instance, Ref. [21]):

$$T_{\mathrm{FM}} \sim t_{\mathrm{eff}} = t \exp\left(-\frac{E_{\mathrm{pol}}}{\hbar\omega}\right) \sim \sin\frac{\langle \mathrm{Mn-O-Mn}\rangle}{2} \exp\left(-\mathrm{const}\, M^{1/2}\right), \qquad (1)$$

where E_{pol} is the polaron shift energy, $\omega \sim \omega_{\mathrm{Debye}}$, and M is the ion mass. Hence, it is clear that compensating the reduction in T_{FM} with an increase in oxygen mass necessitates increasing the angle $\langle \mathrm{Mn-O-Mn}\rangle$, which can be attained by lowering y [12]. The relative changes of T_{FM} caused by these two factors can be compared when the constant in the exponential index is known. Agreement with experimental data on the shift, for instance, of the transition point from the pure FM state to the mixed FM + AFM state is reached for const ≈ 0.3. However, the functional dependences of the temperature difference ΔT_{FM} on y that follow from expression (1) and are observed in experiments for the compounds with ^{16}O and ^{18}O isotopes are inconsistent: ΔT_{FM} should increase with T_{FM} according to expression (1), but this temperature difference decreases according to both the magnetic and diffraction data. A plausible explanation of this effect, involving the assumption of a higher stability of polarons with ^{18}O isotopes, was put forward in Ref. [22].

The presently available comprehensive experimental material appears to be quite sufficient to arrive, relying on its theoretical analysis, at a definite conclusion as to what the cause of the CMR effect in manganites is. However, neutron diffraction investigations of isotope-enriched compounds bring up new questions, some of which are quite important. Why does the giant isotope effect manifest itself in a relatively broad range of variability of the average A-cation radius? What underlies the occurrence of the mesoscopically mixed state (in other words, why does the AFM – FM phase transition not proceed to completion)? Why does a significant volume fraction of the sample become magnetically disordered in the course of transition to the dielectric state? Why does the noncollinear AFM structure in LPCM-y with the ^{16}O isotope become collinear in LPCM-y with the ^{18}O isotope?

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Atmospheric adaptive optics

V P Lukin

1. Introduction

Research aimed at developing adaptive optical systems has been pursued in the Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences (IAO, SB RAS) for more than 25 years. Traditional optical problems, namely, the problems of optical beam and image formation, are solved with the goal of providing:

— concentration of laser beam energy;
— improvement in the sharpness of an optical image;
— increase in the rate of data transmission in optical communication lines;
— fulfillment of several other specific requirements.

These problems are solved by adaptive optical – electronic systems by incorporating in their structure such new elements as:

— a wavefront corrector (an active optical element);
— a wavefront distortion sensor (a fluctuation meter);
— a reference source;
— a data processor and working algorithm.

Since these new elements (see Fig. 1), to say nothing of the system as a whole, are not commercially available, we had to

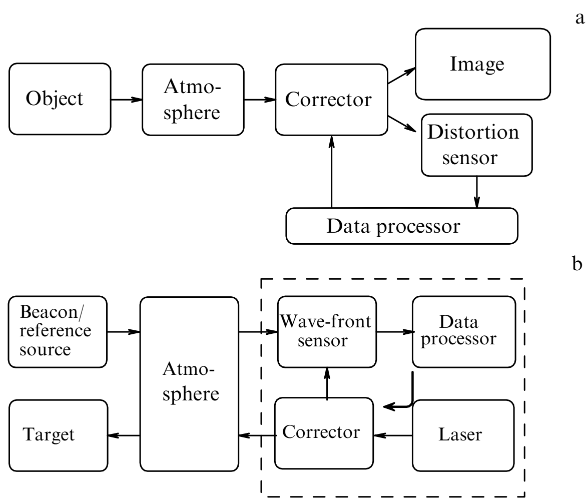

Figure 1. Atmospheric adaptive optical systems: (a) imaging, and (b) beaming.

devise and develop them by ourselves. That is why the investigations in this scientific field involved both the elaboration of the theory of adaptive systems and the development of new elements, system prototypes, and their control algorithms.

2. Measurements of the phase fluctuations of optical waves propagating in the atmosphere

Most often by an adaptive correction of distortions caused by atmospheric irregularities (turbulence, refraction, thermal self-action of radiation) is meant a phase correction. Controlling the phase (the optical path difference) is effected with the aid of wavefront correctors, and the relevant information is extracted from a distortion sensor.

That is why the first stage of the work involved the investigation of statistical properties of the phase fluctuations in an optical wave during its propagation through atmospheric turbulent region. The early 1970s saw the creation of interference phase meters for waves in the optical range. In this case, advantage was taken of the highly coherent sources of visible optical radiation.

An investigation was made into the statistical properties of phase fluctuations, both temporal and spatial. Theoretical calculations were made employing the method of smooth perturbations, and experiments were carried out for uniform overground paths of different lengths. In so doing the structure functions and correlation functions, as well as their Fourier transforms, were thoroughly investigated.

The phase structure function (see Fig. 2) was found to be sensitive both to the intensity of turbulence and to its inner and outer scales.

The optical measurement data for turbulence scales were shown to be consistent with the results calculated on the basis of meteorological observations (measurements of wind velocity and temperature) (Fig. 3).

