MODELS OF THE ATMOSPHERE AND ADAPTIVE OPTOELECTRONICS SYSTEMS (THE USE OF ATMOSPHERIC MODELS BY MODERN OPTOELECTRONIC SYSTEMS)

V.P. Lukin

*Institute of Atmosphere Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk*
Received January 20, 1997

The use of information about the atmosphere by the developers of adaptive optoelectronics systems at all stages of the development and operation is analyzed. Analysis is given of most important researches in this field and the papers by the author.

INTRODUCTION

At present it is accepted that information about the atmosphere at the level of models is needed for the developers at all stages of design, construction, and operation of the adaptive optoelectronic systems.

First of all, let us make it clear what is called a modern optoelectronic system (OES). If we will follow the OES classification introduced in Ref. 13, then most up-to-date are OESs, with phase processing of information, among which heterodyne, holographic systems and different system using Doppler effects, as well as the adaptive optoelectronic systems (AOESs).

Although these two classes of OESs differ markedly, there is a deep cause-and-effect relation between them. And most important is the use of information about the phase (and its fluctuations) of the electromagnetic wave. If in the first case this phase is the information carrier, or phase relations are decisive when determining OES characteristics, then in the second case – for adaptive optoelectronic system – the phase of optical wave is the subject under control, and it is used for optimizing parameters of a system and signal.

Most significant stages in the use of information about atmospheric models in the development and operation of modern OESs have the following structure:

I. Models of the atmosphere at the stage of selecting OES location.

II. The stage of design
1. Selection of technical characteristics of OES itself;
2. Characteristics of the contour of signal adaptive correction in OES;
3. Determination of OES limit characteristics

III. The stage of operation
1. Passive mode
2. Active mode – "laser reference stars".

IV. The stage of design of renewed OES.

Thus, models of the atmosphere are needed for the developers of optoelectronic systems at the following stages: selection of OES location, selection of main parameters of OES itself, determination of OES limit capabilities, development of control algorithm, system modernization.

1. MAIN PROBLEMS TO BE SOLVED IN MODERN OESs

1.1. Adaptive Vision Through the Atmosphere

Certainly, one of the main goals of OES under development is to increase, in any way, the range of obtaining high-quality image of an object and to improve the accuracy. Theoretical and experimental research in adaptive optics, design of optical devices with adaptive optics elements, analysis of atmospheric distorting factors are widely conducted in such countries as USA (here are developed most up-to-date adaptive optics telescopes: Kekk–1 and Kekk–2; and the system of Real Time Atmospheric Correction); France (created are two adaptive systems for astronomy: the system "Come-on-Plus", the project ADONIS – adaptive system for near IR range), Germany which deals, in collaboration with other members of European community, with the project of "Very large telescope" providing for adaptive image correction. Theoretical part of this project includes distortion estimation and development of methods for distortion compensation; Italy develops the projects of telescopes "Galilei" and "Large binocular telescope" with adaptive optics elements, Great Britain and Australia are active the design of English-Australian adaptive telescope.

The above mentioned and similar projects cause the progress in adaptive atmospheric optics, both in theory and experiment. Of special interest in the area of basic research is the development of algorithms of compensation for atmospheric distortions and the study of optical wave propagation in the atmosphere. Research in these directions are conducted in the USA (Livermor Lab, Phillips Lab, Navy Research Lab, Lincoln Lab), in Germany (European South Observatory).

0235-6880/97/04–05 322-15 $02.00

1.2. Systems for Laser Radiation Focusing

The systems for transportation of high-power laser radiation through inhomogeneous media, such as the Earth's atmosphere, are developed simultaneously with systems of image formation. USA deals with the project of SELENE system for transporting the energy of high-power ground-based laser to geostationary satellite with the help of an adaptive telescope. To minimize the influence of atmospheric turbulence and effects of thermal blooming, the adaptive optics methods are used. These methods are applied in practice by introducing three principally new elements into the optical system, namely, wavefront sensor that measures the wavefront deviations from the required one, computer providing for phase measurement data conversion into control signals, and mirror under control that converts the control signals into a deformation of its surface thus correcting for wavefront distortions. These elements are usually used in the system with a closed feedback, in which the sensor measures deviations of already corrected wavefront.

It is known, that most important are two parameters of the system: the number of channel and the frequency band or the rate of data renewal in the system. Just these technical characteristics of an adaptive optical system are calculated based on the models of the atmosphere.

Up-to-date technologies make optical systems using adaptive optics elements or systems too expensive, that is why the adaptive optics has been used only in most expensive optoelectronic systems, comparable in their cost with the cost of adaptive system itself. But now some countries have already the basis for new high-tech adaptive optics, which will lower the cost of adaptive system by an order of magnitude. This means that adaptive optics will be widely used in military optoelectronic systems. And only the atmosphere will remain the most serious restriction of the optical systems application. It is the algorithm of adaptive system performance and estimation of parameters of the adaptive system itself that requires indepth knowledge of the atmosphere as the refractive turbulent medium with intense radiation absorption by air molecules will become the most expensive part of the adaptive system. And of primary importance now becomes the study of the peculiarities of laser radiation propagation under conditions of real atmosphere as a turbulent, scattering and absorbing medium.

2. ANALYSIS OF ATMOSPHERIC CHARACTERISTICS AT A PROPOSED LOCATION OF THE TELESCOPE

Let us consider the first stage of the problem under study, namely, the use of atmospheric models when choosing the place for location of the system of imaging through inhomogeneous medium using the ground-based astronomical telescope as an example. It is known that large astronomical telescopes, in addition to optimization of their parameters, require good conditions for optical observations.[1–12] In this section we present the data characterizing the conditions of astronomical objects observation for the well known observatories all over the world.

2.1. World Experience in Study of the Astroclimate at the Telescope Locations

The stage of choosing a place for modern optoelectronic system, for example, adaptive astronomical telescope, is one of the critical stages of a design of future system and determination of its parameters. The place for location of a large adaptive telescope requires significant investments. As a rule, many-year survey and atmospheric research proceed this stage. As a result, the model of the atmosphere for the place of OES location becomes clear. This model has often more parameters than the model, on which the engineering calculations of the main parameters of the system were based. The place for future observatory should meet all requirements for such systems from the viewpoint of air transparency, the number of clear days and nights, low content of water vapor and other atmospheric inhomogeneities absorbing optical radiation, low level of average turbulence, as well as the requirements to the level of scattered radiation determining the value of the stray light background.

The place for future telescope location should meet the requirements of possible obtaining of high-quality images without adaptive correction. The following thesis is true: the more expensive is the telescope (adaptive telescope is really expensive), the better should be the place for its location.

To confirm this thesis, let us consider some results[12] as routine study of quality of vision through the atmosphere for different USA regions obtained for about 20 years. Table I lists geographical positions of measurement points, measurement periods, and atmospheric parameters measured. These geographical points are the places which were selected for location or testing of modern OESs.

It is seen from Table I that most often measured parameters characterizing the vision quality at a given geographical point are the Fried radius approximately equal to the size of coherent aperture and the isoplanatism angle of the atmosphere. These two parameters are determined from direct optical measurements with small telescope. Measured parameters in this case are star *scintillation variance and image jitter* reduced to zenith.

The altitude profiles (C_T^2) of atmospheric temperature structure constant are often measured based on micropulsation measurements from meteorological mast or balloon. In addition, in the same places acoustic sounding is conducted. All the above allow obtaining vertical temperature profiles, temperature lapse rate, wind velocity (vector), as well as vertical profiles of wind velocity and turbulence intensity.

TABLE I. Some regions of USA where quality of vision through the atmosphere is routinely studied.

Observatory, State	Year	Measurement type
China Lake, California	1978–1979	r_0, at the mast C_T^2, acoustic sounding
Capistrano, California	1981–1983	r_0, at the mast C_T^2, acoustic sounding
Mt. Wilson, California	1986–1990	r_0, Θ_0
Anderson Peak, California	1986–1990	r_0, Θ_0, acoustic sounding
Mt. Hamilton (Lick), California	1986–1987	r_0, Θ_0
Mt. Laquna, California	1990	r_0, Θ_0
White Sandes Missile Range, New Mexico	1977+ 1983+	r_0, at the mast C_T^2, acoustic sounding, Θ_0
Starfire Optical Range, New Mexico	1985+	r_0, Θ_0
Haleakula, Maui, Hawaii	1985–1992	r_0, Θ_0, balloon C_T^2
Kihei, Hawaii	1988–1990	r_0, Θ_0, balloon C_T^2
Обсерватория McDonald, Taxes	1985–1986	r_0, Θ_0
Rock Springs, Panama	1986	r_0, Θ_0, balloon C_T^2
Melbourne, Florida	1986–1990	r_0, Θ_0
Anderson Mesa, Flagstaff, Arisona	1990–1992	r_0, Θ_0

Let us now present the data characterizing the observation conditions for astronomical objects[1–14] for some well-known observatories.

