UDC 621.396; 550.388 **DOI:10.30837/rt.2025.1.220.12**

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IMPROVEMENT SOUNDING MODES IN THE INCOHERENT SCATTER TECHNIQUE

Introduction

The study of the state of the Earth's ionosphere occurs in the process of conducting geophysical experiments, when information is obtained about the structure and dynamics of the ionospheric plasma simultaneously in a wide range of altitudes. Currently, this opportunity is provided by the most informative and accurate method, namely the incoherent scatter (IS) technique that includes radio pulse sounding of the ionosphere (in particular, vertically), reception of a signal incoherently scattered by the ionosphere, and its processing [1]. This method makes it possible to obtain the characteristics of the signal: its spectral and autocorrelation functions (ACF) with the subsequent calculation of parameters characterizing the altitude-time behavior of the ionospheric plasma [2]. Using this method, the IS radar, created by Kharkiv Polytechnics [3, 4], simultaneously determines several ionospheric parameters for a number of altitudes (h) and discrete instants of time (t): electron density $N_e(h, t)$, electron $T_e(h, t)$ and ion $T_i(h, t)$ temperatures, plasma drift velocity $V_{dr}(h, t)$, components of the ion composition $\gamma(h, t)$ in the form of the relative content of oxygen $O^+(h, t)$, hydrogen $H^+(h, t)$ and helium $He^+(h, t)$.

The scientific and practical value of these results is very high. They are necessary for solving a significant number of applied problems, including for the purpose of ensuring reliable operation of ground and space radio communication systems, navigation and radar systems. After all, the functioning of many systems depends on the conditions of propagation of an electromagnetic wave in geospace along the route “space object – consumer” [5, 6]. A number of studies examine the operational and technical requirements for such a radar signal, which has increased noise immunity against the background of emerging electromagnetic interference, including in the ionosphere [7, 8].

In general, subsequent geophysical analysis of the obtained parameters of the ionized environment makes it possible to observe variations in the ionosphere caused by both natural and anthropogenic influences, including the appearance of anomalies in the near-Earth environment. All this has a direct impact on critical infrastructure, which determines the relevance of these studies.

Since the main carrier of data containing the necessary information about the state of the ionospheric plasma is ACF (or spectrum) of the scattered signal obtained during experiments, it is necessary to implement further efforts to improve radiation, reception, and signal processing methods aimed at increasing the accuracy and reliability of measuring ionospheric parameters.

This paper considers the case when the carrier of information about the state of the ionosphere is the correlation function $r(\tau)$ of the IS signal. *The purpose* of the work is to improve the process of its determination and analysis. To do this, the article discusses different options for determining the ACF of the IS signal. In particular, various options for coded pulses have been proposed, each of which depends on the goals of the geophysical experiment.

Analysis of Sounding Modes

Ionospheric plasma has a complex structure. This situation indicates the need to use sounding pulses of different durations in order to be able to obtain the ACF shape over a significant range of correlation delays (τ) (preferably up to the appearance of the second zero of the function). On the other hand, proper resolution in height and time must be ensured.

Let us analyze the sounding modes that currently exist while carrying out experimental studies of the ionosphere and that enable to determine these statistical characteristics of the IS signal.

Long Pulse Sounding Mode

The study of the lower ionosphere began and continues today with the use of vertical sounding stations [9–11]. IS radars make it possible to study the ionosphere both below and above its peak.

