Instrumentation and technologies for remote sensing of the atmosphere and underlying surface

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The paper summarizes the results of investigations and basic research carried out at the Institute of Optical Monitoring, SB RAS, over 30-year period. These investigations were aimed at the development of instruments and technologies for laser and acoustic sensing of the environment that might have promises from the viewpoint of remoteness and efficiency when determining profiles of both aerosol pollution and meteorological quantities, as well as monitoring spatiotemporal variations of their fields. The ground-based, airborne, and space-based lidars created at the Institute and intended for sensing the atmosphere and underlying surface are described. The design and application technologies are described as well. The investigation in acoustic sensing of the atmospheric boundary layer and achievements in creation of new instruments and sensing techniques are presented. The results of application of these instruments and acoustic sensing techniques to monitoring the atmospheric boundary layer and sound propagation inside this layer are presented.

Introduction

Much attention of scientists has been always given to remote sensing of the atmosphere and underlying surface using different types of radiation since it is an efficient method of studies. Sufficiently high cross sections of interaction with the components being studied (high sensitivity) and the space-time resolution obtained at significant sounding range provides for this method high efficiency when investigating the atmospheric characteristics and phenomena as well as the processes of interaction of the atmosphere with underlying surface, especially in laser (using lidars) and acoustic (using sodars) sounding. Therefore, new instrumentation for remote sensing of the environment and technologies of their application are being developed at the Institute of Optical Monitoring SB RAS since the moment of its foundation.

The first lidar with an automated control system of regimes of measurement and data processing, which is part of a large complex of prompt measurement of atmospheric parameters, was developed late in 1973.[1] The results of 25 years development at the Institute of lidar manufacturing as a component of optical instrumentation manufacture were described in literature.[2] Lidar systems were created by stages from ground-based stationary and mobile systems to airborne ones and then to space-based lidars.[3–6] Simultaneously with the design of instrumentation for laser sounding of the environment the methods of design of lidars and their components were developed.[7–15] Some results of the development at the Institute of lidar systems and technologies of laser sounding are also given in Ref. 16.

Instrumentations of acoustic sounding of the atmosphere were developed at the Institute since 1978, first in the form of components of meteorological acoustic radars (systems of data processing[17,18]) and after 1985 – in the form of fully completed acoustic radars and ultrasound meteorological systems.

The paper describes the results of the investigations carried out at the Institute in the development of the instrumentation, methods and technologies of laser and acoustic sounding of the environment being promising from the viewpoint of ranging and efficiency when determining the profiles of aerosol pollution and meteorological values as well as ecological monitoring of space-time variations of their fields.

1. Technologies and laser sensing technique

Technical character of the scientific-design developments performed at the Institute since its foundation, has determined their basic line of investigations in the field of design of technical means for laser sounding of the atmosphere, hydrosphere, and underlying surface. Along with the design, manufacture, and field comparative lidar tests to determine their potentialities, the software and hardware are developed for automation of the scientific research. For this purpose the foundations of the calculation and optimal design of lidar systems and their components were developed, test facilities for their metrological certification were created as well as technologies of remote laser monitoring of the studied media were developed.

1.1. Instrumentation for laser sensing

Ground-based lidar systems. Apart from special mobile lidars, being a part of complexes of prompt determination of atmospheric parameters,[1,2,6] in the first decade at the IOM SB RAS aerosol lidars have been designed for scientific research, in particular, for ecological monitoring of atmospheric contamination. Among these are lidars of "LOZA" series.[2,3] Simultaneously with developing lidars the methods of their optimal design[7] were developed. For solving optimal technical problems on the components of lidar, a special lidar testing unit was created.[10] More than 20 inventor's certificates of the USSR were received for the majority of the designs (techniques and units).

The parameters and performance characteristics of the above-mentioned ground-based mobile lidars meet the best prototypes created at the research centers of SRI (USA), DFVLR (German Federal Republic); CNR–IROE (Italy), and at some Institutes of Japan as well as lidars produced (short runs) late in 1970s by the Impuls Physics GmbH firm (German Federal Republic). The only drawback was related to the lidar return recording systems – A/D converters and computers.

The transmitter-receiver unit of lidar "LOZA-2," based on the Cassegrainian objective, was manufactured (5 units). In 1976 some units were delivered to scientific-research institutions of Russia and abroad. Lidar complex "LOZA-3", which was modernized and improved at the Institute of Atmospheric Optics, to the present day provides the performance of remote measurements in the atmosphere under different research programs.

In 1980s the scientists of the Institute took part in the design and manufacture of the transmitter-receiver unit of a high-altitude lidar with a 1-m diameter primary mirror and a receiving system for the Siberian Lidar Station of the IAO with the receiving mirror of 2.2 m diameter,[2] as well as in the work for creating lidar prototypes using other effects of light scattering.[19–21]

Early in 90s the most important work was the design and manufacture of the receiving system of the meteorological lidar MEL-01 based on the Schmidt camera.[12] A special space filter was used in this camera to realize the correlation technique for measurements of wind velocity in three sounding directions at the general viewing angle of 6.5° Ref. 13. This filter provided the reception of backscattered radiation at a narrow instantaneous viewing angle of several angular minutes in a laser beam direction that increased the value of the signal-to-noise ratio when operating under daytime conditions.