Thus, the Mauna Kihei (Hawaii, USA) is most likely characterized by the best observation conditions. Here, at a height of 4250 m, average size of an image formed (literature usually uses the term FWHM) proves to be equal to 0.45″ under medium conditions and not worse than 0.25″ in 10% of observations. Observation conditions in this observatory are practically comparable with conditions for observatories at Chili plateaus: Sierra-Paranal (2660 m above the sea level), La Silla, and others.

The Hopkins mountain (Arisona, 2200 m height) is the place of location of 6.5 m MMT (multimirror telescope) and is characterized by the Fried radius $r = 90$ cm under medium observation conditions at 2.2 μm wavelength.

The Siding Spring Observatory in Australia (approximately 400 km from Sydnei) at the height of 1150 m is characterized by a bad image quality (FWHM ≈ 1.3–1.8″) that corresponds to $r \cong 6$ cm in the visible range.

Observations in the Sacramento Peak Observatory (New Mexico, USA) have shown that for night conditions here the most significant turbulence is observed in the thin layer at 1 km height above the surface. The "vision" quality is here characterized by the Fried radius $r = 3.3$–17.2 cm (for $\lambda = 0.55$ μm).

The image quality in the region of Maidanak mountain (Uzbekistan) under conditions close to the free atmosphere corresponds to the medium vision at the level of 0.7′ in 50% of observations.[1]

Our measurements[2] near the place of 6-m BTA telescope location (Zelenchukskaya station, Pastukhova mountain, 2100 m) in January-February of 1982 gave the value of r (at $\lambda = 0.55$ μm) within 4–16 cm for night observation conditions in the direction to zenith.

2.2. Programs of European South Observatory on Astroclimate Study

Of special interest is the example of development[6–9] of the special group on evaluation and selection of the place for Very Large Telescope (VLT) in the European South Observatory (ESO–Munchen–Chile). When the decision on VLT construction was made, the first task to be solved was the task of finding the place for location of this unique astronomical device. The group for investigating the astroclimate of several regions adjacent to the La Silla Observatory (La Silla, Chili) was organized in 1984. In 1986 the Lassca'86 experiment was conducted in the region of La Silla Observatory (European South Laboratory). The wide set of measurement devices was used. This devices allowed the measurement of the point-spread function (PSF) of star image. Among these devices are the following:

– meteorological station at the mast;

– SODAR system for acoustic sounding;

– system for radar sensing up to altitudes above 20 km;

– 2.2 m telescope operating as a speckle-interferometer;

– 1.52 m telescope equipped with SCIDAR – special measurer of star image jitter;

– 0.52 m telescope equipped with shear interferometer.

Measurement results on meteorological and optical characteristics in the Lassca'86 experiment can be reduced to measurement or estimation, based on the model of the atmosphere, of the following parameters:

$C_T^2(h)$ – vertical profile of the structure temperature index;

$C_n^2(h) = \left(80 \cdot 10^{-6} \frac{\rho}{T^2}\right)^2 C_T^2(h)$ – structure parameter of the refraction index;

$r_0 = (0.423\, k^2 (\cos\gamma)^{-1} \int C_n^2(h)\, dh)^{-3/5}$, [m] – Fried coherence radius ($k = 2\pi/\lambda$, λ is the wavelength, γ is the zenith angle);

$$\mathrm{FWHM} = 2.045 \cdot 10^7 \left[(\cos\gamma)^{-1} \int_{H_0}^{H_1} dh\, C_n^2(h) \right]^{-3/5}$$ – the main characteristics of image quality, being the halfwidth of the mean star image (for $\lambda = 0.5$ μm) at the focus of telescope (measured in seconds of arc).

It was revealed that in the La Silla Observatory average vision at the telescope focus is 1.07″, and minimal FWHM value is about 0.48″. And it proved possible to estimate the partial contributions from different sections of optical path, at which the image is formed. These contributions were (in %):

effect from the telescope dome	–	5 ± 3.0
effect from the atmosphere in the layer	10–30 m	4 ± 0.2
the same but in the layer	300–800 m	77 ± 5.0
the same but in the layer	≥ 1000 m	14 ± 1.0

2.3. Possible Estimations of Some Characteristics of the Adaptive Telescope

The optical and meteorological measurement data allow the estimation of the specifications[6–8] of an adaptive telescope (AT).

Among these there are: optimal exposure time for adaptive telescope, isoplanatic angle, outer scale of turbulence. Let us consider them according to Ref. 9.

Optimal Exposure time for Adaptive Telescope. This parameter can be estimated through the time of characteristic change of phase distribution τ_{a0}, which is associated with the vertical profile of turbulence and the effective horizontal wind velocity v^*:

$$\tau_{a0} = 0.31 \frac{\tau_0}{v^*},$$

$$v^* = \left(\int_0^\infty |v(h)|^{5/3} C_n^2(h)\, dh \,/\, \left(\int_0^\infty C_n^2(h)\, dh\right)\right).$$

Isoplanary (or isoplanatic) angle for adaptive telescope determines the angular sector, in which wave front perturbations at one and the same point of entrance pupil, coming in two different directions, can correlate efficiently. Numerically it can be written as

$$\theta_a = 0.31 \frac{r_0}{h_{a0}},$$

where

$$h_{a0} = \left(\int_0^\infty h^{5/3} C_n^2(h)\, dh \,/\, \left[\int_0^\infty dh\, C_n^2(h)\right]\right)$$

is the effective atmospheric depth.

Outer scale of turbulence L_0 is especially important for adaptive telescope, it can be estimated from the following equations:

$$C_n^2 = 2.8\, M^2(h)\, L_0^{4/3}(h);$$

$$M(h) = -78 \cdot 10^{-6} \frac{\rho(h)}{T(h)} \frac{\delta \ln T_\rho(h)}{\delta h};$$

$$T_\rho = T(1000/\rho)^{0.286}.$$

The latter equations allow one to estimate the outer scale L_0 from the data of current measurements of vertical profiles $C_n^2(h)$, temperature $T(h)$ and pressure $\rho(h)$.

The outer scale of turbulence is the key parameter[4,5,14,17,18,23,49,50] for estimating relative energy (variance) of the first mode for phase fluctuation, as wells correlation scales for the second and third mode components – wave front random tilt vector.[14] This is especially important for telescopes – interferometers, as well as for telescopes with large apertures.[41,42] In this connection, developers of equipment for modern observatories should provide for introduction of additional optical measurer for current recording of this atmospheric parameter.

2.4. Proposals on the Development of Measuring Devices

Modern astronomical observatory equipped with high–technology telescopes and interferometers imposes enhanced requirements to the quality of information about atmospheric conditions, as well as to the parameter of the atmospheric models used. This is true not only for such characteristics of the atmosphere, widely used in observatories, as "visibility", "transparency", "the number of clear hours a year", but also a number of quantitative parameters and some functional characteristics.

Thus, M. Sarazin (head of the group on selecting the place for VLT telescope–interferometer[6–8]) recommends to use the following parameters to characterize observation conditions at an astronomic observatory:

L_0–outer scale of turbulence;
r_0–Fried radius;
θ_{a0}–isoplanary angle;
Q_{si}–isoplanary angle for speckle–interferometry;
τ_{a0}–coherence time for adaptive optics;
τ_{si}–coherence time for speckle–interferomenetry;
$v_{\max}$–maximum wind speed (in the troposphere);
v_0–average wind speed;
H_2O–amount of water vapor collected.

If the observatory is equipped with an adaptive telescope, then the above parameters are required both at the stage of selecting specifications of the telescope (such as characteristics of the place of telescope location) and at the stage of telescope functioning (for determining the control algorithm).

In addition, the development of algorithms of postdetector image processing requires the knowledge (measurement or calculation) of the short–exposure optical transfer function for the system "atmosphere–telescope".[10]

In this connection, the following set of instruments can be recommended as a basic one[13]:

1. Balloon measurements using micropulse temperature sensors for mean temperature, temperature lapse rate, and wind velocity.

