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ROLE AND PLACE OF ACOUSTIC SOUNDING IN ATMOSPHERIC RESEARCH

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A review of modern advances in remote sensing of the atmosphere with the use of electromagnetic (radio and optical) and sound waves is presented. Ground-based systems for measuring vertical profiles of meteorological parameters, including wind speed and direction, temperature, humidity (water vapor) and parameters of turbulence, cloudiness, and hydrometeors are described. The existing remote sensing systems, their application fields, stage of their development (commercial or research product), and cost are discussed. Advantages and disadvantages of different techniques are discussed together with prospects for their implementation and application. Most attention is concentrated on the opportunities and application fields of systems of acoustic and radioacoustic sounding of the atmosphere. Results illustrating these opportunities on the example of sounding of the atmospheric boundary layer are given.

Weather and climate of our planet are determined by various processes occurring within the atmosphere. To forecast reliably the behavior of the atmosphere, its characteristics at different altitudes, in different regions, and at different moments of time must be known. In the last few years, alongside with the refinement of conventional methods of measuring the meteorological parameters, the methods of remote sensing of the atmosphere with the use of electromagnetic (radio and optical) and acoustic waves have been developed intensively. This is explained by the increasing requirements of the society for obtaining a larger volume of information on the meteorological parameters that is no longer provided by the conventional methods of contact measurements from meteorological masts, air planes, balloons, and other carriers. The well-known advantages of the remote methods that allow long-term continuous measurements to be carried out in the entire sounding layer with low expenditures and thus vertical profiles of the meteorological parameters to be measured and dynamics of the atmospheric processes to be monitored favor their further development.

The remote sensing methods can be subdivided into active and passive ones. In the active methods, a directed signal transmitted into the atmosphere interacts with it during propagation. Radiation scattered by inhomogeneities or transmitted through the atmosphere is received with a receiving antenna, and its parameters are used to retrieve the atmospheric parameters. In passive sensing, radiation of an external source transmitted through the medium is analyzed.

The main components required for active remote sensing are a transmitting system of directional energy transmission into a given region of the atmosphere and a sensitive receiving system of scattered signal recording and processing. Systems of remote sensing that operate in the radio wavelength range are called radars (abbreviation of RAdio Detection And Ranging), systems operating in the acoustic wavelength range are called acoustic radars or sodars, and those operating in the optical wavelength range are called optical (laser) radars or lidars. Systems of radioacoustic sounding are called RASS systems, and passive systems operating in the radio wavelength range are called radiometers.

A review of modern achievements in application of atmospheric remote sensing technology with the use of electromagnetic (radio and optical) and acoustic waves based on the materials published in Russian and foreign press [1–25] is presented in this study. Principles (methods) of remote sensing are considered together with ground-based sounding systems for measuring vertical profiles of the meteorological parameters including wind speed and direction, temperature, and humidity (water vapor) as well as the characteristics of cloudiness, hydrometeors, and turbulence (radars, lidars, sodars, radiometers, and RASS systems).

Figure 1 shows percentage of application of different remote sensing technologies for tropospheric research based on reports delivered at the Fifth International Symposium on Tropospheric Profiling [2]. On the Sixth Symposium [3], percentage of lidars increased, but as a whole, radio wave and laser (optical) methods and means possessing richer opportunities for measuring the atmospheric parameters are still dominant in tropospheric profiling.

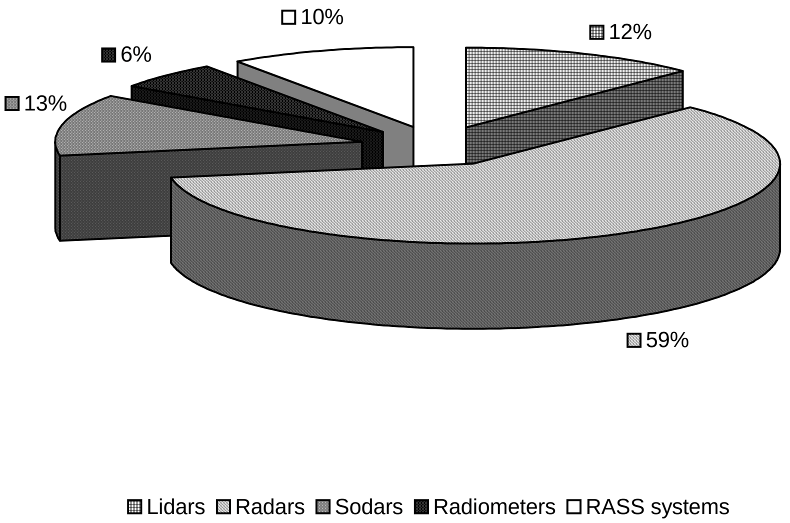


Fig. 1. Percentage of application of different remote sensing technologies for tropospheric research based on the reports delivered at the International Symposium on Tropospheric Profiling [2].

