A NEW 800 mm AUTOMATIC TELESCOPE

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ABSTRACT. A new automatic telescope, a 800-millimeter main mirror catadioptric anastigmatic aplanat, was constructed by specialists of Odessa National University Astronomical observatory (Ukraine) in cooperation with their colleagues from the ISON project (Russia), and was recently put into operation. The telescope is mounted at Mayaki station in suburb of Odessa. It is equipped with a focal corrector and a professional CCD camera. The telescope is used now for observations of geostationary objects, asteroids, and comets. In addition, this telescope can be used for the high precision photometric observations of faint objects up to 20^m.

Key words: small telescope construction, telescope design.

1. Introduction

By the 1980–90th the space telescope projects had started to play an increasingly important role, and they seemed to be the undoubted thing of the future (e. g. see the article of that time by member of Armenian National Academy of Sciences Grigor Gurzadyan, issued in the Literary Newspaper (Literaturnaya Gazeta) No. 18, the 4th of May 1988).

Nevertheless, in the mid of 90-s the IAU have registered all telescopes with primary mirror diameters of more than 6 m as a separate class of large telescopes. The construction and putting in operation large and very large telescopes enabled the ground-based astronomy to maintain its position and obtain a large amount of high-quality observational material. Keen competitiveness of large telescopes resulted in discontinuation of use of some telescopes with 1–2 m mirror diameter.

With a tremendous up-growth of the ground-based and space astronomy, small telescopes (conditionally those with primary mirrors of less than 1 m diameter) definitely succeeded in taking their niche. The absence of competition between different observational programmes, practically unlimited possibility to use the periods available for observations and low power inputs associated with operation of such instruments, made existing small telescopes irreplaceable in discovery and photometry of variable stars, discovery and astrometry of asteroids and cometary nuclei, observation of artificial satellites, and it is extremely important that with such telescopes regular monitoring of active satellites and passive orbiting fragments (space debris) in the geostationary orbit has been conducted.

The concept of a reflecting telescope with primary mirror diameter of 800 mm (OMT-800, i. e. Odessa Multifunctional Telescope) occurred to two co-authors of this paper while their participating in the KOLOS conference in Slovakia (at Vihorlat observatory) in the end of 2006. It took them several years to implement that concept – to design the telescope and its infrastructure, necessary for its operation. Despite huge problems associated with the construction of that instrument, we succeeded in building the telescope and putting it in operation at the end of 2012. That became feasible, primary, due to enthusiasm and self-sacrifice of some observatory staff members, who formed the so-called "gruppa vosmidesyatki", i. e. the 80-cm telescope group.

2. New OMT-800 in the International Scientific Optical Network (ISON)

In Russia, the ISON project (Scientific network of optical instruments for astrometric and photometric observations) is one of the main sources of information on the near-Earth space. There are 33 observatories in 14 countries in the world that are involved in observations of satellites, space debris objects and asteroids. Based on the data of the ISON, the problems of the near-Earth space hazards prediction are being solved within the framework of the Automated System on the near-Earth Space

Figure 1. OMT-800

Hazards Warning. As of today, the ISON measurements make up 97% of the total local data on high-orbit space objects and 85% of the data on asteroids. In 2012, more than 5.8 millions measurements were obtained for space objects (more than 15 million measurements have been collected over 6 years) and more than 140 thousands for asteroids (more than 300 thousands of measurements have been gathered since 2010).

The ISON surpasses the capability of the USA space control system by its parameters of geostationary orbit space monitoring as a larger number of objects are tracked with greater accuracy. The project is coordinated by the Keldysh Institute of Applied Mathematics of the Russian Academy of Science where the Centre for Man-made Space Debris Information Collection, Processing and Analysis was established, as well as the division of the ASSHW on the hazard monitoring of objects in the geostationary (GEO), highly elliptical (HEO) and medium-high Earth near-circular orbits.

New telescopes have been developed and manufactured (30 telescopes are installed at the involved observatories); the reconditioning and retrofitting of the outmoded facilities have been carried out, and more than 50 CCD cameras have been purchased to equip to working telescopes. The unified software systems for the telescope control and automatic processing of the CCD-frames of satellite and asteroid observations were developed, and they have been used at all the ISON observatories.

70 telescopes of the ISON are combined in five subsystems:

1. The search and survey subsystem of explorer telescopes (with apertures of 19.2–25 cm).

2. The subsystem of telescopes to monitor faint space debris fragments (with apertures of 40-80 cm).

3. The subsystem of telescopes to monitor the bright target satellites in the designated orbit (with apertures of 25-36 cm).

4. The subsystem of telescopes to detect asteroids and comets (with apertures of 40, 60 and 65 cm).

5. The subsystem of telescopes (with apertures from 40 cm to 2.6 m) for the photometric observations of the near-Earth approaching asteroids.

The ISON monitors about 1800 GEO objects, including 300 small-size space debris fragments and around 500 objects in the highly elliptical orbits. Unexpectedly, a significant number of GEO objects of a new class have been detected, such as those with high area-to-mass ratio that with time are to traverse highly elliptical and even lower Earth orbits. Due to the ISON activities six near-Earth approaching asteroids, three comets and more than 1500 asteroids of different types were discovered; the rotation periods of 14 asteroids were measured; two binary asteroids were discovered; the YORP-effect (Yarkovsky–O'Keefe–Radzievskii–Paddack effect) was successfully detected for three asteroids.

New telescope OMT-800 will be used in the ISON for the GEO monitoring, new asteroid search, as well as to provide useful astrometrical information about known asteroids and comets.

3. The optical layout

The main optical instruments and devices of the described telescope are manufactured in the optical workshop of the Astronomical Observatory of Odessa National University. The workshop is situated at the Observatory suburb station in Mayaki at the distance of about 40 km from the Odessa city. It was established as early as in 1971 for the planned at that time building a telescope with 1.5-meter mirror diameter according to the P. P. Argunov design. Unfortunately, it did not ever proceed to the construction of that telescope, but later a telescope with 1 meter mirror diameter was built under the mentioned design and installed in Slovakia in 2001 (Vihorlat observatory), and it has been still in operation.

There are three rooms with equipment in the above-mentioned workshop, a corridor for the knife-edge tests of optical instruments, as well as a separate room for the vacuum aluminizing of mirrors. There are ten optical machines, most of them were commercial non-sellers and were subsequently partly repaired and upgraded.

The edge-trimming and grinding-and-polishing machines KOS-750 and SP-700 can be used for large mirrors. The latter was considerably reworked so that it became possible to make mirrors with diameters larger than 700 mm and, what is crucial, to control the mirror shape just by placing mirrors into vertical position not taking them away from the machine.

The sital mirror blanks were purchased as early as the Soviet times, generally, from the Lytkarino Optical Glass Factory (Russia). In the late 70's our Astronomical observatory managed to purchase three off-the shelf mirror discs of 0.8-m diameter. That mirror size was in very short supply. Those mirror blanks were used to make mirrors for our telescopes mounted at Terskol peak, Northern Caucasus (the Cassegrain telescope), in Turkmenistan (the Ritchey–Chrétien telescope), and also a mirror for the telescope described in the present article.

We started to make the mirror for the described telescope (of the Ritchey–Chrétien design) in late 80's (for the other purposes at that time), but shortly after, the work was stopped. It was resumed only about twenty five years later under another programme, and for another optical layout, namely for prime focus with corrector.

The optical layout of the new telescope that was put in operation with a mirror diameter of 800 mm can be called a catadioptric plan anastigmat. When developing the layout, it was intended to have as wide angular filed of view as possible with 2-inch CCD with a good relative aperture. A rather high image quality across the whole filed of view was implied. We also made some additional requirements to ourselves.

The known arrangement of hyperbolic mirror with four-lens Wynne corrector (Wynne, 1949) was chosen as a prototype. The corrector with four lenses of the most common types of glass, which are easily available, showed quite good results only provided that the last element of length is small. That is why we had to secure that a camera with extremely small distance between the cover glass and the light-sensitive chip had to be used as a light sensor.

The layout with aspherical primary mirror and four-lens corrector has a rather adequate number of corrector parameters both to compensate most aberrations and to gain a series of extra properties. We managed to get not only a working value of aberration spot with the flat filed of view of 1.3°, but also the following: 1) two of four lenses can be stuck together with optical balsam; 2) the rearmost surface of the corrector is flat; 3) the curvature of non-adjacent surfaces of two lenses is the same. Extra properties were necessary, in particular, to reduce the number of trial lenses to control the surface shape. Those lenses were manufactured at the factory of special instrumentation "Arsenal" (Kiev, Ukraine).

When checking each next manufactured lens, the inevitable inaccuracy of the lens thickness was obtained. The layout was optimised according to the actual situation with thickness of unmanufactured lenses and air gaps varying. Though a slight deterioration of the result ensued from each variation, the final set of the telescope design values remained quite good. Such methods are called "optical maintenance", they promptly facilitate the manufacturing of unique optical sets.

At first, we intended to install a flat mirror next to the primary one to shorten the tube, and such mirror was manufactured. But due to the reasons of minimization of optical surfaces number we refused to use this flat mirror afterwards.

In accordance with the new decision, it was necessary to lighten the telescope tube as the supporting mounting APT-6 (astronomical parallactic tripod of type 6) operates at the breaking point.

The basic parameters of the telescope are as follows: the entrance pupil, focal ratio, total length of the telescope optic layout, field of view and spectral range. The design values are surface curvature, air gaps and lens thickness, refractive and asphericity indices. The image quality for large- and medium-size non-visual telescopes can be adequately represented by dot charts.

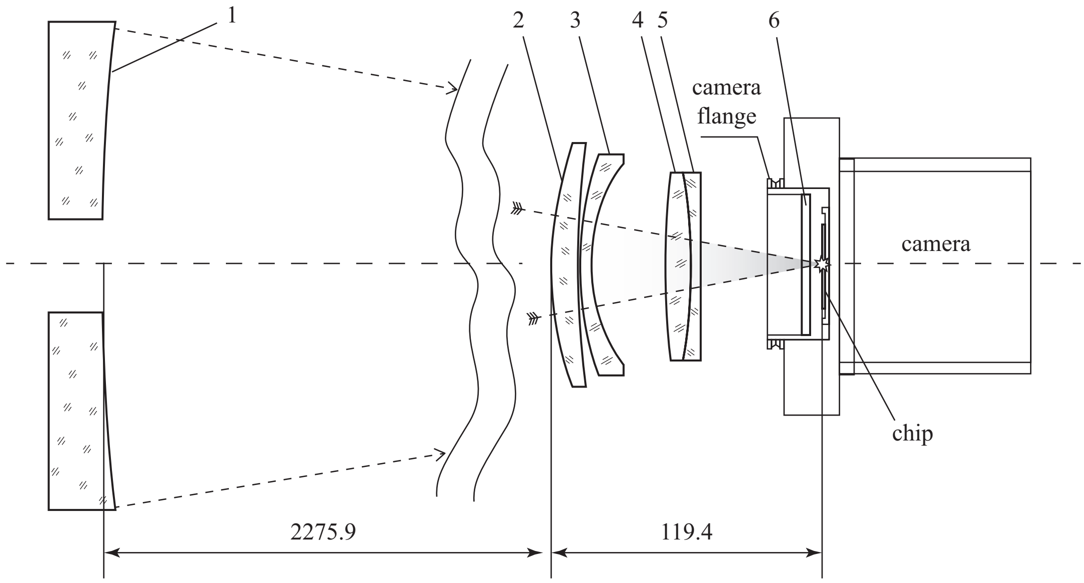

Figure 3.1. Catadioprtic scheme with corrector (see numeration in Table 3.1).