2. Acoustic sounding in the altitude range from 30 to 600–800 m. (Synchronous measurements of temperature and wind velocity at the mast improve the calibration of acoustic sounding data for altitudes below 30 m.)

3. Measurement of star image scintillation and jitter using specialized photodevices at small telescopes.[2] And, additionally, two–ray stellar interferometer (with a changeable bases within 12–30 m.)

In addition to the above–mentioned, the telescope (diameter < 1 m) is required to operate in the mode of speckle–interferometer, as well as the base (at a mast of a 30–40 m height) meteorological complex to measure average and instant values of meteorological parameters.

At the Institute of Atmospheric Optics SB RAS, the set of such devices has been developed, as well as the entire measuring complexes[2,13,14] providing for analysis of astroclimate in different regions of the former USSR. When creating national astronomical observatory, this experience should be certainly be used.

Figures 1 and 2 show the instrumentation complexes developed at the Institute of Atmospheric optics SB RAS, providing for measurements of practically all necessary optical and meteorological characteristics forming the structure of astroclimate at the place of astronomic telescope location.

Let us describe now the main specifications of the devices shown in Fig. 1. Instrumentation complex includes: meteorogical mast 36 m high equipped with standard meters of temperature, wind velocity, and pressure. Portable ultrasound thermoanemometer[14] measuring temperature, two components of average wind velocity and its pulsations, as well as structure temperature constant.

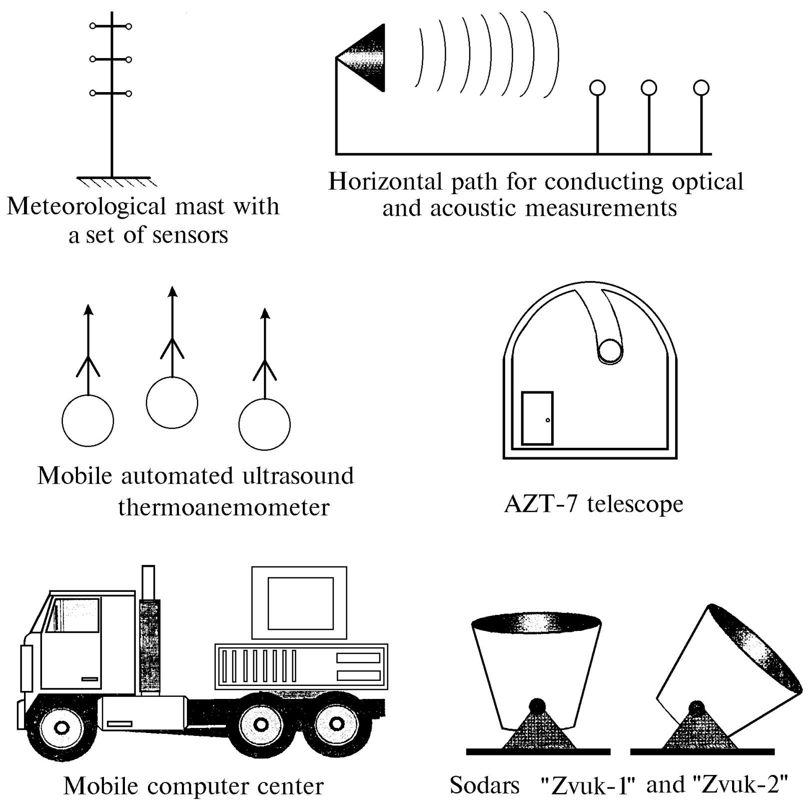

FIG. 1. Measuring tools of the scientific station of the Institute of Atmospheric Optics.

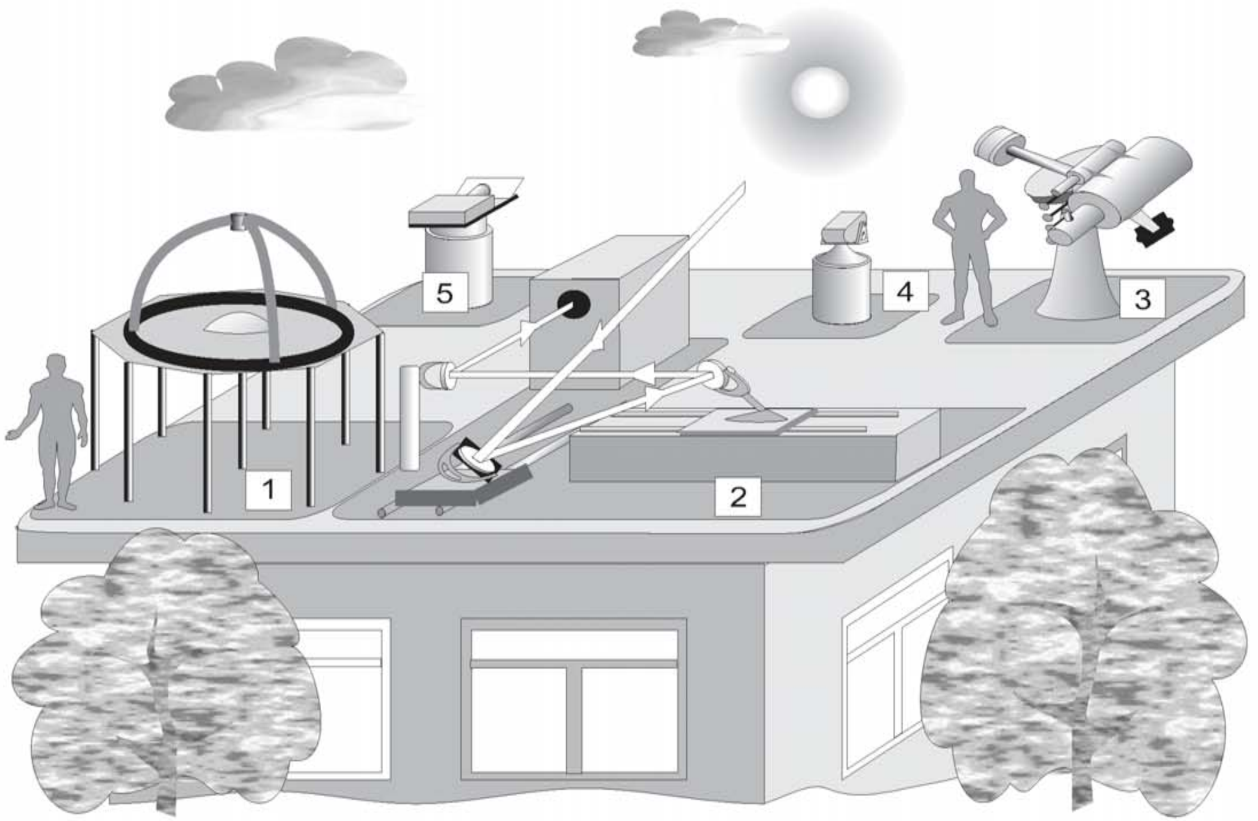

FIG. 2. Geometry of the instrumental complex located at the astronomic site of the IAO SB RAS: whole sky photometer (1), solar telescope with spectrophotometer (2), multiwave stellar-solar photometer (3), multiwave solar photometer (4), infrared spectroradiometer

The acoustic system for sounding the atmosphere ("Zvuk–1" and "Zvuk–2" system), being the mobile complex, comprising one or three acoustic antennas and instrumental van. These systems provide for measurements of wind velocity vertical profiles, temperature and turbulence characteristics in the altitude range from 40 to 1000 m.

Instrumental complex for measuring spectral transmission of the atmosphere, star scintillation and jitter built around photoelectric tools of the AZT–7 small astronomic telescope.[2,14] Parameters of the telescope and its photoelectric tools based on photodissectors enable determination of the angular position of a star image center of gravity accurate to 0.08" and measurement of its deviation in the 0.01–100 Hz frequency band.

All devices shown in Fig. 1 were developed at the IAO SB RAS and metrologically certified; they have proved their normal operation in experiments on studying optical radiation propagation in the atmosphere.

The instrumental complex shown in Fig. 2 (Fig. 2 and its description were kindly given to us by Dr. V.P. Galileiskii, research worker at the IAO SB RAS) is relatively new, however, it is already tested in a number of expeditions. It includes:

–"all sky" photometer which operates both in daytime and at night and estimates atmospheric transmission, including the presence of cloudiness (cloud cover index);

–solar telescope combined with spectral photometer provides for estimation of the effective atmospheric thickness at different sun elevation angles;

–solar–stellar multiwave photometer built around a small AZT–7 telescope which measures spectral transmission of the atmosphere at different zenith angles in a fixed spectral ranges.

