Detection of changes of characteristics of the scattering ability of superficial and subsurface structures of the Earth in the short-wave range of radio waves

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Abstract. The problem of remotely diagnosing a "rough" earth surface and dielectric subsurface structures in the short-wave radio wave band. A new incoherent method for estimating the signal-to-noise parameter is proposed. This range makes it possible to diagnose a subsurface layer of the earth, since the scattering parameter is also determined by inhomogeneities in the dielectric permeability of subsurface structures. By using this method to organize a monitoring program through sounding, it is possible to identify the areas of variation for these media, for example, for hazardous natural phenomena, changes ecosystems. The idea underlying the method for determining this parameter is that, by having synchronous information about a wave reflected from the ionosphere and one reflected from the earth and the ionosphere (or having passed through the ionosphere twice when probing from a satellite), it is possible to extract information about the scattering parameter. A comparative analysis was performed, and it showed that, according to the analytical (relative) accuracy of the definition of this parameter, the new method is an order of magnitude better than the widely used standard method. Evaluation of the analytical errors in estimating this parameter prompt us to recommend the new method instead of the standard one.

Keywords: remote sensing, surface scattering of radio waves, measurement technique, short-wave range, the scattering parameter signal/noise ratio, Ionosphere.

1. Introduction

Parameter of returned partially scattered ionospheric signal β_K is of interest to an important characteristic of the "perturbation" and "turbidity" of statistically inhomogeneous ionospheric plasma and to the work index of reliability of ionospheric communication channels including diagnostic one [6]. Prompt and reliable estimate of the parameter β_K is of interest to radio physics, geophysics, and optics [9, 10]. Specification for ionospheric case is implemented [7].

This range 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 [43].

The problem of measuring and accounting of the scattering power of the earth's surface in the short-wave 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 [11-42].

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 [2, 44].

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 [4]. 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 [8]. 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. 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) [18]. The work addressed issues of sensitivity of the model parameters that were studied [13].

The measurement, mapping, and computation of the "rough" Earth Surface Scattering Power (ESSP) in the SW range are of interest for a set of problems (communication, geology, etc.) [11]. The ESSP parameter is the signal/noise ratio of the β_K waves reflected from the earth’s "rough" backing. There is the back of the β_K -data and measuring method is in SW range. The paper [9] presents the experimental method of β_K determination.

In this paper, this method is tested on the parameter of β_K sensitivity. 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 [43], β_K (numerical experiment) was determined. 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 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 [6].

In this paper, we propose a new method for estimating the parameters of the noncoherent signal/noise ratio β_K ionospheric echo. 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 [9]. The paper presents the results of comparison of the measurement method from the point of view of their admissible relative analytical errors [2]. The new method is suggested.

2. 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 [1]:

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

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.

Scattering parameter is the ratio:

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

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)[1]:

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

$I_n(x)$ 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 [8]:

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

It should be noted that the measured primary parameters are the ratio of moments $\overline{R^2}/\left(\overline{R}\right)^2$, $\overline{E_m^4}/\left(\overline{E_m^2}\right)^2$ respectively. Relations (3), (4) are obtained by taking into account the specific models of structure of the ionospheric signal [7].

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 obtained based on the Rice model with a displaced spectrum [6].

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

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:

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

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) [35]:

$$\varepsilon_k = \left|\frac{\Delta\beta_K}{\beta_K}\right| = \left|\frac{1}{\beta_K}\cdot\frac{dG_K}{dZ_K}\cdot\Delta\left(Z_K\right)\right|, \quad (6)$$

where K=R2, E4, R4; $G_K=f$, γ_{E4}, γ_{R4} ; and $\Delta(Z_K)$ – absolute statistical errors of measured values: $Z_K = \frac{\overline{R^2}}{\left(\overline{R}\right)^2}, \frac{\overline{E_m^4}}{\left(\overline{E_m^2}\right)^2}, \frac{\overline{R^4}}{\left(\overline{R^2}\right)^2}$.

Measures of inaccuracy, including statistics for the different techniques of determination of β_K, are [37]:

;

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

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

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 normalize (7) on $\Delta(Z_K)$ for focusing on the errors due to differences in functional dependencies (3)–(5) [39].

Dependency Graphs $\varepsilon_K^* = \frac{\varepsilon_K}{\Delta(Z_K)}$ for β_{R2}, β_{E4} and β_{R4} are shown in figure 1. ε_K^* will be called analytic (relative) error method.

