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Observations of artificial space objects with the 2.6 m Shajn Telescope at the Crimean Astrophysical Observatory

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ABSTRACT

The paper provides an overview of studies of artificial objects in the near-earth space, which have been carried out with the Shajn telescope since 2005. One of the study objectives was to develop a technique for observing and cataloging small objects (~10–25 cm) in the geostationary orbit with a brightness of 18–20^m. Despite the strong limitation of observational time, the use of Shajn telescope for solving this problem was quite effective. It is shown that it is possible to detect and catalog small-size objects in the geostationary orbit even with a telescope with a small field of view (~8–12 arcmin).

A new modern device (panoramic CCD photometer) was created and placed at the prime focus of the Shajn telescope to solve tasks of searching for faint, highly variable, "dynamic" objects.

In the period from 2011 to 2021, the Shajn telescope carried out observations of distant spacecrafts Spektr-R, Gaia, Spektr-RG, and Mars-2020. Particular attention was paid to the Russian astrophysical observatory Spektr-RG in the halocentric orbit around the L2 Lagrange point of the Sun – Earth system. Observations of this scientific spacecraft are continuing to this day. The accuracy of the obtained astrometric estimates is such that the median values of root-mean-square errors in right ascension and declination are $0.055''$ and $0.075''$, respectively. The Mars-2020 spacecraft on the flight trajectory to Mars was observed at a distance of up to 6.5 million km as an object of 21.8^m.

The task of observing distant spacecrafts remains relevant for identifying artificial objects among numerous natural ones detected in the near-earth space.

Key words: near-earth space, geostationary orbit, artificial space objects, small space debris, distant spacecrafts

1 Introduction

Observations of artificial space objects with ZTSh (CrAO) can be divided into two stages.

The first stage took place between 1962 and 1973. It was associated with observations of the first distant spacecrafts launched to the Moon and Mars. At that time, there were simply no radio-technical facilities to control the position of spacecrafts in space; therefore, the direct optical observations of distant spacecrafts were used for the mentioned purpose. This part of the history of ZTSh is outlined in detail in a series of publications (see, e.g., Prokofjeva-Mikhailovskaja, 2008). It is worth noting that for 11 years the observations of 19 spacecrafts were carried out, 14 of them launched to the Moon, including fly-by trajectories, and 5 toward Mars.

The second stage of observations for objects in the near-earth space was associated with investigations of the small-size "space debris" in the geostationary region (from 2005 to 2012), as well as observations of the selected distant spacecrafts, which are currently being conducted.

In 2003, the employees from the Keldysh Institute of Applied Mathematics (KIAM) V.M. Agapov and I.E. Molotov asked us to find and observe the small-size objects in the geostationary region in order to construct based on them a reliable orbit for subsequent cataloging. Speaking about small-size objects, we imply faint objects with a brightness less than 16^m, which corresponds to the sizes less than 1 meter in the geostationary orbit (GSO).

At that time, the observations of small-size space debris had already been carried out, but these works had mainly statistical nature. For the insurance of new spacecrafts it was required to estimate the risks of their collision with space debris. To this aim, the theoretical models of "contamination" of the near-earth space were created, whereas the appropriate observations were conducted for the verification of these models. In the course of this work, the objects that transit in the field of view of the stationary telescope were counted. The size of objects was estimated by brightness and mean albedo. Such "verified" observations in Europe and USA were carried out periodically. The obtained results made an important but strongly limited contribution to the study of space debris. There was no question about cataloging such objects.

Until recently (early 2000s), the study of GSO contamination was mainly based on the regular updates of orbital data produced and distributed by the US Space Surveillance Network, as well as on the observations acquired within the

ZTSh, primary focus

F = 10 000 mm
D = 2 600 mm
CCD: FLI PL-1001E, 1024 × 1024 @ 24 mcm
Scale: 0.5 arcsec/pix
FOV: 8.4 × 8.4 arcmin
Limit mag GEO: 20 m @ 1 sec

Fig. 1. Shajn's reflector.

coordinated observation campaigns under the aegis of the Inter-Agency Space Debris Coordination Committee (IADC) (Technical Report on Space Debris, 1999). These observations showed the presence of a great number of objects of various brightness in a range of 15–20^m (and, correspondingly, of various sizes) in the GSO region. Using this observational technique, there was no possibility to construct the reliable orbits of the recorded objects (Klinkrad et al., 2005; Seitzer et al., 2005; Schildknecht et al., 2001).