The sounding mode with a pulse of long duration (T_p, Fig. 1a) is intended for estimating ionospheric parameters along a relatively extended altitude range, over which these parameters change monotonically and insignificantly [12]. In the case of correlation analysis, the procedure for obtaining ACF ordinates involves recording samples of the received IS signal at times t_0, t_1, t_2, ., t_n in the process of propagating the sounding pulse along the height (Fig. 1c). The computer multiplies the corresponding quantized samples, as a result of which, for a selected altitude section of length Δh with a center at height $h_0 = ct_0/2$, an algorithm is implemented to obtain the power $R(0)=u_0^2$ of the IS signal (at time t_0 according to the voltage reading u_0), and also, during the same radar scan (pulse repetition period), n ordinates of normalized ACF are calculated with a correlation lag step $\Delta\tau$: $r(i\Delta\tau)=u_0u_i/R(0)$, where i = 1, 2, …, n are indices of u_i samples during the scan, c is the speed of light, t_0 is the time delay between transmission and reception of the signal from height h_0. After statistical accumulation of the results of calculating the ACF for this and other heights (usually during a session lasting 1 minute) and subsequent taking into account a number of instrumental factors, these ordinates take the form shown in Fig. 1b (dots). Their discrete nature quite accurately reflects the behavior of a real correlation function, suitable for use in an algorithm for identifying ionospheric parameters using it.

The duration of the sounding signal in this case provides a correlation interval from 0 to τ_2 ($\tau_2 \geq 600$ μs), sufficient for further analysis, where τ_2 is the correlation lag when the correlation function crosses the abscissa for the second time. Therefore, when the radar operating wavelength λ_0 = 2 m, we actually have $T_p \geq \tau_2 \geq 600$ μs (Fig. 1a) for the case shown in Fig. 1b.

This radio pulse duration corresponds to the height resolution $\Delta h = c\tau_2/2 \approx 100$ km, promotes sufficient statistical accumulation of the results of processing a random IS signal, determines the high energy of the sounding signal and thereby contributes to a sufficient signal-to-noise ratio for studying the ionosphere at altitudes above the ionization maximum. However, such height resolution does not allow us to distinguish in detail the layer structure of the lower ionosphere to study its characteristic features. Such a signal is especially unsuccessful for IS radars with a significant operating wavelength, such as, for example, for the IS radar in Jicamarca (Peru) with λ_0 = 6 m, T_p = 3 ms and Δh = 450 km. The situation is somewhat more favorable in installations with operating frequencies 400 and 1300 MHz (Hystack, USA and EISCAT, Northern Scandinavia) [2, 13].

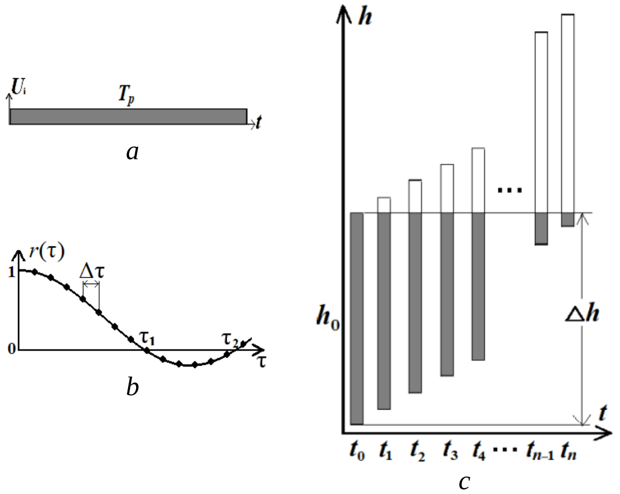

Fig. 1. Envelope of the sounding pulse (*a*), normalized ACF of the scattered signal for the altitude section $\Delta h = cT_p/2$ centered at height h_0 (*b*), and the process of propagation of a long sounding pulse in space (*c*)

