AGO70 Telescope, Slovak Optical System for Space Debris Research, Surveillance and SLR Tracking Support

Jiří Šilha(1), Stanislav Krajčovič(1), Matej Zigo(1), Juraj Tóth(1), Leonard Kornoš(1), Pavol Zigo(1), Jaroslav Šimon(1), Srinivas J. Setty(2), Tim Flohrer(2), and Beatriz Jilete(3)

(1) Faculty of Mathematics, Physics and Informatics of Comenius University, Bratislava, Slovakia
(2) ESA/ESOC, Space Debris Office, Robert-Bosch-Strasse 5, DE-64293 Darmstadt, Germany
(3) ESA/ESAC, Space Safety Programme Office, Camino Bajo de Castillo S/N, 28692 Villanueva de la Cañada, Madrid, Spain

ABSTRACT

The Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI) operates its own Astronomical and Geophysical Observatory in Modra, Slovakia (AGO). AGO consists of several optical systems, some also developed by FMPI. One of those systems is a 70-cm Newtonian design telescope (AGO70) with primary focus on the space debris research and space surveillance and tracking (SST) to support the European attempts for autonomous SST operations. Slovak Republic is currently in the process of membership acceptance to the European Space Agency (ESA). A part of this process is the Plan for European Cooperating States (PECS) which is a program allowing the candidate countries to develop their capabilities to a competitive level before they fully join the ESA market. FMPI has been granted two consecutive ESA PECS projects so far to improve and develop missing functionalities at AGO70 to increase its data quality, data latency and overall efficiency.

In our work we present the AGO70 system's technical characteristics and observation programs. We introduce the overall design of the system and its functionalities. We will present the image processing pipeline which improves the obtained data's quality and latency. The planning, acquisition and processing of light curves, BVRI photometric data, and astrometric measurements will be discussed in detail.

1 Introduction and system design

The 70-cm Newtonian design telescope (AGO70) is situated at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO) (17°16'25.07"E, 48°22'21.11"N, 536.1 m), which is roughly 40 km north from Slovakia's capital. The system is operated and owned by the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI). It has several parallel scientific programs with primary focus on space debris characterization from low-earth orbits (LEO) up to high altitude orbits (HEO), including geosynchronous orbits (GEO). In the last two years we created our own space debris light curve catalogue which is available for scientific community [1] [2]. It provides an archive of apparent rotation periods of selected objects and their evolution over time. Additional information is also available - such as the phase-diagram and its amplitude which is the function of object's shape, reflectivity properties (albedo) and the mutual geometry between observer, object and the Sun. The light curve catalogue is further used for the BVRI photometry [3] and attitude determination [4]. Astrometric measurements are used for three goals; to validate and calibrate the AGO70 system's data [5], to support the cataloguing efforts which requires orbit determination and improvement, and to improve the tracking efficiency of Satellite Laser Ranging (SLR) stations. All necessary corrections are performed to provide high quality data to our international partners such as the Astronomical Institute of the University of Bern (Switzerland), Space Research Institute, Graz and its Graz SLR station (Austria). All data is in the required international formats such as CCSDS Tracking Data Message (TDM) [6].

Part of the improvement of AGO70 system is also hardware and software modifications which are done within the framework of the European Space Agency's Plan for European Cooperating States (PECS). There have been quite extensive efforts given to the improvement of the image processing software responsible for the real-time processing of acquired FITS frames. Image Processing Elements (IPE) pipeline we created is designed modularly to make it more flexible for modifications and implementation to other systems. Currently, there are nine IPEs in total responsible for many different tasks like image segmentation, astrometric reduction, tracklet building or object correlation [7].

1.1 System parameters

The AGO70 system parameters are listed in Tab. 1. The system is installed on an equatorial mount with a primary mirror with 700 mm diameter. The CCD is from Finger Lakes Instruments (FLI) manufacturer and has dimensions of 1024 x 1024 pixels with pixel size of 24 μm. The focal ratio is f/4.2 and the resulting field of view (FOV) and pixel iFOV is 28.5 arc-min x 28.5 arc-min and 1.67 arc-sec/pix, respectively.

