Scientific engineering: from designs for investigation in atmospheric optics to production of prototypes controlling the natural and technogenous systems

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Received February 9, 2007

The results of activity of IMCES SB RAS for 35 years at different stages of its development and brief descriptions of principal devices for study atmospheric optics produced by small series and used in practice in the period from 1972 to 1992 are presented. Particular attention is paid to new hardware components based on interaction between optical, acoustic, and radiowave effects with environment. All new objects operate in the network monitoring of climatic, ecological, and technogenous systems.

Introduction

The fiftieth anniversary of the Siberian Branch of the Russian Academy of Sciences coincides with jubilee of one of the scientific directions, which became the basis for the leading scientific school of Academician V.E. Zuev and the appearance of the academic science in Tomsk.[1] In 1957, a group of scientists under the guidance of V.E. Zuev prepared the first report on propagation of IR-radiation through the atmosphere. It was a government task, initiated the investigations of atmospheric optics in Tomsk. In the same year, after the first semester at the Tomsk State University, students M. Kabanov, S. Khmelevtsov, S. Tvorogov, and M. Elyashberg carried out the first research works on the above subject. Further, professor V.E. Zuev organized a special student scientific society and more than three years worked with them. To the fifth course, these students were well prepared as specialists in atmospheric optics. After graduation the University, three of them became the post-graduate students, defended the candidate and then doctor theses. At present, M. Kabanov and S. Tvorogov are the Correspondent Members of RAS.

A peculiarity of the new for Siberia scientific direction was the fact that the experiments were conducted in the field under different meteorological conditions, at all seasons of the year. At that time, the devices for such investigations have not been produced in our country and abroad. In addition, even the necessary elements for the devices (detectors and optical radiation sources, recording units, etc.) were only as prototypes. Therefore, most time of any natural physical experiments was spent for producing of necessary measuring devices.

This forced orientation to self-help from the very beginning of field experiments predetermined their future development. When the first lasers have been invented, V.E. Zuev has organized a special group for laser producing and the scientists of the laboratory conducted the pioneer investigations on propagation of laser radiation in the atmosphere. The results of these fundamental investigations including a series of firstly found atmosphere-optical effects were published in the leading scientific journals, reported at international scientific conferences, delivered at lectures at foreign universities, and received the world recognition. The necessity to use these new results, to conduct further complex investigations, and widen the appeared international communications favored the creation of new academic institute on the base of the laboratory.

In 1969, under the guidance of V.E. Zuev, the development of complex optical-electronic and laser systems in IAO was brought up to a new level. It was necessary to provide scientific investigations and, primarily, advanced solutions of many applied problems connected with the use of lasers at their operation through the atmosphere. High requirements to technical characteristics of the developed systems required essential widening of specialists in engineering. Therefore, already in 1972, a new specialized academy institute was constructed (Special Design Bureau of Scientific Instrument engineering "Optics" (SDB "Optics"), which in 1992 was renamed into the Design-Engineering Institute "Optics"; and M.V. Kabanov, the Correspondent Member of RAS, became its director. For long lime this institute has been working in close interaction with scientists of IAO and many unique OES have been developed for these years in cooperation. Some of them have been improved and successfully operate up to the present time.

To organize a research command, a group of scientists from IAO came to work in the new Institute. The difficult financial situation of 90s caused to force conversion of all scientific directions

0235-6880/07/05 424-07 $02.00

of the Institute oriented both to the development of new devices and their practical application. In 2003, the Institute was united with the Tomsk branch of the Forest Institute, SB RAS, and renamed into the Institute of Monitoring of Climatic and Ecological Systems, SB RAS (IMCES). The main scientific direction of the IMCES became: *scientific and technological principles of monitoring, modeling, and forecasting of climatic and ecosystem variations under the influence of natural and anthropogenic factors*.

It should be noted that in the beginning of 2007, IMCES has celebrated a thirty fifth anniversary.

Design of meters for investigations of atmospheric optics

The main task of SDB "Optics" established in 1972 is the development, manufacturing, and supply the IAO SB RAS by experimental prototypes of devices and complexes in order to provide the fundamental researches of atmospheric optics both by contact and remote-sensing methods. The description of first components of the devices is presented in collected articles.[2–4] Characteristics of main measuring devices produced in SDB "Optics", are also presented in Refs. 5–8. The manufactured experimental prototypes were tested under the field conditions, and their parameters and service conditions were then modified and improved.

