SYSTEM "GOROD" FOR ROUTINE MONITORING OF AIR POLLUTION IN AN INDUSTRIAL CENTER

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In this paper we discuss a concept, a structure, and a system for routine monitoring of air pollution in an industrial center which is under development at the Institute of Atmospheric Optics, SB RAS. The system combines two basic approaches to the development of such systems, i.e., spatially representative and emission–source oriented. A combination of these principles is achieved by introducing aerosol scanning and Raman lidars into the system structure. Specifications of the system and its operation are also described in the paper.

The problem of air pollution and, correspondingly, of the environmental monitoring has assumed particular importance in the last 20–30 years, when an increasing number of irreversibly drastic changes of the environmental conditions in different regions of the Earth resulted in mass diseases or even in deaths of people, animals, birds, fish, and vegetation. For example, smog in London in 1953 and 1957 caused about 5000 deaths among the citizens.[1] In Japan pollution of sea water and fish with mercury and cadmium resulted in new diseases of Hi–Hi and Minamoto types.[2,3] Destruction of the ozone layer due to reactions with freon is also among such harmful events.[4]

The problems of ecology found a solution by environmental monitoring under the aegis of the World Meteorological Organization (WMO), World Weather Watch (WWW), and World Health Organization (WHO). The concept of monitoring was detailed in Ref. 5. The atmospheric air monitoring is a central line of environmental monitoring.

There are about 5 million chemical compounds known throughout the world, with more than 60 thousands being produced industrially.[6] Moreover, the total yield of chemical compounds in the world increases by a factor of 2.5 every ten years.[7] Each chemical compound being produced or used enters the atmosphere fully or partially and either accumulates in it or undergoes chemical transformations. As a result, the number of compounds existing simultaneously in the atmosphere turns out to be much more than 60 thousands. Naturally, it is almost impossible to monitor this number of compounds, and practically impossible to monitor them continuously.

Because of this some reference compounds which characterize specific groups of substances should be used in constructing the system for monitoring of the atmospheric air. Finally, the structure of the monitoring system is found as a compromise between the desire to measure as many parameters as possible and expense of conducting these measurements.

Most of the countries have two–level systems of environmental monitoring which consists of federal and regional units.[8,9] Russia is expected to have a three–level system, i.e., federal, regional, and local units,[10] which can most likely work very well with regard for the expanse of our country. Reasoning from the fact that local monitoring is basic in any case, in this paper we describe the lower cell of the system of global monitoring, i.e., a subsystem of monitoring of the atmosphere of a large industrial center.

1. GENERAL DESCRIPTION OF THE ROUTINE MONITORING SYSTEMS

Nowadays the automatized systems of routine monitoring of the atmospheric air have been developed in the towns of the USA,[11,12] Japan,[13,14] Italy,[15,16] France,[17,18] Germany,[19–21] and some other countries. In France and the USA, e.g., they cover the entire regions: Ile–de–France (France) and New Jersey (USA) (see Ref. 9). In Japan each of 47 prefectures has its own monitoring system being a part of the national monitoring system.[8]

In the former USSR the ANKOS–AG monitoring system was developed by the State Committee on Hydrology and Meteorology and Ministry of Instrument Engineering based on the domestic instrumentation and computers.[22,23] The system was put into trial operation in several industrial centers: Leningrad, Kemerovo, and Kazan.[24] However, for a number of reasons this system has not received wide acceptance,[25] and efforts to its further modernization have been ceased.

In view of variety of approaches to developing the systems of routine monitoring of the atmospheric air, we will point out some general tendencies.

As a rule, the basic units of the automatized systems for routine monitoring of the atmospheric air of an industrial center are ground–based stationary posts or sensors, mobile measuring complexes, and data collection and processing center.

Common to these systems is the centralized principle of their construction: acquiring of the initial data by peripheral stations or sensors and transferring them to the central control station (or, in rare cases, to a cluster post) or the central computer. The system elements are interconnected through specialized and public telephone or broadcast channels.

The list of controllable ingredients may differ strongly at different stations of a single system or different systems. A number of measurable parameters at the station or post may be minimum or may reach 30. The measurements are made automatically at data sampling rate $1–10^{-4}$ Hz.

