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The BTA project: history, state, outlook

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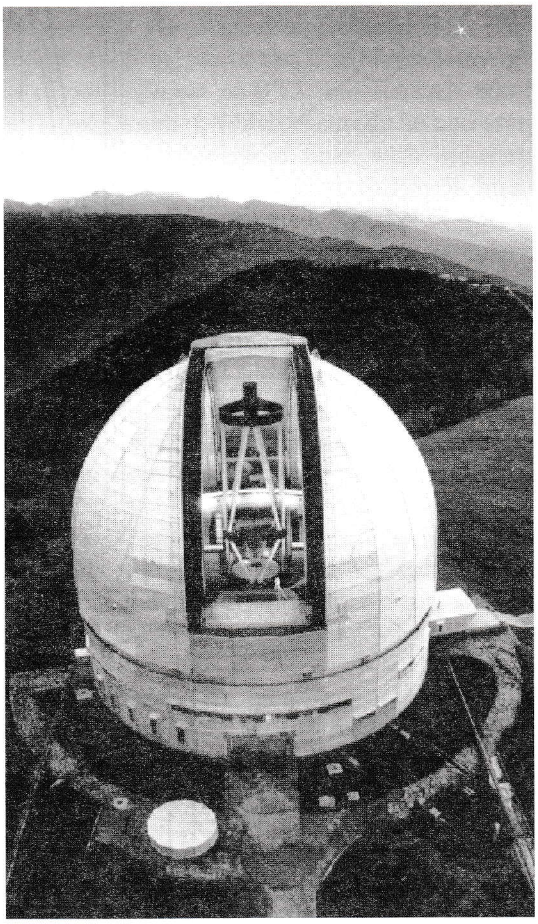
1. Introduction

In November 1974 first photographs of the sky were taken with the Big Alt-azimuth Telescope (BTA). In December, 1975 the telescope was put into trial service, and on January 4, 1977 the first programme observations were started. By 1994 BTA with the main mirror 6 m in diameter had been the world largest optical telescope and actually a model of all large telescopes of the next generation due, first of all, to the successful implementation of the alt-azimuth mounting. The scheme of the telescope is presented in Fig.1 taken from the paper of Ioannisiani et al. (1982). Now the progress in technology of optical telescope building rejects nearly all alternative approaches to the BTA project. In connection with the break-down of the USSR the 6 m telescope remains the only telescope in Russia that allows independent definition and solution of the most urgent observational astrophysical problems. Apart from keeping up BTA competitive with other large telescopes, home astronomy confronts the problem of creating a new large telescope, whose successful solution will necessarily require the experience of design, consruction and use of BTA.

The bold project of the world largest 6 m telescope on an alt-azimuth mounting was approved in November, 1960. Indeed, the project was a darting step to the unknown. The problems of functioning of the alt-azimuth mounting and its digital control to meet the stringent requirements of optical astronomy had to be solved for the first time in the world. The experience of operating large parabolic radio telescopes did emphasize the difficulty of this problem. It was also necessary to invisage efficient performance of the telescope under given conditions of astronomical climate, while the quantitative theory of astronomical climate was only being elaborated. At the time of development of the project a "technical revolution" in astronomy was started, which led to the replacement of classical photography by panoramic photoelectronic detectors and digital methods of recording which changed requirements to the optics of telescopes and spectrographs. At last, in the early 60s the epoch of grand discoveries in astronomy was initiated, which was chiefly associated with the beginning of space exploration and advance in radio astronomy and led in the long run to the formation of a picture of the "violent" Universe.



The general view of the BTA (photograph by Yu.V. Sukharev)

Thus, the development and realization of the BTA project was in many respects of a searching nature and took place under the conditions of rapid changes in the practice of astronomical experiments and observational tasks. The headquarters factory for designing and manufacturing the telescope was the Leningrad Optical and Mechanical Plant (known in Russia as LOMO). The team of designers was headed by an outstanding engineer B.K. Ioannisiani, the Chief Designer of BTA. Many departments, enterprises and institutions of the country took part in the construction of BTA and the observatory. The history of development and creation of BTA is stated in (Buzhinskij et al., 1976), where all the participants in this long-term work are indicated. The first publi-

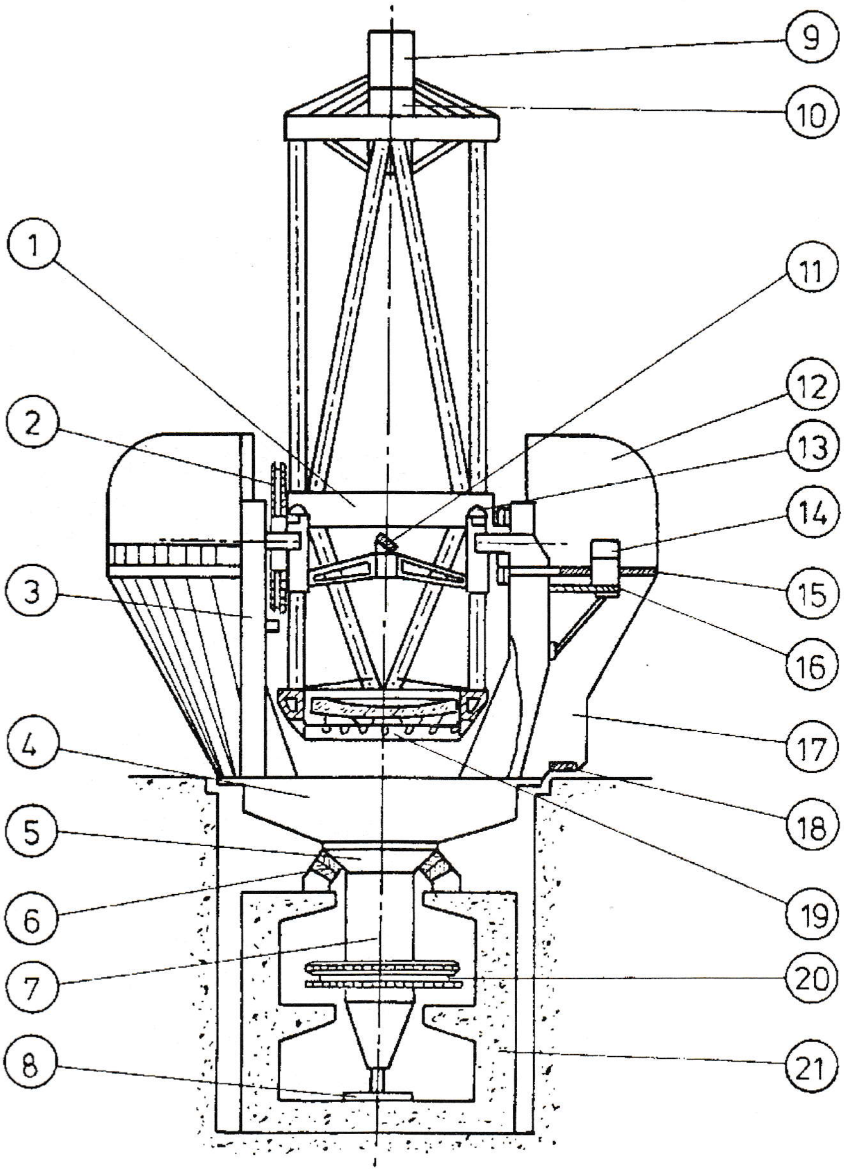


Figure 1: *The 6 m telescope (BTA). 1, middle unit; 2, worm gear; 3, elevator; 4, rotation support platform; 5, spherical support of vertical axis; 6, spherical pads; 7, vertical axis; 8, lower bearing; 9, observer's cage; 10, prime focus unit; 11, flat mirror; 12, platform cover; 13, oil pads; 14, mail spectrograph; 15, observing platform; 16, support for spectrograph; 17, pier; 18, 2 m camera mirror of the main spectrograph; 19, primary mirror cell; 20, spur and worm gears; 21, reinforced concrete.*

cations on the subject-matter of the project became accessible to the astronomical community in the early 70s (Ioannisiani, 1971; Kopylov, 1971), the real characteristics in the early 80s (Ioannisiani et al., 1982; Snezhko, 1986).

Initially the Main Astronomical Observatory of the USSR AS and then the Special Astrophysical Obervatory of the USSR AS (SAO) created in 1966 were responsible for the astronomical aspect of the BTA project. A known astrophysicist I.M. Kopylov, who had experience in putting into operation and observations on the largest in Europe 2.6 m telescope of the Crimean Astrophysical Observatory, was appointed a director of SAO. At that time no alterations could be introduced in the project, since the construction of a building for the telescope in the mountains of Karachai-Circassian Autonomous Region at an altitude of 2100 m had already been started. In 1968 the workshop tests were finished and transportation of the large-sized parts of the telescope was initiated. Construction of a scientific settlement of the observatory was started in the vally of the river Bolshoi Zelenchuk. Within the framework of the project the problem of developing spectrographs, auxiliary equipment, light detectors, and active control of temperature conditions of the dome was left for the observatory to be handled. The group "Astroclimate" (O.B. Vasil'ev, N.F. Nelyubin) went on working over sampling meteorological characteristics at the BTA. The first laboratory that emerged at the observatory was one of Astronomical Light Detectors (LALD) (headed by V.S. Rylov). This laboratory was concerned with the development of snandard spectrographs and registration methods.

In the first half of the 70s the scientific management of the observatory (I.M. Kopylov, S.V. Rublev) solved a difficult problem of establishing the scientific staff of the observatory and ensuring their activity. The researchers had to tackle a broad variety of tasks: from the development of research programs to elaboration and assimilation at BTA of modern observational techniques. The departments of Physics of Stars and Nebulae (DPSN) (headed by S.V. Rublev) and Extragalactic Research and Relativistic Astrophysics (DERRA) (I.D. Karachentsev) were organized. The task of creation of a computing basis was imposed upon the Laboratory of Automation of Scientific Research (LASR) (Yu.P. Korovyakovsky). The young staff members worked out the principal trend of the observatory's scientific-and-technical policy: it was impossible to realize the capabilities of the 6 m telescope without a collaboration with industry in elaboration and introduction of photoelectric detectors of light and digital reduction of observational results. That is why light detectors were devised not only in LALD but also in the research departments. In the Ingeneering Group (G.N. Alekseev) of DPSN apparatus and techniques for investigation into rapid spectral variability were developed, methods of measuring stellar magnetic fields were realized (Yu.V. Glagolevskij). In the Ingeneering Group (V.L. Afanasiev) of DERRA image tubes were introduced, on the basis of which methods of moderate- and low-resolution spectroscopy were worked out. A unique technique, as for its scientific lead and engineering approach, of super-high time resolution (MANIA experiment) was developed by V.F. Shvartsman. As a result of this work BTA was able to compete in a number of observational techniques with the 4-m-class telescopes being put into operation in the West at that time.

