SOME PROBLEMS IN ECOLOGICAL MONITORING OF THE ATMOSPHERE OF LOCAL TERRITORIES

V.S. Komarov

*Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk*
Received November 15, 1993

Some problems in ecological monitoring of the atmosphere of local territories (on the scale of a city or an industrial region) are discussed. The problems center around optimization of networks for ecological observations and development of automated systems for in situ *monitoring of air pollution. Some aspects of the methodology of construction of municipal information system of intellectual decision support for problems on atmospheric ecology are also discussed in the paper.*

1. INTRODUCTION

The current stage of development of mankind is characterized by threatening contradictions that have arisen between the nature and the society due to fast development of productive forces. The most serious hazard among such contradictions is the constantly increasing pollution of the environment – the atmosphere, the hydrosphere, and the biosphere, resulting in disturbance of the ecological balance. The planetary atmosphere in particular, constantly affected by anthropogenic factors, is currently losing its unique self–purification and recuperative properties, so that significant changes of the composition of air ensue (solid particulate matter containing soot, industrial dust, laden with base metals, minor gas pollutants, such as SO_2, CO, CH_4, NO_x, etc., and other impurities accumulate in the air). All that might quite soon bring about deleterious changes in the physical state of the atmosphere, comparable in their scale to those expected from a nuclear war.[1]

Man's industrial impact upon the natural environment, including the atmosphere, is so deep that the most unhealthy ecological situation is formed in certain parts of Russia, as well as in other areas of the globe, which calls for permanent monitoring and routine ecological expertise. These actions should be based on data specially collected, so that urgent measures must be taken to improve the situation. Since the broad expanse of our country, the diversity of its climatic, ecological, and social conditions in separate regions leave their mark, making difficult or even excluding any universal methodology of ecological monitoring throughout Russia, it makes sense to try to solve various problems in such monitoring on a regional level initially.

All things considered together with the fact that local disturbances of the environment usually tend to grow into global, so as to change fundamental properties of the atmosphere (such as its chemical composition, temperature and humidity, the state of the ozone screen, the radiation background, etc.), extensive applied scientific studies, aimed at solving various problems in ecological monitoring of the atmosphere of local territories appear necessary in the nearest future. Large cities, separate industrial zones, selected regions, etc. are among such local areas. The problems of such observations, which we see as the most urgent and calling for their fastest implementation, include:

– organizing an optimal network for stationary ecological observations, so as to monitor objectively and reliably the level of air pollution in local territories;

– developing automated municipal systems for ecological monitoring of the atmosphere (AMSEMA) comprising both ground–based and airborne means of monitoring and geoinformation technology for data processing and aimed at continuous monitoring of air pollution at local level (a city, a region, an industrial zone), routine estimate of the current and future ecological situations, and recommendations for Environmental Protection Agencies, if a need arises to normalize such a situation in case of an ecological hazard.

The present publication considers certain aspects of the above problems and ways to solve them.

2. OPTIMIZING THE NETWORK FOR ECOLOGICAL OBSERVATIONS AS AN IMPORTANT FACTOR IN ECOLOGICAL MONITORING OF THE ATMOSPHERE OF LOCAL TERRITORIES

The existing national system for monitoring of atmospheric pollution is based on a network of stationary ground–based posts of Roskomgidromet equipped with POST–1 and POST–2 booths with GMK–3 and GKP–1 gas analyzers,[2] as well as on separate and poorly coordinated ecological laboratories belonging to various state departments. Note that the spatial arrangement of stationary posts is usually quite approximate. It is based on special studies of the examined territory, in particular, its physico–geographical and climatic features, the level of air pollution, the distribution of sources of such pollution, etc. In addition, the dominating approach to organization of regional networks for ecological observations remains subjective, that is, the number of stationary posts is increased in proportion to population of either populated area affected by anthropogenic pollution. For example, Ref. 3 states that the network for ecological observations should number 5–10 stationary posts for areas numbering up to 500 thousand inhabitants, while if that number exceeds 1 million, the network should include 10–20 stationary and en route posts. Meanwhile, even if these conditions are met (which is never the case in practice), sharp spatial and temporal inhomogeneities of the emissions render such a network unrepresentative enough. Indeed, according to opinion of experts of the A.I. Voeikov Main Geophysical Observatory, St. Petersburg, an objective estimate of air pollution level of both large cities and industrial zones calls for the data of ecological observations with a spatial resolution of 100×100 m.