Airborne polarization lidars. Based on the experience obtained, when creating and using airborne lidars in different foreign research centers, our subsequent developments were concentrated on the improvement of polarization lidar systems since they are the best when determining the shape of scattering particles and when investigating the effects of multiple scattering. In the design a possibility was also taken into account of sensing different objects in the atmosphere and hydrosphere and from other mobile platforms. Airborne polarization lidars "Svetozar-3," "Makrel-2," "Makrel-2M"[2,4] make it possible to study not only the atmosphere but also industrial pollutions as well as underlying surface (the upper layer of the hydrosphere and the dry land surface). Lidar monitoring of different objects using the above lidars was performed not only from onboard an aircraft but also from ships, car trailers, stationary points.

Multifunctional lidar "Svetozar-3" with three receiving channels enabled one to measure, when emitting only one sounding pulse, simultaneously all Stokes parameters in the backscattered radiation flux from a quick-changing object (taking into account the motion velocity of the platform-carrier and time variations of the object studied).[14] In a lidar transmitting channel a possibility was provided to set different polarizations of sounding radiation. The most appropriate development is the lidar "Makrel-2" intended for remote sensing of cloud fields, underlying surface, and hydrosphere from onboard an airplane. Along with the measurements of the state of radiation polarization obtained due to the elastic backscattering of a laser beam by the components of a medium sounded, the lidar provides for recording the fluorescent radiation from organic contaminations on the underlying surface as well as bioproductive zones in the sea. Because of lidar universality a small series of instruments, 8 prototypes, were manufactured. One lidar, up to now, has been in operation onboard an "Optik-E"[22] instrumented aircraft laboratory that took part in national and international research missions of the IAO SB RAS.

"Balkan" spaceborne lidar. The experience gained while developing mobile ground-based and airborne lidars has made it possible in collaboration with IAO and a series of branch firms of Minobshchemash SSSR to develop, manufacture, and test late in 1990 the first home-produced spaceborne lidar "Balkan."[6] The scientists of the Institute prepared the designer documentation for the lidar, a series of units were manufactured, and the whole cycle of ground-based tests of the lidar was conducted including tests before being launched on the orbital module. After launching into the orbit in 1995 lidar was included in the instrumentation of the orbital station MIR and during two years this lidar was operated as the first stationary spaceborne lidar in the world. Using this lidar the technologies were tested of space laser sensing of the atmosphere and the Earth's surface.[23–25]

Metrological support of lidar systems. Lidars, as a new class of instrumentation, have their own peculiarities. The error of lidar measurements, besides the methodical problems associated with the methods of solving the lidar equation (see, for example, Ref. 26) is also determined by a series of technical factors. One of them is the instrumental error, a basic part of which is the transmission coefficient of the receiving system from the input aperture to the recording A/D converter.[15] Problems connected with the lidar alignment and calibration were partly considered in Refs. 1 and 3.

Lidar systems, used to determine the quantitative values of optical and meteorological atmospheric parameters, must be subjected to metrological tests and certification after the manufacture and should undergo periodic tests during their routine operation. The most suitable for these purposes is a simulator of an optical signal enabling one to model different time dependences of the emitted power.[27] If an optical signal of a definite shape is fed into the input of the lidar receiving system, one can calibrate the entire receiving-recording channel, using the lidar system response, and obtain the controlled final result at the output of the detector or a computer. The sets of control-checking instrumentation were specially designed for multichannel lidars "Svetozar-3," "Makrel-2," and "Balkan" lidar.

1.2. Lidar sensing technologies

Spatiotemporal scales of measurements at scanning. When performing lidar monitoring of the environment, a problem occurs of its optimal organization, which must take into account both technical characteristics of lidar (power potential, spatial resolution by angle and transmission range, pulse repetition rate, possibilities of sounding direction scanning) and dimensions of controlled space and possible time variations of the atmospheric fields being studied. The sounding range is determined by the lidar power potential $P = P_0 AKS$, where P_0 is the pulse power of the laser transmitter, A and K is the area and the transmission coefficient of the receiving system, S is the photodetector sensitivity. For aerosol ground-based lidars with the mean value P, operating along ground paths, the sounding range is several kilometers.[7] Spatial resolution along the laser beam propagation path depends on the laser pulse duration, regime of operation and photodetector frequency characteristics, and lidar return recording electronics.[26] The other lidar parameters, affecting its resolution, are the sounding radiation divergence θ_0, which determines the angular resolution in the scattering medium and the pulse repetition rate f_p.