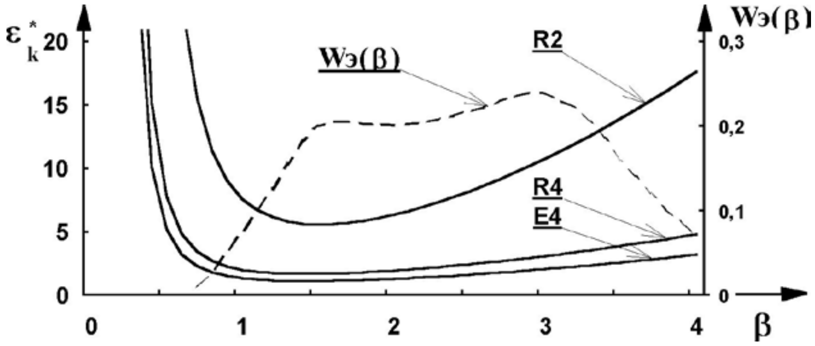

Figure 1. Dependency Graphs ε_K^*, K=R2, R4, E4 (solid curves) and the experimental distribution $W_Э(\beta)$ (dashed curve) (F2-layer, 4,5–9,5 MHz, single signal).

Experimental distribution $W_Э(\beta)$ determines the range of variation of β [9].

From equation (4) and (5), we conclude that $\varepsilon_{E4}^* = \frac{2}{3} \cdot \varepsilon_{R4}^*$ have the same order and significantly (by order) exceed the measurement accuracy of the standard R2-method [7].

Analysis of analytical error of estimation of the parameter β_K allowed us to recommend the R4-method instead of the standard R2-method [6]. A sufficiently high analytical (relative) accuracy of parameter estimation for β_K can be achieved using a noncoherent apparatus applying (5) the R4-method. Naturally, the ability to optimize the statistical error by the relevant special digital processing of ionospheric signal is keep on coherent methodology E4 [3].

3. Test 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 [35].

Scattering parameter is formed also inhomogeneities of the dielectric permeability of the subsurface structures. According to the method of the organization of the monitoring may detect fields of environmental changes [44]. For example, there is estimation of seismic hazard and seismic risk.

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

1. Method of remote diagnostics in sort wave diapason is sensitive by studying parameter. If sample volume $N \geq 240$ then accuracy of estimation of studying parameter is better than 5%.

2. Sensitivity of this method, its accuracy characteristics are saved even after significant changing of parameters of spreads of environment.

3. A comparison of data of numerical and physical experiments shows that, to provide estimation of scattering parameter in real experiment conditions with precise comparing with equipment error, it can be recommended to increase the duration of the sessions of observation till 8÷10 minutes.

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

To obtain the necessary experimental data using the pulse method of coherent reception. This method allow 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 using 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 simultaneously determinate field of ionospheric signal and such complex approach to the study of the properties of the radio signal is necessary with studying of multiple ionospheric reflections [23].

It's necessary to allow separation and simultaneous recording parameters of different multiplicity. All of the above identified ways to modernize the equipment of the coherent reception to ensure that work on the 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 above-mentioned signal parameters simultaneously for signals of different multiplicity. This is achieved using a special multi-channel strobbing (gating) system and registration. Figure 2 is a block diagram of the installation with the scheme of registration and strobbing. Installation allows simultaneous recording of the parameters of multiple ionospheric reflections. Below we consider the work and purpose of the individual blocks [5].

5. The principle 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 20 ms, it's 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 50 m and 25 m horizontally and vertically, respectively.

The reflected from the ionosphere signal is received to the symmetrical dipole with a ray length 14 m and arrives at the receiver input on two-wire cable. There is amplified signals. The amplification factor can be adjusted, its maximum value is 20 db. Further there is a frequency conversion. As local oscillator (heterodyne) in transform schema uses the generator by inductive scheme with three points. With the mixer of the receiver voltage is applied to the intermediate-frequency amplifier, which provides for adjustment 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 is 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 you 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, it can be registered the low-frequency quadrature signal components, and even with the use of a computer with not very high speed due to the use of original optimization algorithms. Patent [3].

Functional diagram registrar is substantially modified for simultaneous recording of parameters of the various multiplicities of the signals. It is established a multi-channel strobe system and a special synchronizer. 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 (CRT) is a “Test indicator” in the system for visual observation and guidance strobe system. By changing the time position of the strobes, you 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. Performance management of measurement complex and coordination of its components is carried out synchronizing scheme, on the input of which receives the voltage frequency of 50 Hz, which runs all the basic building blocks of the installation. With this frequency modulating pulse is formed for controlling the operation of the transmitter, the lock impulse of the receiving channel for the duration of the probe pulse, and a number of voltages to control the operation of the control indicator and computer.

6. Methodology of experimental research

Earlier issues of theory of common methodologies and methods of determining the parameters of the signal/noise in the study of the properties of multiple ionospheric reflections have been discussed: a method of determining a parameter β for reflection of different multiplicity, a method of determining β_2 in the new statistical model for multiple reflections; estimation of scattering power of "rough" earth surface in the short-wave-range [9].

