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ANALYSIS OF THE EMPIRICAL MEDIAN IONOSPHERE MODEL CONSTRUCTED USING IRI LOCAL PASSIVE RADIOSONDING DATA

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The article describes one of the ways to establish radio communication on short waves, which is actively used in practice. When establishing such a connection, it is necessary to take into account the parameters of the ionosphere, which is subject to various external influences. Therefore, in order to establish a reliable communication channel of this kind, it is necessary to use models predicting the parameters of the ionosphere. The author of the article describes the methods of constructing such models and analyzes one of the most frequently used models of the ionosphere, which is based on passive radiosonding data. Using methods of statistical data processing, ways to improve the parameters of such an ionosphere model are proposed.

Keywords: statistical data processing; ionosphere model; short wave radio communication.

Introduction

Short-wave radio communication has not lost its relevance and is actively used in practice, despite the intensive development of modern types of Internet, mobile and satellite communications. First of all, this type of communication is used as a means of operational information exchange in the national economy. The main advantage of shortwave communication is the ability to organize the transmission of information over long distances, significantly exceeding the distance of direct visibility of subscribers (hundreds and thousands of kilometers).

At the same time, traditionally, the disadvantages of this type of radio communication include the fact that the establishment of a stable and predictable two-way communication channel between two geographically separated points with predetermined coordinates in a given time interval on short waves is not guaranteed and presents certain difficulties. The main reason for such uncertainty is the specificity of the physical medium of transmission of a short-wave radio signal, which is the ionosphere. This region of the atmosphere is located at altitudes from fifty to two thousand kilometers and is characterized by a high content of ions and free electrons formed due to photoionization under the action of ultraviolet, X-rays, as well as cosmic rays. It is ionization that plays a leading role in the formation of the radio signal reflection effect during long-distance and ultra-long-distance radio communication sessions [1]. Establishing radio communication on short waves is fraught with difficulties introduced by disturbances of the ionosphere. Therefore, ionospheric models that take into account various types of fluctuations play an important role.

This article describes the creation of radio routes and justifies the need to build a model of the ionosphere. The possible ways of constructing such models are given below and the properties of the empirical median model constructed using passive radiosonding data are analyzed in more detail.

1. Description of the Problem

The ionosphere is conventionally divided into several sections, called "layers", each of which is characterized by its own height, the specifics of the lifetime and reflectivity (Fig. 1).

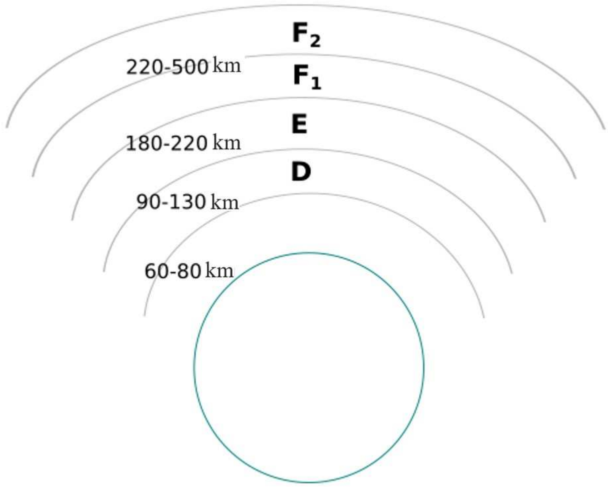

Fig. 1. Conditional division of the ionosphere into reflective layers D, E, F1 and F2

A simple and quite effective way to calculate the radio paths of signal propagation between two given points in a calm (undisturbed) ionosphere is to use the approximation of geometric optics [2] (Fig. 2).

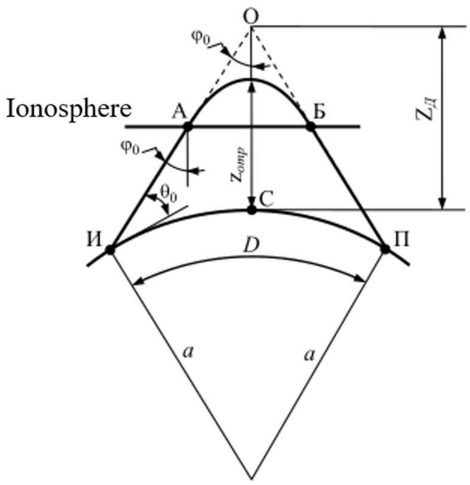

Fig. 2. Graphical representation of the ionospheric radio path

between the source and receiver, based on the approximation of geometric optics

The reflecting properties of the Ionosphere are characterized by an electron concentration profile determined by the frequency of the electrons' natural oscillations (plasma frequency):

$$F_0 = \sqrt{80.8 \cdot N_e}, \quad (1)$$

where N_e is the electron content in $1m^3$.