When determining the atmospheric pollution with the use of a ground-based scanning lidar a number of operation regimes is possible (Fig. 1). If the sounding is performed in sectors by the angle of elevation from 0 to ε_m and by azimuth from 0 to α_m degrees with homogeneous angular velocities ω_ε and ω_α, the scanning periods by these angles are equal to $t_\varepsilon = \varepsilon_m / \omega_\varepsilon$ and $t_\alpha = \alpha_m / \omega_\alpha$, respectively. Total amount of laser pulses for one scanning cycle is determined by the angle of elevation: $n_\varepsilon = f_p t_\varepsilon$ and by azimuth: $n_\alpha = f_p t_\alpha$. For a successive row azimuth scanning within the entire solid angle $\Omega_m = \varepsilon_m \alpha_m$ (Fig. 1*a*) the time is required, which is equal to $t_{sc} = \alpha_m \varepsilon_m / \omega_\alpha \theta_0$. Even at conventional parameters $\alpha_m = \pi$ rad, $\varepsilon_m = 1$ rad, $\omega_\alpha = 0.2\pi$ rad/s, $\theta_0 = 1.0$ mrad we obtain that $t_{sc} = 5000$ s, i.e., about one hour and a half. At the monitoring of fast varying atmospheric fields it is unacceptable. In this case the correct direction of laser radiation and not so high laser pulse repetition rate do not enable us to construct lidar systems similar to the all-round visibility radars.

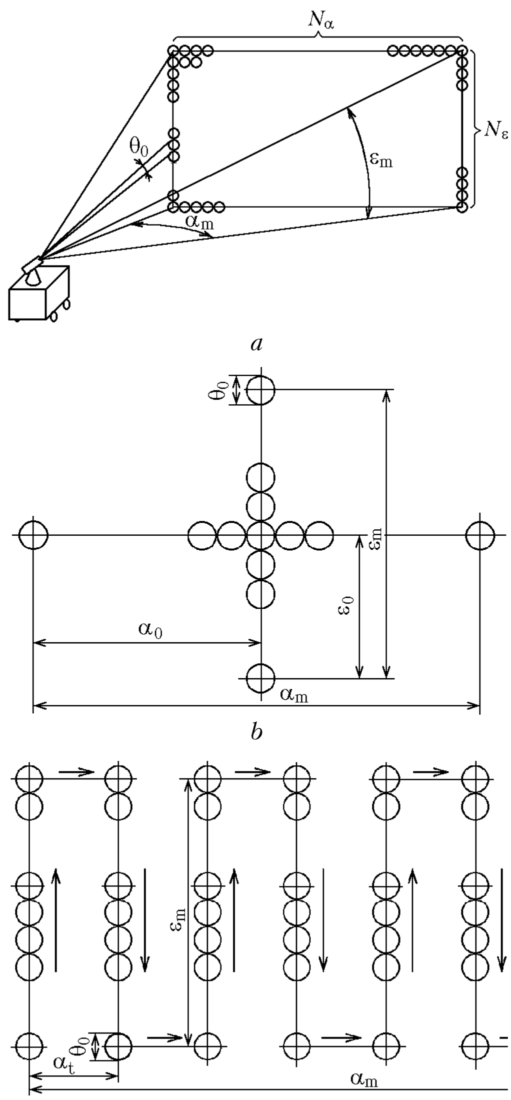

Fig. 1. Possible scanning regimes: the overall picture at the solid angle $\Omega_m = \varepsilon_m \alpha_m$ (*a*); the scanning at two principal angles (*b*); the scanning by the meander shape (*c*).

Figures 1*b* and *c* show two other possible scanning regimes. In the first version a total vertical atmospheric section is taken by scanning starting from an azimuth α_0 over the elevation angle from 0° to ε_m. This makes it possible to determine the height of a possible inversion layer and to give for further scanning the limiting angle of elevation $\varepsilon_{limit} < \varepsilon_m$. The angular resolution in this case can be found within the range from θ_0 to $n \cdot 10 \cdot \theta_0$ because it depends on f_p and ω_ε. At the same time, the angular height ε_0 is determined, to which the maximum pollution density corresponds and at which further sounding is made when scanning over azimuth.

In the second version (Fig. 1*c*) the scanning is made following meander shape, with a period α_t, being equal to several degrees. The angular resolution ε is chosen also from θ_0 to $n\cdot 10\cdot\theta_0$. In the same way the azimuth scanning can be performed. The use of such truncated scanning regimes enables one to increase greatly the prompt service when viewing the space within a solid angle Ω_m.

In Ref. 14 the peculiarities of organization of the polarization lidar sounding and optimal design of lidar systems are considered with variable polarization state in the transmitting and receiving channels with taking account of the time variations in the medium studied.

Airborne sensing with scanning. The directional scanning of the airborne lidar optical axis makes it possible to expand additionally spatial scales of lidar monitoring. The height H and the flight duration T as well as the path length L are the decisive characteristics. The characteristics H and T depend on the carrier type: aircraft, helicopter, or dirigable, and T and L are interconnected through the flight velocity V; in this case the height H can vary during the flight in multiple interval even for one type of a carrier. Besides, a helicopter or a dirigable can provide conducting detailed monitoring of a local object at required locations along the flight path due to hovering above a required point.

