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Determination of statistical parameters of fluctuations in the refractive index of the ionosphere according to the data of the space—earth information transmission radio line

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The study considers the problem of restoring the covariance function of fluctuations in the refractive index of the ionosphere based on the analysis of random changes in the frequency of the radio signal. To solve the problem, a trans-ionospheric signal of an information transmission radio line is used, radiated from a low-orbit spacecraft and received at a stationary receiving point. A method for estimating ionospheric parameters based on data from one typical communication session is described. To conduct a full-scale experiment, the signal emitted by the P-band radio transmitter of the on-board monitoring and control system of the Aist-2D spacecraft is used during a typical communication session. To receive the signal, ground-based equipment of a bistatic radar complex with a synthesized aperture of the P frequency band is used.

Keywords: the ionosphere, fluctuations in the refractive index, the radio line of information transmission from the spacecraft, the scale of inhomogeneities and the dispersion of the electron density of the ionosphere.

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As you know, the ionosphere is the ionized part of the Earth's atmosphere, which significantly affects the propagation of radio waves. The ionosphere has a complex structure in height and space. Usually there are three main layers located at different heights: D, E and F; the latter is in turn divided into $F1$ and $F2$. The electron concentration, temperature, layer heights, and other parameters of the ionosphere are characterized by significant variations in time and space.

The development of many modern radar, navigation and communication technologies requires knowledge of the current characteristics of the Earth's ionosphere and magnetosphere. In addition, the ionosphere interacts with other layers of the atmosphere, as well as with the hydrosphere, lithosphere, cryosphere, the state monitoring of which is important for many areas of human activity [1–3].

Creation of a system of global monitoring of ionospheric parameters is one of the urgent tasks of our time. At the same time, the question of determining the size and concentration of ionospheric inhomogeneities, especially medium- and small-scale ones, is one of the most difficult [3].

Since the 1920s, a large number of very effective methods have been developed for studying the ionosphere: vertical, oblique, and oblique backscatter sounding; method for measuring the Doppler frequency shift; method of incoherent scattering of radio waves, transionospheric sounding. Comparative characteristics of these methods were widely discussed in the publications (see, for example, [3]).

In particular, for ionospheric sounding with the help of spacecrafts in Russia and abroad a path was passed from single spacecrafts to space systems for comprehensive monitoring of geophysical parameters of the near-Earth space. For example, in the near future it is planned to begin deployment of the Russian space system „Ionosond" comprising five specialized spacecrafts for observing the ionosphere and solar activity [4].

To solve such problems, not only ionosondes, but also any other radio engineering systems using a trans-ionospheric radio signal can be used. Currently, the most effective tool for satellite ionospheric sounding is the second generation space radio navigation systems, such as GPS, GLONAS, Beidou, Galileo [4–6]. In addition to navigation systems for trans-ionospheric sounding, signals from space radar systems for remote sounding of the Earth [7], communication systems craft—Earth [8] can be used. The relevance of telecommunication system signals use for monitoring the ionosphere parameters is growing in recent years due to the increased number of small spacecrafts (SSC) and nanosatellites, as well as the expansion of the geography of ground-based receiving points.

The purpose of the study is to develop a method for determining the statistical parameters of fluctuations of the ionospheric refractive index according to the data of an information communication session of a information transmitting radio link space—Earth located on board the spacecraft, and also to test the method on mathematical models and in a full-scale experiment.

During a communication session the on board equipment of the radio link emits a data-modulated signal that can be received at a ground receiving point (GRP). Fig. 1 shows the corresponding diagram.

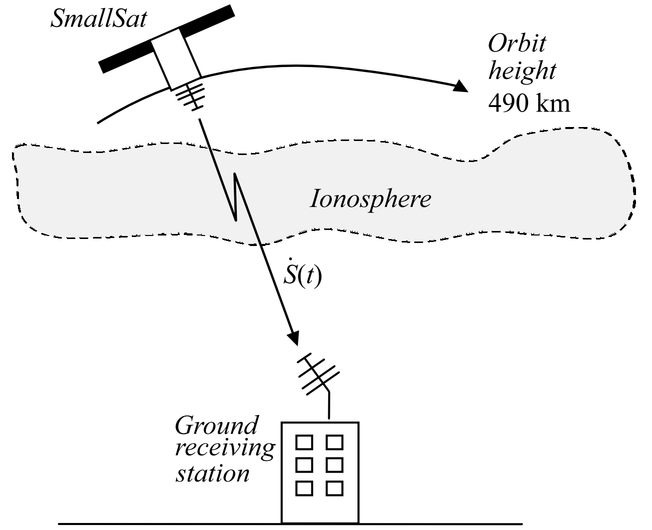

Figure 1. Diagram for registration of the trans-ionospheric signal of the SSC radio link.