Tab. 1. Configuration of AGO70 telescope.

Telescope Name	**AGO70**
Telescope Design	Newtonian
Mount	Equatorial with open fork
Camera	CCD
Pixel size [μm]	24
Dimension [pix]	1024 x 1024
Primary mirror [mm]	700
Focal length [mm]	2962.0
Focal ratio	f/4.2
FOV [arc-min]	28.5 x 28.5
iFOV [arc-sec/pix]	1.67

1.2 System design

The main technical objective for the AGO70 within the current ESA PECS activity is towards the astrometric and photometric measurements acquisition and processing of space debris situated on higher Low Earth Orbits (LEO), orbits with mean altitudes above the Earth‘s surface higher than 800 km, and to support the tracking of these objects by SLR stations. To achieve this goal, it is necessary to improve the hardware and software (S/W) of AGO70, to provide real time improvement of Two-Line Element (TLE) set, astrometric positions and light curves. The overall design of the system is plotted in Fig. 1. There are several crucial sub-systems which are needed for the routine operation, namely telescope hardware (consisting of the mount, tube, CCD camera, dome, filter wheel, electronics, epoch registration system), Low-Level Telescope Control (LLTC) system, scheduling (SatEph), Image Processing System (IPS), TLE improvement software, pointing model and acceleration database. LLTC is responsible for the communication between user and the telescope hardware systems such as CCD camera, mount control, mount encoders, filter wheel and dome control. Scheduling provides the ephemerides of debris objects by using standalone S/W SatEph developed by FMPI [3]. This S/W contains Simplified Perturbations Model (SGP) [8] and is compatible with the TLE format. IPS is responsible for the image processing and extraction and provision of the astrometric and photometric measurements. The TLE improvement S/W uses available TLE set and acquired astrometric positions to correct the along-track component of the object’s position or to extract the time difference between observed minus calculated (O-C) positions. This improved TLE can be then provided to the SLR station to improve its tracking efficiency. Pointing model helps to improve the astrometry, especially for LEO objects.

2 Hardware installation and development

2.1 Telescope installation

The telescope was purchased from the Austrian manufacturer in 2015 and delivered to AGO in 2016. The installation itself was performed in September 2016 when all the original components such as mount, tube, control system, and others were deployed at AGO. The mount had been installed before the tube, the primary mirror installation followed along with the weights balance adjustment, pointing investigation and first collimation of the telescope. The original mount control unit has been deployed as well. AGO70 is situated in the upper dome of AGO (Fig. 2, left), a dome which was used for hosting small optical systems for students’ projects in the past. During the analysis for the installation configuration (Fig. 2, right) it was discovered that the closest point between the telescope and the dome is only few centimeters which eventually showed up not to be a showstopper.

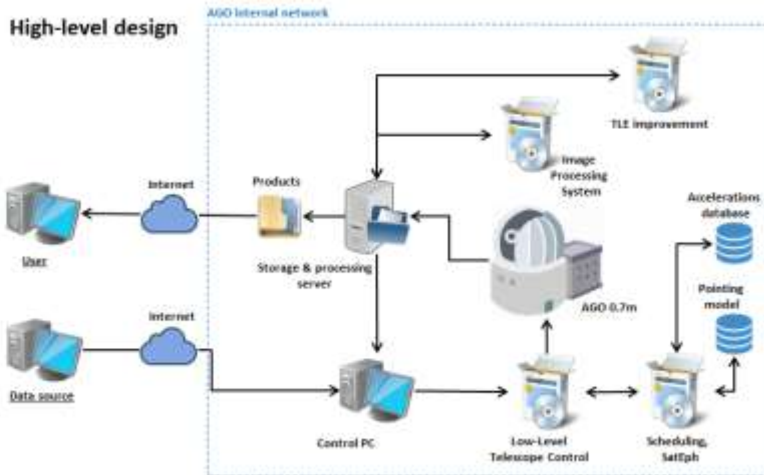

Fig. 1. High-level design for the AGO70 system to be developed during the ESA PECS activity to support the LEO tracking with SLR systems.

