physical processes that determine the behavior of the electron density N_e are well known, in any case at heights $h \leq 500–600$ km, and there is quite extensive experimental data obtained by radiophysical methods, as well as with missiles and satellites. All this served as the basis for developing a set of theoretical, empirical, semi-empirical ionospheric models of varying complexity and purpose in Russia (USSR) (see, e.g., [Danilov, 1967, 1981, Polyakov et al., 1968; Ivanov-Kholodny, Nikolsky, 1969; Danilov, Vlasov, 1973; Gershman, 1974; Ionospheric models 1975; Chavdarov et al., 1975; Gershman et al., 1976; Andriyako et al., 1978; Kozlov et al., 1978, 2014; Krinberg, 1978; Fatkullin, 1978, 1982; Ivanov-Kholodny, Nusinov, 1979; Namgaladze, 1979; Smirnova, Vlaskov, 1979; Ivanov-Kholodny, Mikhailov, 1980; Mizun, 1980, 1983; Fatkullin et al., 1981; Koshelev et al., 1983; Krinberg, Tashchilin, 1984; Bryunelli, Namgaladze, 1988; Zevakina et al., 1990; Chasovitin et al., 1990; Shefov et al., 2006; Bekker et al., 2013, 2017; Lapshin et al., 2016a, b; Pavlov, Pavlova, 2016; Wang Zheng et al., 2017; Dashkevich et al., 2017; Krivolutsky et al., 2017; Shubin, 2017; Bekker, 2018; Deminov, Shubin, 2018; Shubin, Deminov, 2019; Sergeenko, 2019]).

It is not our task here to give an overview of published works, and the above list is far to be complete. Nevertheless, let us state some general considerations. The vast majority of the developed models are deterministic, although it is well known that the ionosphere is a continuously changing (randomly inhomogeneous) medium; hence probabilistic and statistical methods are best suited to describe it. Domestic empirical ionospheric models were mainly designed using foreign experimental data due to a serious gap in quantity and quality of instruments for measuring ionospheric parameters in the USSR and then in the Russian Federation. At the same time, theoretical models were not, in fact, inferior to foreign ones. Many models can be characterized as particular (e.g., models of critical frequency f_oF2, maximum electron density $N_{em}E$, etc.). In general, the existing and currently developed ionospheric models (with rare exception) can be used for calculating propagation of only HF waves, i.e. for one-hop over-the-horizon radars [Aksenov et al., 2019].

So what criteria should we use to select a model for further analysis? We apply three very simple principles.

1. The model should be developed in the last 15–20 years (it is supposed that the ideas for such a model have been put forward and validated much earlier), i.e. it should be up to the latest scientific standards.

2. The ionospheric model can be used for both over-the-horizon and imaging radars, i.e. it should also be capable of describing the outer ionosphere.

3. There is a more or less detailed description of the model that allows us to evaluate it for compliance with the requirements [Aksenov et al., 2019].

It turned out that only three models more or less satisfy the above requirements. Firstly, the deterministic model developed by the Institute of Terrestrial Magnetism, Ionosphere and Propagation of Radio Waves (IZMIRAN) and Fedorov Institute of Applied Geophysics (IPG), Roshydromet [Lapshin et al., 2016a]; secondly, the deterministic model designed by the Institute of Solar-Terrestrial Physics (ISTP) SB RAS and the Institute of Geosphere Dynamics (IDG) RAS [Krinberg, Tashchilin, 1984; Strelkov, in 2012; Korsunskaya, Strelkov, 2013; Ponomarchuk et al., 2015a, 2016; Korsunskaya, 2015; Ponomarchuk et al., 2015b]; and thirdly, the probabilistic and statistical model worked out by the Institute of Geosphere Dynamics RAS [Kozlov et al., 1978, 2014; Bekker et al., 2013, 2017; Bekker, 2018]. Below we analyze these models, give their brief descriptions, and present results of assessments according to the main purpose of the study.

IONOSPHERIC MODEL DESIGNED IN IZMIRAN AND IPG, ROSHYDROMET

Development of theoretical, empirical, and semi-empirical ionospheric models has been the most important line of ionospheric research. Depending on solar and magnetic activity, season, time of day, geomagnetic latitude, models have been developed of the D-, E-, F1-, F2-regions, E_s layer, rarely of the outer ionosphere, as well as of ionospheric disturbances of different nature [Aksenov et al., 2019].

One of the results of the study on the problem of ionospheric modeling is the development of a joint project of new GOST by IPG and IZMIRAN [Lapshin et al., 2016a]. Let us briefly describe the main approaches and principles used in developing the model.