Automated optical-meteorological complexes

Between 1970 and 1980, more than 15 prototypes of the automated complexes of land and sea purposes were made for IAO and its general customers. They were intended for measuring efficiently the optical-meteorological parameters of the atmosphere at special testing sites. The construction idea of such complexes has been generated in IAO, but the actual technical solutions, designing, manufacturing, and testing were performed in SDB "Optics". The complexes usually included the multifrequency meters of the atmosphere transparency along the ground trace; devices for determination of structural characteristics for the refractive index of atmosphere air and refraction; devices for measurement of the intensity fluctuation and geometry of the laser radiation spot; standard meters of basic meteorological parameters at the multilevel meteorological mast; lidars for measuring the spatial profiles of different atmospheric parameters.[2–4,7] The necessary condition of the complex was its automation (data processing and control for operation). The complexes provided on-line measurement of the optical weather parameters in place. Simultaneously, the development and manufacturing of individual optical-electronic measuring devices, especially lidars continued.

Lidars

An advantage of the lidar as a measuring device is a possibility of the remote measurement of profiles of aerosol and gas components in the atmosphere along the trace of laser beam propagation and efficient control for their dynamics during the observation period. Apart from the special lidars being the part of complexes for efficient determination of atmospheric parameters, during the first decade, the mobile aerosol lidars were generated; for instance, "LOZA-3", for ecological monitoring of atmospheric pollution.[11]

The lidar design methods have been developed in SDB "Optics" and directed to optimization of the receiving and transmitting devices, as well as the calculation methods for estimation of the lidar energy potential and dynamic range of their signals. Various types of spatial filters have been developed in lidars of different purposes. The investigations on optimal supply behavior of photodetectors and on methods of the time adjustment of their sensitivity have been carried out when recording the fast-varying lidar signals. The obtained results on optimal lidar design have been systematized.[10]

The experience acquired when the ground lidars designing allowed generating the aircraft polarization lidars at the end of 70s.[9,10] The engineering principles of synthesis of the receiving and transmitting systems allowed measurements of the Stokes vector components of a lidar signal, and then scattering matrix elements, when sounding the dispersion media. The sensing technologies have been developed for laser radiation scanning by ground, airborne, and space lidars.[8,10]

All the acquired experience allowed us to produce the first space lidar "BALKAN" in cooperation with IAO and a series of other specialized institutes.[12] The research workers of SDB "Optics" developed a complete set of documentation for construction of the lidar, produced a series of its units, technology, and test mockups to conduct the required cycle of ground selecting and approval tests. In the end of 1990, the joint tests of the lidar operated as a part of module "Spectrum" of the "Mir" orbital station were conducted. In May of 1995, the lidar was put into orbit together with the «Mir» orbital station and had operated for two years as the first space-borne lidar. The lidar participated in development of technology for sensing the the atmosphere and underlying surface of the Earth.[13] The depressurization of the "Spectrum" module, which took place in summer of 1997, disturbed the whole cycle of the planned experiments (lidar served only 10% of its plan life).

A series of controlling devices was constructed to provide the lidar meteorologically. In particular, special optical imitators of lidar signals were produced allowing the modeling of different time dependences of the emitted power.[14] When sending an optical signal of a known shape to the input of the receiving system, one can calibrate the lidar by its response and obtain the end result at the output of the recording device.

Other optical devices and element base

To determine radiation attenuation factors in the visible and IR ranges, the double-wave (0.63 and 10.6 μm) laser meters of horizontal atmosphere transparency were developed, as well as output reflectors located at 0.5–1.0 km far from the receiving-transmitting unit.[2–4,7] These meters were produced by small batch and incorporated into the optical-meteorological complexes.

