RADIO ELECTRONIC SYSTEMS
РАДІОЕЛЕКТРОННІ СИСТЕМИ

УДК 621.396.96 **DOI:10.30837/rt.2026.1.224.11**

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ANALYSIS OF THE STATE OF THEORY AND TECHNOLOGY OF RADIO-ACOUSTIC ATMOSPHERIC SOUNDING SYSTEMS

Introduction

The Radio-Acoustic Sounding Systems (RASS) are an effective remote sensing tool for obtaining information on vertical profiles of atmospheric temperature, wind speed, and turbulence [1, 2]. They are used in atmospheric research, to support aircraft takeoff and landing operations, and in weather forecasting.

As a result of an extensive period of research on the RASS method, conducted over several decades (from the early 1960s to the late 1990s), the capabilities of RASS for measuring atmospheric temperature were studied, various types of sounding signals were investigated, and multiple specific error types unique to these systems were identified and analyzed [3–8]. Over this time, a significant body of scientific knowledge accumulated regarding the physical processes involved in sounding and the operational features of RASS.

However, several unresolved issues remained – for example, the development of advanced methods for processing radio signals scattered by the acoustic pulse that would enable unbiased estimation of informative signal parameters, and the creation of efficient methods for adapting the system to changing atmospheric conditions to maintain the Bragg matching between the wavelengths of the acoustic and electromagnetic probing waves [2, 4]. Existing algorithms for adapting RASS to variable wind conditions, which have a substantial impact on system performance, also fail to meet practical requirements. Additionally, measurement methodologies for atmospheric parameter profiles, based on such signal processing and adaptation algorithms, remain insufficiently developed.

The primary reason for the lack of solutions –or their insufficient effectiveness – lies in the following: the dominant direction in the technical development of RASS has been the transfer of well-known solutions from radar engineering. However, because the acoustic pulse constitutes a highly specific radar target with unique properties, these transferred solutions do not always ensure adequate effectiveness. Furthermore, no dedicated scientific framework for resolving the associated challenges has been developed in this field [1–5].

In the early 2000s, commercial research and manufacturing companies specializing in this area emerged. Using available scientific knowledge and advances in technology – particularly in digital signal processing and computing – they developed RASS stations that were considered sufficiently advanced at the time [1, 2]. The unresolved scientific issues were effectively “bypassed” through engineering solutions derived heuristically. These solutions, in turn, deteriorated other system characteristics. The technical details are proprietary and not published in the literature. Nevertheless, the resulting systems provide acceptable measurement results, which are then presented to users through modern visualization tools and computational capabilities.

Thus, the sensing systems developed and produced by industry appear, on the one hand, sufficiently advanced, capable of providing acceptable sounding results and equipped with effective digital tools for data processing; on the other hand, they function as a “black box” for researchers using them for atmospheric studies. This situation has led to a near-complete halt in fundamental research in the field for an extended period. The publications that do appear primarily address atmospheric studies conducted using these instruments rather than the theory of RASS itself. As a result, progress in the theoretical foundations of RASS has been effectively frozen for more than two decades.

The aim of this paper is to analyze the current situation in the field, with particular attention to the evaluation of industrial RASS systems. It is also necessary to assess the state of the scientific and methodological framework that supports research in this domain, as well as the methodologies used in system design.

The main tasks include: a concise review of the existing scientific and methodological apparatus for studying and designing RASS; an analysis of industrial RASS systems and the effectiveness of their functional algorithms and measurement methodologies for deriving atmospheric parameter profiles; and the identification and formulation of the key contemporary challenges in this field.

Review and Analysis of the Theory of the Method and of RASS

The first publications devoted to radio-acoustic sounding (RASS) of the atmosphere date back to 1961. In the work of P. L. Smith [6], the fundamental concept of the method was formulated, the feasibility of its practical implementation was analyzed, and a measurement configuration enabling wind speed and direction determination using three spatially separated RASS channels was described. The paper provided quite optimistic projections of the method’s potential, especially regarding sounding range (tens of kilometers).

The report by R. W. Fetter [1] introduced the EMAC RASS system, presented its block diagram, and described experimental test results. However, the experimental data revealed very limited performance: the maximum sounding height did not exceed 30 m.

As a result, skepticism toward the method emerged, and RASS was regarded for many years as having low practical value. Its development in Western countries was subsequently suspended.