In most cases the peripheral stations and posts incorporate meteorological parameter measurement units. A set of measurable elements is variable. In the simplest case the speed and direction of wind are recorded. The maximum set of parameters consists of solar radiation, electrical conductivity of air, infrared radiation, temperature, humidity, pressure of air, turbulence intensity, and characteristics of precipitation.

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The best systems of monitoring involve software to forecast the pollution level that allows one to take measures for salvaging our environment. The systems without the models of forecast have a threshold alarm unit which operates when the pollution level of air exceeds the threshold level.

It is significant that the systems of routine monitoring of atmospheric air constructed abroad are not intended for measurements of the entire set of ingredients emitted into the atmosphere of the given region. The available close correlations between the concentration of indicators and that of other impurities enable one to assess reliably specific pollutants based on the results of monitoring of their indicators.

2. BASIC REQUIREMENTS IMPOSED ON THE SYSTEM OF ROUTINE MONITORING

The central problem in constructing systems of routine monitoring is its optimization: extraction of maximum amount of useful (required) information with minimum expense. As a rule, efficiency of these systems is determined by rational arrangement of a network of peripheral posts, their number, correct choice of a place of post location, a set of controllable parameters, and program and period of observations.[26] Clearly each of the aforementioned parameters differently influences the efficient operation of the system.

Most important or more precisely, key is the principle of constructing the air monitoring system. All of the known systems of routine monitoring may be divided into two classes[27] with respect to the principle (concept) of their construction. The first class incorporates the systems which allow one to reconstruct the most realistic field of concentration based on the data obtained from the stations. These are spatio–representative systems. The second class consists of the systems oriented toward the sources, i.e., the systems which provide for the estimate of contribution from individual sources to the resultant field of atmospheric pollution.

The second important point is determination of the most rational step of ground–based stations and their total number in the network. The existing approaches were described at length in Ref. 28. We go along with Bezuglaya when she proposed optimal calculation of the network density be based on correlation (structure) functions of pollution distribution. However, the direct use of this approach in the city may result in large errors due to the effect of local factors.

The remaining factors, in our opinion, are not determining and can be assigned using the available requirements and rules.[26,28,29]

3. SYSTEM OF ROUTINE MONITORING DEVELOPED AT THE INSTITUTE OF ATMOSPHERIC OPTICS (IAO), SIBERIAN BRANCH OF THE RUSSIAN ACADEMY OF SCIENCES

In the present paper we describe some principles and approaches to the construction of the system of routine monitoring of air quality, which have been developed at IAO based on the experience accumulated from its practical use.

3.1. Concept of constructing the system

The monitoring system must:

– combine the efficiency of a spatio–representative network and a network oriented toward sources;

– be fully automated;

– incorporate elements for monitoring of products of photochemical reactions;

– make the best use of correlation relations when choosing the parameters to be measured;

– be constructed based on the centralized principle and be extensible for other subsystems;

– involve a model for warning or forecasting.

The system of routine monitoring under development differs from the available ones in that it combines both principles of construction of these systems, i.e., spatio–representative and oriented toward the sources. This is realized by introducing lidars into the system structure.[30] It should be noted that this idea is not a new one. Thus, e.g., in Ref. 31 the automated system was described. It was tested in 1987 in Sendai and now is used to monitor suspended substances in the North–East regions of Japan where their concentration increases strongly in winter. However, in connection with the fact that our industry does not produce meteorologically certified lidars (except the "Elektronika–02" base lidar of the Scientific–Research Institute "Zenit"), the lidars in the system described are thought to be used as indicators.

In this approach the lidar systems are responsible for orientation toward the sources while a network of ground–based posts must be constructed based on the spatio–representative principle. Combination of both principles in one system provides for an objective pattern of pollution distribution in the examined region using the information from the network of ground–based posts, while the results of lidar sounding enable one to detect the major sources of pollution, to assess the rate and composition of emissions, to trace the directions of their spread, and to obtain a map of pollution distribution in the atmosphere. Examples of realization of the aforementioned capabilities of lidars were presented in Refs. 30, 32, 33, and 42.

