Experimental adaptive-optics system for Big Solar Vacuum Telescope. I. Test results and prospects

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The possibility of applying adaptive-optics devices to ground-based solar astronomy and high-resolution spectroscopy is considered. An experimental adaptive-optics system for image stabilization is described, as well as the results of its tests. Different ways of the further development of the adaptive-optics system for use in the Big Solar Vacuum Telescope (BSVT) of the Baikal Astrophysical Observatory are discussed.

1. Introduction

Big astronomic devices are needed for obtaining a high-quality image of an object under study, that is, an image with high angular resolution and high brightness. This can be achieved by increasing the telescope's pupil. As the pupil is increased, diffraction blurring of an image decreases. However, along with this process, the factors distorting the image become more pronounced, such as turbulent blurring, aberrations of an optical system, and other instrumental imperfections.[1,2]

Adaptive-optics systems complementing the main optical system of a telescope are intended for compensating for these negative factors. The main executive element in an adaptive-optics system is a spatial modulator of the optical path length, for example, controllable flexible or segmented mirror, that is, adaptive aberration corrector. The information needed for control is extracted from an optical wave by an aberration sensor. Now we know a sufficient number of schemes of aberration sensors and aberration correctors, as well as the ways of closing the loop of adaptive correction.

2. Peculiarities of adaptive optics to be used in solar astronomy

Adaptive-optics systems have achieved maximum progress in stellar astronomy. To say generally, the problem of creation of adaptive mirrors and wave front sensors is now solved. However, the problem has some other aspects that have not yet been thoroughly analyzed. The bottleneck in this technology is now a reference source, whose radiation carries information on aberrations of a wave front. It is interesting that solar and stellar astronomy are contrary to each other from this point of view. Let us consider the problem of selecting or formation of a reference source for an adaptive-optics system in these two branches of astronomy.

Source brightness

Not every star has brightness sufficient to provide for measurement of aberrations even in the photon counting mode. For these reasons the technology of formation of a laser reference star is now actively being developed. As to the solar astronomy, source brightness is usually more than enough.

Source size

A star is a point-like object spaced at almost infinite distance. This is very convenient when measuring aberrations, which coincide with fluctuations of the optical path length in the case of atmospheric turbulence. The Sun is also a star in the astrophysical meaning, but the image of its disk can be used only for correction of the error due to telescope rotation about the polar axis in order to compensate for the Earth's rotation.

Effects of nonisoplanatism

The term "nonisoplanatism" in adaptive correction of turbulent blurring of an image means a decrease in correlation between the wave-front aberrations formed at different angles as the angular distance increases. The angular size of an astronomic object (star) is, as a rule, much smaller than the angle of isoplanatism, which is about 10 seconds of arc, while the angular size of the Sun is about 2000 seconds of arc.

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Some authors propose to use a dark spot or even granulation of the photosphere, whose contrast is only several percent relative to the mean image brightness, as a reference source to measure atmospheric and (or) instrumental aberrations in a solar telescope.[3–5]

3. Experimental adaptive-optics system

Let us first say a few words about the Big Solar Vacuum Telescope (BSVT). The BSVT was constructed at the Institute of Solar-Terrestrial Physics SB RAS ashore the Lake Baikal. It is a part of the Baikal Astrophysical Observatory (BAO). It is at about 1 km distance far from the Baikal shore at a hill about 400 m above the Lake Baikal level and about 700 m above the sea level. The telescope is designed for high-resolution spectroscopy of the Sun. The feeding optics of the telescope is a siderostat with a tracking mirror of 1-m diameter. The lens system with the pupil size of 76 cm and the focal length of 40 m gives the solar image of 38 cm in the focal plane. This corresponds to the spatial resolution about 5 seconds of arc per 1 mm of the image. Shadows of dark spots are typically from 5 to 15 seconds of arc in size, what corresponds to 1 to 3 mm in the image plane. Just this provides the basis for spectral measurements with a sufficiently high resolution.

However, observations are hampered by several effects caused by the following factors:

1. *Turbulent blurring and jitter of an image*. This effect depends on a season, weather conditions, state of the surface, and time of a day; according to our estimates, this effect introduces from 1 to 5 seconds of arc, that is, from 0.2 to 1 mm in the image plane.

2. *Wind jitter* caused by the effect of wind on the tracking mirror of 1 m in diameter. The mirror has sufficiently large sail area, and only from rear it is partially protected against the wind gusts by the northern wall of the dome. The amplitude of the image jitter, in millimeters, is roughly equal to half wind speed, in m/s, thus achieving 5 mm at the wind speed of 10 m/s. According to our estimates, characteristic frequencies of this jitter, in Hz, are roughly equal to the ratio of the wind speed, in m/s, to the telescope size, in meters. That is, they are described by the equation $f = V/D$, where V is the wind speed, and D is the mirror diameter. Note that this equation, according to the theory of turbulent aberrations, gives the maximum of the turbulent jitter spectrum.