A characteristic of the airborne and spaceborne monitoring is that lidar, located on a mobile carrier, moves together with it in a basic coordinate system $O_gX_gY_gZ_g$, whose center O_g is conventionally related to any point of the Earth's surface. The position of a lidar optical axis (sounding direction) is given in a fixed coordinate system of the carrier and then, with the account for its motion parameters, is determined in the basic system. Using the navigation carrier equipment, which determines its space-time position in a geodesic coordinate system, the sounding points (trajectory of motion of lidar optical axis) can be related to the coordinates on the Earth's surface. In Ref. 30 the relationships are given, which determine the laser spot distribution density as well as the transfer path of lidar optical axis on the underlying Earth's surface or on a cloud. Thus, when the carrier moves parallel to O_gX_g axis at conic scanning, the beam transfer path over the plane $X_gO_gZ_g$ is described by a cycloid:

$$\begin{cases} X_g(t) = Vt \pm H \tan\delta_m \sin\omega_c t \\ Z_g(t) = H \tan\delta_m \cos\omega_c t \end{cases},$$

and at planar scanning – by a sine curve:

$$\begin{cases} X_g(t) = Vt + H \tan(\delta_m \cos\omega_c t) \cos\beta, \\ Z_g(t) = H \tan(\delta_m \cos\omega_c t) \sin\beta, \end{cases}$$

here δ_m is the maximum angle of deviation of the optical axis from nadir; ω_c is the angular velocity of the scanning; t is the current time; β is the angle between the axis O_gX_g and the scanning plane, in this case the axis O_gY_g is directed normal to the surface. With the increasing frequency ω_c and at constant frequency f_p, the laser spot distribution density on the surface decrease, i.e., the spatial resolution on the surface decreases.

Technology of spaceborne laser sensing. When performing the experiments on remote sensing of the Earth's surface with lidar "Balkan" the technologies of the spaceborne laser sensing of the Earth were developed for orientation of axes of the fixed coordinate system of the orbital station MIR $O_bX_bY_bZ_b$[23,24] in basic orbital $O_oX_oY_oZ_o$ (Fig. 2*a*) and inertial (Fig. 2*b*) coordinate systems. In the first orientation of the orbital station the lidar optical axis (LOA) was directed to the nadir (γ ≈ 0°). In the second orientation the angle γ between LOA and the nadir varied constantly. The experience of operation of lidar "Balkan" has shown that in the orbital coordinate system the path of LOA motion along the Earth's surface, even with no scanning, in the general case does not coincide with the projection of the orbital path. This is due to the errors in the real LOA orientation relative to the orbital station axis, the errors of setting the station orientation, orientation fluctuation of the orbital station axes during the flight.[25]

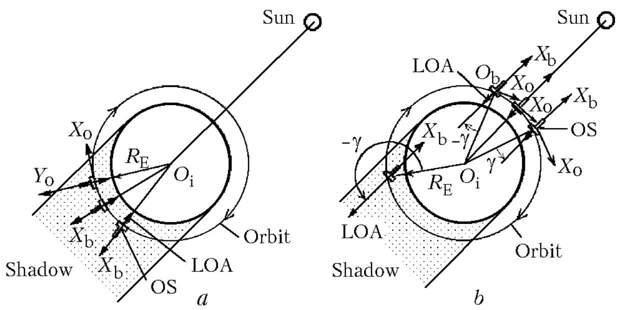

Fig. 2. Possible regimes of orientation of OS and LOA in flight: in the orbital coordinate system (*a*); in the inertial system (*b*); O_i is the Earth center (inertial coordinate system).

1.3. Development of the methods of optimal design of lidar systems

Our concept of methods of optimal design of lidars and their components[8,9,11–15] includes: a review of available technical solutions, creation of the system of their classification using generalized criteria, a selection of quantitative and qualitative evaluating criteria, the performance of a comparative analysis of available technical solutions using these criteria, a selection among these solutions of optimal ones using given criteria of quality as well as a seeking possible new technical solutions.

For example, in Ref. 12 the criteria are given for estimating the efficiency of lidar receiving lenses of different types and their comparative analysis is made using a proposed diagram of power and overall size characteristics (Fig. 3). Depending on the problems to be solved using lidar, the diagram enables us to select a lens with optimal relationship between its minimum length L_{min} proportional to the focal length f_{ob} of the objective with the diameter D_{ob} and the coefficient of relative efficiency $\overline{K_{ob} A_{ef}}$, being the product of the objective transmission coefficient and its effective area. Left boundary of the diagrams determines the minimum possible relative dimensions and the upper limit determines the maximum attainable power indices of each objective of a specific type. Such a work was under way on the optimization of technical solutions for other elements of the lidar receiving system: spatial filters,[13] polarization analyzers,[14] as well as methods of compression of dynamic range of the lidar returns.[15]

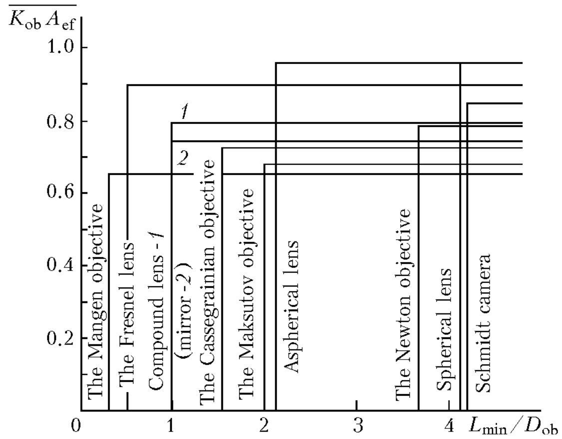

Fig. 3. Diagram of power and overall size characteristics of receiving objectives of different types.