The produced meters of atmospheric refraction determined fluctuations at the arrival angles up to 5 ang. min in the frequency range of fluctuations up to 100 Hz along ground horizontal traces of 6 km long. To estimate the atmospheric turbulence effect on the laser radiation propagation, the optical meters of structural characteristic of fluctuations of the refractive index C_n^2 were worked out.[2,3] Several modifications of stellar-solar electrophotometers were developed on the basis of a standard telescope AZT-7 for measuring the optical atmosphere transparency at the extended inclined traces during day and night hours in the visible and near IR ranges.[3]

One of important achievements was the development of mercury analyzer MGA-11, produced since 1990 by small batch. The portable device without preliminary sampling determined the concentration of mercury vapors in the atmospheric air, and special adapters allowed measuring the mercury content in soil, water, and biological objects.[15] The device and corresponding measurement procedures were meteorologically certificated and registered in the State catalogue of meters.

The flexible technological base provided for the development and manufacturing of meteorologically-certificated single and small-scale prototypes of optical systems and elements of different glasses, quartzes, glass ceramic, and crystals for operation over the range from UV to near IR (13 μm) spectral ranges. A high quality of the produced optics was attained by the complex control at all stages of manufacturing: from design to the technological processes. To do this, the high-precision interferometer techniques and devices have been developed for efficient quality control of optical details. In 1974, there appeared a necessity in organization of a special department producing metal-vapor lasers. As a result, a series of lasers at copper vapors "MILAN" has been developed.[2,3] One of the laser modifications was used in the Raman scattering lidar, constructed by specialists of the IAO.[16]

Since 80s, in SDB "Optics" nonlinear optics has been developed for broadening the frequency range of the generated monochromatic radiation. Frequency tuning lasers were intended for using in lidars and trace gas analyzers. The investigations are going on up to the present time both to develop the high-efficient crystal-growing technology[17] and by studying the characteristics of parametric frequency converters of the mean IR range based on different crystals and solid solutions.[10,18]

New scientific problems of the Institute

The most difficult period in the Institute history was from 1991 to 1997 when very small financial support of SB RAS was directed mainly to the new research sector dealing with the problems of climate-ecological monitoring in Siberia. In this situation, it was necessary to find a new field of activity using the available instrumental and scientific resources in the sphere of optical-electronic engineering. In 1993, a mobile ecological-meteorological station "Ecolid"[19] was constructed to order of the East Kazakhstan department of ecology and biological resources.

In 1995, at the Kuznetsk integrated iron-and-steel concern, the certificated system for the automated photometric testing of the railway rails linearity during their transportation was constructed. The small-scale production of laser therapeutic devices and devices for the laboratory practical investigations in physical optics has been started. During the period between 1990 and 1997 the laser specialists began to produce laser show systems.

In 1997, the Joint Institute of Atmospheric Optics was completely reoriented to production of instrumentation for the environmental monitoring and control of technogenic systems.[20] Construction of new devices was based both on optical effects and on effects of acoustic and radiowave interaction with the environment. Despite many of them had foreign analogues, most parameters of created devices exceeded the parameters of these analogues.

Automated ultrasonic meteorological complex AMC-03

The reliable ultrasonic hot-wire anemometer has been conducted in the Institute for more than 15 years. The meteorological complex AMC-03, which has stationary, mobile, and airborne modifications was the result of that work. The final prototypes of the complex (produced to order of the Defence Ministry of Russia) have rather broad measuring ranges: ambient air temperature can vary between −50 and +50°C; horizontal wind velocity is between 0 and 40 m/s; vertical wind velocity is up to 15 m/s; relative humidity is from 15 to 100%; atmosphere pressure is from 560 to 800 mm hg [Ref. 21]. The prototypes were certificated and recommended for commercial production.

The main difference of these devices from foreign ones was the rigid structure of the hot-wire anemometer head representing two orthogonal tubular rings with eight fixed ultrasonic piezoceramic converters (Fig. 1).

They form four pairs of radiators and receivers arranged in opposite vertices of the cube. High frequency of sensor survey (up to 160 Hz) allowed measuring the instantaneous temperature values and three orthogonal wind velocity components at a threshold sensitivity no worse than 0.01°C and 0.01 m/s, respectively. According to these data, it is possible to estimate up to 60 numerical characteristics used for description and analysis of the atmospheric turbulence. Modifications of AMC-03 are additionally supplied with the corresponding software, which allows storing measured data for any observation period with the subsequent reproduction of results from the data bank as tables, histograms, graphs, etc.[21]