Let us assume that the signal propagation medium is isotropic, and the radio link signal is narrowband. Then the received quadrature signal in the geometrical optics approximation can be written as

$$\dot{S}(t) = \dot{E}_0 \exp\left(j\frac{2\pi f_c}{c}\int\limits_0^{R(t)} n(r,\, f_c)dr + \varphi_i(t)\right). \tag{1}$$

Here $n(r,\, f_c)$ is the refractive index of the medium along the propagation path set by the distance vector between the GRP and the spacecraft $\mathbf{R}(t)$ and $|\mathbf{R}(t)| = R(t)$, $\varphi_i(t)$ is information component when using phase modulation, f_c is carrier frequency, c is the speed of light. We write the refractive index of the atmosphere as the sum of a deterministic (regular) and a random (fluctuation) components under the assumption that $\mathbf{M}\big(n(r,\, f)\big) = n_{reg}(r,\, f)$:

$$n(r,\, f) = n_{reg}(r,\, f) + n_{\varphi}(r,\, f). \tag{2}$$

The system of accepted assumptions can be described as follows. In general, $n(r,\, f)$ depends on time, which is related to the dynamics of turbulent layers. However, at the time intervals of the space communication systems operation (few minutes maximum) we will consider the random field of the refractive index as „frozen“. Besides, we will assume that fluctuations in the refractive index in the reviewed time intervals of registration of trans-ionospheric signals are determined mainly by medium- and small-scale variations in the electron density along the flight path of the spacecraft, while the effect of tropospheric fluctuations in the reviewed frequency ranges (meter and lower part of decimeter waves) is insignificant. Quantitative analysis shows that in these ranges the contribution of phase fluctuations caused by the troposphere does not exceed 1 and 1.5

$$\dot{s}(t) = \dot{E}_0 \exp\left(j2\pi f_c\left(t - \frac{1}{c}R(t)\right) + \varphi(t) + \varphi_i(t)\right), \tag{3}$$

where $\varphi(t)$ is a random phase due to electron density fluctuations. Knowing $R(t)$, we can write down the phase change depending on the distance SSC$-$GRP $\phi_b(t) = 2\pi f_c R(t)/c$, reference signal $\dot{s}_b(t) = \exp\big[j(2\pi f_c t - \phi_b(t))\big]$, then the signal at the output of the synchronous detector $\Delta\dot{s}(t)$ has the form

$$\Delta\dot{s}(t) = \dot{s}(t)\big(\dot{s}_b(t)\big)^* = \dot{E}_0 \exp\left(j\left(\frac{\partial}{\partial t}\varphi(t)\right)t + \varphi_i(t)\right). \tag{4}$$

Further, from the recorded digital signal $\Delta\dot{s}(t)$, using the sliding discrete Fourier transform, one can find the difference frequency dependence on time and then restore the phase fluctuations due to the ionosphere. At the same time, note that the frequency fluctuations associated with the information component of the instantaneous phase are several orders of magnitude higher than the ionospheric ones, and therefore do not affect the difference frequency estimate obtained.

The autocorrelation function of phase fluctuations due to the ionosphere can be written as

$$B_{\varphi}(t_1, t_2) = \left(\frac{2\pi}{\lambda}\right)^2 \int\limits_{R_{\max}(t_1)}^{R_{\min}(t_1)} \int\limits_{R_{\max}(t_2)}^{R_{\min}(t_2)} B_0\big(|\mathbf{R}_1(r_1, t_1) - \mathbf{R}_2(r_2, t_2)|\big)dr_1 dr_2, \tag{5}$$

where $B_0(r)$ is the correlation function of fluctuations of the ionospheric refractive index, $\mathbf{R}_1(r_1, t_1)$, $\mathbf{R}_2(r_2, t_2)$ is position vectors of the beam propagation path in the ionosphere, $R_{\min}(t_1)$, $R_{\max}(t_1)$, $R_{\min}(t_2)$, $R_{\max}(t_2)$ are limits of change of the parameters r_1 and r_2, respectively.

