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Small telescopes and their application in space debris research and space surveillance tracking

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Abstract. Space debris is an essential threat to the satellite infrastructure. Possible collisions with even small particles, e.g. 1 cm of size, can cause catastrophic events when the parent body, a spacecraft or an upper stage, breaks up into hundreds of small fragments. The space debris research and space surveillance tracking (SST) helps to discover, monitor and characterize these objects, identify their origins and support their active removal.

There are two major observations strategies recognized for optical observations. The optical surveys aim to discover new objects for cataloguing or for statistical purposes. The follow-up observations are performed for catalogued objects to improve their orbits or to investigate their physical characteristics. A majority of the systems are focused on the high orbital regions when objects' orbits have mean motion less than ~ 10 revolutions per day. For lower altitudes, so-called Low Earth Orbits (LEO), more complex tracking capabilities of the system are needed.

In our work we present applications of small telescopes in space debris area, their usage for surveys, tracking and cataloguing. We discuss the world's largest optical SST networks, individual space debris research telescopes as well as the space debris research program at the domestic 70-cm telescope installed at the Astronomical and Geophysical Observatory in Modra (AGO), Slovakia, which belongs to and is operated by the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia. We present products provided by these systems.

Key words: space debris – research – telescopes

1. Introduction

In the last 60 years the human space activities created an expansive population of unused and unwanted objects in the close vicinity of the Earth. This population is known as space debris (alternatively orbital debris) and poses a huge threat to the present and future space missions. Research and regular tracking is important to understand and protect against it. These objects move in various types of geocentric orbits, from low Earth orbits of several hundreds kilometres above the Earth's surface to geosynchronous orbits at the heights of about 35,800 km above the surface.

1.1. Space debris sources

The creation of space debris objects is a direct consequence of human space activities. The largest, and also easiest to monitor, are non-functional payloads and spared rocket bodies (R/Bs). More than 97 % of total mass situated on the Earth orbit is concentrated in this type of debris along with functional spacecrafts (Liou, 2011). The mass of the International Space Station (ISS) is not included. The most abundant portion of objects larger than 10 cm are fragments from payloads and rocket bodies, fragmentation debris. Shapes, sizes and material types of this kind of debris differ from piece to piece. Many additional objects can be discharged during a spacecraft's launch - heat covers, launch adapters and objects lost by astronauts are all part of mission-related debris. All aforementioned objects can reach brightness and sizes detectable by the ground-based optical systems.

A specific type of debris are particles with small additional velocities, released from spacecrafts caused by unknown mechanisms, called anomalous debris. One of the representatives of anomalous debris is multilayer insulation (MLI), a material used as a thermal protection for sensitive systems placed on board of spacecrafts. During a breakup event, or under the influence of space environment (impacts from small particles, extreme ultraviolet radiation), the MLI parts can degrade and be released to the space environment.

1.2. Space debris spatial distribution

Spatial distribution of the debris population is directly associated with orbits used for satellite operations. The Low Earth orbit (LEO) is the most populated. Satellites on LEO have mean altitudes lower than 2,000 km above the surface, which corresponds to orbital periods P below 2.2 hours. According to the website www.space-track.org (hereafter public catalogue) of the United States Strategic Command (USSTRATCOM) (see also section 2.1), almost 80 % of catalogued objects are situated on LEO. Medium Earth orbits (MEO) have P from 2.2 hours to 24 hours and a wide range of eccentricities. Global navigation satellite systems' (GNSS), like European navigation system Galileo, US Global Position System (GPS) and Russian Globalnaya navigatsionnaya sputnikovaya sistema (GLONASS), are part of GNSS operate on MEO orbits. GNSS have circular orbits with $P \sim 12$ hours and orbital inclinations between 60° to 70°. Eccentric MEO orbits, marked as a geosynchronous transfer orbit (GTO) and Molniya orbits, are very common too. MEO is mostly populated by rocket bodies, fragmentation debris and mission-related debris. A unique type of the orbit is the geosynchronous Earth orbit (GEO). GEO has $P \sim 24$ hours, low inclinations (i from 0° to 15°) and low eccentricities. According to the public catalogue (see section 2.1) about 7 % of the catalogued objects are placed on GEO, mostly payloads and rocket bodies. For better visualization of the spatial distribution see Fig.1.