These devices can be duplicated by multiwave solar photometer and infrared spectral radiometer.

The devices were constructed of Russian parts and have direct data input into a personal computer for storage, statistical processing and constructing the models of atmospheric optical characteristics.

2.5. Effective Outer Scale of Turbulence

One of the traditional ways to estimate the imaging ability of a future telescope is to measure the parameters of an image with a smaller–diameter telescope. However, turbulent PST of smaller telescope will correspond to PST of larger telescope only if the outer scale of turbulence in both cases will be significantly greater than the diameter of the large telescope. In some recent papers it was shown that for modern telescopes with apertures greater than 10 m this condition fails.

When speaking about the outer scale of turbulence, one should keep in mind that in real atmosphere it changes as the height of observation point over the underlying surface increases. In this connection, the problem of estimation of the image parameters for telescope from measured altitude profiles of turbulence outer scale and intensity becomes urgent. However, the use of altitude profiles is not always convenient because they depend on geographical position.

Of great interest from the viewpoint of practical application is the possibility of introducing the *effective* outer scale of turbulence, having the meaning of some integral parameter describing the character of atmospheric turbulence as a whole.[49,50]

The main goal of our works in this field[17–19,23,24,49,50] was to estimate the error in calculation of some integral characteristics of an image formed by an optical system associated with the replacement of altitude profile of outer scale by the *effective* outer scale of turbulence.

Calculations were made for a number of altitude profiles of turbulence intensity and outer scale, known from the literature. To determine the *effective* outer scale of turbulence, we minimize the integral rms deviation of real structure phase function (calculated on the basis of real profiles of turbulence intensity and outer scale) from the effective structure function of phase calculated on the basis of effective outer scale and Fried radius. Clearly the discrepancy depends on the upper boundary of the integration interval at which it is determined. We used[49,50] three different intervals:

1. 10 m that corresponds to the diameter of the largest known telescope;
2. Arg (90%) that corresponds to the argument at which the phase structure function reaches 90% of saturation level;
3. Infinity that corresponds to the determination of the phase structure function from the saturation level.

One can see from Tables II and III that the value of effective outer scale of turbulence is strongly affected by both the altitude profile of turbulence intensity and the determination method.

Introduction of the effective outer scale of turbulence may significantly simplify mathematical calculations allowing for the influence from atmospheric turbulence on the phase characteristics of an optical wave propagated along vertical and slant atmospheric paths.

TABLE II. Effective outer scale of turbulence for the "best" model of the altitude profile of turbulence. Models of altitude dependence of the outer scale of turbulence (B, C, D, E) are presented in Refs. 18 and 19.

Model	Method		
$L_0(h)$	10 m	Arg (90%)	∞
B	34.7	50.6	58.4
C	32.5	39.9	42.9
D	0.60	0.66	0.71
E	0.68	0.75	0.84

TABLE III. Effective outer scale of turbulence for the "worst" model of the altitude profile of turbulence. Models of altitude dependence of the outer scale of turbulence (B, C, D, E) are presented in Refs. 18 and 19.

Model	Method		
$L_0(h)$	10 m	Arg (90%)	∞
B	55.4	88.5	98.0
C	40.6	49.3	52.3
D	1.04	1.13	1.78
E	1.31	1.46	1.56

3. IMPORTANCE OF MODERN RESEARCH ON LASER RADIATION PROPAGATION IN THE ATMOSPHERE

The next stage of creation of a modern system is the stage of selection of main parameters of the optoelectronic system itself. At present such investigations are conducted by practically the whole word optical community. The up-to-date requirements make this problem rather complex.

3.1. Modern Problems in OES Design

Technology of application of modern optoelectronic systems under conditions of real atmosphere requires more and more indepth knowledge about characteristics of the main medium, in which laser radiation propagates, namely, the atmosphere. Costs of the design of optoelectronic systems are now very high, and so it should provide for their best possible performance characteristics.

Problems of adaptive optics were the theme of several conferences (1992–the Hawaii, USA; 1993–Munchen, Germany; 1994–the Hawaii and Orlando, USA; 1995–Munchen, Germany; 1996–Hawaii, USA), NATO Summer School (1993, Korsika, France), NATO Winter School (1996, France). Our works also were presented at these conferences and schools.[20-22, 24,25,27-31,33-36,45-47]

When formulating the theory of atmospheric adaptive optical system functioning we think it is necessary to take into account the main fluctuation components of the atmosphere: atmospheric refraction, atmospheric turbulence, thermal blooming due to molecular absorption.

We have studied possibility of focusing high–power laser radiation using adaptive algorithms in numerical experiment for different scenarios of radiation propagation. First of all, for homogeneous optical paths the relative efficiency of adaptive focusing was studied on the basis of different control algorithms. We have analyzed, in order of increasing complexity, the algorithms of "*a priori* phase" correction, "slow" and "fast" adaptive phase correction based on reference radiation, as well as the algorithms of amplitude–phase correction for distortions of high–power laser beams.[14-16,26]

Let us summarize briefly the results obtained. Efficiency of the "*a priori* phase" correction proves to be proportional to the Fresnel number of the emitting aperture. For the near infrared range (< 3 μm), atmospheric turbulence significantly decreased the laser beam intensity at a focus, while "a priori" correction increased the intensity at a focus almost twice. An adaptive optical system at a horizontal path tends to focus high–power beam into "point" ("fast phase conjugation") and into "line" ("slow phase conjugation") near the emitting aperture, and the defocussing degree is limited by high–power beam diffraction and dislocations in the reference beam.

Analyzing different propagation scenarios, in particular, slant atmospheric paths, homogeneous "high–altitude" paths, scanning of high–power laser beams, we established that the most important effect accompanying the process of high–power radiation focusing is the manifestation of "instability". Of principal importance in this case are both the instability of the process of thermal blooming itself and its manifestation under conditions of adaptive control.[26, 33] We have studied different modes of adaptive system operation along atmospheric paths of different type. Critical point here is the fact that manifestation of instability transforms the process of adaptive focusing of high–power laser radiation into an iteration process, in which "good" and "bad" iterations alternate.

3.2. Writing of a 4–D Computer Code for Dynamic Modeling of Adaptive Systems

At present we have created the basis for a 4–D dynamic model[30, 37-40] of an adaptive optical system operating in the atmosphere. In particular, we created numerical models of separate components of an adaptive contour, namely,

a) the model of laser beam propagation through a refractive and turbulent medium;
b) the model of low–frequency range of atmospheric turbulence spectrum (for the case of surface atmospheric layer and for the entire atmospheric depth)[21, 23, 25, 28, 31];
c) the models of wave–front sensors;
d) the model of quantum fluctuations of radiation beam.

Using this dynamic computer model, we studied the limited possibilities of ground–based adaptive telescopes as functions of the number of measurements in the wave–front sensor, turbulence intensity and structure, and the value of optical signal detected.

As to the problems of adaptive focusing of high–power laser radiation, such a dynamic model allows us to study temporal modes of AOS operation, to reveal physical regularities of instability formation at beam thermal blooming, to understand causes and sources of these instabilities. Development of such computer models allows one to proceed to AOS design from the position of choosing optimal configurations of wave–front sensor and deformable controllable mirror, to take into account, in calculations, such effects as nonisoplanarity manifestation in large optical systems, to simulate artificial reference sources, as well as to analyze the efficiency of different algorithms of control over both a dynamic active mirror and the system as a whole.

The numerical dynamic model of an atmospheric adaptive optical system, created at the Institute of Atmospheric Optics SB RAS, is a unique instrument for analyzing optoelectronic systems in the atmosphere. This model was checked at different institutes of Russia, USA (Lincoln Lab, Livermor Lab), China (Nankin Center of Astronomical Instruments, Beijin Institute of Applied Physics and Computing Mathematics). The calculational results were compared with the calculations by Molly model developed in the USA.

3.3. Modern Problems in Adaptive Optoelectronic System Design

The next stage of OES use, requiring in depth knowledge about the atmosphere and its models, is associated with the design and construction of the adaptive optical system itself. On the whole, we offer the completely closed analysis of an adaptive system with calculation of its separate components. As a future development of our works we plan, in particular,

1. To conduct analytical and numerical calculations of statistical characteristics of phase fluctuation of optical waves propagating in randomly inhomogeneous medium at arbitrary values of characteristic parameter: intensity fluctuation variance, relations between size of inhomogeneities or receiving aperture and radiation coherence scale.