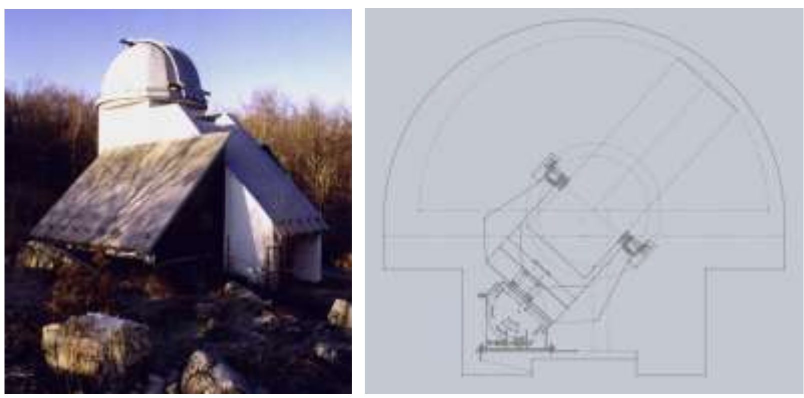

Fig. 2. The AGO upper dome which hosts the AGO70 telescope (left) and cross section of the internal geometry between the dome and the telescope (right).

2.2 Dome control unit

To be able to perform observations in semi-automated mode, the dome control unit has been developed at AGO. Currently, installed motors along with the gear allow the cupola to be rotated with speed up to 3deg/s and can be operated by a custom control unit via software which also keeps track of the current cupola orientation.

2.3 Telescope mount control unit

Mount control needs to be able to task the mount motors arbitrary velocities within the hardware limits of the system. The original control unit has several different options how to set-up arbitrary rates, however, the set value is applied to both axes, right ascension and declination. Additionally, the set-up is done manually which does not allow to task the system remotely. We are currently developing our own control unit for which we defined following basic functions to be performed: “Go to” function, “Slew” function, “Tracking” function, and “Stop” function. Necessary interfaces need to be established, especially with LLTC (see Section 3.1) and scheduling S/W (Section 1.2). The selected programming language is Python and C++. First expected tests are in early spring 2020.

3 Software development

The ESA PECS studies revealed a need to develop certain software tools to be able accurately and efficiently perform the space debris dynamical and surface characterization analysis.

3.1 Low-level Telescope Control system

This sub-system is crucial for the operation of the telescope during data acquisition and it was developed in C++ programming language. Fig. 3 depicts the interfaces for the LLTC with AGO70's hardware sub-systems. LLTC controls the mount motion (element 1, COM1) through the mount control unit, right ascension (1.1) and declination motors (1.2) independently. It also reads the Heidenhain encoders installed on the both axes trough the IK220 PCI card to get the exact position of the mount. This way user has a full control over the mount as well has the full overview where the system is pointing. By combining the information from the encoders, the LLTC's interface with the dome control (2, 2.2, COM2) helps to adjust the pointing of the dome slit which is done automatically. LLTC controls also the FLI PL1001 Grade 1 CCD camera through a USB port. The major functions are image acquisition, set exposure time, set number of frames to be acquired in series, set type of image DARK, FLAT FIELD, or LIGHT frame. Interface with the filter wheel allows user to select specific filter, namely from Johnson/Bessel's BVRI filters currently installed in the filter wheel. LLTC is also connected to the data storage and processing server (4).

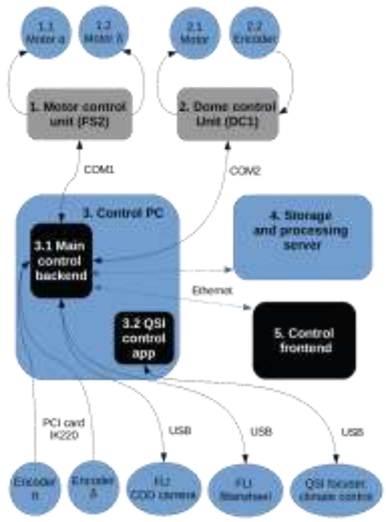

Fig. 3. Description of Low-Level Telescope Control's interfaces with sub-systems of AGO70.