Table 3.1. Optical characteristics of the constructive elements of OMT-800.

#	*detail*	*surface curvature radius*	*next surface distance*	*eccentricity square*	*type of glass*	*diameter of detail*
1	main mirror	–4796.35	–2275.90	+1.1986	LK5	800
2	first lens	–135.52	–11.54	0.0	K8	98.4
		–498.90	–0.10	0.0		
3	second lens	–135.52	–7.29	0.0	K8	90.2
		–66.76	–30.20	0.0		
4	third lens	–219.95	–10.00	0.0	K8	74.8
		+219.95	0.0 (glued surfaces)	0.0		
5	fourth lens	+219.95	–3.00	0.0	F1	74.8
		∞	–48.70	0.0		
6	protective glass of the CCD		–3.20	0.0	quartz	60
7			S′=–5.334	0.0		

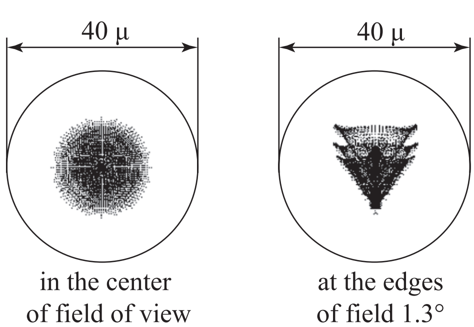

Figure 3.2. Estimated image quality for catadioprtic scheme with corrector.

We provide the optical layout, measured design values, as well as estimated dot charts of our telescope optics (Fig. 3.1, Fig. 3.2 and Table 3.1).

As is seen, the stellar images corresponding to one pixel of the astronomical camera might be expected across the whole field of view.

Actual image quality as for all other telescopes, by the way, will yield to the estimated quality due to deflections, manufacture inaccuracy, alignment, focusing, sideral tracking, as well as the limb effect, atmospheric turbulence, etc. The focal surface of the telescope is flat. The distortion is the only essential aberration. It reaches 7.25% at the edges of the field of view.

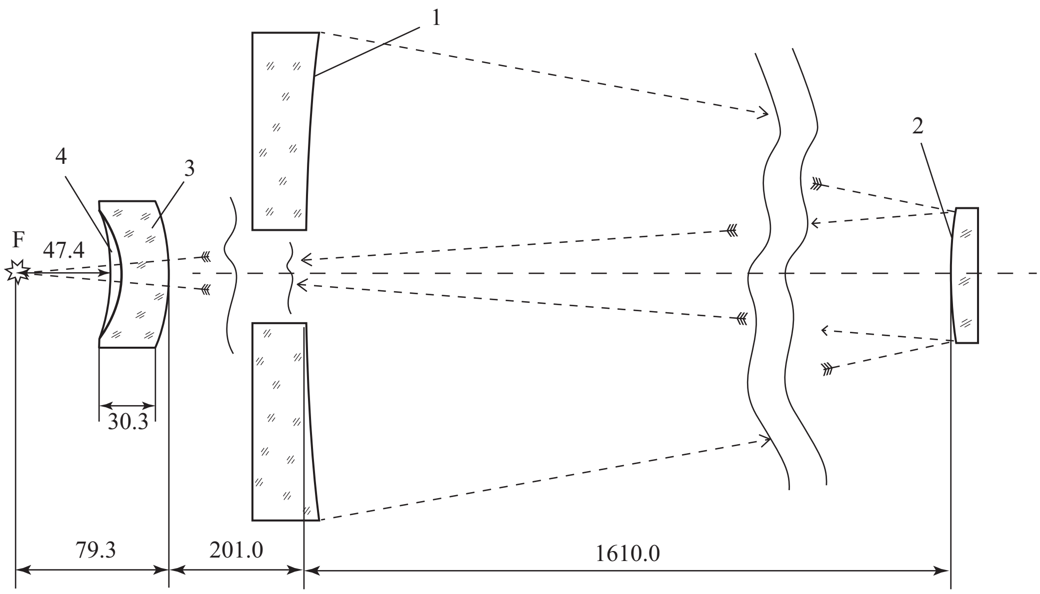

Figure 3.3. Optical layout for alternative two-mirror scheme (see numeration in Table 3.2).

Table 3.2. Optical characteristics of the constructive elements for the alternative scheme.

#	detail	surface curvature radius	next surface distance	eccentricity square	type of glass	diameter of detail
1	main mirror	–4796.35	–1610.00	+1.1986	LK5	800
2	secondary mirror	–2700.00	+1811.00	+8.8980	LK5	270
3	first lens	+103.60	+25.00	0.0	F1	80
		+58.37	0.0 (glued surfaces)	0.0		
4	second lens	+58.37	–7.00	0.0	K8	80
5		+103.60	S'=+47.50	0.0		

As the primary mirror of our telescope is a hyperboloid, and moreover, it has a central opening, we manufactured additional second convex mirror to have an alternative optical layout similar to the Ritchey–Chrétien design in case of any possible future changes in the observation programme. The alternative optical layout expanded with special field-flattener lens that also corrects astigmatism, and scarcely causes chromatic aberrations, (according to the estimated dot charts) will allow to obtain very high-quality image, higher relative aperture (for such type of layouts) A = 1:6.4 and relatively wide field of view $2w = 0.66°$ deg or 58.9 mm in diameter. The total length of the telescope optic layout L = 1890.5 mm (see Fig. 3.3). The spectral range of achromatisation is still the same, i. e. $\lambda = 0.486 \div 0.820$ μm. Fig. 3.3, Fig. 3.4 and Table 3.2 explain alternative scheme.

As is seen, the estimated aberration images do not exceed 10 micrometers. The distortion at the edges of the field of view is just 0.23%.

While polishing the primary mirror, its shape was controlled by the Maksutov compensation scheme (Maksutov, 1948) with a spherical auxiliary mirror of 320 mm diameter and a flat diagonal mirror to shift the auto-collimation point to the Foucault knife. The asphérization was executed by the method of almost critical overhanging of the polisher sideways at minimum crank velocity and relatively high spindle velocity. It took almost six months to manufacture the mirror.

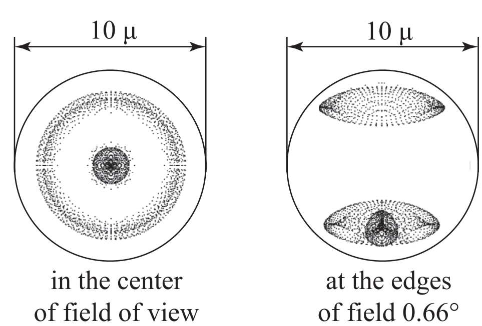

Figure 3.4. Expected image quality for alternative two-mirror scheme.

Table 3.3. The main characteristics of OMT-800

Main mirror diameter, *mm*	800
Telescope effective diameter, *mm*	755
Telescope total optical length, *mm*	2395.3
Telescope effective focal length, *mm*	2134.3
Focal ratio	1:2.67
Mass of main mirror, *kg*	75
Focal length of main mirror at apex, *mm*	2398.2
Main mirror eccentricity square	1.1986
Max deviation of main mirror from the ideal surface, *nm*	60
Linear diameter of the field, *mm*	49.14
Angular diameter of the field, *arc min*	78
Spectral range of achromatization, *nm*	486–820

While manufacturing lenses, the most intricate problem was to adjust radii without sagging of the lens thickness as such adjustment was made with glass grinders that do not keep their curvature. The first results, obtained with our telescope, show an expected image quality.

The main characteristics of OMT-800 are listed in Table 3.3. More detailed information about optical layout can be found in Fashchevsky (2011) and Michelson (1976).

4. Telescope mechanics

A modern telescope is an integrated complex that contains optical components, mechanical assemblies, systems for their control and monitoring, as well as system of recording and pre-processing of optical data.

Correct operation and interaction between any component and all the others are crucial for the whole system performance and successful resolving of the set observation tasks.

Generally, when commencing the telescope design work, the tasks that should be solved with this instrument and relative requirements for all system components are defined. However, it is not always the case. When building OMT-800, we had to proceed, first of all, from our technological capabilities and financial resources.

Though the concept of such an instrument with the primary mirror diameter of about 1 meter was discussed by Odessa engineers several decades ago (and there was a considerable background for that, since comprehensive experience in manufacturing of rather large-size astronomical optics existed as the whole department for instrument making, headed at that time by L. S. Paulin; and there was an availability of suitable optical blanks, required equipment, instruments and materials), only 4 such instruments were manufactured for the whole period. Two reflectors with a 0.8 m primary mirror diameter were installed in Turkmenistan (on the Mt. Dushak-Erekdag) and in the Caucasian mountains (Terskol Peak); one reflector with the primary mirror diameter of 1 m was installed in Slovakia, and one reflecting telescope with a 0.6 m primary mirror diameter – at the observation station in Mayaki. It should be noted that the control of those reflectors demanded great efforts and that rendered the work of observers hard.

One of the basic features that could distinguish OMT-800 from all previous telescopes with mirrors of similar diameters was to manufacture a modern automatic telescope that could make observations not only useful from the astronomical standpoint, but a pleasant occupation. Such reflector was aimed to solve the set of tasks at a qualitatively new level. It was those conditions that determined basic requirements for mechanics and control system.

First, several alternate solutions of the task were suggested. But we proceeded primarily from our capabilities. There was a factory-made telescope mount APT-6 (astronomical parallactic tripod, manufactured by Leningrad Optical Mechanical Association) available; it remained after disassembly of the time-expired Seven-camera astrograph at Mayaki observation station, which should be thoroughly remodelled to become a basis for building an automatic telescope. The operational experience of our reflecting telescope with 800 mm diameter of the mirror with such mount, installed in Turkmenistan, showed that such a combination enabled to solve some observation tasks, but the load of the telescope mount was provided to be limit in so doing. The telescope automation inevitably demands large reworking of APT-6 as the stiffness, accuracy and the limit torque requirements are much tighter in that case. APT-6 has a 360 tooth precision worm gear pair in the polar axle for the sideral tracking. That worm gear pair was retained after rework and has been used to control telescope's motion relative to that axle. The axle itself is in a rather strong mount, and it required relatively small reworks. Nevertheless, for many years of the previous exploitation of APT-6 its bearings and some components were notably threadbare and needed replacing or reworking. We removed all unnecessary components related to the manual control and provided for the possibility of obligatory installation of the angular displacement sensor. We made necessary adjustment, repaired the angle of altitude and azimuth control mechanisms.

