AGO70: passive optical system to support SLR tracking of space debris on LEO

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ABSTRACT

Primary motivation for Low Earth Orbit (LEO) objects tracking with passive optical systems is from operational point of view to support the tracking of space debris objects with Satellite Laser Ranging (SLR). The Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI) operates 70 cm Newtonian telescope (AGO70) situated at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO). Observation program of this sensor focuses on space debris tracking situated from Low Earth Orbit (LEO) up to Geosynchronous Earth Orbit (GEO).

In our work we present the AGO70's overall design and discuss in detail all its subsystems, as well as interfaces. Presented will be its performance for real-time observation data provision towards SLR station to improve the station's tracking efficiency of LEO debris and of calibration objects (validation). Furthermore, the angle and range measurements acquired by two different sensors, AGO70 (passive optical) (SK), Graz SLR (active optical) (AT) are used for astrodynamic analysis of observed targets.

1. INTRODUCTION AND INSTRUMENTATION

Since the 2016 the Faculty of Mathematics, Physics and Informatics (FMPI) of Comenius University in Bratislava, operates it own 70 *cm* newton reflector (AGO70), which primary focuses on the observation and characterisation of the Space debris objects. In recent years several major updates have been performed to the AGO70's hardware and software including telescope's mount control unit (MCU), observation scheduling and control system (SCH, LLTC), image processing system (IPS) and TLE improvement system (TLEI). MCU along with SCH and LLTC allows to observe objects on LEO with angular velocities up to 1.5 deg/s. One of the most crucial sub-system is IPS which has been extensively tested and validated on different types of images, from images acquired with sidereal tracking, to images acquired for LEO objects. TLEI provides interface with Satellite Laser Ranging (SLR) sensor, namely Graz SLR station operated by the Space Research Institute (IWF), Austrian Academy of Sciences (Austria). The general motivation of these developments was to demonstrate and validate of the the real-time space debris TLEI to improve detection efficiency by the SLR sensor and also provision of the acquired tracklets for the sensitive analysis. The orbit determination and astrodynamical analysis using acquired data is done by the Astronomical Institute of University in Bern (AIUB), Switzerland using their own advanced LEO orbit determination tools.

1.1 AGO70 telescope

The data acquisition chain starts with the AGO70 (Fig.1(a)), which has been installed at Astronomical and Geophysical Observatory of FMPI in Modra, Slovakia (AGO) (Minor Planet Center code 118) in September 2016. Its observations are primarily dedicated to the space debris research and Space Surveillance and Tracking (SST). We distinguish three major observation programs at AGO70 - the astrometry to support SST and cataloguing activities, instrumental photometry to characterize the debris attitude states, and BVRI photometry to characterize the debris surface properties and hence identify the object's origin.

(a) AGO70 (b) Graz SLR station

Fig. 1: (a) AGO70 in its cupola at Astronomical and Geophysical Observatory in Modra, Slovakia; (b) Graz SLR station at Observatory Lustbuehe, Austria

The presented system is a Newtonian design telescope with a very thin parabolic mirror with diameter 700 mm from Alluna optics supported by gravity actuator. The focal length of the system is 2962.0 mm. The CCD sensor is the FLI Proline PL1001 Grade 1 CCD camera with 1024 x1024 pixels and 24μm pixel size which results in a field-of-view (FoV) of 28.5$'x$ 28.5$'$ and iFOV of 1.67 ”$/pixel$. AGO70 is equipped with a filter wheel with Johnson-Cousins filters BVR$_c$I$_c$. In 2020, the AGO70 was upgraded to be able to track objects up to the angular velocity of approximately 1.5 deg/s [1].

1.2 Graz SLR station

The Space Research Institute (Institut für Weltraumforschung, IWF) in Graz is a leader in SLR measurements to non-functional cooperative and non-cooperative targets and the SLR data processing and orbit improvement. IWF's Satellite Laser Ranging (SLR) Station Graz (Observatory Lustbuehel, 47.0678N, 15.4942E, elevation of 495 m) (Fig.1(b)) includes a 400 μJ / 2 kHz / 10 ps pulse width laser for retroreflector equipped satellites i.e. cooperative targets (accuracy single shot 2-3 mm, and $<<$ 1 mm for Normal Points), laser operates at 532 nm wavelength. For laser ranging to non-cooperative space debris, used is a 100 Hz / 3 ns / 200 mJ per shot laser, laser operates at 532 nm wavelength. The telescope used for SLR has a 10 cm transmit telescope, and a 50 cm receive telescope in Cassegrain configuration [2]. Graz SLR station is roughly 250 km Southwest direction from AGO Modra.