The electron concentration profile (also called the ionospheric profile, or ionogram) has several proper maxima (in each of the ionospheric layers) corresponding to the maximum content of the electron concentration for this layer (Fig. 3).

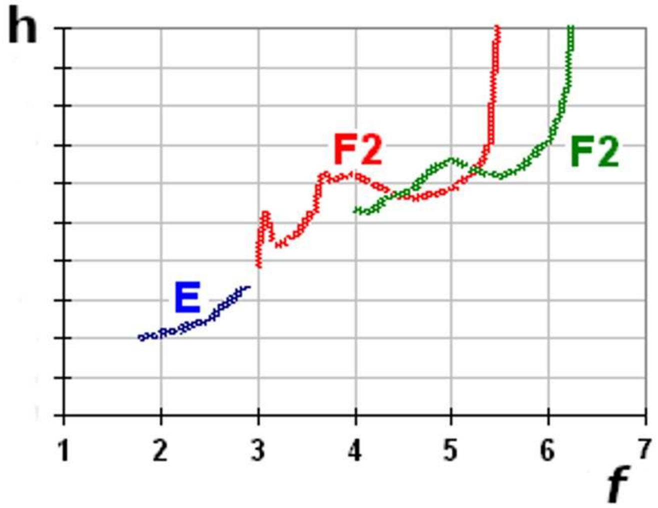

Fig. 3. Ionogram of the electron density distribution

Thus, the main properties of ionized layers of the ionosphere that determine their reflectivity are two parameters: the height of the maximum electron concentration h and the critical frequency (F_{cr}) of the layer, which is the maximum value of the plasma frequency for this layer.

A radio signal emitted vertically (that is, falling on the ionosphere at angles close to 90 degrees) at frequencies exceeding the value of F_{cr} does not encounter significant resistance of the ionospheric layer and goes into outer space, forming a so-called "dead zone" in the immediate vicinity of the transmitting station, within which signal reception is impossible. The same signal, emitted at small angles to the horizon, still continues to be reflected. In this regard, the value of the maximum possible frequency at which two-way radio communication is still permissible, which is called the maximum applicable frequency (MAF), becomes practically significant. Another important boundary value is the lowest applicable frequency (LAF) acceptable for the given conditions. Conducting stable radio communication with the initially set parameters of the radiation power, the distance between the transmitting and receiving points occurs in the frequency range (MAF – LAF) and significantly depends on the time of day and the state of the ionospheric parameters.

The problem of the practical application of the geometrical-optical approximation in the modeling of ionospheric radio paths is the high variability of the ionosphere parameters: daily, seasonal, etc. In particular, we note a pronounced relationship between the state of the ionization parameters and the Solar flare activity.

The need for forecasting (operational, long-term) the state of the ionosphere in conditions of its continuous variability is determined by a fairly wide range of applied tasks (planning radio communication sessions, scientific research in the field of meteorology, seismic activity, etc.) and leads to the need to build effective models of the ionosphere and ionospheric propagation of radio waves. The most detailed classification of ionospheric models was proposed in [3].

The existing models of the ionosphere, depending on the approach they use, are traditionally classified into the following classes:

1) according to the methods of construction: theoretical, empirical, semi-empirical;

2) according to the approach: deterministic (statistical), dynamic, probabilistic-statistical;

3) according to the scale of the space described by the model: global, regional, covering a limited region (equatorial, mid-latitude, polar) and local, built for a specific localization;

4) by season;

5) by altitude range: for regions D, E, F1, F2 of the ionosphere, sporadic layer E, outer ionosphere;

6) by time of day;

7) according to the set of ionospheric parameters determined by the model: an electron concentration N_e; electron collision frequencies with ionized v_{ei} and neutral v_{en} components; gradients of N_e with respect to height h, latitude and longitude; temperature of electrons (T_e), ions (T_i), neutrals (T_n); ionospheric inhomogeneities;

8) according to the degree of disturbance of the ionosphere, depending on latitude, solar and magnetic activity, external influences;

9) according to the form of presentation of the model: tabular, graphical, analytical.

Empirical median models based on the results of averaged statistical analysis of ionospheric parameters have received the greatest use for solving practical applied problems.