However, it was evident that the capabilities of brightness amplifiers with photographic recording of images was limited. In the discussions of 1974–1975 a strategy of SAO was picked to furnish BTA with panoramic digital TV-detectors. This approach was developed in the Laboratory of Advanced Design (LAD) headed by A.F. Fomenko, and a digital TV-scanner for BTA made in this laboratory was the main technique in moderate-resolution spectroscopy recording in the 80s. The laboratory initiated a plan of manufacturing and introduction at BTA of digital panoramic registration apparatus. This was included in the program of the USSR Academy of Sciences of development of BTA and RATAN-600 (Velikhov's programme), which ensured the necessary finance and establishment of links with industry. In cooperation with the All-Union Research Institute of Television a system named "QUANT" was elaborated and made, which allowed extensive introduction at BTA of digital panoramic methods of registration with both image-tube and solid-body detectors in the late of 80s. The potential accumulated in the course of this work enabled the LAD (headed by S.V. Markelov) to devise and manufacture at SAO apparatus for digital image recording based on home charge-couple devices. Since the early 90s CCD cameras, which are on a par in the basic parameters with the foreign analogues, have been widely introduced in the methods of observations with BTA. Now planned work is being done on the adoption of large-size matrices, a possibility of using mosaics from them is being investigated.

We deliberately lay emphasis on the history of scientific and technical activity of SAO since it was aimed at remedying the weakest, apart from the astronomical climate, aspect of the BTA project — the considerable lag in the technology of astronomical observations relative to the world level, which actually canceled the advantage of the light-gathering area of BTA at the moment it was put in operation. It should be emphasised that no observational methods worked out outside SAO have been realized at BTA for 20 years. This reflects the general level of the experimental base of Soviet astronomy and justifies fully the efforts of the SAO staff for overcoming the difficulties of reduction to practice of the advances of modern technology of registration and processing of images, which were made by the defence departments of the country. Based on digital panoramic detectors with a high quantum efficiency and high signal/noise ratio, such powerful and promising techniques of observations as multiobject and two-dimensional spectroscopy (V.L. Afanasiev, S.N. Dodonov), speckle interferometry (Yu.Yu. Balega), high-resolution spectroscopy (V.E. Panchuk) were successfully developed and carried to the level of standards, the techniques of obtaining direct images at the BTA prime focus were revived. And it is with the use of BTA that the most striking scientific results in the problems of current concern — from the behaviour of matter in the vicinity of relativistic objects to the large-scale structure of the Universe — were obtained at SAO.

The possibilities of increasing the limiting magnitude of BTA by introduction of new light detectors are close to exhaustion since the quantum efficiency of up-to-date detectors is nearing the theoretical limit. The classical factors: astronomical climate, gathering area, and quality of the optics, precision characteristics of pointing and guiding are put in the foreground. To estimate the prospects of the BTA project, we cite the present-day state of these basic characteristics of the BTA complex.

2. Astronomical climate

Astroclimate characteristics of the BTA site, obtained as a result of exploration in the early 60s, were completely verified (Erokhin and Plyaskin, 1983). In Table 1 the data are presented on the BTA observing time for the period from 1984 to 1994. Here we define the observing time as the full time of the dome being open on a given night; the theoretically possible time is determined by the length of a calender night including twilight. One can see that for the last ten years the average annual budget of observing time at BTA has amounted to 1653 ± 215 hours, i.e. it is 42 ± 6 % of the theoretically possible annual budget. The actual observing time is less than the presented data since the dome slit is opened beforehand untill the observational conditions are settled completely.

From the data of Table 1 it is seen that the monthly contribution to the annual budget of observing time is distributed uniformly, only with a little maximum in September-October. The large values of the mean-square deviations point out to the poor reliability of observing time forecast for any month or season of a year.

For scheduling observing programmes and discussing the problems of astronomic climate inside the dome the distribution of observing time on a short scale is of interest. Considering the night on which the dome was open longer than half of the astronomical night as full, we broke up the observational season August 1992 — April 1993 into observational runs (the dome is open) and non-observational (the dome is closed) and obtained a sample from 42 values of the run lengths. Their distribution is presented in Table 2. The data of Table 2 show that short observing runs are most likely, the distribution of the runs is more uniform. The mean value of the full run length — observational plus non-observational — totals (6 ± 3) days, 2.5 ± 2 out of them will be observational; during (3.5 ± 2.5) days the dome will be closed, but the observing run duration in this case with a probability of 80 % will not exceed 3 days. The 6 m Telescope Time Allocation Committee allows for these data when allocating observing time.

On the whole, with the present-day requirements to the main parameter — the observing time budget and its distribution — the BTA site can not be suitable neither for a large telescope nor even for a moderate-size one.

A serious problem is posed by the necessity to control temperature inhomogeneities in the dome (with its large volume and thermal inertia), which are determined by temperature variations of outdoor air. The standard system of thermal protection of BTA includes:

- double insulation walls of the dome to protect from insolation, a system of cooling the floor to prevent heat diffusion from the interior rooms of the BTA building;
- ventilation system of artificial climate to set up the conditions of the coming night in the dome.

Obviously this thermal protection system was based on the assumption of slow variations of night temperature and minimum influence of heat sources. However, the initial test of the standard system in 1974 showed that it was entirely useless:

- the pipelines for cooling the floor, which were grouted in concrete, acted as generators of temperature inhomogeneities, and in winter time they were coated with snow crust;
- the power of the air-cooling installation proved insufficient to control temperature in the dome because of the large nightly drops of outdoor air temperature, which was unexpected for the designers, and the great losses of cold in the airways.

The attempts of the working group "Astroclimate" to employ the standard ventilation system were a failure. This necessitated utilization of outdoor air to level temperature in the dome (Erokhin, 1984).

In order to illustrate the actual difficulties in solving problems of thermal protection of BTA, in Fig.2 are shown the measures of night-time (at 0^h local time) temperature of outdoor air during the seasons from November 1990 to March 1991 and from August 1992 to April 1993. In Fig.2 are also presented the seasonal trends of night temperature obtained by the moving average. Fig.3 displays the nightly temperature variations relatively the seasonal trends. Analysis of these data shows that at the BTA site only in 35 % of cases the nightly drop of temperature is $| \Delta t | \leq 2^\circ$C, whereas in 20 % of cases this drop is $| \Delta t | \geq 4^\circ$C.

The periodogram (power spectrum) of the short-period component of the night temperature variations relative to the seasonal trend for the two seasons has the shape of a narrow-band noise with a central frequency $| \nu | = 0.1\mathrm{d}^{-1}$ and width $\Delta | \nu | \simeq 0.05\mathrm{d}^{-1}$. Thus, a sinusoidal component with a period of $\simeq 10$

Table 1: *Observational time in 1984–1994*

Month	Theoretical observational time (hours)	Observational time at BTA (hours)	Time in units of theoretical	Contribution to year budget
1	424	130±38	0.31±0.09	0.08
2	358	141±53	0.39±0.15	0.09
3	343	146±44	0.42±0.13	0.09
4	282	122±36	0.43±0.13	0.07
5	249	112±31	0.45±0.12	0.07
6	219	99±25	0.45±0.11	0.06
7	235	110±25	0.47±0.11	0.07
8	276	146±35	0.53±0.13	0.09
9	313	174±31	0.56±0.10	0.11
10	370	187±51	0.51±0.14	0.11
11	398	129±57	0.32±0.14	0.08
12	433	149±71	0.34±0.16	0.09
Mean per year	3900 hours	1653±215 hours	0.42±0.06	1.00

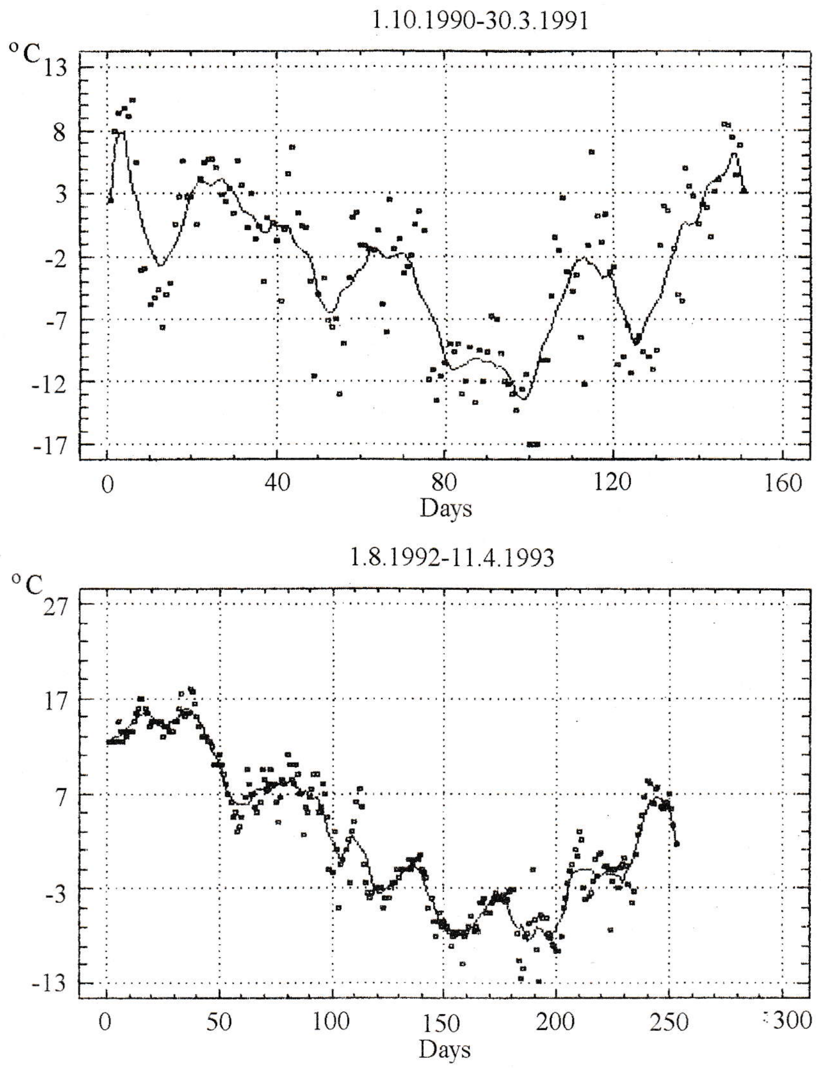
days and amplitude $\simeq 5^\circ$ is continuously present in the night temperature variations. It is this rapid variability of night temperature (for 1/4 of the period of the main component, i.e. for $\simeq 3$ days the outdoor temperature changes by $\simeq 5^\circ$) that determines the difficulties in solving the heat problems of BTA.