At present at the Institute's Geophysical Department a special lidar post is created[31] for conducting remote monitoring of local pollution sources over Tomsk, where technologies of lidar monitoring of aerosol pollutions will be tested. The work on further optimization of lidar system components is planned.

2. Technology and technique of acoustic sensing of the atmosphere

Effects of strong interaction of sound with the atmosphere determine the prospects for investigating the structure and dynamics of the atmospheric boundary layer by acoustic methods. Long-term fundamental investigations in the field of atmospheric acoustics[18,32] have given rise to the atmospheric acoustic technologies: creation of a series of prototypes of meteorological acoustic radars (sodars), ultrasound meteorological stations (complexes), instrumentation complexes for taking account of the effect of atmospheric channel of sound propagation, forecast of the transmission range of sound broadcasting and noise monitoring, for determining atmospheric parameters and different objects. Basic applications of such techniques are outlined in Fig. 4.[33]

The sodars and ultrasound meteorological stations are successfully used in atmospheric monitoring. Sodars are used for remote monitoring inside the atmospheric boundary layer (ABL) to determine the temperature and wind stratification, the class of atmospheric stability, the height of mixing layer, parameters of turbulence. Ultrasound meteorological stations perform local monitoring and high-accuracy measurements in a local atmospheric volume of air temperature and wind velocity as well as their fluctuation by which a complete set of parameters of turbulence in the atmospheric boundary layer is determined. All these makes it possible to control in real time the meteorological conditions in the atmospheric boundary layer, which affects greatly the wave propagation of different nature and where all kinds of contamination affecting the people are accumulated, namely, aerosol, gases, radiation, as well as to predict the development of meteorological situation.

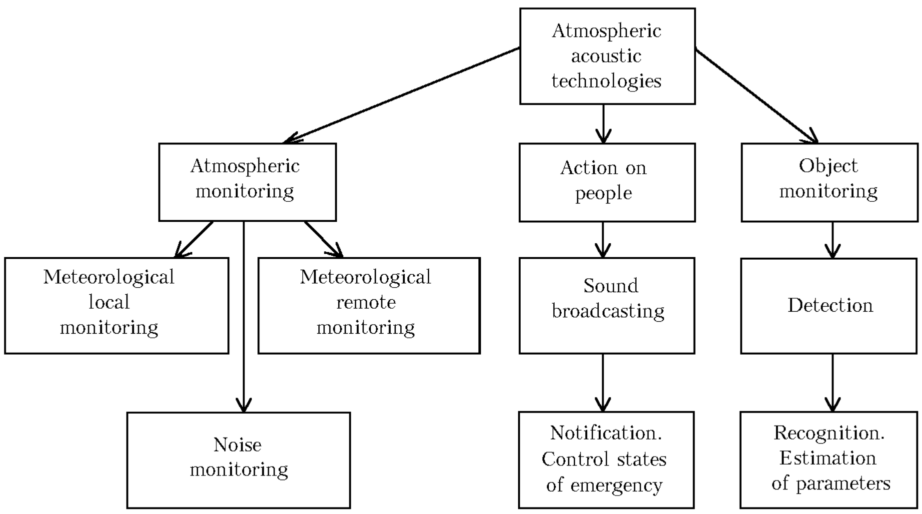

Fig. 4. Areas of applying atmospheric acoustic sensing technologies.

Acoustic noise becomes actual from the viewpoint of the impact on a human being and plays an increasingly important part in the world. The results of basic research into the surface sound propagation and creation of the instrument-program complexes, which consider and predict the atmospheric effect on the surface sound propagation, enabled us to make the noise (sound) monitoring for purposes of sound broadcasting, urban development, determination of sanitary zones, protection of people, and so on. In recent years of special interest are the problems of notification and control of people on the emergency situations as well as when conducting accident-life saving operations on contaminated areas.[34] At passive reception of sound waves (passive acoustic detection and ranging) with taking account of the effect of atmospheric propagation channel the problems are solved of detection of sound sources and recognition and estimation of sound source parameters and motion characteristics.

