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Monitoring of parameters of coastal Arctic ecosystems for sustainability control by remote sensing in the short-wave range of radio waves with use of the experimental equipment of coherent reception of a ground-based measuring complex

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Abstract

Monitoring of the earth's surface by remote sensing in the short-wave band can provide a quick identification of some characteristics of coastal Arctic ecosystems. This band range allows to diagnose subsurface aspects of the earth, as the scattering parameter is affected by irregularities in the dielectric permittivity of subsurface structures. This method is based on the organization of the monitoring probe and may detect changes in these environments, for example, to assess hazardous natural phenomena, assessing sustainability, as well as some man-made hazards and *etc.* The problem of measuring and accounting for the scattering power of the earth's surface in the short-range of radio waves is important for a number of purposes, such as e.g diagnosing properties of the medium, which is of interest for geological, environmental studies. In this paper, we propose a new method for estimating the parameters of incoherent signal/noise ratio. The paper presents the results of comparison of the measurement method from the point of view of their admissible relative analytical errors. The new method is suggested. Accuracy new method on the order exceeds the widely-used standard method. Interpretation of the data is based on a statistical multiplicative model of the signal. Testing the method of obtained a signal/noise ratio in this model was produced by the example of a double reflection of the probe signal from the SW ionosphere in a vertical sounding (when using a satellite, the signal passes twice through the atmosphere and ionosphere). In this paper, a sensitivity of the model parameters was studied. To obtain the necessary experimental data, the pulse method of coherent reception was used. Analysis of analytical error of estimation of this parameter allowed to recommend a new method instead of standard method. A comparative analysis showed that the analytical (relative) accuracy of the determination of this parameter by a new method exceeded the widely-used standard method by the factor of ten.

Key words: surface scattering of radio waves, measurement technique, the scattering parameter signal/noise ratio, ionosphere

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List of abbreviations: SW (Short-Wave), ESSP (Earth Surface Scattering Power), SM (Statistical Model), β_K (signal/noise ratio), ADC (Analog-to-Digital Converter)

Introduction

Parameter of returned partially scattered ionospheric signal β_K is of interest because it is an important characteristic of the "perturbation" and "turbidity" of statistically inhomogeneous ionospheric plasma. It also allows to determine the index of reliability of ionospheric communication channels including diagnostic purposes. Prompt and reliable estimate of the parameter β_K is of interest to radio physics, geophysics, and optics (Belov 2014). Consideration is carried out on an example for an ionospheric case. This range (3–12 MHz) allows us to diagnose subsurface layers of the earth because the scattering parameter is formed by inhomogeneities in the dielectric permittivity of the subsurface structures. The problem of measuring and accounting of the scattering power of the earth's surface in the shortwave range of radio waves is important for solving such challenges as diagnosing properties of the environment using methods that apply this radio band, when in the channel there is an intermediate reflection (scattering) of the earth's surface, which is of interest for exploration and environmental studies (Belov et Belova 2015a).

Selection of the working sensing range and the impact of environment on the passing radiation are an important issues for using space-based tools, for environmental management and environmental monitoring (Belov et Belova 2015b). The most important aspects of using space-based tools for environmental management and environmental monitoring are the choice of the operating range and probing questions about the influence of media on the passing radiation. The problem of this discussion is the "rough" remote diagnostics of the earth's surface and subsurface of the dielectric structures in the SW range (Belov 2010a). Selection of SW range takes into account the subsurface layer (thickness of the order of the wavelength of the incident signal). Interpretation of the data is based on a statistical multiplicative model of the signal (Belov 2016k). Testing the method of obtaining a signal/noise ratio in this model was produced by the example of a double reflection of the probe signal from the SW ionosphere in a vertical sounding (remember that when using a satellite, the signal passes twice through the atmosphere and ionosphere - Mirkotan et Belov 1998b). The work presented in this paper addresses sensitivity of the model parameters that were studied (for parameters *see* Belov 2015c).

The measurement, mapping, and computation of the "rough" Earth Surface Scattering Power (ESSP) in the SW range are of interest for a wide range of problems (communication, geology, *etc*., Mirkotan et Belov 1998c). The ESSP parameter is the signal/noise ratio of the β_K waves reflected from the earth's "rough" backing (Belov 2010b). There is no β_K -data, and methods for measuring them in the SW range. Mirkotan et al. (1999a) presents the experimental method of β_K determination.