2. To compare the results of analytical calculations and numerical solution of parabolic wave equation in the regions of both "weak" and "strong" intensity fluctuations.

3. To develop efficient algorithms for optical wave phase reconstruction from the data of optical measurements. And, on this basis, to develop the methods for optical wave phase measurement under conditions of speckle structure appearance in the field measured. Experimental setup should provide for measurements of phase fluctuations at manifestation of "zero" intensity values of the field measured. Already in 80s–90s at the Institute of Atmospheric optics SB RAS the mathematical apparatus was developed allowing the concept of optical wave phase to be defined more rigorously for the cases when the field intensity fluctuations are strong. Several versions of the optical wave phase measurers were developed, as well as the methods of wave front reconstruction from the data of optical measurements under conditions of "strong" intensity fluctuations, i.e. when separate or multiple bright and dark regions – "speckles" appear in the field distribution. Obviously, here new mathematical apparatus is required which would allow the description of the so–called phase dislocations in optical waves.

4.To describe optical wave phase fluctuations based on the atmospheric model constructed based on the data of experimental measurements. To develop the model of spectral density of fluctuations the refractive index of turbulent atmosphere (for different propagation conditions) in the region of large–scale optical inhomogeneities. To study changeability of turbulence outer scale and whole spectrum against thermodynamic instability of the atmosphere.[21, 23, 25, 28, 47]

3.4. Simulation of an Adaptive System Providing for Minimization of Distorting Atmospheric Effect on Radiation Characteristics

Today most researchers accept that when constructing modern optoelectronic systems there is no alternative to the use of adaptive correction. In this connection it should be accepted worthwhile to analyze the possibilities of application of adaptive methods to correction of atmospheric distortions simultaneously with the development and design of an optoelectronic system itself.

Modern optoelectronic systems for transfer of both energy and image information through the atmosphere certainly should be designed on the basis of a comprehensive, if possible, knowledge about the characteristics of optical waves and about regularities of their fluctuations in the atmosphere. World experience in this field allows us to say that application of adaptive correction is very promising for improving the efficiency of optical systems operation.

At present the leader in the development of adaptive optoelectronic systems is the USA. It should be noted that at a number of international conferences in 1993–1996 American specialists reported that they are most successful in the use of adaptive optics for astronomy (ground–based and space based telescopes), while the use of adaptive optics in high–power radiation transfer gives, by their estimates, not very good results. Most successful in this field are specialists of two largest USA national laboratories (Lincoln and Livermor Labs). In the USA, France and Germany, the programs on adaptive optics in astronomy already now give practical results.

On the whole, one can conclude that researches in application of adaptive optics receive considerable attention in the USA (Lincoln Lab, Livermor Lab, Arizona and Hawaii State Universities, "Adaptive Optics" Special Association). In the nearest future, two telescopes: Kekk–1 and Kekk–2 will be put into operation in the USA. These telescopes have the main mirror of 10 m size comprising of 36 active elements. They are set up at the Hawaii, Mauna Keya Observatory. An adaptive solar telescope is constructed in California; the special program on designing a family of telescopes 8 m in diameter ("Twins" project) is developed. In the USA, within the frame of SDI conversion, works are conducted on the use of high–power lasers for artificial reference star formation, as well as on the use of lasers for energy transfer to geostationary satellites and stations – the SELENE Project.

Germany and France conduct works on creation of the "Very Large Telescope" – the telescope–interferometer comprising of four 8–m telescopes which will be located in Chile. Italy conduct works on creation of the "Galilei" adaptive telescope. Adaptive telescopes are also being created in China (2 m, 4 m), Great Britain, Canada, Australia (14 m), Sweden, Mexico (6 m), Japan ("Subaru" 8–m telescope).

Developers of adaptive optical systems at the Institute of Atmospheric Optics SB RAS are aimed at development of the theory of modern adaptive systems for image and energy transfer through the atmosphere as applied to most recent optoelectronic systems. In particular, along with the development of theoretical grounds, several prototypes of new optoelectronic devices will be constructed. These problems seems to be especially urgent in view of implementing of adaptive optics and its elements in modern specialized OESs.

Within the frame of these problems, research workers of the Institute of Atmospheric Optics SB RAS develop:

a) software for simulation of adaptive system operation in the atmosphere;
b) design of general construction of an adaptive telescope and other optical systems;
c) models of the atmosphere for most promising points for location of Russian large–size telescopes and other optoelectronic systems;
d) prototypes of some elements of an adaptive system with the following testing of these elements in the atmosphere.

Table IV presents the calculated values of the main parameters determining the characteristics of an adaptive telescopes: Fried coherence radius, isoplanatism angle of the atmosphere, life time of phase distribution for three different radiation wavelengths (0.5, 1.6 and 2.2 μm) and for two different models (MK and MMK) of atmospheric turbulence.[11, 12]

The design of adaptive telescope was done. Figure 3 presents the structure diagram of an adaptive telescope with an active mirror and two adaptive mirrors. The results of calculations made for the project of Russian AST–10 telescope with a compound main mirror[46] are shown in Fig. 4 as four fragments: three of them correspond to PST calculations for different modes of turbulence; the fourth shows the behavior of Shtrel ratio for such an adaptive telescope.

TABLE IV

Parameter	MK			MMK		
	λ = 0.5 μm	λ = 1.6	λ = 2.2	λ = 0.5 μm	λ = 1.6	λ = 2.2
r_0, m	0.18	0.72	1.06	0.15	0.61	0.89
θ_0, sec of arc	3.0	12.0	17.7	1.3	5.2	7.7
t_0, ms	3.6	14.4	21.2	1.8	7.2	10.6

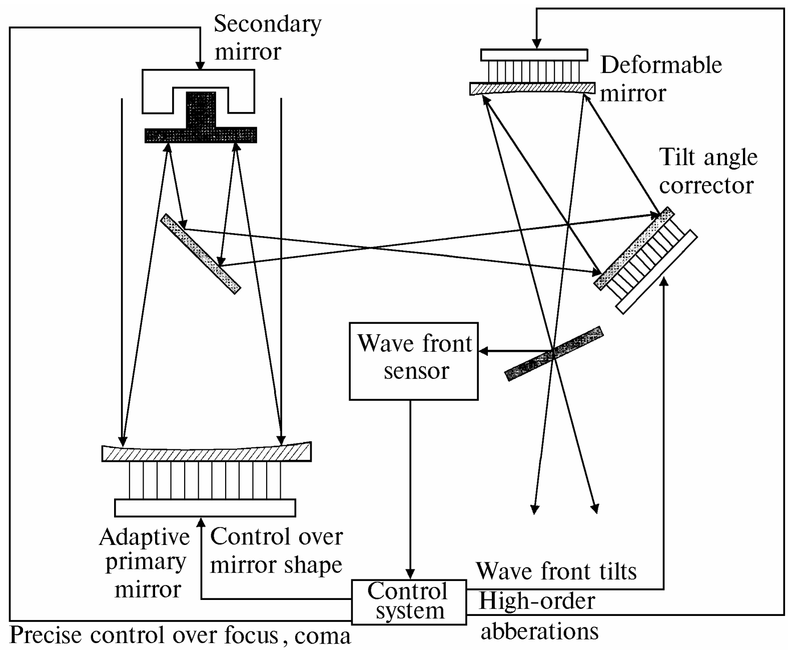

FIG. 3. Structure diagram of an adaptive telescope with active primary mirror and two adaptive mirrors.