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, and 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 the spatial concentration of buildings, on its distribution and combination with open spaces (the degree of polarization with a conditional natural elements); on functional content areas (residential, industrial or recreational) causes the intensity and nature of the activity, as well as the permittivity of the inhomogeneities of the subsurface structures [43].

7. 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 short-wave band can provide quick identication of some ecological characteristics for the purposes of control and management in the fields of Environment [44].

This band range allows one to diagnose subsurface aspects of the earth, as the scattering parameter is affected by irregularities in the dielectric permittivity of subsurface structures [43]. This method based on the organization of the monitoring probe may detect changes in these environments, for example, to assess seismic hazard and seismic risk. 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 diagnosing properties of the medium using this radio band 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 [11-42].

As a result, it was found that sufficient β_K analytical measurement accuracy can be achieved when using an noncoherent apparatus applying a new R4-method. But the coherent E-method reserves the possibility of statistical error optimization with a special processing of the ionospheric signal [3].

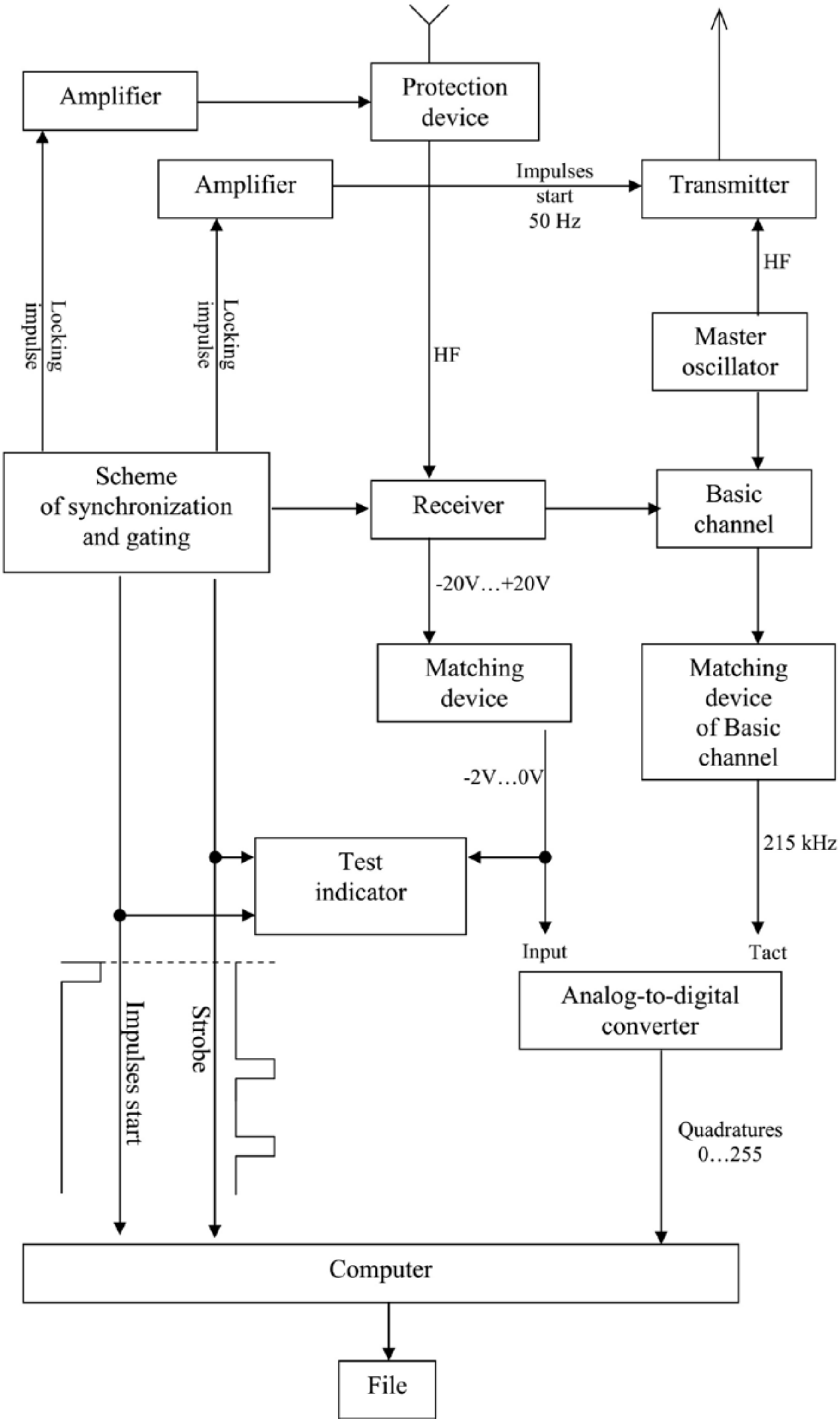

Figure 2. Functional diagram of the experimental installation.

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