0235-6880/94/02 66-05 $02.00

In addition, when organizing an optimal network for ecological monitoring, one should also account for possible pollution of air basin in the examined area by pollutants penetrating from other parts of the region.

One possible way to break this deadlock is the use of routine data of spaceborne ecological monitoring of the atmosphere by means of various space–based sensors (e.g., space–based lidars[4]). However, low accuracy of remote sensing in combination with its low spatial resolution, so far typical for satellites employed in the exploration of natural resources and meteorological satellites,[5] prevent their use for detailed local and regional monitoring of air pollution in local areas (such as a large city or a separate industrial zone).

Thus all the enumerated circumstances placed the search for alternative, more reliable approaches to the problem of organizing an optimal network for ecological observations on the agenda. The most reliable and efficient solution to that problems can be obtained by mathematical simulation based on the assumption that fields of pollution within the different territorial–ecological areas remain quasi–homogeneous, which accounts for the random character of their fluctuations affected by numerous factors.

Indeed, according to Ref. 2, concentration fields of various pollutants I_{il} (i is the current index of pollutant, l is the area affected by atmospheric pollution) varying in space R and in time t, are formed under the random effect of pollution sources $Q_i(R, t)$ and the hydrometeorological characteristics of a medium, i.e.

$$I_{il}(R, t) = f(Q_i, V_R, K_R, v_g, \ldots), \tag{1}$$

where V_R, K_R, and v_g are the wind speed and the coefficients of eddy diffusion and gravitational sedimentation, respectively. The dependence of the form

$$Q_i(R, t) = \sum_j q_{ij}(R, t) \tag{2}$$

is also obvious, where q_{ij} is the amount of ith pollutant, emitted by individual source. It may be assumed that the formation of field $I_i(R, t)$ is controlled, to a large extent, by the spatial distribution of these sources as well as by their strengths varying with time.

From the preceding, it may be stated that the numerical methods of solving the problem in optimizing the network for ecological observations, i.e., choosing the minimum number of sensors and arranging them optimally in the examined area (with the aim of monitoring of the spread of pollutants) are more objective and therefore, more promising than a simple increase of the number of ecological posts in the same area, in spite of the fact that certain physical factors are taken into account during such an increase.

To solve the problem of optimal arrangement of sensors, the technique of parametric identification has lately found quite a wide use,[6–11] which accounts for the spatial dynamics of the system. The essence of this technique is the following: using the available measurement data for $Y(\tau)$ at $\tau \in (0, t)$ and a certain prescribed mathematical model of the form

$$\frac{\partial X(t, z)}{\partial t} = L_z(\theta)\, X(t, z) + D(t, z)\, U(t, z) + W(t, z) \tag{3}$$

for $z \in \Omega$, $t \in (0, t_f)$

(see Refs. 9 and 11), one determines the set of N sensors at points z^j (here $j = 1, 2, \ldots, N$), so as to maximize a certain criterion for accuracy of identifying the unknown parameters θ, where t is the time of observations, $z = [z_1, z_2, z_3]^{\mathrm{T}}$ is the vector of spatial coordinates of sensors (posts), T is the transposition operator, $X(t, z)$ and $U(t, z)$ are vectors of the variables of state and of control, respectively, $L_z(\theta)$ is the matrix operator with the unknown vector of parameters θ, $D(t, z)$ is the prescribed matrix, $W(t, z)$ are random disturbances of the object. To solve the problem thus posed either the Fisher information criterion (see, e.g., Ref. 10) or the criterion for minimizing the rms error[6,11]

$$J(\theta) = \left[\sum_{j=0}^{N} \int_0^{t_f} || Y(t, z^j) - H(t, z^j; \theta) ||^2 \, d\, t \right], \tag{4}$$

is used, where $|| \cdot ||$ is the norm in the Euclidian space.