1.3 AIUB

The Astronomical Institute belongs to the Faculty of Natural Sciences of the University of Bern. From software tools relevant for the study are sophisticated performance simulations tools for observations in optical space surveillance networks and for catalogue build-up and maintenance, as well as for space-based optical observation and orbit determination. The tools use the CelMech package from Gerhard Beutler for sophisticated applications in celestial mechanics [3]. These tools are used for the detail astrodynamical analysis and LEO orbit determination.

2. DATA ACQUISITION AND PROVISION CHAIN

This section summarizes the operational version of the data acquisition and provision of AGO70, which preliminary version was discussed in [4]. The overall logic with all steps and interfaces is depicted on Fig. 2 and in detail presented in Section 2.1.

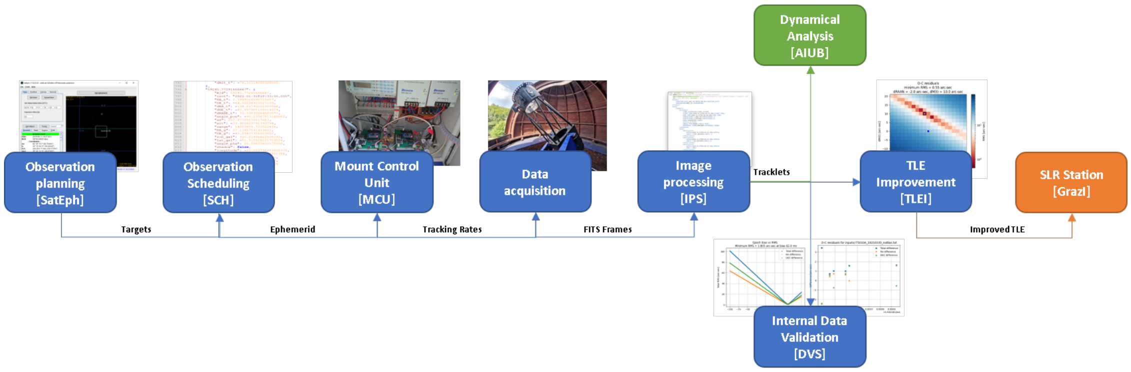


Fig. 2: The complete chain of the AGO70 telescope's observations planning, acquisition, processing, validation and provision to external users.

2.1 SLR tracking support

Observation planning - The whole chain starts with the target selection and visibility window calculation. For this step was used the SatEph [4], software tool for the calculation of the ephemeris from the TLE data acquired from the Space-Track [5]. For the proof-of-concept observation campaign we focused on the High LEO orbits with mean altitude above the 800 km. Firstly, selected were the LEO cooperative targets equipped with retro-reflectors situated on higher altitudes which accurate positions were available in form of International Laser Ranging Service's (ILRS) CPF (Consolidated Prediction Format) file. These have been selected for validation of the interfaces along the full chain. The next step was to select non-cooperative compact space debris objects in mean altitude interval from 800 km to 1000 km, which can be simultaneously observed by AGO70 and also by the SLR station in Graz.

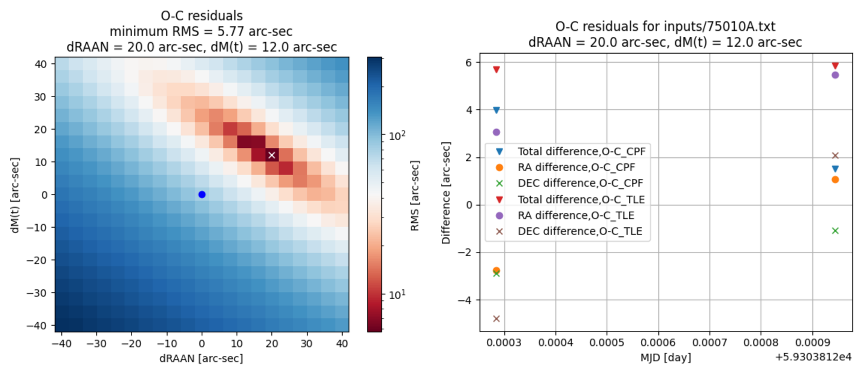
Observation scheduling - SCH - The Scheduling software is responsible for the calculation of the detailed ephemeris information for the selected target. The output contains all necessary information for the telescope tasking as tracking rates and also the geometric parameters of the observation, which are useful during the FITS frame processing. The SCH uses Python-implemented version of the SGP4 engine to calculate the detailed ephemeris from the TLE data with specific step and duration.