In this paper, the sensitivity of the model to the parameter under study was considered. According to the statistical model (SM), a database ("records" for the numerical experiment) adequate to the real conditions was created. The properties of the "rough" earth area were defined by the theoretical β_K value. Based on the method of Mirkotan et al. (1999b), β_K (numerical experiment) was determined (Belov 2015c). Then, the arrays of the β_K and β_K^t were compared and analyzed. In this paper, the admissible sensitivity and stability of the method (Mirkotan et Belov 1998a) were justified. The comparative analysis of the real experimental data and adequate numerical ones were fulfilled. As a result, the plausibility of the ionosphere echo statistical structures used were justified (Belov 2009).

In this paper, we propose a new method for these parameters estimation, *i.e.* noncoherent signal/noise ratio β_K ionospheric echo (Belov 2015a). A comparative analysis shows that the analytical (relative) accuracy of the determination of the parameter β_K using the new method exceeds the widely-used standard, and the same order of known coherent methodology (Belov 2016f). The paper presents the results of comparison of the measurement method from the point of view of their admissible relative analytical errors (Belov et Belova 2015f).

Material and Methods

1. Calculation methods

Narrowband random process $\mathcal{E}(t)$ in fixed point of reception in the ground in scalar approximation is the superposition of mirror $\mathcal{E}_0(t)$ and scattered $\mathcal{E}_P(t)$ components distributed by the normal law (Belov et Belova 2016d):

$$\begin{aligned}\mathcal{E}(t) = \mathcal{E}_0(t) + \mathcal{E}_P(t) &= E_{00} \cdot e^{i\cdot(\omega_0 \cdot t - \varphi(t))} + \mathcal{E}_P(t) = \\ &= R(t) \cdot e^{i\cdot(\omega_0 \cdot t - \Phi(t))} = \left[E_C(t) + i \cdot E_S(t)\right] \cdot e^{i\cdot\omega_0\cdot t},\end{aligned} \qquad \textit{Egn. } 1$$

where $\varphi(t)$, $\Phi(t)$, $R(t)$, $E_m(t)$, m=c,s – shown to slow random processes on the period $T = \frac{2 \cdot \pi}{\omega_0}$; E_{00} = Const (Belov et Belova 2016c).

Scattering parameter is the ratio:

$$\beta_k^2 = \frac{\textit{power of mirror components}}{\textit{power of scattered components}} = \frac{E_{00}^2}{2 \cdot \overline{\mathcal{E}_P^2}} \qquad \textit{Egn. } 2$$

Here and below, "—" means statistical averaging. $E_C(t) = R(t)\cdot\cos\Phi(t)$ and $E_S(t) = R(t)\cdot\sin\Phi(t)$ are the low-frequency quadrature of the ionospheric signal, R(t) is the envelope, Φ(t) is the total phase.

The subscript k = E4, R2, R4 means experimentally recorded primary random processes, and the appropriate method of their registration: E4 – coherent; R2, R4 – noncoherent amplitude. Index k indicates the primary parameter recorded: E – quadrature, R – envelope of the ionospheric signal.

Standard noncoherent R2-method based on the relationship (3) is widely used for estimating β_K (2) (Alpert 1960):

$$\frac{\overline{R^2}}{\left(\overline{R}\right)^2} = f\left(\beta_{R2}\right) = \frac{4}{\pi}\cdot\frac{\left(1+\beta_{R2}^2\right)\cdot\exp\left(\beta_{R2}^2\right)}{\left[\left(1+\beta_{R2}^2\right)\cdot I_0\left(\beta_{R2}^2/2\right)+\beta_{R2}^2\cdot I_1\left(\beta_{R2}^2/2\right)\right]^2} \qquad \mathit{Egn.}\ 3$$

$I_n(x)$ is the Bessel function of the n_{th} order of a purely imaginary argument.

Using the coherent E4-method and estimating β_{E4} by γ_{E4} kurtosis of quadrature (Belov 2013):

$$\gamma_{E4}\left(\beta_{E4}\right) = \frac{\overline{E_m^4}}{\left(\overline{E_m^2}\right)^2} - 3 = -\frac{3}{2}\cdot\frac{\beta_{E4}^4}{\left(1+\beta_{E4}^2\right)^2}; \quad m = c,\ s. \qquad \mathit{Eqn.}\ 4$$

It should be noted that the measured primary parameters are the ratio of statistical moments $\overline{R^2}\Big/\left(\overline{R}\right)^2$, $\overline{E_m^4}\Big/\left(\overline{E_m^2}\right)^2$ respectively. Relations (3), (4) are obtained by taking into account the specific models of structure of the ionospheric signal (Belov et Belova 2015d).

