Instrumentation for climate and ecological monitoring

N.P. Soldatkin and A.A. Tikhomirov

Institute of Optical Monitoring,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received November 12, 2001

Specifications of the devices, instruments, and systems developed at the IOM SB RAS during the previous 30 years are briefly described. All these facilities have been designed for the research into optical and meteorological characteristics of the atmosphere and can be used in environmental, ecological, and meteorological monitoring. Problems concerning metrology for the instrumentation developed and measuring techniques are considered.

Introduction

Intense development of the research in atmospheric physics that started almost everywhere in the 1950s and accelerated with the advent of first lasers initiated the development of new devices for these purposes. Large-scale basic research on atmospheric optics conducted in the IAO[1] demanded development of the up-to-date basis for optical instrumentation in Tomsk, which began to be developed after organization of the Special Design Office of Scientific Instrumentation "Optika" in 1972. The research problems solved in the IAO ("what to observe" and "how to observe") were thus complemented with the instrumental and technological aspect "with which instruments to observe."[2]

The well-timed organization of the SDO "Optika" under the scientific supervision of the IAO favored solution of several problems. Mockups and experimental setups developed at the IAO based on the new physical principles and tested practically both under laboratory and field conditions formed the basis for the development of pre-production models of new devices. Model devices, instruments, and systems came then to customers for test operation in the atmosphere. Simultaneously with the development of new devices for atmospheric studies, the staff of the developers and designers improved, the optical instrumentation production basis grew, and the problems of metrological certification of new devices and measuring techniques were solved, along with other problems of metrology for new methods of atmospheric research. Supplying the basic research with new instrumentation based on the effects of interaction of optical electromagnetic fields and acoustic waves with the atmosphere[2,3] has made it possible investigations in many fields of atmospheric physics.

Then, in the 1990s, as the SDO "Optika" was reorganized into the Design and Technology Institute "Optika" and then into the Institute of Optical Monitoring, the engineering and design works aimed at creation of new equipment for environmental studies were complemented with the research component in the field of regional monitoring of climate and ecological changes. The equipment developed at IOM along with other devices began to be used for solution of problems on scientific-methodical and technological principles of monitoring and prediction of the development of atmospheric and ecosystem changes.

This paper describes the history of the development and describes briefly technical characteristics of the opto-electronic devices, instruments, and systems developed at the IOM for 30 years. The considered equipment can be used for ecological and meteorological monitoring of the environment.

1. Period of 1972–1990

1.1. Automated optical-meteorological systems

The SDO "Optika" was organized initially for further development of the works aimed at designing equipment for remote real-time determination of atmospheric parameters with the use of laser sources.[2] The first of such systems was designed and manufactured for two years and delivered to a customer late in 1973. In 1974–1975 this system was tested under field conditions near Balkhash Lake. It included a lidar for determination of atmospheric transmittance profiles along slant paths, a laser open-path transmissometer measuring transmittance along a near-surface path, a laser meter of turbulence, a meteorological system, and a computer for an automated control of the system and processing information.[4]

The set of devices and degree of their automation were determined by the purposes and problems to be solved. Conducting measurements connected with determination of spatial profiles of various atmospheric parameters usually demanded a lidar to be included in the measuring system. Auxiliary devices providing for accompanying measurements may be a meter of radiation extinction along a near-surface atmospheric path and a system for measuring meteorological parameters and their gradients. To estimate the turbulent characteristics of the atmosphere, the system included devices for measurement of structure characteristics of the refractive index of atmospheric air, angles of arrival of optical radiation, as well as the intensity fluctuations and spot geometry of a laser beam. The ideology of such systems was developed at the IAO, and the SDO "Optika" was responsible for engineering and design solutions, production, and acceptance tests.

Real-time measurement of optical and meteorological parameters of the atmosphere motivated the use of a computer for data processing and operation control of the system and its parts. The degree of automation of the measurement process and control of unattended operation of system parts was determined by the problems to be solved with this system and the state of the art in computer technology. To improve the reliability of determination of a atmospheric parameter sought, several devices conducting measurements with the use of different physical principles were used.