But the key work that had to be done was the modernization of the declination axle. First of all, the existing axle did not provide the required stiffness. Careful examination of the design let find reserves for an increase in rigidness. Besides, it was necessary to design, manufacture and install a warm gear pair in the axle not decreasing the stiffness that is already limit enough,

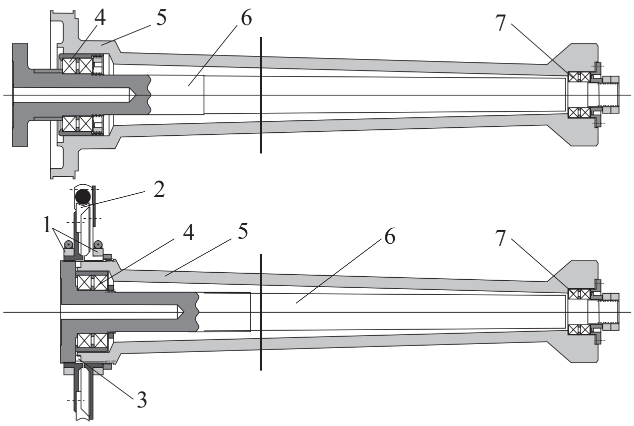

Figure 4.1. The declination axle arrangement before (upper figure) and after (lower figure) reconstruction. reconstruction.

1 – friction clutch couplings, 2 – the worm gear pair, 3 – the front thrust bearing, 4 – the front radial bearing assembly, 5 – the axle housing, 6 – the declination axle, 7 – the rear radial thrust bearing assembly.

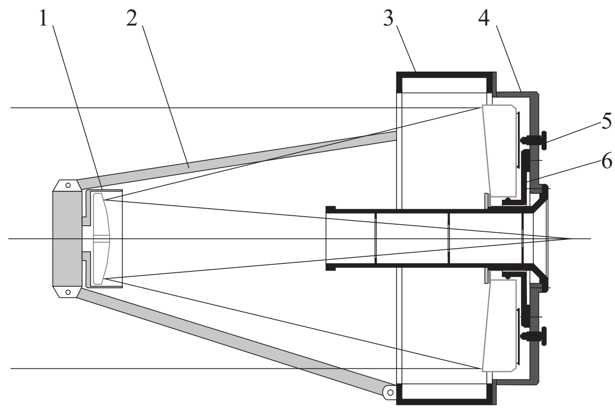

Figure 4.2. The design of the first version of the telescope tube.

1 – the secondary mirror assembly, 2 – support fork arms, 3 – hexagon declination-box frame, 4 – the primary mirror support cell, 5 – supportmechanisms, 6 – the central pivot.

to find place for the declination motor and angular displacement sensor, as well as to provide for proper and reliable joint between the telescope mount and tube; and also to manufacture a new precision friction brake and provide necessary alignment of the worm-gear.

The declination axle arrangement before reconstruction is shown in the upper part of Fig. 4.1, and the result of modernization is shown in its bottom part. It is seen how the design changed and due to what its stiffness increased. The axle became shorter, its overhang from the support bearings became minimum, and at that the flexure deformations are immediately transmitted through the front thrust bearing to the axle body and due to that they are decreased considerably. Being modernised, the centre of mass of the telescope tube can be brought much closer to the axle body that will undoubtedly improve the operating conditions for the mount and considerably decrease quantity and mass of the counterweights and, therefore, the total load and the moment of inertia. The friction gears enable to disconnect the worm gear pair from the axle if necessary and to install it in any convenient position, and due to their specific design they provide additional stiffness. A 300 tooth worm-wheel and worm gear with the same module as that one in the declination axle were available, but required some improvement. After manufacture and assembly that pair was aligned and seated. That procedure shall be regularly repeated to ensure the final adjustment of the worm gear pair.

Using specific couplings in the worm gear drive we installed stepper motors with 200 steps per revolution and 64 microsteps per full step operating at up to 2.8 A, which provide maximum pointing speed of up to 1 degree per second. That ensures the required drive rate, as well as fair accuracy of telescope's pointing to an object. As a result, we obtain a German type parallactic mount with new capabilities, which enables to arrange observations more effectively and to improve the telescope efficiency considerably.

It should be noted that all that hard work on modernization of the mount was done with the only available 1K62 lathe that was far from being new, and for which the machining of components with such dimensions was virtually beyond its capabilities. However, some ingenuity, as well as manufacture of necessary additional auxiliaries eventually let machine the axle, mount body, worm-wheel and friction gears with required accuracy.

The next essential component of the reflector mechanics is the tube. There are a lot of requirements imposed upon it, and those are sometimes mutually exclusive. The tube must secure proper and stable mutual arrangement of optical elements, minimise their inevitable deformations or, if possible, compensate them, enable to perform accurate alignment and focusing of optics within the required limits, and provide specified temperature and humidity conditions. The tube is also aimed to compensate adverse temperature effects, to protect optics against extrinsic interference, polluting light that interferes with the telescope viewing. When manufacturing the tube, it is necessary to provide the possibility to mount accessories on it, as well as to ensure the feasibility of balancing with minimum additional counterweights. And in spite of all that, the tube must be lightweight, high-strength and rigid. And that is far from being a complete list of requirements.

When manufacturing the tube in accordance with the above-indicated requirements, some errors are likely to occur. The first version of the tube design for the described instrument turned out to be faulty, though it was that variant (see Fig. 4.2), which was implemented in manufacturing of our telescope, installed in Turkmenistan.

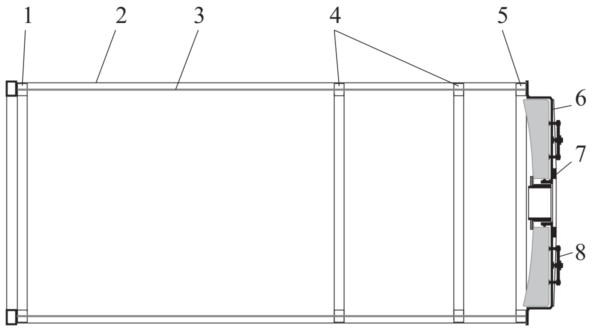

Figure 4.3. The design of the second version of the telescope tube.

1 – the front mounting ring, 2 – the covering shroud, 3 – longitudinal braces, 4 – the declination-box frame, 5 – the rear mounting ring, 6 – the mirror support cell, 7 – the central ball-bearing support, 8 – the support and collimation mechanisms.

Such design includes three fork (three-“feather”) arms that must support the secondary mirror assembly, a hexagon girder declination-box frame, welded dish-shaped primary mirror support cell with load bearings support mechanisms, the central pivot and the light detector mounting assembly at the rear. It was expected that when using corrector instead of secondary hyperbolic mirror, a flat mirror will be installed in its place to let the light passed through the corrector to reach the CCD camera inside the tube. Later, it turned out that despite apparent simplicity and usability of such an arrangement it has a lot of grave disadvantages. The main objections are excessive weight due to ineffective masses of metal and relatively far distance between the optical axis and the mount body that causes a considerable increase in counterweight, the moment of inertia, total load of the mount and control system.

Instead of that a design of solid tube containing thin (of 1 mm thickness) steel shroud with two mounting rings and distance pieces between them in the middle section of the tube and the similar rings at its ends. A holder, where the alignment and focusing mechanism, corrector and the CCD camera are installed, is attached to the front ring with support vanes. The mirror support cell is fixed on the rear ring. The whole construction is tightened with six longitudinal braces and is prestressed, and that considerably decreases the flexure deformation and improves the overall strength. Such a design has been used in telescopes, manufactured by our observatory specialists, more than once and proved to perform well. The primary mirror cell remained the same, but it was machined on a large lathe with ineffective excess metal removed. In accordance with the new design the support and collimation mechanisms were made. The central ball-bearing support was installed. To attach the tube to the declination axle, a special cradle and a thin-walled band clamp were manufactured from a part of remained hexagon declination-box frame. The tube proved to be very strong, light with reliable protection of optics and compliant with main requirements (see Fig. 4.3).

Nevertheless, when manufacturing the tube of the second design we did not take into account the fact that the tube of such design should have a significant windage, which will have significant impact on the observations because of absence of the dome. That is why it was decided to leave the middle and rear sections of the tube unmodified, and to rework the front section (approximately 2/3 of tube length), to the lattice truss made from concurrently as thin as possible and durable bars strengthened with braces. That is how the final design of the tube eventually was worked out (see Fig. 4.4).

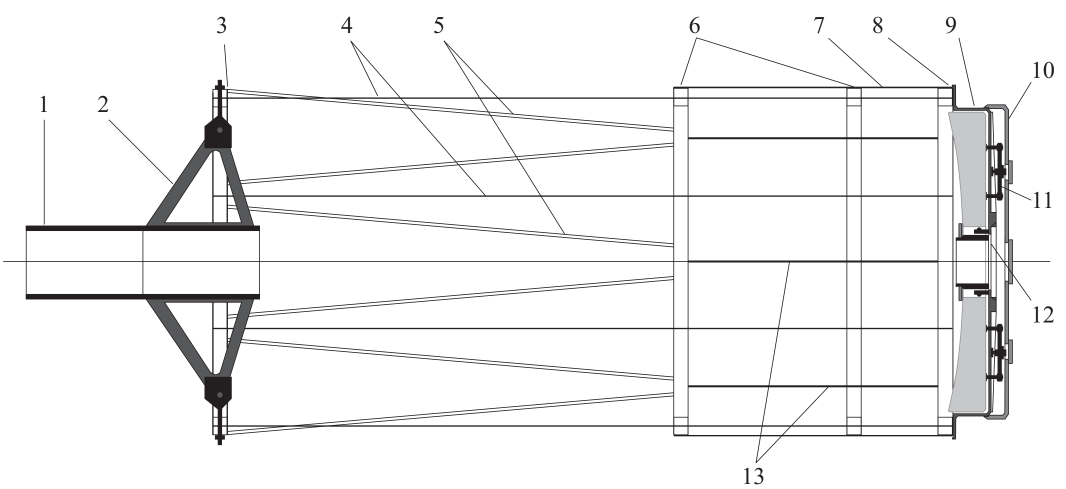

Figure 4.4. The design of the final version of the telescope tube.

1 – the central holder, 2 – support vanes, 3 – the front mounting ring, 4 – longitudinal braces, 5 – components of the front truss, 6 – the declination-box frame, 7 – the covering shroud, 8 – the rear mounting ring, 9 – the primary mirror support cell, 10 – the protective cap, 11 – the support and collimation mechanisms, 12 – the central ball-bearing support, 13 – inner distance pieces.