3.2 Image Processing System

The image processing capability is an essential part of every space debris tracking system. Certain functionalities can be covered by typical astronomical tools such as Astrometrica [9] and AstroImageJ [10]. However, they are quite limited for space debris measurements. Astrometrica is developed for the analysis of the point-like objects, e.g., stars tracked with sidereal tracking. This is not the case for the space surveillance, where object tracking or GEO tracking is used. Additionally, Astrometrica requires usage of the Graphic User Interface which prevents the user to efficiently process astrometric data. AstroImageJ is a high-quality photometric tool which allows to automatize the processing to certain level. Unfortunately, as is the case for Astrometrica, it focuses on the processing of point-like objects and does not allow extensive communication through, e.g, terminal, which would allow higher automatization of the processing.

For previously mentioned reasons and to have full control over the product quality and the data latency we developed and are still improving our own modularly designed Image Processing System (IPS) which contains several Image Processing Elements (IPEs). These are either directly responsible for the processing of FITS frames or with the products extracted from them. The following IPEs have been developed so far: star field identification (IPE-SI), image reduction (IPE-IR), background estimation and extraction (IPE-BE), segmentation (object search and centroiding) (IPE-SC), astrometric reduction (IPE-AR), star masking/removal (IPE-MR), data correction/post-processing (IPE-PC), tracklet building/construction (IPE-TB), object identification/correlation (IPE-OI), and data format conversion (IPE-DC). For more details about each of the IPEs refer to [5], [7].

For the real-time tracking and data provision it is crucial to have very low latency between the data acquisition and provision. This is especially the case for the LEO observations for SLR tracking support. We investigated the processing time of each IPE on several different astrometric and photometric series acquired by AGO70 for GEO, HEO and LEO. The IPEs were tested on a computer with following parameters: Linux Mint 19.1 OS, motherboard: Supermicro SuperServer 7048R-TR, CPU: 10-core Intel® Xeon® E5-2640 v4 with Turbo Boost, Hyper-Threading and Virtualization, RAM: 32GB ECC, SSD: 400GB, HDD: 4TB Raid 1 array. The results obtained for each IPE can be seen in Fig. 4. Plotted is the average processing time per frame for given IPE. While majority of the steps are taking only seconds, there are three time-heavy IPEs, namely IPE-BE, IPE-SC and IPE-OI. IPE-OI duration fully depends on the number of objects in the TLE catalogue to be used for the correlation. Once this catalogue is reduced to a smaller number, the processing time decreases drastically. IPE-BE is not a mandatory step which can be skipped during the processing, but it helps to improve the performance of the IPE-SC. IPE-SC is one of the most crucial parts of the processing because it defines the quality of the data (detection rate, astrometric and photometric accuracy, etc.). Once all the system cores are used during the processing, the processing time is around 10s. In this case the frame is split into smaller sub-frames which are then sent to individual cores for processing. However, for LEO objects, the whole frame needs to be processed because the stars or the object can be a longer streak (several hundred of pixels) which leads to using only one system core. This leads to long duration of processing which makes system not feasible for the LEO processing. We are currently analyzing the possibility to optimize the code for IPE-SC to improve this issue.

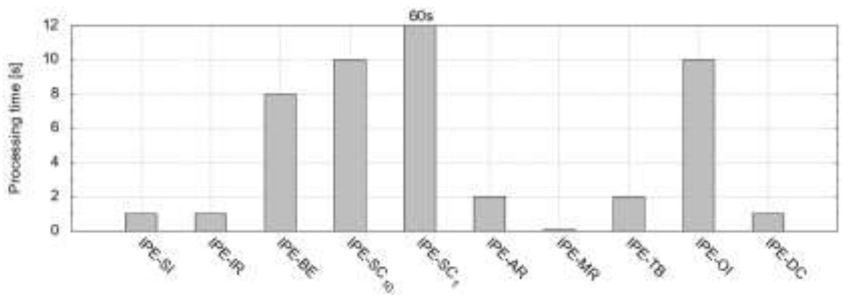

Fig. 4. Time budget for the processing of given IPE tested on the FMPI's processing server

3.3 TLE improvement

Once the astrometric data is acquired for the object, they can be used to improve the TLEs. This should lead to improvement of the tracking direction of SLR system and in increase of its efficiency. In the current project we are cooperating with two international partners which operate their own SLR stations. The ZIMLAT system of the Astronomical Institute of the University Bern, Switzerland is a hybrid system capable of performing passive and also active optical measurements. The Graz SLR station is a well-established in the LEO space debris SLR tracking.