The investigations accomplished in 1984-1985 arranged possible sources of heat trapped by the dome. It turned out that the main heat releasing source, producing ≥ 1000 kcalories/hour, is the oil pumps: oil heated when it passes through the delivering pumps and oil bearings with subsequent cooling when it drains into the oil collector. The liberated heat is transferred into the dome through the metal structures of the telescope. However the mechanism of a stove is chiefly operative here: the cool air from the dome is sucked into the housing of the oil bearings through the grated openings of the slewing circle, while the heated air is ejected into the dome through the "tubes" of the lifts and telescope pillars at a speed of 1-2 m/s. Air heated by the structures of the basement and building of the telescope, which comes directly into the dome through the channels of the idle standard artificial climate system, proved to be the second, as to the power, heat source. The data on the temperature conditions in the dome, obtained on March 17, 1987 test of the new ventilation system, are shown in Fig.4. At 21^h the dome was closed and the ventilation system was turned off. The air temperature in the dome immediately began to rise at a rate of 1.4 degrees per hour. At 23^h the system was turned on, and during the next hour the air temperature in the dome fell by 1.8°, then the rate of temperature drop drastically decreased. This example illustrates the small inertness and great power of the sources heating air in the dome. The two heating mechanisms mentioned above are suffice to explain the data of Fig.4, other sources of heating air in the dome (from other rooms, thermal conductivity, apparatus etc.) are of minor importance.

Table 2: *Duration of observational and nonobservational runs in 1992–1993*

Run duration in days	Frequency	
	Observed	Nonobserved
1	0.43	0.24
2	0.26	0.21
3	0.10	0.21
4	0.04	0.14
5	0.04	0.05
(6–9)	0.10	0.08
(9–12)	0	0.08

The data of Table 1 show that natural ventilation may play only a secondary part in solving the thermal problems of BTA: because of the weather the dome must not be open for 60 % of calendar time; in the most important autumn-winter season the possibilities of opening the dome are reduced due to the harmful effects of strong insolation. That is why the conception of continuous forced supply of outdoor air into the dome was accepted. The task of realizing this conception was solved by the BTA Maintenance Service (Yu.M. Mamet'ev, A.M. Pritychenko, V.N. Erokhin and others). In the ventilation system now in service all the channels of the standard system of artificial climate are used for evacuating air from inside the dome; the intake of outdoor air occurs through a window (12 m^2 in size) in the lower part of the shutter of the dome, which allows keeping ventilation on even when it rains or snows. An additional exhaust ventilation channel of the interpanel space of the dome


1.10.1990-30.3.1991

1.8.1992-11.4.1993

Figure 2: *The night temperature of the atmosphere in seasons: top — 1.10.1990 — 30.03.1991; bottom — 1.08.1992 — 14.04.1993. Solid curves show the seasonal trend obtained by the moving average.*

through the windows in its upper part mixes air in the dome and prevents accumulation of warm air in the upper parts. Another exhaust channel via the aluminizing shop chills the housing of the oil bearings. The ventilation system is operated automatically by control signals from the temperature sensors and performs the following operations:

- minimizes the temperature difference inside and outside the dome;
- shuts off the heat flow from the interior rooms of the building through the floor;
- minimizes the amount of warm air coming by the channels of the standard system of artificial climate.

The power of the major heat liberating source was reduced by a factor of 2 by the creation of a two-tank oil supply system and use of seasonal oils, which made it possible to decrease the oil working temperature by 10°.

The system of heat reflection and ventilation was tested by thermovision measurements which showed the following:

- the dome effectively shields the telescope from insolation;
- the temperature inside the dome, including its upper part, is distributed uniformly; within the sensitivity of the technique only the observer's cage is found to be heated by 0.2° by the observing apparatus.
- the main source of heat release — the oil supply system — shows up clearly by the high temperature of the oil pipes as well as by the increased ($\simeq 1°$)

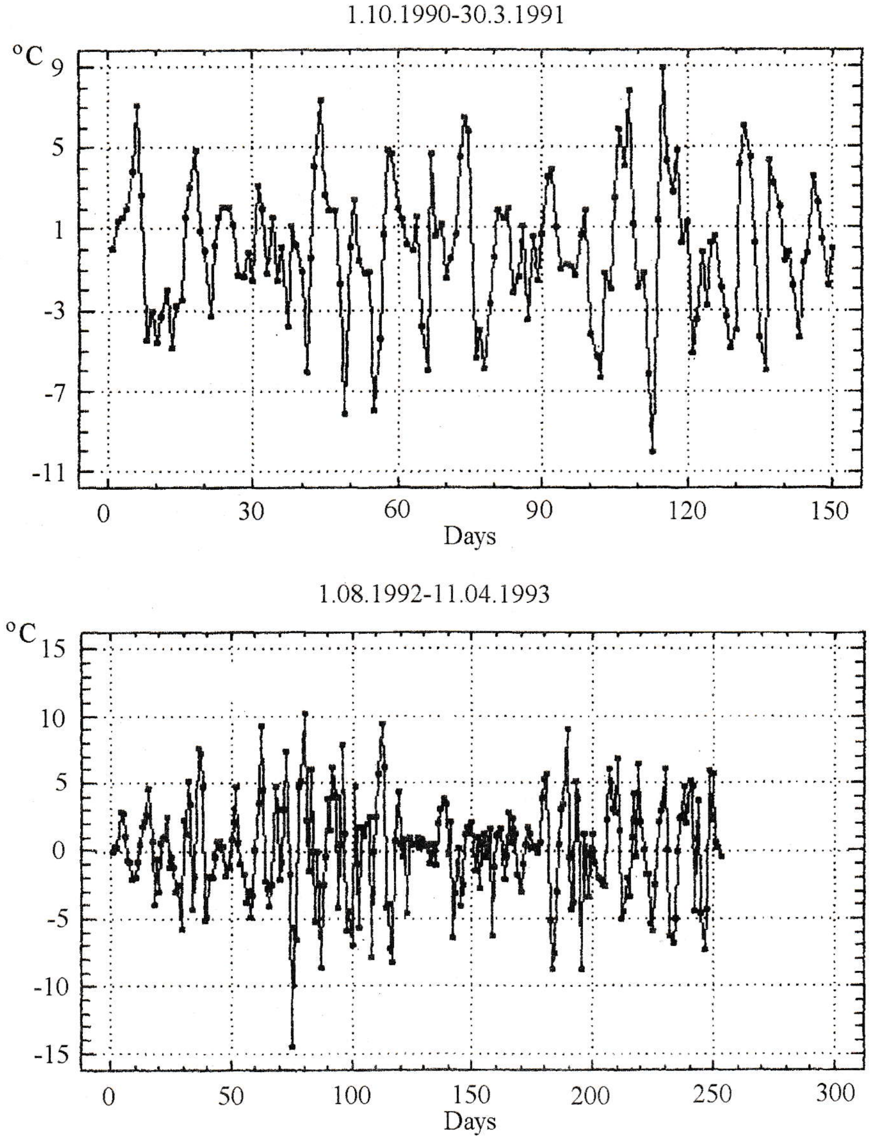


Figure 3: *Night temperature variations relative to the seasonal trends of Fig.2.*

temperature of the slowing circle and the places inletting warm air from the housing of the oil bearings.

The achieved level of performance efficiency of the forced ventilation system is illustrated by the data of Fig.5, where the histograms of values of the night temperature difference inside and outside the dome for the autumn-winter seasons 1990/91 and 1992/93 are presented. Regarding the negative values of the air temperature difference in the dome and outdoor to be a positive factor, we obtain the following distribution of nightly values of Δt:

— in 40 % of cases $\Delta t \leq 0°$,
— in 60 % of cases $\Delta t \leq 2°$,
— in 70 % of cases $\Delta t \leq 3°$.

Actually these estimates do not change for the subsamples of nights with the dome open or closed, which points out only to a secondary part played by the natural ventilation in the temperature control in the dome. At the same time in 25 % of cases the values of $\Delta t > 3°$, while in $\simeq$ 3 % of cases $\Delta t \geq 10°$, which causes complete degradation of images. We explain this by the rapid outdoor air temperature fluctuations and increasing heat flow into the dome when the temperature inside is lowered. The data of Fig.2 and Fig.3 show that in 20 % of cases the 24-hourly

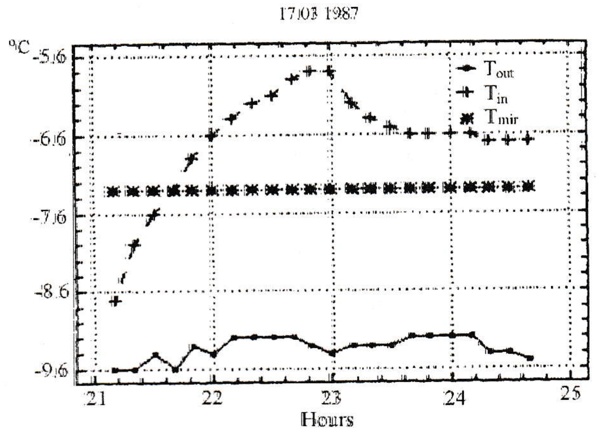


Figure 4: *Response of the temperature inside the dome and that of the mirror on ventilation regime. At* 21^h *the dome slit is closed and ventilation is switched off. At* 23^h *ventilation is switched on.*