2.1. Instruments for remote acoustic sensing of the atmosphere

The use of acoustic radiation for remote sensing of atmospheric boundary layer has some advantages as compared with radio- and optical radiation including high efficiency and a possibility of conducting continuous and long-term atmospheric monitoring.[18,32]

During recent 25-years period (from 1974) of the development of the above-mentioned direction vast experience has been accumulated in creating the means for atmospheric acoustic sensing – sodars.[17,18,32] Researchers from SDO "Optika" participated in the development of the first acoustic radars "MAL-1" and "MAL-2" for measuring the temperature stratification and wind velocity profile in the lower 1-km atmospheric layer. Using these sodars a number of the field research missions on studying the atmosphere were carried out. In particular, in 1987 in accordance with the program funded by USSR Goskomgidromet and Khazakh Republican Administration on hydrometeorology and control of the environment at the Alma-Ata airport the measurements of the wind shear and atmospheric temperature stratification were made. In 1979, 1980, and 1987 on the polygons in Leningradskaya and Nizhegorodskaya regions the investigations were made on the use of sodars for purposes of prediction of sound wave propagation in the atmosphere.

The long-term development of investigations in this area at the Institute of Optical Monitoring SB RAS is directed to the creation of a network of stations of acoustic sounding for atmospheric monitoring.

For this purpose a series of sodars has been developed including small portable high-frequency sodars[35–40] and low-frequency stationary ones for various altitude range of their possible application. In the first sodars MAL-1, MAL-2, "Zvuk-1," and "Zvuk-2,"[17,18,32] having large dimensions, the frequencies from 1 to 1.7 kHz were used providing the sounding range up to 500–1000 m altitudes. In the new high-frequency sodars the frequencies 2.2–7 kHz are used that enable us to make sodars more compact.

At the present a high-frequency sodar "mS-1" has been developed and used at the IOM SB RAS.[39] This sodar uses a small-size mirror parabolic antenna. This antenna is protected by a sound-protective blind in the form of frustum of a cone. This minisodar is intended for measuring the atmospheric stratification, the mixing layer height, height and power of inversions, wind velocity profile, structure characteristics C_T^2, C_V^2. Minisodars have been developed in few recent years and they were successfully used in the investigations of the atmospheric boundary layer because such sodars are small and have higher spatiotemporal resolution and some other advantageous potentialities. Undoubtedly, the use of higher frequencies decreases the sounding range; however, the increase of radiation frequency results in the decrease in size of the antenna system, and, hence, the over-all dimensions of a sodar itself.

The minisodar "mS-1" can operate in monostatic, bistatic, and tristatic regimes at the frequencies from 3 to 7 kHz. Its external view is given in Fig. 5, and basic parameters are given below.

The main specifications of minisodar "mS-1"

Operating frequency, Hz	4273
Sensing range, m	8 – 200
Sensing interval, s	1.8
Resolution, m	8
Acoustic pressure power, dB	130
Width of directional pattern at the half-power level, degrees	13
Overall size, mm	640×520×700
Supplying voltage, V	
Line supply	~220
Independent	12

As acoustic converters the horn-type heads of power up to 180 W are used. First tests of the minisodar[39] have shown its normal, stable operation both at pulse and continuous radiation, in regime of monostatic and bistatic sounding.

Besides, tests are being performed at present of a model of one more higher frequency sodar,[37,40] which characteristic property is a mirror of TMA type (a two-mirror antenna with a small elliptic mirror). Such mirrors provide a narrower directional pattern. The number of sodar channels is from 1 to 5, the operation frequency is 2–5 kHz (basic frequency is 2.2 kHz). The width of the directional pattern at the frequency of 2500 Hz is 14°. The acoustic heads with the power up to 300 W are used as emitters. The sodar supply voltage is 12 V. The area of application and information potentialities of this sodar are the same as those of "mS-1" sodar.

The tentative tests have shown a possibility of effectively using the developed acoustic radars to measure the turbulence, wind profiles, temperature stratification, and control of the atmospheric boundary layer, as well as their ability to compete with foreign analogs.

Fig. 5. Sodar "mS-1".

The third sodar, being developed, is a stationary one located at the geophysical stationary complex of IOM, the Doppler three-component (three-channel) sodar operating with low sound frequency, less than 1 kHz.

2.2. Technology of Monitoring of Acoustic Noise (Sound Propagation) in the Ground Atmospheric Layer

Surface propagation of sound waves (noise) in the atmosphere (above the Earth's surface) has its peculiarities as opposed to the sound propagation in a free space.[18] Along with numerous meteorological parameters (temperature, pressure, humidity, wind velocity and direction, atmospheric turbulence) geometric factors also affect the surface propagation of sound, namely, relative position of a source, receiver, and underlying surface as well as their characteristics. The most important for practical problems (see Fig. 4) resulting from the problem of surface sound propagation, are the problems of prediction of sound propagation. First of all, this is a forecast of signal level or sound attenuation at a definite propagation path based on the measured and predicted meteorological parameters in the ground atmospheric layer.

Because there is no any unique theory of surface sound propagation, taking into account the joint action of the above factors, the emphasis is on the field experimental investigations under controlled propagation conditions.

The presently designed instrumental and program complex[41] makes it possible to perform real-time calculation and prediction of the mean field of sound pressures of an audible frequency range in the surface atmospheric layer at the distances up to 10 km taking into account meteorological parameters of the atmosphere, characteristics of the propagation path, and of the underlying surface. Upon completion of prediction, the sound pressure area distribution is calculated in the direction of sound broadcast and diagrams of areas source audibility are designed as well as the areas of recommended position of a sound source relative to a reception point are calculated and drawn.