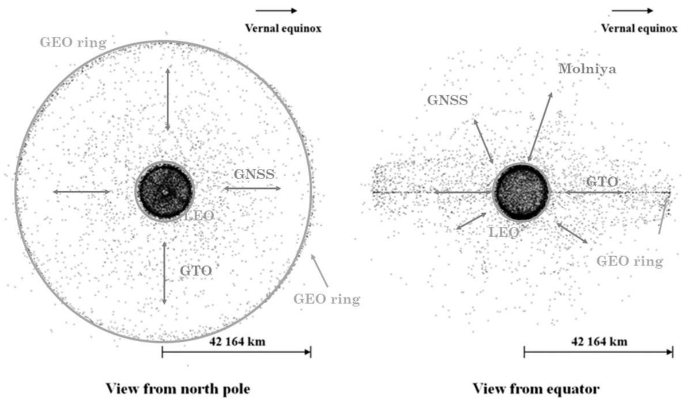

Figure 1. Space debris spatial distribution. Data generated by the using public catalogue www.space-track.org (Šilha , 2012).

1.3. Optical observations

Two major observation strategies are recognized for space debris optical observations. Optical surveys aim to discover new objects for cataloguing or for statistical data collection. Tracking (follow-ups, FUPs) of and observations on catalogued objects are performed to improve their orbits or investigate their physical characteristics. A majority of optical systems are focused on high orbital regions where objects' orbits have mean motion less than ~ 10 revolutions per day. Moreover, more complex system capabilities are needed for LEO tracking.

Space debris research helps to improve the understanding of creation mechanisms of space debris. The research characterizes the debris dynamical (e.g. orbital elements) and physical properties (e.g. surface material); it analyses the attitude information (e.g. through light curves) for supporting the debris mitigation efforts, deals with the models of the spatial distribution for small populations (from μm to cm), etc. In general, space debris research is performed by using optical, radar and in-situ techniques.

So-called space surveillance and tracking (SST) is responsible for regular tracking by using optical (passive and active) and radar systems. This service requires orbit determination and maintenance of a catalogue. When compared to the research function, SST is a service which requires a network of sensors coupled with the real-time data acquisition and processing (Šilha et al., 2017a).

2. Surveillance networks

To cover a large part of a specific orbital region one needs to use the network of dedicated sensors. For the SST application, there are several networks which provide constant monitoring of debris.

2.1. USSTRATCOM network

The primary network and the source of orbital elements providing the most extensive data set is operated by the United States Strategic Command (USSTRATCOM). It consists of several ground-based radar and optical sensors and one space-based telescope. The USSTRATCOM network covers all orbital regions, from LEO up to GEO. The network has been operational since 1957 and it focuses on tracking objects larger than 10 cm in diameter by using radar and optical means. The USSTRATCOM's catalogue contains the mean osculating elements in a form of TLE (Two-Line Elements) and it is publicly available at www.space-track.org. In June 2018 the public catalogue contained orbital data for almost 17,000 objects from which almost 80% were situated on LEO. Fig. 1 was generated by using the public catalogue data.

2.2. The International scientific optical network

The largest civilian network performing the SST function is the International scientific optical network (ISON) operated by the Keldych Institute of Applied Mathematics, Russian Academy of Sciences, Russia. There are more than three dozen of observation facilities worldwide contributing to the ISON network. ISON is continuously increasing its coverage and currently contains 90 telescopes with apertures in range from 0.125 m to 2.6 m (Mokhnatkin et al., 2017). A majority of the telescopes' operators are from academic institutions. ISON focuses on the cataloguing and research of objects on higher orbits and Near Earth Asteroids (NEA). Three ISON telescopes, a 64-cm AT-64 (a), a 2.6-m ZTSh in Nauchniy-1 (b) and a new 50-cm VT-40/500 in Ussuriysk (c) are shown in Fig. 2. The 2.6-m ZTSh telescope, situated in Nauchny, is the telescope with the largest aperture from all sensors contributing to ISON.

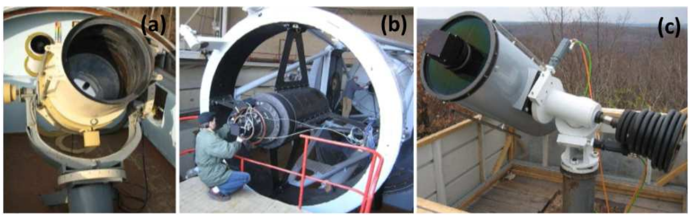

Figure 2. Examples of ISON telescopes for the faint fragment observations: a 64-cm AT-64 (a) and a 2.6-m ZTSh in Nauchniy (b) and a new 50-cm VT-40/500 in Ussuriysk (c) (Molotov et al., 2014).