The basic logic behind the TLE improvement to be performed by AGO70 system and be provided to the SLR stations is plotted in Fig. 5. Once the FITS images are acquired by the AGO70 system, they will be sent to the IPS system. This system performs segmentation and astrometric reduction and extracts the astrometric measurements of the LEO object. Then this data are provided to the TLE improvement S/W which will modify the TLE data, TLE data used for the pointing determination, by iteratively alternating some of the TLE parameters, e.g., reference epoch or mean motion, until the smallest residuals between observed and calculated (O-C) positions are reached. Then this data is sent to the SLR stations which use it for the accurate pointing. The TLE improvement S/W is under development at this moment.

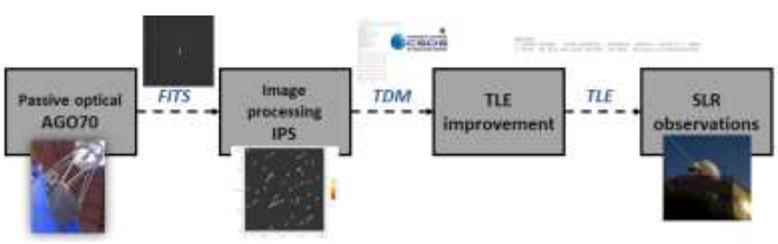

Fig. 5. General scheme demonstrating the chain for LEO tracking improvement starting with passive optical measurements, continuing with the image processing and TLE improvement and finalizing with SLR measurements of a LEO object.

4 Observation programs

There are several observation programs running simultaneously at AGO70, majority of them performed within several bachelor, master and doctoral studies.

4.1 Astrometry

In 2018 we performed an observation campaign with primary task to acquire astrometric measurements to demonstrate the AGO70's capabilities for space debris/SST cataloguing. We distinguished two types of targets for the astrometric observations - the global navigation satellite system (GNSS) objects and AIUB/ESA objects discovered during the ESA/AIUB Optical Ground Station (OGS) surveys [11]. There were 20 nights of GNSS observations processed by AIUB. AIUB performed AGO70's validation by using the measurements with the goal to identify and remove epoch bias (a constant epoch registration time shift in the measurements) from the measurements and to quantify the astrometric accuracy of the AGO70's data [5]. The results are shown in Fig. 6 where are plotted RMS (root mean square) of the measurements. The analysis revealed that the astrometric accuracy varied between specific observation periods, namely the quality largely decreased during April 2018. Outside this time the astrometric accuracy for the GNSS objects was below 1.0 arc-sec. The epoch registration analysis revealed that during the April 2018 data acquisition the time stamp in the FITS headers had accidentally precision of 1.0 s which is highly nonsufficient for GNSS, GEO, LEO or HEO tracking. This error was corrected for the future data acquisition which can be seen in data from May and June 2018.

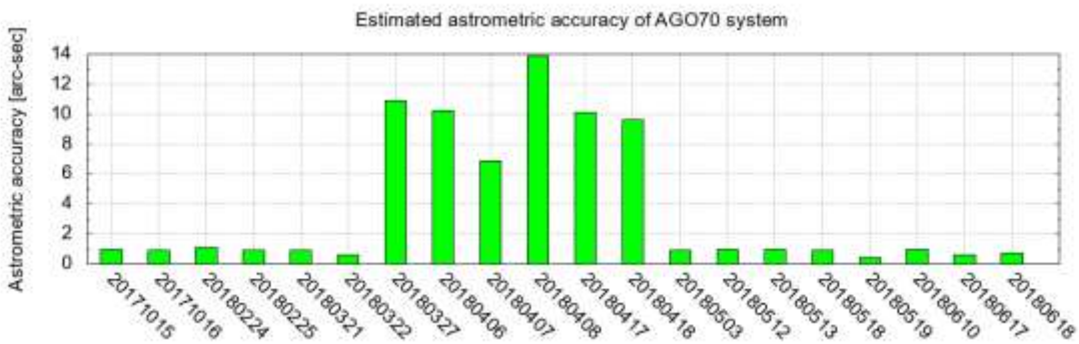

Fig. 6. Measurements' residuals (RMS) of AGO70 system. Data obtained from AGO70's GNSS measurements processed by AIUB [5].