On the whole, more than 15 experimental and pre-production models were designed and produced for the 20-year period. These models for determination of optical and meteorological parameters of the atmosphere had different composition and were intended for ground-based and shipborne operation (see, for example, Refs. 4 and 5). The systems were produced in both mobile and stationary versions and used for real-time evaluation of the optical weather at the field test sites of new optoelectronic systems operated in the atmosphere.

1.2. Lidars

The main advantage of a lidar as a measuring tool in ecological and climate monitoring of the atmosphere consists in the feasibility of remote measurement of profiles of aerosol and gas components of the atmosphere along the path of laser beam propagation and real-time monitoring of their dynamics (Fig. 1).

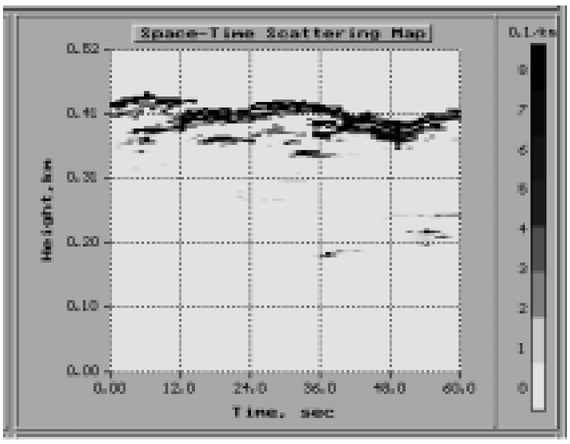

Fig. 1. Lidar observations over the dynamics of stratus cloudiness for one minute. The time is plotted as an abscissa, and the slant range is plotted as an ordinate; gray scale is proportional to the extinction coefficient, in km^{-1}.

In the period of 1972–1991, more than ten various modifications of ground-based mobile and stationary lidars or their transmitting/receiving systems were produced; they employed various effects of laser radiation interaction with atmospheric components. Among them were the LOZA lidars for solution of research problems,[6] as well as the receiving system of the Siberian Lidar Station of the IAO. Three modifications of airborne polarization lidars (Svetozar-3, Makrel'-2, Makrel'-2M) were developed, as well as the spaceborne lidar BALKAN. Some of best designs of transmitting/receiving systems of ground-based and airborne lidars were replicated.[2,7]

1.3. Other optical-meteorological devices

Open-path transmissometers

Several modifications of a laser transmissometer for measurement of atmospheric transmittance were developed for use in optical and meteorological systems. To be noted among them is *the two-wave device for measuring the horizontal transmittance* at the wavelengths of 0.63 and 10.6 μm (Ref. 8). Its transmitting/receiving system was made as a single unit, and a plane mirror reflector was installed at the end of the path. The cross size of the aperture of the receiving system allowed the laser radiation to be fully intercepted at the path $2L = 2.0$ km long. The device provided for measurement of the extinction coefficient in the range $\alpha = 0.025...1.3$ km^{-1} with the error decreasing in this range from 10 to 0.5%. Wedge compensators in its transmitting channel automatically compensated for variations of the angles of arrival due to refraction within 1.5 min of arc. Thanks to its design, the device could be used under field conditions at negative temperatures. The device was produced in a small series and used in several systems.

Multiwave atmospheric transmissometer MIP-1 (Ref. 9). To study the spectral transmission function of the atmosphere in the region from 0.44 to 1.62 μm, a pre-production model of the transmissometer with a DKSSh-150 gas-discharge lamp as a source of radiation and an FD-7G germanium photodiode as a detector was made. Changeable interference filters provided for measurement of transmission in eight narrow spectral regions: 0.440 (8), 0.487 (8), 0.551 (8), 0.693 (8), 0.870 (15), 1.060 (15), 1.221 (16), 1.620 (20) μm (filter band pass, in nm, is given in parentheses). The MIP-1 had separated source and receiver of radiation. Its power potential provided for measurements along paths of up to 4 km length.