The geographic distribution of the ISON telescopes and its cooperating telescopes as to 2017 are plotted in Fig. 3. Most of the ISON telescopes are situated in the Russian Federation but are continuously deployed to other locations such as South and North America, Australia and Africa.

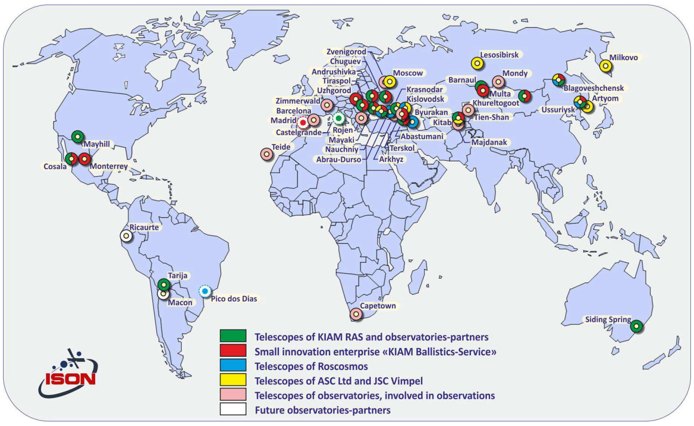

Figure 3. Geographical distribution of sensors participating to the ISON (Mokhnatkin et al., 2017).

3. Research telescopes

A single sensor is not able to cover any mentioned population completely and is usually used to acquire statistical information about a specific orbital region by using sky surveys, or to acquire scientific data for a specific object. This data can be further used for the improvement of the space debris model such as ESA MASTER (Flegel et al., 2011) and NASA ORDEM (Krisko et al., 2015), or to study physical characteristics of selected objects. There are dozens of telescopes dedicated to the research of space debris. This section discusses only a representative fraction of it. Some of these presented systems can also perform the SST functions.

Basic characteristics of presented systems are listed in Table 1. The 1-m ESA Space Debris Telescope (ESASDT) is situated at the Optical Ground Station (OGS), Canary Islands, Tenerife (Spain) and is operated by the European Space Agency (ESA). The MODEST telescope (Michigan Orbital DEbris Survey Telescope) is situated at Cerro Tololo Inter-American Observatory (CTIO) in Chile and is operated by the University of Michigan in cooperation with the National Aeronautics and Space Administration (NASA). ZIMLAT (Zimmerwald Laser and Astrometry Telescope) is situated at the the Swiss Optical Ground Station

Table 1. Configurations of selected optical telescopes used for the space debris research.

Operator	*ESA*	*NASA*	*AIUB*	*FMPI*
Telescope	*ESASDT*	*MODEST*	*ZIMLAT*	*AGO70*
Telescope design	Ritchey-Chretien	Curtis Schmidt	Ritchey-Chretien	Newton
Mount	Equatorial (English/Yoke)	Equatorial (Cross-axis)	Alt-azimuth	Equatorial (Open fork)
Camera	CCD	CCD	CCD/sCMOS*	CCD
Dimension	4096 x 4096	2048 x 2048	2048 x 2064	1024 x 1024
Primary mirror [m]	1.00	0.61	1.00	0.70
Focal length [mm]	4500.0	2135.0	4000.0	2962.0
Focal ratio	f/4.5	f/3.5	f/4.0	f/4.2
FOV [arc-min]	42.0 x 42.0	78.0 x 78.0	25.0 x 25.0	28.5 x 28.5
iFOV [arc-sec/pix]	0.62	2.30	0.70	1.67

*configuration with sCMOS not listed

and Geodynamics Observatory Zimmerwald (Switzerland) and is operated by the Astronomical Institute of the University of Bern (AIUB). The last listed telescope is a 70-cm Newton telescope (hereafter AGO70) of the Faculty of Mathematics, Physics and Informatics, Comenius University (FMPI) situated at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO).

Fig. 4 depicts all four telescopes, namely ESA OGS (a), NASA MODEST (b), AIUB's ZIMLAT (c) and FMPI's AGO70 (d).