4.2 Light curves

Targets for the light curve observational campaign were selected according to the visibility rule (objects higher than 30 degrees above the horizon and sun below 12 degrees below the horizon) and to the tracking options of the AGO70 [12]. For each object we acquired at least two series of images with different sampling, each consisting of approximately 120 frames in the R-filter. The exposure time was set according to the angular velocity of the object, usually 1-5 seconds. The whole observation duration was no longer than 20 minutes, so the phase angle, angle between the sun-object-observer will not change significantly during the observation.

Processing is performed with a set of tools, including the ones developed by FMPI. The whole procedure starts with the extraction of the light curves by using tool AstroImageJ [10]. Then, the series is processed with the time series analysis when we look for the frequencies present in the acquired data. This is done by Phase dispersion minimization method [13] which provides the user identified periodic signal along with the phase diagram, i.e. folded light curve for given period. Then the processing continues with fitting the phase diagram by the Fourier function [1]. We use this fit to obtain the mathematical amplitude of diffuse reflection of the body and to estimate the uncertainty of phase function and apparent rotation period determination. Amplitude of the signal in the brightness is determined as difference of the global maximum and minimum, firstly on mathematical function and then also in observed data.

By analyzing the phase diagram's Fourier fit one can extract the complexity of its shape. In Fig. 7 are shown phase diagrams with their Fourier functions for two different objects, Ariane 5 R/B (COSPAR ID 12035C) and H-2A R/B (17048B). The first case has a quite simple shape, containing only two maxima/minima and amplitude is 1.151±

0.004 mag. For the second case the complexity, number of extrema, is higher with several secondary small maxima/minima. For this case we identified five maxima/minima and amplitude of 3.437±0.018 mag. Measured complexity is directly linked to the physical properties of the target, namely its shape and albedo along the mutual geometry between observer, the target, its rotation axis and the sun. It can be used for characterization and identification of the object.

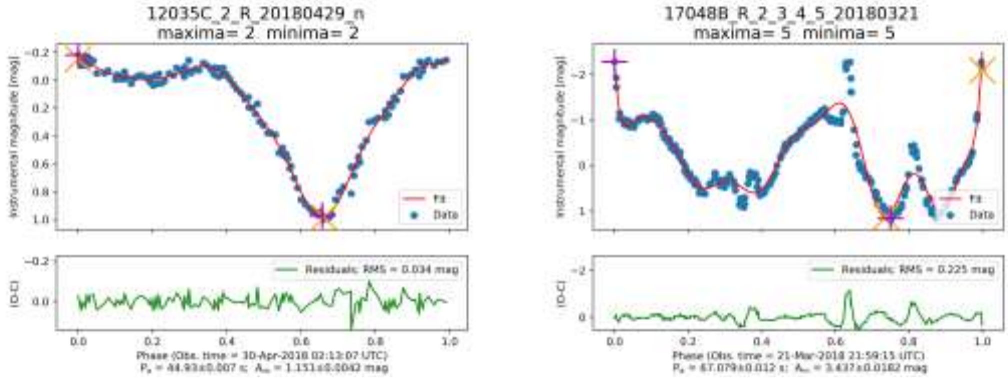

Fig. 7. Phase diagram obtained for Ariane 5 R/B (12035C) (left) and for H-2A R/B (17048B) [1].

In total, there were 153 light curves for 103 individual objects in FMPI's public catalogue [1] for which we were able to construct the phase diagram and extract the information about its shape's complexity. Complexities for two populations, upper stages and payloads, are plotted in Fig. 8. Even the maximum number of extrema for upper stages is 2, large part of phase diagrams also have three or four maxima/minima. For payload, the complexity is clearly around four and five maxima/minima, where some sharper extrema were omitted by the Fourier function fit.