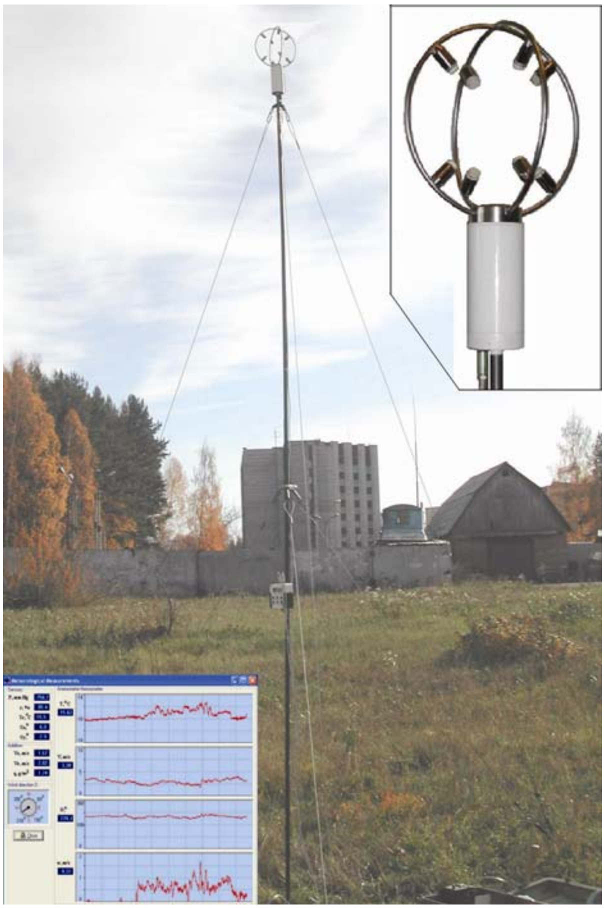

Fig. 1. Mobile modification of AMC-03 (knapsack variant) in the unfold position on the 4-meter mast. The head of acoustic hot-wire anemometer is at the top right; the window of the software menu with a sweep of instantaneous values (from above downwards): air temperature, horizontal wind velocity, wind directions, vertical wind velocity, is in the lower left.

Several tens of AMC-03 modifications were produced, which are used not only at Institutes of SB RAS and in Higher Educational Institutions, but also at industrial enterprises in our country and abroad. The program of short-term forecast of variation of fundamental meteorological parameters based on the results of current measurements of AMC-03 has been developed.[22]

Gas analyzers for continuous monitoring of technogenic gas

To control for the atmospheric air pollutions, the stationary gas analyzers have been developing in the Institute during the last ten years for testing the concentration of basic technogenic gases in smoke emissions of the fuel-burning plants. Operation of the gas analyzers is based on the differential absorption method in the optical range. Several modifications of "DOG" gas analyzers of the UV range are made for measuring the NO and SO_2 concentrations in smoke emissions of heat boilers of the plants (Fig. 2).[23,24] Engineering solutions, being the design basis for gas analyzers DOG-1M and DOG-4, are granted of patents and registered in the State catalogue of measuring facilities of the Russian Federation.

The test prototype of the gas analyzer operating in the IR range is made for control the carbon monoxide content in smoke emissions.[25]

Fig. 2. External view of the gas analyzer DOG-4 for control the concentration of emissions of NO and SO_2.

New modification of mercury analyzer

In the beginning of the XXI century, the mercury analyzer MGA-11 was modernized.[15] The differential absorption method of resonance spectral mercury line was used in the analyzer at $\lambda = 253.7$ nm on the basis of Zeeman longitudinal effect. In a new device, the cross Zeeman effect is used.[26] The analyzer sensitivity weekly depends on the mercury isotope applied in the gas-discharge lamp. The linear polarization of Zeeman components simplifies the procedure of their alternate separation (photoelastic polarization modulator is not required). This simplifies the optical trace adjustment of the device. The device electronics also changed due to application of the modern electronic base. The device external construction was not changed (Fig. 3).

To conduct the field works, the device is supplied with the GPS-receiver and FLASH-memory, which contains the measured concentration values of mercury vapors, time and coordinates of measurement. The device has an output providing the information transfer, obtained for the daily measuring session, to the computer. The analyzer specifications are not worse than the corresponding domestic and foreign analogues of the same class and are used for testing the mercury concentration in the air at trace surveys and at mercury monitoring of peatbog systems.