3. *Image drift* can be caused both by the errors due to telescope rotation and by the diurnal rotation of the Sun image because of the siderostat design of the telescope. The Sun image rotates through 360° for 24 hour, so a point set at the distance of 2/3 radius off the center of the Sun image moves along the circle with the speed of 35 mm/h, that is, about 0.6 mm/min. If a given area is observed for several minutes, the drift becomes larger than not only turbulent, but also wind shifts.

We obtained these estimates during the Baikal–98 mission in July–August 1998. They have formed the basis for the prototype of an adaptive system for image stabilization. This prototype was made in order to

(a) demonstrate the possibilities of improving the performance and increase the time of efficient use of the BSVT with the help of an adaptive optics;

(b) gain experience in operation of the solar telescope, as well as understand thoroughly the peculiarities of observational solar astronomy and the part of adaptive optics in telescope operation, on the one hand, and obtain new basic knowledge in solar physics, on the other hand.

We proposed the following design of the adaptive-optics system:

1. *Adaptive mirror* (AM) controllable over two angles is mounted directly on the diagonal mirror of the telescope. AM specifications: diameter – 36 mm; actuator – bimorph piezoelement; total span of the reflected ray tilt angle in each direction at the voltage of ±300 V – 1.44 mrad; frequency of mechanical resonance – 120 Hz. The diagonal mirror, on which the AM is mounted, is 2.8 m apart from the image plane. This allows compensation for linear displacements of the image with the amplitude up to 4 mm. Some vignetting of the effective pupil of the system takes part in this case, causing almost fourfold decrease in the intensity at the image axis. The calculation shows that to save the image intensity all over the height of the spectrograph slit (30 mm), the AM diameter should be 10 to 12 cm.

2. *Displacement sensor*. As a displacement sensor, an FDK–142 commercial quadrant photodiode 13.7 mm in diameter is used. The photodiode is set in the image plane. A beam-splitting cube with the size of 3 cm spaced at 40 cm from the spectrometer slit directs about a half of the light flux toward this sensor. The sensor illumination is roughly one fourth of the total image brightness, which is about 300 000 lux outside the area of a dark spot. The integral sensitivity of each element of the sensor is 1 mA/lm, and the rms value of the dark current is 16 μA.

3. *Electronic control unit* includes high-voltage amplifiers feeding the voltage to AM piezoceramics and the decision device, which receives four signals from the displacement sensor after preamplification. The decision device is based on micrologics and generates a control signal in each of the two coordinates independently. Since the system is operated in a closed loop mode, the control algorithm is based on the search for the value of control signal at which the signals from the left and right halves of the sensor are equal to each other, as well as those from the top and bottom halves.

4. Results of the experiment on the sunspot image stabilization

The adaptive system was tested for several fine sunny days in August 24–30 1999. As a reference object for the sensor of the adaptive system, we selected rather a large round spot about 3 mm in diameter. The spot was manually (using the telescope control panel) set at the center of the sensor with the adaptive system turned off. Then the control circuit was closed, and the control signal was sent to the adaptive mirror. As this took place, we observed visually a significant decrease in the amplitude of the image jitter. To estimate quantitatively the residual jitter, electronic and optical channels were used.

The electronic channel included an analog-to-digital converter (ADC) connected to a computer. The difference signal from the quadrant receiver (jitter sensor) came to the ADC. The difference between the electric signals from the left and right (or top and bottom) halves of the sensor corresponds to the difference in their illumination and equals zero if the dark spot is exactly at the center of the sensor. The efficiency of jitter suppression was estimated as a signal variance ratio at the control turned off and on.

The correction efficiency was simultaneously checked with a SONY–740 video camera with the following grabbing of the digitized frames into the computer through the Miro DC10 videocard with the resolution of 320×288 pixel. For convenience the signal was also sent to a TV monitor (color TV set with a diagonal of 54 cm). In the selected image scale, every pixel corresponded to 0.1 mm (0.5 seconds of arc). The image centroid was computed for every frame, and then the centroid variance along each coordinate and the difference between the maximum and minimum value of the centroid coordinate were calculated for the whole set of frames.