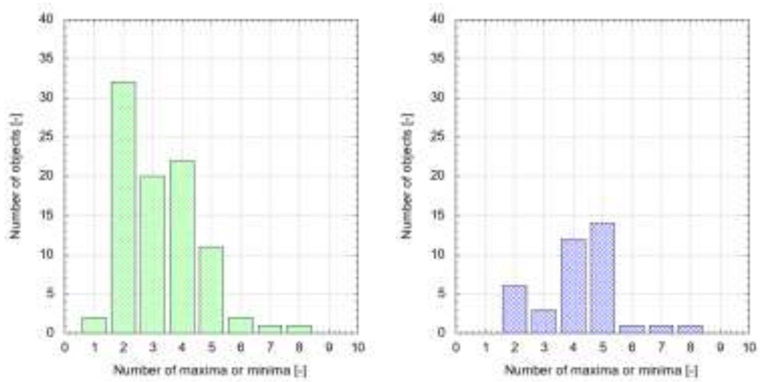

Fig. 8. Complexity of the phase diagram's shape for 67 upper stages (93 light curves) (left) and 27 payloads (38 light curves) (right) published in FMPI's light curve catalogue [1].

4.3 BVRI photometry

The fact that AGO70 is equipped by the filter changing wheel with Johnson/Cousins BVRI photometric filters enables us to perform also the techniques of BVRI photometry, which can also be understood as standard photometry in different passbands of the visible light. In the first step the instrumental magnitudes have to be transformed to the standard system of magnitudes using the transformation equation for our photometric system. For this transformation we use the Landolt's catalogue of standard stars [14] and using the least square method we can calculate the transformation coefficients for each night. The captured light does not belong to the object itself, but it is a reflected sunlight from the object's surface. Therefore, it contains the information about the surface properties of the target body. This fact is used also in the article [15], where authors specified three categories according to the B-V and R-I color indices using the methodology of reflective spectroscopy. The first category (I) holds for the solar cell similar materials – with monotonic increasing with concave up shape; the second (II) one for the gold similar materials – with monotonic increasing with concave down shape; and the third (III) one for silver similar materials – relatively flat with possible negative slope in the blue range.

This categorization can serve for the first identification of object's surface properties, whether the reflected light dominantly originate from the reflective solar panel or from the insulating foil of satellite's body. But the value of the color index strongly depends also on the observation geometry between sun-object-observer, object's rotation state and object's age (total time spent in space). Our methodology is to monitor the dependences of the color index on the phase angle or on long time exposure to the space condition, so possibly to see the space-weather and aging effects on the materials. Also, by using the techniques of light curve processing (see Section 4.2) we are able to monitor the color index variations along the rotational phase of the spacecraft [15]. Fig. 9 shows average values of measured color indices for functional GEO satellites acquired during nights 13th of May 2018, 15th of November 2018 and 6th of February 2019 by the AGO70 system along with the data obtained from work [15] (black dots). This type of data visualization should help to characterize the object's surface properties.

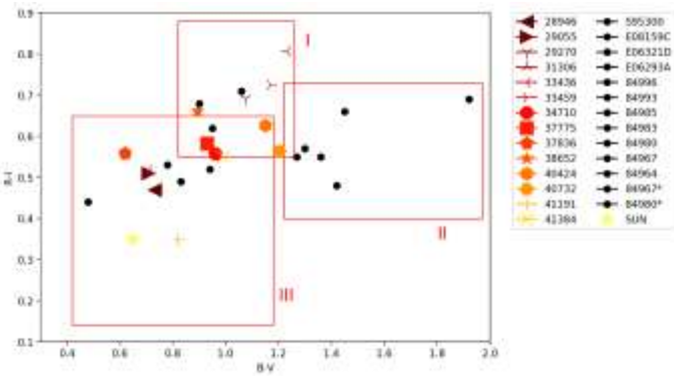

Fig. 9. R-I vs. B-V color index diagram with marked categories from defined in [15]. Color markers stand for our data obtained with AGO70 and black dots represent data taken from [15]. AGO70 represent color indices averaged through the phase angle and trough three observation nights.