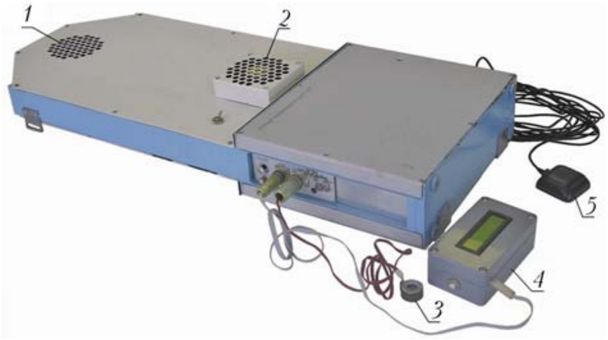

Fig. 3. External view of a gas analyzer DOG-05: *1* are the holes for air intake pumped through the multi-pass optical basin; *2* are the outlet holes; *3* is the standard cell with controlled temperature; *4* is the external unit of control and indication; *5* is the antenna of the GPS-receiver.

Devices based on using the effects of electromagnetic emission of solids

Since 2001, new methods and equipment are developing in order to control the natural and technogenic media. The new equipment is based on recording the radiofrequency electromagnetic emission (EME) of solids and natural pulse electromagnetic earth field (NPEMEF) in the range of tens and hundreds of kilohertz. Information about elastic properties of the material and information connected with the change of its electric state contains in parameters of the EME signal. The dedicated recorder “Strength” was developed for testing the quality of the concrete.[27] It is based on recording the electric component intensity of the EME pulses, which originates from the mechanical action on dielectric bodies. The test error of concrete strength does not exceed 10%; survey volume at single measurement is equal approximately to 0.4 m^3, the measurement time in one point is no more than 5 s. The area measurements allow obtaining the topogram of structural strength distribution with determination of defective regions. The “Strength” recorder is successfully used in estimation of technical state of concrete constructions, roadway covering, and bridges.

Multichannel geophysical recorder MGR-01

Investigations conducted in the 70s of the last century in the Tomsk Polytechnic Institute have shown that the Earth crust is a source of electromagnetic pulses of the radio-frequency range. In the structure of the NPEMEF emission, there are pulses connected with mechanic-electric energy conversion in the Earth crust, originating at the boundaries of crust blocks, as well as structural inhomogeneities due to the continuous geodynamic motion of the planet envelope.

To record these pulses, the multichannel geophysical recorder MGR-01 was constructed. It represents a set of sensors of NPEMEF electric and magnetic components joined into the antenna unit and recording unit (Fig. 4).

Fig. 4. Multichannel recorder MGR-01 at field tests: *1* is the notebook for fixation of results; *2* is the packing case with recording unit; *3* is the supply cable coil; *4* is the external antenna unit.

An electric sensor registers pulses in the frequency range from 500 Hz to 100 kHz, magnet sensor operates in a narrow band at 14.5 kHz. The long-term investigations have shown that there are daily and seasonal variations of the NPEMEF pulses, moreover, time (day or night) of the maximal number of pulses changes depending on a season.[28]

The detailed observations for seasonal variations of NPEMEF have revealed certain regularities connected with stressed states of the Earth crust and earthquakes that allows the use of the MGR-01 as a stationary local central station, when solving the problem of the fast earthquake forecasting. It was found that the NPEMEF intensity is essentially reduced on the eve of the earthquake. The monitoring network provides forecasting of time and place of future earthquakes.[29] At present, the devices of this kind are located in eight points of the Western and Eastern Siberia. The MGR-01 is registered in State catalogue of measuring facilities of the Russian Federation. The device is also applied in development of geophysical methods for mapping the lithologic inhomogeneities, estimation of the intensively deformed state of mountains, and search for the mineral deposits.

Devices for express-diagnosis of road constructions technical state

Ultrasonic radiation is also used in the multichannel system for measuring superstructure deflections of bridges “Phase”, overbridges, and viaducts. Operation of measuring sensors is based on acoustic detection and ranging, however, application of the original software and special controllers exclude the effect of temperature, pressure, humidity, and air flow displacement on measuring results.[30] The sensors are arranged at tension members so that the acoustic radiator is rigidly attached to the construction and the receiver – to the ground (Fig. 5).