The situation changes for atmospheric boundary layer (ABL) research. Here remote sounding of the atmosphere with acoustic waves occupies the special, leading place caused by strong interaction of these waves with the atmosphere. It appears much stronger than the interaction of the electromagnetic waves in the majority of spectral ranges, and hence rather simple equipment can be used for sounding. Certainly, such diagrams illustrating application of different means of atmospheric sounding is somewhat subjective in character and depends on adherence of participants of the symposia; nevertheless, they show the tendency.

The use of acoustic radiation for remote sounding of the atmosphere (acoustic sounding) is based on the ability of acoustic waves to be scattered by inhomogeneities of the refractive index formed by the atmospheric turbulence. At the same time, sound waves of audible frequence range, conventionally used for acoustic sounding, possess small, in comparison with the electromagnetic waves, penetrating ability in the atmosphere. Their sounding range is limited (alongside with noise) by the molecular absorption, wind and temperature refraction, and turbulent attenuation. Therefore, the natural application field of acoustic sounding is the lower troposphere to altitudes of about one kilometer – one and a half kilometers, called the atmospheric boundary layer. In this layer, acoustic sounding has a number of essential advantages over radar and laser sensing.

To increase the sounding range, low-frequency acoustic radiation is used, including infrasound radiation and spaced sound sources (including explosive ones) and receivers. In this case, sound waves can propagate to great altitudes, up to the ionosphere, interacting with the troposphere. However, this field of sound wave application [18, 19] is beyond the scope of the present report.

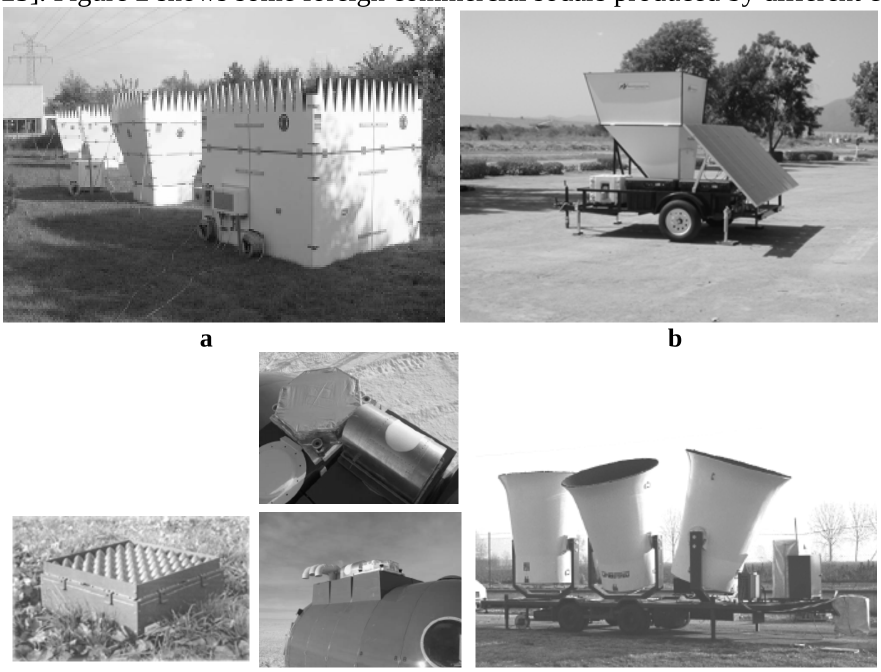
Foundations of acoustic sounding of the atmosphere were laid in works of the Soviet (Russian) scientists A.M. Obukhov, V.I. Tatarskii, D.I. Blokhintsev, A.S. Monin, and M.A. Kallistratova in 1940–1960. Nevertheless, the first meteorological acoustic radar (sodar) was developed and tested by McAllister from Australian Scientific-Research Defence Institute only in 1968. Since that time acoustic sounding – the new method of investigation of the atmospheric structure – has been developed intensively. The first session of the International Working Group on Acoustic Remote Sounding was held in 1972 in Boulder (Colorado, USA), where 20 scientific-research reports devoted to the development and application of acoustic radars were presented. In 1979, the International Society on Acoustic Sounding was organized for coordination of scientific research in this field. The First International Symposium on Acoustic Remote Sounding of the Atmosphere and Ocean was held by the University of Calgary (Canada) in 1981. Scientists from 11 countries took part at the Symposium. The last but one – the Twelfth Symposium – was held in Cambridge (Great Britain) in 2004. At this Symposium, it was decided to rename the symposium. After 35-year research and development in the field of methodology, techniques, and technologies of acoustic sounding, the primary goal becomes introduction of these advances into atmospheric science and practice. Now the Symposium is called the International Symposium for the Advancement of Boundary Layer Remote Sensing, and the last (Thirteenth) Symposium was held in Garmisch-Parterkirchen (Germany), where 75 reports were delivered by participants from 14 countries all over the world. The number of acoustic radars and countries where they have been developed and used continues to increase. Acoustic radars and other acoustic (ultrasonic) *in situ* measuring systems are commercially produced by a number of foreign companies [26–38], and individual prototypes are manufactured in our country, in Tomsk.