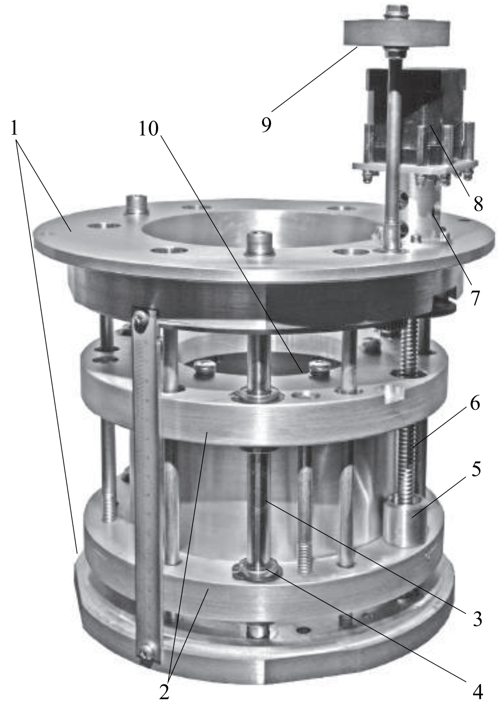

Figure 4.5. Focusing mechanism.

The large-aperture telescope requires quite frequent and precise focusing procedure. For this aim we developed and manufactured the focuser of our own original design. A general view of this focuser is shown in Fig. 4.5. For the better visibility of details we give its image as it looked before painting. Focuser provides very precise linear movement of its movable part 2 relatively to its fixed part 1. Movement is provided by three pairs of linear motion bearings 4, rigidly coupled to the movable part on the three precisely fixed guides 3, which in turn are rigidly coupled to the fixed part 1. The motion can be achieved either by the rotation of the handle 9, or the by the stepper motor 8 related to the screw drive via zero-backlash flexible coupling 7. Screw 6 is mounted on the fixed part of the focuser between the two angular contact ball bearings with adjustable buttress screw. Ball screw nut 5 is mounted on the moving part of the focuser. Both together screw and nut form precise ball-screw pair (made by Hiwin, http://hiwin.com) with a step of 2.5 mm per turn. Flange 10 of the moving part is used to attach corrector to the camera FLI ML9000.

Remotely operated focusing mechanism, including the lens corrector, adapter flange of the CCD camera and the CCD camera itself, is installed in the central holder. The alignment mechanisms are placed on the outer surface. The arrangement allows for temperature regulation and drying-out when the humidity is excessive. The holder being two-point fixed to the support vanes is four-point attached to the front mounting ring with four support vanes. Such an arrangement distinctly stabilises its centred position, although slightly worsens the diffraction pattern. Thin (15x15 mm) standard hollow bars that form a truss similar to the Serrurier truss are welded in six points to the front mounting ring and to the first ring of the central section of the tube. The central section of the tube is clamped with a thin (1 mm) band and special cradle that secure the tube's attachment to the declination axle with very slight deformations, as well as provide for adjustment of the position of its centre of gravity relative to the axle that is useful when the preliminary balancing is performed. The end rear ring holds the primary mirror cell, which is bolted on the inside of the tube. The mirror held in support cell is mounted on the central ball-bearing support that provides the lateral support and the mirror's tilting not changing the required centred position. To provide the longitudinal support, the Grebb classical nine-point support system is used with arrangement of mechanisms, which also allow for adjustment to the collimation, on the outer side of the cell. The support cell is equipped with the mirror temperature offset and ventilation system. A light rear cap protects the supports and the mirror and makes the manual control of the telescope easier that is crucial in case of emergency.

The complete telescope general arrangement is presented in Fig. 1.

5. Electric and electronics of OMT-800

The power supply for all telescope systems is provided by four switching power supply units, placed in the IP54 damp-proof and dustproof power distribution electroassembly box, mounted on the telescope column. All cables enter the power distribution box through the cable glands not damaging its leak-tightness. To maintain the temperatures permissible by manufacturers of the power supply units and the telescope control system, as well as to avoid condensation, a 50 W heating element and the regulation relay that automatically switches it on at temperature below +10°C are installed in the power distribution box.

A&I GoTo System controller (http://gotosystem.xm4.ru) is selected as the telescope control system. That controller uses common control protocol compatible with the Synta EQ-6 mount control protocol. The controller software is compatible with the ASCOM standard; hence, the telescope control can be carried out by any ASCOM-compatible software.

Further to our request, the following modifications of the off-the-shelf controller were designed:

1. Heavy-duty control switches for the stepper motor windings were installed.

2. The Trimble Copernicus II GPS receiver module that differs from the standard one in availability of two serial ports and the high-accuracy pulse per second output was installed. One serial port of the GPS module is connected to the telescope control processor to assign the observation point position and accurate time; the

second serial port is connected to the control workstation to provide the NTP-server functioning. The pulse per second is used to the precise synchronization of the CCD-camera shutter.

3. The controller is equipped with emergency contacts allowing of development of the system of telescope emergency stop on the occurrence of different events associated with the tube orientation or dangerous proximity of the camera to various objects without losing orientation of the tube axes. Such a system is currently being developed on the basis of ultrasonic sensors.

4. Taking into account the great weight of the telescope, the controller firmware has been modified to provide a smoother acceleration and deceleration of axial motors.

The telescope management controller operates two Trinamic QSH6018-86-28-310 two-phase hybrid motors. Those stepper motors were optimized to achieve the microstepping mode. The step angle of the motor is 1.8°. The maximum torque is 3.1 nm. The motors have standard NEMA23 flange that enables to easily replace the telescope control system with another one, for instance, with the DC motor control system, just by changing the stepper motors and telescope controller.

The focusing mechanism is controlled by the ASCOM-compatible Colibri focus controller (http://goto-system.xm4.ru/astrokinethic _ fokuser _ kolibri) that was modified just by repacking in the IP54 case. The controller operates Trinamic QSH4218-51-10-049 focusing stepper motor (with the step angle of 1.8°, the torque of 0.49 nm and NEMA17 flange). The stepper motor functions in the microstepping mode at 1/16 stepping and rotates the screw of the ball screw assembly with the thread pitch of 2.5 mm. Thus, one microstep of the focuser stepper motor corresponds to the linear displacement of 0.781 µm. The temperature sensor is connected to the focuser controller, and on having correspondingly configured the focus controller, it allows of automatically readjusting the focus when the tube temperature changes. The parameters of the automatic thermal tuning of the focus are empirically determined following several estimations of the focuser best position at different temperatures.

The power supply for all telescope systems is provided by four power supply units, installed in the power distribution box. The functionality, marking and peak current for each power supply unit are given in Table 5.1. It should be noted that the peak voltage available on the telescope tube is 12 V. Therefore, the telescope is accident-proof in terms of electrical safety.

There are three emergency buttons mounted on the telescope column, beside the outer door of the pavilion, and on the operator workplace. Pressing of any of those buttons, results in immediate breaking power supply to the power distribution box of the telescope. Therefore, in case when immediate emergency stop of the motion of the telescope or any other device is needed, the observer can promptly perform such a stop staying in the control room or in the pavilion.

The IP video camera Axis 206, whose image is displayed on one of the operator's monitors, is installed in the pavilion with the aim to visually survey the telescope motion when pointing. While pointing, switching on the spotlight in the pavilion from the control room is provided.

On the assumption that most telescope movements are to be not controlled by an operator, we pay particular attention to the cable that is laying from the fixed column to the tube of the telescope and to the further cable routing through the telescope tube, so that the snagging and damage of the cables are avoided (Fig. 5.1). To ensure safety of the cables, the declination axes and two cable masts were manufactured and installed on the declination axis body and on the telescope tube mounting assembly, respectively. Six Lapp SILVYN FD-PU flexible tubings, that are resistant to mechanical damage and keep flexibility within a wide temperature range, were laid between the cable mast of the declination axis body and the column, as well as between the telescope tube cable mast and the declination axis body. Those tubings are connected to each other by the line connectors that integrate them in the united flexible flat cable trunk. It

Table 5.1. Power supply characteristics.

Marking	*Power supply unit, current, type*	*Using equipment*
24V	24V, 12A, switching	A&I GoTo System telescope management controller.
12V-S	12V, 12.5A, switching	Camera FLI ML09000, meteor camera, Colibri focusing controller.
12V-U	12V, 20A, switching	Devices for heating the tube, focuser, telescope finder and guiding telescope, as well as for the primary mirror cooling.
5V	5V, 10A, switching	USB concentrators, lighting of the filed of view of finderscopes.

Table 5.2. Cable characteristics.

Cable line	*Functionality*	*Cable type*	*Quantity*
1	Power supplies	Lapp Ölflex FD 855 P 7G2.5	1
2	Signal lines	Lapp Ölflex FD 855 P 25G0.5	1
3	Operation of the declination motor	Lapp Ölflex FD 855 CP 4G1	1
4	Coaxial video cables	TASKER RG58PUR	6
5	Ethernet cables	Molex PCD-00183-0E	6
6	USB 2.0 cables	Belkin F3U154CP4.8M	2

is possible to replace any group of cables without disconnection or disassembling of other cables. The functionality and quantity of cables in each tubing are given in Table 5.2.

Continuous-flex cables, designed for moving applications down to –25°C, are used for flexible cable trunks. Power cables, signal line cables, as well as shielded cables for declination motor control on the side of the column, and on the side of the tube are terminated with high-quality industrial EPIC® connectors, produced by Lapp Group. The coaxial cables on the side of the column and on the side of the tube are terminated with BNC connectors. The Ethernet cable lines are terminated with RJ-45 connection modules.

Two plastic tubes with junction boxes in the middle and at their heads are laid along the telescope tube for cabling. Cable glands are fitted in those boxes to feed the cables through to connect to the devices as required. Therefore, the cable trunks have a level of dust and humidity protection not less than IP54.

The larger the telescope size is, the oftener the limitation of the USB cable length, which can not exceed 5 m as per specification limits, causes inconvenience at the designing stage. There are USB active extension cables available in the market, but, generally, most of them are of poor quality, and their lengths do not exceed 10 meters. Hence, it was decided to omit USB active extension cables, and to use USB concentrators with cables not longer than 5 meters between them. We also considered the limit for the number of USB concentrators to be not more than 5 units per chain. The USB concentrators' layout and the lengths of cables between them are given in Fig. 5.2. As a result, we are enabled to connect the USB 2.0 devices to the telescope wherever possible using short cables.