Fig. 5. Arrangement of the «Phase» system under the bridge span: *1* the acoustic sensors; *2* the tension members; *3* the notebook.

The system simultaneously measures both static deflections and amplitudes of superstructure vibrations with an error of 10 μm in the frequency range of the measured displacements from 0 to 40 Hz. The quantity of the measuring channels is equal to 10. The natural vibration frequency, dynamic coefficient and logarithmic decrement of attenuation of the selected construction are determined automatically. The "Phase" system is registered in State catalogue of measuring facilities of the Russian Federation.

Element base. Nonlinear crystals

A mathematical model of the parametric frequency translation in solid solutions with spatial mixing ratio variations of x-components is developed. The model accounts for both parameters of the optical beam pumping and solid solution inhomogeneity, as well as the beam drift affecting the conditions of phase synchronism and the translation efficiency. The calculations of optimal values of the working element length are calculated, as well as conditions of phase adjustment differed from conditions of full phase synchronism, which provide the maximal generation efficiency of the second harmonics, combination frequencies, and parametric generation in compounds $LiGa(Se_{1-x}S_x)_2$, $LiIn(Se_{1-x}S_x)_2$, $AgGa_{1-x}In_xSe_2$, $Hg_{1-x}Cd_xGa_2S_4$ owing to the experimentally determined values of x variations.

Last years, the development and tests of a new high-precision thermal plant on the basis of original planar constructions have been completed, providing the necessary spatial resolution and the accuracy of the thermal control system for growing monocrystal $ZnGeP_2$ with unique sizes (up to ∅30×150 mm) for the high-power pulse sources of coherent radiation of the IR and terahertz ranges. The growing technique of $ZnGeP_2$ epitaxial layers is developed with a lower concentration of defects as compared to the base for creation of the planar waveguide structures and increase of the optical breakdown of nonlinear elements $ZnGeP_2$.

Element base. Metals with shape memory

The designing of metals with shape memory began at the Institute since 1994. Principal practical use of such metals is based on their property to reconstruct their initial shape, acquired due to the special thermomechanical treatment. The shape can be regenerated millions times. When reconstructing the shape, the element applies great forces and can make some useful work. The metals with shape memory have considerable advantages relative to the traditional sensitive elements: in the displacements, forces, complexity of configurations of the reconstructed shapes, operating temperature range, resistance to the corrosive media, working cycle resources, environmental safety, etc.

Owing to the ability of the elements of reacting to changes of parameters of the environment (temperature, humidity, and solar radiation), they can be used as executive elements in prototypes of devices. To the present time, the material has been developed on the basis of the compound Ti–Ni–Cu (TU-2-02-87-94) capable of simultaneously fulfill the functions of a sensor and actuator in monitoring and environmental control for temperature, humidity, and solar radiation.[31]

Conclusion

The prospects of future development of the instrumental engineering in IMCES are determined by its main scientific direction. The object of instrumental observations are the «climatic and ecosystem variations», which depend on many factors of natural and anthropogenic origin and are determined by the processes with different time structure. Therefore, new instrumentation components should provide measurements of not only mean parametric values of these processes, but also of their highest moments. Some measuring facilities, for instance, the meteorological complex AMC-03 are under development and modernization.

Another important requirement for field devices is connected with observed spatial inhomogeneity of complex natural-climatic variations in regions and sub-regions. To observe this inhomogeneity, the regional monitoring nets are necessary on the territory of several typical ecosystems. Therefore, to synchronize the instrumental observations, the information measuring systems are necessary with channels for collection of remote information. The development of such systems and the corresponding geoinformation technologies for the monitoring systems is referred to the foreground directions of the Institute.

A major part of new developments was carried out during the period from 2004 to 2006 within the limits of the project No. 28.2.3, SB RAS "Development of new methods, technologies, and devices on the basis of optical, radiowave, and acoustic effects for control of natural and technogenous systems and for solution of special problems". In future, the study will continue for three years (from 2007 to 2009) within the limits of the program SB RAS "Fundamentals of instrument engineering for the sciences about the Earth and solution of special problems" in the project No. 7.13.1.2 "Development of methods and instruments on the basis of optical, radiowave, and acoustic effects for studying natural and technogenous systems".

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