2. Analysis of Empirical Median Models

So, the empirical model of ionospheric parameters IRI, recommended by URSI as a basic model for predicting the propagation of radio waves, is a sufficiently adequate median model that calculates the values of F_0F_2 by (1) and the profile of the electron concentration of $N_e(h)$ in an undisturbed (calm) ionosphere [4].

The parameters calculated by the IRI model can be refined by ionograms of vertical (VZ) and inclined (IZ) sounding of the ionosphere [5, 6, 7, 8] (see Fig. 4).

The complexity of using ionograms VZ for practical refinement of the values of the critical frequency F_0F_2 is mainly due to the complexity of algorithms for automatic interpretation of images, as well as the low density of placement and insufficient number of ionosondes in the network, leading to the inevitable need to interpolate ionosonde data to the local coordinates of the receiving point of the radio path. In addition, a significant obstacle to the use of VZ on the way to creating systems for continuous monitoring of the state of the transmission channel is the complexity of using the ionosonde at the lowest possible capacities.

A more accurate correction of empirical models is possible by using geolocation (GPS, GLONASS) satellite data using the method of trans-ionospheric sounding [9]. The resulting value of the total electron content (TEC) is the total number of electrons in an ionospheric vertical column of a single section. This approach allows for the correction of model ionospheric parameters practically in real time, but implies either the availability

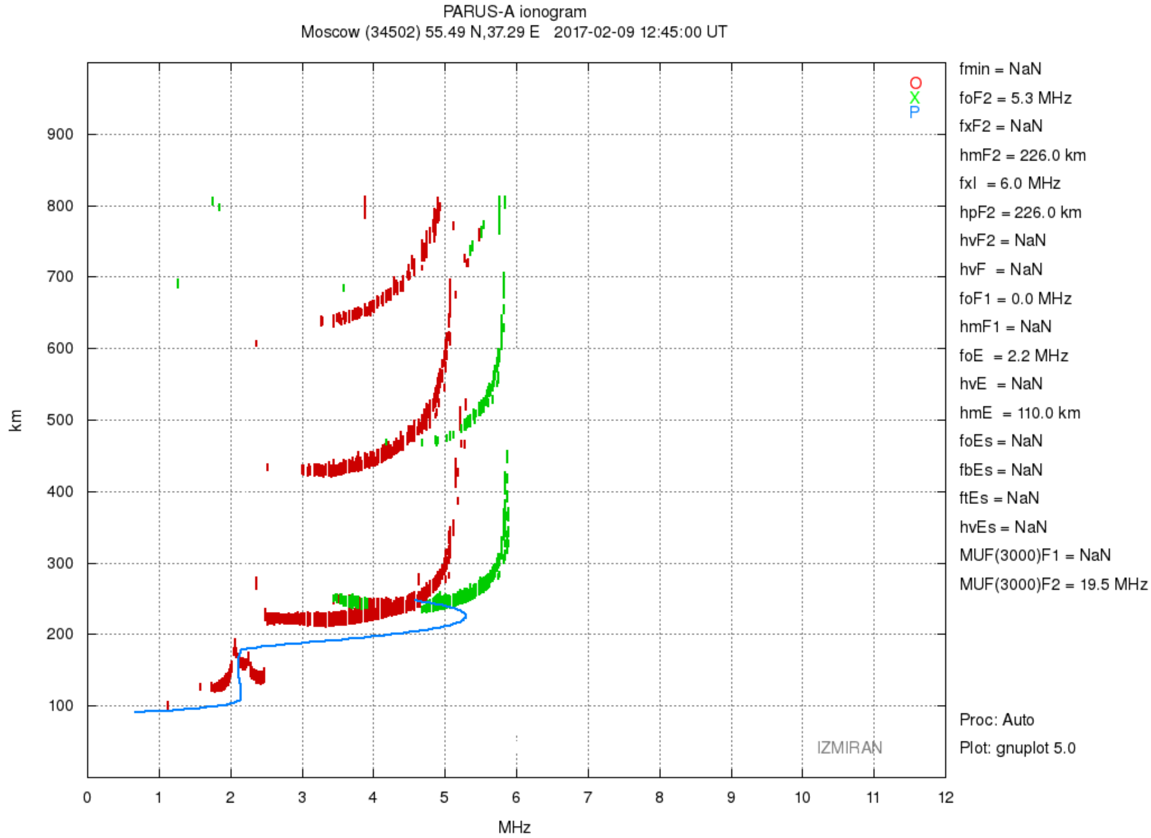

Fig. 4. Ionogram of vertical sounding
at the IZMIRAN station 03/04/2023 10:00 UT

of specialized navigation equipment for direct monitoring of GNSS, or operational access to the results of such monitoring.