Small-size pulsed transmissometer IIP-10 based on a light-emitting diode ($\lambda = 0.67$ μm) and a photodiode was designed and manufactured in a small series.[10] Its measuring path did not exceed 10 m; a set of cubic-corner prisms was used as a remote retroreflector. The range of transmission measurements was $T = 0.6–0.99$. The IIP-10 was used both in research and for monitoring of dust content in premises.

Raindrop measurer IKDAN. The IKDAN was designed for measuring the size and fall rate of raindrops.[11] Its operation is based on the principle of Nollenberg's shadow spectrometer, in which an image is read out along the horizontal through scanning of a linear array of photodetectors and vertical scanning is performed due to the motion of a drop itself. The pre-production model had the following characteristics for measurement of raindrop parameters: drop diameter ranging within D_d = 0.25–9 mm, the upper limit of the fall rate from 4 (at D_d = 0.25 mm) to 144 cm/s (at D_d = 9 mm), absolute error in determination of the diameter no more than 0.1 mm, the mean relative error of the rate measurement no more than 10%.

A prototype of a measurer of snowflakes was developed as well. It had the following characteristics: size range of 0.1–3.2 mm with the step of 0.1 mm or 0.2–6.4 mm with the step of 0.2 mm, the range of rate measurements of 20–128 cm/s with the step of 4 cm/s or 20–256 cm/s with the step of 8 cm/s.

Meteorological visibility meter IKOS-2. Unlike other devices for measuring the meteorological visibility that are applied in meteorological observation networks and based on the basic or nephelometric measurement technique, the IKOS-2 is based on observation over the phenomenon of seeming blooming of the line of visible horizon up to its complete disappearance at the increasing turbidity of the atmosphere. Thus, the IKOS-2 used the method of passive sensing, what allowed it to be used under marine conditions, when other methods can hardly be applied.[12] The working range of the visibility measurements was from 4 to 50 km with the relative measurement error no more than 20% in the middle of the operation range.

2. Last decade

The experience gained in the process of production of the above devices and their parts made it possible the further development of equipment for ecological and meteorological monitoring of the atmosphere, including mobile monitoring laboratories, meteorological devices, gas analyzers for monitoring of atmospheric air and industrial emissions.[13]

2.1. Mobile laboratories for environmental monitoring

Station "Ekotekhnologiya." Early in 90s, due to cooperation of the three organizations: IOM, IAO, and Scientific-Production Association "Ekotekhnologiya," a mobile laboratory was designed for monitoring of gaseous and aerosol pollution of the atmosphere. The monitoring equipment was housed in the passenger compartment of a GAZ-66 truck equipped with the microclimate and power supply systems. The laboratory included a chromatograph for analysis of gaseous air pollutants (SO_2, NO, NH_3, and some organic compounds), an AZ-5 aerosol meter for determination of the number density and disperse composition of aerosol, a system for measuring basic meteorological parameters, and a meter of the radioactive background. Besides, the station was equipped with the device for air sampling in various zones of industrial enterprises for the following analysis of samples in a stationary laboratory. The parameters measured in air samples were the mass concentration of aerosol, its chemical composition (43 ions and chemical elements), and the gas composition (more than 100 ingredients). Measurement results were archived on a computer. This mobile station was used in surveys of aerosol and gas pollution in Pavlodar, Nizhnii Tagil, Khabarovsk, and Ust'-Kamenogorsk.