At noise monitoring the instrumental and program complex also allows:

– real-time estimation of sound source audibility;

– calculation of noise contamination of the atmosphere using a projected instrument specimen;

– calculation of sanitary-protective zones of industrial objects based on the noise in the atmosphere;

– construction of the noise distribution map of populated areas when the number of noise sources is limited;

– determination of the amplitude-frequency characteristic of a noise source taking into account the effect of atmospheric channel of noise propagation.

The use of the instrumental and program complex of prediction of acoustic noise level necessitates the availability of a computer, a meteorological complex based on the ultrasound meteorological station for local acoustic monitoring of the ground atmospheric layer, and the corresponding software. An operating model of the program complex is realized in the Visual Delphi 3.0 environment for an operating system MS Windows.

2.3. Technology of Acoustic Monitoring of the Atmospheric Boundary Layer

The observed global changes of the environment and the climate are caused by natural and anthropogenic factors playing a diverse part in different regions of the planet. To study these changes, it is necessary to perform long-term continuous investigations of the atmosphere (atmospheric monitoring) with the use of new developed laser and acoustic measurement means and technologies. In this case the studies of space-time structure and dynamics of meteorological fields, as well as aerosol and gas components of air over a long period, have a significant place in the research of climate-formation factors.

Monitoring of the atmospheric boundary layer is more urgent since this layer is characterized by the greatest variability. Even over limited areas of the Earth's surface one needs, for a detailed research of the atmosphere, to know a large number of parameters such as temperature, humidity, wind velocity and direction, turbulence characteristics, distribution of cloud and aerosol fields, radiation balance, and so on. At the Institute, on the territory of the Geophysical Department, such investigations are made with the use of the above new meters.[42–49] In addition to the standard meteorological parameters measured by a standard meteorological station, as well as by an ultrasound meteorological complex, since 2000 the researchers have been determining in the regime of routine monitoring of the atmospheric boundary layer such parameters of turbulence as the net power of turbulent motions, heat and momentum fluxes, wind and temperature scales, Monin–Obukhov scales, and so on, as well as their statistical characteristics. In the atmospheric boundary layer the investigations are carried out using sodars. The behavior of measured parameters is estimated depending on the overall state of the atmosphere.

In addition to atmospheric monitoring the result of these investigations is, first of all, the development of algorithms for processing meteorological data and methods of calculation of turbulent characteristics.[48,49] This is confirmed by good correlation between parameters measured by the ultrasound meteorological complex as well as by an acceptable similarity of the classes of atmospheric stability determined by different methods.

An attempt has been made to perform measurements and analysis of space-time structure of meteorological fields in the lower atmosphere over a limited territory.[42,43] Complex studies were carried out of the structure and dynamics of the atmospheric boundary layer on the limited territory of Akademgorodok at three measuring points with the use of both standard meteorological measurement facilities, and an acoustic radar and an ultrasound meteorological station, which measures a series of meteorological and turbulent characteristics of the atmosphere, as well as some other facilities. The synoptic situation was also controlled. The atmospheric stability classes and the height of mixing layer were determined. It is shown that under conditions of an urban area (at the outskirts of the city) even at relatively short distances between the measuring points (up to 700 m) significant distinctions are observed in the values of meteorological parameters in the atmospheric boundary layer including standard meteorological measurements. The use of sodar and ultrasound meteorological station in this case enables one to catch a finer space-time structure of meteorological fields in the atmospheric boundary layer and its dynamics having supplemented standard meteorological measurements.

In connection with the problems of atmospheric contamination of industrial centers, sodars are effective in systems of air basin control because sodars give real-time information on the meteorological conditions of the atmospheric boundary layer and its dynamics. The investigations performed in the regions of our country, which are critical from an ecological point of view, have made it possible to obtain certain initial data to evaluate the ecological conditions of urban atmosphere in these regions. Some investigations were made with the use of a sodar, aerosol and Raman lidars, a trace gas analyzer, a local gas analyzer, ground-based meteorological stations including ultrasound stations. Figure 6 shows one of the examples[18] of joint laser-acoustic vertical sounding of the atmosphere. On the digital double-tone record of a sodar signal (in isometry for a convenience of overlapping of other signals) the temperature profile is superimposed which was obtained with a Raman lidar, the profile of the aerosol backscattering coefficient normalized to maximum and recorded by "LOZA-3" lidar. Blackening (stars) on the facsimile record of a sodar signal indicate the increased turbulence in the temperature inversion layer. White background, the absence of signal in the beginning of the path, correspond to "blind zone" of the sodar. Figure 6 shows the presence of surface temperature inversion (first doubled layer) up to 180–200 m height and, besides, starting from 19:00, a quickly descending layer of elevated temperature inversion is observed, which, after some oscillations on altitude closely approached by 21:00 the layer of surface temperature inversion. Results of this experiment show good agreement of lidars and sodar data in the research of vertical structure of the atmospheric boundary layer.