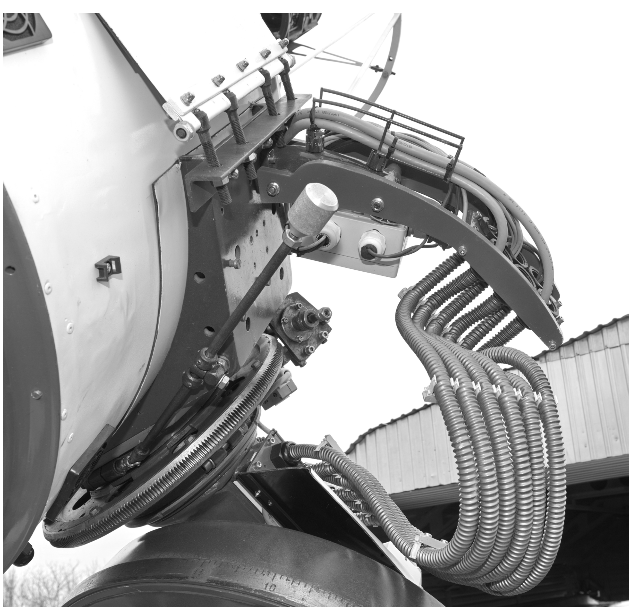

Figure 5.1. Cable-main at the telescope mounting.

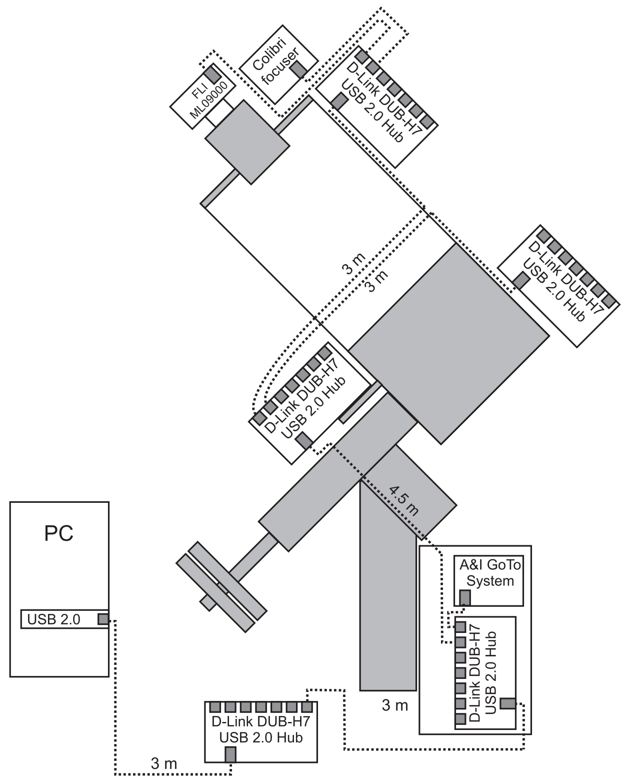

Figure 5.2. Architecture of the USB network of OMT-800.

When designing our telescope, we paid an attention to the heating-up of the optics to prevent condensation and freezing problems. The 18W self-adhesive film heating elements connected to 12V power supply were used for optics heating. There are six heating elements mounted inside the tube near the mirror cell: two of them were mounted inside the outer housing of the focusing sleeve, and one each — on the dew caps of the guiding telescope and finders.

Taking into account a considerable mass of the telescope primary mirror, to equalise the primary mirror temperature to ambient temperature, six fans were mounted on the rear cover of the mirror cell and six fans were placed within the lateral surface of the pipe for blower cooling of the primary mirror. The fans of 80 mm in diameter have replaceable filters that prevent ingress of dust to the telescope tube. The blowing and heating are controlled by the blowing and heating control console mounted on the mirror cell of the telescope.

Telescope is operated from the control room, which is located next to the pavilion of telescope. USB network of telescope is connected to the only one USB 2.0 port of managing workstation HP Compaq 6000Pro. There is also output of GPS receiver connected to RS-232 port of this workstation providing operation of the NTP server.

6. Optical adjustment procedure of OMT-800

Telescopes rarely achieve the image quality that is accomplished "on paper". When computing, it is assumed by default that all optical components are coaxial and mutually distant in a quite definite manner. However, in fact, the main optical axes are rather speculative, and their actual adjustment is not controlled; meanwhile, long typical length of a telescope's body tube makes it difficult to align the optical components with adequate accuracy.

There are certain methods to optimise the image quality, which depends on optical adjustment of a telescope. The procedure consists of such shifts and tilts of the components that must result in the image enhancement. The sequence of operations depends on the specific optical circuit and methods applied by a technician.

Theoretically, each optical component of the axisymmetric telescope optics should be five-degrees-of-freedom aligned. Our telescope consists of six components: the primary mirror, four internal lenses, assembled in the corrector's body and CCD camera. There is a good reason to suppose that this body was likely to be constructed rather efficiently, providing proper mutual arrangement of lenses, therefore it can be suggested to assemble them as an integral block. Besides, the mirror, which is fixed by axial and lateral supports, is generally not allowed of any linear shift. Hence, the number of possible angular and axial adjustments can be rather small, i.e. the adjustment (centring and focusing) of our telescope should not be technically intricate to perform.

Though the above-mentioned corrector lenses assembly is placed very near to the telescope's focus, the angular and lateral misalignment of the components manifests itself mainly as the decentring coma, i.e. comatic aberration that seriously damages the quality of images. On the sky snapshots, obtained under these conditions, the stellar images are blurred and wedge-shaped, even in the centre of the field.

Just a 10 mm parallel shift of any component relative to another one across the principal optical axis results in inadmissible aberration spot expansion up to 0.2 mm. A shift up to 1 mm can be considered not hazardous as such the aberration spot does not yet exceed the dimensions of one pixel.

Parallel misalignment of the mirror and the corrector axes also adds to a certain lateral shift, by so doing summing up the damage from both types of decentring. Mutual tilting of axes of our telescope is not critical unless the tilt exceeds 1.5 arc minutes. It is difficult to provide such order of accuracy of centring.

The situation can be saved by counterdecentring, i.e. by counterbalancing the mutual tilted axes with lateral shift of components in the opposite direction. In that case, both decentring comas are differently directed, and they compensate each other to a great extent. For instance, with the tilt of axes of a quarter of a degree, the counterdecentring lateral shift by 10 mm results in a quite adequate aberration spot of average diameter of about 0.015 mm. Although, in so doing, the centre of the filed and the centre of the best images diverge by about the same 10 mm as mentioned above, the radial symmetry of the spots dimensions relative to those centres is broken, and there is some inclination of the focal surface to the light detector plane occurred. All that could be neglected, but it should be taken into account. Thus, examining the shape and size of the star image on the monitor allows of possible more or less adequate centring the telescope.

However, at the very beginning of adjustment procedure, the instrument tends to be poorly adjusted and its star-image-wise centring is not efficient due to very strong coma. That is why the first-approximation centring is carried out by indirect methods, which are described below.

Other considerations on the tolerances are as follows:

1. Inaccuracy in the distance between the lenses, as well as in the distance between the lens assembly and the mirror and (or) light detector generally results in the increase of spherical aberration – the star images enlarge, and fringes around bright stars' images or the ring-shaped images of dim stars on the monitor screen are clear evidences of such aberration.

2. Inaccuracy in measuring the thickness of lenses increases the chromatic aberration substantially. Such aberration is clearly seen on the RGB monitor, and on the monochrome monitor the edges of starspots are blurred with fringes noticeable around. At the periphery of the filed starspots are oblong in the radial direction due to the lateral chromatic aberration.

As the lens thicknesses and distances between them in the assembled corrector do not vary, all such failures are on the manufacturers' conscience. In our telescope the rear element of length, i.e. the distance between the rearmost surface of the fourth lens and the camera, is fixed. It is only the air gap between the mirror and the first lens, which is still within a technician's power to fix. The focusing is carried out by adjusting that distance.

To make the initial centring of corrector accurate and reliable, it is possible to use the concave mirror attached and clamped to the corrector's body (Fig. 6.1). The wedge angle of that mirror should be corrected during the manufacturing process, and the mirror's curvature should be such as with ideal telescope focusing and centring its centre coincides the centre of curvature of the primary mirror.

Let us fix our light source in the point of convergence, i. e. the centre of curvature C of the primary mirror 2. If the mirror and corrector axes are not parallel to each other, then the adjustment mirror will reflect that light source in some point 4 as another spot of light on the screen. Should our corrector be turned around using the adjustment devices so that the spot of light 4 would also converge to point C, then the corrector is to be equally

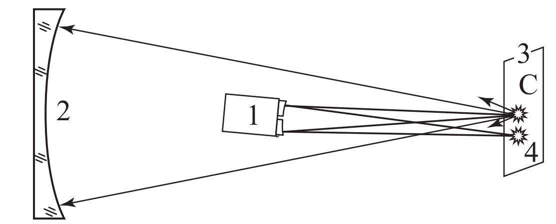

Fig. 6.1. Explanation of the procedure of initial centring of the corrector.

1 – corrector and temporarily attached adjustment mirror assembly; 2 – primary mirror of the telescope; C – centre of curvature of the primary mirror, which can be found by the Foucault knife-edge test or by convergence of some light source with the spot of light reflected by that mirror. The light either a knife source per se is edge or a torch bulb or at least a light-emitting diode or even a laser pointer. The reflected spot of light can be observed on screen 3.

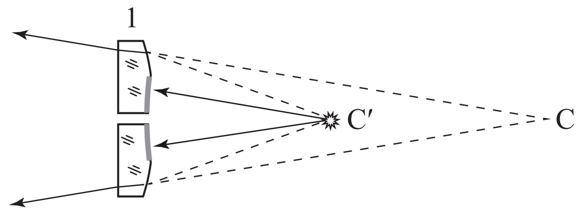

Fig. 6.2. Virtual image of the centre of curvature C.

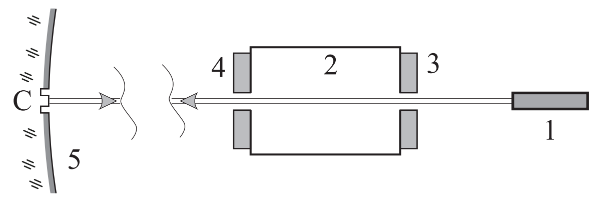

Figure 6.3. Adjustment procedure.

1 – laser collimator; 2 – corrector's body; 3, 4 – covers; 5 – primary mirror.

centred (but only in the first approximation). Using the Foucault knife edge as a light source, the telescope can be also focused and rather accurately at that.

As the centre of curvature of the primary mirror is at a distance equal to two focal lengths from the latter, then point C can be inaccessible in the small-size observation pavilion. In that case, the adjustment reflecting surface can be figured in the centre of the convex lens 1 (Fig. 6.2), clamped to the corrector's body. The lens will make the virtual image of the centre of curvature C appear closer to the corrector, and the above-described procedure can be carried out using near point C′ to place a light source.

However, in this case, it is impossible to focus the telescope adequately by the Foucault knife-edge as the light beam from the light source on having passed through the adjustment lens and the block of corrector lenses, being reflected back by the primary mirror and then again passing through the same lenses, will acquire severe spherical aberration.