The principal outcome of this series of investigations was the discovery of growth saturation of the phase structure function of an optical wave (see Fig. 2) for long separations of the observation points. In our papers this phenomenon was explained for the very first time on the basis of the turbulence spectrum with a finite outer scale, employed for its description [1]. The previously invoked Kolmogorov–Obukhov model assumes the outer scale of turbulence to be infinite. Based on optical and meteorological measurements, we showed that the outer scale of turbulence in the atmospheric surface layer depends on the thermodynamic stability of the atmosphere (see Fig. 4). Furthermore, the atmospheric turbulence in the region of strong optical nonuniformities was found to possess anisotropy [1, 2].

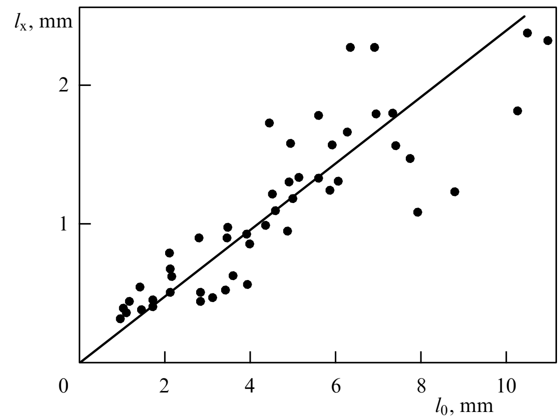

Figure 3. Comparison of inner scales of turbulence, reconstructed from optical and meteorological measurement data: points — experiment, straight line — calculation.

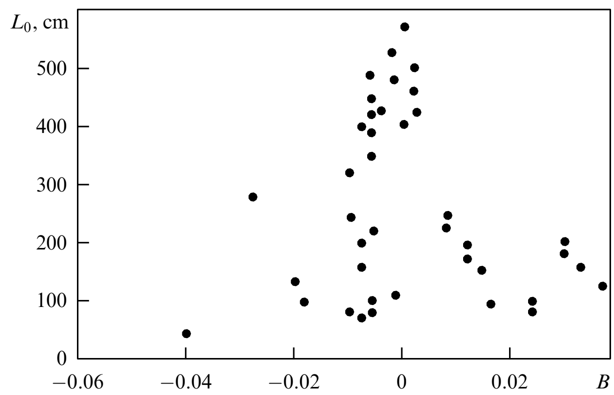

Figure 4. Comparison of optical measurement data for the outer scale of turbulence and Monin's atmospheric instability parameter B.

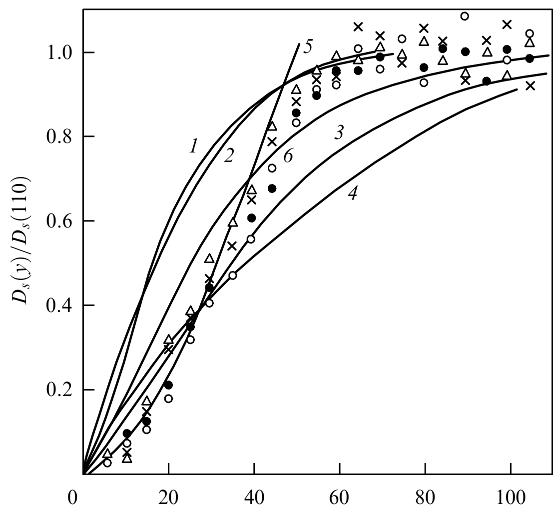

Figure 2. Phase structure function of an optical wave in a turbulent atmosphere: *1–4, 6* — results of model calculations for the spectrum with a finite outer scale, *5* — calculation for the Kolmogorov–Obukhov spectrum, •, △, ×, ○ — experimental data.

3. Atmospheric adaptive optical systems theory development

In 1977, a start was made in the IAO, SB RAS on research aimed at exploring the feasibility of applying phase correction to reduce the effect of the atmosphere on the parameters of optical systems. First and foremost, theoretical investigations were undertaken. The mathematical formulation of the problem consisted in the solution of the wave equation for the optical wave being corrected and for the counter-propagating reference wave with the inclusion of turbulence, radiation absorption by matter, and wind and thermal effects. The adaptive system incorporated the numerical models of distortion sensors as well as of distortion correctors. The elaboration of the theory of atmospheric adaptive optical systems was completed in 1984–1986. The main results provided the basis for a monograph issued in Novosibirsk in 1986 [2]; its English translation was published in the USA in 1995 [3].

We endeavor to briefly summarize the most significant achievements made in this field during the first years.

(1) Two-color adaptive systems were proposed and studied for the first time. In this case, the wave being corrected and reference wave have different wavelengths. The scheme of scaling the reference-channel measurement data was substantiated for the control in the correcting channel. The first paper on the two-color adaptive systems was published in 1979 [4].

(2) The use of an optical signal scattered from atmospheric irregularities was proposed for the first time to produce the reference source. The first publication (1979) on this issue outlined the calculated results covering the mutual correlation function of the phase fluctuations in a Gaussian beam and the plane reference wave. In Ref. [5], we came up with a pioneering proposal to employ the signal backscattered from atmospheric irregularities for image correction. Also calculated were the limiting potentialities of image correction in a telescope with the aid of a reference source produced in the atmosphere at a fixed distance [6].

These investigations have come to be extensively pursued and a new line of research has emerged — the creation and application of laser reference stars. A Galileo Galilei Prize and Medal were awarded for these investigations in 2000.