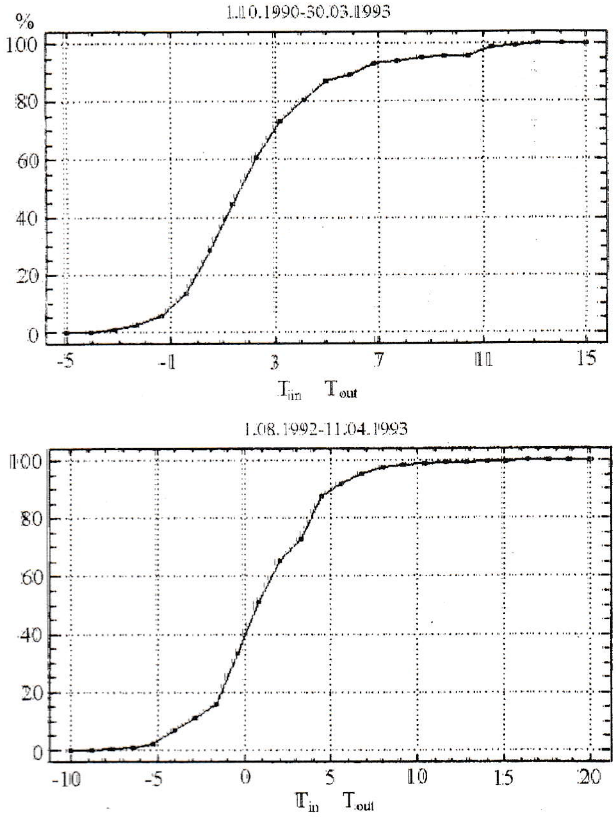


Figure 5: *Histograms of night temperature differences inside and outside the dome. Top — 1990/91; bottom — 1992/93.*

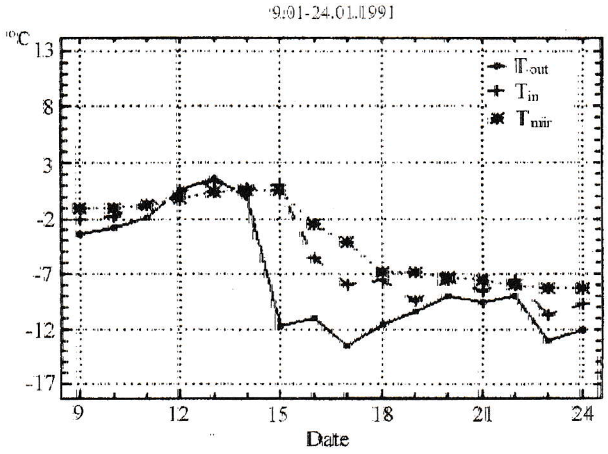


Figure 6: *Night temperatures of the mirror and of the air outside and inside the dome at the period of thermal shock, 9.01-24.01.1991.*

drop of outdoor temperature is higher than 4°. The temperature of the basement of the telescope building is never lower than the annual average, $+4°C$. In the production and living premises of the building the temperature is forcefully maintained no lower than $+16°C$. Fig.6 illustrates the response of temperature in the dome to the thermal shock on 14 January, 1991, when the outdoor air temperature dropped by 12° for a day. With a lag of $\simeq$ 12 hours the temperature in the dome began to fall at a rate of $\simeq$ 6 degrees/days, however for the next day the rate of cooling lowered to $\simeq$ 2 degrees/day, then the cooling stopped — the outdoor chill and the heat from the rooms of the building leveled. The temperature of the mirror surface began to decrease with a lag of $\simeq$ 2.5 days at a rate of $\simeq$ 2 degrees/day. On January 20 the temperature leveled as a result of the increase in outdoor temperature by 5°. Before January 14 the difference between the temperature in the dome and the temperature in the interior rooms of the telescope building Δt had been 15°, the accumulation of heat in the dome being controlled by ventilation. At the minimum air temperature in the dome the difference Δt amounted already to $\simeq$ 24°, i.e. the speed of air flows from the interior rooms of the building increased by a factor of $\simeq$ 1.5, and the excess of heat introduced by them grew $\simeq$ 2.5 times. Thus, with falling temperature in the dome the efficiency of ventilation in winter time decreases since its energy is spent more and more on cooling the interior rooms of the building, which is successfully controlled by the personnel working at the telescope through turning on additional heating.

On the whole the data presented above characterize the current possibilities of temperature control in the dome. It is evident that these possibilities have actually reached the limit, and further advance is possible only with cardinal improvement of the oil supply system and withdrawal from the building of all production and living premises.

The temperature difference inside and outside the dome causes temperature microfluctuations, i.e. the air refraction index, which determines degradation of images. The Hartmanofilm taken at a rate of 20 frames/s with "hot" air in the dome shows the degree and character of wave-front perturbations by the whole path — optics and atmosphere. The results of reduction of a sample of 16 successive frames of the film yielded the momentary value for the concentration of energy in the images $d_{0.85} = (3.40 \pm 0.22)$ arcsec. The exclusion of all Seidel aberrations yields $d_{0.85} = (3.09 \pm 0.23)$ arcsec, i.e. does not actually improve the image. The mean-square focal length variation totaled only ±0.13 mm. Thus, degradation of image is not determined by the low-frequency wave-front deviations, including Seidel aberrations. A dispersion analysis showed that for the high-frequency wave-front deviations the correlation radius is less than 200 mm — the Hartman diaphragm resolution limit. It is established by the measurements of temperature microfluctuations throughout the whole volume inside the dome that the maximum of microfluctuations is concentrated between upper ring of the telescope and dome slit. The investigation of this phenomenon of formation of a phase screen at the entrance pupil of the telescope is continued; it is in prospect to estimate the contribution to this phenomenon of air streaming down from the exterior surface of the dome at night.

The problems of the BTA main mirror thermal protection will be discussed in the next section.

3. Telescope optics

From 1972 to 1974 the staff workers of the observatory Eh.A. Vitrichenko, Yu.P. Korovyakovsky, A.F. Fomenko and others took part in the elaboration of quantitative techniques for control and testing of the BTA main mirror. From 1975 to 1978 the firms "Optika" and "Rubin" manufactured a second 6 m mirror. The intensive investigation of the first mirror at the telescope grounded the necessity of its replacement, which was accomplished in 1979. Since the disks of the two mirrors are identical, we do not distinguish between them in the discussion of mechanical and thermal problems of the BTA main mirror.

The mirror surface quality prespecified in the manufacture is characterized by the data of the workshop tests (here and hereafter d_q is the diameter of the scattering circle on the spot diagram that contains the q portion of energy): $d_{0.5} = 0''.4$, $d_{0.9} = 0''.8$.

The matter of preserving these characteristics when changing the position of the mirror was especially acute when the decision on the mirror replacement was adopted. Numerous experiments under the workshop conditions did not reveal weight deformations of the surface in both the low-frequency range (Hartman method) and the high-frequency range (interference methods of control). The final test made by the Hartman method, when the mirror was placed on the telescope, showed that with the variation of the zenith distance Z from 0 to 70° the concentration of energy in the image actually does not change, and only a turn of the axis of astigmatism with keeping up its amplitude is revealed (Snezhko, 1980). The position of the plane of the main mirror is determined by three supports and a central pin, which defines the orientation of the optic axis. Direct measurements of the sway of the mirror in the cell showed that the orientation of the optic axis in the azimuth direction is varied with evolution of the tube with an amplitude of $\simeq 6$ arcsec and hysteresis within 2 arcsec, whereas the inclinations in the plane of the vertical and the radial shifts of the mirror lie within the measurement errors. This characteristic swaying of the mirror in the cell is determined by the fact that in the procedure of adjustment of the support systems the distribution of density throughout the disk of the mirror was assumed uniform, whereas in the real mirror variations of density up to 10 % occur. The small but detectable hysteresis of the mirror swaying is most likely caused by friction and backlashes in the support units. The control of the position of the main mirror in the cell made in 1985–1986 showed both the stability of the optic axis position at $Z = 0$ in the limits of ±1.5 arcsec and the constancy of the sway parameters, which is verified by the analysis of pointing errors of many years. There are no fundamental difficulties in readjusting the support units for the real distribution of the weight of the mirror disk. However this procedure involves the time- and labour-consuming methods of control of the surface shape by the Hartman method, which is difficult to be done on the operating telescope. Since the residual instability of the main mirror position lies within the adjustment tolerances and is eliminated to a sufficient degree in the correction of pointing errors, we have abandoned this procedure. We conclude that on the whole in the BTA project the problem of supporting and fixing the mirror of 42 tons in weight has been solved successfully.

The optics of the prime focus of BTA apart from the parabolic main mirror incorporates a two-lens corrector, correcting coma and spherical aberration, so that the field diameter of 10′ is limited by the field astigmatism. The quantitative adjustment performed in 1982–1984 with the application of the Hartman method not only minimized inclinations and collimation errors, but also allowed us to reveal and correct a defect of manufacture of one of the support units, which caused the instability in the main mirror position. At the present time the quality of image produced by the optics in the prime focus is determined only by the quality of the main mirror surface and the designed aberrations of the corrector.

The problem of thermal deformations of large mirrors has been known since the time of the 5 m telescope project. One should add here the problem of turbulization of air in the optical path above an inertial massive mirror when changing outdoor temperature. These two problems are very acute for BTA, at which site the temperature variations contain components with an amplitude up to 5° and characteristic times of 3–5 days. In Fig.7 are shown the temperature variations of the mirror surface and the seasonal trend of the atmosphere temperature as well as the cross-correlation function of these processes. One can see that with a shift of $\simeq 3$ days the mirror temperature tracks the seasonal trend with a correlation coefficient of 0.95. The same estimate of characteristic time of the mirror response to outdoor temperature follows from the thermal shock pattern presented in Fig.6, which fully agrees with the estimate of the Fourier number $\simeq 3$ days following from physical characteristics of glass and disk of the mirror.

With such a time lag and rapid fluctuations of outdoor temperature, temperature gradients continuously develop in the disk, which deform the shape of the surface. In Table 3 the data are listed which characterize the response of the BTA main mirror to thermal shock, at which time the mirror was force-cooled through the ventilation system of the cell (here and hereafter A_{ik} are the amplitudes of Seidel aberrations in the wavefront, the errors are found from averaging the data of reduction of no less than 3 hartmanograms).

Following a drop of temperature by 11° the image strongly degraded, the scattering circle grew by a factor of $\simeq 1.5$. In the degradation of the wavefront not only the amplitude increase A_{40} of spherical aberration is detected (edge effect), but also the development of coma and astigmatism, i.e. non-axially-symmetric aberrations. The latter is a major risk when attempting to actively cool the disk of the mirror — composition of the heat stresses with the residual stresses in the disk is possible, which may result in destruction of the disk. In the example presented the rate of coolling was kept for 48 hours at a a level of $\simeq 2$ degrees/day. The level of mechanical stresses developing here can be evaluated from a comparison with the distortions presented in Table 4 which arise with one fixing element made inoperative (4-19.05.1984).