Probabilistic properties of the ionospheric signal (1) of the first multiplicity response is well described by the Rice model with a displaced spectrum (RS-model). Expressions (3) and (4) are based on the Rice model with a displaced spectrum (Belov et Belova 2016a).

A priori expression (4) of coherent method E4 contributes an order of magnitude higher relative analytical accuracy of the estimation of parameter β_K (Belov 2016c).

In this paper, we propose a new noncoherent R4-method of determination of β_{R4} by γ_{R4} kurtosis of the envelope for the RS-model (Belov 2015b):

$$\gamma_{R4}\left(\beta_{R4}\right) = \frac{\overline{R^4}}{\left(\overline{R^2}\right)^2} - 3 = \gamma_{R4}\left(\beta_{R4}\right) = -1 - \frac{\beta_{R4}^4}{\left(1+\beta_{R4}^2\right)^2} \qquad \mathit{Eqn.}\ 5$$

For comparison of the given methods in the sense of relative errors permitted in calculating β_K, due to their functional dependencies $f(\beta)$, $\gamma_{E4}(\beta)$ and $\gamma_{R4}(\beta)$, we obtain the following expressions (6) (Belov 2016j):

$$\varepsilon_k = \left|\frac{\Delta\beta_K}{\beta_K}\right| = \left|\frac{1}{\beta_K}\cdot\frac{dG_K}{dZ_K}\cdot\Delta\left(Z_K\right)\right| \qquad \mathit{Eqn.}\ 6$$

where K = R2, E4, R4; $G_K = f, \gamma_{E4}, \gamma_{R4}$; and $\Delta(Z_K)$ – absolute statistical errors of measured values: $Z_K = \dfrac{\overline{\mathrm{R}^2}}{\left(\overline{\mathrm{R}}\right)^2}, \dfrac{\overline{\mathrm{E}_m^4}}{\left(\overline{\mathrm{E}_m^2}\right)^2}, \dfrac{\overline{\mathrm{R}^4}}{\left(\overline{\mathrm{R}^2}\right)^2}$

Measures of inaccuracy, including statistics for the different techniques of determination of β_K, are (Belov 2016a):

$$\varepsilon_{R2}(\beta) = \frac{\pi}{8} \cdot \frac{\left[\left(1+\beta^2\right)\cdot \mathrm{I}_0\left(\beta^2/2\right) + \beta^2 \cdot \mathrm{I}_1\left(\beta^2/2\right)\right]^3}{\beta^2 \cdot \exp\left(\beta^2\right)\cdot \mathrm{I}_1\left(\beta^2/2\right)} \cdot \Delta\left(Z_{R2}\right)$$

$$\varepsilon_{E4}(\beta) = \frac{\left(1+\beta^2\right)^3}{6\cdot\beta^4} \cdot \Delta\left(Z_{E4}\right) \qquad \textit{Eqn. } 7$$

$$\varepsilon_{R4}(\beta) = \frac{\left(1+\beta^2\right)^3}{4\cdot\beta^4} \cdot \Delta\left(Z_{R4}\right)$$

Statistical error $\Delta(Z_K)$ depends on the sample volume N. It may be different for identical sample volume for each of the methods. We normalized (7) on $\Delta(Z_K)$ so that the errors due to differences in functional dependencies (3) – (5) could be distinguished (Belov 2016d).

Dependency Graphs $\varepsilon_K^* = \dfrac{\varepsilon_K}{\Delta\left(Z_K\right)}$ for β_{R2}, β_{E4} and β_{R4} are shown in Fig. 1.

ε_K^* will be called analytic (relative) error method (Belov 2016g).

Experimental distribution $W_{Э}(\beta)$ determines the range of variation of β (Belova et Belov 2016).

From equation (4) and (5), we conclude that $\varepsilon_{E4}^* = \dfrac{2}{3} \cdot \varepsilon_{R4}^*$ have the same order and significantly (by order) exceed the measurement accuracy of the standard R2-method (Belov 2016i).

Analysis of analytical error of estimation of the parameter β_K allowed us to recommend the R4-method instead of the standard R2-method. A sufficiently high analytical (relative) accuracy of parameter estimation for β_K can be achieved using a noncoherent apparatus applying (5) the R4-method. Analytical (relative) accuracy of the determination of this parameter by a new R4-method exceeded the widely-used standard R2-method by the factor of ten. Naturally, the ability to optimize the statistical error by the relevant special digital processing of ionospheric signal is keep on coherent methodology E4 (Belov 2016b).

