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ANALYSIS OF THE ARCHITECTURE OF THE HARDWARE AND SOFTWARE COMPLEX FOR GROUND-BASED IONOSPHERE RADIOSOUNDING

Nurzhan Zikiryaev✉
Department of Mechanics[1]
n.zikiryaev@tanu.pro

Valentina Grishchenko
SLLP «Institute of Ionosphere»
117 Sadovodcheskoe Tovarischestvo «Ionosfera», Almaty, Republic of Kazakhstan, 050020

Zaure Rakisheva
Department of Mechanics[1]

Alexander Kovtun
Department of Special Disciplines
Military Engineering Institute of Radio Electronics and Communications
Ministry of Defense of the Republic of Kazakhstan
53 Zhandosov str., Almaty, Republic of Kazakhstan, 050036

[1]*Al-Farabi Kazakh National University*
71 Al-Farabi ave., Almaty, Republic of Kazakhstan, 050040

✉**Corresponding author**

Abstract

The relevance of the study is conditioned by the need for qualitative consideration and analysis of the basic architectural principles taken as a basis for the development of a hardware and software complex designed to conduct work on remote radiosounding of the ionosphere. The purpose of this study is to analyse the basic principles of building the architecture of a hardware and software complex for ground-based ionosphere radiosounding, to create a high-quality scientific base for further research of various processes occurring in ionospheric plasma, changes in its structure and state. The basis of the methodological approach in this study is a combination of methods of system analysis of the basic principles of building the architecture of a hardware and software complex of ground-based ionosphere radiosounding with an analytical investigation of the features of the radiosounding procedure, to obtain the most objective and reliable information about the real state of this atmospheric layer of the Earth and the processes occurring in it. The results obtained emphasise the importance of practical issues of creating a high-quality architecture of a hardware and software complex for ground-based radiosounding of the atmosphere and indicate the presence of a systemic relationship between the quality of the hardware and software complex, the presence of disturbances in the ionosphere, and the nature of these disturbances. The results obtained have significant practical significance for developers of modern radiosounding systems of atmospheric layers, and for operators of systems of this kind, whose direct duties include monitoring the state of these systems and maintaining an adequate level of their operability to conduct scientific experiments.

Keywords: digital signal processing, hardware and software architecture, measurement automation, short-wave signals.

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1. Introduction

In the last few decades, there has been a significant increase in interest in the creation of equipment capable of providing high-quality monitoring of the state of the layers of the atmosphere and the possibility of obtaining accurate data on the nature of processes occurring in its various layers. Particular attention in this context is paid to the problems of the architecture of a hardware and software complex, whose immediate tasks include conducting work on remote ground-based ionosphere radiosounding [1]. The principles of building the architecture of this complex require detailed study to create the conditions necessary for the development of methods of ground-based remote sensing of the ionosphere in the long term [2].

Efforts on the design and creation of ionospheric remote sensing systems using short wave signals can go in several ways, in particular, along the way of creating tools for detailed analysis, study with the identification of the main defects that occur when weak signals are isolated, all kinds of interference, etc. In addition, such scientific developments may follow the path of creating means of conducting operations with large amounts of information, which implies the search for hidden opportunities to improve the applied analysis techniques [3]. The statistical data arrays collected as a result are of significant value from the standpoint of the prospects for their subsequent use to create a high-quality architecture of a hardware and software complex for ground-based ionosphere radiosounding, which would allow forecasting the corresponding parameters of the ionosphere and ionospheric radio lines in the future [4].

Communication systems, the principle of operation of which is based on the practical application of data obtained during ionospheric radiosounding, play an important role in the military industry, in solving a whole range of issues of ensuring high-quality communication between troops and managing them in combat conditions [5]. To date, it is not necessary to talk about the homogeneity of the ionosphere as a static medium, moreover, the wide variability of its parameters are necessary to consider when planning radio communications and determining frequencies [6]. In this context, in the conditions of a large length of radio lines and the need to ensure high-quality radio communication for accurate coordination of all aspects of the manoeuvres performed, the issues of practical implementation of satellite radio communication systems and radio lines of a wider range than those already in use are of particular relevance [7]. Accordingly, problematic issues related to the need to ensure the stability, continuity of the functioning of this communication channel, and the efficiency of delivering information to the final recipient come to the fore [8].

The aim of this study is to analyse the basic principles of building the architecture of a hardware and software complex for ground-based ionosphere radiosounding, to determine the conditions necessary for effective monitoring of any external interference and disturbances in the ionosphere.