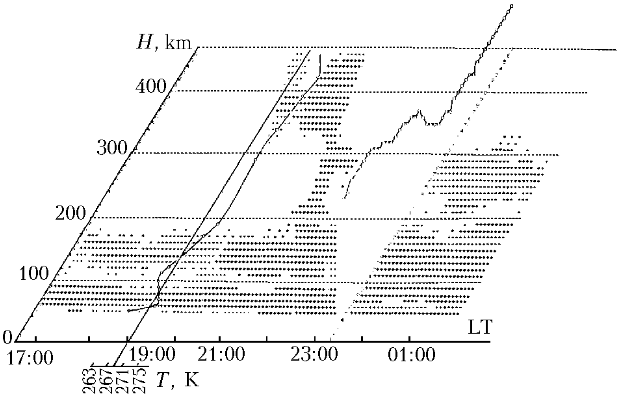

Fig. 6. Results of laser-acoustic sensing of ABL. Digital facsimile recording of a sodar signal and temperature profile (in the left) and profile of aerosol backscattering coefficient.

As a result of long-term investigations it was shown that the characteristics of temperature stratification in different regions differ and essentially depend on the local peculiarities that results in the difference depending on meteorological conditions for accumulation of the contaminants. Figure 7 shows one of such examples[18] on altitude distribution of temperature inversions in Kemerovo and Almaty based on the data of acoustic sounding. Thermal structure of the atmospheric boundary layer, observed in Kemerovo, differs essentially by its character from the structure observed in Almaty. In particular, there is no multilayer elevated inversions. Lower boundaries and their larger instability are typical for the elevated inversions. Surface inversions differ by frequent occurrence and high stability of boundaries. For Almaty a more complex thermal structure of the atmospheric boundary layer (ABL) with multilayer elevated temperature inversions is typical. These inversions varied slightly during 24 hours. Evidently, this is explained by the peculiarities of orography of the locality.

The ABL investigations with the use of laser and acoustic facilities of remote sensing have shown their efficiency for the control of pollution of the air basin in a city. Experimental investigations on simultaneous sounding of ABL using sodars and aerosol lidars have shown that the main impediment to vertical aerosol distribution in the atmosphere is the presence of retarding layer in the form of temperature inversions under which the aerosols are accumulated. In this case the height of the upper boundary of aerosol cloud practically coincides with the height of the inversion layer (the correlation coefficient is 0.9 and higher).[46,47] Further investigations are directed to the determination of correlation between the parameters of atmospheric stratification and concentration of some gases, in particular, ozone and carbon dioxide.

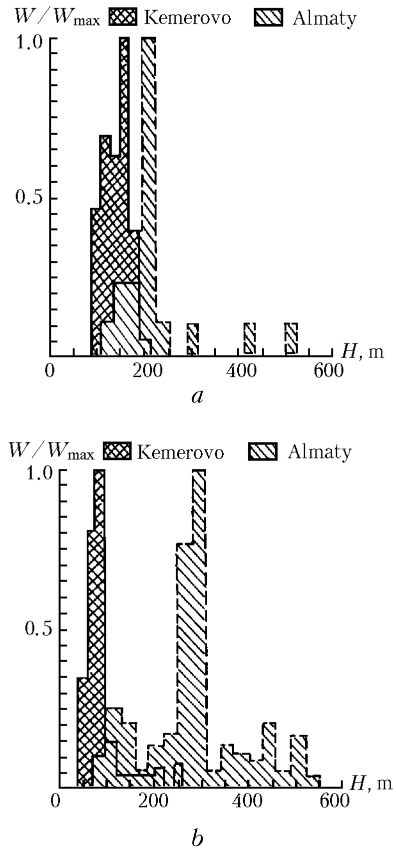

Fig. 7. Normalized histograms of distributions of the upper boundary of ground temperature inversion (*a*) and lower boundary of an elevated inversion (*b*) for Kemerovo and Almaty.

Conclusion

The results considered in this paper on application of the instrumentation, technologies, and some results of laser and acoustic sounding of the environment summarize the progress of the 30-year development of the research in this field. The instrumentation, units, and complexes created at the IOM SB RAS[2] considerably extended the instrumentation basis of the IAO SB RAS and favored the basic research into the atmospheric optics.

The problems, the Institute faces at the present time, are directly connected with the environmental monitoring and, first of all, of the atmosphere. In this connection new techniques, instrumentation, and technologies for remote sensing should be developed and put into practice of experimental studies.

Acoustic technologies are of considerable importance in the investigations of IOM SB RAS. These technologies have made it possible monitoring of the surface and boundary layers of the atmosphere with great success as well as to predict the sound propagation in the atmosphere providing a combined program of the investigations. The level and the importance of scientific investigations and technologies in this field are supported by the orders from national state industries of the research developments.

All these techniques, instrumentation, and technologies of simultaneous laser and acoustic sounding of the Earth's atmosphere are not only a high-power instrument for solving scientific problems but also an important part of educational process. In the framework of integration with the Tomsk universities the branches of chairs and Center of Atmospheric Technologies were founded at the IOM SB RAS for making scientific investigations in the field of the development and use of new technologies of atmospheric monitoring and granting modern educational services.

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