The period from the early 1960s to the early 1970s – when Western countries suspended RASS development – was actively used in Ukraine for research in this field. During this time, effective RASS stations were developed, and substantial practical experience was accumulated. This experience was subsequently used in developing methods for applying RASS to various scientific and applied problems, as well as in formulating the theoretical foundations of RASS systems. Research in Ukraine continued actively in the following years [9].

A renewed international interest in RASS emerged only a decade later – in 1972 – when Marshall [1,8] identified the causes of the failures of early studies and substantiated the potential for further improvement of the method. This marked the beginning of a new cycle of theoretical and experimental research that eventually led to the development of modern RASS systems.

During the 1970s–1990s, research in radio-acoustic sounding became highly intensive, covering theoretical studies, technological developments, and experimental testing [5,7,8]. At this stage, the fundamental principles of RASS system design were established, including configurations of transmitting and receiving antennas, forms of the emitted acoustic and radio signals, and methods for processing the scattered radiation [3]. In parallel, sounding methodologies were developed that enabled estimation not only of atmospheric temperature, but also of wind profiles, humidity, and turbulence characteristics [9].

A major research focus involved the study of measurement errors inherent to RASS, particularly temperature-measurement errors [7–9]. Significant attention was paid to the influence of atmospheric turbulence on both the propagation of the acoustic wave and on the characteristics of the radio signal scattered by acoustic inhomogeneities [4, 8]. During this period, extensive experimental data were accumulated from numerous measurements conducted in various climatic zones and under diverse weather conditions [10].

A distinctive feature of this stage was that most research was carried out using experimental equipment developed at university and academy laboratories [4, 5, 8, 9]. These experimental setups served as platforms for testing a wide range of engineering solutions, developing sounding methodologies, and validating data-processing algorithms.

An important milestone in the development of the method was the publication of the monograph by Lataitis R. J. [3], which systematized the theory of RASS and described options for the practical implementation of sounding systems. This work laid much of the foundation for the modern methodology of theoretical and applied research in radio-acoustic measurements.

From the earliest stages of development, a key trend emerged – one that remains relevant today: the technical evolution of RASS systems has largely relied on borrowing solutions from radar engineering [1, 3, 5, 7]. During the same period, several additional tendencies were observed: specialists in wave propagation refined the understanding of the mechanisms of radio-wave scattering by sound, while meteorologists – who served as the main end-users—focused on interpreting sounding results [8, 10] and promoted the integration of RASS systems into existing meteorological observation networks.

A fundamental peculiarity of the method lies in the nature of the acoustic wave packet, which serves as the radar scattering target and possesses unique characteristics not encountered in other areas of radar engineering [3–5, 8]. Consequently, many engineering solutions directly borrowed from radar prove insufficiently effective under RASS conditions, which affects the overall performance of existing stations [5, 7, 9].

In particular, the radio signal scattered by the acoustic pulse exhibits a number of significant structural features, and improper or inadequate processing and parameter estimation – especially when performed solely from the standpoint of Doppler-frequency measurement – can lead to adverse consequences [1, 3, 5, 11, 12].

In publications [3, 5, 8, 11, 13], it has been shown that the frequency shift of a radio signal scattered by an acoustic wave packet (AWP) is not purely Doppler in nature, but also contains an additional frequency component, Δf, whose value depends on the parameters of the probing signals of the RAS system.

The uninformative shift of the scattered signal spectrum in the spatial frequency domain is

$$\Delta k = -2L_e^2 q/(4L_e^2 + L_s^2), \tag{1}$$

where L_s, L_e – spatial extent of acoustic and electromagnetic sounding signals in the environment, respectively; $q = 2k_e - k_s$ – parameter of the Bragg condition detuning; k_e, k_s – wave numbers of electromagnetic and acoustic waves, respectively; c – the speed of propagation of radio waves, and the shift in the time-frequency domain, respectively

$$\Delta f = c\Delta k/(2\pi). \tag{2}$$

Arbitrarily small values of the non-informative shift Δk of the spatial frequency of a radio signal scattered by an acoustic pulse under conditions of Bragg detuning, when the parameter $q \neq 0$, during the transformation of the spatial signal into a temporal oscillation in the antenna system, are accompanied by the formation of an arbitrarily appreciable temporal frequency shift Δf due to the sufficiently high propagation velocity of electromagnetic waves c.