Mount Control Unit - MCU - The major developments were done on the AGO70's mount control unit. To achieve the required tracking speeds, the FMPI had to develop its own MCU. The final design of the MCU consists of two separate units, where each controlled each from the two axes and tasked the stepper motors with three general information: Start-Stop, direction (clockwise-CW or counterclockwise-CC) and frequency (rotation speed). This communication was implemented into the AGO70's Low-Level Telescope Control (LLTC) software, which uses the ephemeris calculated by the SCH to task the mount through this "AGO protocol".

Data Acquisition - AGO70 is operated by its own LLTC, which provides complete information to the observer about the telescope status as pointing, acquisition status etc. The LLTC is also responsible for the tasking of all components installed on AGO70, so also for the setting up of the camera and FITS frames acquisition. The resulting FITS frames contain also the additional information about the observational conditions, geometry of the observation and the used tracking rates. These are later used during image segmentation process to recognize the frame objects according to their shape, point-like vs streak-like profile.

Image Processing System - IPS - The IPS is an astronomical software for the FITS Frames processing developed by the FMPI for casual astronomical and also LEO tracking purposes [6]. The pipeline consits from so-callled Image Processing Elements (IPEs) and it all starts with the background extraction (IPE-BE) using the sigma-clipping algorithm to flatten the background noise and increase the signal-to-noise ratio of the frame objects. The major development was done primarily in the segmentation part (namely Search and Centroiding, IPE-SC) of the software. IPE-SC had to be adjusted to process the images with combined point-like and streak-like frame objects to be able to extract the relative positions and than perform the astrometric reduction. From the tracking rates listed in FITS header were calculated the shape of the aperture suitable for the frame objects. Extracted position of the frame objects are then processed by the Astrometric reduction (IPE-AR), which uses the Astrometry.net offline engine [7] to provide the astrometric solution for each image. After that the most crucial element Tracklet Building (IPE-TB) associates all moving objects in the series into the tracklet using the linear regression and weighting algorithm according to the frame objects angular velocity and its positional angle. The tracklets are then cross-correlated with the TLEs within Object identification (IPE-OI), corrected for the annual aberration and epoch bias (IPE-IPC) and converted to the desired output format (IPE-DC).

TLE Improvement - TLEI - After the successful transformation of FITS frames into the tracklet by using IPS, the next major task is to use the acquired positions to improve the original target's TLE and to provide to the SLR station in the real-time. According to [8] the single-station short-arc ranging data cannot be used directly for orbit determination. We assume that similar statement is valid for short angle measurements (1-2 minutes) which are provided by the AGO70. For that reason, we focused on refining a single TLE set to achieve improved pointing in very close time of prediction (few minutes) by using SGP4 model. The basic approach is to improve two elements of a specific TLE set, mean anomaly $M(t_{TLE})$ (t_{TLE} is the reference epoch of TLE set) and right ascension of the ascending node RAAN, in the way, that the O-C residuals, where "Observed" are the measurements and "Calculated" are the positions obtained from modified TLE and SGP4 model, will be the smallest (Fig. 3). The mean anomaly M and $RAAN$ corresponding to the minimum of the residuals are then saved as improved TLE (iTLE) and send directly to the Graz SLR station through the FTP server. In Fig. 3(a) is shown the O-C search by using different values for RAAN and $M(t_{TLE})$. The modified TLE with the minimum O-C value is selected and residuals are plotted (Fig. 3(b)).



(a) (b)

Fig. 3: Output diagrams generated by TLEI S/W. Plotted is the search heatmap dRAAN vs dM(t) (a) and O-C residuals between observed and data calculated from improved TLE and from CPF (b).

For each object AGO70 tried to track it, acquire images, tried to solve the plate constants, improve the TLE and provide the iTLE to Graz SLR station via FTP server. While AGO70 was acquiring the images, Graz SLR station was tracking the object by using Consolidated Prediction Format (CPF) [9, 10] files from International Laser Ranging Service (ILRS) (for cooperative targets) or by using CPF generated from original TLEs retrieved from Space-Track service (for non-cooperative targets). CPF data can be found publicly available online [11, 12]. Once iTLE was available, Graz SLR switched the tracking from original CPF to iTLE and tried to track the object again with new predictions. This should lead to investigate how the iTLE predictions improved performance/quality comparing to the original predictions.