2. Materials and methods

The basis of the methodological approach in this study is a combination of methods of system analysis of the basic principles of building the architecture of a hardware and software complex of ground-based ionosphere radiosounding with an analytical investigation of the features of the radiosounding procedure, to obtain the most objective and reliable information about the real state of this atmospheric layer of the Earth and the processes occurring in it. At the same time, in the future, it is planned to use a hardware and software complex based on the Linux-Ubuntu operating system, and the GNU Radio software suite to compile a graph for the operation of HacRF One SDR, to carry out a complex of works on ground-based ionosphere radiosounding in the Kazakhstan region [9].

The theoretical basis of this study is made up of available papers of Kazakh and a number of foreign researchers on problematic issues of constructing the architecture of a hardware and software complex for ground-based ionosphere radiosounding, to determine the optimal conditions of this complex when obtaining information about the processes occurring in the ionosphere, their influence on the nearby layers of the atmosphere, and the sequence of propagation of radio signals in the ionosphere [10–12]. To ensure the fullest possible perception of the information provided and to create an objective picture of research, all the developments of researchers taken in the order of citation and presented in this paper have been translated into English.

This study follows a clear sequence of work, implying the presence of three main stages. At the first stage, a theoretical analysis of the papers of Kazakh and a number of foreign authors available within the framework of the stated topic was carried out to form the theoretical basis necessary for further research. At the second stage, an analytical investigation of the main features of the radiosounding procedure was carried out to obtain the most objective and reliable information about the real state of this atmospheric layer of the Earth and the processes occurring in it. At the final stage, based on the results obtained, conclusions were formulated, acting as their full-fledged reflection and summing up the entire complex of research efforts within the framework of the stated topic.

3. Results

The study of the features of creating the architecture of a hardware and software complex for ground-based ionosphere radiosounding yielded the following results. The main idea of the practical application of the complex of remote ground sensing of the ionosphere is to emit a continuous signal in the short wave range (2–30 MHz). The signal propagation occurs in the zone of the ionospheric radio line, after which it enters the receiver input. The technology of oblique sensing assumes that there is a distance of several thousand kilometres between the transmitter and receiver, which corresponds to changes in the transmission rate of a radio wave in the range of tens of milliseconds [12]. The received signal is processed in the frequency plane by compression, while it is multiplied by the signal of the receiving device. The frequency dispersion of a radio wave having different frequency parameters causes differences in the values of reflection coefficients and the time of phase delay.

Fig. 1 shows the dependence of the frequency ranges of the signals of the ground-based ionosphere radiosounding complex on the parameters of world time when using this complex.

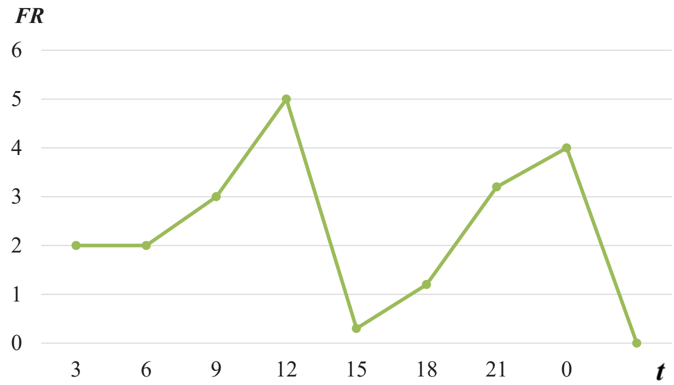

Fig. 1. Dependence of the frequency ranges of the signals of the ground-based ionosphere radiosounding complex on the time of its use: *FR* – frequency ranges; *t* – time

As follows from the data presented in **Fig. 1**, the frequency range of signals of the ground-based ionosphere radiosounding complex during the day has two peaks and two declines, which fit into a 12-hour cycle. This is conditioned by changes in the frequency characteristics of the transmitter, and changes in the frequency characteristics of the ionosphere during the operation of the radio signal transmitter.

The calculation of the radio wave propagation model in the operation of hardware and software of ground-based ionosphere radiosounding complex requires the adoption of certain assumptions, in particular, the length of the radio emission path D and the frequency of radio wave propagation *F*. Such parameters are taken from the ionograms of inclined or vertical sensing. In addition, the kriging method is used to correct the calculation models, which is an interpolation in which the radio frequency parameter at the end point of the calculation is determined by averaging several frequency values at specified points of the radio emission path. To enhance the influence of these points on the quality of correction, an additional coefficient K is introduced, which is the ratio (1):

$$K = \exp\left(D_{Log}^2 / D_{Lin}^2\right) \times F, \tag{1}$$

where, D_{Log}^2 and D_{Lin}^2, respectively, are the frequency and longitude parameters of the correction point. Accordingly, these values are the determining distances within which the critical frequency changes.