The active observations of the small-size space debris were also carried out with the Zeiss 1-meter telescope at the Teide Observatory on the Tenerife island (Schildknecht et al., 2005). They showed a number of uncataloged objects in the geostationary region. But these investigations were more statistical and did not make it possible to trace the detected fragments for a long time. Thus, it was impossible to estimate the precise orbits and catalog objects (Schildknecht et al., 2005).

The fragments of disrupted artificial Earth satellites comprised a considerable part among the observed objects. The fact that the artificial objects are disrupted in the geostationary region was indirectly manifested in the occasionally detected significant sporadic changes of their orbital elements. Slow variations of orbit elements abruptly change with time; this is a clear sign that something occurs with an object (Sochilina et al., 2001, 2002). By the late 1990s, several cases of the destruction of objects in the geostationary region had been known. But their locations and spatial distributions of fragments remained unclear. A search for their fragments and a study of population of the disrupted objects were important for assessing a risk of collision with them.

With this purpose, test observations were started with the partially automated telescope AT-64 (D = 640 mm, F/1.4) since 2003. They were carried out based on both individual search programs and in cooperation within the IADC observational campaigns. As a result of these studies, new objects of near space were detected, not being involved into the public catalogs of more developed American means for near-earth space surveillance (Agapov et al., 2005a, b). Their brightness reached 17–18^m, whereas the astrometric accuracy of measurements was better than 1$''$, which had not been achieved earlier by locally produced surveillance means. The first object at number 90003[1] was cataloged on October 18, 2004.

In some cases, objects with strongly variable brightness were detected; they had not been recorded in their minimum with a 64 cm telescope. Moreover, faint objects lost their brightness more at large phase angles, which limited their measuring arc. And most importantly, it was of interest to estimate the population of near-earth space by objects weaker than 18^m. This circumstance required larger telescopes to be involved. To this aim, the observations at the primary focus of ZTSh – the largest CrAO telescope – were resumed in 2003. Such observations had not been carried out with this telescope since 1963. In fact, the total alteration of the primary focus cassette was required because all the previous versions were intended for using photographic plates as a detector. The available field correctors were designed for different spectral bands and a very short back segment. The manufacturing of a modern photometer of the primary focus with the CCD detector gave a new life for panorama observations at ZTSh.

It is worth noting that ZTSh in the used configuration has a primary focus of 10 m. At that time, we used the CCD camera FLI IMG-1001E as a detector; this device was provided by the KIAM employees, which gave a field of view of just 8.4 × 8.4 arcmin (Fig. 1). Such a field of view is very small for exploration. Nonetheless, a technique for observations and searching for extremely faint objects in the GSO was developed and tested.

As a result of a set of works it was detected a significant number of faint fragments up to 20^m, which at the distance of the geostationary region corresponds to a size of 10 cm! The long focus of ZTSh enabled the accuracy of the observed faint objects to be increased. As an example, Fig. 2 shows the residuals of the object 90024 observed with ZTSh on September 19, 2006. The root-mean-square (RMS) errors of the position were 0.23$''$ in RA and 0.22$''$ in Decl.