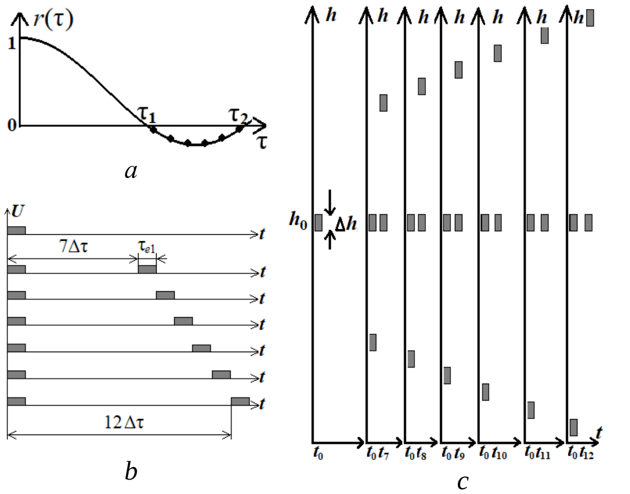

Fig. 2. Normalized ACF of the scattered signal for the section $\Delta h = c\tau_{el}/2$ centered at height h_0 (*a*), envelopes of the elements of the sounding signal (*b*), and the process of alternate propagation of pairs of short pulses in space (*c*)

Mode of Sounding using a Two-Element Signal with Varying Distance between its Elements

To provide better height resolution when studying the lower ionosphere (h < 400 km), the duration of the sounding pulse is reduced [12].

At the same time, they take into account the fact that due to the predominant presence of oxygen ions at these altitudes, the spectrum of the IS signal is narrower than at high altitudes, where light ions are present, the correlation interval increases, and the interval of correlation lags from τ_1 to τ_2 becomes the most informative, that is, from the first to the second zero of the ACF (Fig. 2a). Therefore, the interval of correlation delays from 0 to τ_1 is ignored, which allows the use of sounding signals with a more complex structure.

In this case, short double pulse elements of the sounding signal are emitted (Fig. 2b) with a corresponding interval between them, which varies from scan to scan. At least 7 sounding periods are required [12]. Six periods of double-pulse sounding are intended to determine the ACF ordinates, and one period of sounding with the single pulse of the same duration (for example, 30 μs) is to obtain the power of the IS signal.

The determination of the ACF ordinates consists of the registration of quantized samples u_i of the scattered signal at time instants t_0 (u_{01} when the single pulse propagates along the height), as well as at time instants t_0 i t_7, t_0 i t_8, …, t_0 i t_{12} in the process of alternate propagation of double pulses (Fig. 2c). The computer multiplies the corresponding samples, as a result of which, for the altitude section centered at the altitude h_0, an algorithm for determining the power of the IS signal $\left(R(0) = u_0^2\right)$ is implemented; the ordinates of the normalized ACF calculate for different corresponding sounding periods: $r(i\Delta\tau) = u_0 u_i / R(0)$, where i = 7, 8, …, 12 (indices of the instants t_i of voltage readings u_i relative to the corresponding instants t_0 in alternating periods of double-pulse sounding).

The result is a significantly better altitude resolution, which corresponds to $\Delta h = c\tau_{el}/2 \approx 4.5$ km for the pulse element duration presented above. However, such a sounding signal has a significant drawback: the time of statistical accumulation of data for each ordinate of the ACF has decreased by (n+1) times, due to which the calculation error significantly increases for the same duration of the measurement session. To ensure acceptable measurement accuracy, the duration of measurement sessions is increased; and this is associated with a deterioration in temporal resolution, which is not acceptable in the case of studies of fast processes in the ionosphere.

Improving the Structure of Sounding Signals Due to Coding their Elements

As the practice of ionospheric research shows, it is possible to use more complex combinations of elements in the sounding signal to improve resolution. The efficiency of measurements increases significantly if you transmit not an ordinary pair, but several (five or more) elements with certain correctly selected intervals between them. Such composite signals should contribute as much as possible to the effective study of variations in ionospheric parameters, both in height and in time. At the same time, the level of methodological and statistical errors must satisfy the requirements so that the local characteristics of the ionospheric plasma obtained as a result of correlation processing form the basis for further reliable analysis of processes in near-Earth space.

According to this requirement, a computer program was developed to search for such combinations of coded elements in the signal structure that make it possible to calculate the ACF ordinates for a larger number of correlation lags. Fig. 3 shows the results found by the program for options for using codes from 4 to 8 elements. In particular, two combinations are demonstrated (highlighted in dark), providing a uniform correlation lag step, on the basis of which the modernization of the sensing modes discussed above is proposed.