(3) The use of ideas of statistical fluctuation prediction in the analysis of dynamic properties of adaptive systems was proposed for the first time. This enabled the adaptive systems to be first analyzed as dynamic [7]. Apart from traditional permanent-lag adaptive systems, the possibilities of 'fast' and 'predictive' adaptive systems were also considered. The permissible time delays in adaptive systems, providing a given level of correction, were determined. It was found that they are determined by the effective wind velocity, the coherence radius of the atmosphere, and the parameters of the optical system.

(4) During the same period, the principles of separate components of an adaptive optical system were elaborated and their model samples were produced [11]; they involved:

— composite multicomponent mirrors (Fig. 5);

— mirrors for the fast control of wavefront obliquity;

— flexible bimorphous optical elements;

— servomechanisms utilizing image dissector and coordinate-sensitive photodetectors;

— phase-fluctuation-tracking meters in the optical range.

Furthermore, a whole line of phase fluctuation meters in the optical range was devised: IFAS — an analog phase-tracking meter; IFUP — a wave-angle fluctuation meter; IRSAN — a refraction meter, i.e., a laser reference system with correction of atmospheric refraction, and Interkon and SKIF quality control systems for optical products.

These systems were promoted in the optical works of the country. The systems operated both with laser radiation and the radiation of bright (+4) stars.

(5) In 1981, the first experiments were staged with the aim of adaptive correction of turbulent and refractive distortions of laser beams and images for overground atmospheric paths. On the basis of designed model samples of separate components of the adaptive systems, experiments [8] were performed on the phase correction of turbulent and refractive distortions when forming optical images and laser beams in the atmosphere.

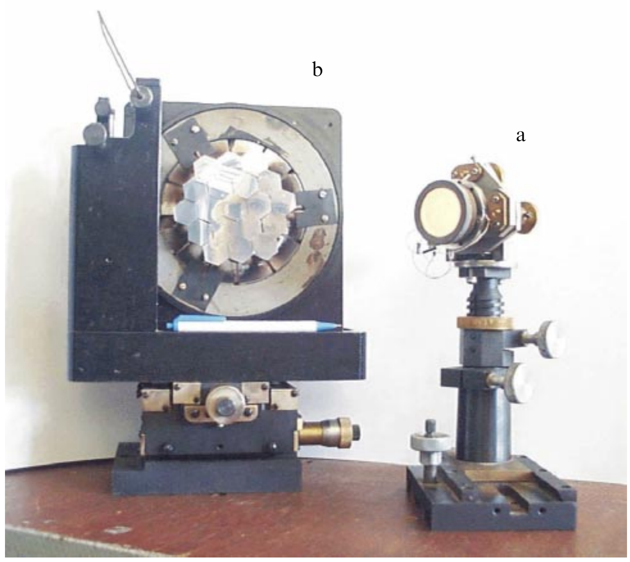

Figure 5. Composite multicomponent mirror (a) and mirror for the fast control of inclinations of the wave front (b).

(6) Efficient algorithms were elaborated for the correction of thermal self-action of high-power laser beams in the atmosphere. On the basis of numerical calculations it was shown [9] that phase correction can be applied to combat the effects of both atmospheric turbulence and the thermal self-action occurring when high-power laser radiation propagates through an absorbing medium. The feasibility of compensating for wind walk-off and the thermal spreading of focused laser beams was demonstrated (Fig. 6).

Exceptionally interesting is the conclusion that the phase correction ensures not only the elimination of atmospheric effects, but also an increase in the limiting power density of the radiation transmitted through the atmosphere.

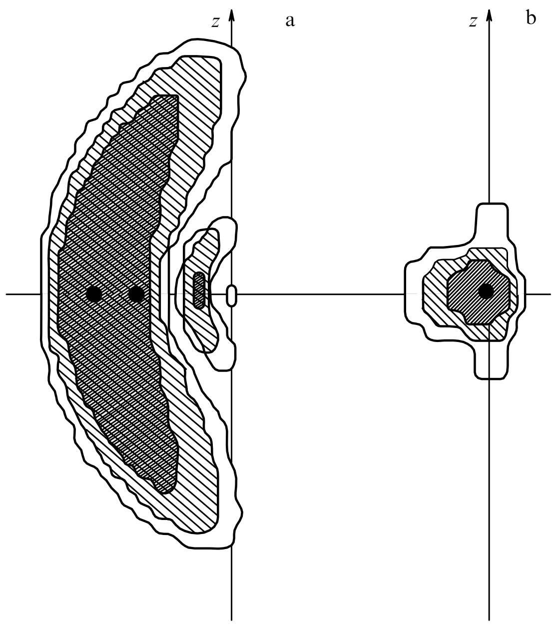

Figure 6. Correction of thermal effects for a focused Gaussian beam: (a) intensity distribution over the focal spot without correction, and (b) intensity distribution with a phase correction.

(7) In Ref. [10], we substantiated the importance of the correct inclusion of the outer scale of atmospheric turbulence in the calculation of optical characteristics. In so doing several different models were compared:

$$\Phi_n(\varkappa, \xi) = 0.0033 C_n^2(\xi)\left[\varkappa^2 + \varkappa_0^2(\xi)\right]^{-11/6},$$

$$\Phi_n(\varkappa, \xi) = 0.0033 C_n^2(\xi)(\varkappa^2 L_0^2 + \varkappa L_0)^{-11/6},$$

$$\Phi_n(\varkappa, \xi) = 0.0033 C_n^2 \varkappa^{-11/3}\left[1 - \exp\left(-\frac{\varkappa^2}{\varkappa_0^2}\right)\right],$$

which describe the behavior of the spectrum of atmospheric turbulence in the range of large-scale irregularities; all of these models correspond to Kolmogorov turbulence in the inertial range and describe the saturation effect of the phase structure function.