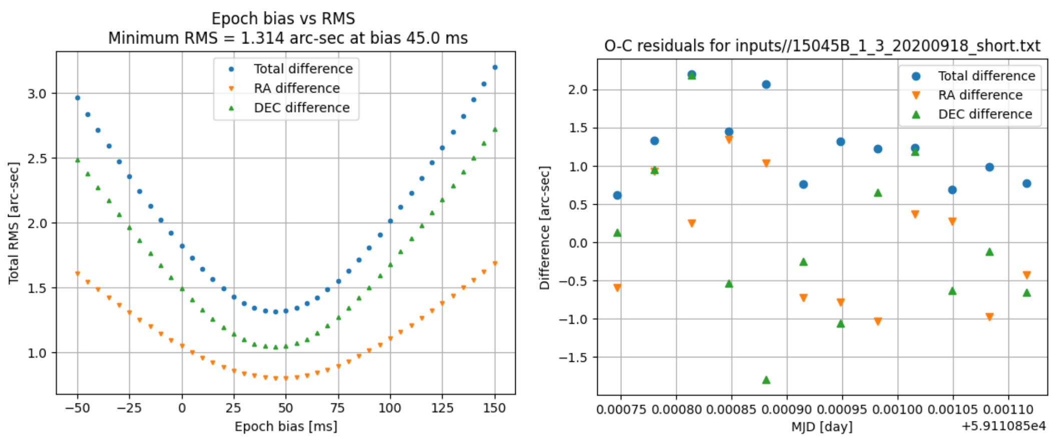
Once the tracklets were acquired for both, cooperative and non-cooperative targets, we provided them also to AIUB for the detailed astrodynamical analysis. The AIUB's task was to determine or improve the object's orbit and compare them to the original one. The results of this analysis can be seen in the Section 3.3.

2.2 Internal data validation

There are two options how to validate the astrometric measurements: compare them to the very high accuracy predictions/positions (O-C analysis); or to use the data directly for further processing like orbit determination which should eventually reveal that the data is for example of low quality or corrupted. For the first option we are using our own software Data Validation System (DVS).

To perform O-C analysis, several steps are conducted within DVS. It is needed to have so-called ground-truth data from which the "Calculated" positions are obtained. Geodetic community provides products in form of orbit solutions [13] for satellite constellations such as GALILEO, GPS, GLONASS, BeiDou or for individual satellites such as ESA Sentinels fleet or geodetic satellites LAGEOS-1/-2. The ILRS [14] provides data in CPF which contains position vectors in ITRF2005/ITRF2008 reference frames. Then these data need to be interpolated to the exact time of observations. Last, the calculated and observed positions must be in the same reference frame. Then the data can be compared where the O-C angular difference is the required output. To compare the observations which are in J2000 topocentric reference frame (right ascension $\alpha_{(O,J2000,i)}$ and declination $\delta_{(O,J2000,i)}$ for i-th measurement at time t_i to calculated positions which are in ITRF, it is needed to transform the calculated vectors to the same reference frame, preferably to the topocentric J2000. To achieve that we followed the logic of work [15].

For the internal data quality validation, selected GNSS satellites were measure and validated by using DVS. First step was the estimation of the epoch bias i.e. the error of AGO70 time tag registration. Our estimated value was 62 milliseconds. All data were then corrected for this value to avoid any contamination. The next step was the comparison of the measured positions with the accurate CPF predictions. Our resulting astrometric accuracy is relatively constant around the value of 0.7 arc-sec for the MEO objects. Example of validation of observations for object 15045B (GALILEO 10 (206)) is shown in Fig. 4. Plotted is search for the best epoch bias in Fig. 4(a) and O-C for each measurement point for the found best epoch bias value Fig. 4(b).



(a)

(b)

Fig. 4: Results of the internal Data Validation Suite (DVS) for object GALILEO 10 (206) (NORAD 40890, 2015-045B) observed by AGO70 during night 2020-09-18. (a) RMS of RA, DEC and total residuals as function of epoch bias. (b) O-C assuming used measurements and found epoch bias value.

3. RESULTS

For LEO *Stare* & *Chase* campaign i.e. improvement of the tracking effectiveness of the SLR station proof-of-concept, were selected 7 observations nights during the Spring of 2021. Primary focus was to acquire and extract astrometric measurements of the targets by using AGO70, to extract the measurements with IPS, to improve the TLE set available from Space-Track service with using TLEI and acquired angles and provide in real-time iTLE to Graz SLR station. The campaign was split into two parts. During the first part we conducted interfaces validation of observations by observing cooperative targets, for which the Graz SLR station used the nominal laser. The second part consisted of the observation of the non-cooperative compact debris LEO targets such as Soviet Launchers (SL-) and Chinese CZ-3 rocket bodies, for which the SLR station used configuration with the debris laser. Targets have been selected by using several criteria: object had to be visible from both stations (AGO and Graz SLR) after sunset (sun elevation below 10 deg), the minimum object's elevation above the horizon was 30 deg, object mean altitude was between 750 km (AGO limit) and Lageos mean altitude of 6000 km (for cooperative targets) or 1000 km (for non-cooperative targets), which is the debris laser's limitation.