We succeeded in achieving the direct processing rate of 5 frame/s (without recording of the initial signal onto videotape or digitized signal onto a magnetic disk). We used a computer with the AMD K2–6 300 MHz processor. To increase the rate of frame processing, a square 100-pixel window was separated out. The center of the window was first manually and then automatically (by a program) set at the computed centroid.

The system efficiency can be estimated by the data of video control in both absolute and relative units, that is, we can either calculate the accuracy of image stabilization in millimeters or seconds of arc or determine *how strongly* the image jitter was decreased due to the use of our system. For a scientist, the absolute characteristic is important, that is, the fact that the optical systems warranties stabilization of the image of the Sun photosphere area under study on the spectrometer slit with a preset accuracy during the time of observations.

The relative efficiency depends on the characteristics of the system itself and weather conditions determining the initial jitter amplitude. Among weather conditions, the most important parameter is the wind speed, which varied in our case from 2–3 to 8–10 m/s. Table 1 gives the rms (RMS) values and the span (max, in pixels) of the centroid of the dark spot in the Sun image at the mean wind speed of 6 m/s.

Table 1

With correction		Without correction	
RMS	max	RMS	max
0.84	4.3	3.6	16
0.88	4.6	3.7	16

N o t e . 1 pixel roughly equals 0.1 mm.

The values are given for four 30-second realizations, two of them with the system turned on and two with the system turned off. The values presented were obtained as a geometric mean along two axes. As seen from the Table, the image jitter is decreased by a factor of four in both RMS and span. In terms of the jitter variance, the gain is about 18 times. Similar estimates of the efficiency can be obtained in the electronic channel: as the correction was turned on, the variance of fluctuations of the electrical signal from the jitter sensor (quadrant detector) decreased by 10–16 times and in some case, at high wind, even 25 times. Thus, this adaptive system is capable of significantly (several times) decreasing the jitter, thus stabilizing the image accurate to 0.5 mm in span.

In the experiment we have revealed some peculiarities of the wind component of image jitter. From analysis of jitter projections onto the hour axis (α) and declination axis (δ), this component was found to be significantly non-isotropic. It proved that image jitter along the δ axis several times exceeded the image jitter along the α axis, especially, at high wind. Most probable, this is due to the mount design of the tracking mirror, which is most sensitive to gusts. This mirror is controlled by the declination angle δ, therefore the mirror axis prevents wind beats of the mirror along the α axis. As a result, image jitter along these two axes can differ by several times.

5. Prospects

The first problem to be solved is to increase the robustness of mounting of the tracking mirror. Large amplitudes of the jitter along the declination axis impose certain restrictions on the accuracy of image stabilization, since any adaptive system has a limited dynamic range.

Further development of the adaptive system of the image stabilization is thought to be the following. First, we should develop the jitter sensor capable of operating using spots of different shape and size, a group of spots, and even low-contrast granulation. Prototypes of such sensors are known: correlation guides, whose construction includes a specialized technical video camera. We plan to use DALSA video cameras (www.dalsa.com), in particular, qA–D1–0128 or qA–D1–0256 models (128×128 and 256×256 pixels, and 736 and 203 frame/s, respectively). Image frames will be subjected to computer processing, and the shift with respect to a reference frame will be determined by correlation methods.

Further prospects are connected with construction of an adaptive system for compensation for higher aberrations, that is, turbulent blurring of an image. Here we should clearly understand the limitations caused by the effects of angular nonisoplanatism. As a result of this effect, only the central part of an image about 10 seconds of arc (or 2 mm) in size in the BSVT image plane will be sharp. The spectrometer slit lying in the image plane has the size of 30 mm, therefore only a part of measurements will benefit from the use of adaptive optics.

The use of adaptive-optics systems with a wide field of view has even more long-term prospects. The operating principle of such systems is based on distributed correction of aberrations with several adaptive mirrors, each lying in the plane optically conjugate to some atmospheric layer. Thus, the angular size of the area of sharp image can be increased by increasing the number of adaptive mirrors. However, in this approach there are not only technological, but also conceptual problems associated with the necessity of creating sensors capable of measuring instantaneous values of wave-front aberrations introduced by turbulent layers at different altitudes.

Adaptive optics for stellar astronomy has the corresponding approaches to this problem, which are based on measurements of wave-front aberrations for several reference stars. To apply them to solar astronomy, we should generalize the corresponding methods to the case of a distributed source, like the Sun.

6. Conclusion

Thus, the tests of the adaptive-optics system for stabilization of the Sun image in the BSVT have demonstrated its efficiency and prospects in operating the telescope. Further development of the system assumes creation of new generation sensors based on up-to-date computer and video technology, as well as integration of the adaptive system in the telescope by creating a user-friendly control interface.

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