The primary mirror of our telescope has an axial hole that is absolutely unnecessary for the prime focus design, but it can be used in the alternative optical system of the two-mirror Ritchey–Chrétien design. It is not assured that the hole's axis coincides with the principal axis of the aspherical reflecting surface, and that to some extent deprives reasonableness of the above-mentioned initial adjustment methods.

If the mirror was monolithic, its geometric centre should be marked (supposing that centre coincides with the pole of the aspherical surface C, it can not be otherwise when manufactured competently). It is possible to do as early as on the machine tool, for example, in the form of the ring flute of a tubular drill.

The centring is carried out with a narrow bunch of beams from the laser collimator 1 (Fig. 6.3). Covers 3 and 4 with narrow openings in their centres are clamped to open ends of the corrector's body 2 (with all its integral parts). It is not difficult to mechanically achieve that the openings are aligned exactly along the body axis. By admitting the light beam through those openings, the corrector is oriented so that the light rays arrive to the geometric centre C of the primary mirror 5 marked with a groove. By tilting the primary mirror, it is provided that the reflected light beam passes the same openings on its way back. Such adjustment is more rigorous, although it is likely to be less accurate.

7. OMT-800 control system software and image analysis pipeline

The present OMT-800 *telescope control system* (TCS) software is built around the CHAOS package. CHAOS is an integrated framework for controlling the various astronomical instrumentation, including robotic mounts and domes, charge-coupled device (CCD) cameras, and filter wheels. Its major focus is on accurate timing which is essential for observations of fast-moving objects like near-Earth asteroids (NEAs), space debris, and other rapid transient phenomena like gamma-ray burst (GRB) afterglows or exoplanet transits. CHAOS is designed for maximum flexibility in working with different types of objects and observation modes and for a reasonable degree of automation combined with the possibility of manual operator's intervention and fine-grained control of the observation flow. The package is being developed and maintained at Pulkovo observatory (Devyatkin et al., 2009) since 2000, and within the ISON project (Molotov et al., 2008) since 2005. Currently, its development is mostly frozen, and it is superseded now by a newer TCS platform FORTE (Kouprianov, 2012); however, CHAOS is still responsible for routine operation of almost all optical sensors of ISON.

CHAOS is a modular (mostly Windows-based) package; its basic components include: accurate timing subsystem disciplined from an atomic clock or a GPS receiver, datalogging facility, hardware abstraction modules, networking and remote control, ephemeris engine, scheduler, data storage, and graphical user interfaces (GUIs). Separate modules are written in different programming languages and frameworks (C, Python, Delphi, Ada'95, Fortran) and are connected via dynamic linking using the appropriate C application programming interfaces (APIs) and via sockets with a set of dedicated networking protocols. CCD camera control subsystem may also serve as a standalone application for interactive image acquisition and examination.

A special hardware abstraction layer separates the high-level part of the package (GUIs and scheduler) from hardware protocols and device drivers. It consists of a set of mutually interchangeable modules each of which controls the particular type and model of hardware and provides a generic API with functions common to all hardware devices of this type. This kind of design is characteristic to most of the general-purpose TCS platforms like RTS2 (http://www.rts2.org) and Indi (http://www.indilib.org), as well as to many freeware and proprietary planetarium and observatory control packages. The specific set of hardware abstraction layer components used in the OMT-800 setting is quite basic and includes modules for A&I Goto System stepper motor controller (gotosystem.xm4.ru/a _ i _ goto _ system _ 2), and Finger Lakes Instrumentation (FLI) (http://www.flicamera.com) CCD cameras with the Universal Serial Bus ver. 2.0 (USB 2.0) interface.

System time is provided by a dedicated stratum 1 Network Time Protocol (NTP) server driven by a Trimble Copernicus II GPS receiver. Accurate exposure timing is guaranteed by hardware triggering from the pulse-per-second (PPS) signal generated by the GPS receiver connected to the corresponding port of the camera. The formal accuracy of hardware triggering of this kind is better than a microsecond, and hence is far beyond any practical demands. However, the real timing accuracy is limited by the finite speed and instability of the mechanical CCD shutter, as well as by its poor reliability at low temperatures and high air humidity. The ISON's broad experience with Uniblitz shutters over the years allows us to estimate the average timing accuracy achievable with these shutters as several hundredths of a second, and it may easily drop to several tenths in the less favorable conditions without special precautions.

The integrated CHAOS *scheduler* can work with the following types of objects:

1. Deep-sky objects with fixed right ascension (α) and declination (δ); arbitrary tracking rates (v_α,v_δ) can be also applied.

2. Geostationary-like objects with fixed hour angle (t) and declination (δ); arbitrary tracking rates (v_t,v_δ) can be also applied.

3. Major planets of the Solar system, asteroids, comets, and Earth-orbiting objects; their ephemerides are given in the tabular form in text files, and CHAOS can track them in real time according to the ephemeris.

4. Satellites of major planets — same as other moving objects, but CHAOS can apply an offset to move the central planet away from the field of view.

For each type of object, one can specify the desired priority, constraints, and mode of observation, including the number of exposures, their duration, time step, and sequence of optical filters (unused in the OMT-800 setting, since at present it has no filter wheel). The optional exposure constraints and scheduling hints include constraints on the time of observation, apparent magnitude of the object, zenith angle or airmass, and hour angle. The actual scheduling algorithm depends on the objects observed; for instance, for deep-sky and slow-moving Solar system objects (asteroids, comets, etc.) it is as follows: descending objects are observed first, by decreasing zenith angle; these are followed by objects near culmination, sorted by decreasing hour angle; finally, ascending objects at sufficiently high altitudes, or sufficiently close to culmination are observed, as well as lower-priority objects, in the same order. CHAOS also accepts observation plans from external schedulers – for example, OMT-800 can do follow-up observations of faint space debris according to the optimal strategy calculated by the ISON planning and analysis center in Keldysh Institute for Applied Mathematics, Moscow. Although scheduling is generally targeted at fully automatic operation over the whole night, the telescope operator can manually pause, resume, restart, and edit the schedule when necessary, as well as initiate any manual observations or maintenance operations, like capturing calibration images or re-alignment. Figure 7.1 shows the main TCS components in action.

The OMT-800 data processing pipeline is based on the Apex II image analysis platform (Kouprianov, 2008; Devyatkin et al., 2010). Apex II project started in 2004 at Pulkovo as an effort to create a modern open software platform for general astronomical image analysis and, in particular, to fill the gap of non-specialized and all-purpose, but still highly reliable software for accurate automatic positional astronomy. The first application of the package was massive everyday data reduction in the continuous NEA follow-up campaign conducted by Pulkovo observatory and its mountain site near Kislovodsk (Devyatkin et al., 2009). Since 2005, Apex II is supported by the ISON project, where its major goal is the initial data reduction of survey and follow-up observations of artificial Earth's satellites and space debris on almost all ISON sensors, including OMT-800. Other current applications include double and multiple asteroid photometry, GRB astrometry, and search for exoplanets. Although the Apex II core and library remains open-source for the scientific community, the satellite/space debris package and its key

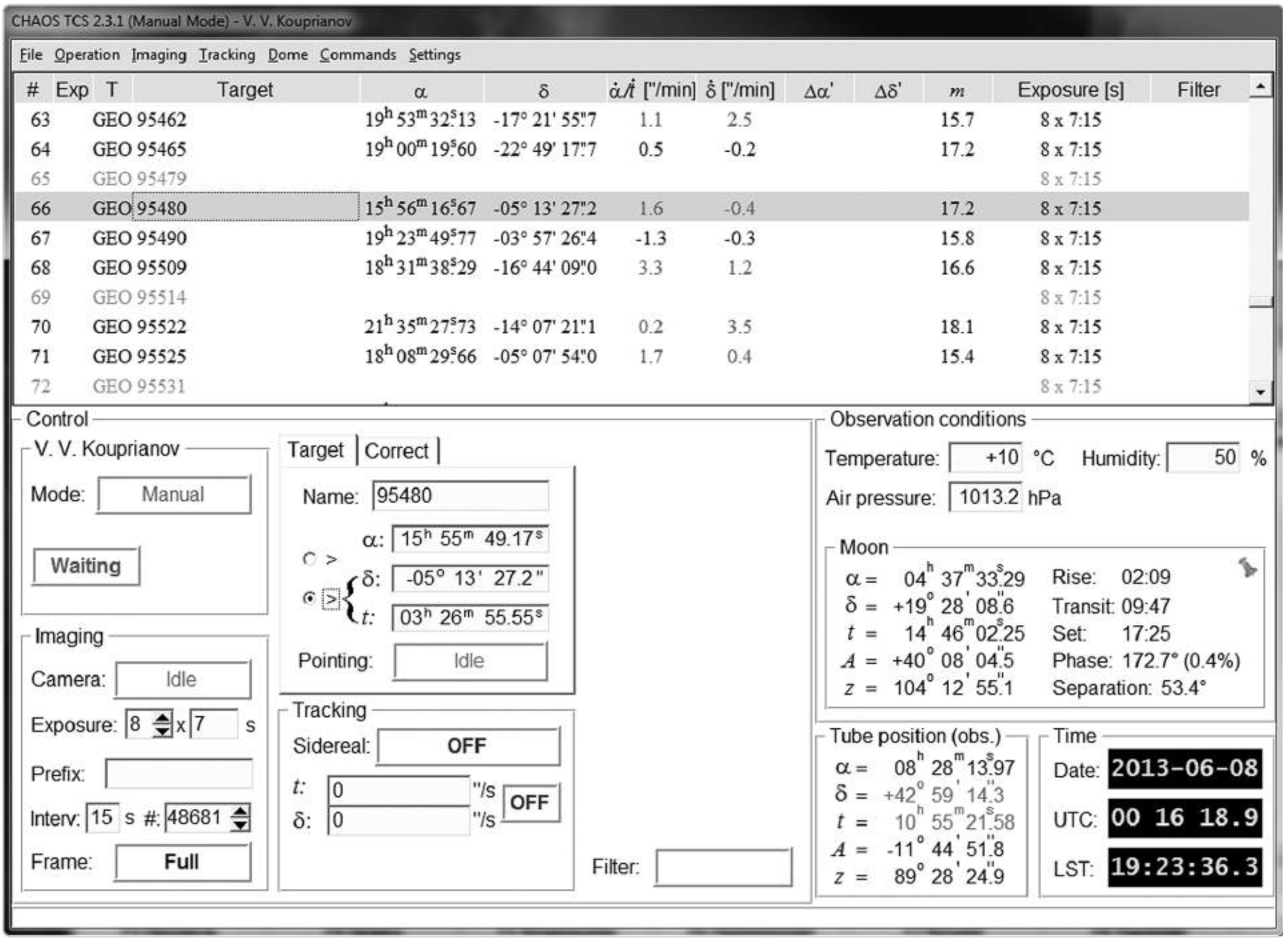

Figure 7.1. Screenshot of a working session of CHAOS TCS on the OMT-800 control workstation.

algorithms are the property of ISON and available to ISON members only.