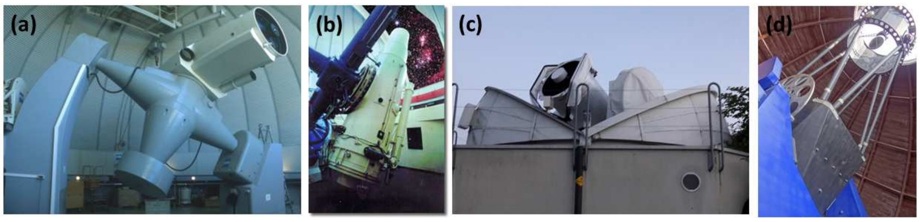

Figure 4. Selected optical telescopes used for the space debris research. Plotted is ESA OGS (a), NASA MODEST (b), AIUB's ZIMLAT (c) and FMPI's AGO70 (d). Photo credit: www.esa.int (a) and orbitaldebris.jsc.nasa.gov (b).

3.1. ESA ESASDT

For almost two decades the ESA OGS has dedicated its observation program to the continuous surveys of the GEO ring (Schildknecht et al., 2004). Additionally, surveys of GTO and Molniya orbits (Šilha et al., 2017b) are also performed. In 2004, Schildknecht et al. (2004) presented a discovery of a new population of objects: High Area-to-Mass Ration (HAMR) objects. As the name suggests, these objects have very high area-to-mass ratio (AMR), specifically above 1 m^2/kg. This population also showed a rapid change in orbital elements over time, mostly in eccentricity and inclination. This dramatic orbital change could be explained trough the AMR parameter and the solar radiation pressure as showed in Schildknecht et al. (2008). However, the origin and material type of HAMR objects remains unknown.

In 2017, Vananti et al. (2017) published the work where authors presented photometric and spectroscopic data of HAMR objects acquired by ESA OGS. They defined three categories of populations according to the colour indices B-V and R-I as plotted in Fig.5a. The authors confronted the defined categories with the reflectance spectra obtained for given objects and they classified the categories even further. High values of the R-I index are typical for category I, values for B-V index are between 0.8-1.3 and this category has monotonic increase in reflectance spectra with a concave-up shape. Category II has very high values for both the B-V index and R-I index - between 0.4-0.8 with monotonic increasing in reflectance spectra with concave-down shape. Category III has the low values for B-V and R-I indices and spectra relatively flat with possible negative shape in the blue range. Examples of reflectance spectra for categories II and III obtained for real objects E08152A and S95300, as well for representative materials gold and silver coating foil obtained in laboratory, are plotted in Fig.5b and Fig.5c, respectively.

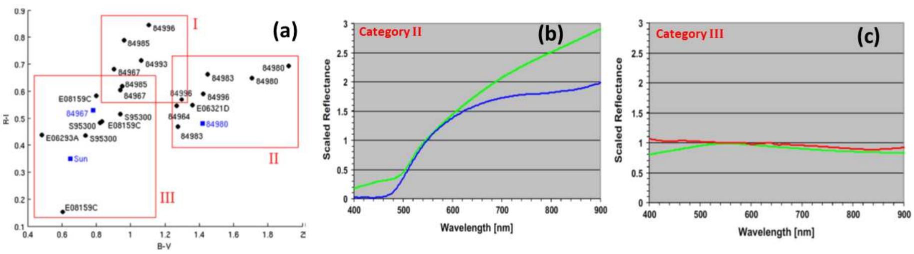

Figure 5. A diagram B-V vs. R-I of the observed HAMR space debris objects (a), reflectance spectra of the object 84980 (green) and gold MLI (blue) (b), and reflectance spectra of object S95300 (green) and silver MLI measured in laboratory (red) (Vananti et al., 2017).

3.2. NASA MODEST

The NASA MODEST system primary focuses on regular GEO surveys to monitor the population status over time. Each observed object is analyzed and classified as a correlated (CT) or un-correlated target (UCT) - whether the object is or is not in the public catalogue. Additionally, the preliminary orbital elements, assuming a circular orbit, such as inclination, right ascension of ascending node and mean motion are obtained. Once the FUP is performed, all six orbital elements are determined. Each object has extracted brightness in the R-filter. Consequently, also the size distribution of the observed population by assuming the Bond albedo of 0.175 is estimated. Fig. 6 plots the absolute magnitude distribution of GEO objects as observed by the MODEST telescope in years 2007-2010 (Seitzer et al., 2011). The absolute magnitude is calculated by correcting the measured magnitude to the zero-phase angle. Fig. 6 also indicates the size of an object by assuming the Lambertian sphere. For transformation from the absolute magnitude to the physical size, see e.g. Šilha (2012).