Automated station "Ekolid." Creation of the mobile laboratory "Ekolid," which was housed in a thermally stabilized body of a ZIL-131 truck, was completed in 1993. The laboratory was produced on a request from the East-Kazakhstan Department of Ecology and Bioresources (Ust'-Kamenogorsk). It was intended for real-time detection and measurement of the concentration of technogenic gaseous (SO_2, NO, NO_2, mercury vapor, CH_4, and hydrocarbons C_xH_y) and aerosol pollutants in the atmospheric air of towns and industrial zones, mapping of the state of air basin on the scale of a big city, and formation of a short-term prediction of the development and transport of dangerous gaseous and aerosol emissions.[14] All measuring equipment of the station was manufactured at the IOM, sometimes in cooperation with the Scientific Research Institute of Analytical Instrumentation (Kiev). Gas analyzers being a part of the station have passed metrological certification in the Mendeleev Research Institute of Metrology. The station also included a computer and an air sampling and sample preparation system. Operation of the station in the measurement mode and data acquisition from gas analyzers and other measuring devices were controlled by a computer through an interface following a given algorithm. The measurement results were added to the database for compiling the pollution map and predicting the transport of dangerous aerosol and gas emissions (Fig. 2).

2.2. Ecologo-meteorological devices

Automated meteorological system AMK-01 was made based on the previous results achieved at IOM in the field of acoustic meters of the temperature and the three-component wind velocity vector.[2,15] It provides for measurement of the basic meteorological quantities (temperature, pressure, humidity, wind speed and direction) in the temperature range from − 50 to +50°C with the sampling frequency up to 100 Hz, which allows the turbulent characteristics of the atmosphere to be determined at the place of its location. In its characteristics, the AMK-01 is highly competitive with foreign analogs and can be used at stations of the Russian meteorological network. The AMK-01 is produced in the following versions: (1) stationary version for automated monitoring of meteorological parameters with transfer of primary measurement data to a remote computer through a cable and/or telephone line; (2) mobile meteorological station installed aboard land and water carriers; (3) knapsack self-contained portable meteorological station.

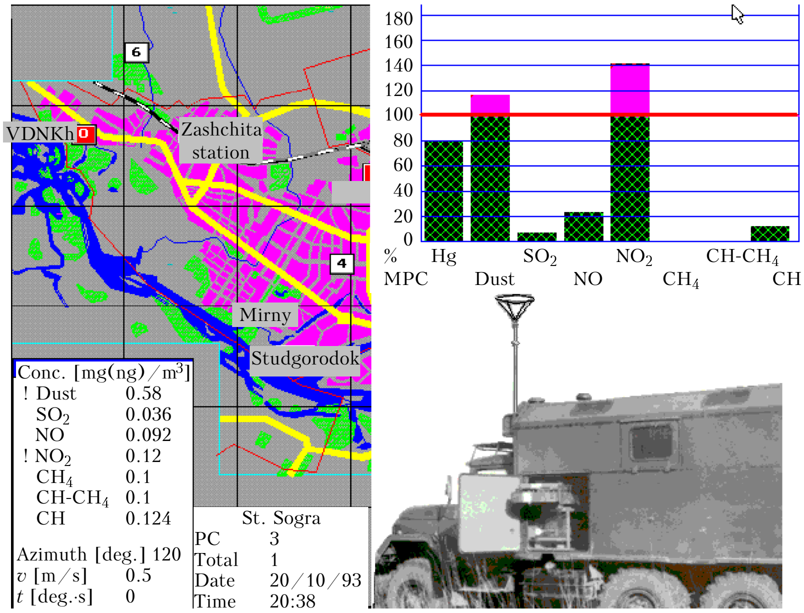

Fig. 2. Station "Ekolid" ready for measurements. Sites, at which measurements were conducted, are shown by points on the map of Ust'-Kamenogorsk. Tables on the left give the documented results of one measurement. Diagrams on the top show the excess over the maximum permissible level for some pollutants.

Laser densitometer for measurement of the mass concentration of dust. Its operation is based on the phenomenon of laser radiation extinction by aerosols in a local volume with application of a two-ray measurement scheme and a multipass cell.[16] At the cell length of 0.5 m, the total travel path can be up to 100 m long, what significantly increases the densitometer sensitivity. The densitometer has passed metrological certification in the Mendeleev Research Institute of Metrology. Parameters of the analyzed dust: mean particle radius of (1.2 ± 0.1) μm and density of 2.16 g/cm^3. At 64 passes, the range of the measured dust concentration is 3–18 mg/m^3 at the 25-% relative measurement error. The densitometer was included in the mobile automated station "Ekolid."