Apex II is designed along the guidelines similar to those of such well-known proprietary packages as MATLAB® (http://www.mathworks.com) and IDL® (http://www.exelisvis.com/idl). Namely, the platform is based on a high-level scripting language convenient for vector and matrix operations, includes a large library of relevant algorithms (mostly implemented in the same language, but with bindings to high-performance and mature libraries in "classical" languages like C and Fortran); the library is accessed by user-level batch-mode or interactive GUI applications doing some specific data analysis tasks. Moreover, for those, who learn the language and library, interactive console mode is also available for the data analysis beyond the existing applications and for rapid prototyping of new algorithms. However, unlike the packages mentioned, Apex II makes extensive use of the existing open-source infrastructure for scientific computing which is built around the modern high-level programming language Python (http://www.python.org) and includes the following packages: NumPy (http://www.numpy.org) for basic array operations, vectorial notation, and numerics; SciPy (http://www.scipy.org), a huge collection of advanced numerical methods, including optimization, computer vision, and many others; matplotlib (matplotlib.org) for scientific plotting; PyFITS (http://www.stsci.edu/institute/software _ hardware/pyfits) for Flexible Image Transport System (FITS) format input/output; PyWCS (http://www.astropy.org) for coordinate system transformations; wxPython (http://www.wxpython.org) for building GUIs, and several others. In recent years, these packages gained a growing popularity among the scientific community.

The basic automatic data processing pipeline in Apex II is a console-mode Python script that works in batch mode without any user intervention. Its details depend on the problem it is intended for (e. g. the details of object extraction for asteroids and space debris are different), but almost any complete data reduction pipeline always contains the following large blocks:

1. Calibration.
2. Source extraction.
3. Source measurement.
4. Differential astrometry.
5. Differential photometry.
6. Post-processing.
7. Reporting.

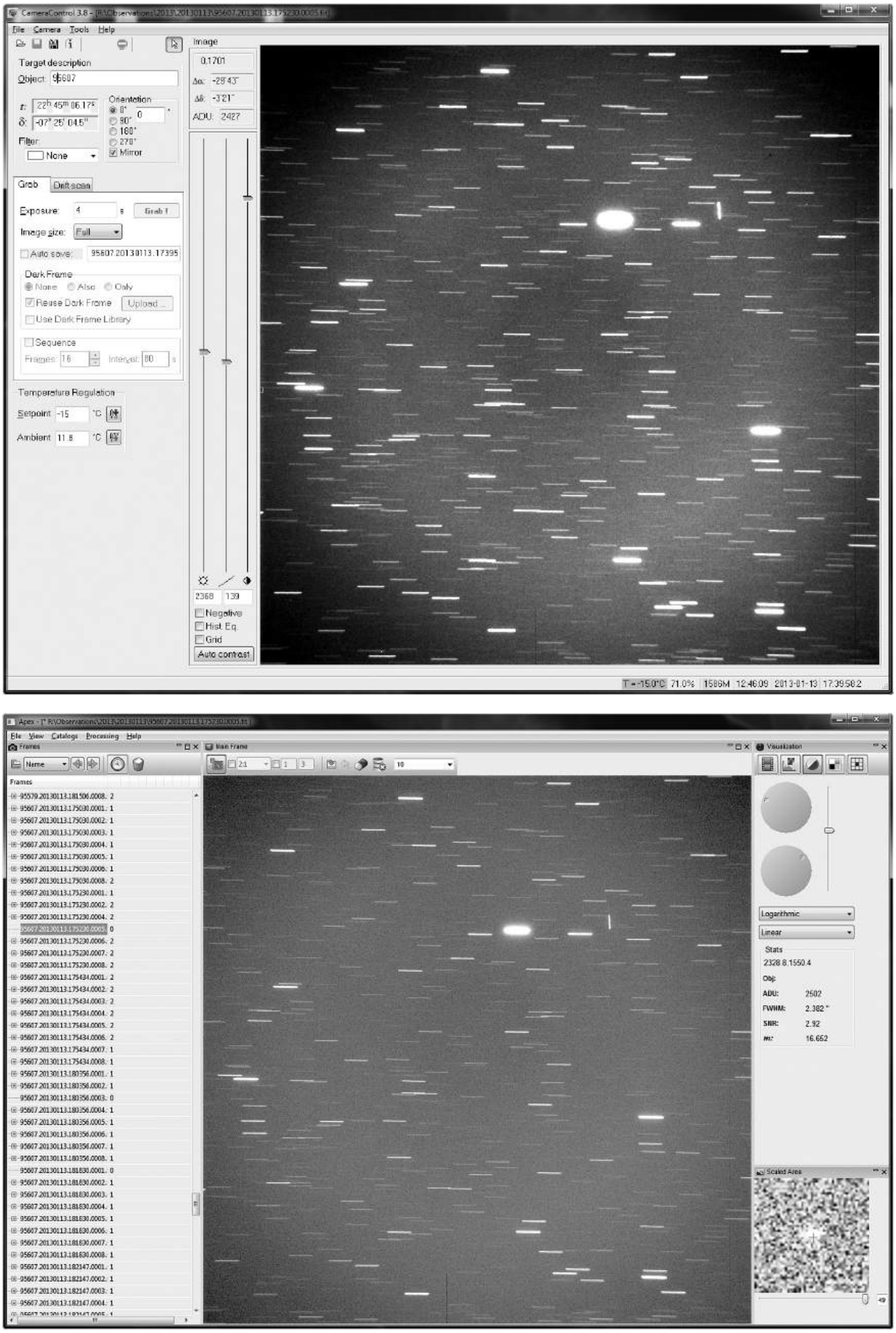

Figure 7.2. The screenshots of CameraControl panel (up) and Apex GUI panel (below). The figure shows a typical image of the sky with the object being tracked (telescope tracking switched off).

As an example, let us consider the data reduction pipeline for faint space debris follow-up. In general, image *calibration* includes cosmetic, dark, and flat correction; however, the main goal of this kind of observations is obtaining the accurate orbital data, and since positional measurements are practically not affected by dark and flat calibration, these steps are optional and are applied only when better characterization of a space debris fragment by means of photometry is required. As described in (Kouprianov, 2008), *source extraction* includes flattening the sky background, segmentation by global threshold, accompanied by binary morphological filtering to better detect faint star trails, and isophotal analysis. A separate source extraction pass is required to detect space debris, since their morphological properties are completely different from those of the field stars, which is actively exploited by the pipeline to eliminate the latter and thus substantially reduce the number of false detections at the very early stage of the pipeline. However, this pass only results in the list of *candidate* detections that still contains false positives; the final decision is made later by correlation of detections from several frames (see below). *Source measurement* is intended to obtain a set of more accurate parameters of each object, including its position, shape, and flux, than those provided by isophotal analysis; this is done by point-spread function (PSF) fitting, both for point-like and for trailed sources. This also helps to identify most of the initial false detections (including cosmic ray hits and background noise due to a low detection threshold value): since the real objects' full widths at half-maximum (FWHM) after PSF fitting usually lie within a rather small range of values, posing constraints on the post-fit FWHM serves as a very efficient method of identifying false positives. Differential astrometry implies matching centroid positions of the field stars detected to the appropriate catalog (since the OMT-800 field of view is large, Tycho-2 catalogue (Høg et al., 2000) is the best choice; UCAC4 (Zacharias et al., 2011) can also be used when appropriate), calculating plate model parameters, including nonlinear terms in coordinates to account for the residual optical distortions, and applying them to candidate space object detections; the resulting nominal frame-to-frame root-mean-square (RMS) error of positional measurements of space debris is of the order of 0.1″-0.2″ for an average object, and down to several hundredths of arcseconds for the bright objects with signal-to-noise ratio (SNR) of 100 and more; this is usually several times worse than the values achieved for point source-only images that do not involve any trailed sources, but is still fully acceptable in terms of the required orbital data accuracy. Differential photometry is done by matching the field stars to the reference catalog (UCAC4 is the better choice here, since its magnitude range better matches that of the target objects, and its own instrumental system is close enough to the integral band of OMT-800), calculating reduction model parameters with optional correction for differential extinction, which is essential at high airmass values for the large fields of view, and applying them to the measured fluxes of candidate space object detections. For the OMT-800 space debris astrometry pipeline, the purpose of *post-processing* is to correlate candidate space object detections from several images comprising a single cadence in order to identify tracklets of separate space objects and eliminate false detections that do not belong to any tracklet; the k-d tree-based moving object detection algorithm behind this is similar to the one used at PanSTARRS (Kubica et al., 2007) for intra-night correlation. Finally, all tracklets found are validated by initial orbit determination and *reported* in the format appropriate for further analysis at the Keldysh Institute for Applied Mathematics planning and analysis center.

As it was mentioned above, this pipeline runs fully unattended. However, visual inspection of images and detections found by the pipeline is still possible by means of a special integrated Apex GUI application (see Fig. 7.2, bottom panel). This application is, first of all, an advanced FITS image viewer written in wxPython and based on the OpenGL (http://www.opengl.org) shader technology which allows for smooth real-time image enhancement aimed at visual detection of the faintest objects possible. In particular, manual operator's control is required in an extremely rare case of false detections that may still survive all validity checks of the automatic pipeline with non-vanishing probability, mostly due to a very low detection threshold of about 2.5σ; then Apex GUI allows to quickly identify a suspicious uncorrelated detection as either real or spurious. Apex GUI currently evolves to a full-featured general-purpose astronomical data reduction application for both controlling the high-level automatic pipeline operation and for low-level interactive image analysis.

Whenever possible, all pipelines are accelerated by the Apex II parallel subsystem which is designed to utilize the full central processing unit (CPU) power of the data processing workstation. With its help, data analysis achieves the realtime performance (i. e. it is faster than the image acquisition rate) without sacrificing the capability to detect the faintest objects. Currently, the parallel subsystem is being gradually transferred to the OpenCL framework (http://www.khronos.org/opencl) to further increase performance by utilizing the computing capabilities of general-purpose graphics processing units (GPGPUs).

Thus we may conclude that the software currently installed at the OMT-800 control and processing workstation is capable of doing the full cycle of image acquisition and initial data reduction, and is sufficiently flexible to suite the needs of a broad range of observation campaigns.