Note first that it is designed to replace a part of GOST [Chasovitin et al., 1990], which calculates N_e in the interval of heights h=65–1000 km over the entire Earth surface at any time of day, season, and at different solar activity levels. Input parameters of the model are geographic latitude and longitude, day of the year or date, local or universal time, the solar activity index R_Z averaged over 12 months of the year (R_{12}). First, we calculate maximum electron densities N_{em} and their associated heights h_m, i.e. h_mD, N_{em}D; h_mE, N_{em}E; h_mF1, N_{em}F1; h_mF2, N_{em}F2. In many cases, we use the N_{em} associated critical frequencies of the layers f_o in MHz, N_e in m^{-3}. $N_e(h)$ in different ionospheric regions is described with the well-known Epstein function.

$N_e(h)$ in different ionospheric layers was calculated on the basis of both relatively old studies and radically new ones. For example, the D-region was modeled using the IRI model [Bilitza, 1981], and the median model of the F2-region was developed using the traditional method of spherical harmonics. The description of the F1-region has much in common with that in [Bilitza, 2001]. At the same time, the models of the E-region and F2 layer for the Northern Hemisphere are new. Particularly noteworthy is the development of the model of the high-latitude E layer that plays an important role in HF and VHF radars located at polar latitudes (this fact is confirmed during operation of the radars).

The ionospheric model developed by IPG and IZMIRAN is empirically deterministic in general. As noted by the authors, it does not cover the conditions of high magnetic activity and ignores the sporadic layer E_s.

IONOSPHERIC MODEL DEVELOPED BY ISTP SB RAS AND IDG RAS

The software package for modeling the ionosphere and radio wave propagation was co-developed by ISTP SB RAS and IDG RAS in 2008–2015. The aim of the development was to design a hardware and software package (HSP) for predicting HF and VLF/LF radio wave propagation in the entire observed range of geomagnetic and solar activity parameter variations. Later, it was understood that the model can also be used for SHF, UHF, and VHF wavelength ranges.

HSP includes five separate blocks:

1) block for modeling the ionosphere and plasmasphere at heights above 100 km;

2) block for modeling the auroral ionosphere at the E-layer heights (90–150 km);

3) block for modeling the ionospheric D layer (40–100 km);

4) block for modeling HF radio wave propagation (2–30 MHz);

5) block for modeling VLF/LF radio wave propagation (10–100 kHz).

Elements of the model were developed using the numerical models existing in 2008 and the results of studies in the D-region [Strelkov, 2012; Korsunskaya, Strelkov, 2013; Korsunskaya, 2015]. During the development of HSP, full verification of software codes was made, hence reliable reproducibility of calculations in runs under the control of different operational systems and in linkage under different compilers. A separate problem addressed during the development of HSP was to maximally increase the computational speed. This problem was partially solved. Let us take a brief look at separate model blocks.

The block for modeling the ionosphere and plasmasphere at heights above 100 km

This model belongs to the class of deterministic semi-empirical models of the ionosphere and plasmasphere. The model numerically solves equations of plasma dynamics. Neutral atmosphere parameters are specified by the empirical model NRLMSISE-2000. The neutral wind speed in the working HSP version is calculated from the empirical model HWM-2007. The research version used a mode of numerical calculation of neutral wind velocities, thus increasing the accuracy of calculation of the F2-layer critical frequency and height of its maximum. Geomagnetic field parameters are calculated by the model IGRF-2012.

The model is semi-Lagrangian; it is based on explicit splitting by physical processes. This approach yields a basically arbitrary spatial resolution. In fact, spatial and temporal resolution is determined by physically accessible parameters of neutral atmosphere models (15° in longitude and 1 hr in time). Minimum resolution is used for calculations in the auroral zone and in taking into account the constraints imposed by radio wave calculation blocks.

The ideology adopted in the model is unique to date. The calculation starts with assignment of required coordinates and current time. Formation of initial data involves specifying the prehistory of geomagnetic activity (K_p index) for eight three-hour intervals, current and three-month averaged solar activity ($F10.7$ index). In the three-dimensional dipole coordinate system, an ionospheric (plasmaspheric) flux tube at a point with given coordinates is constructed. Next, with reverse time for three days back, we solve the problem of motion (finding the trajectory) of the selected flux tube in the ionosphere and plasmasphere, with sunlight conditions, fluxes of particles precipitating from the magnetosphere, electric fields, and neutral atmosphere parameters recorded. From a point of space, we calculate forward in time to the initial point. In the selected tube in the Eulerian grid, a system of equations is solved in partial derivatives, which describes ionospheric plasma dynamics.

The fundamental difference of the ISTP SB RAS model from the well-known foreign flux tube models FLIP, CTIP, Graz, SAMI-2, -3 lies in consistent consideration of kinetics of superthermal electrons in the ionosphere and plasmasphere.