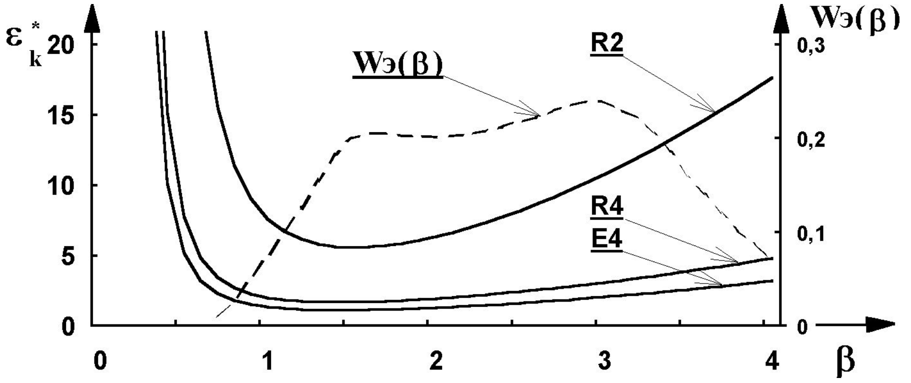

Fig. 1. Dependency Graphs ε_K^*, K = R2, R4, E4 (solid curves) and the experimental distribution Wэ(β) (dashed curve) (F2-layer, 4,5 – 9,5 MHz, single signal).

2. Testing method

Interpretation of the received data is based on statistical signal multiplicative model. Testing method for obtaining "scattering parameter" signal/noise ratio in this model is produced by the example of the double reflection of the signal at its vertical distribution. In progress issues of sensitivity pattern of the studied parameter are considered (Belov 2015c).

Scattering parameter is formed also by the likely inhomogeneities of the dielectric permeability of the subsurface structures (Belov et Belova 2016f). According to the method of the organization of the monitoring may detect fields of environmental changes (Belov et Belova 2016e). For example, there is estimation of seismic hazard and seismic risk.

Test method in usual ionospheric conditions with varying parameter of scattering “substrate” was carried out. The analysis of numerical experiment revealed that:

1. Method of remote diagnostics in shortwave diapason, the studied parameter in particular, were found sensitive. If sample volume $N \geq 240$ then accuracy of estimation of studied parameter was better than 5%.
2. Sensitivity of this method, its accuracy characteristics are guaranted even after significant changing of parameters of spreads of environment.
3. A comparison of data of numerical and physical experiments showed that, to provide estimation of scattering parameter in real experiment conditions with an accuracy comparable to the equipment error, it can be recommended to increase the duration of the sessions of observation till 8 ÷ 10 min.

3. The experimental setup for simultaneous recording of ionospheric signals of different multiplicity

To obtain the necessary experimental data, the pulse method of coherent reception was used. This method allows to register low-frequency quadrature components of ionospheric signal $E_c(t)$, $E_s(t)$. To determine signal modulation functions, the envelope $R(t)$ and the phase $\Phi(t)$ are possible to use these components. The equipment of coherent reception allow to register directly the envelope and the phase of the reflected signal from the ionosphere. A number of factors co-act simultaneously to form a field of ionospheric signal. Therefore, such complex approach to the study of the properties of the radio signal is necessary, especially the study of multiple ionospheric reflections.

It is necessary to allow separation and simultaneous record of the parameters of different multiplicity. All of the above identified ways to modernize the equipment of the coherent reception were applied to ensure a higher-quality study of the properties of multiple reflections. The installation uses a scheme of registration of low-frequency quadrature component of the ionospheric signal E_c(t), E_s(t) and envelope R(t). Modernization of the installation provided the registration with the aid of computer for the above-mentioned signal parameters simultaneously, *i.e.* for the signals of different multiplicity. This is achieved by the use of a special multi-channel strobbing (gating) system and registration. Fig. 2 presents a block diagram of the installation with the scheme of registration and strobbing. Installation allows simultaneous recording of the parameters of multiple ionospheric reflections (Figs. 3-4). Below we consider the work and purpose of the individual blocks (Belov et Belova 2015c).

4. The principles of basic units

The master oscillator generates a voltage of sine wave with amplitude 1-2 V in frequency diapason 2-15 MHz. This voltage is supplied to the transmitter controlled by synchronizing pulses. As a result, the transmit antenna receives rectangular radio pulses adjustable duration in interval 100 ÷ 500 μs. The period of the pulse repetition is a 20 ms interval. It is enough for receiving several multiple reflections in the time between sending. The transmitter has a pulse power of about 12-15 kW. Radiation occurs via rhombus type antenna with diagonal length of 50 m and 25 m in horizontal and vertical directions, respectively (Belov 2016h).