ZTSh is a primarily astrophysical telescope used by CrAO researchers for spectral and polarimetric observations of stars

[1] In this article, the numbering of objects corresponds to their number in the KIAM catalog

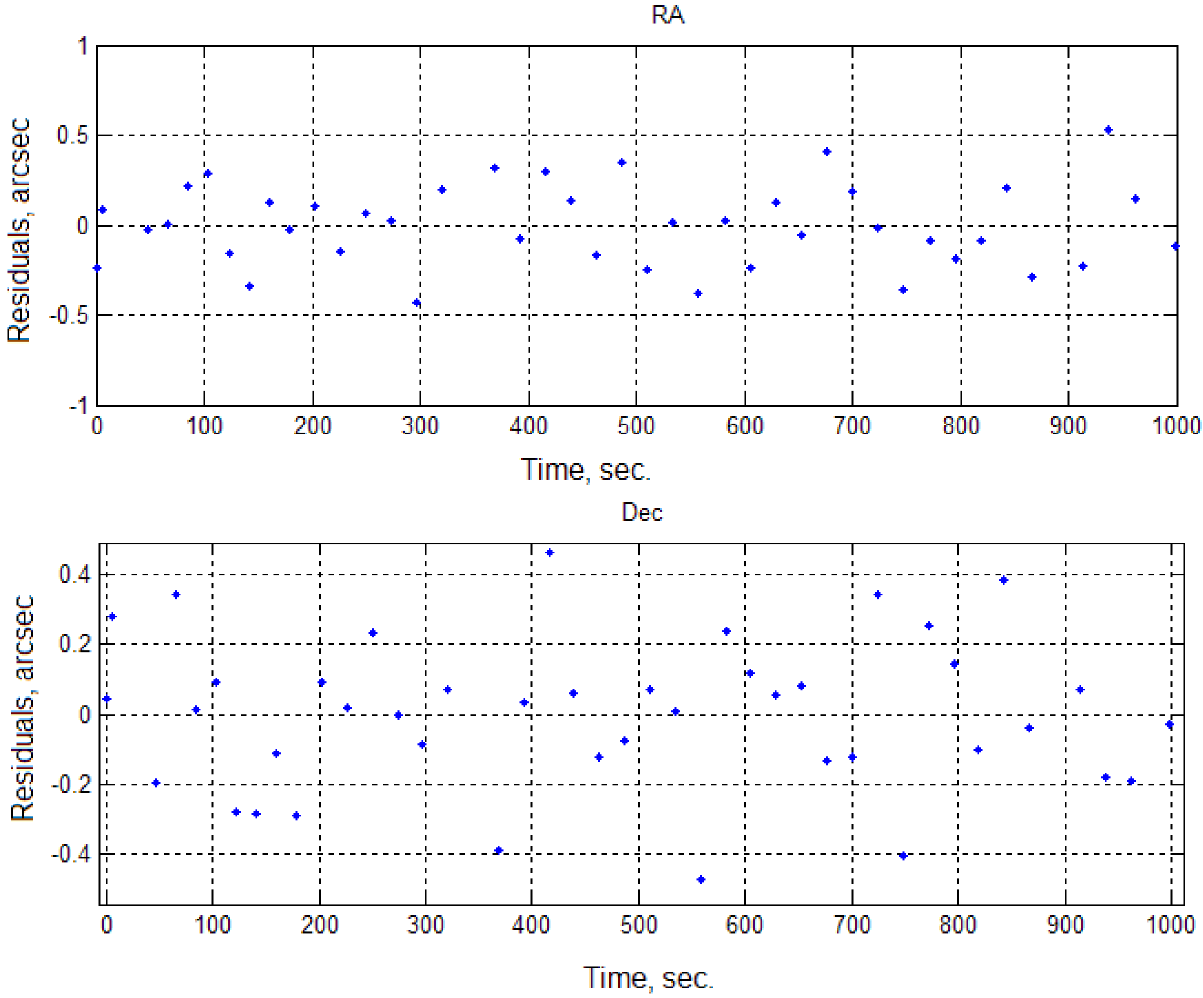

Fig. 2. Position residuals of the object 90024 observed with ZTSh on September 19, 2006.