3.1 Cooperative targets

The validation part of the campaign started with the observation of the high altitude geodetic satellites LAGEOS 1 and 2. These tests were done to verify all interfaces in the data acquisition and provision chain to SLR station. After successful observations and data hand-over, we proceeded to the cooperative targets in the high LEO region. As an example of this observation is selected the case from night 31^{st} of March 2021, when the cooperative geodetic satellite STARLETTE (COSPAR 1975-010A) with mean altitude of 962.8 km was observed. The first successfully processed observation for STARLETTE was acquired at 2021-03-30T19:30:38.381 UTC. In total two observations were used to improve the TLE, while the rest of obtained astrometric positions was used to screen the data from outliers. In Fig. 5 are plotted two frames used for TLEI analysis (see Fig. 6), which generated iTLE with O-C difference of 5.81 arc-sec with change in $RAAN = 2.0$ arc-sec and in $M(t) = 20.0$ arc-sec. With original TLE the O-C residuals were 76.7 arc-sec.

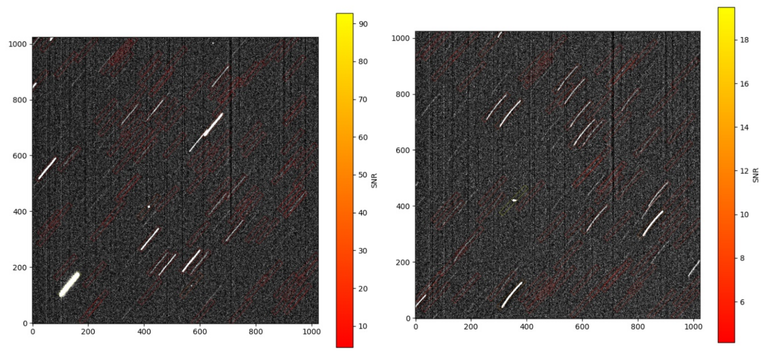


Fig. 5: AGO70 observation frames containing target's positions used for TLE improvement

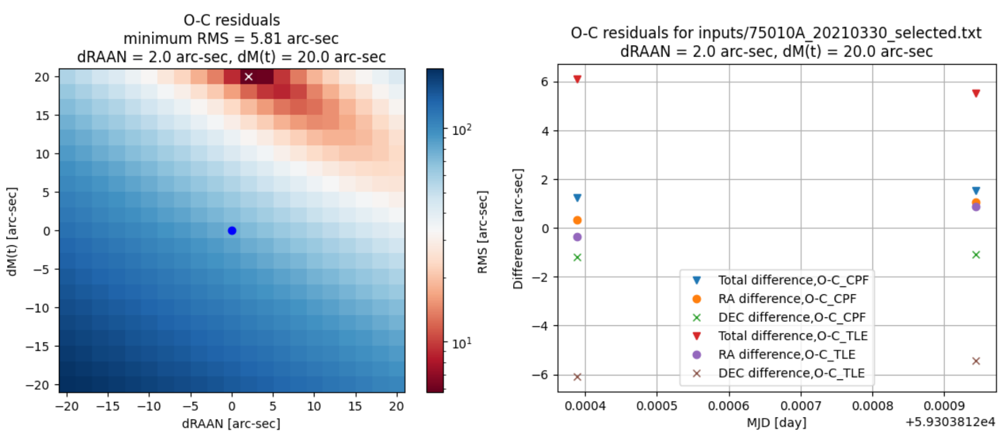


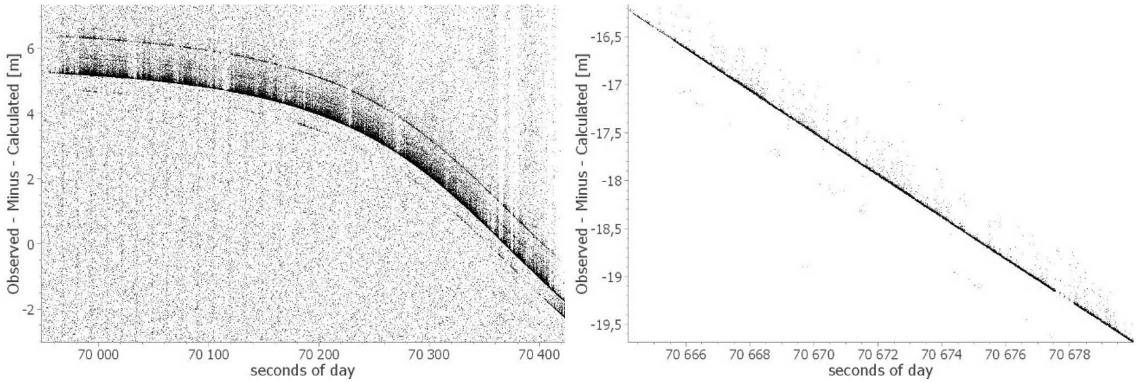
Fig. 6: Outputs of the TLEI S/W for observations of object 75010A observed during night 2021-03-30