It should be noted that despite the appearance of modern effective instrumental solutions for diagnosing the state of the ionosphere (networks of various ionosondes, trans-ionospheric sounding, etc.), the own instrumental and diagnostic potential of shortwave radio communication is far from completely exhausted. This assumption is supported by the appearance of works in the direction of the concept of the so-called cognitive radio communication, which implies the presence of built-in technical means of diagnosing the state of communication channels in the data transmission equipment [10].

It is known from the theory of radio communication that the radio signal emitted by the source, in addition to natural signal energy losses at the distance of the radio path, is subjected to various forms of distortion associated, among other things, with the state of the ionosphere such as random fading, multimode interference, etc. The state of the channel (scattering function, SFC) can be described by three main parameters:

$$\left(\sigma_{\tau n}, \sigma_{dn}, \left(\frac{S}{N}\right)\right), \tag{2}$$

where $\sigma_{\tau n}$ is a scattering by delay, σ_{dn} is a Doppler shift scattering, $\left(\frac{S}{N}\right)$ is a signal-to-noise ratio for a given mode in a radio channel [1].

The signal-to-noise ratio in (2) is estimated based on data on the total energy of the channel and the spectral power of interference: $\left(\frac{S}{N}\right) = \left(\frac{2 \cdot E_s}{n_0}\right)$, where E_s is a signal power spectral density, n_0 is a one-way spectral noise power density.

To study the variation of the signal-to-noise ratio in the range of decameter (short) waves, a prototype of a software and hardware complex was designed and implemented, including an SDR signal receiver and software for processing the received data.

The radio signal of the Moscow reference time signal transmitter operating under RWM radio callout at frequencies 4996, 9996 and 14996 kHz, which practically overlap the range of permissible frequencies from the NPH to the MPH of the daily period, was taken as the studied model signal source. An example of the observed signal form and the self-noise form of a radio channel are shown in Figures 5, 6 and 7.

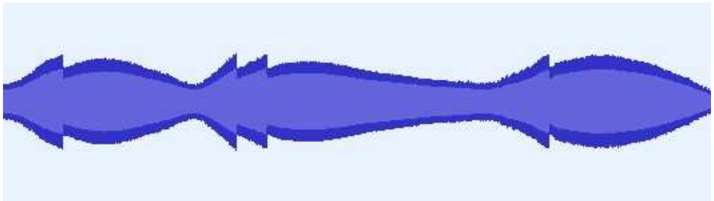

Fig. 5. Example of the form of the useful signal of the RWM transmitter

The phonogram clearly reveals both amplitude and phase deviations of the original beacon signal.

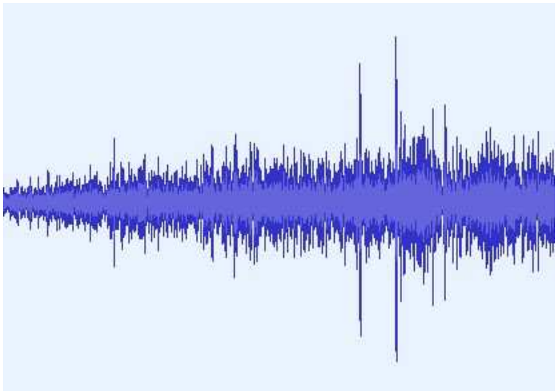

Fig. 6. An example of a phonogram of the intrinsic noise of the studied radio channel

Fig. 7. Example of a phonogram of second pulses of the studied radio channel

The graph of variations in the signal-to-noise ratio is shown in Figure 8.

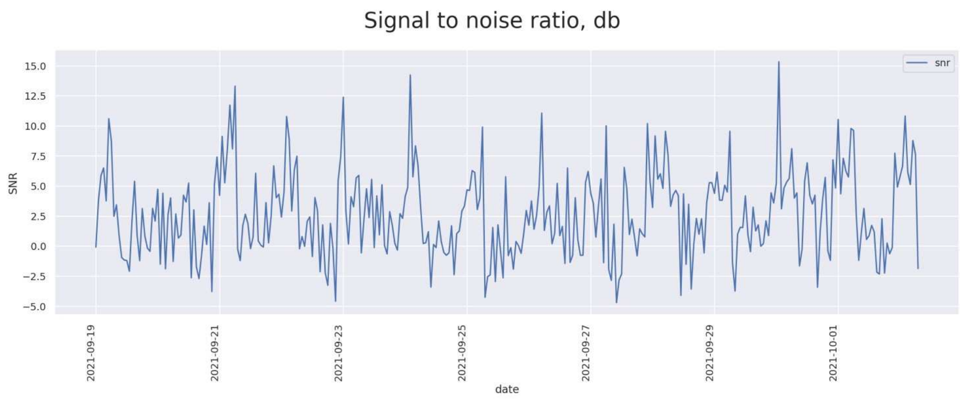

Fig. 8. Graph of signal-to-noise ratio variations for the 9996 kHz channel for the period from 09/19/2021 to 10/10/2021