The comparison shows that the mirror surface deformations which develop under the action of thermal shock are comparable with those when one fixing unit is out of operation, i.e. it is as if a point mechanical load of $\simeq 700$ kg is apllied. Thus, the limitation of 2 degrees/day imposed on the rate of cooling of the main mirror is justified; greater cooling rates are dangerous for the mirror disk. The cooling rate of 2 degrees/day is achieved at the difference in temperature between mirror and ambient air $\Delta t \approx 10°$, that is why it is forbidden to open the dome shutter at $\Delta t > 10°$. Losses of observing time for this reason do not exceed 5 % of the annual budget, and since these are chiefly caused by the large and rapid nightly temperature variations at the selected BTA site, one should attribute them to such natural losses as those caused by clouds, precipitation, wind etc.

The data of Table 3 illustrate the limiting degradation of image $d_{0.9} \simeq 1.6$ arcsec, the duration of thermal shocks amounts to 4–5 days, after which the image quality is recovered. Beyond the periods of thermal shocks the image quality produced by the BTA optics is $d_{0.9} = (1.1 \pm 0.16)$ arcsec (from the results of the Hartman tests in 1985–1986).

The rapid variability of outdoor temperature and the great inertia of the main mirror glass disk make it impossible to control the development of temperature gradients in it. Since the defocusing can be easily eliminated through equipping the BTA foci with TV guides, we abandoned active use of the asymmetric system for ventilating the main mirror cell, which magnifies development of aberrations and "freezes" them in the short periods of thermal shocks.

On the whole the problems of thermal deformations of the surface and the mirror disk safety create additional restrictions on the possibility of temperature control in the dome. In 1984–1985 a project of manufacturing a sitall primary mirror for BTA was worked up with the participation of B.K. Ioannisiani. The computations performed at LOMO showed that the depth of the mirror disk can be reduced from 65 to 40 cm for the standard support system, the accuracy being preserved. This simplifies the problem of sitallizing and diminishing the thermal inertia of the disk. The firm "Rubin" is capable of both manufacturing of an appropriate sitall disk and forming the optical surface using the up-to-date technology. However, the main mirror of BTA has not so far been replaced with a sitall because of financial problems.

4. Pointing and tracking

The design of BTA provided for the following precision characteristics of the automatic control system (ACS): the pointing accuracy no worse than ±20 arcsec in the focal plane, the built-up error of tracking should not exceed 5 arcsec in 10-minute exposure. Such lenient requirements were caused by difficulties of objectives facing the group of BTA ACS designers (headed by E.M. Neplokhov). A one-motor combined system with control links and astatism of the 2nd order (BTA, 1976; Najshul', 1966) was adopted for the program control by the telescope. The program con-

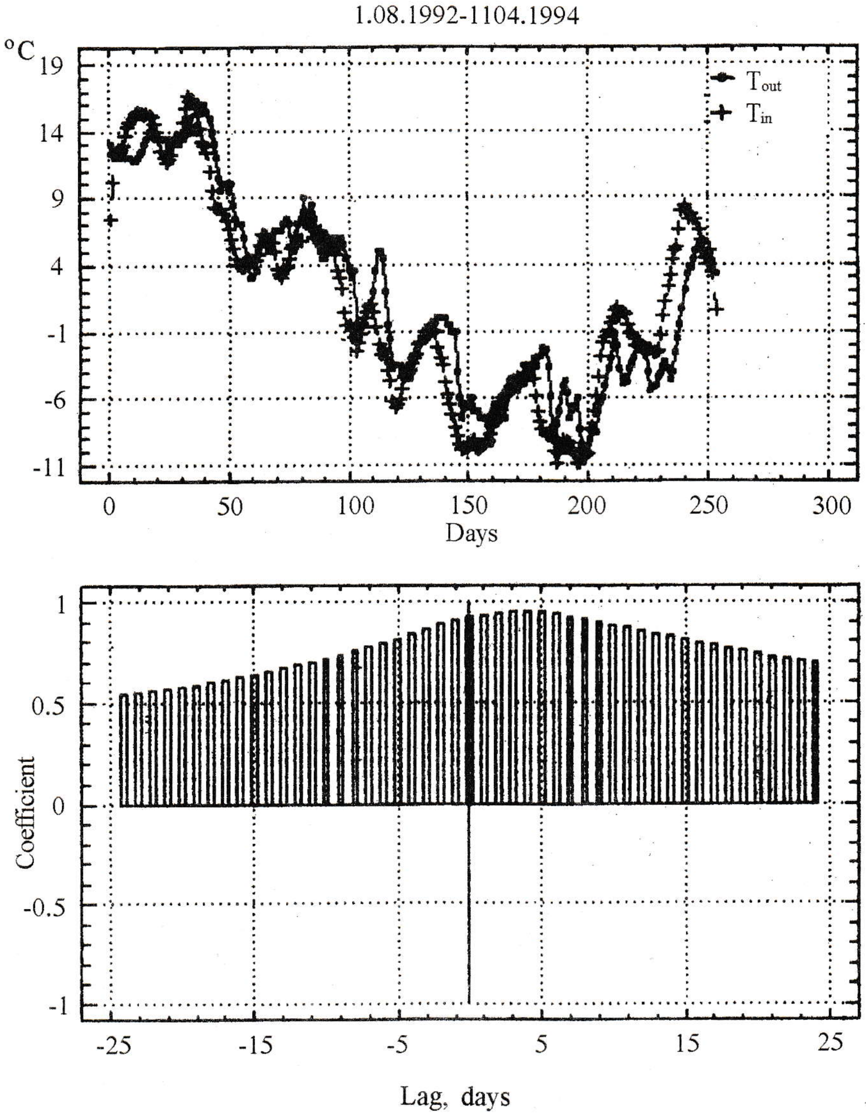


Figure 7: *Top — the temperature of the primary mirror and the seasonal trend of night temperature of 1992/1993; bottom — cross-correlation function of these processes.*

Table 3: *Results of Hartman method in the period of thermal shock* ($t_{out,mir}$ *— respectively, outside temperature and mirror temperature)*

Date	08.06.84	09.06.84	10.06.84	12.06.84	16.06.84
t_{out}	13.0°C	15.5	4.0	4.5	7.5
t_{mir}	12.0°C	12.0	12.0	9.0	8.0
$d_{0.85}$	$0.87''$ ±.02	—	1.47	1.52	0.89 ±.01
A_{40}	0.1 μm ±.3	—	4.7	6.4	0.9 ±.4
A_{31}	1.1 μm ±.5	—	3.4	7.7	2.0 ±.2
A_{22}	1.5 μm ±.6	—	5.0	2.2	1.3 ±.6

Table 4: *Deformation of the primary mirror surface when one fixing support is switched off*

Date	$d_{0.85}('')$	A_{40} (μm)	A_{31} (μm)	A_{22} (μm)
07.05.84	1.45	0.89	6.87	4.14
	±.06	±.11	±.11	±.27
11.05.84	1.56	5.36	5.36	5.30
	±.11	±.76	±.17	±1.30
12.05.84	1.43	5.56	5.47	2.05
	±.02	±.34	±.13	±.35

trol was intended for "rough" guiding, the system of photoelectric automatic correction was supposed to be responsible for the fine tracking with an error no larger than 0.2 arcsec. However, the system of photoelectric automatic correction, in which the coordinate transducers were mounted on a separate guiding telescope, proved completely inoperative due to both the low penetrating power and the impossibility to take into account and exclude the differential flexures and the effects of field rotation. Only the local photoguide of the Main stellar spectrograph, used for observations of bright objects, was operated successfully. As a result of this, the program control became the only condition for the fine tracking. For this purpose by the end of 1984 the resolution of feedback transducers had been brought to 0.15 seconds of arc, the smoothness and stability of control had been optimized. It should be noted here that the problem of control is unique not because of the mass and dimension of the telescope, but because of the necessity to ensure the limiting accuracy since it is operated under the atmospheric conditions, when the external disturbances are comparable with the control action.

The theory of alt-azimuth mounting is stated in the papers by N.N. Mikhelson (1966; 1970). Classification of errors and their description for BTA are presented in the papers of the creators of BTA ACS (Vilenchik, 1972). Direct measurements of geometry of the telescope were made by V.Ya. Veinberg and generalized in his thesis (Veinberg, 1985). Investigations of pointing errors of the telescope showed the high quality of all systems and units which determine this characteristic of BTA. The following components were included in the analysis of pointing errors:
— nonperpendicularity of the horizontal and vertical axes;
— nonperpendicularity of the horizontal and aiming axes of the telescope (collimation error);
— errors of zero points of the angular position transducers;
— flexure of the tube;
— hour-angle errors;
— inclination errors of the vertical axis of the telescope.

It should be noted that the components are called rather by tradition, since each of them is the sum of several independent effects. The modal representation of appropriate conditional equations, but not the decomposition in orthogonal functions, causes poor certainty of the corresponding set of normal equations. In consequence, it is impossible to define each parameter separately without additional analysis due to the arising linear dependence in the solution corresponding to a given sample of pointing errors. Summing up the results of the analyses of pointing errors in 1984–1985, we derive the following conclusions about the stability of the mounting and optics of BTA.

1. The azimuthal component $\Delta\gamma = \Delta A \cdot \sin Z$ of pointing errors is consistently reproduced for 10 years. Its exclusion by a program way with one and the same system of parameters yields a residual scattering circle with a size of ±5 arcsec and mean-square deviation $\sigma \leq 3$ arcsec (excluding hour angle errors).
2. The component ΔZ of pointing errors has also remained unchanged for 10 years. Its elimination with one and the same parameters gives a residual scattering circle of ±8 arcsec and $\sigma \leq 5$ arcsec (excluding hour angle error).
3. The tube flexures are described by the expression $\mathrm{d} \cdot \sin Z + \mathrm{d1} \cdot \cos Z$. If the first term is typical of the Sereurier tube, then the second results from the shifts of the suspension of the worm of the Z gear.
4. If the system of BTA is stable in pointing in A, then the pointing error in Z involves a random zero-point displacement within 10 arcsec at all time intervals. A likely source of this instability is backlashes in the system of automatic balancing and the residual unbalance of the tube.
5. The accumulated errors of the position angular transducers are undetectable in the fields of pointing errors. The accuracy of the angular transducers is sufficient for the purposes of pointing.
6. The swinging of the mirror in the cell is added to the effects of inclination of the axes and does not show up separately. Hysteresis of the mirror swinging shows up in the fields of pointing errors with an amplitude of ±1 arcsec.