Optical humidity meter. The deficit of up-to-date devices for measuring the absolute and relative humidity at stations of the Russian meteorological network stimulated development of new gauges. A prototype of an optical hygrometer was developed at the IOM. This device has no foreign analogs.[2,15] It uses the differential absorption technique with radiation from two light-emitting diodes in the near-IR. The analyzed air is purged through an optical cell, and the radiation from two light-emitting diodes at the wavelengths of 0.94 nm (on the H_2O absorption band) and 0.86 nm (off the absorption band) passes through the cell. The difference signals from photodetectors measuring the radiation at two reference and two working wavelengths after digitizing are used for calculation of the parameter sought.

Standard meteorological devices. On the request from the West-Siberian Department of the Hydrology and Meteorology Service of the RF, the IOM produced various auxiliary equipment. In 1998–2000, twenty coring winches, fifty Wilde weathervanes (both these devices were certified as useful models), as well as other accessories for hydrology and meteorology services were produced and handed over for use.

2.3. Equipment for air pollution monitoring

The presence of various gaseous pollutants in the atmosphere significantly affects the ecological situation in industrial centers. The IOM continues its works aimed at modernization of the earlier developed equipment for monitoring of the concentration of heavy metals in the environment, as well as designs new devices for monitoring of the concentration of technogenic gases in smoke emissions.

Portable mercury gas analyzer RGA-11M. In the 90s, the techniques for measuring the mercury content in the atmospheric air, water, soil, and bioproducts with a designed RGA-11 gas analyzer were developed and certified, and the RGA-11 was included in the State Measuring Technique Register.[17] Then the RGA-11 was modernized. With the unchanged optical arrangement, its size and mass were decreased markedly (down to 5 kg). In the recording scheme, analog processing of signals was replaced with the digital one. The range of the measured concentration of mercury vapor in air (30–10^4 ng/m^3) and the sensitivity were kept at the same level. The RGA-11M serial model has been patented (Fig. 3).

Gas analyzers of DOG series. In recent years, the IOM develops gas analyzers for measurement of the concentrations of main technogenic gases (SO_2, NO, CO), which are present in smoke emissions of fuel burning plants and engines. A part of a gas flow from a flue is continuously blown through the measuring cell of a device employing the principle of differential absorption in the UV spectral region.[18]

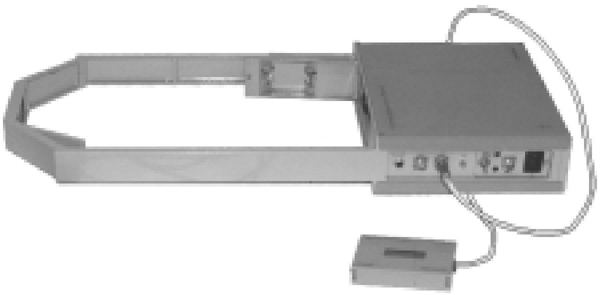

Fig. 3. The appearance of the modified RGA-11M gas analyzer with a remote indicator.

The DOG-1 gas analyzer for determination of the NO concentration was certified in the Mendeleev Research Institute of Metrology and included in the State Measuring Technique Register. A series of DOG-1 analyzers (60 items) was installed at all large gas heat and power stations of Tyumen Region. The DOG-3 gas analyzer for simultaneous monitoring of the NO and SO_2 concentrations in smokes of boilers burning any type of fossil fuel is now prepared for serial production. These gas analyzers are analogs of the corresponding foreign devices.

3. Metrological provision of technical tools and monitoring

Measurement tools were developed at the IOM keeping in mind the requirements of basic state standards in metrology, which were put in force mostly in the 80s. For the last decade, organizational and technological issues in metrology were changed in connection with the law "On the Consistency of Measurements" approved in 1993. At the same time, the state metrological control and inspection are kept in such fields as public health, environmental protection, etc. Therefore, when developing systems for ecological monitoring, it is necessary to follow the requirements of the corresponding normative documents.