Improved TLE was sent to Graz SLR station which started to track the object. Results of the observations can be seen in Fig. 7 where are plotted O-C residuals between observations and ephemeris generated from CPF file (7(a)) and between observations and ephemeris generated from iTLE file (Fig. 7(b)).

The time t_b and range bias r_b results of the orbit fitting evaluated during the post-processing of data acquired by the Graz SLR station are summarized in Table 1.

Table 1: The time and range bias results of the orbit fitting evaluated during post processing

Pass	t_b [ms]	r_b [m]	Pass	t_b [ms]	r_b [m]
CPF residuals	-0.006	-0.039	iTLE residuals	5.362	-34.773

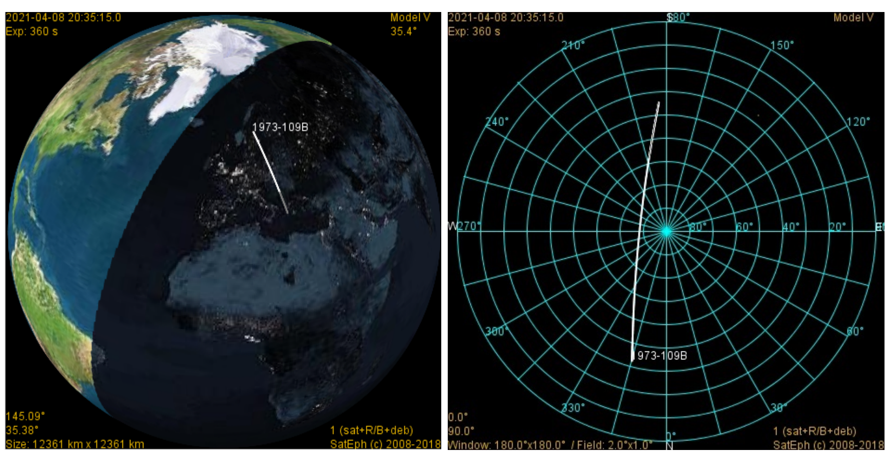


(a) 1975-010A CPF residuals (b) 1975-010A improved TLE residuals

Fig. 7: Object 75010A residuals measured by SLR Graz station. (a) Plotted are residuals obtained by using CPF predictions. (b) Plotted are residuals obtained by using iTLE generated from AGO70's measurements.

3.2 Non-cooperative targets

After number of the successful observations and real-time data handover to SLR station, the campaign proceeded into the second phase of non-cooperative targets. These observations were focused only on the large compact upper stages. To demonstrate the proof-of-concept of our approach we selected the case 1973-109B (SL-8 R/B, NORAD 7009) from the night 8^{th} of April 2021. Object is situated in the nearly circular orbit with perigee distance of 968.9 km, apogee distance of 995.7 km and 82.9 deg inclination. The complete passage from both sites lasted for 6 minutes in total and the object came into the shadow in the second part of the passage. The observed part of its orbit and the geometry of the passage above the Eastern Europe can be seen on the Fig. 8(a) and the geometry of the passage as seen from AGO location can be seen in Fig. 8(b) (object started its motion from the North-N). In both figures white streak represents trajectory when object was illuminated by the sun (object was tracked by AGO70) and grey streak represents trajectory when object was in Earth's shadow (object tracked by Graz SLR).



(a) Geometry from space-based position (b) Geometry from AGO position

Fig. 8: Geometry of the passage of objects 73109B observed during night 2021-04-08 shown from two different perspectives.

Object 1973-109B was observed once during the night, with the first successfully processed observation acquired at 2021-04-08T20:36:06.785 UTC. In total two observations were used to improve the TLE, while the rest of obtained astrometric positions was used to screen the data from outliers. TLEI analysis results can be seen in Fig. 9, which obtained iTLE with O-C difference of 1.39 arc-sec with change in RAAN element = 10.0 arc-sec and in M(t) = -18.0 arc-sec. With original TLE the O-C residuals were 82.5 arc-sec.