4. Modern problems of adaptive optics

The result of the 1991 – 1995 research was the construction of a four-dimensional numerical dynamic model of atmospheric adaptive systems [12, 13]. It relies on atmospheric models (turbulence, refraction, and absorption) and the models of adaptive system components (active optical elements, wavefront distortion meters, reference sources, and the working algorithms of adaptive systems).

Early in the 1990s, we started finding out the fields of widest application of adaptive optics (AO). Its application primarily for the development of laser reference systems and for use in astronomy proved to be most realistic. In 1993 – 1994 we embarked upon the search for a direct approach to specific systems. Astronomical telescopes came to be the answer. During these two years we elaborated an adaptive optical system for the AST-10 telescope — the project of a Russian compound 10-meter adaptive telescope.

The telescope itself (Fig. 7), which has a composite 91-element mirror, proved to be too slow to compensate for turbulent distortions in real time. That is why a conception was put forward to effect correction on the basis of an adaptive secondary mirror.

We generalized the world's experience in the development of such systems and modelled the entire optical system of the telescope, beginning with alignment errors of its primary mirror, by taking advantage of our computer system. As is well known, two parameters are significant for a telescope operating with radiation transmitting through the atmosphere: the angular resolution, and the Strehl parameter.

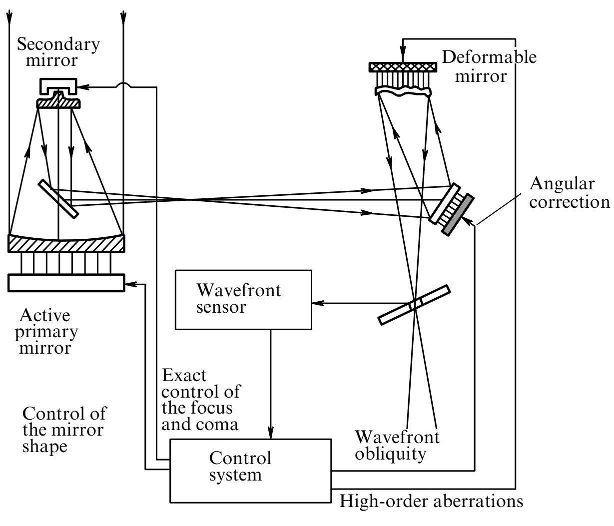

Figure 7. Schematic of an astronomical telescope with a composite primary mirror and an adaptive system for correcting distortions.

In a vacuum, the limiting angular resolution of a telescope is approximately numerically equal to the ratio between the wavelength and the diameter of the primary mirror. For the visible region this constitutes hundredths of the second of arc.

We studied (see Fig. 7) the effect of technical errors — the misphasing of the primary AST-10 mirror on the magnitude of the Strehl parameter. Next investigated was the feasibility of a partial phase correction of the image with the help of an adaptive secondary mirror. In doing so we investigated:

— different turbulence levels proceeding from atmospheric models;

— different types of active mirrors (composite, flexible, modal);

— different wavefront meters.

In particular, an investigation was made into the influence of fluctuations of the number of photons in the light flux entering the telescope, when operating with weak stars. Also, suggestions were made concerning the approaches to the telescope operation with the use of a laser reference star for different wavelength ranges.

At about the same time, investigations were underway concerning the effect of turbulent atmosphere on long-base interferometers, including stellar ones [15].

4.1 Modeling and creation of real operative prototypes of adaptive optical systems for astronomy

The software elaborated enabled us to simulate [14 – 16] the operation of optical systems in the atmosphere: interferometers and adaptive astronomical telescopes (Fig. 8). The signal fluctuation spectra were calculated for long-base optical 'stellar' interferometers with a base length ranging from 3 to 85 m. It was also shown that the correct model of the height variation of the outer scale of turbulence plays a decisive role.

We proposed the introduction of the 'effective' outer scale of turbulence for the atmosphere as a whole, which permitted us to simplify the estimation of parameters and the characteristics of the adaptive telescope.

The employment of the numerical model of the adaptive system made it possible to analyze the adaptive optical system for the AST-10 telescope. In doing so the Strehl parameter and the integral telescope resolution were investigated. An analysis was also made of the distortions due to the phasing errors of the elements of the primary mirror and of the feasibility of utilizing the secondary active mirror to correct turbulent distortions.

4.2 Adaptive solar telescope

We made an effort to incorporate the AO system into the one-meter solar BSVT telescope of the Institute of Solar-Terrestrial Physics (ISTP), Siberian Branch of the Russian Academy of Sciences. During the first season devoted primarily to the collection of observed data on the daytime astronomical climate of the Baĭkal Lake region, a special-purpose instrument was designed — a differential meter of image tremor — and an investigation was made into the behavior of distortions of the solar image produced by this telescope, which are caused by the specific features of the region.