In practice, the additional non-informative value of the frequency of the signal, as follows from (1), and is confirmed by the results of sounding practice, can lead to significant changes in the results of temperature variations, up to $1 - 2^0$ C C and even more.

The physical reason for the Bragg condition mismatch (in which the parameter $q \neq 0$) is the change in the wavelength of the acoustic radiation resulting from variations in atmospheric characteristics – temperature, pressure, and humidity – with altitude [3, 7, 8, 11, 12]. To ensure zero error in Eq. (1), it is necessary to maintain the Bragg condition throughout the sounding process; that is, the parameter $q=0$ must be achieved at each altitude level during the measurements.

Algorithms for frequency adaptation of remote sensing systems to changing meteorological conditions have been described in the literature, in which the Bragg condition is satisfied by tuning the frequency of the probing acoustic or radio signal. However, the effectiveness of these algorithms is insufficient, and they have found only limited practical application.

In the late 1990s and early 2000s, the stage of industrial development and production of RASS systems began. Modern systems produced in series [14–19] are based on the previously accumulated knowledge and methodological framework, and are used primarily for applied atmospheric monitoring tasks.

This stage of development concludes with attempts to integrate radio-acoustic sounding systems into the structure of acoustic and wind radar profilers manufactured by industry, in particular into the structure of the Vaisala wind profiler (RWP) and into the structure of the METEK acoustic profiler.

Let us conclude that at the current stage of development of the RASS method, no effective technical solutions have been proposed for measuring the parameters of the scattered radio signal that would eliminate the systematic errors characteristic of RASS [1, 3, 8, 13]. The existing methods for adapting RASS systems to the meteorological conditions that vary along the sounding path in order to satisfy the Bragg condition do not meet practical requirements, nor do the methods for adapting to wind conditions intended to compensate for the drift of the acoustic wave packet.

It was precisely under these conditions, given the current state of science and technology, that industrial prototypes of equipment were created.

Let us now consider the existing industrial RASS systems and analyze how the sounding process is implemented in these systems to obtain atmospheric parameter profiles, how signal processing is carried out, and how adaptation to changing meteorological conditions is achieved.

It should be noted that after the early 2000s, the activity of fundamental and applied research in the theory and practice of RASS systems noticeably declined, and the number of relevant publications decreased significantly. In modern studies, the emphasis is placed primarily on the interpretation of remote atmospheric monitoring results from the standpoint of meteorology and on the investigation of rare and poorly studied atmospheric phenomena using existing systems [20, 21], whereas significantly less attention is devoted to further development of the theoretical foundations of the method.

Analysis of the State of Technical Means and Algorithmic Support of RASS

Review and Analysis of Existing RAS Systems. Let us examine in more detail a number of modern RASS stations that are currently produced by specialized companies, offered on the market, and actively used for solving applied tasks. One such development is the RAS system (METEK company [14]), which is based on the Doppler acoustic locator PCS.2000, supplemented with radar modules. Owing to this configuration, the system is capable of simultaneously obtaining vertical profiles of atmospheric temperature, temperature gradients, and inversion layers in parallel with acoustic sounding.

Functionally, RASS is integrated into the structure and algorithmic base of the sodar: it uses its probing acoustic signals, the software for processing the radio signals reflected from acoustic waves, and a personal computer running Windows, all of which are components of the PCS.2000 locator. The radar subsystem includes transmitters and receivers operating at frequencies of 915 and 1290 MHz; for extended measurement range, a modification at 482 MHz is provided. In all versions, continuous unmodulated radio emission is used with two antennas – one transmitting and one receiving.

Figure 1 shows the block diagram of the RAS system: the PCS.2000 acoustic antenna is located in the center, with the transmitting radio antenna on the left and the receiving radio antenna on the right. The PCS.2000-24 emitter operates in the 1500–2000 Hz range, generating acoustic pulses of variable duration and carrier frequency, which enables atmospheric sounding up to an altitude of approximately 1000 m.

Another example is the RAS system developed by Biral, which is also based on the PCS.2000 sodar (manufactured by METEK); however, it incorporates a different set of radio equipment [15]. Extending the functionality of the acoustic locator to the RASS level includes two parabolic antennas, a radio receiver, a radio transmitter, and electronic modules – a radio signal generator and a power amplifier. The radio channel operates at a frequency of 1290 MHz in continuous-wave (CW) mode without modulation.