The most reliable aerosol lidars, LOZA (see Ref. 33), must be used as lidar–indicators. This is warranted for the following reasons. First, the total coefficients of scattering measured with these lidars are directly proportional to mass concentration of suspended particles. Second, gaseous impurities also transform into aerosol particles in the course of physico–chemical reactions. Third, gaseous emissions are usually accompanied by aerosol ones. Fourth, the aerosol is a good tracer of atmospheric movements that makes it possible to estimate remotely the velocity of pollution transport. Our previous studies show that for towns with population 500–600 thousand people 3–4 lidars with the 5–km sensing range are sufficient to reconstruct the pollution field in the town. They must be elevated (positioned, e.g., on a roof of a high building) for the entire territory of the town to be covered and the plumes of optically thick emissions not to create shadow zones.

The TV monitoring used in some monitoring systems[34] can supplement the lidar measurements on reconstructing the pollution field in the town. To this end an "all sky" wide–angle photometer is being constructed at IAO. However, this means has one serious disadvantage (disregarding methodical difficulties) since it can be used only in the day–time. Taking into account the fact that the basic element of the lidar (a laser transmitter) has relatively small resource of operation (from a standpoint of continuous operation), it is worth while to combine a wide–angle photometer and lidars into an integrated system to prolong the service life of the lidars.

A network of ground–based posts for the IAO system of routine monitoring was developed based on the idea of Bezuglaya about correlation of the pollution field in the town.[28] It was taken into account that this approach gives the excess number of monitoring posts.[35] First, this results in a large bulk of redundant information and second, increases the cost of the system. Moreover, to involve the forecast model into the system, the network of stations must approach a rectangular form.[36] One should also exclude the effect of local factors by averaging the initial data that allows turbulent fluctuations to be filtered.[37]

From the above reasoning it is clear that most optimal is the calculation of autocorrelation function based on the data of airborne sounding at altitudes between 100 and 200 m above the town. The methods of data extraction and calculation technique were described in Ref. 38. The fact that the scales of distribution of pollution inhomogeneities decrease as altitude increases made it possible to extend the results from a 100–m altitude to the ground layer.[39] Hence a step of the network determined by the correlation function is not overestimated for lower altitudes.

The experiments carried out in some towns of Russia showed that when the step of the network is determined at half amplitude of the correlation function, it changes from 0.4 in the polluted regions to 0.5 km in the regions without industrial emissions. Figure 1 depicts the scales of variations of autocorrelation functions R_{xx} calculated for different flight routes over Nizhniy Tagil.

However, the network with such a step remains an excessive one. Therefore, at the second stage the stations, which do not coincide with the nodes of plumes from different plants located in the town at different wind directions, are rejected. As a result of these procedures, we obtain a network with a variable step in different regions of the town: more dense where there are sources of emissions and widely spaced where there are no such emissions. Moreover, the network of stations keeps geometric shape that facilitates integration of the forecast model into this system.