The reflected signal from the ionosphere is received by the symmetrical dipole with a ray length of 14 m and arrives at the receiver input on two-wire cable. In this receiver, the signals are amplified. The amplification factor can be adjusted, its maximum value is 20 db. Further there is a frequency conversion. As a heterodyne in the scheme of transformation the generator according to the scheme of an inductive three-point is used. A mixer of the receiver voltage is applied to the intermediate-frequency amplifier, which provides the adjustment of both the gain and the bandwidth. The amplifier has 4 amplification stage with intermediate frequency transformers. The second and third transformers are adjustable, which changes the bandwidth of between 7 to 30 kHz.

The amplified voltage of intermediate frequency is detected and fed to the amplifier of low-frequency receiver and the ADC. On the “Test indicator” goes low frequency voltage from matching device after the receiver and strobe pulses from the synchronization and strobe scheme. The “Test indicator” allows to visually select the desired signal multiplicities and determine the order of their registration. Coherent reception method provides, *inter alia*, the comparison phases of the received signal and emitted. This requires channel reference voltage. Since the comparison in this installation takes place at the intermediate frequency, then to the reference voltage input of channel occurs transformation of the oscillator frequency to the intermediate one in the reference channel mixer block (“Basic channel”). The reference voltage of the intermediate frequency is generated from the reference generator voltage and the local oscillator' receiver. Further, the reference voltage is supplied to the amplifier of the intermediate frequency channel of the reference voltage. The reference voltage empowered to the required level is applied to the matching device of reference channel, where the pulse sequence is generated from sinusoidal voltage. These pulses are applied to the ADC. As a result, the low-frequency quadrature signal components can be registred, and even with the use of a computer with not very high speed due to the use of original optimization algorithms. Patent: (Belov 2016b).

Functional registrar scheme is substantially modified for simultaneous recording of parameters of the various multiplicities of the signals. A multichannel gating system and a special synchronizer were created (Fig. 2). Earlier the recorder lets you record on film quadrature components of signals of different multiplicity and also the power envelope and the total phase.

Cathode-ray tube is a “Test indicator” in the system for visual observation and guidance strobe system. By changing the time position of the strobes, an operator can select the desired reflection as of different multiplicity corresponds to different delay with respect to the probe pulse. Contact signals of different multiplicity to the appropriate ADC registrar channel is provided by synchronization and strobing scheme and controlled by a visual indicator. Control of the operation of the measuring equipment and the coordination of its nodes is carried out synchronization scheme, on the input of which receives the frequency of 50 Hz, which starts all the main units of the installation. With this frequency, a "Impulses start" is formed to control the operation of the "Transmitter", the "Locking impulse" of the receiving channel for the duration of the emitting pulse, and a number of voltages for controlling the operation of the "Test indicator" and "Computer".

5. Methodology and outputs of experimental research

Earlier issues of theory of common methodologies and the methods of determining the parameters of the signal/noise in the study of the properties of multiple ionospheric reflections have been discussed. They comprised (1) a method of determining a parameter β for reflection of different multiplicity, (2) a method of determining β_2 in the new statistical model for multiple reflections; including the estimation of scattering power of "rough" earth surface in the short-wave-range. Performed comparative analysis of the effectiveness of different methods for determining a parameter β on the one hand allowed to justify the selection of the optimal methods of reliable parameter β estimation in the conditions of the present experiment. On the other hand, the analysis has a more general significance, since the receipt of prompt and reliable information about β is of interest in solving reliability problems and improving the communication channel. The analysis also gives an indication of the mechanism of the ionosphere and the earth scattering of the signal structure. Parameter of scattering power of "rough" surface of the earth in the short-wave-range may depend on (1) spatial arrangement of buildings, (2) its distribution and combination with open spaces (the degree of polarization with a conditional natural elements). Additionally, may depend on (3) functional content areas (residential, industrial or recreational), which determines the intensity and nature of the activity, as well as (4) the permittivity of the inhomogeneities of the subsurface structures (Belov 2016e).