Fig. 1. METEK RAS system based on the PCS.2000 sodar

The RAS system by Remtech [16, 17] is based on the company’s own PA-0 or PA-5 acoustic locators and includes a CW radar integrated with these sodar models. The acoustic signal is emitted by the base locator, while the radio signal scattered by the acoustic waves is processed by the sodar’s digital data processing system.

A modern RAS system built on the LAP 3000 radar wind profiler (RWP) platform is offered by Scintec [18, 19]. The profiler is designed for reliable measurements of wind speed and direction at altitudes up to 4 km, operates in the radio frequency range of 900–1400 MHz, uses a transmit–receive antenna with an aperture of 3 m² and no moving parts, and is equipped with an integrated electromagnetic interference shield. Thanks to its phased-array antenna, the system forms five radar beams: four tilted and one vertical.

The determination of the speed of sound in the atmosphere is based on measuring the Doppler frequency shift of the radio waves scattered by the acoustic wave packet; this parameter directly depends on air temperature.

Further signal processing is performed by the standard digital system of the wind profiler, which not only extracts the spectra of radio signals scattered by acoustic waves, but also analyzes signals reflected from turbulent atmospheric inhomogeneities. This makes it possible to obtain data on both temperature and wind speed and direction. Due to the active sounding method used in the system, the propagation time of the acoustic wave can be determined accurately, and this time corresponds unambiguously to the altitude at which the measurement is performed.

Thus, modern RAS systems, which have become widespread in solving both scientific and applied tasks, are built on the basis of acoustic locators or radar wind profilers, into the structure of which specialized electronic modules are incorporated to enable radio-acoustic atmospheric sounding.

Algorithmic Support of Systems for Measuring Atmospheric Temperature Profiles. The algorithmic support of RAS systems is based on methodologies for measuring profiles of atmospheric parameters. Under a profiling methodology, or a methodology for measuring atmospheric parameter profiles, we shall understand a sequence of actions involving the use of a chosen combination of sounding signals, implemented through the system’s algorithms for processing scattered signals and algorithms for controlling station parameters, in order to obtain vertical profiles of meteorological variables [22].

Let us examine in more detail the combinations of sounding signals currently used in industrially manufactured RAS systems. We will separately analyze RAS systems built on the basis of acoustic wind profilers and those based on radar wind profilers.

In RAS systems implemented on the basis of acoustic profilers (systems produced by Scintec, Remtech, METEK) [14–17], the most commonly used acoustic sounding signal is a pulsed signal with sinusoidal, single-tone filling and a pulse duration ranging from several tens to several hundreds of milliseconds (up to approximately 500 ms). Occasionally, an acoustic pulse with intrapulse frequency modulation or phase manipulation is also employed.

As the radio sounding signal in such systems, an unmodulated continuous-wave (CW) sinusoidal emission is most frequently used, or a relatively short radio pulse with sinusoidal filling.

In RAS systems built on the basis of radar wind profilers [37, 38], the acoustic sounding signals are quasi-tonal pulses (with frequencies of 1–3 kHz) and durations of 100–500 ms. Sometimes pulses with frequency modulation or pseudo-random frequency shifting within the pulse are used in order to broaden the frequency spectrum and thus enable reception of the scattered radio signal under a wider range of atmospheric conditions.

As the radio sounding signal, complex coded pulses (such as Barker-coded signals or M-sequences), chirp pulses (linear frequency-modulated pulses), or a simple pulse with sinusoidal filling may be used.

Let us consider the methods used by RAS systems to measure atmospheric temperature profiles. Currently, in industrial RASS systems built on the basis of radar wind profilers (RWPs) [18, 19], the following methodology for obtaining temperature profiles is most commonly used. Relatively long acoustic pulses with durations on the order of hundreds of milliseconds (e.g., 100–300 ms in the LAP-3000 system) or even continuous emissions of tonal, sinusoidal frequency are transmitted into the atmosphere. Pulsed acoustic emissions with frequency variations within the pulse may also be used. When pulsed signals are employed, their repetition frequency may be such that several acoustic wave packets are simultaneously present in the radar's observation zone. In this case, the emission of acoustic packets is synchronized with the moments of radio pulse transmission, allowing the determination of the distance to each scattering region during sounding based on the time delay.