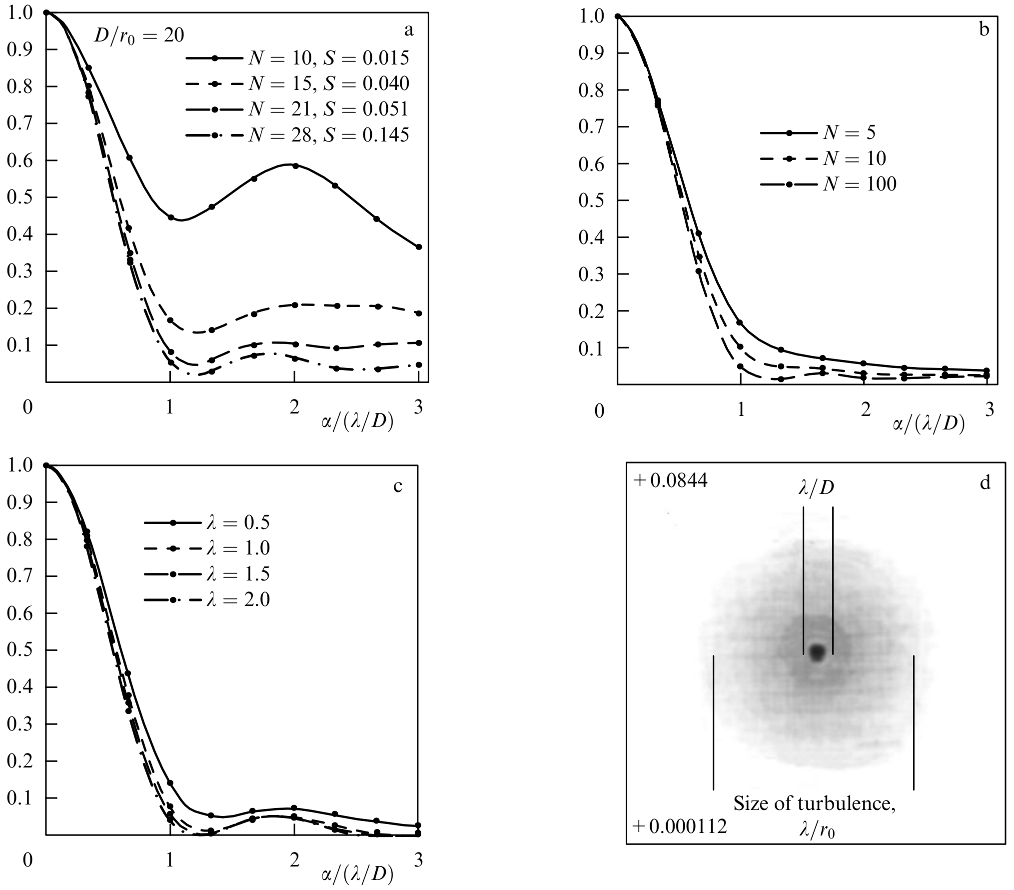

Figure 8. Example of modeling the operation of the astronomical telescope with an adaptive correction system: (a) modal corrector, N — the number of corrected modes; (b) Hartmann sensor (10 subapertures across the diameter, $d = r_0$), N — the number of photons per subaperture; (c) laser reference star in a sodium layer, $H = 100$ km, and (d) diffraction core.

The first version of the AO system for the BSVT was produced (see Fig. 9), which ensured stabilization of a fragment of the Solar image with the use of a tracking device involving a coordinate-sensitive photodetector to measure the displacement of the center of gravity of the image. For an element to be tracked, advantage was taken of a spot (a pore) on the solar surface. The system afforded an improvement of the quality of image by a factor of 4 – 16.

Subsequent work along these lines was carried out in the framework of a complex interdisciplinary IAO – ISTP, SB RAS project entitled the "Solar Adaptive Telescope". In 2001, a prototype of the image displacement meter was made, which furnished the possibility of investigating astronomical objects in the conditions of small intensity variations and functioned by the correlation method. Numerical experiments were performed to determine the effect of different solar image parameters on the operation of the correlation algorithm with the use of computer-synthesized models of the images of solar surface fragments as well as real photographs of granulation pictures obtained with the BSVT.

The principal problem to be solved with this system consisted in the correction of wavefront inclinations, i.e., the stabilization of image position.

At the next stage, a system was developed (see Fig. 10) for the correction of general wavefront obliquity, relying on the correlation displacement sensor. One of the test results for this system (shown in Fig. 11) demonstrates the efficiency of image tremor suppression for a fragment of the solar surface.

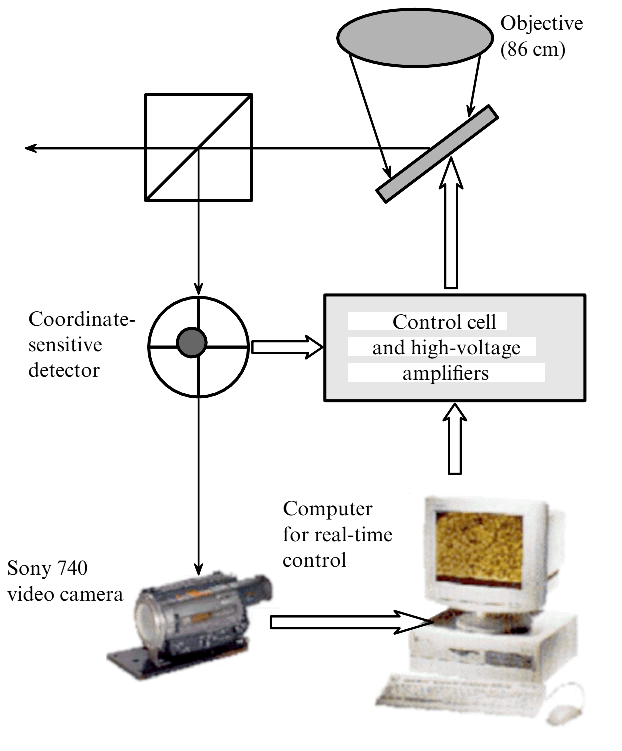

Figure 9. Skeleton diagram of the adaptive optical system for the solar astronomical telescope.