Development of new devices and systems requires the presence of three basic items of monitoring: measurements, estimation, and prediction.[19] The measurement unit, in its turn, is also characterized by three aspects: measurement methods, techniques, and tools. They all together should provide for real-time monitoring of the state and dynamics of natural and anthropogenic systems or their components, as well as monitoring of the intensity of ecological factors. Thus, metrological provision of measurements conducted at climate and ecological monitoring is a combination of scientific principles, organizational measures, technical tools, and rules needed to achieve the consistency and required accuracy of measurements.

Metrological requirements to techniques are given in the State Standard R 8.563-96 "Measurement techniques." The techniques are certified by the same bodies, which test measurement tools. The list of environmental monitoring techniques active in Russia, which are regulated by the State Standards, normative documents of the State Ecological Committee of the RF, regulating documents of the Russian State Hydrology and Meteorology Committee and the Russian Committee of Water Resources, methodic guidelines of the State Committee of Sanitary and Epidemiological Inspection, as well as other documents is given in Ref. 19. Thus, for example, in 1998 there were more than 180 techniques for monitoring of the physical and chemical parameters of atmospheric air, more than 30 techniques for monitoring the atmospheric aerosol and precipitation, and more than 40 techniques for monitoring of industrial emissions.

In view of the above-said, the process of the development of measurement tools based on the use of new physical phenomena and measuring methods is rather long. A significant part of this process consists in various tests with the use of secondary and working standards of measured parameters and standard samples of composition or properties of a substance. Execution of the whole cycle of works is connected with creation of the needed material and technical basis.

Technical tools being a part of any system of ecological monitoring should be efficient in a wide range of external factors. The developed devices should be tested not only under normal climate conditions, but also under all operating conditions. In this connection, the IOM has organized its own Checkout Test Station (CTS) to test developed devices under various climate and mechanical impacts, as determined by normative documents. This Station includes a set of heat-chambers (temperature range from −70 to +100°C), humidity chamber (humidity from 10 to 100% in the temperature range from 10 to 60°C), thermal/pressure chamber (pressure from 1 to 770 mm Hg), shock table (multiple shocks with acceleration up to 150 g), vibration table (effect of sinusoidal vibration with acceleration up to 40 g in the frequency range from 20 to 2500 Hz), and table for checkout of insulation strength and resistance in supply circuits.

The Geophysical Station existing at the IOM since the mid-90s and equipped with standard measuring tools[20] facilitates some comparative tests of new devices designed for climate and ecological monitoring. This Station is useful for refining measurement techniques. The following use of new certified devices and measurement techniques at the Geophysical Station leads to the growth of its technological potential and extends its capabilities.

Conclusion

New devices and systems made at the IOM[2] significantly extended the instrumental base of the IAO and for 25 years favored the development of atmospheric optics research. Some devices were used at the IOM for comparative tests with standard devices. Such tests were conducted under field conditions on customer's proving grounds or at the IOM Basic Experimental Station, what allowed their refinement and modernization in the process of operation testing. Then some of these devices were used at the IOM Geophysical Station.[20]

New devices and systems for ecological and meteorological monitoring of the atmosphere are developed either within research programs of the Siberian Branch of the Russian Academy of Sciences (for regional ecological monitoring) or on requests from industrial enterprises (for monitoring of industrial emissions and air pollution).

References

1. V.E. Zuev and M. Kabanov, Atmos. Oceanic Opt. **15**, No. 1, 2–7 (2002).

2. M.V. Kabanov and A.A. Tikhomirov, Atmos. Oceanic Opt. **10**, Nos. 4–5, 236–248 (1997).

3. M.V. Kabanov, ed., *Regional Monitoring of the Atmosphere.* Part 2. *New Devices and Measurement Techniques* (SB RAS Publishing House, Tomsk, 1997), 295 pp.

4. P.P. Vaulin, A.F. Kutelev, A.A. Tikhomirov, and I.Ya. Shapiro, in: *Abstracts of Reports at V All-Union Symposium on Laser and Acoustic Sensing of the Atmosphere,* Tomsk (1978), Part IV, pp. 8–15.