4.4 LEO tracking

Under current limited technical conditions of the telescope control unit, the LEO tracking with AGO70 can only be performed for a short period of time, around dozens of seconds [12]. This is the time when we can keep the object in the FOV. A short LEO tracking campaign has been performed during 27th of August 2019 to investigate the AGO70 system's hardware capability to track LEO objects with angular velocities below 0.5 deg/s. We successfully observed three LEO objects, Jason 3 (16002A), Topex/POSEIDON (92052A) and SL-12 R/B (02037D). Composition of two obtained series is shown in Fig. 10 for Jason 3 and SL-12 R/B objects. Series always started with object being close to the FOV's center and slowly drifting to the edge of the FOV. This is due to the missing capability to track LEOs at the moment (see Section 2.3).

Fig. 10. Left: Jason 3 (16002A) observed by AGO70, start of exposure 2019-08-27T18:46:46.000. Compilation of 6 frames, exp = 0.1s, filter I. Right: SL-12 R/B(2) (02037D) observed by AGO70, start of exposure 2019-08-27T19:55:15.809. Compilation of 9 frames, exp = 0.1s, filter I.

One frame of SL-12 R/B (02037D) has been analyzed by the IPS (see Section 3.2) to test the processing on frames with long streaks. To evaluate the quality of the extracted data, we compared the extracted positions to the ephemerides calculated by our internal planning tool SatEph which uses available TLE set and SGP4/SDP4 model. The result is listed in Tab. 2. The observed minus calculated (O-C) analysis revealed that the difference is about 1.11 arc-min. This value should be taken cautiously because the O-C angular difference in our analysis can have different sources: the TLE uncertainty, SGP uncertainties, SatEph calculations uncertainty, the measurement data error obtained from the IPS processing. For a more accurate analysis we will use in the future the so-called Consolidated Prediction Format (CPF) files generated by the GNSS and SLR communities which can then be used as a ground-truth data for the comparison [16].

Tab. 2. Observed data (AGO70) minus calculated data (TLE/SGP4) (O-C) for LEO object SL-12 R/B (02037D) observed by the AGO70 system in August 2019. The listed observation time is for the middle of exposure.

COSPAR	Name	t_{obs} t_{TLE} [UTC]	RA_{IPS} [deg]	DE_{IPS} [deg]	RA_{TLE} [deg]	DE_{TLE} [deg]	Δ_{RA} [arc-min]	Δ_{DE} [arc-min]	Δ_{Total} [arc-min]
02035D	SL-12 R/B(2)*	2019-08-27 19:55:24.57 2019-08-26 18:10:17.31	266.86760	6.45256	266.88354	6.44291	0.95	-0.58	1.11

5 Conclusions

In our work we present the applications of standard astronomical telescope, 70-cm Newtonian telescope situated at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO), toward the space debris tracking and research. We are focusing on orbital regions from 800 km above the surface and higher. Several developments were and still are being performed at our institute with focus on the hardware and software improvement. Two crucial elements are currently being improved. From the hardware we are focusing on developing our own telescope control unit to be able to set arbitrary tracking rates. For the software the most crucial is high quality and low latency of the measurement data. Therefore, our work is dedicated to the development of the so-called Image Processing Software (IPS) which is presented in the work.

For the routine operation of the telescope we perform astrometry, light curve acquisition and BVRI photometry for characterization. Astrometric data are used for the system validation and orbit improvement in collaboration with international partners. Light curves are used for research, object dynamical and physical characterization. We built a public catalogue of space debris light curves currently containing almost 300 light curves for more than 200 individual objects. BVRI photometry is performed to characterize the surface properties of the objects and to analyze the color index dependency on the phase angle, phase function and material age.

Last but not least we demonstrated on few LEO cases our experimental set-up for the LEO tracking, which has been already tested on real cases and processed by IPS. The hardware seems to be working properly, the IPS still needs to be validated.

Our future work will be dedicated to the finalization of the ongoing developments, including control unit and IPS. More extensive validation of IPS needs to be done by using the Consolidated Prediction Format (CPF) files generated by the Global Navigation Satellite System (GNSS) and Satellite Laser Ranging (SLR) communities.

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