Tonal radio emissions with durations on the order of a few microseconds (or, alternatively, tenths or tens of microseconds) are also used, with repetition periods of a few kilohertz (e.g., 2–4 kHz in the LAP-3000 system). Thus, at any given moment, multiple scattering zones of the radio signal, separated in height, are created in the atmosphere. Their localization is performed based on the time delay of the scattered radio pulses. Subsequently, the signals are processed, the frequency of each reflected signal is determined, and the obtained estimates are accumulated for each of the sounding altitudes, which are spaced approximately 20–80 m apart.

Sounding to obtain the temperature profile is carried out over a time interval ranging from several minutes to tens of minutes (for example, 60 minutes for the LAP-3000), during which the obtained results are averaged and the temperature profile is subsequently calculated for those altitudes where a sufficient number of individual measurement results have been accumulated.

This sounding algorithm is heuristic; it allows, by performing a sufficiently large number of soundings and obtaining a significant number of individual measurement results – for each specific altitude and for the profile as a whole – to achieve acceptable sounding results. The accuracy of the obtained temperature profile measurements is ensured by implementing significant measurement redundancy (both in time and in the number of performed soundings), taking advantage of computer technology and digital signal processing methods, which make it technically feasible to implement the employed redundant measurement techniques.

A slightly different sounding methodology for obtaining atmospheric temperature profiles is characteristic of RAS systems [14–17] based on acoustic wind profilers (sodars). These systems use pulsed acoustic emissions and a continuous electromagnetic sounding signal. A continuous, unmodulated, single-tone radio sounding signal provides good accuracy in measuring the velocity of the observed object but does not allow measurement of the distance to the object. When this type of radio sounding signal is used in RAS systems, the distance to the object – the pulsed acoustic wave packet – is determined based on the time elapsed since the emission of the acoustic signal. This approach, especially when using a calculated speed of sound obtained from measurements of the ambient temperature near the ground, ensures acceptable accuracy in determining the location – that is, the height of the acoustic wave packet.

However, in this case, multiple acoustic wave packets cannot be present simultaneously within the radar beam, since the scattered radio signals from them cannot be identified (as is possible in RWPs using pulsed radio sounding signals). Therefore, sequential emission of pulsed single-tone acoustic signals (with the emission frequency potentially changing from pulse to pulse) or broadband acoustic signals is used.

Next, multiple acoustic pulses are emitted over a certain period (the averaging time), the required number of individual measurements is accumulated at various altitudes, these measurements are averaged, and the temperature values are calculated at the points spaced along the vertical profile.

The main feature of the methodologies used by industrial RAS systems for measuring atmospheric temperature profiles lies in providing diverse scattering conditions at different points in the atmosphere over a given period of time. These conditions are achieved by using different values of the acoustic sounding signal frequency, due to changes in the current atmospheric conditions – such as temperature, humidity, and wind speed – during the averaging period, which lead to changes in the spatial wavelength of the acoustic sounding signal at specific points of the profile.

This process is accompanied by variations in the magnitude and sign of the systematic error in the speed-of-sound estimates for each individual measurement, as well as by slight temporal changes in the true speed of sound. As a result of averaging the obtained measurement results, the values of the systematic error are averaged, with the resulting value tending toward zero, and the values of the noise (additive) error are also averaged. Additionally, the instantaneous values of the speed of sound, which change over time due to variations in meteorological parameters affecting it, are averaged.

The mathematical model of the results of sound speed measurements at a specific point of the profile when obtaining a temperature profile using the RAS method has the following form

$$V_s(t_i) = V_{s0}(t_i) + \mathit{\Delta} V_s(t_i) + \delta V_s(t_i), \tag{3}$$

where V_s – the result of measuring the speed of sound; V_{s0} – true value of the speed of sound; $\mathit{\Delta} V_s$ – systematic error in sound speed measurement caused by Bragg condition detuning; $\delta V_s(t)$– noise-induced error in sound speed measurement caused by the influence of noise and interference.

As a result of a sufficiently long averaging time of the individual sound speed measurements, the last two terms in expression (3), which determine the measurement errors, tend to zero, and the following averaged measurement result is obtained $\overline{V_s} = \overline{V_{s0}}$.

This measurement methodology is a heuristic procedure, and its effectiveness and accuracy are confirmed in practice by the fact that, during sufficiently long measurement sessions, the average temperature results agree quite well with temperature measurements obtained by other contact instruments (thermometers mounted on towers, radiosondes, etc.).