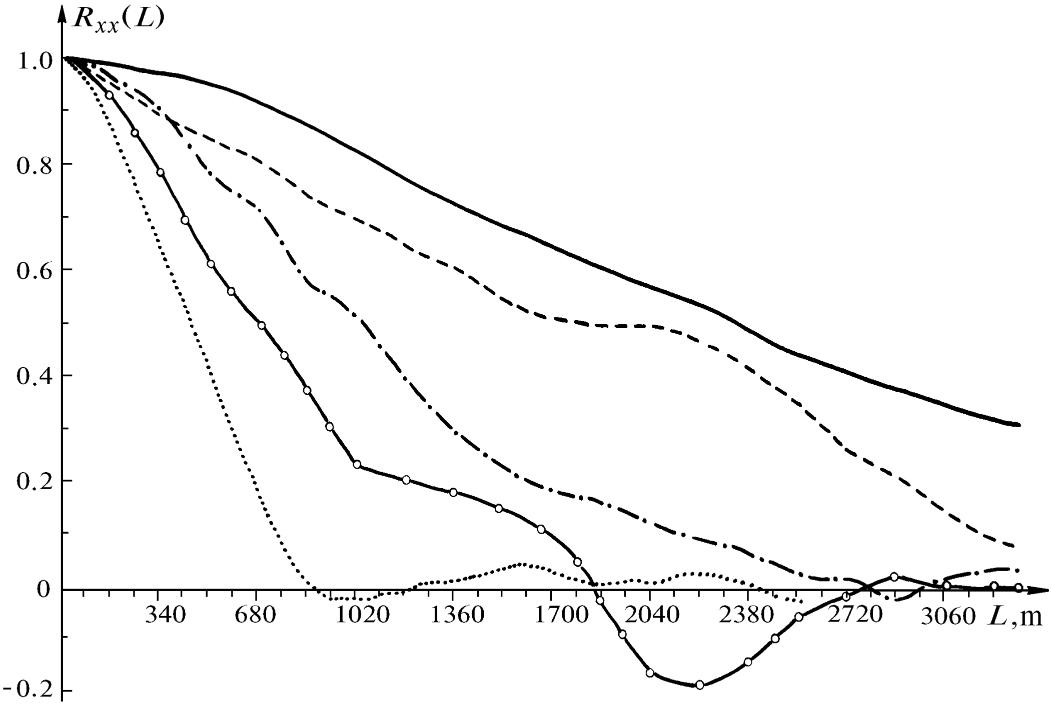

FIG. 1. Spatial correlation functions R_{xx} of the suspended particles above Nizhniy Tagil (L is the distance passed by the aircraft).

It is known[28] that the meteorological potential of air pollution is largely determined by vertical stratification of temperature and wind. The same characteristics are also important to forecast the level of pollution based on the majority of the available models. Therefore, a device is needed in the system which could measure the aforementioned characteristics. This may be an acoustic radar (sodar) or a high–altitude meteorological mast.[3,40,41]

As noted above, the systems of routine monitoring of atmospheric air usually incorporate a mobile station equipped with instrumentation intended for en route measurements under plumes, examination of microregions of the town, etc. The recent developments of IAO allow one to create one more type of station based on an aerosol or RS lidar for remote determination of composition and amount of emissions near the mouths of high stacks and mapping of the pollution field.

Thus the remote means in the system of routine monitoring widens its capabilities and imparts to it a qualitatively new level.

3.2. Structure and composition of the routine monitoring system "GOROD"

The automatized system of routine monitoring of the atmospheric air described below is intended for determining the level of pollution in the ground layer; measuring of volume and amount of emissions from sources located in the examined territory; detecting the traces of the spread of pollutants in the town; examining individual and distributed sources of emissions; observing photochemical processes; and, finally, acquiring, processing, storing, and transferring information.

The system is assembled based on the centralized principle and consists of the following units (Fig. 2): the central control post *9*, at which the all–sky photometer *4*, the sodar *5*, and the receiving antenna of a radiochannel are mounted; several lidars *1*; the MS–1 and MS–2 mobile stations *2*; and, the posts of ground–based monitoring *3*.

The system is extensible. Subsystems of industrial sensors *6*, control of water supply *7*, etc. can be integrated into it.

The analytical laboratory *10* must be incorporated into the system of routine monitoring since some operations, such as determination of chemical composition of suspended particles, cannot be fully automated so far both in our country and abroad. The users of information *8* are connected to the CCP (central control post) through the communication lines.

The central post is designed for control of the whole system of monitoring, acquisition, processing, storage, and long–term storage of information; warnings and forecasts; servicing the users of real–time and climatic information; and, preparation of the documents for imposing fines. Two computers are the central part of the control post. One computer functions in routine regime. The other processes the climatic information. It is also a "hot" reserve for the first computer.

The control post incorporates the following graphics: indicator boards, displays, digital printers, plotters, and others. It has a center for communication with peripheral stations and users, radio station, and long–term storages.

