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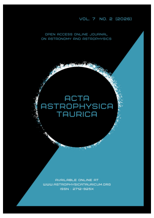

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Automatic control system for small telescopes at the Crimean Astrophysical Observatory

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ABSTRACT

We present a software and hardware complex of the control system for small telescopes (D = 20–64 cm), which is primarily used to observe objects in near-Earth space and those in the Solar system (comets, asteroids). The complex allows observing both in operator mode and fully automatically, according to a given program. This makes it possible to implement various observation methods: surveys of the selected areas of the sky, search and tracking of objects according to target designations. The angular velocities of tracked objects can reach about 1 deg/sec. The complex provides power supply management for telescope components, control of the telescope mount drives, and operation of auxiliary equipment. The roof of the pavilion is also controlled. Full control of the telescope camera is organized, from power supply and cooling to setting exposure and transferring frames to the image processing system. Failure-free operation for 16 years has demonstrated the reliability of the developed system. The acquisition of more than 20 million measurements of coordinate and photometric information has shown its efficiency. The control system is being gradually improved and is expected to be robotic in the future.

Key words: automatic telescope control system

1 Introduction

In 2003, observations of small-size objects in the geostationary region were initiated at the Crimean Astrophysical Observatory (CrAO) using the AT-64 telescope (Chernykh, Rumyantsev, 2002) with the aim of cataloging these objects. The objects in the catalog were of 15–18 mag, which approximately corresponds to a size of 100–25 cm. The steady growth in the number of cataloged objects required additional observations to maintain the accuracy of their orbital elements.

As a result of extensive observational campaigns and data processing, a class of small-size objects was identified in the geostationary region, which undergo orbital evolution significantly different from that of classical geostationary objects (Agapov et al., 2005a, b). These differences are strongly affected by radiation pressure due to a high area-to-mass ratio. Long-term trajectory prediction is not feasible for objects of this class; they require greater attention and more frequent observations in order to prevent their loss.

Conducting such observations in manual mode is quite exhausting for observers, and automation of the observational process is required.

At present, several dozen automated and robotic telescopes involved in different scientific tasks are in operation worldwide. Here we can note some of them: BOOTES (Jelínek et al., 2010), TAROT (Klotz et al., 2008), ROTSE (Akerlof et al., 2003), and MASTER (Lipunov et al., 2004).

2 ACS objectives

The automatic control system (ACS) must ensure automatic control of the telescope mount and recording equipment, opening and closing of the pavilion roof, and power supply management for the main components.

A universal control system is needed for different small telescopes that enables the use of various drive motors depending on the dynamical characteristics of the telescope.

This will allow the following tasks to be performed automatically without human involvement:

- tracking space objects according to target designations with compensation for their angular motion and acquiring the series of images stored to the hard drive of the control computer;
- conducting surveys (repeated coverage) of the selected regions of the sky throughout the night; acquiring images and storing them.

Observations of objects with high motion rates, of the order of 1 deg/sec, and search operations are supposed to be carried out in operator mode.

The ACS must ensure remote operation and control of the entire observational process via the Internet from any location, with a bandwidth of no less than 100 kB/sec.

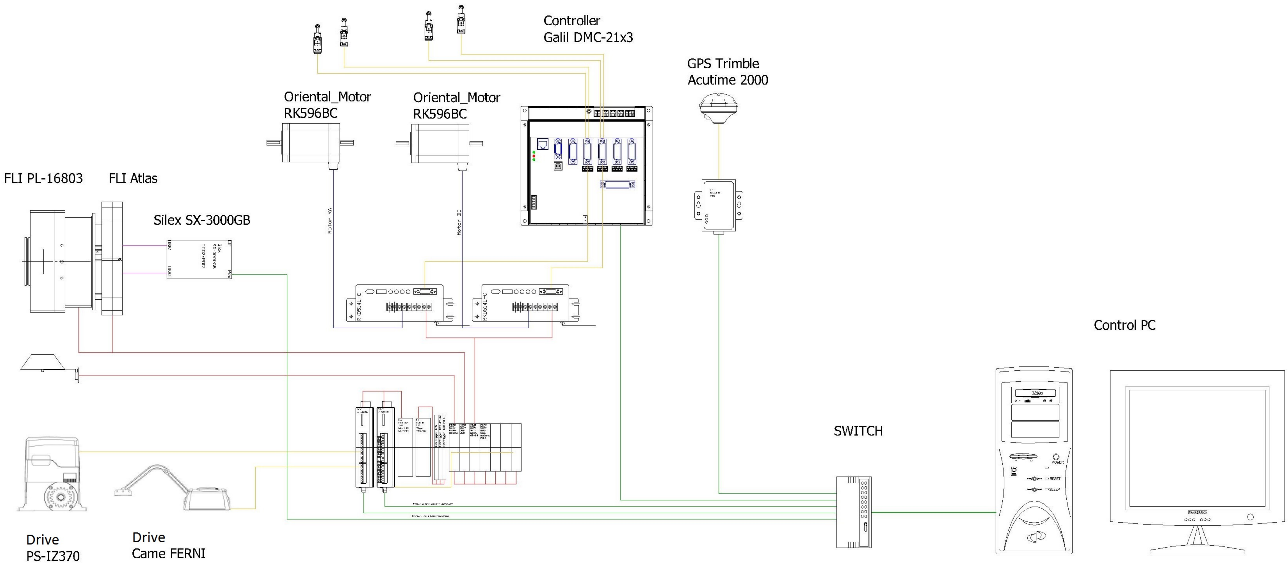

Fig. 1. ACS scheme.