The small total amplitude of pointing errors, which are not eliminated by allowance for geometry of the telescope, permitted employment at BTA of a purely programme algorithm for rulling out pointing errors. This program algorithm supplemented by simple observational procedures allows achievement of the following accuracy characteristics of BTA.

1. The usage of one and the same system of parameters for the given focus suffices to ensure for a number of years the mean square error $\sigma \leq 3$ arcsec with a range of ± 6 arcsec.

2. Specification/determination of the hour-angle error and the zero-point errors by observations of two pairs of stars at equal elevations in the meridium and in the 1st vertical leads to reduction of pointing error values $\sigma \leq 2.5$ arcsec with a range of less than ± 5 arcsec during a few days (weeks).

3. To achieve the pointing accuracy $\sigma \leq 1.5$ arcsec with a range of ± 3 arcsec it is necessary to conduct observations of the minimum field of pointing errors (4-5 points for $5^\circ < Z < 70^\circ$ in two verticals) for a given night and redetermine the whole system of parameters for the given focus of BTA.

To illustrate the above said, Fig. 8 presents the fields of pointing errors obtained on October 17.10.1994 at the Nasmyth-2 focus. One can see that the behaviour of the errors, when the telescope geometry errors are not excluded is similar to theoretically expected. The exception of the geometry errors by the "mean" system of parameters reduced the residual pointing errors to the value $\simeq 3$ arcsec with a range of ± 5 arcsec. The redetermination of the system of parameters for the given night reduced the pointing errors to the value $\sigma \simeq 1$ arcsec with a range ± 2 arcsec.

In general one can say that the high quality of design and manufacture of the principal units of the mounting (except for the unit of automatic tube balancing) allowed us to solve the problem of pointing accuracy of BTA.

From 1975 to 1985 the presence of the telescope geometry errors necessitated permanent manual correction of tracking (guiding) by the observer. The guiding correction compensates for the geometry errors and also for the field rotation when observing an actually off-axis object. It is evident that this procedure is undesirable since in this case the BTA ACS is operated under transitive conditions with excitation of the whole spectrum of oscillations. The programme correction of geometry errors improved the telescope tracking having removed trends in the tracking errors. The procedure of back recalculation of coordinates acquired the physical sense of the real elimination of errors in setting equatorial coordinates of the object, which amount in practice to tens of arcseconds for faint objects. Now the accumulated correction for all the foci of BTA does not exceed 0.3 arcsec for an exposure of 20 minutes.

The presence of high-frequency tracking errors had been persistently noted by observers, however from 1975 to 1985 this component was masked by permanent hand correction. The first quantitative definitions of tracking quality from observations by speckle-interferometry techniques showed the presence in the spectrum of guiding errors of a component with a frequency of $\simeq 1$ Hz and amplitude up to 0.5 arcsec (Balega et al., 1990). In order to examine the quality of tracking in a wide frequency range, in 1991–1992 a digital TV-guide of the Main stellar spectrograph of BTA was used. The first recordings showed the presence of components in the interval of frequencies from 0.1 to 1 Hz, the scattering circle produced by the image centre during a 15-minute exposure being $\simeq 1$ arcsec in diameter. In Fig. 9 a,b is presented an example of BTA tracking records at a wind velocity of ≤ 2 m/s. Sequentially the initial series, trend and high-frequency components and their power spectra (time is given in seconds, amplitudes in arcseconds, frequencies in Hz) are shown.

It can be seen that a low-frequency component with $\nu \lesssim 0.1$ Hz and an amplitude of $\lesssim 0.5$ arcsec dominates in the spectrum. In the high-frequency component of tracking errors in both coordinates a component with $\nu \simeq 0.9$ Hz and amplitude $\simeq 0.2$ arcsec is dominant. A quantitative analysis of recordings of BTA tracking obtained with the digital TV-guide allowed us to make the following conclusions.

1. In the errors of programme-controlled BTA tracking the component with $\nu \lesssim 0.1$ Hz and an amplitude of $\lesssim 0.5$ arcsec is persistently present.

2. In the high-frequency part of guiding errors a simple set of frequencies, $\nu 1 \simeq 0.4 - 05$ Hz, $\nu 2 \simeq 0.6 - 0.7$ Hz and $\nu 3 \simeq 0.8 - 0.9$ Hz, of oscillations on the γ and Z axes is present.

3. The quality of BTA tracking is degraded drastically by external disturbances, the amplitude of all the components increases 2-3 times at a wind velocity of > 2 m/s. At a wind velocity of $\simeq 10$ m/s bounces of a star by 15 arcsec are observed with slow returning to the centre (loss of control).

Some work was done in 1990–1991 in order to investigate into dynamical characteristics of the telescope and its control system, on the basis of the facilities and methods for measuring oscillations (tansducers of linear and angular velocities and accelerations, optical direction finder), which were developed at the Research Institute of Precision Engineering. Disturbances were set both as impulse action of the control system and as mechanical action on the units of the telescope. The following experimental data were obtained as a result.

1. If disturbances are applied to the prime focus

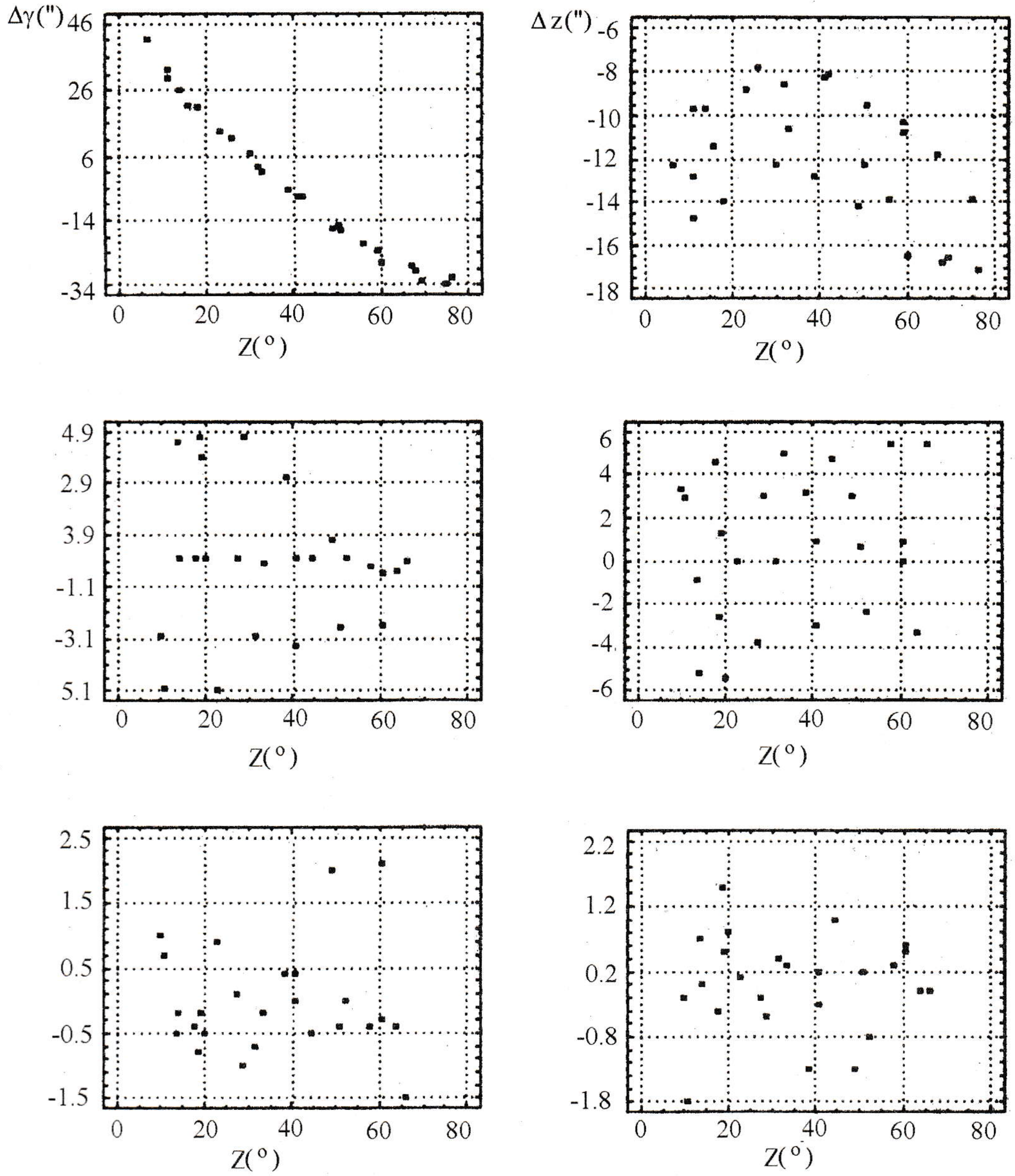


Figure 8: *Tracking errors $\Delta\gamma$ and ΔZ in the Nasmyth-2 focus, 17.10.1994. From top to bottom: without corrections of the telescope geometry errors; with the "mean" system of the correction parameters; with the system of correction parameters for the given night.*

cabine, the oscillations of the mounting of the worm of the A drive with a damping time of $\simeq$ 10 s are concentrated in a range of frequencies from 0.7 to 1.2 Hz with the maximum of spectral density at 0.8 Hz. In this case the outlet telescope axis oscillates with an amplitude reaching $\simeq$ 2.5 arcsec.

2. With the standard mode of program tracking random perturbations on the part of the control system lead to vibrations of the mounting of the worm of the A drive with a frequency of 0.8-0.9 Hz and oscillations of the outlet telescope axis with frequencies of 0.4 and 0.8-1 Hz and an amplitude up to 1 arcsec.

3. If disturbances act on the cabine oscillations of the worm mounting of the Z drive are concentrated in a frequency range of 0.4 Hz with a damping time of $\simeq$ 28 s. The oscillations of the Z axis have the maximum at 0.41 Hz with an amplitude up to 2.5 arcsec.

4. With the standard mode of driving the telescope around the Z axis oscillations of the telescope axis occur at frequencies 0.8-0.9 Hz, the amplitude of the oscillations reach values up to 1 arcsec.