Application of remote sounding for the ABL study is necessary for solving the fundamental problems of atmospheric physics and many applied problems, including near-ground propagation of electromagnetic and sound waves. The ABL state has the main effect on life support of human beings. High variability and a variety of thermal stratifications determined by the local orography, properties of the underlying surface, radiative conditions, and synoptic processes are characteristic of this layer. The parameters of stratification obtained with the help of sounding systems are important for estimation and forecast of atmospheric pollution. This calls for a development of new remote sounding systems with additional information opportunities.

There are a number of main effects (laws) that have already been used in acoustic sounding or on the basis of which new methods can be developed, including

- Dependence of the sound velocity on values of the meteorological parameters that provides the basis for operation of *in situ* ultrasound systems for measuring temperature and wind velocity and radioacoustic sounding systems.
- Effect of sound scattering on small-scale turbulence that provides the basis for acoustic detection and ranging. Fluctuations of the acoustic refractive index are determined mainly by temperature and wind velocity fluctuations. The sound wave scattering cross section exceeds by about million times the scattering cross section of the electromagnetic waves.
- Effect of sound scattering by particles of various atmospheric formations is used for sounding of hydrometeors.
- The refractive index also has an imaginary part that describes the absorption of sound waves propagating in the atmosphere. Sound waves are absorbed much stronger than the electromagnetic ones. The sound absorption has strong frequency dependence.
- Refraction effects determined by vertical profiles of the temperature and wind speed and direction are also significant for sound waves.
- The Doppler effect that determines the frequency shift of sensing radiation underlies the wind velocity measurements.

Such strong interaction of sound waves with the lower atmosphere testifies to the fact that various methods and systems of remote acoustic sounding can successively be used in atmospheric studies and monitoring of the atmospheric state. They are mainly used to monitor the ABL temperature-wind stratification, to determine the mixing layer height and stratification type (class of the atmospheric stability), to measure vertical profiles of the turbulence characteristics, in particular, structural constants of the temperature and wind velocity fluctuations, turbulent flux, external scale of turbulence, wind velocity vector, etc. [1–25]. Figure 2 shows some foreign commercial sodars produced by different companies.