Thus, in calculations the selected plasma tube exists for 72 hrs, being exposed to variable influence of solar and corpuscular ionization and passing through different neutral ionosphere. This allows us to take into account the memory effects of atmosphere-ionosphere and plasmasphere-ionosphere coupling.

Initial verification of the model was carried out from measurements of ionospheric parameters in the network of high-latitude and mid-latitude ionosondes.

Median values of the absolute deviation of calculated f_oF2 from measured ones exceed 1 MHz only for high solar activity and are less than 0.52 MHz for low solar activity. The tendency for f_oF2 to increase with solar activity remains for all seasons.

Maximum values of the absolute deviation of calculated f_oF2 from measured ones exceed 2 MHz only for two cases of 48 at low solar activity, for eight cases of 48 at moderate solar activity, and for 31 cases of 48 at high solar activity.

According to estimated expectation of this law of distribution, the most likely error in the developed model during simulation of spatio-temporal characteristics of the ionospheric F2-region is 0.9 MHz. In the research version, a self-consistent model of the neutral wind has been developed. Preliminary results of model evaluation received using a self-consistent approach to the calculation of winds have shown that it is possible to significantly improve the accuracy of calculations, at least under quiet geophysical conditions.

Secondary verification of the model was performed from radiophysical measurements along oblique ionospheric sounding paths in an HF band. In general, quite satisfactory results have been achieved for semi-empirical models, which were confirmed by both physical and radiophysical testing.

Disadvantages of the model:

1. The software code cannot be used for modern 64-bit computers. Stable operation of the block for calculating the ionosphere is achieved only when compiling in a 32-bit mode and only in 32-bit operational system.
2. The need for calculation of the history for 72 hrs back leads to required computation time of 1 min per one point in coordinates, with information output at heights 40–500 km with a step in height of 10 km on a 3 GHz Xeon processor. In fact, the calculations are made up to the heights of the magnetic flux tube apex (for closed field lines) or up to 10 Earth radii for open lines in the polar zone. Verification of results of the electron density calculation in the plasmasphere from satellite data has not been performed. The correctness of the calculation of the plasmasphere-ionosphere coupling was indirectly verified from improvement in the accuracy of calculation of F2-region parameters.
3. The model has basically been written for simulation of natural conditions. A "hot" start from the current time with an additional ionization source is impossible in the existing software code.
4. The response of the neutral atmosphere and the system of neutral winds to geomagnetic disturbances, intense electron and proton precipitation is considered only by empirical models. Accuracy of the latter requires further study.
5. Effects of hard precipitation at high latitudes are ignored. We employ the empirical model HARDY-08 that sets median values of mean energy and particle flux as a function of the K_p index, geomagnetic latitude, and magnetic local time.
6. Temporal dynamics of the electric field responsible for the formation of the ionospheric tube path for 72 hr is calculated by the empirical model WEIMER-2001. Self-consistent calculation of the electric field and current system variations has not been made.

Block for modeling the auroral ionosphere at E-layer heights

This block can be used to define E-layer characteristics at high latitudes under simultaneous proton and electron precipitation. This block is a zero-dimensional 38-component plasma-chemical model that takes into account ionization by UV radiation and precipitating electrons and protons. The model considers 16 vibrationally excited states of NO. The model was verified by measurements of the vertical electron density profile made with incoherent scatter radars in Sondestrom and Tromsø, by measurements of optical emission intensity (in visible and infrared ranges), by ionosonde measurements of f_oE, and by recording oblique ionospheric sounding tracks along the Sodankylä–Mikhnevo path under strong geomagnetic disturbances. A 5–20 % calculation accuracy was achieved depending on the use of the empirical model of precipitation or actually measured spectra of electrons and protons with a satellite located in the geomagnetic flux tube ending at a ground-based observation station.

Disadvantages of the model:

• the use of the empirical model of the neutral atmosphere;

• the use of the empirical model of energetic particle precipitation;

• lack of consideration of plasma dynamics and electric fields;

• ~5 s computation time per one point in height on a 2.2 GHz processor.

Block for modeling the lower ionosphere

It is a fairly typical 22-component zero-dimensional plasma-chemical model. Its main advantage is that it correctly takes into account the ionization by X-rays during solar flares. The verification was performed using radiophysical methods by comparing calculation results with observations of signals from VLF/LF transmitters. Comparison between amplitudes of signals from VLF transmitters and observations provided a qualitatively correct response along paths of different orientation and length during flares of different classes. Scatter of initial data in emission parameters in open sources reaches an order of magnitude.

Calculations of HF radio wave damping during solar flares of different classes are in agreement (in a first approximation) with experimental oblique sounding data in a frequency range 2–30 MHz.