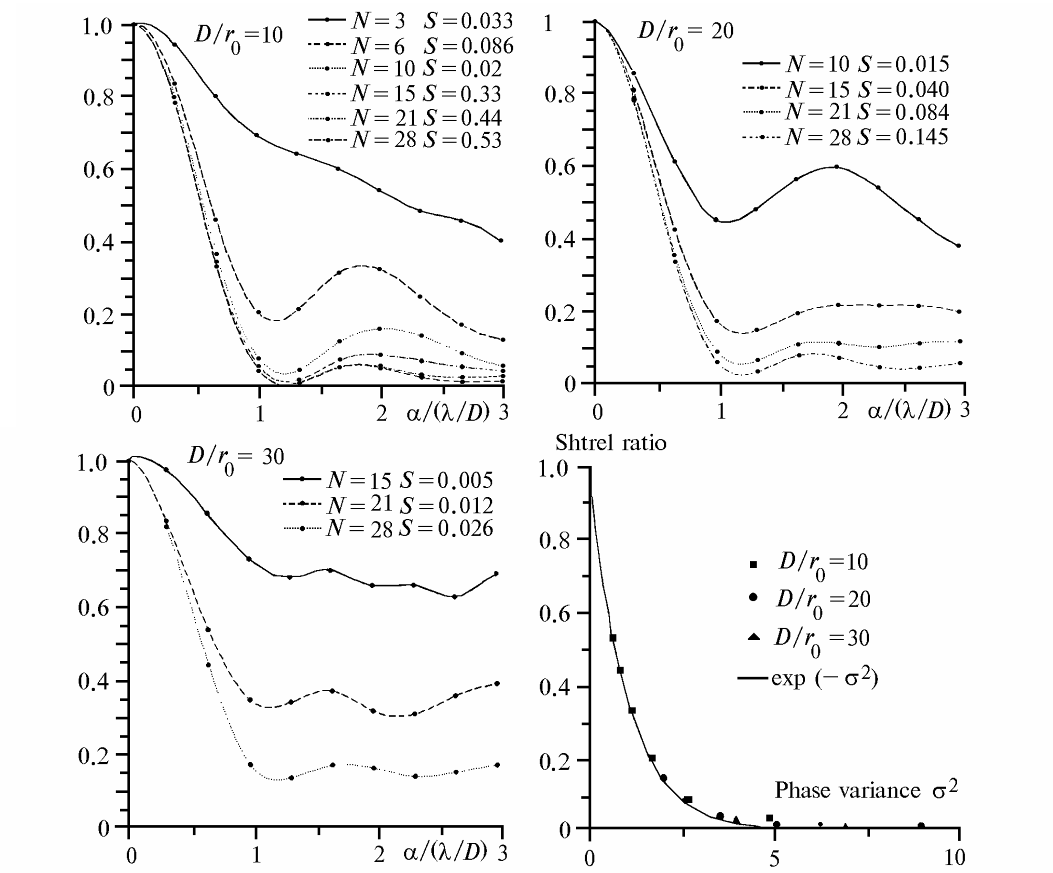

FIG. 4. PST for AST-10 telescope when using the modal corrector. The parameter N corresponds to the number of Zernike polynomials. PST is normalized to axial value. S is the Shtrel parameter.

4. THE STAGE OF ADAPTIVE OPTICAL SYSTEM OPERATION

At this stage, for an optoelectronic system several significantly different operation modes exist, in which the information about the system is used at different levels.

4.1. Passive Mode of OES Operation

The problem on the use of data of optical measurements against real reference star in the feedback loop should be considered separately. In this case, the atmospheric model is invoked at the level of determination of permissible angle between working direction of the axis of optoelectronic system and the direction to a reference star, the so–called angle of atmospheric isoplanatism (see Table IV). The model of the atmosphere is used here for calculation of limited angle of isoplanatism in a given direction when operating though the entire atmosphere.

Of great importance become different algorithms using *a priori* information about distorting properties of the atmosphere during OES operation. These are algorithms based on statistical forecasting of phase fluctuations. In one of the first paper on this problem,[15] the algorithm was described for statistical forecasting that ensures stable operation at any temporal delay in an adaptive system. This algorithm in a modified form realizes the so–called modal forecasting of fluctuations.[14]

Recently a number of approaches have been developed that use the value of optical transfer function of the atmosphere at short exposures for postdetector correction of images obtained in the telescope. There are two different types of algorithms: the algorithms of postdetector processing using optical transfer function calculated on the basis of the model of turbulent atmosphere ("blind inverse convolution") and the algorithms using the data of direct measurements of this characteristics. Several alternative approaches should be separated: when optical transfer function is measured directly in the experiment and when the data from wave front sensor are used to calculate this function. In addition, when constructing OES, one faces the problem of obtaining qualitative phase information when using actual reference sources. It decreases the possibilities of OES.

4.2. Problems of Using of Laser Reference Stars

One of serious engineering problems developers of adaptive optical telescopes face with is the possibility of using sufficiently bright stars as reference sources, because often the wave front sensors of such a telescope needs for a most part of star radiation energy for its normal functioning. Requirements to the power of reference source, as well as the need for simultaneous location in one isoplanary region of a star (or any other space object) under study and sufficiently bright reference star due to small isoplanatism angle of the atmosphere (in the visible range at propagation at zenith it is 10–15″) significantly decrease the percentage of sky coverage by such a telescope.

Adaptive optics developers found the way to solve this problem in the use of focused laser radiation emitted from the ground and backscattered by atmospheric inhomogeneities. It may be elastic aerosol scattering from 8–20 km altitudes or stimulated reradiation from 80–100 km altitudes at clouds of atomic sodium.

The problem of creation of laser reference stars is accompanied by a lot of scientific and technical problems, such as creation of specialized laser device, selection of optimal height for location of this reference star, change of the phase of laser radiation backscattered in the atmosphere, and, finally, selection of a control algorithm.

In this connection, the statement[51] of one of a well known american developers of such systems, Doctor Robert Fugate is interesting that in the period of writing the report (February of 1996) he did not know successfully operating laser reference stars using scattering from sodium clouds. Although just sodium reference stars can provide for the best characteristics of an adaptive telescope.

First work on this problem in the USSR was done more than 15 years ago (see references in Refs. 14, 24, and 45). However only in recent years these researches received real perspectives for experiments. In this connection, when developing design of AST–10 Russian telescope, the possibilities of operation of such a telescope with the use of laser reference stars were investigated. Figure 5 shows the PSF calculation for AST–10 telescope operation assuming the use of a laser reference star. However, in this case it was proposed that there is a parallel channel for measuring fluctuations of general tilt of wave front (tip–tilt), because the laser reference star gives no such information.

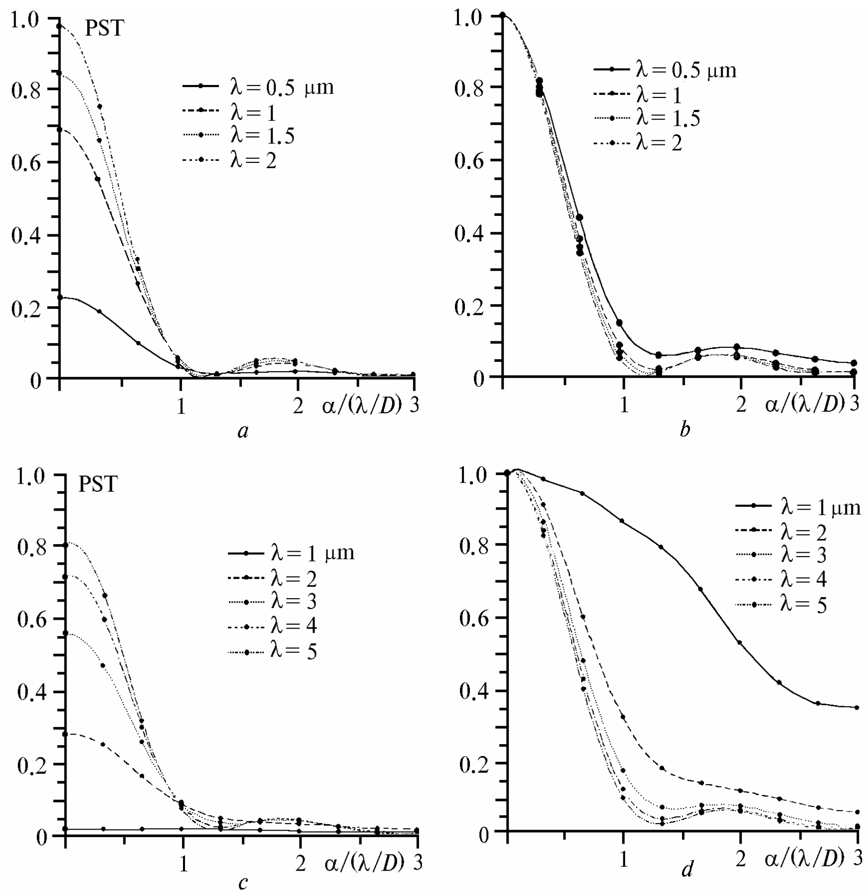

FIG. 5. PSF for AST–10 telescope for different wavelengths at adaptation against laser reference star (LRS): sodium LRS, H = 100 km *(a, b), Rayleigh LRS, H =* 10 km *(c, d), PST normalized to diffraction maximum (a, c), PST normalized to axial value (b, d).*

4.3. "Optimal" Algorithm for "Tip–Tilt" Correction

The use of laser reference star increases the zone of stable operation of an adaptive OES. But because the laser star is formed at finite distance, the necessity appears in correction of the data of optical measurements from laser star to provide for efficient correction of the distortions for real astronomic objects. Here the models of the atmosphere can be used again. This use is necessary:

a) for estimation of the value of turbulent distortions located above the star to determine the optimal height of the star formation;
b) for although partial compensation for "focus isoplanatism";
c) for selection of the scheme of laser reference star formation;
d) for improving the possibilities of "tip–tilt" estimation.