3 ACS hardware

Ethernet was selected as the main information network integrating all ACS components into a unified architecture. On its basis, the control system is easily developed, being stable against device disconnection or reconnection during operation and capable of adding new devices in virtually unlimited numbers. Such a network is appropriate for distributed objects, uniting system components over distances of up to 100 meters.

The AT-64 telescope is located in the pavilion on the fork-type equatorial mount, with a total mass of approximately 250 kg. The five-phase stepper motors RK596AW (2.1 N·m) and RK569BW (1.66 N·m) with Oriental Motor drivers on the right ascension and declination axes, respectively, are used as mount drives. The microstepping driver allows the motor shaft step angle to be set within the range of 0.00288 and 0.72 deg. Control of the stepper motors is implemented via the Galil DMC-2143 programable logic controller. This controller is operated via the Ethernet network, incorporates a 32-bit microcomputer, and is capable of driving up to eight motors in its most powerful configuration. The controller is equipped with random access memory for a user program and supports multitasking, enabling up to eight programs to run simultaneously. The maximum output frequency for stepper motors is 3 MHz, which allows both rapid telescope pointing and fine single-motor motion. In our case, the controller drives four motors, enabling two telescopes located within the same pavilion to be connected to it. Embedded software has been developed for the Galil DMC-2143 controller based on its internal command system. This software enables the autonomous implementation of various telescope motion functions ranging from pointing to a given position to tracking an object moving at a specified velocity and acceleration. An hour angle – declination coordinate system has been implemented within the controller. Hall-effect sensors are used to limit telescope motion at the end positions. The scheme of the automatic telescope control system is shown in Fig. 1.

The ML-16803 CCD[1] camera and the Atlas digital focuser from FLI are mounted on the telescope as a detector. The camera and focuser are controlled via a USB 2.0 interface. In cases where the equipment is remotely located, the Silex SX-3000GB Ethernet server of USB devices is used, providing a data transfer rate of 1 Gbit/sec.

Power supply management for the telescope and detector equipment is implemented via the MOXA ioLogik E1211 Ethernet input/output controller, with an intermediate relay unit used. The MOXA ioLogik E1200 series controller features a built-in dual-port Ethernet switch, enabling improvement of the control system without need for additional long twisted-pair cable runs.

When observing fast-moving objects, one should know the precise exposure start time. The Trimble Acutime 2000 GPS receiver installed at the pavilion is used to register this time. Time stamp requests and reception are implemented through software via the RS-232/422 port. The MOXA NPort-5150 COM-to-Ethernet converter (RS-232/422/485) is used to connect the GPS to the main communication channel.

The telescope is located in the pavilion with a sliding roof and a hinged southern shutter. The semi-cylindrical roof slides horizontally along the tracks toward the north. Since the telescope extends above the level of the tracks, a blockage of the shutter is ensured to open the southern horizon. The southern shutter is attached to the wall on a hinge and is equipped with counterweights. To automate the opening and closing of the roof, the sliding gate drive PS-IZ 370 was

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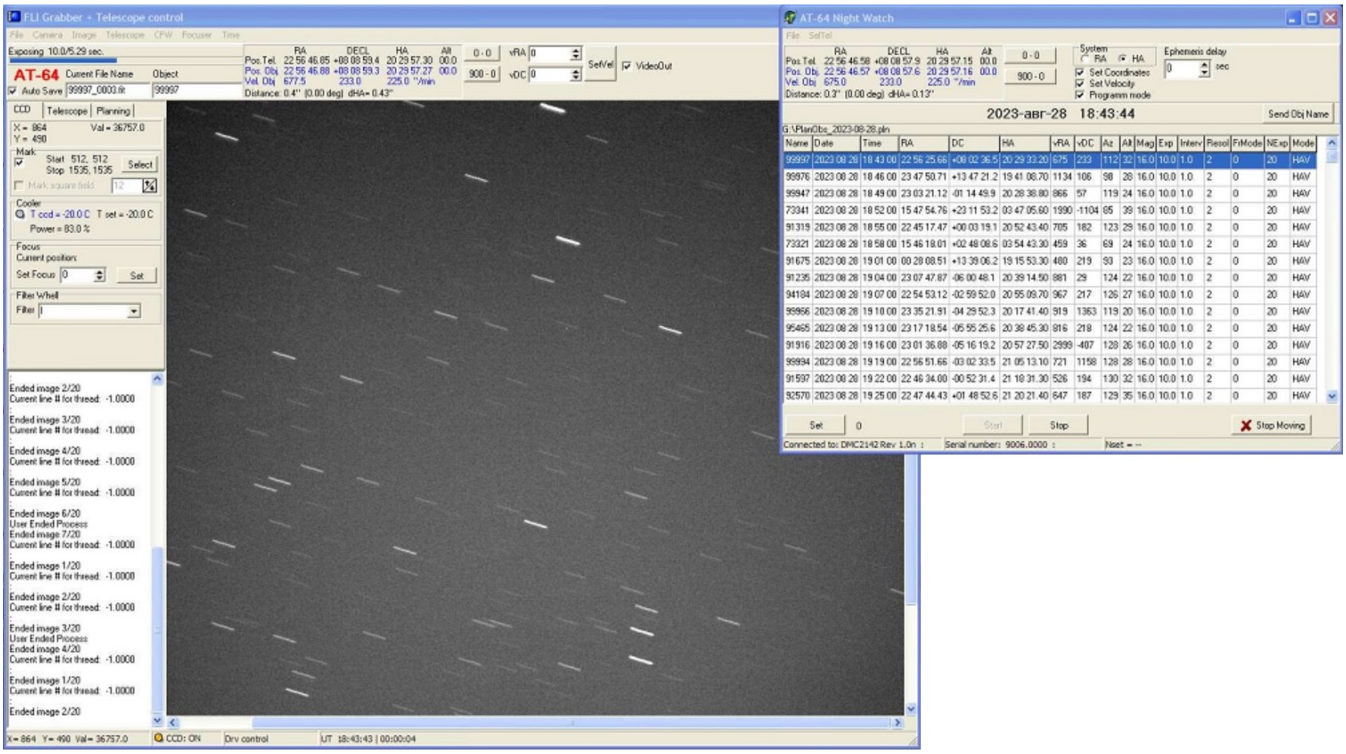
[1] CCD – charge-coupled device



Exposing 10.0/5.29 sec.