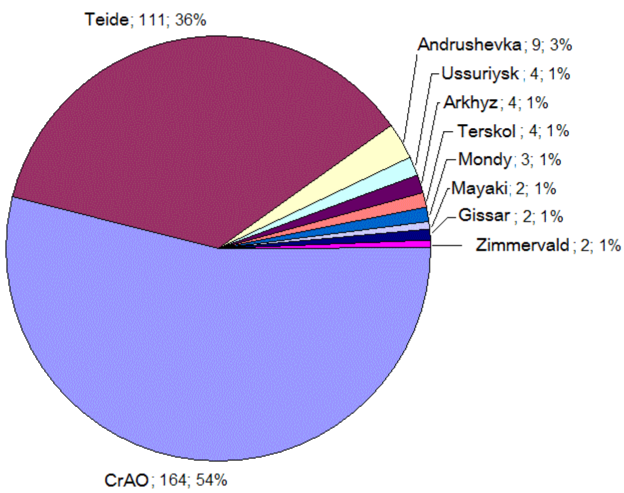

Fig. 3. Distribution of the cataloged small-size objects according to the data from observatories in the period between 2007 and 2009.

and galaxies. No more than 3 nights per month were allocated for our objectives (we are grateful to R.E. Gershberg who was the Head of the Laboratory of Stellar and Galactic Physics at that time and actively supported our project). Nonetheless, the rates of discoveries of new small-size objects with ZTSh per month were higher than with any other telescope (Fig. 3). This, in turn, had generated one more problem. The faint objects detected with ZTSh could not be further observed, and the next observation run occurred only in a month. This caused the loss of objects. To overcome this problem, we had to make stricter requirements for the measuring arc length of the detected objects. In addition, we began to elaborate a technique for searching for objects along the trajectory at the telescopes with a small field of view. The undertaken actions allowed us to find some objects even in a month after their first detection. Moreover, the 1 m telescope Zeiss-1000 on Mount Koshka not far from Simeiz was applied to support observations of faint objects. During the downtime, due to limitations in the observational time, the equipment of the ZTSh primary focus was brought to Simeiz. Observations were carried out for several nights, after which the equipment was returned. Observations with the 1 m Zeiss telescope were partially useful to support the validity of orbits for faint objects, which made it possible to reduce the number of losses of new objects detected with ZTSh, but it could not substitute the full-value ZTSh observations.

In a year of such observations it became obvious why after the war G.A. Shajn initiated the transferring of the observatory from Simeiz to the current location – settlement Nauchny. The proximity to the South ridge of the Crimean Mountains on the one hand and to the sea on the other hand created unfavorable seeing conditions for observations. Moreover, "the rise of wild capitalism" on the south coast of the Crimea in the early 2000s and decreased protection of astronomical institutions from excessive light (which is still ongoing) just made things worse. After two years of active supporting the space debris observations in Simeiz were ceased and relocated.

During a close interaction with researchers from the Crimean Laboratory of Sternberg State Astronomical Institute MSU we were able to involve instruments of the South Station – Zeiss-600 and Engelhardt reflector with apertures 60 and 125 cm, respectively. Observations with these telescope were not so intensive, but they proved to be useful while working out an observational technique, as well as enabled a few fairly faint objects in the GSO region to be detected and cataloged.

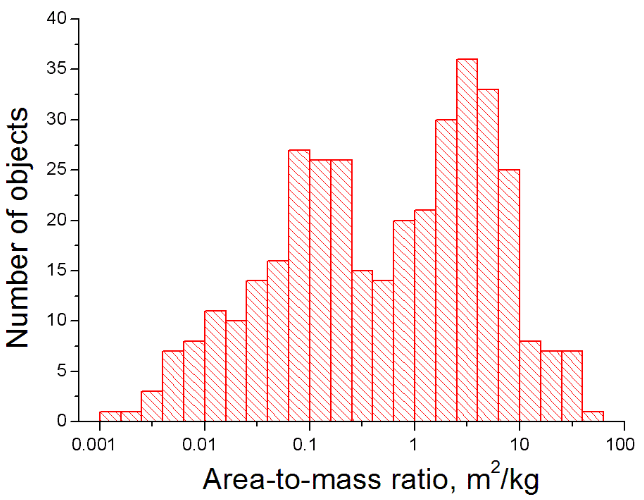

Fig. 4. Distribution of the area-to-mass ratio for 367 objects at the end of 2011.

As a result, the rates of discoveries were so high that CrAO at that time occupied the leading positions among other observatories involved in the described studies.