In this case, ensuring measurement redundancy makes it possible to improve accuracy by reducing the influence of random errors, which leads to a more accurate determination of the true value of the measured quantity. The availability of a large number of measurements also helps to smooth systematic errors arising from the influence of changing atmospheric conditions. In addition, increased reliability is achieved by minimizing the impact of isolated erroneous readings.

Discussion of the Obtained Results

Overall, the situation regarding temperature profile measurements in the atmosphere using RAS systems remains insufficiently studied from the standpoint of existing systems theory. Currently, there are no signal-processing or measurement methods that ensure the absence of systematic errors in temperature measurement results, and science is presently unable to offer a sufficiently rigorous and scientifically justified measurement methodology under the existing conditions [1, 11, 20, 21].

As often happens, when science cannot provide a well-grounded answer to a question posed by practical needs – due to insufficient research and the lack of a necessary scientific and methodological framework – resourcefulness and ingenuity of engineers working in this field come to the rescue. They find heuristic solutions to the existing problematic situation, relying on intuitive understanding. This is exactly what is observed in this case, in the implementation of algorithms and sounding techniques in industrial RAS systems aimed at determining vertical temperature profiles of the atmosphere.

However, the proposed sounding methodologies, which make it possible to significantly reduce the influence of systematic errors of individual measurements on the final result – the averaged temperature profiles – lead to a deterioration of other system characteristics; in particular, the time required to obtain meteorological parameter profiles increases [22–25]. Yet, in a number of scientific and applied problems, there is a need for remote retrieval of profiles over a relatively short averaging period, or even for “instantaneous” temperature values obtained from a single emitted acoustic sounding signal.

Moreover, the measurement time required to determine temperature values by averaging over a sufficiently long period may, in some cases, exceed the quasi-stationarity time of the atmospheric processes. As a result, a non-stationary trend of the measured processes will accumulate in the averaging results, generated in expression (3) by the term $V_{s0}(t)$. Thus, when temperature profiles are obtained by RAS systems using the considered sounding methodology over a 60-minute interval, the resulting profile will contain a certain error caused by the non-stationarity of the ongoing atmospheric processes.

Thus, the advantage of the remote sensing systems considered lies in their relatively high accuracy in obtaining meteorological parameter profiles, which is achieved due to the redundancy of the measurements performed. However, this results in the degradation of other system characteristics, in particular a significant increase in the time required to measure the profiles, as this time is spent on ensuring and creating the necessary redundancy.

The main direction for the further development of RAS systems is the design of more advanced algorithms for processing scattered signals and algorithms for adaptation to changing external conditions. This will make it possible to improve the accuracy of the retrieved profiles and significantly reduce the measurement time.

Conclusions

The paper provides a review of existing stations and analyzes the sounding techniques and temperature-profile retrieval methods implemented in industrial RAS systems. It is shown that the shortcomings of imperfect RASS system algorithms – used because science has not yet solved the problems of synthesizing efficient processing algorithms for scattered signals that ensure unbiased and consistent estimates of informative parameters, as well as effective algorithms for frequency adaptation of the systems to changing propagation conditions along the sounding path in order to satisfy the Bragg condition – are, to some extent, compensated by the redundancy of the measurement processes used to obtain meteorological profiles. The applied sounding techniques are heuristic in nature and were proposed by engineers to compensate for the aforementioned limitations of the station algorithms. The advantage of the considered systems is their sufficiently high accuracy in retrieving atmospheric parameter profiles, which is achieved through redundant measurements. However, this leads to the degradation of other system characteristics, particularly a significant increase in the time required for profile acquisition.

Therefore, in order to improve the efficiency of radio-acoustic sounding stations, it is necessary to intensify scientific research in this field aimed at synthesizing effective algorithms for processing scattered signals and adapting to changing meteorological - especially wind - conditions, as well as at developing more advanced methods for measuring atmospheric parameter profiles. This would make it possible to improve the accuracy of the obtained profiles and significantly reduce the time required for their acquisition.

Author contributions: Kartashov O.V. prepared the material on the review and analysis of the current state of theory and algorithmic support of RAS systems, analyzed the advantages and disadvantages of frequency adaptation algorithms and methods for measuring temperature profiles. Kondrashov I.E. prepared the material on the state of the technical means of radio acoustic sounding currently produced by industry.

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Надійшла до редколегії 14.01.2026
Прийнята до друку після рецензування 23.04.2026
Публікація (оприлюднення) 30.04.2026

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