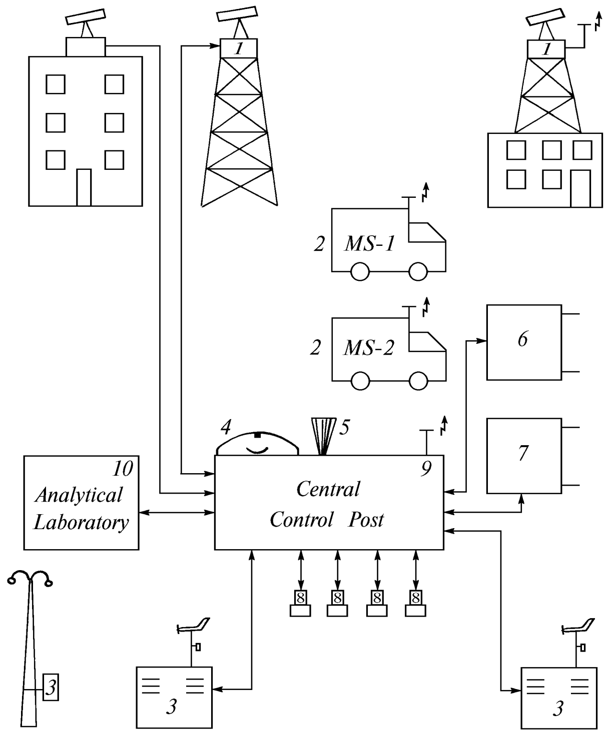

FIG. 2. Configuration of the system of monitoring of the atmospheric air.

The lidar systems are installed on the roofs of high buildings and towers. The instrumentation of control, record, and processing of data of sounding is indoors, and the lidar receiver–transmitter can be located at a 500–m distance.

The number of lidars depends on the examined area, level of air pollution, location of emission sources, wind rose, and some other factors. Table I lists the specifications of the aerosol lidar of intermediate radius of action.

TABLE I.

Characteristics	Dimensionality	Numerical value
Range and direction of sounding:		
Range of sounding of plumes	km	5–7
Angle of elevation	degree	–10–90
Azimuth	degree	0–340
Angular resolution	minutes	10
Spatial resolution	m	7.5–15
Rate of scanning	degree/s	≤ 1 (variable)
System of control, recording, processing, and transmission of information		based on IBM PC/AT

It has been mentioned above that mobile stations of two types are used in the system (item *2* in Fig. 3). The first type of the station which is equipped only with analytical instrumentation is traditional and well known in the literature.[43,44] So we will not dwell on its description. Let us concentrate on the station incorporating the lidars, in particular, the RS lidar. Such a station is capable to measure the concentration of gases and suspended particles near the mouths of plant stacks and has the following specifications:

Sensing range	500 m
Concentration of suspended particles	≥ 1 mg/m^3
Concentration of CO, NO, NO_2, and SO_2	≥ 100 ppm
Gas temperature	≥ 100 K
Rate of jet outflow	≥ 1 m/s >

The ground–based posts of monitoring are containers with instrumentation, systems of microclimate, metrology, and energy supply. They are installed stationary in places chosen beforehand. A set of measurable parameters can change depending on composition of emissions in each town. The examinations in Khabarovsk gave the following composition of the substances being measured:

NO	0.2–100 ppm
NO_2	0.02–100
SO_2	0.1–50
NH_3	0.2–40
H_2S	0.005–10
H_2CO	0.5–10
CO_2	2–2000
CO	1–1000
CH_4	1–200
O_3	0.5–500 ppm
Suspended particles	Gravimetric method
Temperature	–50 – +50°C
Humidity	10–100%
Wind velocity	1–40 m/s
Wind direction	0–360°

Depending on the area of the town, from 10 to 30 stations of ground–based monitoring are needed in its territory.

3.3. Algorithm of system operation

Under normal conditions only the ground–based posts of monitoring which acquire the information about the level of pollution in the town microregions operate in an attendant regime. The lidar systems periodically observe the territory of the town and monitor the major sources of emissions. An operator visually monitors the atmospheric air using the wide–angle photometer. The mobile stations make envisaged examinations or en route measurements. The sodar provides for the information about a vertical stratification of the atmosphere. The information obtained is processed at the control post and future situation is forecasted.

When information about the excess of the maximum permissible concentration (MPC) and maximum permissible amount of emissions (MPAEs) or about predicted adverse meteorological conditions is obtained, the mobile stations are changed over to examination of these sources of emission. The rate of sampling of the data of ground–based posts, lidar systems, and the sodar increases.