The main disadvantages of the techniques of parametric identification for systems with distributed parameters, including the ecosystem (as envisaged when optimizing the network for ecological observations) are as follows: approaches to estimating the quality characteristics of such techniques on the basis of the actual observational data are poorly developed as yet. These techniques fail to account for the mobile sensors in numerical schemes (currently available). Solving these problems would make it possible to perform routine monitoring of the atmospheric pollution using both a certain number of stationary sensors and mobile measurement systems, for which their optimal routes and speeds could then be specified.

Along with parametric identification, other techniques are also employed to optimize networks for ecological monitoring (assuming pollution is randomly formed), in particular those based on the theory of experimental design (see, e.g., Refs. 12 and 13), and that using the correlation (structure) functions of spatial distribution of pollutants.[14]

More detailed and extensive data on the techniques currently applied to the solution of the problems of optimal arrangement of air pollution monitoring posts may be found in Refs. 7 and 13.

3. AUTOMATED SYSTEMS FOR LOCAL AND REGIONAL MONITORING OF ATMOSPHERIC POLLUTION: STATE OF THE ART AND PROGRESS TO DATE

Accumulated experience in actual ecological monitoring of the atmosphere in various regions of our country definitely shows that environmental protection should be organized and implemented on a regional basis. Such regions may be selected against both spatial and economic criteria, and the necessary measures are based on reliable real–time and comprehensive data on the level of air pollution not only near the sources of industrial emissions, but also in large industrial centres and its environs. It is demonstrated above that the existing national system for ecological monitoring of the atmosphere of local territories does not meet the current practical needs, particularly in what concerns the real–time and representative nature of observations, or the automation of data collection and processing. Therefore, it is urgent to develop an efficient automated system for local and regional monitoring of atmospheric pollution, on the basis of the state–of–the–art hardware (first of all, the most efficient and promising systems of laser sensing of the atmosphere[4,15]) and modern information technology, e.g. the geoinformation technology. The latter has found wide application abroad to estimate natural resources.[16,17] Such a system may serve as a basic element for the national system of environmental protection (see Fig. 1, which shows an approximate structure of such a system). It should meet certain criteria, namely:

– complement (with its new automated ground–based systems for ecological monitoring) the standard network for ecological observations, already existing in the country;

– include, among other things, automated mobile stations and airborne measurement and monitoring complexes placed on board aircrafts, helicopters, balloons, etc.;

– be capable of integrating results of ecological monitoring from a comprehensive set of measurement sensors, using its communication and data processing subsystems;

– provide for reliable local estimate and forecast of air quality in a city (or an industrial center) on the basis of background (climatological) and current information coming from all the monitoring systems arrangement in the city and its environs;

– be highly adaptable to higher level automated systems, even to national and global ones.