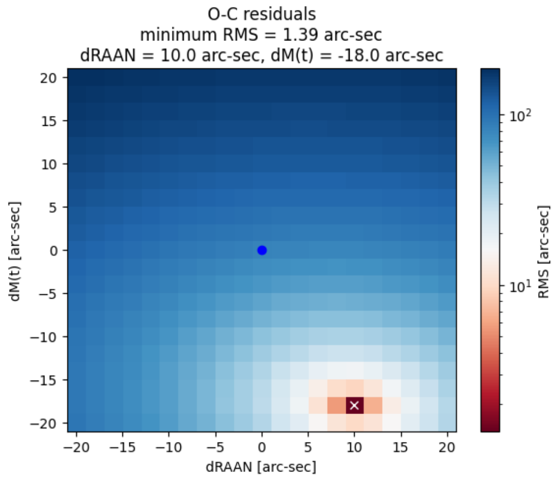
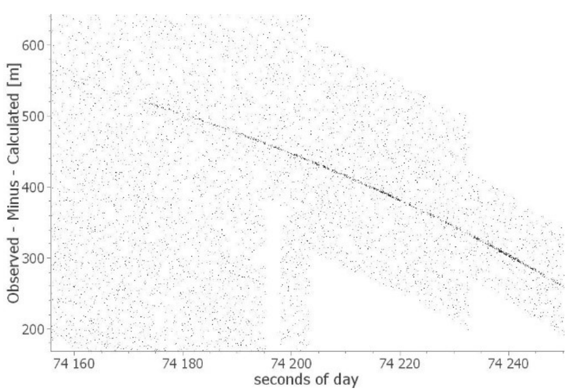
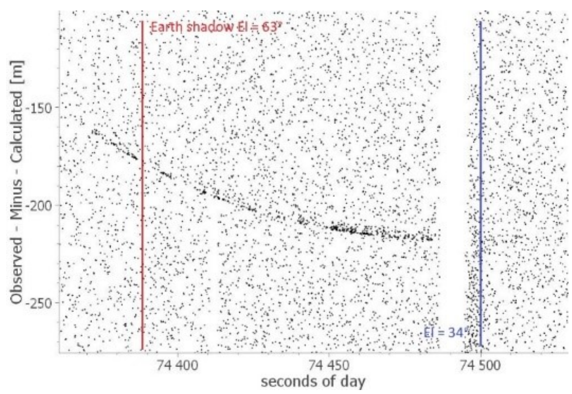


Fig. 9: Output of the TLEI S/W for observations of object 73109B observed during night 2021-04-08.

Improved TLE was sent to Graz SLR station which started to track the object. Results of the observations can be seen in Fig. 10, where are plotted O-C residuals between observations and ephemeris generated from CPF file (Fig. 10(a)) and between observations and ephemeris generated from iTLE file (Fig. 10(b)).



(a) 1973-109B old TLE residuals



(b) 1973-109B improved TLE residuals

Fig. 10: Object 73109B residuals measured by SLR Graz station. (a) Plotted are residuals obtained by using old TLE predictions. (b) Plotted are residuals obtained by using iTLE generated from AGO70's measurements.

The time t_b and range bias r_b results of the orbit fitting evaluated during the post-processing of data acquired by the Graz SLR station are summarized in Table 2. Post-processing showed a time bias for tracking with original TLE of -121 *ms* and a range bias of 114 *m*. After successful improvement of the TLEs tracking was continued with the iTLE. Returns were immediately detected and due to the low and stable time bias it was possible to continue "blind"-tracking the object for more than 100 seconds after it entered the Earth shadow. The time bias was reduced to -33 *ms* while the range bias remained almost constant at 95 *m*. Fig. 10(b) highlights the elevation at which the space debris object has entered Earth shadow and space debris laser ranging continued.

Table 2: The time and range bias results of the orbit fitting evaluated during post processing

Pass	t_b [ms]	r_b [m]	Pass	t_b [ms]	r_b [m]
TLE residuals	-121	114	iTLE residuals	-33	95

3.3 Orbit determination analysis for LEO targets

All acquired tracklets during the campaign were sent to AIUB for the Orbit Determination (OD) analysis and data quality assessments. This methodology is a third possible approach for the sensor validation and data quality assessment after the DVS and real-time data hand-over to the SLR tracking. The primary objective for the OD analysis was to determine, whether data originated in AGO70 are usable for LEO OD applications. Orbit determination analysis does not require a priori information about orbital elements and employs the low-fidelity modelling of perturbations. This analysis is performed using tool ORBDET that is available to the AIUB group.TLE set available for given target on the day of observations was used as a priori elements to compare with the orbit solutions, as TLEs were the only external orbit data available. During OD process additional dynamical parameters and the inclusion of atmospheric drag model were not consider because those would only weaken the solution.