If we know the dispersion of phase fluctuations $\sigma_{\varphi}^2 = B_{\varphi}(0, 0)$ and the correlation interval of phase fluctuations τ_{cor}, defined as

$$\tau_{cor} = \sqrt{\int\limits_{-\infty}^{+\infty} t^2 B_{\varphi}(0, t)dt \Big/ \int\limits_{-\infty}^{+\infty} B_{\varphi}(0, t)dt}, \tag{6}$$

then the model parameters, for example, the bell-shaped electron density correlation function $B_0(r)$ can be determined from the dependences of phase dispersion on the electron concentration and of the correlation time on the scale of inhomogeneities.

To execute a full-scale experiment, a signal emitted by the transmitting unit of the radio channel equipment of the decimeter band from the onboard monitoring and control system of SSC „Aist-2D“ [9] was used. The signal was received by GRP from the SSC „Aist-2D“ bistatic

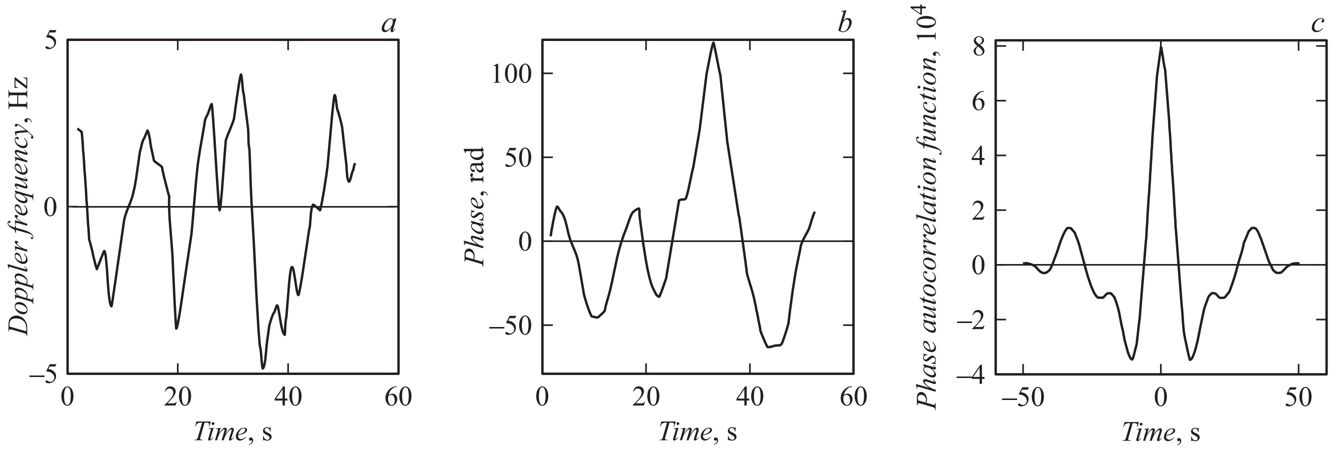

Figure 2. The difference Doppler frequency (*a*), the phase obtained by integrating the difference Doppler frequency (*b*), and the form of the correlation function (*c*).

radar system at a frequency of 435.34 MHz, recorded and digitized on a zero carrier with a sampling frequency of 100 kHz.

Fig. 2, *a* shows a fragment of the difference Doppler frequency obtained by subtracting the reference signal using estimated data on the trajectory of SSC movement. Fig. 2, *b* shows the phase obtained by integrating the difference Doppler frequency, and Fig. 2, *c* — the resulting function of signal phase autocorrelation at the carrier frequency 435.365 MHz.

From the data in Fig. 2, *c* one can determine the width of the correlation function (6.07 s). The values of the correlation intervals can be used to determine the scale of inhomogeneities (70 km) and the electron concentration in the ionosphere ($3.2 \cdot 10^{12}\,\mathrm{m}^{-3}$), which is in the range of admissible values for a given region (Samara, 53°11′N, 50°07′E) and experiment time 5 h 42 min in UTC format (light part of the coil). Note that the accuracy of the proposed method is determined by the accuracy of knowledge of the following parameters: the position of the center of gravity of the spacecraft, the signal-to-noise ratio, the tropospheric component, the amount of recorded data (duration of the communication session) and the accuracy of the used model of the electron density correlation function $B_0(r)$.

The data obtained can be used in the radar images processing to reduce the destructive effect of the ionosphere on the received information products in the long-wavelength part of the radio spectrum. Unlike most of the known methods, the proposed method does not use a priori knowledge of the structure of the emitted signal, which makes it possible to study the characteristics of the ionosphere in parallel with the transfer of target information. In the context of creating a system of global monitoring of the ionosphere, the integration of information obtained under the proposed approach and other methods seems to be extremely relevant.

Conflict of interest

The authors declare that they have no conflict of interest.

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