One of significant achievements of the first years of collaboration between observers and ballisticians was a confirmation of the existence of "clouds" of fragments in the GSO region generated by the destruction of the Ekran and Transtage spacecrafts. The more significant result was an independent confirmation of the existence of small-size objects with such a high area-to-mass ratio (AMR) that the effect of light pressure leads to substantial evolution of their orbits and makes impossible a long-term prediction of trajectories. To date, the objects with an area-to-mass ratio of up to 70 m^2/kg have been detected; they are literally "swept away" by solar radiation (Fig. 4). Note that the typical AMR values for spacecrafts lie in a range of 10^{-3}–10^{-2} m^2/kg. Owing to intensive observations and qualitative ballistic calculations, such objects can be traced without being lost for a long time.

2 Distant spacecraft observations

The optical observations of distant spacecrafts also remain to be in demand in the 21st century. Between 2011 and 2021, the observations of spacecrafts Spektr-R, Gaia, Spektr-RG, and Mars-2020 were carried out with ZTSh. Among them the following are worthy of attention.

At the end of 2014, within the works on estimating possibilities of applying ground-based optical observatories for Spektr-RG observations on the flight trajectory and in the vicinity of the L2 libration point of the Sun – Earth system the test Gaia observations were carried out at CrAO RAS and ISTP SB RAS.

The Gaia spacecraft – a space optical telescope elaborated by the European Space Agency – was launched in the vicinity of the L2 point on December 19, 2013, whereas it entered the halocentric orbit around L2 on January 8.

Two runs for observing Gaia (from 21:05:11 to 23:39:58) were carried out with ZTSh on October 26, 2014; twenty-six positions were totally acquired. The weather was not favorable in the time available; therefore, the number of observations was limited. The object's brightness was 20.2–21.2^m. The RMS errors of residuals were 0.35 and 0.36″ (Zahvatkin, 2015). We present the comparison Table 1 of the observational accuracy at two telescopes.

Table 1.

Telescope	Observation interval	Number of positions	RMSE RA (arcsec)	RMSE Decl (arcsec)
AZT-33IR, 1.5 m ISTP SB RAS	September 24 – October 1, 2014	45	0.56	0.73
ZTSh, 2.6 m CrAO RAS	October 26, 2014	26	0.35	0.36
AZT-33IR, 1.5 m ISTP SB RAS	November 12–26, 2014	35	0.77	0.34

Spektr-RG (2019-040A)

Gaia (2013-074A)

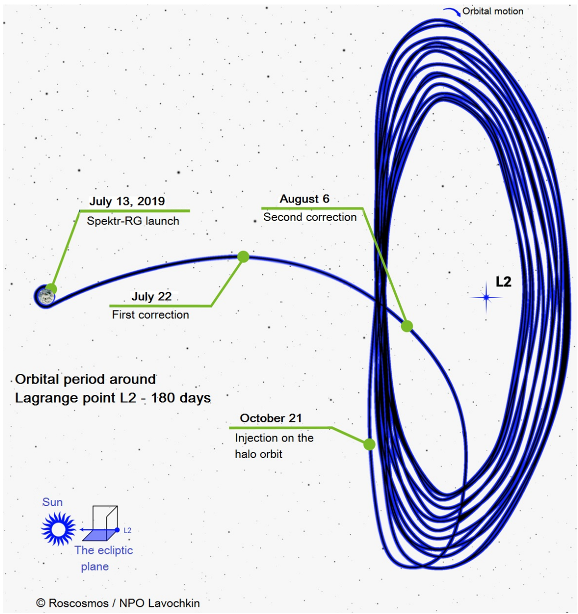

Fig. 5. Trajectory of putting the Spektr-RG X-ray observatory into the L2 point ((c) Roskosmos).

The Spektr-RG X-ray observatory (44432) was launched from Baikonur Cosmodrome on July 13, 2019; it was intended for building a full map of the visible part of the Universe in the X-ray radiation range. The observatory was put into the halo-orbit around the L2 Lagrange point located at a distance of 1.5 million km from the Earth (Fig. 5).