Certainly, the use of laser reference stars formed in the atmosphere based on backscattered signal is related to the problem of selection of optimal algorithm of using the data of optical measurements for correction for random jitter of a star image.

I stated this problem just in recent months. Most complete bibliography of Russian papers dealing with the creation of laser reference stars is given in Refs. 45 and 48.

In the telescope focal plane, we will characterize the image jitter by a random displacement of the center of gravity (under condition of weak intensity fluctuations) of the star image intensity

$$\rho_F^{\mathrm{pl}} = -\frac{F}{k\Sigma}\iint\limits_{\Sigma} d^2\rho\nabla_\rho S^{\mathrm{pl}}(0, \rho) . \quad (1)$$

In its turn, the vector of measurement is

$$\rho_{\mathrm{M}} = \rho_{\mathrm{c}} + \rho_F^{\mathrm{sph}} , \quad (2)$$

where

$$\rho_{\mathrm{c}} = \frac{1}{P_0}\int\limits_0^x d\xi(x-\xi)\iint d^2 R I(\xi, \mathbf{R})\,\nabla_R\, n_1(\xi, \mathbf{R}) \quad (3)$$

is the position of the center of gravity of a Gaussian laser beam focused at a distance x from the source. Believing that laser radiation is focused into a sufficiently small speckle not resolved by the telescope through the atmosphere, the second term in Eq. (2)

$$\rho_F^{\mathrm{sph}} = -\frac{F}{k\Sigma}\iint\limits_{\Sigma} d^2\rho\nabla_\rho S^{\mathrm{sph}}(0, \rho) \quad (4)$$

is the jitter of a point source image in the telescope focal plane. Superscripts "pl" and "sph" in Eqs. (1), (2), and (4) show that calculations of characteristics of optical field were done for plane and spherical waves; k is radiation wave number; F is the focal length of the objective; x is the height of reference star formation; Σ is the area of the objective aperture; S are the fluctuations of optical wave phase; I is the optical wave intensity; $\eta_1(\xi, \mathbf{R})$ is the fluctuation of the atmospheric refractive index.

Let us construct the algorithm of correction for star image jitter in the form

$$\rho_{\mathrm{c}} = A\rho_{\mathrm{M}}, \quad (5)$$

providing for minimum variance of the rest distortions

$$\langle(\rho_F^{\mathrm{pl}} - A\rho_{\mathrm{M}})^2\rangle = \langle(\rho_F^{\mathrm{pl}})^2\rangle + A^2\langle(\rho_{\mathrm{M}})^2\rangle - 2A\,\langle\rho_{\mathrm{M}}\,\rho_F^{\mathrm{pl}}\rangle . \quad (6)$$

Searching for minimum variance in the form (6), we have

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\mathrm{pl}} - A\rho_{\mathrm{M}})^2\rangle_{\min} = \langle(\rho_F^{\mathrm{pl}})^2\rangle - A\,\langle\rho_{\mathrm{M}}\,\rho_F^{\mathrm{pl}}\rangle , \quad (7)$$

where the correcting coefficient A is expressed only in terms of determinate functions

$$A = \langle\rho_{\mathrm{M}}\,\rho_F^{\mathrm{pl}}\rangle \,/\, \langle(\rho_F^{\mathrm{pl}})^2\rangle . \quad (8)$$

It should be noted that the traditional correction algorithm, where $A = 1$, naturally does not provide for minimum variance (6) and therefore cannot be considered as a serious alternative.

In a real experiment, as a rule, we have only the measurement data ρ_{M}, because we cannot measure the vector ρ_F^{pl} characterizing jitter of a real star, whose image must be corrected, since a real star gives too little light for measurements using a wave front sensor.

At the same time, the coefficient A can be calculated from the model description of the altitude distribution of the turbulence intensity.

Now we should tell some words about schemes of the laser reference star formation. Several such schemes were offered, but from the viewpoint of calculation of the variance and correlation from Eq. (8) two of them can be considered as limiting ones: the monostatic scheme, when star image in the telescope and laser reference image are formed through one and the same atmospheric inhomogeneities, and bistatic scheme, when reference star is formed in the isoplanary region for an observed (natural) star, but focused laser beam forming reference star propagates through turbulent inhomogeneities uncorrelated with those on the path the natural star image formation.

4.3.1. Monostatic Scheme of Laser Reference Star Formation

According to Eqs. (1)–(7), the minimum variance of the rest fluctuations of star image angular displacements for monostatic scheme is given in the form

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\mathrm{pl}})^2\rangle\left\{1 - \frac{2^{1/3} f(x, C_n^2)}{\left[1 + b^{-1/3} - 2^{7/6}(1+b^2)^{-1/6}\right]}\right\}, \quad (9)$$

where $b = a_0/R_0$ (a_0, R_0 are diameters of the laser beam and telescope aperture);

$$f(x,C_n^2) = \frac{\left(\int\limits_0^x \mathrm{d}\xi C_n^2(\xi)\Big[(1-\xi/x)\big(1+(1-\xi/x)^2\big)^{-1/6} - (1-\xi/x)\Big]\right)^2}{\int\limits_0^\infty \mathrm{d}\xi C_n^2(\xi) \int\limits_0^x \mathrm{d}\xi C_n^2(\xi)\,(1-\xi/x)^{5/3}}. \quad (10)$$

Thus, one can expect efficient correction with a monostatic scheme of reference star formation only for sufficiently large altitudes of laser beam focusing, in this case the optimal size of focused beam $a_0 \to R_0$.

Based on known models of turbulence altitude profile we can state that the monostatic scheme allows

1. Estimation of a limited level of wave front general tilt correction using Eq. (9), where the second term is estimated based on the models of turbulent atmosphere.

2. Estimation of the recalculation coefficient A when using of the measured values ρ_M to make a control algorithm expressed via average values:

$A = \langle\rho_M\, \rho_F^{\rm pl}\rangle \;/\; \langle(\rho_F^{\rm pl})^2\rangle$.

4.3.2. Bistatic Scheme of Formation

For such a scheme it is characteristic that laser star is formed through turbulent inhomogeneities not correlated with the inhomogeneities through which star image is formed in a telescope. This can be done due to lateral illumination with a laser (at a sufficiently large distance between the optical axis of a laser beam propagation and the telescope optical axis). Using the same procedure of searching for minimum variance of the residual fluctuations of image jitter and making calculation similar to those for the monostatic scheme, we have

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\rm pl})^2\rangle \left\{1 - \frac{2^{1/3} f_1(x,\, C_n^2)}{[1 + b^{-1/3}]}\right\}, \quad (11)$$

where

$$f_1(x,\, C_n^2) = \frac{\left(\int\limits_0^x \mathrm{d}\xi C_n^2(\xi)\,(1-\xi/x)\big(1+(1-\xi/x)^2\big)^{-1/6}\right)^2}{\int\limits_0^\infty \mathrm{d}\xi C_n^2(\xi) \int\limits_0^x \mathrm{d}\xi C_n^2(\xi)\,(1-\xi/x)^{5/3}}. \quad (12)$$

As analysis of the latter expressions shows, efficient correction with a bistatic scheme of reference star formation provides for minimum variance of the residual image jitter (11) with the correction (5). One can see that in contrast to monostatic scheme, the correction using a bistatic scheme is efficient at any ratio a_0/R_0, but the correction is better, the greater is the value of b (see Ref. 11).

Therefore one can expect that the correction with a bistatic scheme will be good. In addition, at any values of b ($b = a_0/R_0$) ρ_M never identically equals zero.