Fig. 2 shows the dependence of the change in the frequency parameters of the ionosphere on the time of day, during the operation of the hardware and software of the ground-based ionosphere radiosounding complex.

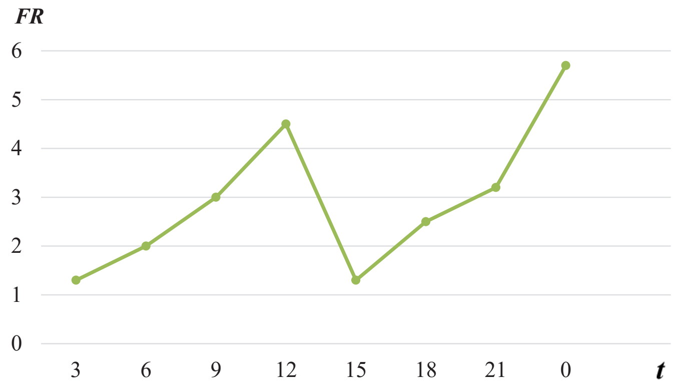

Fig. 2. The dependence of the change in the frequency parameters of the ionosphere on the time of day, during the operation of the hardware and software of the ground-based ionosphere radiosounding complex: *FP* – frequency parameters; *t* – time

Such software should consist of systems for controlling the functioning of the entire complex and registering databases obtained during remote ground-based ionosphere radiosounding. At the same time, the database registration system can be successfully implemented based on a standard card of a personal computer (PC), and based on various highly specialised analogue-to-digital converters (ADCs). Such a system is common, regardless of the digitisation systems used in practice.

Fig. 3 shows the scheme of dividing this system into different layers, which helps to ensure the proper characteristics of its flexibility, extensibility, and adaptation to real conditions of use.

The hardware and software complex of remote ground-based ionosphere radiosounding operates in full automation mode, which provides for automatic change of operating mode parameters and change of operating modes as such. All shifts take place according to the staffing standards previously included in the programme. In accordance with this schedule, the start of the complex takes place, after which the next radiosounding session is selected in accordance with the time of all sessions that are included in the schedule of the complex. Programming of the selection can be carried out using the Linux-Ubuntu operating system, and the GNU Radio software suite for compiling a graph for the operation of HacRF One SDR. Thus, the launch of the ionosphere remote ground sensing mode is carried out by specifying the name of the signal transmission point, and the launch time of the complex τ_{lau}, the estimated delay time of the start τ_{dl}. In addition, the time of preparation for the launch of the substation τ_{sub} and the time of stopping the operation of the entire complex τ_{stop} are set.

In the graphical representation, the cycle of preparation for the launch – launch – operation and shutdown of the hardware and software of the ground-based ionosphere radiosounding complex will have the following form (**Fig. 4**).

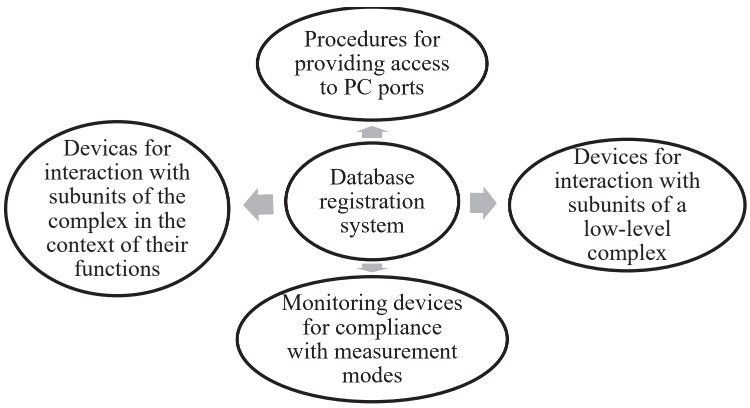

Fig. 3. Scheme of division of the database registration system of the ground-based ionosphere radiosounding complex into layers