Astrometric observations of Spektr-RG were carried out upon the request of our colleagues from KIAM RAS and Space Research Institute (SRI) RAS and aimed at clarifying the spacecraft trajectory and minimizing fuel consumption during planned orbit corrections.

Right after the launch, the observations at the AT-64 telescope were started and continued at AZT-11 and ZTSh with the aim of controlling the spacecraft motion and correcting its orbit. Over 86 observation runs ($\sim$ 3000 positions) were performed during 75 nights, which are still going on. The typical RMS errors of position are $0.23''$ for AT-64, $0.15''$ for AZT-11, and $0.07''$ for ZTSh (Fig. 6).

The DM-03 upper stage, unlike Spektr-RG, went into the heliocentric orbit. It was also observed up to the termination of its visibility. The latest observations were carried out with ZTSh on November 27, 2019 at a distance of 4 million km as an object of 21^m.

Mars-2020 (2020-052A)

The Mars-2020 spacecraft with the Perseverance rover was launched in the USA on July 30, 2020 to explore Mars. Its observations on the departure trajectory to Mars were started

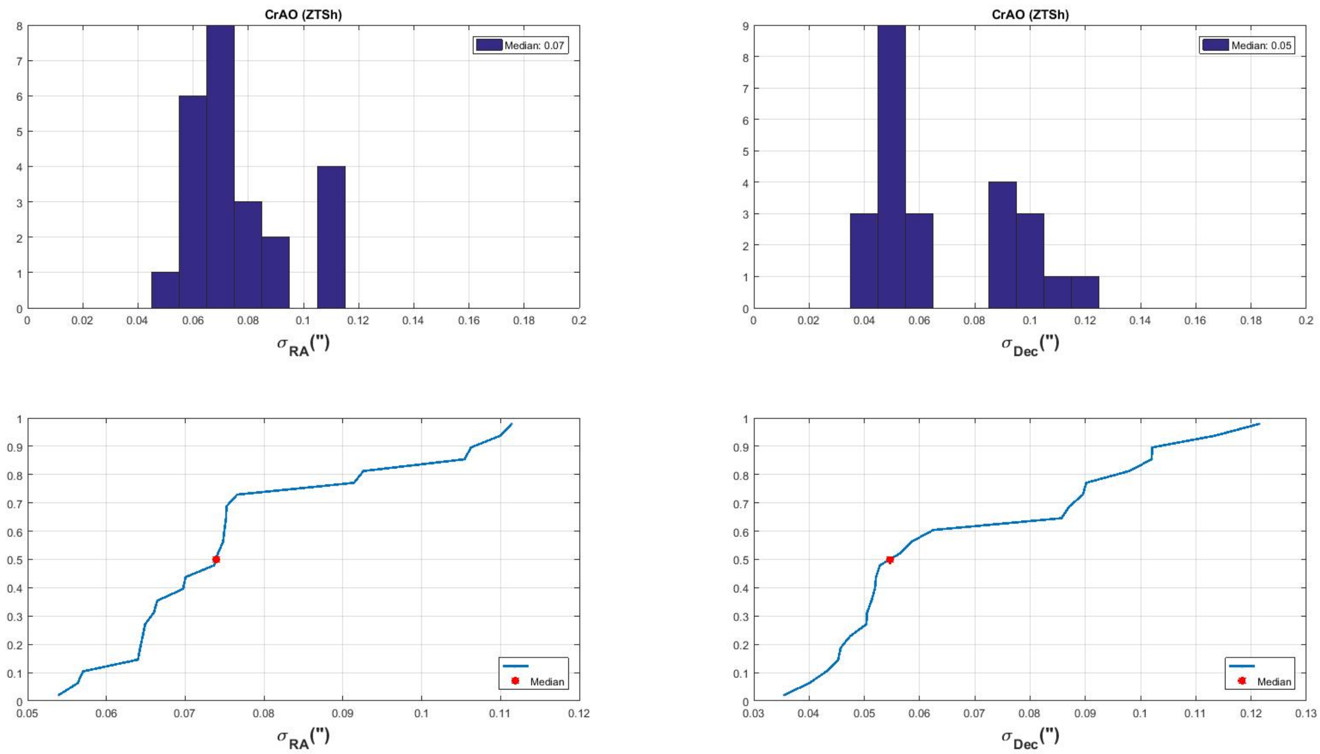

Fig. 6. Histograms of the RMS error distribution in RA and Decl (upper row) and the cumulative function (lower row). The red dot corresponds to the median value.