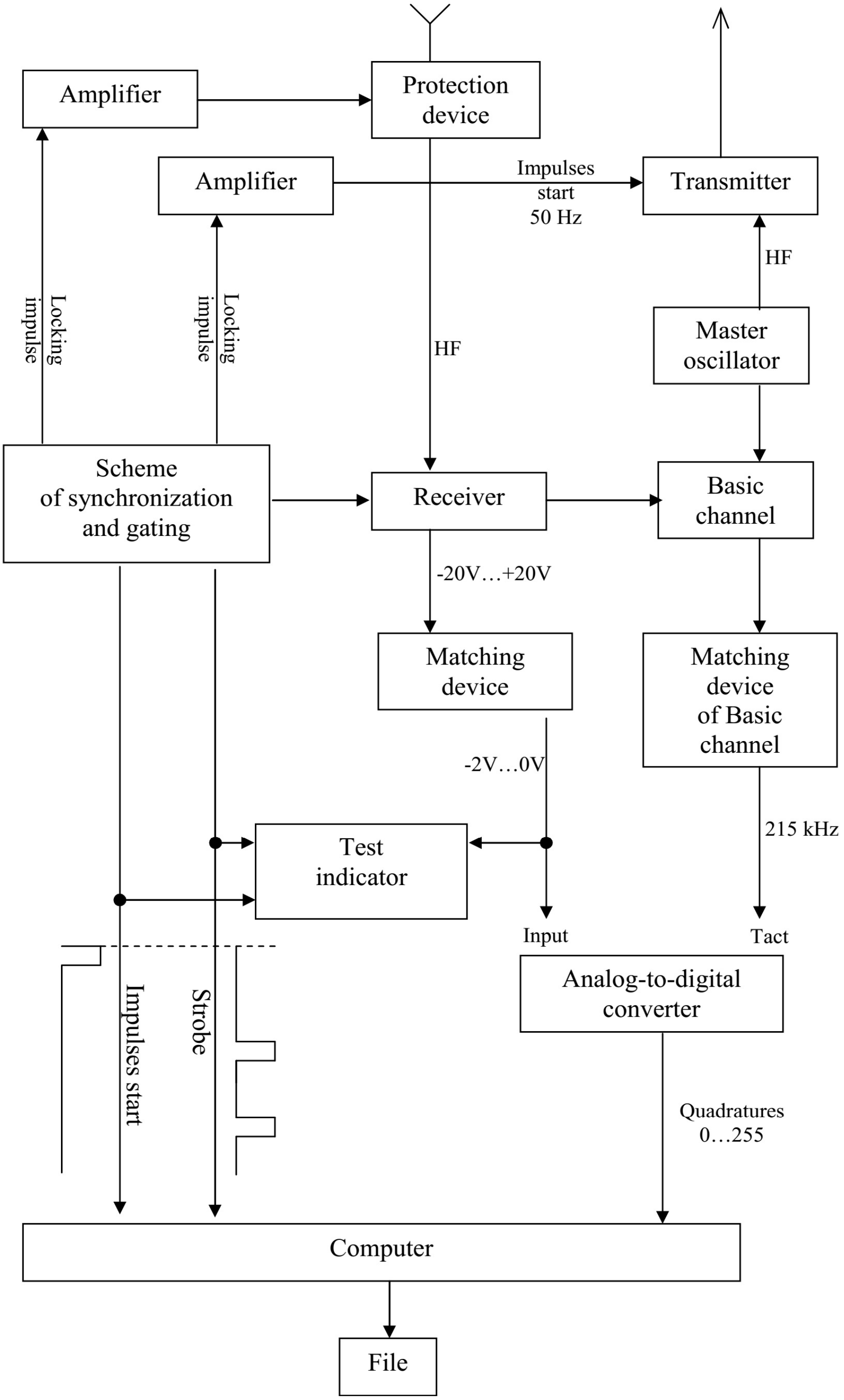

Fig. 2. Functional diagram of the experimental installation.