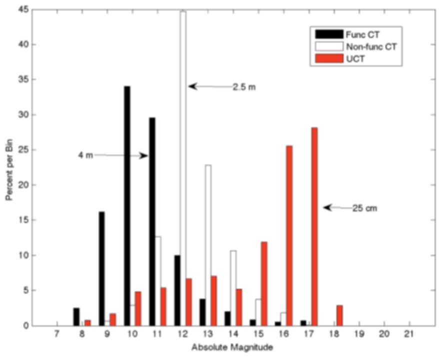

Figure 6. A histogram of R-magnitudes of GEO objects detected during 2007-2010 with the 0.6-m MODEST (Seitzer et al., 2011).

3.3. AIUB ZIMLAT

ZIMLAT is a hybrid system which is used either for SLR to cooperative targets, targets equipped with SLR retroreflectors (RR/RRA), or for optical observations (astrometric positions and magnitudes) of debris and Near Earth Asteroids (NEA). During daytime the system operates in an SLR mode only. During the night time the available observation time is shared between SLR and CCD/sCMOS (Šilha et al., 2016).

ZIMLAT focuses on the SST, as well as on the space debris research. It acquires astrometric data daily to support AIUB's cataloguing and photometric light curve catalogue used to monitor the rotation properties of space debris.

In Šilha et al. (2018) the authors presented the ZIMLAT space debris light curve database, which contained almost 2000 light curves for 400 individual objects situated on orbits from LEO to GEO. Once the light curve was pre-processed, three apparent attitude motion types for an object according to its light curve shape were distinguished. In case the light curve contains no pattern that would relate to the object's own rotation the object was classified as *stable* object. There were cases when a dominant pattern was present in the light curve, but no repetition was visible. Such objects were referred to as *slow rotators*. Finally, once the light curves contained a periodic pattern and the apparent period could be extracted, the object was marked as a *rotator*. The results obtained by ZIMLAT for the LEO population are plotted in Fig. 7. Almost 97 % of observed LEO objects showed stable or slow rotating behaviour and only 3 % of all observed LEO objects could be marked as rotators.

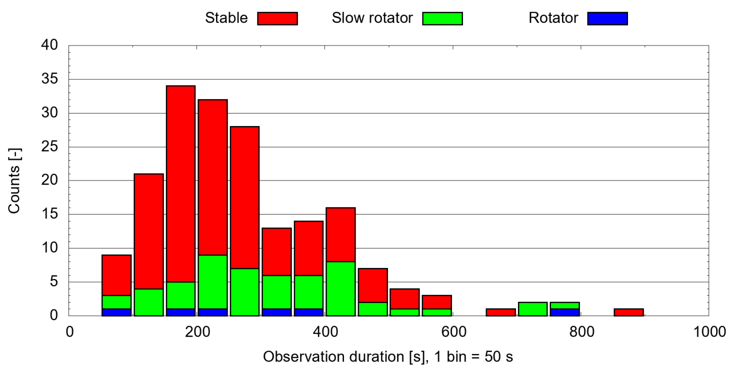

Figure 7. Distribution of acquired light curves durations for LEO objects. The width of one bin is 50 s (Šilha et al., 2018).

3.4. FMPI AGO70

FMPI's AGO70 is a relatively young system, installed at AGO in September 2016. Its observation program is dedicated to the space debris research, as well as to SST. There can be distinguished three major observation programs at AGO70 - the astrometry to support SST, instrumental photometry to characterize the debris attitude states, and absolute photometry to characterize the debris surface properties.

The system has been primarily developed thanks to the European Space Agency's (ESA) Plan for European Cooperating States (PECS) program, namely trough the contract no. 4000117170/16/NL/NDe, which supported the development of the system's software, hardware and observation programs (Šilha et al., 2018).