It should be noted that these encoded structures do not make it possible to obtain the power $R(0)$ of the IS signal for the purpose of normalizing the ACF ordinates (a single pulse is needed). This problem was solved in such a way that in each radar sending, when the proposed combinations of elements are emitted, we add another element at the beginning of the radar scan.

To ensure that the signal scattered from it does not interfere with the reception of scattered signals from other coded elements, its radiation is assumed to be in the opposite circular polarization [14]. This will make it possible to select the echo signal received from it in the antenna-feeder device of the IS radar, and transmit it through a separate receiving channel to a separate processing device (see below).

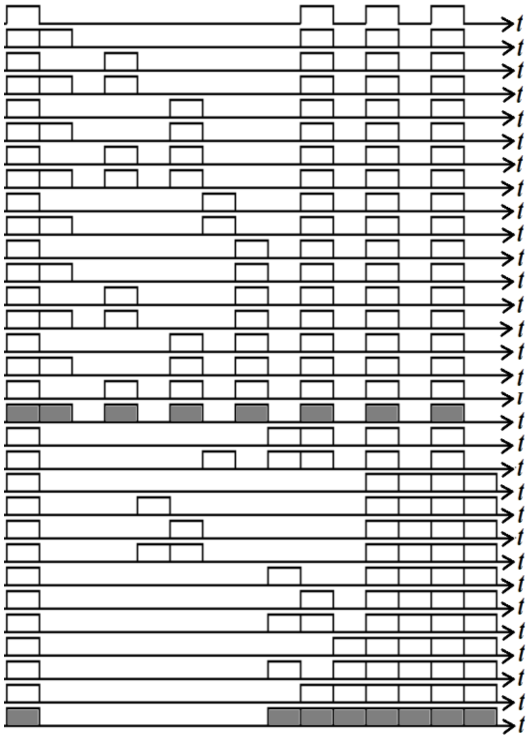

Fig. 3. Results of the search for multi-element coded signals
that provide simultaneous determination of 3 to 7 ordinates of the scattered signal ACF

Multi-Element Pulse Sounding Mode for Lower Ionospheric Altitudes

Based on the above, in order to study the ionosphere at altitudes near the ionization maximum and below, it is proposed to use a sounding signal, the code combination of which is shown in Fig. 4a. Its first element is emitted with the right-hand circular polarization of the radio wave, and the received echo signal is used to determine the power and normalize the ordinates of the IS signal ACF. The remaining elements, intended to determine the correlation coefficients, are emitted with the left-hand circular polarization. In this case, we choose the same duration (τ_{el} = 30 μs) of each code element that ensures good height resolution (Δh). The seven resulting ordinates of the ACF (Fig. 4b) quite informatively reflect the nature of it right-hand side. The procedure for obtaining them is demonstrated in Fig. 4c, which depicts the process of propagating this type of coded sounding signal in space and receiving echo signal at appropriate times by two independent receivers.

In this mode, the computer still multiplies the corresponding quantized samples u_i obtained at times t_i. As a result, for a selected altitude section centered at height h_0, in one radiation cycle, both the powers $\left(R(0)=u_0^2\right)$ of the IS signal (instant t_0) and n = 7 normalized ACF ordinates are calculated: $r[(i-1)\Delta\tau] = u_1 u_i / R(0)$, where i = 9, 10,…, 15 (indices of voltage samples u_i at times t_i).

Multi-Element Pulse Sounding Mode for Upper Ionospheric Altitudes

In a similar way, coded sequences can be used to study the upper altitude range of the ionosphere. To do this, it is proposed to use a sounding signal, the code combination of which is shown in Fig. 4d. The first element still involves the use of right-handed circular polarization of the radio wave, which makes it possible to separately determine the power of the IS signal and, using it, to normalize the ordinates of the ACF, and the remaining elements are intended to determine the correlation coefficients.