The successful observation case of SL-8 rocket body from the SLR support campaign can be also used as an example for this method. The observation series for this target consisted of 7 points with observational arc of 17.5 seconds. The short observational arc resulted into the high uncertainties in the resulting orbital elements. However, we were able to estimate preliminary orbit with the resulting residuals between the measured positions and resulting elements were 0.81 arc-sec and can be seen in the Fig. 11. Even though the value is below 1 arc-sec, complete quality assessment at this stage is not possible due to the short arc and high uncertainties. The reference and resulting elements can be seen in Table 3.

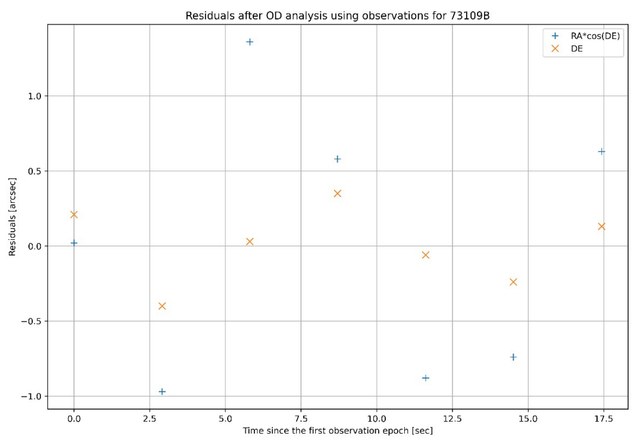


Fig. 11: Residuals for the OD solution for 73109B using all observations acquired on 2021-04-08

Table 3: A priori elements for 73109B on 2021-04-08 (Column 2) and Results of orbit determination analysis for 73109B, using observations on 2021-04-08 (Column 3-4)

REFERENCE EPOCH (MJD)		59311.682116860	
Element	Reference elements	OD elements	Uncertainties
P[m]	7346883.634178	7060833.036592	±1167035.088044
A[m]	7346892.431553	7071171.835271	±1088257.811938
E[-]	0.0010942705	0.0382374871	±0.1486192518
I[deg]	82.9334657	82.9094839	±0.0628996
NODE[deg]	350.3056081	-10.5161744	±0.2402797
PER[deg]	289.4884251	-55.0775095	±2.4758104
TPER[sec]	-2212.9661121	-2937.0404326	±691.9005254

4. DISCUSSION AND CONCLUSIONS

In our work we presented recent developments on the AGO70 telescope situated in Slovakia. AGO70 is an operational system able to acquire SST and scientific data for space debris object situated from LEO to GEO. These data can be used for many different purposes from astrometry used for cataloguing to photometry used for object characterisation. In order to adapt the system for LEO observations, several changes to the system has been performed in last year. First, the motor control unit was replaced by a custom-made solution which allows for control of both axes of movement separately, and for higher tracking speeds. Second, the interfaces of the new hardware were implemented in the software controlling the telescope. Lastly, the Image Processing System was extended to process LEO series.

The next step in the system's development was to demonstrate the capability to track non-cooperative LEOs and provide improved ephemerides to SLR stations in real time to increase their debris detection capabilities. This method was successfully demonstrated during the campaign which was conducted in Spring 2021. The proof-of-concept observation was done during the night at 8^{th} of April 2021, when AGO70 was able to observe the SL-8 rocket body with mean altitude of 982 km, to acquire the tracklet and to hand-over the improved TLE to Graz SLR station in real time. Graz SLR station was able to track the object with the improved TLEs also despite of the fact that object entered the Earth's shadow i.e. SLR station was able to perform 'blind' tracking thanks to provided improved TLE set. This case proved the AGO70 readiness for this type of observations. However, it shall be optimized in the future because the current data acquisition and provision chain contains 'human-in-the-loop', which makes the whole process not reliable. By automatizing these steps the efficiency of the data hand-over will be significantly improved, the latency as well the success rate.

Presented were also additional approaches to the data validation as comparison with the highly accurate CPF data and usage of the acquired tracklets for the subsequent orbital determination analysis. FMPI developed its own Data Validation System for the comparison of the extracted position with the CPF reference data. Thanks to the DVS we estimated our epoch bias, for which the time tag of each observation has to be corrected and we assessed our average astrometric accuracy by using selected GNSS satellites to by bellow 1 arc-sec. Demonstrated was also the usage of our data for the orbital determination analysis performed by the AIUB. However, to perform more detailed analysis it is required to obtain longer observational arcs for the targets (whole passage, two, three consecutive passages from single station, multi-station observations).

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