Current File Name: 99997_0003.fit

Object: 99997

☑ Auto Save

	RA	DECL	HA	Alt
Pos.Tel.	22 56 46.85	+08 08 59.4	20 29 57.30	00.0
Pos. Obj.	22 56 46.88	+08 08 59.3	20 29 57.27	00.0
Vel. Obj	677.5	233.0	225.0 "/min	

Distance: 0.4" (0.00 deg) dHA= 0.43"

vRA 0

vDC 0

☑ VideoOut

X = 864 Val = 36757.0
Y = 490

Mark ☑ Start 512, 512 Stop 1535, 1535

☐ Mark square field 12

Cooler: T ccd = -20.0 C T set = -20.0 C Power = 83.0 %

Focus: Current position: Set Focus 0

Filter Wheel: Filter I

```
:
Ended image 2/20
Current line # for thread: -1.0000
:
Ended image 3/20
Current line # for thread: -1.0000
:
Ended image 4/20
Current line # for thread: -1.0000
:
Ended image 5/20
Current line # for thread: -1.0000
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Ended image 6/20
User Ended Process
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Current line # for thread: -1.0000
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Ended image 1/20
Current line # for thread: -1.0000
:
Ended image 2/20
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User Ended Process
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Current line # for thread: -1.0000
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Ended image 1/20
Current line # for thread: -1.0000
:
Ended image 2/20
```

X= 864 Y= 490 Val= 36757.0 | CCD: ON | Drv control | UT 18:43:43 | 00:00:04

	RA	DECL	HA	Alt
Pos.Tel.	22 56 46.58	+08 08 57.9	20 29 57.15	00.0
Pos. Obj.	22 56 46.57	+08 08 57.6	20 29 57.16	00.0
Vel. Obj	675.0	233.0	225.0 "/min	

Distance: 0.3" (0.00 deg) dHA= 0.13"

System: ○ RA ● HA

☑ Set Coordinates
☑ Set Velocity
☑ Programm mode

Ephemeris delay 0 sec

2023-авг-28 18:43:44

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Name	Date	Time	RA	DC	HA	vRA	vDC	Az	Alt	Mag	Exp	Interv	Resol	FiMode	NExp	Mode
99997	2023 08 28	18 43 00	22 56 25.66	+08 02 36.5	20 29 33.20	675	233	112	32	16.0	10.0	1.0	2	0	20	HAV
99976	2023 08 28	18 46 00	23 47 50.71	+13 47 21.2	19 41 08.70	1134	106	98	28	16.0	10.0	1.0	2	0	20	HAV
99947	2023 08 28	18 49 00	23 03 21.12	-01 14 49.9	20 28 38.80	866	57	119	24	16.0	10.0	1.0	2	0	20	HAV
73341	2023 08 28	18 52 00	15 47 54.76	+23 11 53.2	03 47 05.60	1990	-1104	85	39	16.0	10.0	1.0	2	0	20	HAV
91319	2023 08 28	18 55 00	22 45 17.47	+00 03 19.1	20 52 43.40	705	182	123	29	16.0	10.0	1.0	2	0	20	HAV
73321	2023 08 28	18 58 00	15 46 18.01	+02 48 08.6	03 54 43.30	459	36	69	24	16.0	10.0	1.0	2	0	20	HAV
91675	2023 08 28	19 01 00	00 28 08.51	+13 39 06.2	19 15 53.30	480	219	93	23	16.0	10.0	1.0	2	0	20	HAV
91235	2023 08 28	19 04 00	23 07 47.87	-06 00 48.1	20 39 14.50	881	29	124	22	16.0	10.0	1.0	2	0	20	HAV
94184	2023 08 28	19 07 00	22 54 53.12	-02 59 52.0	20 55 09.70	967	217	126	27	16.0	10.0	1.0	2	0	20	HAV
99966	2023 08 28	19 10 00	23 35 21.91	-04 29 52.3	20 17 41.40	919	1363	119	20	16.0	10.0	1.0	2	0	20	HAV
95465	2023 08 28	19 13 00	23 17 18.54	-05 55 25.6	20 38 45.30	816	218	124	22	16.0	10.0	1.0	2	0	20	HAV
91916	2023 08 28	19 16 00	23 01 36.88	-05 16 19.2	20 57 27.50	2999	-407	128	26	16.0	10.0	1.0	2	0	20	HAV
99934	2023 08 28	19 19 00	22 56 51.66	-03 02 33.5	21 05 13.10	721	1158	128	28	16.0	10.0	1.0	2	0	20	HAV
91597	2023 08 28	19 22 00	22 46 34.00	-00 52 31.4	21 18 31.30	526	194	130	32	16.0	10.0	1.0	2	0	20	HAV
92570	2023 08 28	19 25 00	22 47 44.43	+01 48 52.6	21 20 21.40	647	187	129	35	16.0	10.0	1.0	2	0	20	HAV

Set 0

Connected to: DMC2142 Rev 1.0n : | Serial number: 9006.0000 : | Nset = --

Fig. 2. Interfaces of FLIGrabber and NightWatch programs.

used. This drive supports the sliding roof of up to 1000 kg and provides a substantial power reserve.