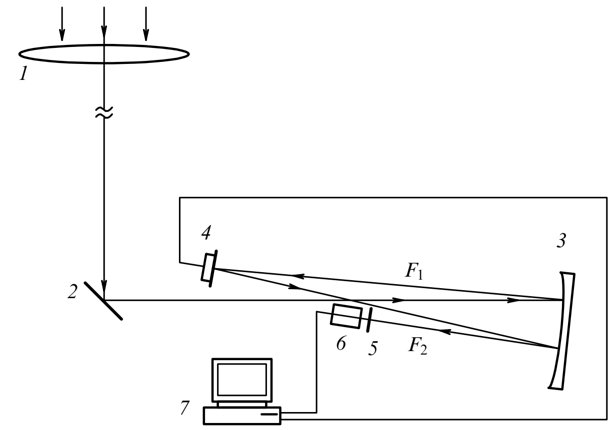

Figure 10. Adaptive system with a correlation image displacement sensor: *1* — lens, *2* — deflecting mirror, *3* — mirror, *4*, *6* — photodetectors, *5* — modulator, *7* — computer display, F_1, F_2 — focal distances of the image-producing system.

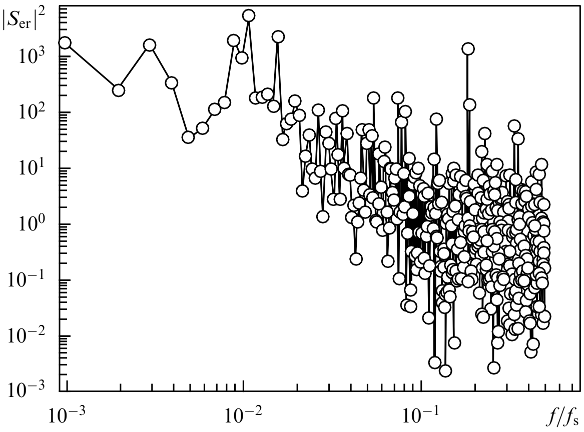

Figure 11. Frequency dependence of the efficiency of image tremor suppression.

As the final result we consider the production of an adaptive system on the basis of a multielement mirror for the correction of higher-order wavefront aberrations. It is pertinent to note that the compensation for wavefront inclinations is crucial, since the contribution from random inclinations to the variance of phase fluctuations amounts to about 87% [17].

4.3 Investigation of the efficiency of laser reference star employment for the correction of images produced through the atmosphere

The problem of compensating for wavefront inclinations in ground-based telescopes became topical especially in connection with the employment of laser reference stars (LRSs). Their employment stems from the fact that weak stars transfer too little energy which is insufficient for the simultaneous operation of the adaptive systems and the telescope.

In our country, the line of research involving the application of LRSs was initiated in 1979. It was then that the first demonstration was given of the feasibility of using the signal backscattered from atmospheric irregularities as the reference buoy. In the early 1980s, several scientific experiments were staged in the 'Astrofizika' Scientific-Production Unit and in our laboratory.

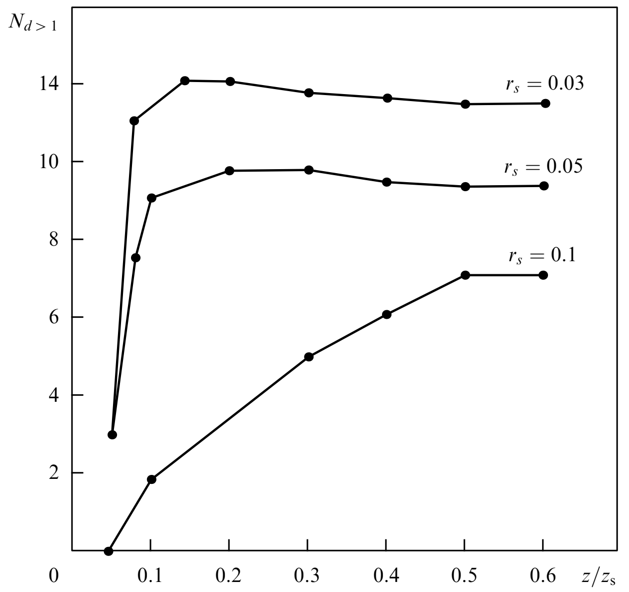

Figure 12. Statistics of singular points as a function of the turbulence level r_s and path length z.

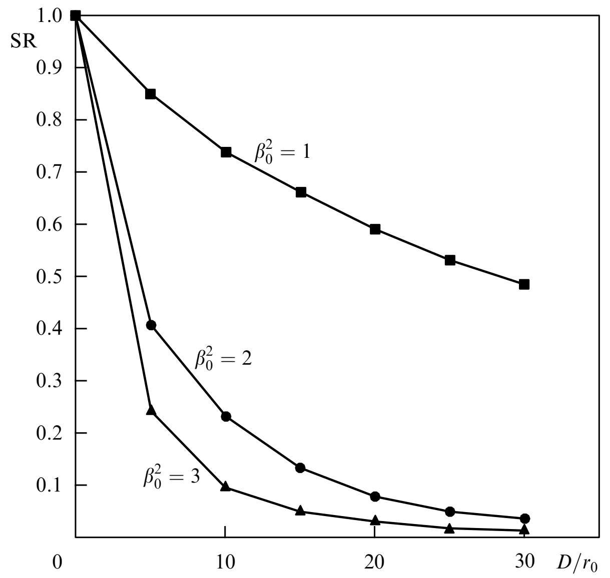

Figure 13. Impairment of image correction efficiency with the use of only the 'potential' part of the phase.