5. Yu.F. Arshinov, Yu.S. Balin, S.A. Danichkin, V.E. Zuev, A.F. Kutelev, I.V. Samokhvalov, and A.A. Tikhomirov, in: *Proceedings of Bulgarian-Russian Seminar on Laser Methods and Tools for Measurement and Monitoring of Environmental Parameters* (Publishing House of the Institute of Electronics BAS, Sofia, 1985), pp. 83–88.

6. Yu.S. Balin and A.A. Tikhomirov, in: *Regional Monitoring of the Atmosphere.* Part 2. *New Devices and Measurement Techniques*, ed. by M.V. Kabanov (SB RAS Publishing House, Tomsk, 1997), pp. 16–34.

7. N.P. Krasnenko and A.A. Tikhomirov, Atmos. Oceanic Opt. **15**, No. 1, 43–52 (2002).

8. Yu.A. Ivakin, I.Ya. Shapiro, and Yu.F. Yatskeev, in: *Prediction and Monitoring of the Optical-Meteorological State of the Atmosphere* (TB SB AS USSR, Tomsk, 1982), pp. 54–60.

9. G.F. Vakurov, A.N. Volkov, and S.M. Sakerin, Zh. Prikl. Spektrosk. **39**, No. 3, 503–507.

10. N.I. Vagin, P.P. Vaulin, B.N. Denchik, and R.Sh. Tsvyk, Opt. Atm. **1**, No. 6, 90–97 (1988).

11. N.P. Soldatkin, in: *Regional Monitoring of the Atmosphere.* Part 2. *New Devices and Measurement Techniques*, ed. by M.V. Kabanov (SB RAS Publishing House, Tomsk, 1997), pp. 217–232.

12. S.M. Sakerin, D.M. Kabanov, and N.P. Soldatkin, in: *Regional Monitoring of the Atmosphere.* Part 2. *New Devices and Measurement Techniques*, ed. by M.V. Kabanov (SB RAS Publishing House, Tomsk, 1997), pp. 243–253.

13. V.V. Klyuev, ed., *Safety of Russia. Legal, Social-Economic, and Scientific-Technological Aspects. Ecological Diagnostics. Encyclopedia* (Mashinostroenie, Moscow, 2000), 496 pp.

14. V.F. Baryshnikov, L.D. Zemlyanovskii, Yu.A. Ivakin, V.L. Perovskii, A.A. Teleganov, A.A. Tikhomirov, L.P. Cherepanov, and I.Ya. Shapiro, Atmos. Oceanic Opt. **7**, No. 2, 93–95 (1994).

15. A.A. Azbukin, V.V. Burkov, and V.A. Korol'kov, in: *Regional Monitoring of the Atmosphere.* Part 2. *New Devices and Measurement Techniques*, ed. by M.V. Kabanov (SB RAS Publishing House, Tomsk, 1997), pp. 208–217.

16. V.I. Kolobov, A.N. Levchenko, A.A. Teleganov, A.A. Tikhomirov, I.Ya. Shapiro, L.P. Cherepanov, and Yu.F. Yatskeev, Atmos. Oceanic Opt. **7**, Nos. 11–12, 879–881 (1994).

17. A.B. Antipov, E.Yu. Genina, G.V. Kashkan, and N.G. Mel'nikov, Atmos. Oceanic Opt. **7**, Nos. 11–12, 886–889 (1994).

18. A.A. Azbukin, M.A. Buldakov, B.V. Korolev, V.A. Korol'kov, and I.I. Matrosov, Atmos. Oceanic Opt. **15**, No. 1, 74–77 (2002).

19. L.K. Isaev, ed., *Monitoring of Chemical and Biological Parameters of the Environment* (Ecological-Analytical Information Center "Soyuz", St. Petersburg, 1998), 896 pp.

20. I.I. Ippolitov, M.V. Kabanov, and V.N. Marichev, Atmos. Oceanic Opt. **15**, No. 1, 30–36 (2002).