5. For oscillations of the tube with respect to the middle unit of the telescope to be produced, it turned

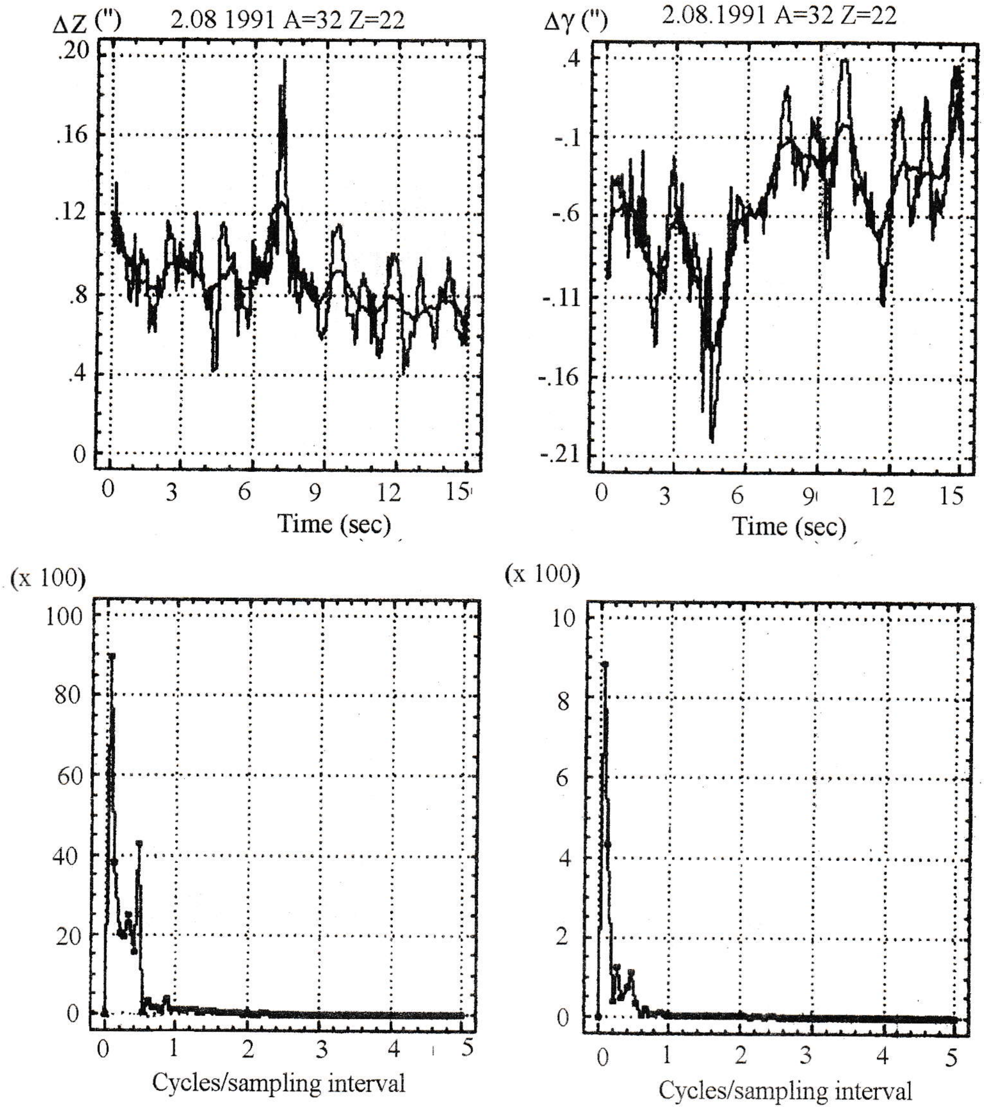


Figure 9: **a.** *Telescope tracking errors on 2.08.1991. Top — initial process and low-frequency trends in the axes γ and Z (in "), bottom — power spectra of the low-frequency trend.*

out necessary to apply greater shocks of the type of speed discontinuities when repointing the telescope. We failed to reveale oscillations in the system "middle unit — mirror cell". In the system "middle tube unit — front ring" complex vibrations with a frequency of the first harmonics $\simeq$ 4 Hz are excited.

To illustrate these results, records of telescope tracking at impulse disturbations of the system, which imitated wind loads, were obtained. Fig.10 presents the consequences of a push on the pillar of the telescope, which gave rise to oscillations of the image with $\nu_z \simeq 0.9$ Hz and $\nu_\gamma \simeq 0.8$ Hz and an amplitude of $\simeq$ 0.6 arcsec, the time of damping of oscillation in azimuth is much shorter.

As a result of the investigations accomplished, V.F. Rukhlev constructed a mathematical dynamical model of the telescope and analyzed the standard control system of BTA, using this dynamical model of control. The analysis not only reproduces the observed pattern of tracking errors, which confirms the reality of the mathematical model, but also defines the limitations imposed on the standard algorithm of control (the oscillatory circuit of the tube without feedback loop and the spring-loaded worm gears, the type 2 servo system, small control moments, etc.). Fig.11 presents the result of an attempt to feed a mismatch signal in azimuth from the digital TV-guide into the standard control system (control loop on the object). One can see the development of vibration

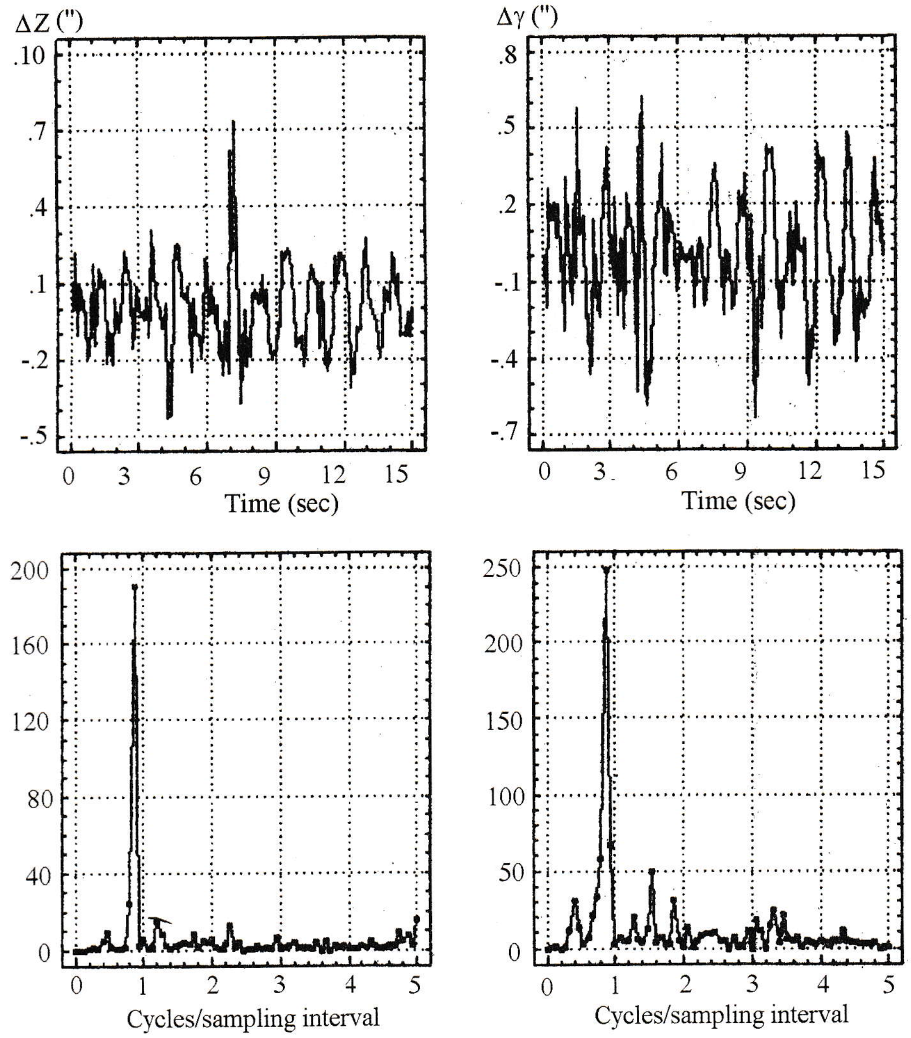


Figure 9: **b.** *High-frequency component of tracking errors of Fig. 9a and its power spectra.*

of the telescope at the frequency $\nu_\gamma \simeq 0.6$ Hz followed by loss of the object of tracking. It is evident that the possibilities of improving the tracking accuracy characteristics reached their limit. With the aid of the automated projecting system "DISPAS" V.F. Rukhlev synthesized an algorithm of invariant (with respect to external disturbances) control with damping and compensating circuits, which employed acceleration as a parameter of control. In this situation the number of feed-back transducers was held to a minimum, since the creation of transdusers of position, speed and acceleration at the outlet axis, which would have the required sensitivity and time resolution, is the major difficulty. It was shown with the mathematical model that one may reach for BTA a tracking accuracy of (0.1-0.2) arcsec with exclusion of both the trend and high-frequency guiding errors.

The quality of control must meet the most stringent requirements in design of modern large telescopes:

— pointing errors is no worse than ±1 arcsec in both axes;
— trend tracking error is no larger than 0.2 arcsec for an exposure of 30 minutes;
— amplitude of high-frequency tracking errors is no more than 0.2 arcsec.