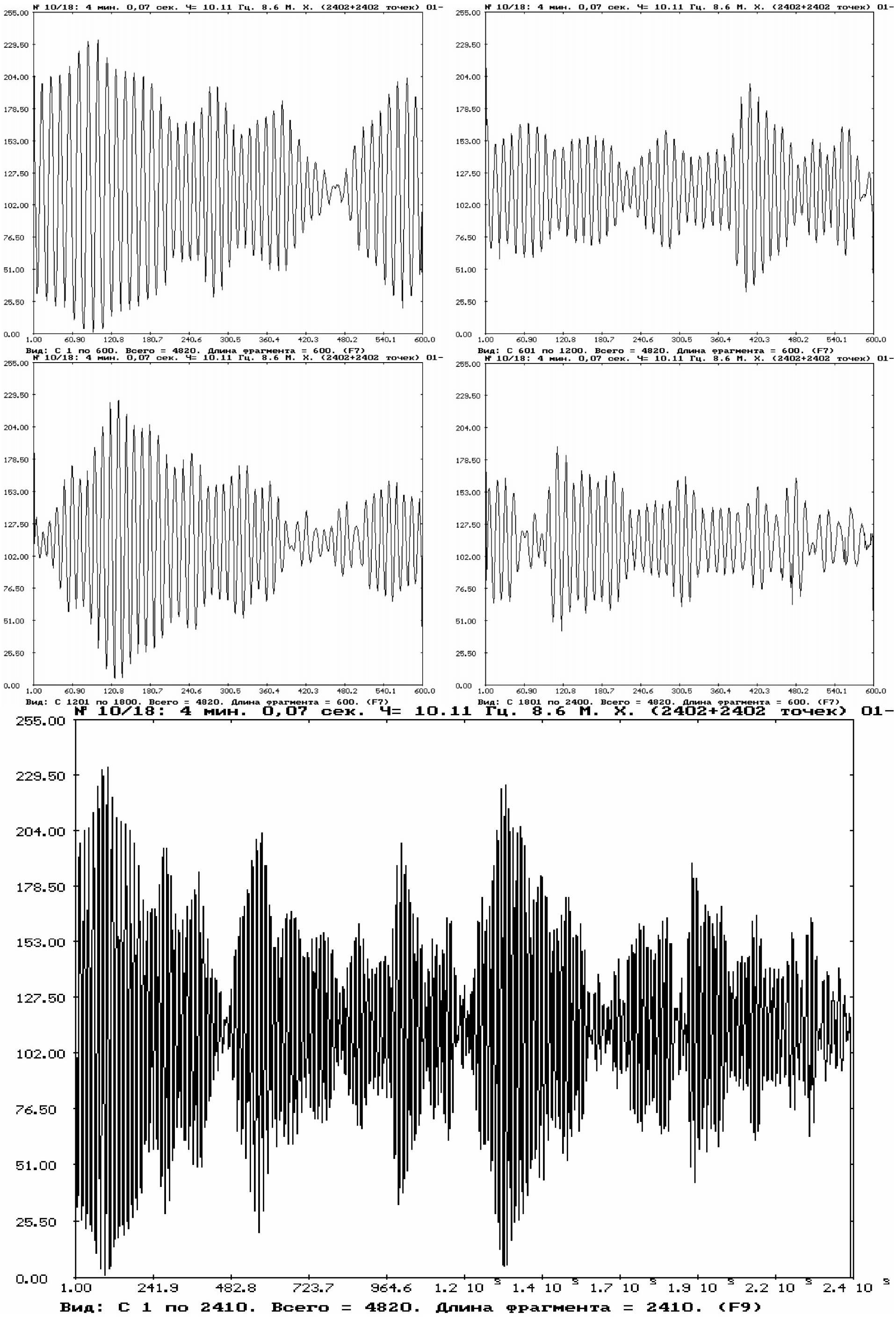

Fig. 3. Change with time of the quadrature component of the ionospheric signal, single-reflected: 1st, 2nd, 3rd, 4th min. and full session (from left to right from top to bottom).