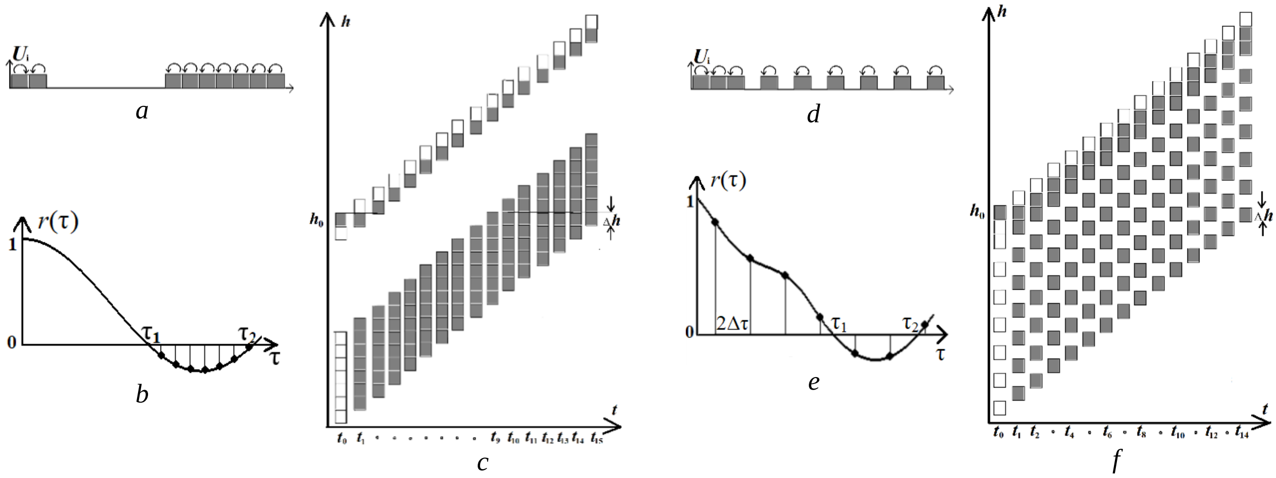

Fig. 4. Envelope of the sounding signal elements (*a*, *d*), normalized ACF of the scattered signal for a narrow altitude section Δh centered at height h_0 (*b*, *e*), and the process of propagation of the coded sounding signal in space (*c*, *f*). The arrows indicate the direction of circular polarization for each element of the sounding signal

The appearance of hydrogen ions, characteristic of high ionospheric altitudes, is additionally reflected in a change in the ACF shape in the range of correlation lags from 0 to τ_1 (Fig. 4e). The ACF becomes informative throughout the entire correlation interval, i.e. from 0 to τ_2. Therefore, in the new mode, the resulting ordinates should reflect the nature of the ACF in a uniform step throughout this interval. This option for determining the ACF ordinates is demonstrated in Fig. 4f, which depicts the case of propagating this type of coded sounding signal in space and subsequent reception of the scattered signal by two independent receivers.

In this mode, the computer, multiplying the corresponding quantized samples u_i, implements an algorithm for calculating the power $\left(R(0)=u_0^2\right)$ of the IS signal (instant t_0) for a selected narrow altitude section with center h_0. In the same radiation cycle, all n = 7 normalized ACF ordinates are calculated: $r[(i-1)\Delta\tau] = u_1 u_i / R(0)$, where $i = 2, 4, 6, \ldots, 14$.

It is important to note that this sounding mode makes it possible to average the results obtained over several adjacent altitude sections. Naturally, in order to achieve satisfactory statistical accuracy in determining the IS signal ACF (and, as a consequence, ionospheric parameters), the number of sections for averaging is different for different height ranges. It can also vary depending on the space weather state that affects the shape of the ACF.

Hardware Implementation

The final requirements for the structure of the sounding signal additionally set the features and real capabilities of the radio equipment of the IS radar. Naturally, the computing processor and control system must correspond to the selected structure of the encoded signal.

The proposed manipulation of the direction of radio wave circular polarization involves the use of two transmitter channels and two receiving channels. Their structure may be as follows (Fig. 5).