The history of related investigations in the USA can be traced back to 1982, but until 1993 they were classified. Several LRS production schemes are possible: monostatic and bistatic. However, despite the attractiveness of employing LRSs, they suffer from a significant drawback — the practical impossibility of correcting the general wavefront obliqueness, whereas it accounts for 87% of the variance of all phase fluctuations. This problem was addressed in several papers, including our paper published in 1995. We believe that one possibility for solving this problem involves the use of an *optimal correction algorithm* which minimizes the residual distortions of obliquity fluctuations. The heart of this algorithm consists in the scaling of LRS image position measurement data by a weighting factor which is derived by way of either calculations (relying on the utilization of atmospheric models) or direct measurements.

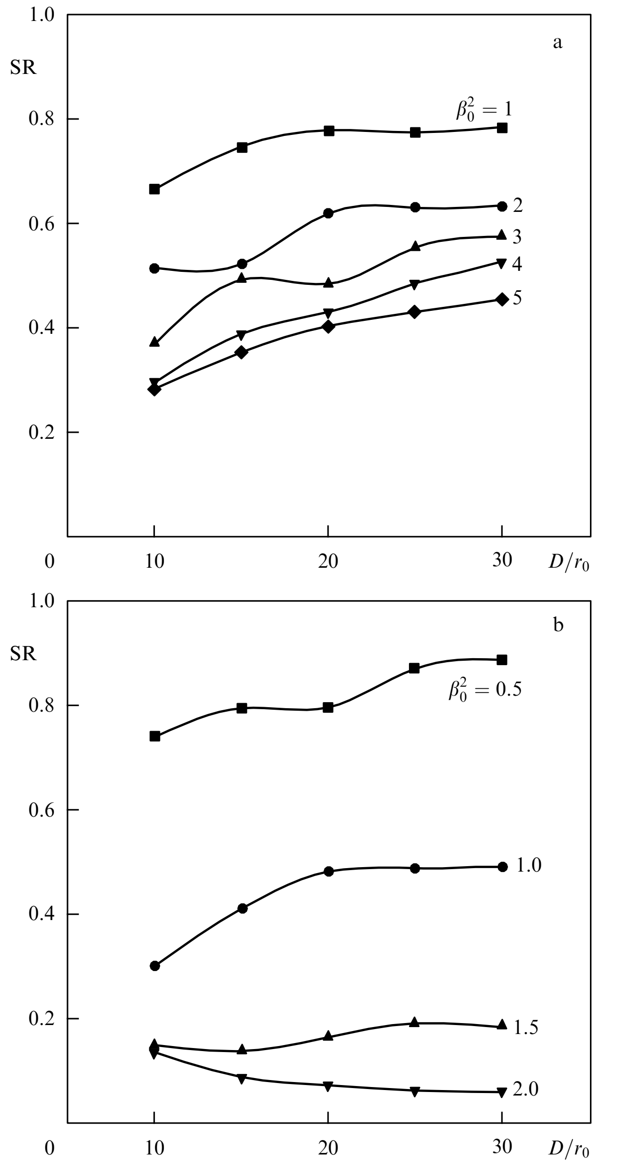

Figure 14. Strehl parameter — criterion for performance in the correction of the total phase (a) and in the filtering of phase dislocations (b) in the laser beam being formed. The values of variance β_0^2 of intensity fluctuations along the path are indicated by the curves. Plotted on the ordinate axis is the ratio between the transmitting aperture dimension D and the coherence radius r_0.

Several authors proposed the use of bistatic schemes for obliquity correction, but they are technically inefficient for a number of reasons. We showed this in a series of exact computations that relied on the development of atmospheric turbulence models. We came up with a hybrid scheme which was free from several drawbacks, as well as a new approach to dynamic LRS formation. The employment of an LRS in the form of a *reference cross* (produced by scanning with two narrow laser beams) was shown to ensure a reliable correction of wavefront inclinations even for large-aperture telescopes [18, 19].

5. 'Strong' fluctuations and wavefront dislocations

The correction referred to in the foregoing is based on linear optics and primarily involves phase correction. However, where significant amplitude fluctuations exist (down to the occurrence of zero-intensity points), the description of phase fluctuations in terms of smooth functions is no longer possible. Figure 12 shows the result of a numerical experiment on modeling the statistics of the occurrence of wavefront dislocations with increasing optical propagation path length. There are wavefront dislocations responsible for the occurrence of singularities at these points. The presence of dislocations necessitates describing the phase of an optical wave in the form of two components: *potential and eddy*.