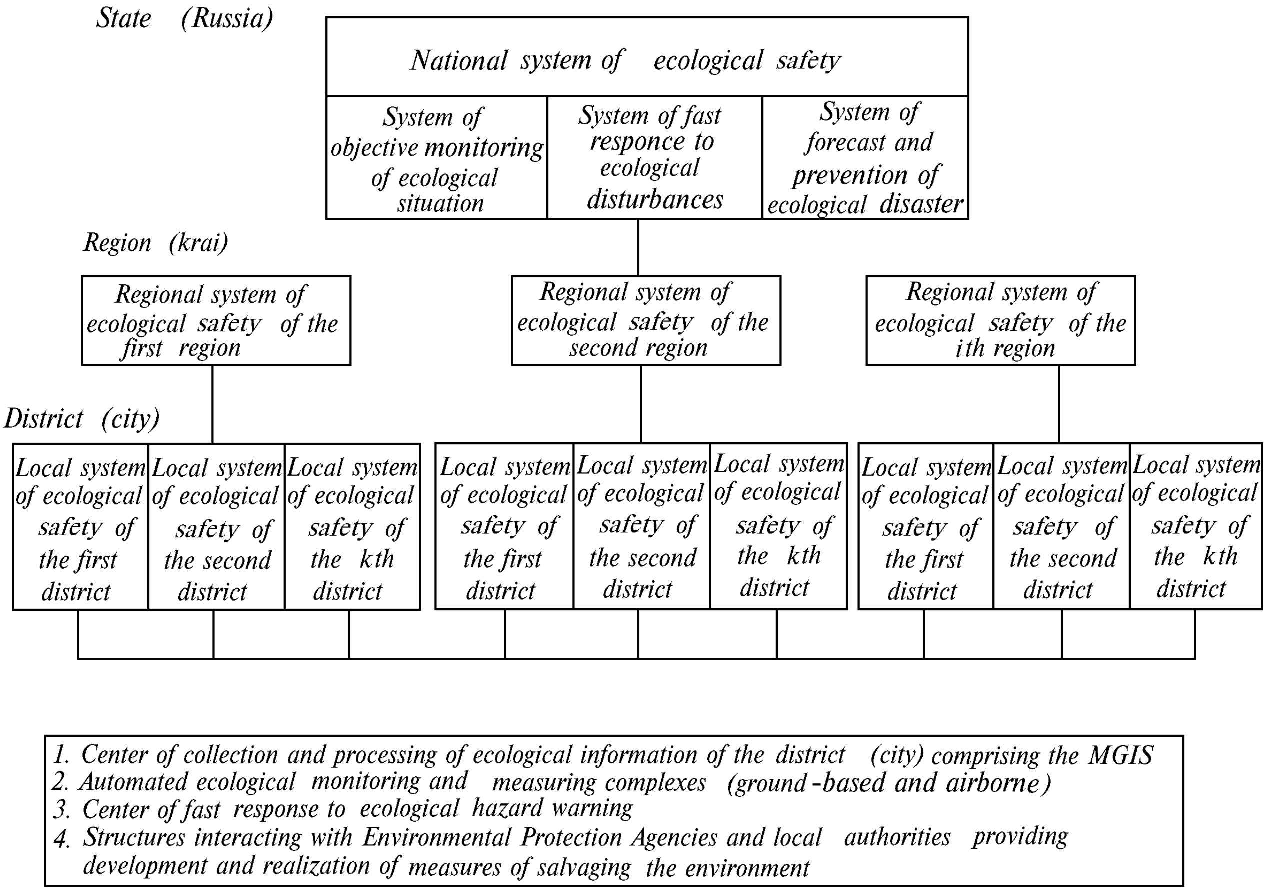

FIG. 1. Approximate structure of national system of ecological safety.

Analysis of the available publications indicates that while a number of such automated systems has already come into being in foreign countries, sometimes covering entire cities or even regions (see, e.g., Refs. 18 and 19), only one system is known in our country. This is the ANKOS–AG,[2,20] whose principal functions are:

–automated collection and accumulation of data on air pollution by principal pollutants (CO, SO_3, NO_x, $\Sigma CH-CH_4$, and O_3) as well as on meteorological conditions, characterized by temperature and wind characteristics;

– detection of high levels of pollutants, which exceed the Maximum Permissible Concentrations (MPCs) and broadcast of storm warnings;

– short–range forecast of the level of pollution;

– analyzing the reasons for exceeding the MPCs and providing recommendations for individual enterprises to reduce the amount of toxic emissions under adverse meteorological conditions.

However, this system, just recently put to test runs, did not find wide use. Which is why the problem of developing an automated system for ecological monitoring of local air basin is still under close scrutiny of experts, and its fastest solution is the main goal of the Federal Special–Purpose Scientific–Technical Program "Ecological Safety of Russia",[21] planned for 1993–1995.