A circularly polarized sounding signal is generated by a transmit-receive antenna with two orthogonally located vibrators, to which signals from transmitters with a phase difference of 90º are supplied (through the transmit/receive antenna switches AS1 and AS2). Manipulation of the direction of circular polarization is ensured by a corresponding change in the phase of the transmitter excitation signal. When the phase of the excitation signal of the first or second transmitter changes by 90º, a corresponding change occurs in the direction of rotation of the electric field vector of the emitted wave.

Reception of IS signals with circular polarization is carried out by the same vibrators in the pause between radiations of the sounding signal. The signals from vibrators are supplied through antenna switches AS1 and AS2 to the inputs of a ring bridge configured to receive a signal with an operating wavelength λ_0.

The operating principle is based on the fact that a circularly polarized signal can be decomposed into two linearly polarized orthogonal signals, which are received by orthogonal antenna vibrators. When receiving the signal with right-hand circular polarization, signals from vibrators with equal amplitudes and a phase difference of 180° are present at inputs 1 and 2 of the bridge, and the resulting signal is transmitted to output 1 of the ring bridge, while there is no signal at output 2. With opposite (left-hand) circular polarization, the signal is transmitted only to output 2, and there is no signal at output 1. To implement this mode, two controlled phase shifters are designed, through which excitation signals are supplied to the transmitters. Alternating phasing of the transmitter input signals (0°/90° and 90°/0°) is carried out under the control of control system signals. The necessary phasing of received signals with circular polarization is carried out by a phase shifter at input 1 of the ring bridge.

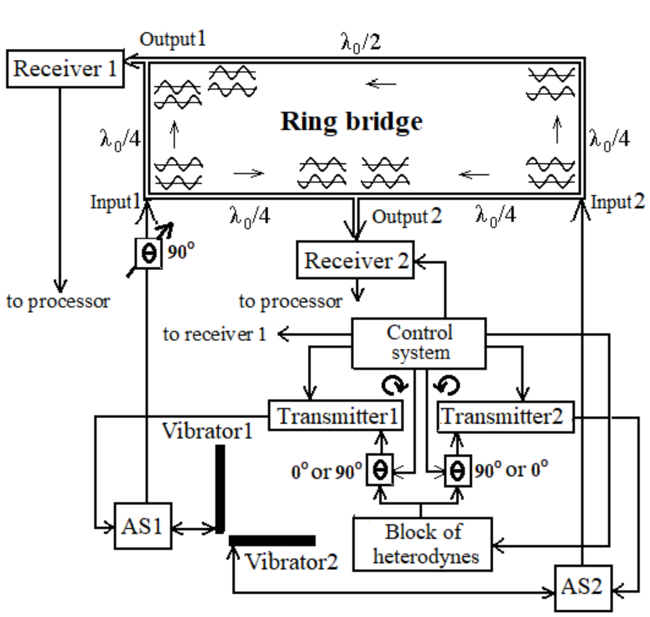

Fig. 5. System for transmitting and receiving signals

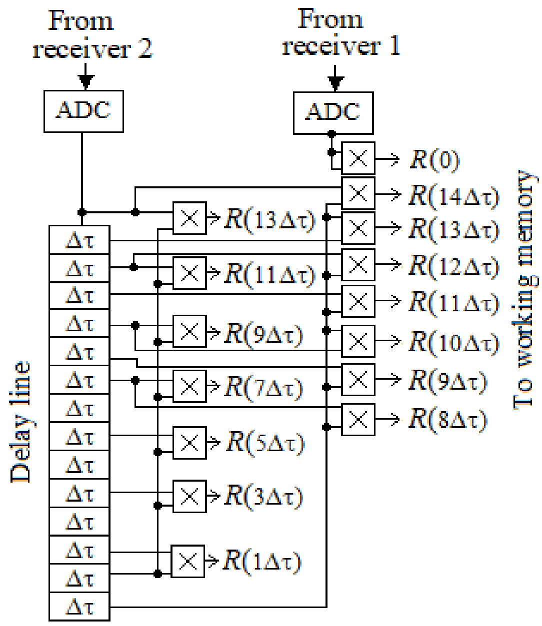

Fig. 6. Multichannel computing processor for calculating the ordinates of the scattered signal ACF