a **b**

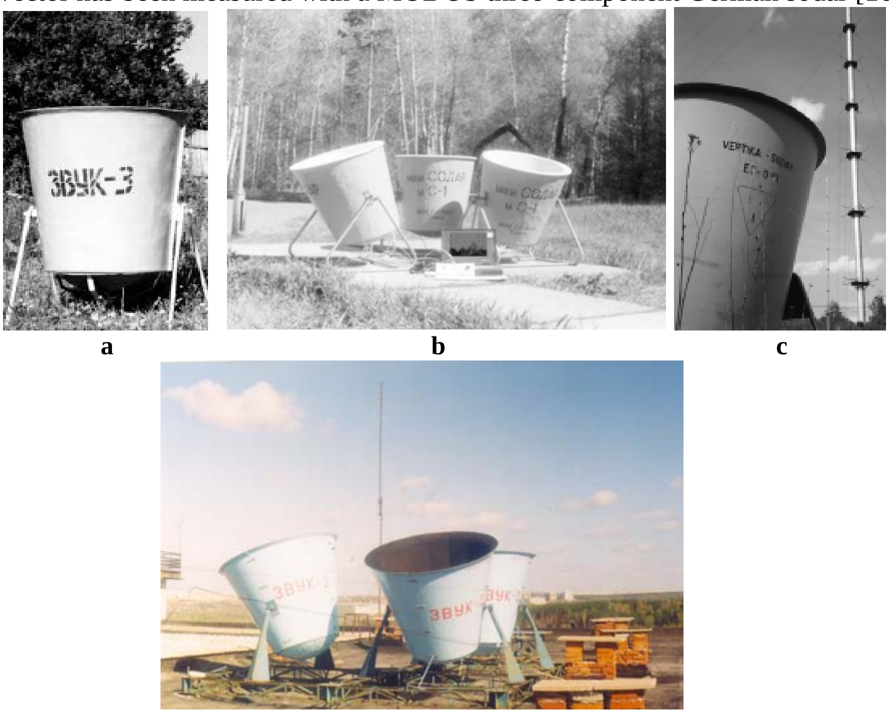
c **d** **e**

Fig. 2. External view of commercial sodars PCS.2000-24 and PCS.2000-64 produced by Metek (*a*), independent AV4000 Doppler minisodar with a solar battery produced by Aerovironment (*b*), SFAS with an acoustic array produced by Scintec (*c*), PA-1 sodar produced by Remtech (*d*), and MODOS 3-component Doppler sodar placed on a trailer produced by Metek (*e*).

In Russia, several scientific-research groups are engaged in acoustic sounding, including Moscow groups from the Iinstitute of Atmospheric Physics of the Russian Academy of Sciences (IFA RAS), Moscow State University (MSU), and Lantan Scientific-Production Company; Obninsk group from Taifun Scientific-Production Company (TSPC); Nizhnii-Novgorod groups from Scientific-Research Radio Physical Institute (NSRRPI); and Tomsk groups from the Institute of Anmospheric Optics of the Siberian Branch of the Russian Academy of Sciences (IAO SB RAS), Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences, and Tomsk State University of Control Systems and Radioelectronics. Most intensively operating sodars are located in Moscow (6 sodars including 2 MODOS sodars and ECHO-1 German sodar, two Russian LATAN-3 sodars developed at the IFA RAN, and Volna-3 developed at the IAO SB RAS), in Tomsk (two sodars), etc. Two Zvuk-1 sodars developed in Tomsk were delivered to the Kemerovo Regional Center on Hydrometeorology (1990) and to the Russian Federal Nuclear Center in Snezhinsk (1996). From the institutions, the largest number of simultaneously operating sodars (three) has MSU. Russian sodars are shown in Fig. 3. Sodars shown in Fig. 3 are monostatic. Special directions connected with application of low-frequency bistatic sodars and corresponding RASS systems for tropospheric sounding are developed in NSRRPI [21–23]; directions connected with vortex-acoustic sounding are developed at TSPC [24].

The longest series of continuous observations of the ABL thermal stratification were obtained at the

Meteorological Observatory of the Moscow State University. Acoustic sounding of the lower 800-m air layer has been carried out with the ECHO-1 sodar made in German Democratic Republic since 1988; Doppler measurements of the vertical wind velocity component have been carried out since 2000, and the wind velocity vector has been measured with a MODOS three-component German sodar [16] since 2005.



a **b** **c**

d

Fig. 3. External view of Zvuk-3 monostatic Doppler sodar (*a*), mC-1 Doppler minisodar (*b*), modernized ECHO-1 German sodar (*c*), and Zvuk-2 (Volna-3) Doppler sodar (*d*).

Characteristics of the existing sounding systems, fields of their application, stage of their development (commercial or research), and cost are given in the report. Advantages and disadvantages of various technologies and prospects for their application and use are discussed. Ultrasound technologies that allow one to carry out *in situ* measurements of temperature and wind velocity with high accuracy together with fluctuations used to determine the parameters of turbulence in the ground layer of the atmosphere are also considered. All acoustic sounding technologies taken together allow one to monitor the meteorological state of the atmospheric boundary layer in real time as well as to forecast evolution of the meteorological situation. Results of investigations of the atmospheric boundary layer structure and dynamics are also presented.

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