Optical system: Richter – Slevogt
F = 895 mm
D = 640 mm
Camera: FLI PL-16803
4 096 × 4 096@9 μm
Field of view: 1.5 × 1.5 deg
Scale: 2.1 arcsec/pixel
Pointing rate:
Vα = 3 deg/sec
Vδ = 3 deg/sec
A α, δ = 3.0 deg/sec^2
Maximum tracking rate: 1 deg/sec.

Fig. 3. The AT-64 telescope.

The blockage of the southern shutter is driven by the Came Ferni sliding gate drive, with a maximum torque of 320 N·m. Both drives have digital control systems and limit switches at the end positions. These drives are controlled by the MOXA ioLogik E1214 switching controller. The roof and shutter drives operate in relay mode (open/closed). The time required to open the roof is 23 sec, and the time for the blockage of the southern shutter to be made is 8 sec.

A single computer is sufficient for complete control and operating the telescope, as well as for pre-processing images. A local Ethernet network with a bandwidth of 1 Gbit/sec has been installed inside the pavilion.

Power supply management for the computers in the pavilion is carried out by the Laurent-112 module from KernelChip. The Laurent-112 module is designed for switching various electronic devices and circuits by means of twelve high-power electromagnetic relays. Control is implemented via Ethernet either through a built-in web interface or by commands through a TCP socket.

When new telescopes were put into operation, subsequent hardware modifications did not require any changes to the control scheme or the control software. This concerns the Acutime GPS, the FLI CCD cameras of the PL, ML, and IMG families, the FLI focusers and filter wheels, the Galil DMC motion controllers, and the MOXA ioLogik E1200 series controllers.

4 Software

Specialized software consisting of several programs has been written by the authors for observation preparation and for control of all the hardware described above.

The PlanSat program is designed for compiling observation schedule for space objects (SOs) in accordance with their priorities. Scheduling is performed taking into account SO visibility conditions, brightness, and the time of the last observation. The position and phase of the Moon, as well as the angular distance to the galactic equator, are also considered. The program is not a direct component of the automatic

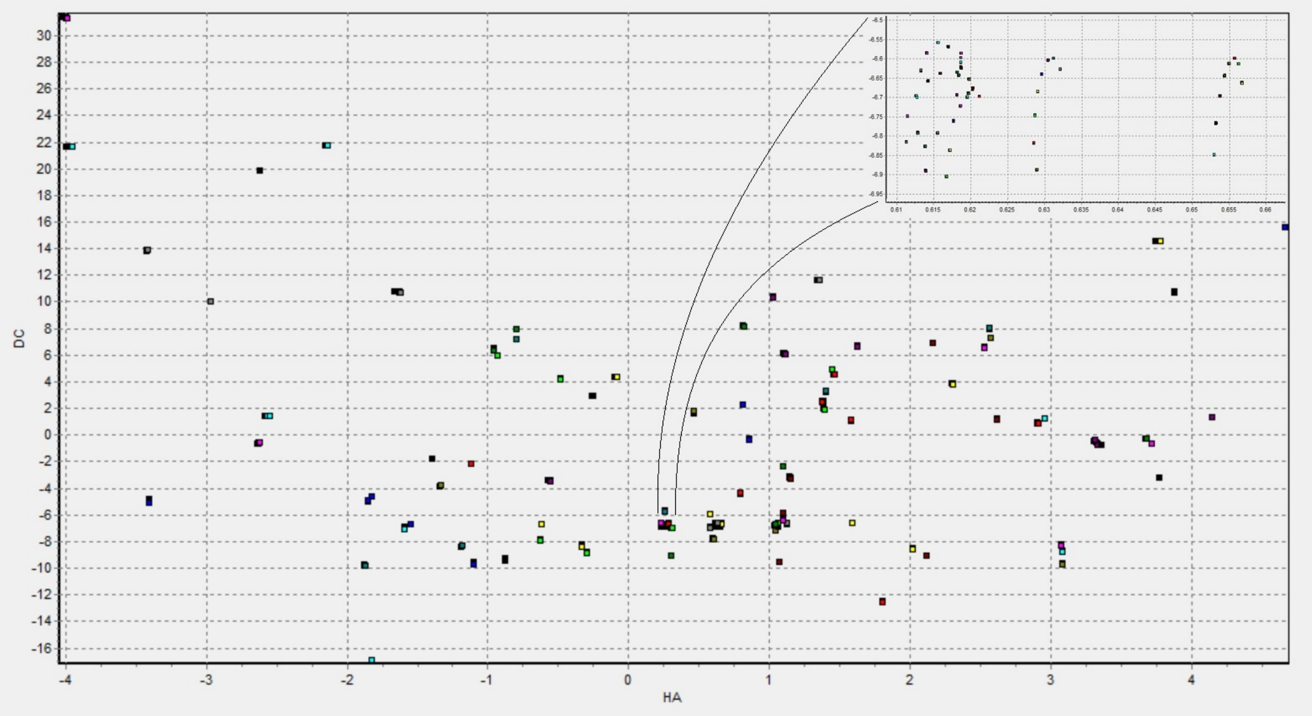
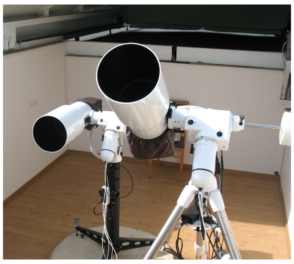


Fig. 4. Example of the object tracking according to target designations with the AT-64 on January 26, 2020. A total of 98 objects (192 sets) and 2337 positions were registered.