Despite the well–known difficulties associated with solving the problem of automated ecological monitoring of local air basins, certain prospects have recently been opened which promise success in the nearest future. The following important factors facilitate such a development:

– first, new efficient means of remote sensing are implemented since lately in the existing traditional systems for ecological monitoring. These are laser radars (see, e.g., Ref. 22), which are winning stronger and stronger positions;

– second, modern mobile automated stations are expected to come to ecological service soon. They are designed to diagnose industrial pollution of air on a scale of an industrial city (such a station, "ECOLID" is described in Ref. 23);

– third, special aircraft laboratories, aimed at local and regional monitoring of the state of environment are being increasingly used for routine ecological observations (note among them the OPTIK–E AN–30 aircraft–laboratory, specifically developed by experts of the Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, to sound urban and industrial atmosphere, which has demonstrated high efficiency during test flights[24,25]);

– fourth, introduction of powerful computers and of modern information technology (e.g., geoinformation) has made feasible highly efficient automated systems for intellectual decision support of problems in ecological monitoring of the atmosphere.

All the above opens wide opportunities for developing principally new automated systems for local (municipal) ecological monitoring of the atmosphere. Which is why, based on the experience gained, the authors of Ref. 26 suggested for implementation in nearest future the GOROD system for local monitoring of air pollution ("The City"). It is constructed as a centralized system and includes three basic monitoring subsystems: a set of laser and acoustic radars, stationary ground–based and automated mobile stations for ecological observations, and a control unit that controls the operation of monitoring and measuring sensors and supports all the routines of data collection and processing.

However, even the GOROD system does not meet in full current requirements upon such a system. The project does not envisage any objective numerical approach to the solution of problems of optimal arrangement of monitoring and measuring sensors (such as the parametric information technique[8,9]). This problem is solved by the authors of Ref. 26 who, however, followed a less effective approach. They calculated autocorrelation functions of the field of pollutants measured during airborne sounding 100–200 m above the city. Gridpoints outside plumes of pollution from different enterprises within the city, under various winds, are excluded upon qualitative considerations.

In our mind, such an approach cannot be objective enough, since it does not in any way account for the specific features of the surface atmospheric layer up to 50–100 km[28] and neither for highly diverse winds and eddy diffusion within the city itself, which actually determine the spread of pollutants. Neither it accounts for the properties of the underlying surface (first of all, for its roughness), for street orientation or positioning of living and industrial buildings (especially tall ones), nor the presence of the island of heat in the centre of the city, etc.[2]

In addition, the principles of modern geoinformation technology were not applied to the design of the subsystem for data collection and processing in the GOROD system. Meanwhile that is one of its central elements, and such a technology may serve an efficient means of ecological monitoring of the atmosphere of local areas.

4. BASIC PRINCIPLES OF MUNICIPAL SYSTEMS DESIGNED ON THE BASIS OF GEOINFORMATION COMPUTER TECHNOLOGY

The existing monitoring network is uncapable to solve such key problems in ecological monitoring of the atmosphere as:

a) early detection of sudden industrial emissions into the urban atmosphere due to accidents or technological failures, aimed at taking real–time environmental protection measures to prevent possible serious consequences of pollution;

b) real–time assessment of spread of pollutants emitted into the atmosphere in the course of large–scale or catastrophic accidents, so as to provide for ecological safety in the disaster zone;

c) nowcasting and short–range forecasting of the processes of atmospheric pollution on the basis of observational data provided solely by the existing network of stationary ecological stations.

Thus when developing a modern municipal system for ecological monitoring of the atmosphere, capable of solving all the above key problems, one needs not only to update and expand the existing network for ecological observations (including into it the GOROD–type automated system for routine monitoring of the atmosphere[26] and conducting occasional airborne sounding), but also to construct an efficient information computer system, which would provide the intellectual decision support of various ecological problems.