The obtained results allow us to confidently identify both the periodic variable component of the original signal associated with the Earth's daily rotation, and to investigate its random fluctuations, including those determined by variations in the parameters of the transmission medium (ionospheric parameters) both during periods of calm (undisturbed) ionosphere and during periods of disturbances caused by solar flare activity (Fig. 9).

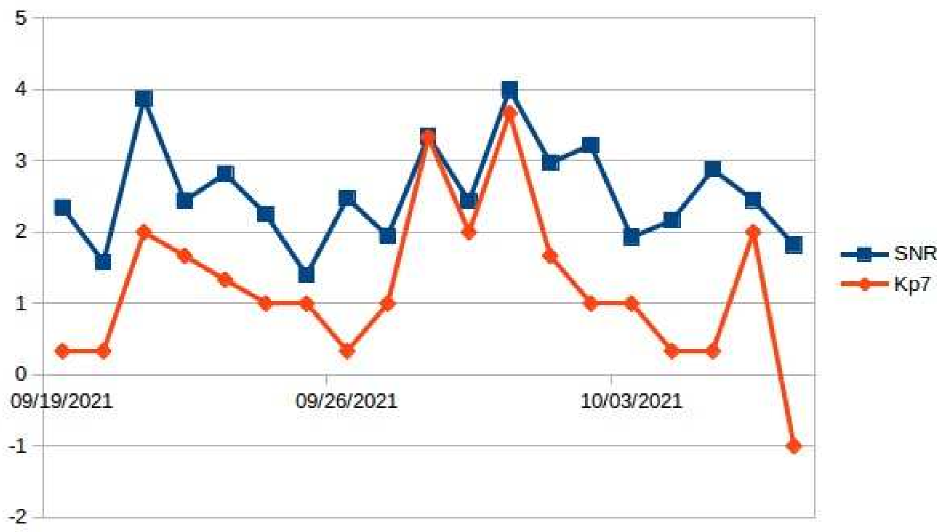

Fig. 9. Dynamics of the signal-to-noise ratio against the background of diurnal variations of the magnetosphere disturbance level index

It should be noted that the results obtained at this stage of the experiment are limited by the bandwidth of the simultaneous frequency survey in the current implementation of the SDR receiver. Nevertheless, the experimental testing of the prototype of the passive monitoring software and hardware complex demonstrated the possibility of round-the-clock monitoring of the state of ionospheric radio communication channels.

Conclusion

Thus, monitoring the value of the signal-to-noise ratio for the reference frequencies of the site (MAF – LAF) in real time complements the ionospheric profiles obtained by mathematical modeling and refined by ionograms of vertical and inclined sounding with local information about the quality of the ionospheric transmission channel for this receiving point, reflecting the level of loss of the useful signal and its excess over the level of the radio channel's own noise.

In this regard, further research work in this direction is focused on the design and experimental testing of the SDR receiver module with the maximum achievable bandwidth, sensitivity and dynamic range, as well as the development of useful signal filtering algorithms and the construction of ionograms. To do this, the methods proposed by the author in [11, 12, 13] will be used.

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АНАЛИЗ ЭМПИРИЧЕСКОЙ МЕДИАННОЙ МОДЕЛИ ИОНОСФЕРЫ ПОСТРОЕННОЙ С ИСПОЛЬЗОВАНИЕМ IRI ЛОКАЛЬНЫХ ДАННЫХ ПАССИВНОГО РАДИОЗОНДИРОВАНИЯ

О. В. Митин

В статье описывается один из способов установления радиосвязи на коротких волнах, которая активно используется в практической деятельности. При установлении такой связи необходимо учитывать параметры ионосферы, которая подвержена различным внешним воздействиям. Поэтому для установления надежного канала связи такого вида, необходимо использовать модели прогнозирующие параметры ионосферы. Автор статьи проводит описание способов построения таких моделей и анализирует одну из наиболее часто используемых моделей ионосферы, основанную на использовании данных пассивного радиозондирования. Используя методы статистической обработки данных, предлагаются способы улучшения параметров такой модели ионосферы.

Ключевые слова: статистическая обработка данных; модель ионосферы; радиосвязь на коротких волнах.

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