Optical system: Richter – Slevogt – Terebizh
D = 220 mm
F = 507 mm
Camera: FLI ML-9000 3072× 3072@12 μm
Field of view: 4.1 × 4.1 deg
Scale: 4.9 arcsec/pixel
Pointing rate:
$V\alpha$ = 3 deg/sec
$V\delta$ = 6 deg/sec
Maximum tracking rate: exceeds 1 deg/sec

Fig. 5. The Peephole-1 telescope.



Optical system: VT-52c
D = 180 mm
F = 295 mm
Camera: FLI ML-9000 3072× 3072@12 μm
Field of view: 7.2 × 7.2 deg
Scale: 8.4 arcsec/pixel
Pointing rate:
$V\alpha$ = 5.5 deg/sec
$V\delta$ = 5.5 deg/sec
$A\ \alpha, \delta$ = 3.1 deg/sec^2
Maximum tracking rate: exceeds 1 deg/sec

Fig. 6. The Peephole-2a and Peephole-2b telescopes.

control system, but the schedule it produces is subsequently carried out by the control system. As a result, the program generates a file containing the observation schedule subsequently used by the NightWatch program.

The FLIGrabber program (Fig. 2) is designed for controlling FLI receiving and auxiliary equipment (IMG, ML, and PL series CCD cameras, digital focusers, and filter wheels). In addition, FLIGrabber is capable of controlling Galil controllers (DMC-21×3 and 41×3 series), as well as the Trimble Acutime 2000 and Acutime Gold GPS receivers. Equipment control is implemented via the FLI Software Development Library API (Application Programing Interfaces) and the Galil Windows API Tool Kit. Time stamp requests are transmitted to the GPS receiver via the COM port using the Trimble Standard Interface Protocol (TSIP).

The program enables the acquisition of single or series exposures with individual setting parameters for exposure, filter, and telescope position. These capabilities allow one to conduct a survey of the selected extended region of the sky in the required tracking mode.

In more complex cases, where precise reference of the beginning of scheduled observations to a specified time is required, the NightWatch program is applied. A pre-compiled schedule is loaded into the program, containing the scheduled observation times, coordinates, and rates of SOs. According to this schedule, NightWatch sends commands to the telescope controller for pointing and tracking an object and commands to FLIGrabber to initiate an exposure series. Communication between NightWatch and FLIGrabber programs is implemented via the Winsock interface. Displacement of

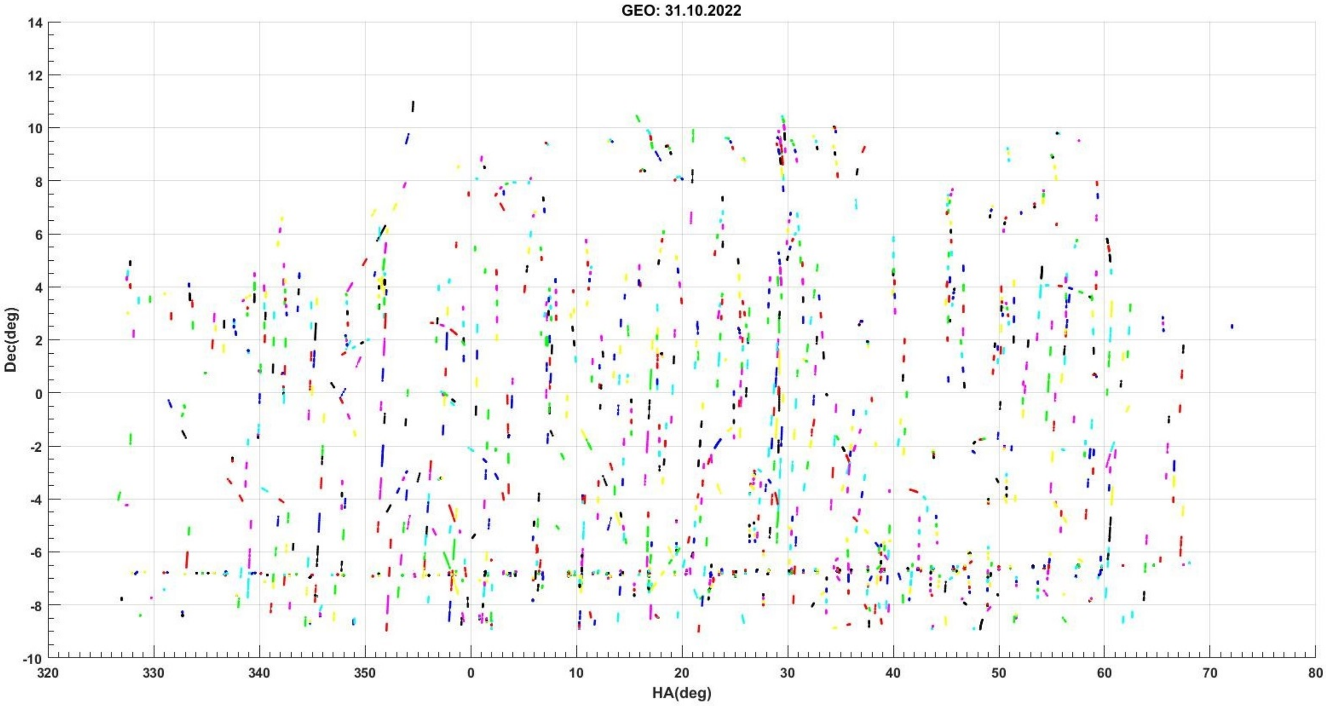


Fig. 7. Results of the geostationary region survey conducted with the PH-2a on October 31, 2022. The tracks of all objects registered during the night are shown within the hour angle – declination coordinate system. Coverage area: 20 × 133.5 deg. A total of 437 objects and 13 796 positions were registered.