Two limiting schemes of laser reference star formation can be compared only using particular estimates. It should be noted here that such a comparison must be done already not for a particular telescope (with adaptive optics), but for an entire observatory, for example, the observatory at the Mauna Kiya mountain at the Hawaii, where three largest telescopes operating with adaptive correction for turbulent distortions are located: Kekk–1, Kekk–2, and CHFT. The first two telescopes have 10 m aperture, and the CHFT telescope (Canada–Hawaii–France) has 3.6 m aperture.

Mutual arrangement of these telescopes is such that when operating by monostatic scheme the variance of residual distortions for each telescope is calculated by Eq. (9).

If the telescope Kekk–1 forms bistatically a star for the telescope Kekk–2 (distance between the telescopes is about 85 m), then we have

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\rm pl})^2\rangle \left\{1 - 2^{-2/3} f_1(x,\, C_n^2)\right\};$$

in the case when Kekk–2 forms a star for CHFT telescope, then

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\rm pl})^2\rangle \left\{1 - \frac{2^{1/3} f_1(x,\, C_n^2)}{1 + (10/3.6)^{-1/3}}\right\};$$

and in the case when CHFT is a star for the pair Kekk–1 / Kekk–2, then

$$\langle\beta^2\rangle_{\min} = \langle(\rho_F^{\rm pl})^2\rangle \left\{1 - \frac{2^{1/3} f_1(x,\, C_n^2)}{1 + (3.6/10)^{-1/3}}\right\}.$$

Thus, summarizing the results, the following conclusions may be drawn:

1. The monostatic scheme is practically inapplicable for correction of general tilt of a wave front at the telescope aperture.

2. The bistatic scheme gives a marked correction for the general tilt.

3. Optimal correction based on the use of information about turbulence intensity altitude profiles is most efficient. At the same time, being used as “direct” correction it can even increase distortions in some cases.

On the whole, these results show that the models of the atmosphere must be used at any stage of the design, construction, and operation of modern optoelectronic systems.

The main results we have obtained in this field are published in Refs. 2, 13–50.

ACKNOWLEDGMENTS

The author would like to express his gratitude to his colleagues from the Laboratory of Applied and Adaptive Optics of the Institute of Atmospheric Optics SB RAS: O.N. Emaleev, N.N. Botygina, B.V. Fortes, F.Yu. Kanev, L.V. Antoshkin, L.N. Lavrinova, and E.V. Nosov.

REFERENCES

1. P.V. Shcheglov, *Problems of Optical Astronomy* (Nauka, Moscow, 1980), 271 pp.
2. V.P. Lukin, O.N. Emaleev, et al., Astronomicheskii Zh. **60**, No. 4, 790–795 (1983).
3. C.E. Coulman and J. Vermin, Appl. Opt. **27**, No. 1, 155–160 (1988).
4. R. Good and R. Beland, Proc. SPIE **982**, 165–186 (1988).
5. T.S. McKechnie, J. Opt. Soc. Am. **9**, No. 11, 1937–1954 (1992).
6. *Site Testing for VLT*, ESO VLT Report, No. 60 (1990).
7. ESO VLT Report, No. 55 (1986).
8. F. Murtaqh and M. Sarazin, *"Nowcasting Astronomical Seeing: A Study of ESO La Silla and Paranal"*, ESO Scientific preprint, No. 934 (1993).
9. B. Lopez and M. Sarazin, *"Optimum Exposure Times for Interferometry"*, ESO Scientific Preprint, No. 36 (1991).
10. *ICO–16 Satellite Conference on "Active and Adaptive Optics"*, Proc. ESO (1993).
11. *Adaptive Optics in Astronomy*, Proc. SPIE **2201** (1994).
12. *Adaptive Optics, Technical Digest Series*, OSA ESO **23** (1995).
13. V.P. Lukin, Atmos. Oceanic Opt. **8**, Nos. 1–2, 145–150 (1995).
14. V.P. Lukin, *Atmospheric Adaptive Optics* [in Russian] (Nauka, Novosibirsk, 1986), 248 pp [in English], SPIE Press, **PM23** (1996), 285 pp.
15. V.P. Lukin and V.E. Zuev, Appl. Optics **27**, No. 1, 139–147 (1987).
16. V.P. Lukin, Kvant. Elektron. **15**, No. 9, 1856–1861 (1988).
17. V.P. Lukin, Atmos. Oceanic Opt. **5**, No. 4, 229–242 (1992).
18. V.P. Lukin, Atmos. Oceanic Opt. **5**, No. 12, 834–841 (1992).
19. V.P. Lukin, N.N. Maier, and B.V. Fortes, Atmos. Oceanic Opt. **5**, No. 12, 801–807 (1992).
20. V. Lukin and B. Fortes, Proc. SPIE **1688**, 477–488 (1992).
21. V.P. Lukin, OSA Digest Series **19,** 243–245 (1992).
22. V. Lukin and B. Fortes, OSA Digest Series **19**, 79–82 (1992).
23. V.P. Lukin, Atmos. Oceanic Opt. **6**, No. 9, 371–374 (1993).
24. V.P. Lukin, Proc. ICO, 521–524 (1993).
25. V. Lukin, Proc. SPIE **1968**, 327–336 (1993).
26. V.P. Lukin, B.V. Fortes, F.Yu. Kanev, and P.A. Konyaev, J. Opt. Soc. Am. **A11**, No. 2, 903–907 (1994).
27. V.P. Lukin, Proc. SPIE **2201**, 46–55 (1994).
28. V.P. Lukin, Proc. SPIE **2200**, 384–395 (1994).
29. V.P. Lukin, B.V. Fortes, and F.Yu. Kanev, Proc. SPIE **2201**, 768–775 (1994).
30. V.P. Lukin, B. Fortes, F. Kanev, and P. Konyaev, Proc. SPIE **2222**, 522–526 (1994).
31. V.P. Lukin, Proc. SPIE **2222**, 527–535 (1994).
32. V.P. Lukin, in: *Adaptive Optics for Astronomy* (Klumer Acad. Publisher, Netherland, 1994), pp. 59–65.
33. V.P. Lukin, B.V. Fortes, and F.Yu. Kanev, Proc. SPIE, **2375** (1995).
34. V.P. Lukin, Proc. SPIE **2471** (1995).
35. V.P. Lukin, OSA Technical Digest **23**, 192–194 (1995).
36. V.P. Lukin and B.V. Fortes, OSA Technical Digest, **23**, 92–93 (1995).
37. V.P. Lukin, Atmos. Oceanic Opt. **8**, No. 3, 152–173 (1995).
38. V.P. Lukin, F.Yu. Kanev, P.A. Konyaev, and B.V. Fortes, Atmos. Oceanic Opt. **8**, No. 3, 210–214 (1995).
39. V.P. Lukin, F.Yu. Kanev, P.A. Konyaev, and B.V. Fortes, Atmos. Oceanic Opt. **8**, No. 3, 215–219 (1995).
40. V.P. Lukin, F.Yu. Kanev, P.A. Konyaev, and B.V. Fortes, Atmos. Oceanic Opt. **8**, No. 3, 220–222 (1995).
41. V.P. Lukin and B. Fortes, Pure and Appl. Optics, **5**, 301–311 (1996).
42. V.P. Lukin and B.V. Fortes, Astronomicheskii Zh. **73**, No. 3, 409–425 (1996).
43. V.P. Lukin, Atmos. Oceanic Opt. **9**, No. 11, 910–915 (1996).
44. V.P. Lukin and B.V. Fortes, Atmos. Oceanic Opt. **9**, No. 11, 948–956 (1996).
45. V.P. Lukin, Proc. OSA, AMB35–1 – AMB35–5 (1996).
46. V.P. Lukin and B. Fortes, Proc. OSA, 211–214 (1996).
47. V.P. Lukin, Proc. OSA, 150–152 (1996).
48. V.P. Lukin and B.V. Fortes, Atmos. Oceanic Opt. **10**, No. 1, 34–41 (1997).
49. V.P. Lukin, B.V. Fortes, and E.V. Nosov, in: *Abstracts of Reports at III Inter-Republic Symposium on Atmospheric and Oceanic Optics*, Tomsk (1996), pp. 31–33.
50. V.P. Lukin, B.V. Fortes, and E.V. Nosov, *ibid.*, pp. 33–34.
51. R. Fugate, 1996 Technical Digest Series **13**, 90–92 (1996).