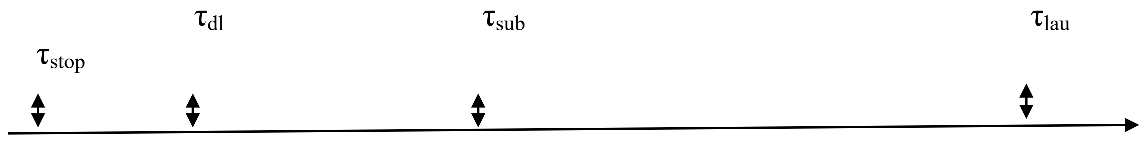

Fig. 4. Diagram of the preparation cycle for starting and stopping a measurement session in time: τ_{lau} – the launch time of the complex; τ_{dl} – the delay time of the start; τ_{sub} – the launch of the substation; τ_{stop} – stopping the operation of the entire complex

Managing the parameters of the start and stop time of the complex requires the development and practical implementation of a separate software suite that accurately calculates all the above time parameters. The software displays all the current received data in the process of operation, and also enters them into a special database registry. Since in the mode of remote ground-based radiosounding of the ionosphere there is a gradual accumulation of the received information about the current course of research and the results obtained, there is an output of an ionogram over the entire band of the propagated radio signal reflecting the entire spectrum of measurements.

The ever-increasing volume of research information, including ionospheric radiosounding data, determines the relevance of the task of not only storing them, but also placing them in a given order, using certain principles of systematisation according to specified criteria [13]. This task involves obtaining certain macroscopic characteristics that allow significantly reducing the volume of homogeneous information about individual ionospheric radiosounding sessions, together with the results obtained during them.

4. Discussion

The practical use of a hardware and software complex for ground-based ionosphere radiosounding allows combining various modes of sounding ionospheric layers and obtaining high-accuracy results [14]. In recent years, there has been a rapid development of decametre radio communication facilities, and this trend is taking place in almost all areas of science and technology, including the military. The reasons for this should be sought in the active development of the Arctic zone, the Far Eastern region, and Siberia, and in the launch of the processes of forming the infrastructure of information communications, which have been developed in conditions of increasing the speed of information transmission while covering the entire country. In the current situation, there is a pronounced economic feasibility of using decametre communication [15]. The accumulated practical experience suggests that the establishment of stable and reliable radio communication using short waves in hard-to-reach areas is often a very problematic issue. This leads to the urgent need to predict the passage of short and ultrashort radio waves using experimental data on the passage of radio waves, and ionospheric models in specific geographical regions, which are subject to correction in accordance with the receipt of new parameters [16, 17].

Oblique ionograms provide abundant information for constructing various extrapolation methods for the maximum allowable parameters of signal frequencies, which generally creates the necessary conditions for creating prompt and accurate forecasts of signal frequency changes. Among the wide variety of methods used for constructing short-term forecasts, the option of partial extrapolation with the use of side model calculations is optimal. In this context, it seems unnecessary to use interpolation polynomials of higher degrees.

Currently, the international ionosphere model is the most widely used model of the structure of the ionosphere on the largest possible scale. The irregularity of the deviations of the distribution in the space of the electron concentration within this particular model is determined not only and not so much by the activity of the Sun, but also by the processes occurring in the earth's interior, together with the consistent intervention of natural atmospheric processes of high energy capacity, such as manifestations of volcanic activity [18]. In addition, the anthropogenic factor has a significant impact, which is human activity for launching rockets, conducting large-scale industrial explosions and testing high-power nuclear charges. All this does not reflect in the best way on the general state of the ionosphere and leads to serious structural changes in its composition and most important characteristics.

As follows from the data presented in **Fig. 2,** there is pronounced dynamics of changes in the frequency characteristics of the ionosphere during the day, with the presence of pronounced ups and downs. In addition, attention is drawn to the fact that the peaks of the frequency characteristics of the ionosphere by time of day almost completely coincide with the peaks of the frequencies of the signals of the ground-based ionosphere radiosounding complex, which indicates the presence of a pronounced relationship between the processes occurring in the ionosphere and the operation of the hardware and software complex of its remote ground radiosounding. In this context, special attention should be paid to the development and practical creation of software for this complex, capable of ensuring the smooth operation of its equipment in the conditions of any disturbances in the ionosphere [19].