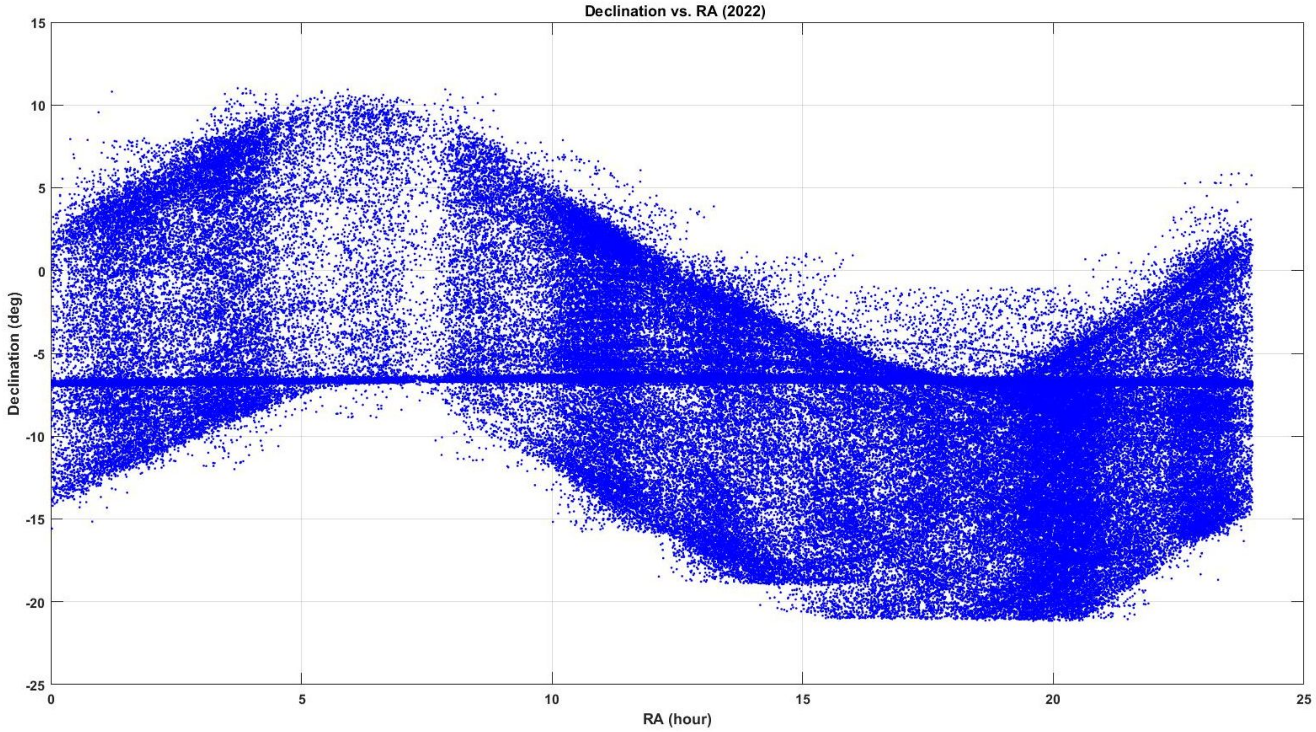


Fig. 8. Map of the positions of all objects registered in the geostationary region with the PH-2a during 2022. A total of 2083 objects and 1 404 600 positions were registered.