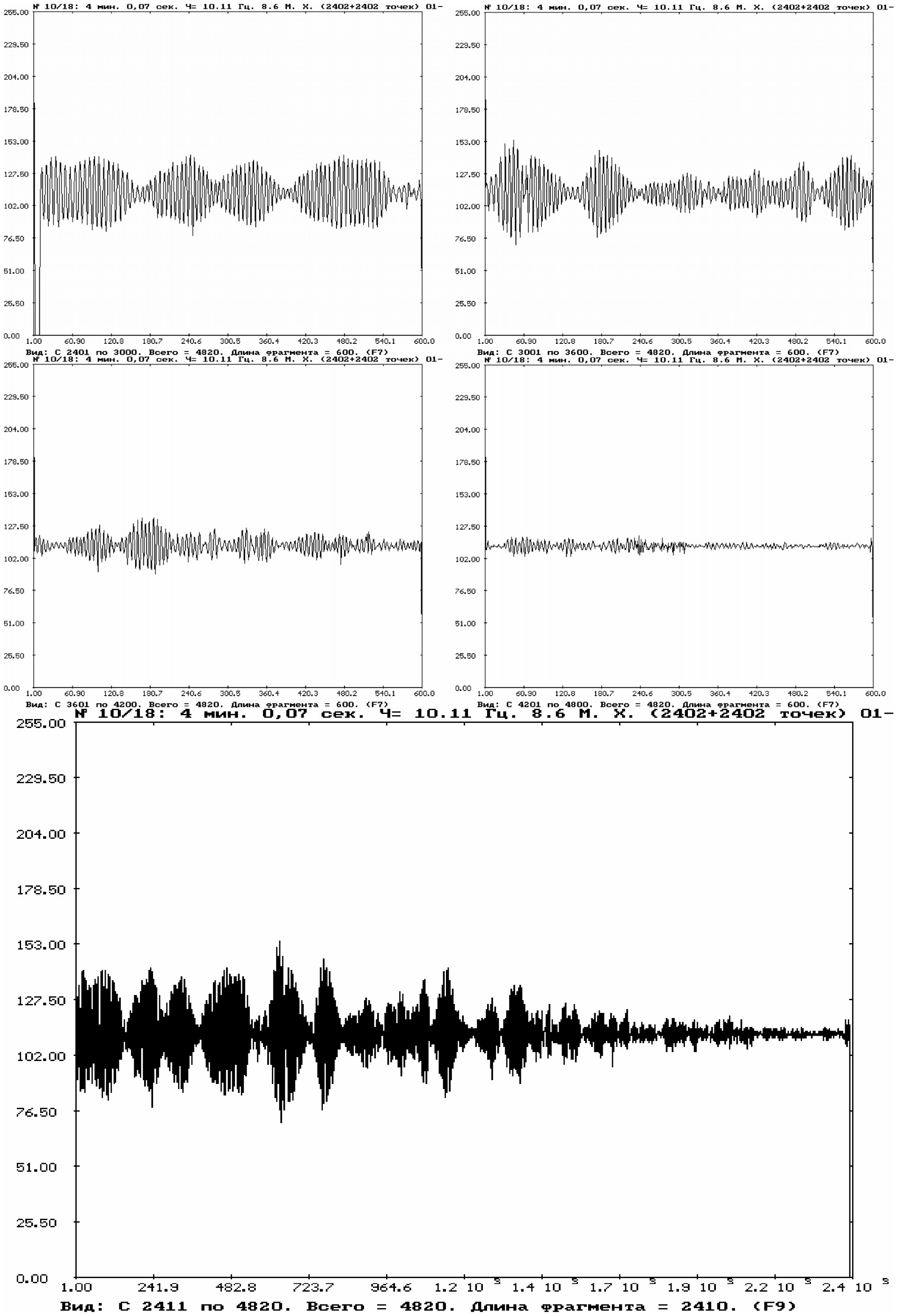

Fig. 4. Change with time of the quadrature component of the ionospheric signal, second-reflection: 1st, 2nd, 3rd, 4th min. and full session (from left to right from top to bottom).

Conclusion

The comparative analysis of the normalized relative analytical errors ε_K^* of the known methods and the new one was performed. It was shown that errors ε_E^* and ε_{R4}^* have the same order, and both errors significantly exceed the error ε_{R2}^* in comparison with the standard R2-method by a measurement accuracy of β_K.

Environmental monitoring of the earth's surface by remote sensing in the shortwave band can provide quick identication of some ecological characteristics for the purposes of control and management in the fields of Environment including such as spatial distribution of surface and subsurface elements, its distribution and combination with open spaces (the degree of polarization with a conditional natural elements); functional content of the districts (residential, industrial or recreational), which determines the intensity and nature of the activity affecting the ecological load; and also inhomogeneities in the dielectric permeability of subsurface structures (Belov et al. 2016). This band range allows to diagnose subsurface aspects of the earth, as the scattering parameter is affected by irregularities in the dielectric permittivity of subsurface structures. This method is based on the organization of the monitoring probe and may detect changes in these environments. For example, seismic hazard and seismic risk can be assesed (Belov et Belova 2015e). The problem of measuring and accounting for the scattering power of the earth's surface in the short range of radio waves is important for a number of purposes. Among them diagnostic properties of the medium (surface and subsurface structures) using this radio band migh be used when going on the road to interpret the intermediate reflection (scattering) from the earth's surface, which is of interest for geological and environmental studies (Belov et Belova 2016b).

As a result, it was found that sufficient β_K analytical measurement accuracy can be achieved when using a noncoherent apparatus applying a new R4-method. On the other hand, the coherent E-method still has the possibility of statistical error optimization with a special processing of the ionospheric signal (Belov 2016b).

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