The existing ionospheric communications are an integral component of radio-electronic information transmission systems, which are actively used in the propagation of radio waves of various ranges. Among the most effective means of studying the possibilities of short-wave radio means, and the influence exerted by space weather on the nature of the propagation of radio waves, is a radiation probe operating in the modes of inclined and vertical sounding of the ionosphere [20]. At the same time, secondary processing of experimental ionograms is performed based on the results of filtering the initial parameters that have passed the compression stage using the capabilities of cellular automation. The main interpretative methods for interpreting the parameters of ionograms are based on the practical application of the results of frequency modelling of the dependencies of propagation parameters in long-term forecasting modes, and data obtained directly during the processing of the results of the experiment [21].

To identify points with significant amplitude, a data compression technique is used, and these data almost completely correspond to the parameters of the signal input to the leading edge, and to the maximum relief of the amplitude. For qualitative elimination of secondary artefacts and partial recovery of the necessary information and identification of the initial track on the ionogram, the use of cellular automation mechanism is effective. The term «cellular automata» refers to discrete systems of a dynamic nature that are functionally in direct relationship with the local mutual connections of all the constituent elements [22]. Elementary cells occupy almost the entire space of these systems, and subsequently they undergo a stage of sequential evolution in accordance with the parameters of discrete time. Dynamic parameters of these systems are displayed in a certain combination of rules, while the states of all cells are interconnected and reflect the general state of the entire system. The implementation of a given algorithm within a specific programme assumes the possibility of achieving compression of the parameters of the source information several times, in accordance with the specified noise parameters.

Identification of the reference trace of the ionogram consists in the sequential calculation of the number of points of the moments of the signals when moving the model masks in the specified frequency ranges. At the same time, all the algorithms and methods used for processing the parameters of ionograms and interpreting the received signals can be consistently implemented as a single software package, which determines the necessary tracks on ionograms in the automatic sensing mode and identify them [23]. Vertical sounding on specific tracks requires recalculation of ionogram parameters with the calculation of sequential concentration profiles. Conducting high-quality inclined sounding requires recalculation of the ionosphere parameters according to the characteristics of ultrahigh frequency, and calculation of the electron concentration profile. As part of the oblique sensing procedure, the adopted methods for analysing the characteristics of ionograms quickly determine the mode composition, and identify each propagation mode [24].

The peculiarities of the influence of the ionosphere on the nature of the propagation of radio waves in this medium are of significant interest from a practical and theoretical standpoint and can be effectively applied in practice to conduct a qualitative scientific study of the dynamics of the ionosphere and changes in its structure. The practical application of methods of inclined and vertical sounding will significantly expand the possibilities of studying the ionosphere, especially when combining these methods within a single radio engineering device. At the same time, significant disturbances on various radio transmission routes often cause full or partial absorption of short-wave radio waves [25, 26]. This fact should be considered when conducting ground-based, remote radiosounding of the ionosphere, to obtain an objective picture of the scientific research carried out.

The limitations and disadvantages of this study are that it did not answer the questions that arise regarding the nature of the propagation of radio waves in the ionosphere and the nature of the numerous processes occurring in this atmospheric layer. Further research in the field of various aspects of building the architecture of a hardware and software complex for ground-based ionospheric radiosounding is designed to bring additional clarity to numerous issues concerning the nature of radio wave propagation and their influence on the processes occurring in the ionosphere. In the future, it is necessary to develop and implement modern software systems for the remote ground-based ionosphere radiosounding complex, capable of processing large amounts of information for a relatively short period of time and storing data obtained during the radiosounding procedure in strict accordance with the established processing and storage structure. Clear structuring and preservation of radiosounding data contributes to the qualitative preservation of all research information and has a positive impact on the prospects for the development of the entire industry of ground-based ionosphere radiosounding as a whole.

5. Conclusions

The authors of this scientific study found that the use of methods of inclined and vertical radiosounding of the ionosphere, provided that the architecture of hardware and software complexes performing such operations is qualitatively improved, allows obtaining accurate information about the state of this layer of the earth's atmosphere and the processes occurring in it. It was indicated that the introduction of software and technological improvements can qualitatively improve this process, which in general would contribute to the effective development of the entire range of technologies for ground-based ionospheric radiosounding. As a result of the application of the technique of oblique sounding of the ionosphere, the dependence of the total delay time and amplitude parameters on the frequency of radio emission is formed. In addition, it is also important to change the nature of the disturbance of the ionosphere during the day, which leaves its mark on the quality of functioning of the hardware and software complex of ground-based radiosounding of the atmosphere.

In general, the results of this study and the conclusions formulated on their basis can later serve as a qualitative theoretical basis for further scientific research in the direction of researching the architecture of the hardware-programmable complex for ground-based radio sounding of the ionosphere, in accordance with the requirements and realities of the time.

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