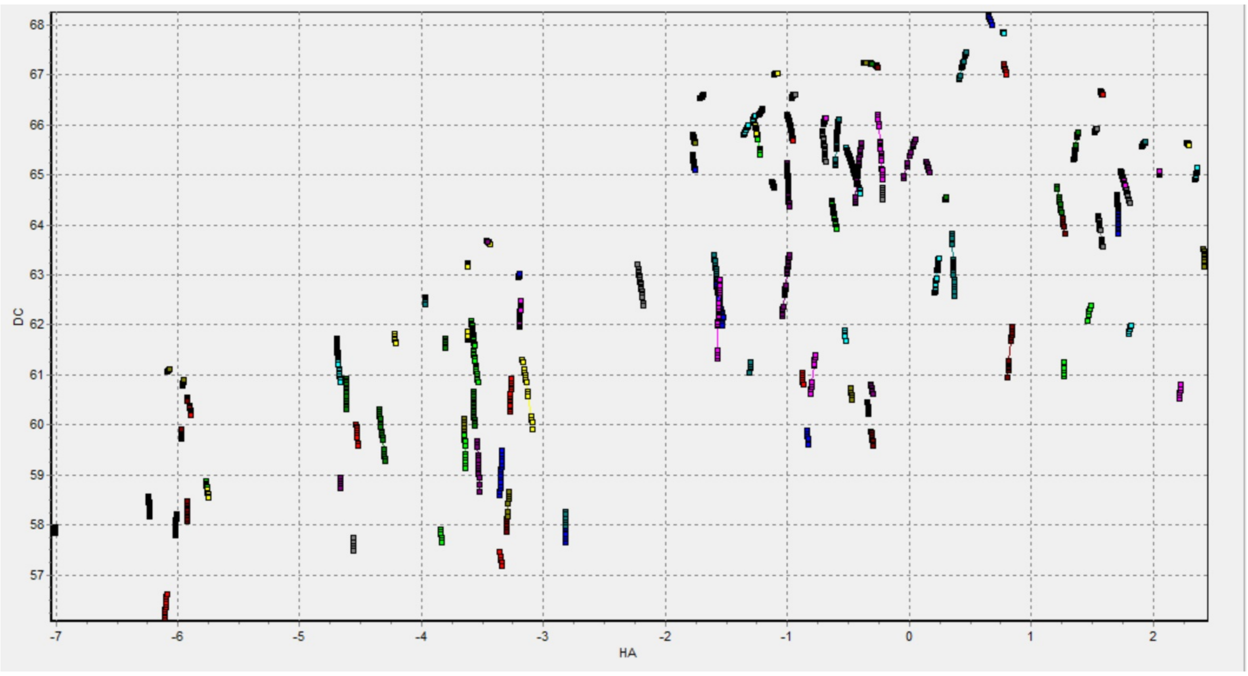


Fig. 9. Results of the survey of the apogee region of Molniya-type orbits during a single night on February 10, 2023, conducted with the PH-2b. Tracks of the objects registered during the night are shown in hour angle – declination coordinates. Coverage area: 7 × 71 deg. A total of 109 objects and 1459 positions were registered.

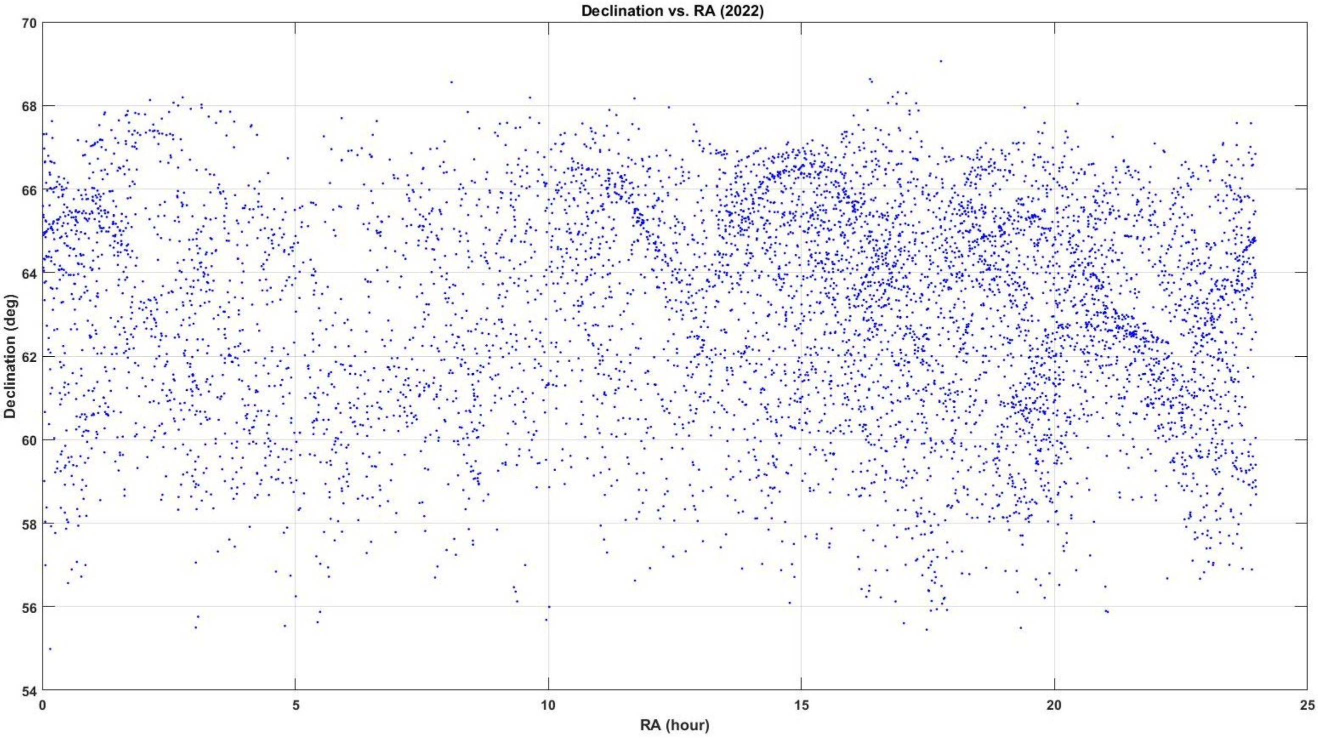


Fig. 10. Map of the positions of all objects registered in the apogee region of Molniya-type orbits with the PH-2b during 2022. A total of 179 objects and 60 178 positions were registered.

the telescope to its parking position at the end of the night is also carried out in accordance with the schedule.

Tracking fast-moving objects can be performed in automated mode by the operator using the Accelerator program. Such objects include low-orbit SOs, highly elliptical SOs near perigee, SOs during the launch stage, etc. These objects are characterized not only by high rates but also by large accelerations in equatorial coordinates. To track such objects, the program changes the telescope drive rate at a prescribed frequency according to the loaded ephemeris, thereby maintaining the SO within the field of view with required accuracy over a long period of time. In our practice, we have successfully tracked low-orbit objects moving at a rate of about 1 deg/sec.

As noted previously, telescope motion control is implemented using the Galil Motion Control controllers of the DMC-21 × 3 and DMC-41 × 3 series. The software provided to users includes both API for various high-level programming languages and its own macro command language. API is used to provide communication between the controller and the primary observation program that synchronizes the pointing to an object and exposure. The telescope stepper motor control module is written in the Galil macro language. Celestial coordinates and rates of the target object come to the input of this module via API. Subsequently, until new external commands are received, the controller, regardless of the main program, ensures object tracking at the specified kinematic parameters. This substantially reduces the load on the control computer, enabling it to control the camera and data processing pipelines.