Since many aspects of modernizing the network for ecological monitoring are covered by the available publications,[19,20,22–24,26,29] it seems unnecessary to dwell on them at any length. Instead, we focus on certain aspects of development of a standard automated information system, aimed at intellectual decision support of the problems in local ecological monitoring of the atmosphere (on a city scale, to be specific). We believe a Municipal Geoinformation System (MGIS) based on up–to–date computer technology could solve this problem. Such a system should be capable most efficiently

– to organize various data and enter them into a respective spatiotemporal matrix;

– to elaborate a spatio–structural model of the examined territory;

– to give optimal intellectual support to the procedures of ecological monitoring of the atmosphere, including accumulation and input of data from various monitoring sensors, their analysis and processing (so as to assess the current and future levels of atmospheric pollution), output data presentation in tabulated, graphic, cartographic, etc. formats;

– to open wide capabilities for manipulating multilayered and diverse information (e.g., geographic, climatological, ecological, etc.).

Such a geoinformational system (GIS) should, on the one hand, be developed on the basis of an IBM–compatible personal computer (AT–386/486) with a coprocessor and periphery including:

– units for data input into computer medium, such as manual tracking digitizers, scanners (with plat and drum, TV and mechanical scanning systems), as well as instrumentation to present positional data in raster and vector formats;

– data output and documentation devices, including videoterminals with single– and double–screen visualization drivers (MDA, HERCULES, EGA, VGA, etc.), matrix and laser printers, plotters, etc.

On the other hand, GIS should be based on the already existing application and system software, such as the ARC/INFO GIS,[30] designed especially for IBM–compatible personal computers, which support input of the spatially distributed data, vector presentation of point and linear objects and objects of other shapes as sets of information layers, the formation and storage of their topologic–geometric attributes, various analytic and graphic operations for data processing, including generation of cartographic information and manipulations with its various information layers.

Such an approach to MGIS will permit us to meet in full certain criteria, which are listed below.

1. A municipal geoinformational system should be local in character and be constructed with the allowance for specific atmospheric and ecological processes and state of environment within the examined area.

2. MGIS should be highly capable of integrating, processing, systematizing, and analyzing diverse information (possible of varying scale and obtained with varying periodicity).

3. Software of MGIS should support computer databases with spatially distributed data, reflecting the geographical, climatological, natural resources, and other peculiarities of the examined area, and contain a certain "mathematical polygon", which would include a set of models of different types (physico–statistical, hydrodynamic, and photochemical), which are necessary to model atmospheric processes and to estimate the current and future ecological situation.

4. A municipal geoinformation system should have a distributed configuration, based on a computer network, providing for interaction between the data processing center, where the central working station operates, with both remote stationary and mobile sensors, as well as with airborne monitoring systems.

5. System architecture of a municipal GIS should envisage high–performance operation of all its subsystems and should support its modular principle, so that additional program modules may be integrated into it in a straightforward manner.

6. A municipal GIS must include a subsystem for automatic decision–making, so as to analyze complex ecological situations, occurring within the examined area, estimate the possible consequences of the scenarios they follow, and provide recommendations for Environmental Protection Agencies so that they make well–grounded decisions to minimize environmental losses.

7. A municipal GIS must permit its integration into automated information systems of higher levels (from regional to national or even global).

The structure and functional capabilities of a GIS of such class are considered in Ref. 30, see current volume.

Thus application of geoinformation technology to develop systems of ecological monitoring of the atmosphere of local areas (e.g., separate cities) permits one to provide a universal integrated approach to these problems, so that a scientific ground is layed for intellectual decision support for problems of environmental protection and safety.