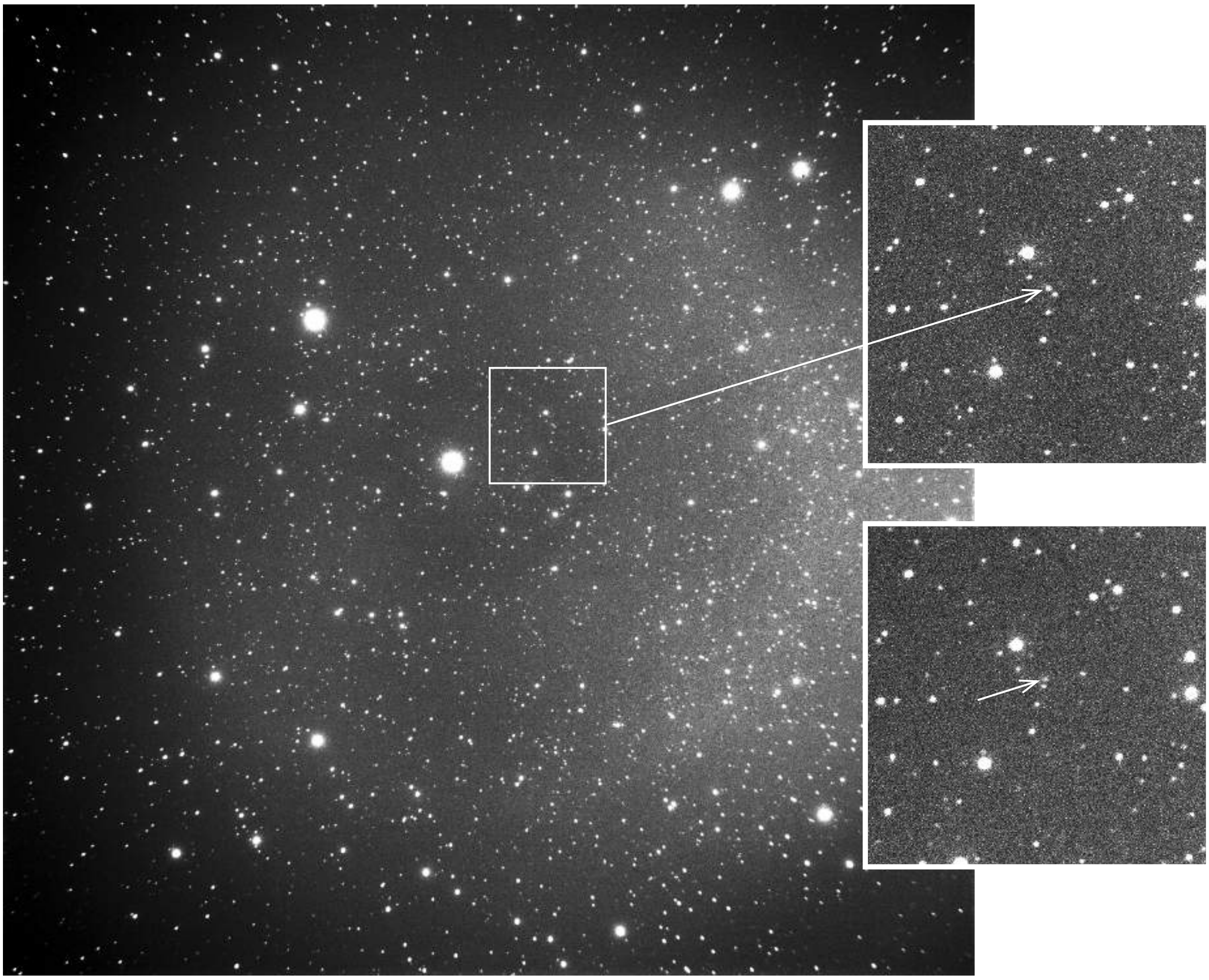

Figure 8.1. The shot is made with OMT-800 March 3, 2013, 0:00UT with exposure time of 10 sec. The arrow shows the image of comet C/2012 S1 ISON. The next fragment of the shot made 25 minutes later is shown at the bottom right.

8. Aims and objectives of the OMT-800

Within a wide range of the astrophysical objectives, the systematic observations using OMT-800 are defined by its characteristics, such as the limiting magnitude, filed of view, telescope control system and astronomical seeing conditions at the telescope's location.

At the observation point in Mayaki the number of the nights available for optical observations per year averages about 170 (Fig. 8.2). The absence of any significant

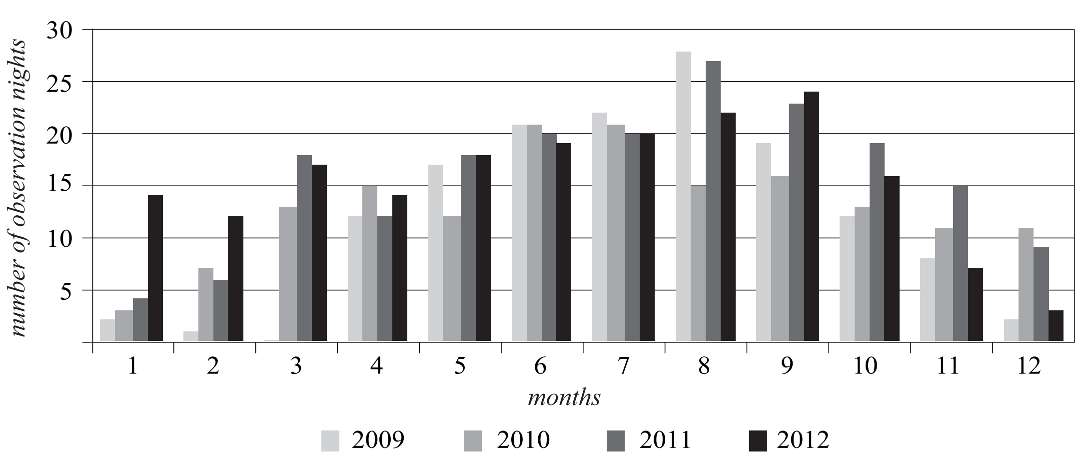

Figure 8.2. Statistics of the clear sky nights at Mayaki station.

artificial light pollution improves the limiting magnitude of the equipment. Nevertheless, the proximity of the observation station to the Dniester river often worsens quality of the images due to the large amount of a water vapor in the surface layer of atmosphere.

Currently, the following observational programs are carried out with OMT-800:

1. Positional observations of artificial satellites in the geostationary orbits (Molotov et al., 2008).
2. Observations of the near-Earth approaching objects.
3. Observations of the Solar system small bodies (Fig. 8.1, as an example; Wibe, Y. et al. 2013).

9. Auxiliary equipment at the OMT-800

The meteor patrol method is applied in meteor studies to determine kinematic and physical characteristics of the meteor events and interplanetary dust particles that cause such events. For this purpose simultaneous operation of at least two base stations is realised. Normally, high-speed cameras with wide-angle lenses are used, and the pre-processing is carried out after each night of patrolling.

The television meteor patrol has been constructed in Odessa in 2003. Television cameras Watec LCL-902K, Watec LCL-902H and Watec LCL-902H2 with a time resolution of 20 ms are used to record meteor events.

The meteor patrol equipped with cameras with fields of view and magnitude limits from 36x49 arc degrees and 7.0^m for the most wide-angle camera to 0.6x0.8 arc degrees and 13.5^m for Schmidt telescope

Synchronous observations, i.e. observations with a few polytypic instruments on the same parallactic mounting, proved themselves to be particularly efficient. The application of the synchronous method of observations enables to maximize the benefits of different optical systems. Depending on the observation task, it is feasible to enlarge the field of view or to record a meteor event with high resolution using different systems.

When designing and building the television meteor patrol on the base of the telescope with the mirror diameter of 800 mm, it was intended to make it possible to mount several cameras for the meteor patrol. One of the cameras (with KO-140 lens), fixed on the OMT-800 tube, is shown in the Fig. 9.1. It is possible to combine different astronomical cameras depending on the posed research tasks.

The following algorithm of work of base meteor stations is suggested. One of the stations (the master telescope at Mayaki station) conducts its planned observations under any non-meteor program at any point on the celestial sphere; and the second station (the slave telescope at Kryzhanovka station), equipped with the Schmidt telescope and several cameras, performs calculations of the point of observation that corresponds to the guidance sector where the first station telescope is pointed at. Thus, both stations, which are at 45 km distance from each other, carry out the meteor patrol session in such a way that instruments on both stations are pointed at the same space area. Whenever the point of observation of the master telescope is changed, the corresponding procedure of recalculation and repointing of the slave telescope takes place.

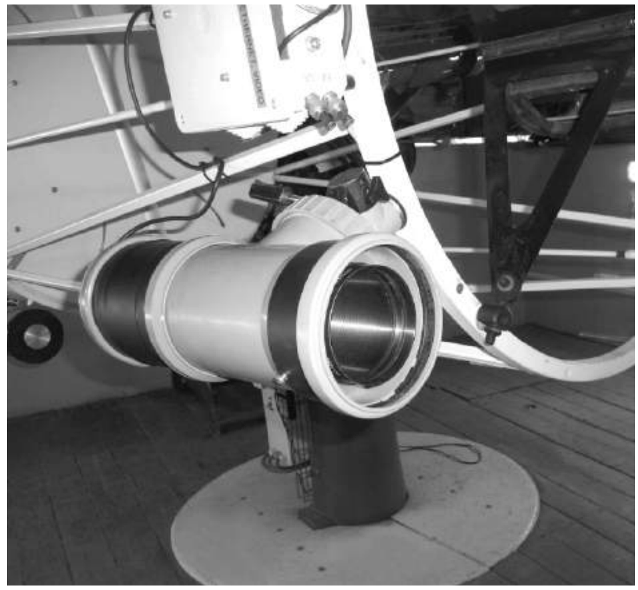

Figure 9.1. Meteor camera attached to OMT-800 tube.

Coordination of observations is realized with specific software “Meteor Explorer software” that was developed by one of the authors of this paper. Every minute, while the master telescope is in operation, the program sends the file with equatorial coordinates of the point of observation to the remote server.

The program enables one to conduct calculations for different meteor showers at different heights of the meteor events (80-100 km), that allows one to increase the number of meteors detected at both stations.

The software also contains program for real time record of meteor events, or record of video streams from meteor cameras, and the subsequent pre-processing of the data.

The methods of the base telescopic observations has been tested during 2009-2012 expeditionary studies on Zmeinii Island in the Black Sea with the 150 km base line between the observation sites (Zmeinii Island – Kryzhanovka station).

It should be noted that a meteor event can be also captured within the master telescope filed of view as the meteor track image, and in that case we can obtain the meteor image with a high spatial resolution across the meteor trajectory.

Reconfiguration of auxiliary equipment will allow carrying out the meteor patrol for various tasks of meteor researches.

10. Conclusion

New automatic Odessa multifunctional telescope (OMT-800) was created by the specialists of Astronomical Observatory of Odessa I. I. Mechnikov National University in cooperation with colleagues from ISON project. This telescope will be used for astrometric and (in the future) photometric observations of the near-to-Earth celestial bodies: high-eliptical orbit artificial satellites, geostationary satellites, asteroids and comets.

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