Power supply management, opening and closing of the roof and southern shutter of the pavilion, as well as external pavilion lighting, are controlled via the MOXA ioLogik E1211 and E1214 remote input/output controllers, operated by software utilities using the MXIO library.

The software and the graphical user interface are written in Borland Delphi 7.0.

Remote computer control is implemented via Virtual Network Computing (VNC), enabling telescope startup and operation from any location with internet access.

5 ACS implementation

The automatic control system described above was put into operation at the AT-64 telescope (D = 640 mm, F/1.4) in 2007, with subsequent upgrades carried out in 2012. The telescope characteristics are presented in Fig. 3. The AT-64 is capable of tracking 120 scheduled objects during a six-hour night, acquiring three-minute exposure series without operator involvement. Figure 4 presents an example of telescope operation over a single night. Each square in the graph represents a three-minute set containing from 5 to 13 positions.

To refine orbits for all active and decommissioned objects in the geostationary region, the 22-cm Peephole-1 telescope (PH-1; D = 220 mm, F/2.3) was put into operation in 2005 (Fig. 3). At that time, the PH-1 did not yet have its own mount and was therefore mounted in parallel with the AT-64 telescope. On October 13, 2005, the first *trial* survey of the geostationary region was conducted with this telescope. This was the first survey within the CIS countries capable of refining the positions of all objects in the geostationary region up to 16 mag within a single night. Subsequent upgrades and automation of the telescope allowed regular surveys of the geostationary region to be initiated in 2007. The telescope was co-located with the AT-64 in the same pavilion, and both were controlled by a single four-axis Galil DMC-2143 controller. The telescope has a detector with a field of view of 17 sq. deg, enabling sixfold coverage of the visible part of the geostationary region, which is 20 deg in width, during a single night.

In 2012 and 2013, the new Peephole-2a and Peephole-2b telescopes (PH-2a and PH-2b; D = 180 mm, F/1.6) were put into operation (Fig. 6). With an objective diameter of 18 cm and a field of view of 51 sq. deg, these telescopes substantially increased the survey rate and enabled a significant extension of the observed arc for registered objects. They are used for surveying the geostationary region and the apogee region of Molniya-type orbits. Figure 7 presents the results of PH-2a operations on October 31, 2022. During the night, more than 13 000 positions were derived for 437 objects up to 16 mag. The results of observations in 2022 are shown in Fig. 8. A total of 2083 objects were observed with this telescope, yielding more than 1.4 million positions. The gaps in the figure near 5–7 h in right ascension are associated with unfavorable weather conditions during the winter period. In contrast to geostationary objects, there is only one class of highly elliptical objects that can be observed in survey mode: Molniya-type objects near the apogee regions of their orbits. Near apogee, spacecrafts have low angular velocities, and consequently the apogee regions of all orbits form a ring of about 14 deg in diameter around the north pole, which can be covered by observations in survey mode. As an example, Fig. 9 presents the results of the survey conducted with the PH-2b on February 10, 2023. Over a year, such surveys densely cover the ring around the pole, registering all objects residing in these orbits (Fig. 10). Under clear-sky conditions, the surveys described have been carried out on every clear night up to the present.

Selected ACS components, including telescope control, were also used at the Zeiss-600 telescope (Crimean Station of the Sternberg Astronomical Institute, Moscow State University) during 2005–2012. Owing to the limited fine motion in declination on the standard Zeiss-600 mount, telescope pointing was performed in manual mode, while all other operations were carried out automatically.

It should be noted that the FLIGrabber program for controlling FLI equipment has also been used at other telescopes: the primary focus of the ZTSh telescope since 2005, the AZT-11 during 2006–2023, Zeiss-1000 (Simeiz) during 2007–2008, and the ZTE (Crimean Station of the Sternberg Astronomical Institute, Moscow State University) during 2008–2011.

6 Conclusions

The automatic telescope control system that has been developed and put into operation ensures the implementation of all the tasks described above.

As a result of commissioning the ACS, operator duties were reduced to the following:

- at the beginning of the night:

  - remote or local software-based observation scheduling;
  - remote opening of the pavilion and power supply management for the telescope and detector;
  - control of the telescope coordinate system;
  - sending the command to perform a survey or tracking according to target designations;
- during the night:
  - monitoring and short-term weather forecasting;
- at the end of the night:
  - remote power outage;
  - remote closing of the pavilion.

Processing the acquired images lies beyond the scope of this paper; however, it should be noted that the image processing pipeline runs and begins operation immediately after the start of observations.

At present, three telescopes (AT-64, PH-2a, PH-2b) are in active operation, conducting observations of objects in near-Earth space. The ACS described in this paper has enabled more effective observational campaigns for cataloging small-size objects in the geostationary region. Introducing ACS allowed CrAO researchers to carry out a continuous 16-year monitoring of the geostationary region and a 10-year monitoring of Molniya-type objects, which is a record among CIS observatories involved in near-Earth space research.

Sixteen years of failure-free operation have demonstrated the reliability of the developed control system, while the acquisition of more than 20 million measurements of coordinate and photometric information has shown its efficiency.

Further development of the ACS is associated with robotization of telescopes, which is expected to include dynamic scheduling of observations, automated monitoring of the sky condition, response to hardware faults and errors, and the implementation of the operator duties described above. Ultimately, the robotic telescopes will be capable of conducting observations autonomously over extended periods (weeks, months) without human involvement.

Acknowledgments. We express our deep gratitude to Yaroslav Kirillovich Golovanov (1932–2003). The financial support he provided in 2000 allowed us to take the first steps toward automation of the AT-64 telescope.

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