General conclusions

The ionospheric model developed jointly by ISTP SB RAS and IDG RAS is currently the only domestic model that has been intensively verified on the basis of HF radiophysical data. The model can be used immediately to address problems of over-the-horizon radars. To obtain reference data in problems of imaging radar, it is first necessary to reduce the computation time by 2–3 orders of magnitude.

PROBABILISTIC-STATISTICAL MODEL DESIGNED BY IDG RAS

The above models, as has been noted, are deterministic. By their physical nature, the deterministic models cannot in principle satisfy the following two requirements [Aksenov et al., 2019]

1) consideration of irregular, constantly changing state of the ionosphere (this property of the ionosphere can be satisfied by empirical, semi-empirical or theoretical probabilistic-statistical models);

2) solution of various probabilistic problems.

Note that the need for the use of statistical methods in ionospheric and radiophysical research (especially in applied ones) has long been declared [Rytov, 1966; Kozlov et al., 1978; Lapshin et al., 2016b]. They have become most widely used in radiophysics.

The statistical modeling that ultimately provides probabilistic assessments involves the following. Taking into account initial data, we first calculate the base level of ionospheric parameters. Then, using random number generators (RNG) included in the model in accordance with their inherent laws of distribution, we select (realize) specific values, which are then used for calculating the HF radio wave damping *W*. In a similar way, we make *N* realizations (iterations). The total number of iterations is determined by convergence of calculation of *W* with *N* increasing (note that there is no need for only damping usage in the general case — we can use any other radiophysical effect).

An important and methodologically incompletely solved problem is the evaluation of laws of distribution of variable (statistical) parameters. It should, of course, be made on the basis of statistical analysis of numerous independent experimental data, but the choice of the data with due regard to methods of its acquisition and great dependence on solar and magnetic activity, latitude, time of day, and season is still not fully clear.

The current status of research can be characterized as follows:

1. The first probabilistic-statistical model [Kozlov et al., 1978, 2014], of course, needs to be improved in view of the experimental data and results of theoretical studies accumulated to date. Focus areas: expansion of the model to polar latitudes and to $h \approx 600–650$ km; selection of more recent reference values of $N_e(h)$ and inclusion of variations of the neutral ionospheric composition; derivation or more exact definition of laws of distribution of variable parameters; development and inclusion of disturbances of different types to the model; development of methodologies and verification of the model based on experimental radar data.

2. The model of undisturbed mid-latitude D-region has practically been developed in two versions (empirical-statistical and deterministic-probabilistic) [Bekker et al., 2013; Bekker, 2018]. Verification of the results from experimental data on VLF/LF radio wave propagation from GPhO Mikhnevo has confirmed validity of fundamentals of the probabilistic-statistical modeling and has identified areas of applicability of the developed directions. The model is being further elaborated.

3. An approximate empirically statistical mid-latitude model of the E_s layer [Bekker et al., 2017] has been developed using extensive data. It requires elaboration and comparison of calculations with experimental data from radars having different geographical location. Similar studies should be carried out for the empirical, close to probabilistic, model of the maximum electron density in the regular ionospheric E-region [Pavlov, Pavlova, 2016].

Obviously, these probabilistic-statistical models are most suitable for radar systems. They meet all the requirements imposed on radio wave propagation models [Aksenov et al., 2019]. Unfortunately, the biggest drawback of this line of research is the absence of probabilistic-statistical models for $h \geq 120$ km for all latitude regions. Furthermore, the methodology of using such models for specific radars of any frequency band is not entirely understood.

CONCLUSION

The results of the analysis are shown in Table, in which requirement imposed on the models [Aksenov et al., 2019] are designated by Roman numerals: I — height range, II — latitude, III — geophysical conditions, IV — estimated ionospheric parameters, V — ionospheric irregularities, VI — consideration of continuously changing environment, VII — solution of probabilistic problems, VIII — computational speed, IX — model verification, X — level of model development. Signs in cells mean: «+» — meet; «–» — fail to meet; «±» — partially meet; «p» — principally can meet.

Summarized results of model analysis

No.	model	Requirements imposed on models									
		I	II	III	IV	V	VI	VII	VIII	IX	X
1.	IZMIRAN, IPG	± p	± p	± p	+	- p	–	–	+	± p	+
2.	ISTP, IDG	± p	± p	± p	+	- p	–	–	±	± p	+
3.	IDG	± p	± p	± p	+	- p	+	+	±	± p	±

As can be seen, none of the models considered satisfy the requirements in full. This is due to two main reasons: the deterministic approach to their development (the first two models) and the absence of many particular models, which is especially true of the probabilistic-statistical developments. Nevertheless, it is clear that probabilistic-statistical models can more or less meet all the requirements [Kozlov et al., 2019]. We believe that this line of ionospheric modeling is the most promising and relevant.

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