The designers of the standard control system successfully, for their time, solved the problem of control of the 6 m telescope, having overcome the difficulty of the extremely limited range of computer and digital facilities, angle-to-code converters etc. However, to meet the present-day accuracy requirements, it is necessary to introduce new control algorithms which would eliminate the effect of external disturbances. A circuit of oscillation damping was experimentally implemented at the BTA A axis, which with the speed

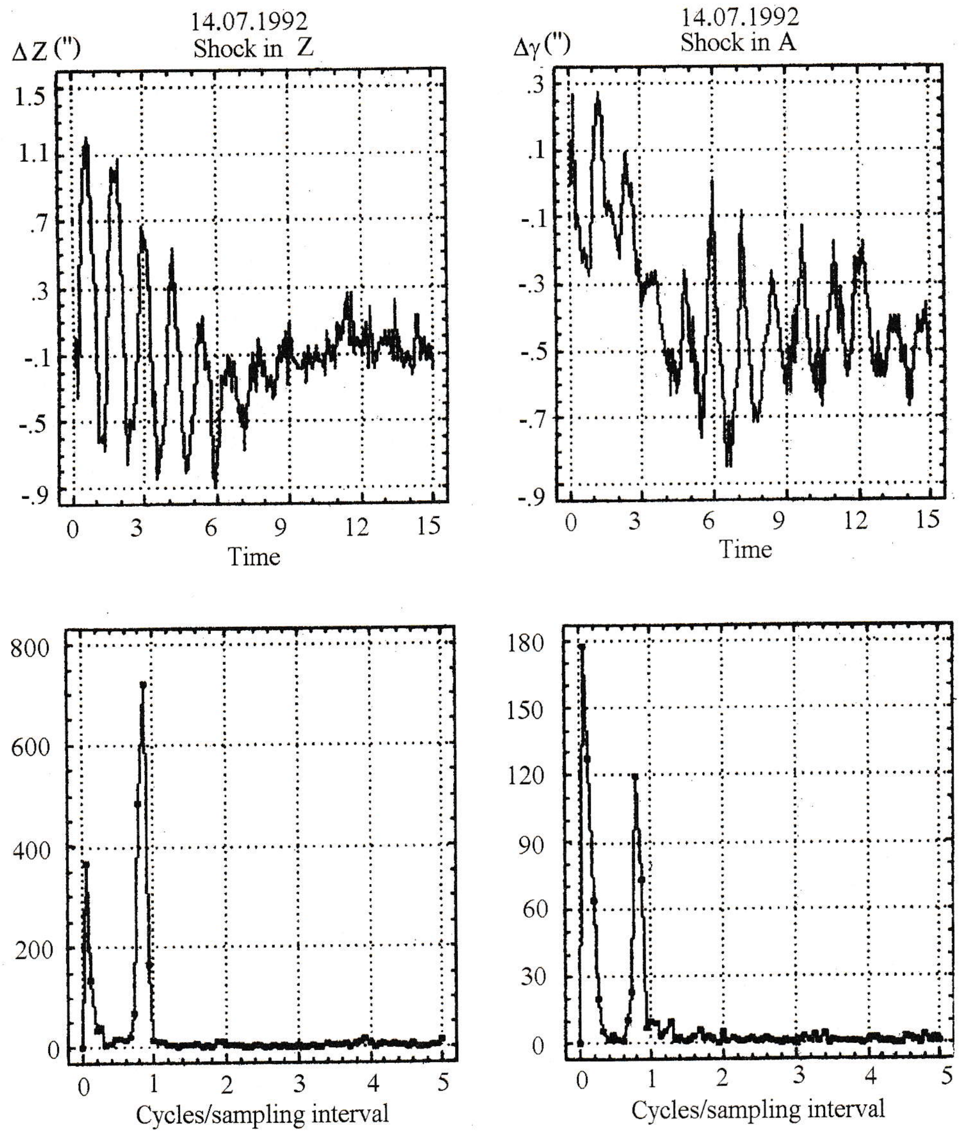


Figure 10: *Response of the telescope tracking on the impulse outer perturbation. Top – image centre oscillations $\Delta\gamma$ and ΔZ (in ''); bottom — power spectra of the process.*

sensor of displacement of the worm gear mounting and the required network which forms the control signal. This resulted in a reduction of oscillation damping time by a factor of 5-6 and improvement of the accuracy characteristics of manual correction. Thus the performance of BTA showed that the model damping algorithms of vibration of the telescope as well as the possibility of using spring-loaded worm gear mountings, as indicators of external disturbances, are justified.

5. Conclusion

We have dwelled above on the quantitative illustration of general problems which determine the efficiency of utilizing the large light-gathering power of the 6 m mirror. The empirical material of many years, the interesting results of its analysis, the development of methods, and the experience of operation of BTA have been published in the papers of the staff members and scientific-and-technical reports of SAO RAS. On the basis of the 20-year experience of BTA operation we apply the following judgements to the basic astronomical approaches of the BTA project.

1. The astronomical climate at the BTA site is the main factor diminishing the observational potential of the telescope. However for the last 20 years it has been ascertained that in the European part of

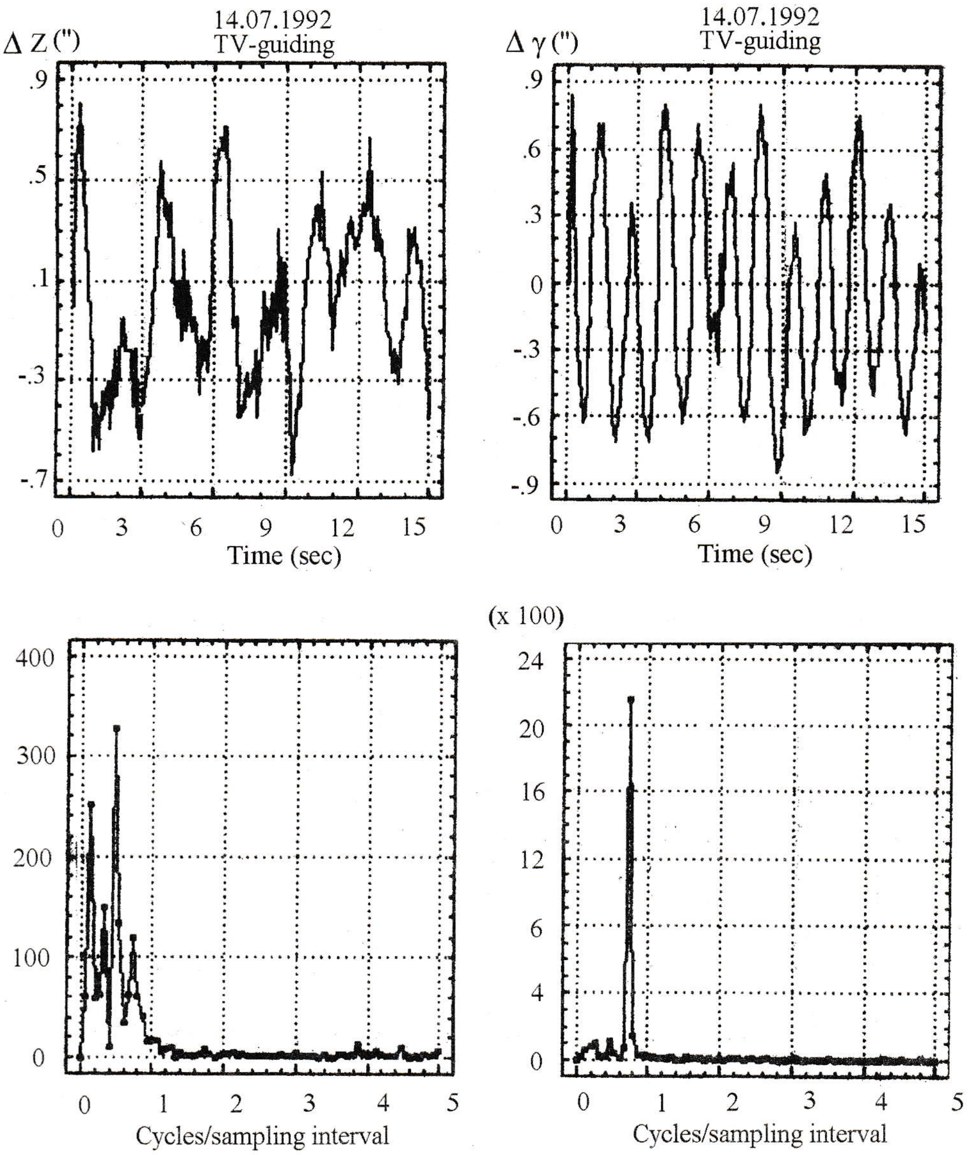


Figure 11: *Response of the standard control system on the error signal of the TV-guide. Top — image oscillations in γ and Z; bottom — power spectra of the process.*

the Former USSR, including the Transcaucasian regions, there are no places with better climatological characteristics for a large telescope.

2. The relative aperture of the main mirror 1:4 was designed with allowance for the technological possibilities of the 50s. This determined the difficulties in solving the thermal and control accuracy problems of the telescope.

3. Stuffed with production areas and even living spaces, the building for BTA replicated the telescope buildings of the beginning of the century and defined the difficulties in overcoming rapid outdoor temperature variations at the site of the telescope.

4. The bold decision to create a large telescope on an alt-azimuth mounting was warranted. Just because of this the successful performance of the alt-azimuth mounting of the 6 m telescope had a strong influence on the trend of large telescope construction, which, together with new optical technology, encouraged the increase of the limiting diameter of a single-mirror telescope.

We do not discuss the aftereffects of the feudal decision to build an academic astronomical institution in a lonely gorge in the mountains far from university and scientific centers and we direct readers to the paper by Yu.N. Efremov (1992) whose conclusions are quite correct at this point.

Actually there have been no losses of observing time for technical reasons during the 20 years of BTA operation. The inspection conducted in 1989–1990 showed a great reserve of service life of all mechanical units of the dome and telescope. At the same time it was found out that the resources of BTA ACS based on the elements of the early 70s had been completely exhausted. Since increasing losses of the limited amount of the BTA observing time threaten, a project of replacement and modernizing of BTA ACS (project BTA ACS-M) was worked out. The aim of the project was not only to restore the service life of the telescope but also to meet the present-day requirements to the accuracy of tracking and pointing. The data presented above show that the efficiency of BTA can be considerably improved by the implementation of the following points of the BTA modernization plan:

- full realization of ACS-M for BTA;
- modernization of the oil supply system through the creation of a unified system with oil temperature control;
- replacement of the glass main mirror by a sitall one having a minimum coefficient of thermal expansion;
- removal from the building of all production and living premises;
- introduction of observations in the infrared range to take advantage of twilight.

This plan, if realized, will bring BTA to the level of current requirements for a large optical telescope and lay a foundation for the effective adoption of local facilities of adaptive optics. On the whole for the 20 years of operation the telescope has lived up to realistic expectations of astronomers, especially in spectral observations. When scheduling further work, SAO RAS proceeds from the evident situation that in the nearest 15 years BTA remains the only home supplier of observational data in the study of extremely faint objects. In so doing it must hold competitive in the collaboration with both other large ground-based and space telescopes. In the past years apart from the scientific results SAO RAS has accumulated valuable methodical experience in solving observational problems of astrophysics. It is this experience that instils confidence that the possibilities of BTA are far from being exhausted and the amount of observational data being obtained at BTA is expected to increase.

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