Table 2.

Date	Time, UT	#pos	Duration (min)	Mag	std pos (arcsec)	Range (10^6 km)
2020 08 14	23:49–00:02	4	12.5	21.2	0.09 0.06	5.18
2020 08 15	00:49–01:21	13	31.7	21.2	0.17 0.27	5.20
2020 08 15	21:53–22:04	4	10.5	21.6	0.02 0.01	5.48
2020 08 19	00:40–00:55	7	14.7	21.8	0.23 0.12	6.50

at AT-64 on July 30 and continued at ZTSh on August 14, 15, and 19.

The observations were aimed at practical determining the limits of optical positional observations at maximal distances.

Four runs (129 positions, a total observational interval of 3 hours) were obtained at AT-64; the position errors accounted for 0.15–0.23″ at a brightness of objects of 14.5–14.8^m. At that time, the distance to the object was 0.001 a.u. (∼ 150 thousand km).

Two weeks later, the ZTSh observations were started. Four observational runs (28 positions, Table 2) were performed during three nights on August 14, 15, and 19, 2020.

Mars-2020 was 5 million km away at that time. The observations were carried out with an exposure of 2 min, the object's brightness was less than 21^m. The apparent motion velocities were 1″/min and less. The latest observations carried out on August 19 at 00:50 UT were acquired 6.5 million km away. The object's brightness was 21.8^m at a phase angle of 51 degrees. The position accuracy amounted to 0.1–0.2″.

3 Conclusions

The work on space debris carried out with ZTSh has shown that this telescope is a "machine of discoveries".

ZTSh made it possible to catalog objects of about 10 cm in the GSO. The time spent for searching for a new object amounted to about 10 minutes. These objects typically have high area-to-mass ratios, which required a regular control of their trajectories.

Photometric observations of the selected objects showed a strong variability; the brightness difference accounted for a few magnitudes, but in some cases it exceeded 5^m, which indicates the "irregular" shapes of such objects. Most likely these may be flat elements of spacecrafts' constructions or fragments of screen-vacuum isolation. The astrometric measurement accuracy of 18–20^m objects amounted to 0.2–0.5″.

But the workload of ZTSh with other astrophysical tasks, little time available to solve a task, and the absence of appropriate optical support have led us to the completion of space debris studies with this telescope.

Observations of distant space objects are relevant not only to control the trajectory (independent of radio-technical facilities) but to identify artificial objects among natural ones (Buzzoni et al., 2019). Indeed, more near-earth asteroids have recently been discovered. This space region has actively been controlled for the latest two decades. One-two thousand such objects are discovered every year. Among them there are artificial objects – spent rocket stages, interplanetary spacecrafts launched between the 1960s and 1970s. For instance, the 2010 KQ object may be a spent fourth stage of the launch vehicle of the Luna-23 station (Miles, 2011; Yeomans et al., 2010). In 2020, the Center for Minor Planets registered an object tentatively numbered 2020 SO. After further investigations it proved to be an upper stage of the launch vehicle Centaur, which was used to deliver the Surveyor 2 lander on the Moon in 1966 (O'Neill, Handal, 2020).

In addition, a number of objects detected during the asteroid sky surveys seem to have an artificial origin. Jonathan McDowell from the Harvard-Smithsonian Center for Astrophysics notes that there were "a number of awkward incidents when objects in far orbit... had been preliminary designated as asteroids a few days before it became clear that these were artificial" (Dunn, 2020).

Obviously, due to the small sizes of stages and vehicles, and taking into account large distances to objects in heliocentric orbits, one fails to observe them for a long time interval. The only thing to do is to carry out observations of distant space objects at the maximum possible interval. It is preferable to organize their monitoring similar to the AES monitoring.

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