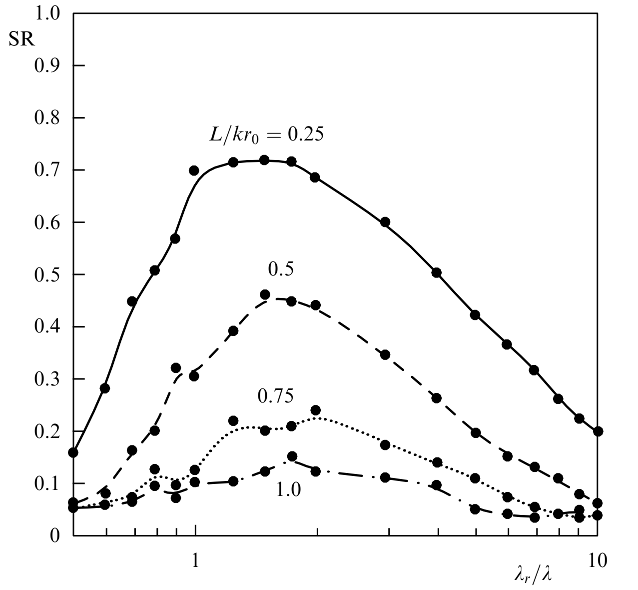

Figure 15. Strehl parameter as a function of the ratio between the correcting wavelength and the reference source wavelength for different distances of light propagation: ——— — $L = 31$ km, – – – – — 62 km, · · · — 94 km, and – · – — 125 km.

In our latest papers [22, 24] we showed that the loss of the eddy component under conditions of 'strong' intensity fluctuations significantly degrades the AO efficiency both in laser beaming and imaging (see Fig. 13).

This purely theoretical result of ours was amply borne out in experiments staged at the Lincoln National Laboratory in the USA.

It was also shown (see Fig. 14) [22] that in this connection flexible adaptive mirrors, which are unfit to reproduce phase discontinuities, quite soon become unsuited for correction under conditions of 'strong' fluctuations; however, composite segmented mirrors operate well in the range of 'strong' fluctuations.

Furthermore, it was noted that *two-color adaptive systems* fail completely in the range of 'strong' intensity fluctuations [20, 21].

Figure 15 depicts the calculated Strehl parameter for a 'two-color' adaptive system as a function of wavelength difference between radiation being corrected and correcting (reference) radiation.

The use of multimirror adaptive correction was substantiated to provide an efficient phase correction [22]; at the same time, an approach involving amplitude – phase correction is currently being developed (see Fig. 15).

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Adaptive distributed optoelectronic information-measuring systems

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1. Introduction

The process of intensive development and promotion of optical fiber telecommunication systems has led to the emergence of one of the most rapidly developing fields of optoelectronics — fiber optical sensors (FOSs) of physical quantities [1]. The organic combination of a communication system and the system of monitoring of physical quantities in a common path of the optical fiber (OF) opens up considerable opportunities for the development of lengthy and ramified information-measuring systems (IMSs) whose functional destination and configuration can be continuously improved without recourse to additional communication lines. In this case, an important advantage of the FOSs is that they introduce into the IMSs such properties as high sensitivity, low dimensions, immunity to electromagnetic interference and environmental attack, the possibility of multiplexing individual sensors into complex measuring systems, and potentially low cost [2]. The above-enumerated virtues and the change-over from discrete FOSs of physical quantities to extended distributed FOSs, which have begun to show in recent years, have made it possible to commence the development of distributed fiber measuring networks (DFMNs) and 'sensitive surfaces' capable of reconstructing the spatial parameter distributions of the physical fields (PFs) under investigation [3].

The transfer to higher-dimension DFMNs, the development and improvement of the processing methods of data arrays at the DFMN output, involving the use of new physical phenomena and the application of modern neural network technologies of signal processing, open up broad opportunities for endowing IMSs with such new properties as the ability to learn and adapt [4, 5]. This is an important step on the road to the production of practical distributed IMSs intended for the investigation of PFs and the monitoring of the state of technical and technological objects.

The aim of our report is to consider the approaches to the solution of the development problem of adaptive distributed optoelectronic IMSs as one of the promising lines of modern physical instrument making.

2. Tomographic DFMNs for reconstructing the distributions of scalar and vector physical fields

The traditional approach to the reconstruction problem of multidimensional physical-field distribution functions through the use of DFMNs consisting of a set of 'point' FOSs, wherein measurements correlate with a definite discrete set of points in space, does not always meet with success owing to the technical difficulties arising in the multiplexing/demultiplexing of the signals received from a large number of 'point' FOSs. This does not permit us to attain a high spatial resolution and a fast response [1, 3]. Unifying 'point' FOSs sequentially in an extended optical fiber measuring line (OFML) or employing distributed FOSs makes it possible to obtain an integral phase or amplitude signal of the action of an external PF on the FOSs along the OF laying path [3, 6].

In the general case, the integral signal of PF action on the OFML can be represented as [7–16]

$$g(p,\phi) = \int_{L(p,\phi)} h(x,y,\phi)\,\mathrm{d}L\,, \qquad (2.1)$$

where $h(x,y,\phi)$ is the function of OFML responsivity to the PF action:

$$h(x,y,\phi) = \begin{cases} qf(x,y) \text{ for a scalar PF}\,, \\ q\hat{F}\big[\mathbf{A}(x,y),\mathbf{m}(x,y,\phi)\big] \text{ for a vector PF}\,, \end{cases}$$

where $f(x,y)$ is the spatial distribution function for the PF parameter being recorded, $\mathbf{A}(x,y)$ is the intensity vector of the field under investigation, $\mathbf{m}$ is the unit vector of the tangent ($\mathbf{e}$) or normal ($\mathbf{n}$) to the OFML laying contour, $\hat{F}[\,..\,]$ is an operator, x, y are the Cartesian coordinates in the detection plane (S), q is a constant coefficient which defines the responsivity per unit OFML length to the PF parameter to be measured, L is the coordinate along the OFML laying contour, and (p,ϕ) are the polar coordinates defining the OFML contour position in the detection plane (see Fig. 1a).

The signals described by expression (2.1) bear the indirect information on the PF parameters distribution function.