To evaluate the AGO70's performance for the SST application, Šilha et al. (2018) acquired 20 nights of observations of GNSS (Global Navigation Satellite System) satellites with the goal to identify and remove epoch bias (a constant epoch registration time shift in the measurements) from the astrometric measurements and to quantify the astrometric accuracy of the AGO70s data. This analysis has been performed by AIUB and it shows that for the last two months of observations in May and June 2018, the system behaved consistently, providing measurements with astrometric accuracies of 0.8-0.9 arc-sec. A systematic epoch bias, which reached consistent value of around 67.7 ms, has been identified. Results of the analysis for the specific night can be seen in Fig.8, where the system's astrometric accuracy (Fig.8a) and epoch bias (Fig.8b), as determined by AIUB, are plotted.

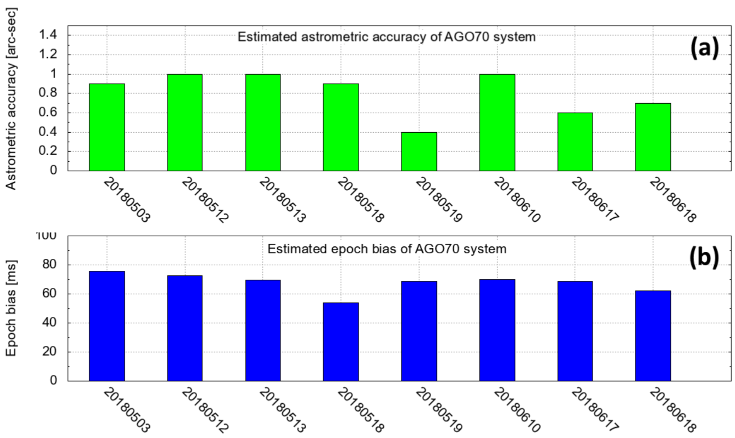

Figure 8. Estimated astrometric accuracy (a) and epoch bias (b) of AGO70 system. Data obtained from AGO70s GNSS measurements processed by AIUB (Šilha et al., 2018).

During the total duration of the observation campaign, which took place between May 2017 and June 2018, Šilha et al. (2018) acquired 339 light curves for 148 individual space debris objects. The example of a light curve for a non-operational satellite Gorizont 7 and its reconstructed phase diagram are plotted in Fig. 9. The satellite was observed in August 2017. To obtain the phase diagram and the apparent rotation period of 76.28s±0.005s the authors used a phase dispersion minimization method (Stellingwerf, 1978). From all observed objects, for more than 55% the apparent rotation periods could be extracted. For more details refer to Šilha et al. (2018).

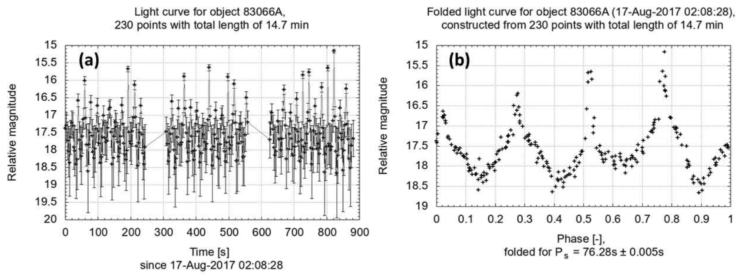

Figure 9. A light curve (left) and a folded light curve (right) acquired by the AGO 70cm telescope for the non-operational satellite Gorizont 7 (1983-066A).

4. Summary

Space surveillance of space debris is essential for space operations safety and long-term sustainability. Surveillance networks such as USSTRATCOM and the Russian ISON are widely using optical sensors/telescopes, which discover new objects and maintain their own catalogues. Both systems' data is publicly available and largely used by different subjects, from governmental entities and space agencies to academic researchers.

Individual research telescopes such as ESA OGS or FMPI's AGO70 can support surveillance functions, but they primarily focus on observations to acquire the physical characteristics of unknown debris objects. They can provide information about the surface material by using multi-band colour photometry and spectroscopy. Brightness variation, captured on photometric series (light curves) provide the information about the rotational properties, which is essential for the future active debris removal missions. A long-term monitoring of a specific orbital region through the optical surveys supports space debris models.

Small optical telescopes play a crucial role in space debris research and space surveillance tracking. Their role in space safety will increase in the next few years due to the large privatization of the space industry, which will bring new challenges like the mega-constellation projects. Therefore, it is important to constantly perform development of the dedicated telescopes, like AGO70.

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