REFERENCES

1. P.N. Belov, Bulletin of Moscow State Univ. Ser. 5: Geography, No. 5, 16–24 (1990).
2. A.M. Vladimirov, Yu.A. Lyakhin, and L.T. Matveev, *Environmental Protection* (Gidrometeoizdat, Leningrad, 1991), 424 pp.
3. N.G. Rybalskii, O.L. Zhaketov, and A.E. Ul'yanova, *Handbook for Expert and Inventor.* I. *Ecological Aspects of Invention Expertise* (VNIIPI, Moscow, 1989), 356 pp.
4. V.E. Zuev and V.V. Zuev, *Remote Optical Sensing of the Atmosphere* (Gidrometeoizdat, St. Petersburg, 1992), 231 pp.
5. M.A. German, *Space Research Techniques in Meteorology* (Gidrometeoizdat, Leningrad, 1985), 351 pp.
6. H. Malebranche, Int. J. Sist. Sci. **19**, No. 8. 1387–1395 (1988).
7. C.S. Kubrusly and H. Malebranche, Automatics **21**, No. 2, 117–181 (1985).
8. N.S. Gaitman, V.O. Bogdanov, and D.V. Kneller, Automatics and Telemechanics, No. 6, 5–17 (1982).
9. Yu.S. Korbich and D. Utsinski, in: *Proceedings of the Fourth International Scientific–Technical Conference*, Kiev (1990), pp. 101–107.
10. E. Rafajiowitcz, IEEE Trans. Aut. Control. **AC–28,** No. 7, 806–817 (1983).
11. V.V. Azhogin, M.Z. Zgurovski, and Yu.S. Korbich, *Techniques for Filtering and Control of Stochastic Processes with Distributed Data* (Vysshaya Shkola, Kiev, 1988), 447 pp.
12. U.N. Brimkulov, T.K. Krug, and V.L. Savanov, *Experimental Design to Study Random Fields and Processes* (Nauka, Moscow, 1986), 351 pp.
13. V.V. Penenko and A.E.Aloyan, *Models and Techniques for Environmental Protection* (Nauka, Novosibirsk, 1985), 256 pp.
14. E.Yu. Bezuglaya, *Monitoring of Pollution of the Urban Atmosphere* (Gidrometeoizdat, Leningrad, 1986), 200 pp.
15. V.E. Zuev, B.V. Kaul, I.V. Samokhvalov, et al., *Laser Sounding of Industrial Aerosols* (Nauka, Novosibirsk, 1986), 188 pp.
16. G. Schultink, Can. J. Remote. Sens. **9**, No. 1, 4–18 (1984).
17. W.G. Shope and R.W. Paulson, IAHS Publ., No. 160, 13–21 (1986).
18. M. Nadal, Rev. Gen. Scenr., No. 66, 62–64 (1987).
19. N.A. Tumanova, *Automated Systems for Monitoring of the Quality Characteristics of the Environment* (VNTIC, Moscow, 1989), 107 pp.
20. A.V. Primak, in: Automation of Monitoring of Environmental Pollution (Nauka, Moscow, 1985), pp. 14–21.
21. *Federal Special–Purpose Integrated Scientific–Technical Program "Ecological Safety of Russia (1993–1995)"*, Zelenyi Mir, Special Issue, December, 3–14 (1992).
22. Yu.S. Balin and I.A. Razenkov, Atmos. Oceanic Opt. **6**, No. 2, 104–114 (1993).
23. V.F. Baryshnikov, L.D. Zemlyanovski, Yu.A. Ivakin, et al., Atmos. Oceanic Opt. **7**, No. 2, 93–95 (1994).

24. B.D. Belan, Atmos. Oceanic Opt. **6**, No. 1, 1–18 (1993).
25. B.D. Belan, Atmos. Oceanic Opt. **6**, No. 2, 124–135 (1993).
26. Yu.S. Balin, B.D. Belan, A.N. Nadeev, and M.V. Panchenko, Atmos. Oceanic Opt. **7**, No. 2, 86–92 (1994).
27. S.P. Khromov and L.N. Mamontova, *Meteorological Dictionary* (Gidrometeoizdat, Leningrad, 1974), 568 pp.
28. V.V. Zuev and V.E. Zuev, *"Laser ecological monitoring of atmospheric gas constituents,"* Advances in Science and Technology, Ser. Meteorology and Climatology **20**, Moscow, VINITI (1992), 182 pp.
29. PC ARC/INFO, ESPI, California, USA (1991).
30. V.E. Zuev, V.S. Komarov, A.N. Kalinenko, and S.A. Mikhailov, Atmos. Oceanic Opt. **7**, No. 2, 72–77 (1994).