The phase switching signals from the control system are supplied alternately to the phase shifters, as a result of which, during the radiation of the first element (right-hand circular polarization), the phase of the high-frequency oscillation in the path of the first transmitter is shifted by 90° relative to the signal in the path of the second transmitter. In this case, at the inputs of the ring bridge, the signals are received in antiphase, that is, they are compensated at output 2, and their total signal is present at output 1 (see the upper diagrams along the arms of the bridge). And vice versa, when emitting the following pulse elements (left-hand circular polarization), the phase of the high-frequency oscillation in the path of the second transmitter shifts by 90° relative to the signal in the path of the first transmitter. In this case, the signals are received in phase at the inputs of the ring bridge, they are compensated at output 1, and their total signal is present at output 2 (see the lower diagrams). Signals from the outputs of the receivers, in which they were converted, amplified, synchronously detected and filtered, are fed to a multi-channel computing processor, at the inputs of which ADC blocks are installed (Fig. 6).

This processor calculates the powers and autocorrelation functions of the received signal as for the case of the sounding mode shown in Fig. 4 (a, b, c), and for the mode presented in Fig. 4 (d, e, f), depending on the situation. The lag (τ) in the correlation channel is a multiple of the sampling step Δτ [15]. This processor structure makes it possible to obtain results at the outputs of channel multipliers, which vary with altitude. At each instant of time t_j, all ACF ordinates refer to a common height section at altitude h_j. These results fill the corresponding column in working memory, where they are statistically accumulated from scan to scan during the measurement session.

Conclusions

As a result of the analysis, examples of the use of certain modes of pulsed radiation of radio waves with subsequent processing of received signals incoherently scattered by ionospheric plasma are considered. The equipment used is the IS radar designed for remote sensing of near-Earth space. The advantages and disadvantages of the sounding mode with single long radio pulses (intended for studying the upper ionosphere) and the sounding mode with a cyclic sequence of double short pulses with a varying distance between them depending on the radar scan number (intended for studying the ionosphere at altitudes near the ionization maximum and below) are shown.

Options have been proposed for improving the structure of the radio sounding signal by coding its elements, taking into account the nature of scattering in the ionospheric plasma. The results of the search for multi-element coded signals are presented, intended for studies of the lower and upper altitude ranges, providing the calculation of the ordinates of the scattered signal ACF with high resolution in both space and time.

The hardware implementation of sounding modes using these multi-element signals is presented. In particular, a block diagram of the IS radar is presented for working with signals with opposite circular polarizations, which uses for this purpose-controlled phase shifters of the transmitter excitation system, orthogonal antenna vibrators and ring bridge of the receiving feeder path. The structure of the specialized multi-channel correlator for calculating the ACF of a scattered signal using the proposed multi-element coded signals is presented. In general, this makes it possible to transmit and receive signals with various options for the arrangement of their elements, most suitable for specific conditions, as well as to use the manipulation of sounding signals with a change in the direction of the radio wave circular polarization and the separation of received scattered signals in the receiver path.

Thus, the goal of research into further development of the key hardware capabilities of the IS technique, the introduction of new algorithmic approaches aimed at improving the process of obtaining ionospheric information with improved altitude and time resolution of the scattered signal statistical characteristics has been achieved. Using the above approach to the process of searching for coded sequences, in a similar way it is possible to offer many options for the arrangement of elements in the structure of sounding signal, depending on the requirements for the conditions for carrying out radar measurements.

It can be noted that the importance of the conducted research is to obtain better ionospheric information by using the potentially high metrological characteristics of the IS radar. This information is intended for the optimal solution of practical problems in areas covering the activities of space weather systems, the safety of satellite communications and critical infrastructure, problems of positioning objects in space, warning systems for adverse biogeophysical conditions, man-made accidents and disasters.

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Received 06.01.2025

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