4. PROGRAM OF DEVELOPMENT OF THE ROUTINE MONITORING SYSTEM "GOROD"

The experience of foreign countries suggests that the automated systems of routine monitoring of the atmospheric air are constructed based on an essential preliminary which is often more expensive than the system of monitoring itself.[45]

A preliminary stage starts with examining the territory and sources of emissions. This is done to determine the real level of pollution and the effect of addition of emissions from different sources, to find regularities in spread of impurities in the region and peculiarities of meteorological processes and their effect on the potential of pollution.[46]

An inventory of sources consists in determining composition and amount of emissions, concentration of their components, as well as in measuring the physical parameters of emission (temperature, rate, etc.) and finding the parameters of the source (diameter, height, position, etc).[47] This is often made using analytical methods based on air sampling with its subsequent analysis at the laboratory. It should be noted that more efficient are the instrumental methods when devices are transported at the given point in space (with the use of aircraft, helicopter, or mobile station).

Classical example of the preliminary is the program of regional monitoring of atmospheric pollution in Northern America implemented by the Agency of Environmental Protection of the USA and by the Department of Atmospheric Air Protection of Canada.[9] In the 1970's these organizations implemented a large program RAPS in several steps. The principal part of the program consisted in conducting continuous observations in the ground layer of the atmosphere at 25 posts. The observations were also made in the free atmosphere using radiosondes, balloons, aircrafts, and helicopters. Every year 2–3 missions were carried out during 4–5 weeks. Analogous investigations were made in 1983 in France where they planned to construct a system of routine monitoring in Ile–de–France.[48] In the former USSR the integrated experiment was conducted at Zaporozhskaya State Regional Power Station when the first system of automatized monitoring of polluted air within the zone of heat–and–power station was updated.[41]

The most important point in examining the regions is wind mapping[49] which can then determine the arrangement of monitoring posts.

According to Ref. 50, during the preliminary examination the following conditions, resulted from metrological requirements, should be fulfilled:

– coordination of methods of measuring atmospheric pollution and emissions;

– universal methods of data processing in calculating spatio–temporal characteristics of pollution fields and meteorological parameters;

– synchronous and universal methods of sampling to monitor atmospheric pollution at all stationary, en route, and mobile posts;

– synchronous measurements in the ground layer for monitoring of atmospheric pollution and measurements of vertical distribution of impurities and meteorological parameters;

– integrated approach to the development of the methods of interpreting the results of *in situ* and remote measurements.

From the above reasoning the Institute of Atmospheric Optics also starts inspection of the territory for which the system of routine monitoring is being developed.[51] To this end the ground–based mobile systems[33,52] and the aircraft–laboratory[53] equipped with remote and contact means are used. It should be noted that a set of the measurable parameters, methods, and devices mounted on them are almost identical.

An avant–project of the system of routine monitoring of the specific city, based on the results obtained and supplementary information is under development. After defence and approval of avant–project of the system by the local authorities, the second stage begins. It consists in developing a design of the system starting with its block diagram and choice, and validation of the instrumental stock, communication scheme, and model (diagnostic or prognostic).

The third stage incorporates installation of the system, verification of the measurable parameters, and adaptation of the model to local conditions.

At the fourth stage the system is put into operation, and the etalone signals are transmitted to the system units with the use of the aircraft–laboratory.

In conclusion we note that what has been described above was realized during our measurements in Pavlodar, Ust'–Kamenogorst, Khabarovsk, Komsomol'sk–on–Amur, Nizhniy Tagil, Nizhnevartovsk, and other towns. The system of routine monitoring in Khabarovsk is under construction now. A design of the system for Nizhniy Tagil is being developed. The system of routine monitoring is being prepared now for Nizhnevartovsk.

The description of the system of routine monitoring in this paper is not the ultimate one. Promising are the means of remote sampling placed onboard small–size remotely piloted flying vehicles, passive correlation gas analyzers, and other instrumentation which enable one to widen functional capabilities and to increase reliability of the system of routine monitoring of atmospheric air.

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