DEVELOPMENT AND OPERATIONAL STATUS OF AGO70 TELESCOPE

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ABSTRACT

Since the 2016 Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI) is developing its 70 cm Newtonian telescope (AGO70) within the framework of the ESA Plan for Cooperating States (PECS) program for Slovakia. The development is performed with focus on space debris tracking situated from Low Earth Orbit (LEO) up to Geosynchronous Earth Orbit (GEO), where majority of work was conducted towards the improvement of hardware, as well as software to achieve the full Space Surveillance and Tracking (SST) capability.

In our work we present the AGO70's overall design and discuss in detail all its subsystems, as well as interfaces. Presented will be performance results of AGO70's most crucial functionalities and we will briefly present all the space debris research programs which are performed at Comenius University and associated with AGO70 telescope.

1 INTRODUCTION, AGO70

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). Since the 2016 FMPI is developing its 70 cm Newtonian telescope (AGO70). Since 2019 the development is performed with focus on space debris tracking situated from Low Earth Orbit (LEO) up to Geosynchronous Earth Orbit (GEO), where majority of work was conducted towards the improvement of hardware, as well as software to achieve the full Space Surveillance and Tracking (SST) capability. AGO70 can be seen in Fig. 1 within the upper dome situated at AGO.

Figure 1. AGO70 in its cupola at Astronomical and Geophysical Observatory in Modra, Slovakia

Since 2019 several major updates have been performed to the system's hardware and software including telescope's mount control unit (MCU), observation scheduling (SCH) and low-level control system (LLTC), image processing system (IPS), data validation system (DVS), TLE improvement system (TLEI), GPS unit for precise timing, and pointing (mount) model construction system (PMC).

MCU along with SCH and LLTC allows to observe objects on low Earth orbit (LEO) with angular velocities up to 1.5 deg/s. DVS helps to validate the acquired astrometric data once the satellites of Global Navigation Satellite System (GNSS) or satellites of International Laser Ranging Service (ILRS) are observed. TLEI provides interface to Satellite Laser Ranging (SLR) sensors to improve the SLR sensors detection efficiency. PMC shall allow the system to perform observations during daylight when the astrometric solution is missing. One of the most crucial sub-systems is Image Processing System (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.

There are three objectives for LEO data acquisition with AGO70. Capability to provide in real-time fashion angular measurements or improved ephemerides based on acquired angular measurements to third party, e.g., SLR station; acquire angular measurements to perform orbit improvement of object's of interest; and acquisition of photometric measurements to investigate object's dynamical/rotation properties.

2 LEO DATA ACQUISITION

AGO70's previous -- default -- motor control only allowed for polar and declination axis to be moved simultaneously, in the same direction, and with one slewing speed. This design choice significantly limited the number of possible objects the telescope would be able to observe. More importantly, the control unit did

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not support sufficient speed generation for tracking of LEOs, even though the motors were capable of reaching it.

To adapt the AGO70 telescope for LEO tracking, several alternatives for motor control were considered. After a failed attempt with a commercial 3rd party stepper motor controller which produced excessive vibrations, a custom driver/controller combination was chosen. The driver and controller hardware were acquired and combined together to form the MCU, capable of generating frequencies up to 250 000 Hz (exceeding 3 arcsec/sec and thus covering all possible LEO tracking rates). Additionally, the in-house-produced MCU contains an electrically erasable programmable read-only memory (EEPROM) containing a firmware which allows for communication with the hardware inside the MCU, and therefore, the motors themselves.

The MCU firmware contains all the required commands for proper control of the telescope motors. The list below contains selected commands (called "telegrams") that provide both basic and advanced functionality:

- **ZERO** -- sends and receives and empty telegram, suitable for verifying connection status,
- **STATUS** -- requests status of the MCU's current frequency,
- **GP** -- "Go Positive" - commands the MCU to move in the positive direction,
- **GP** -- "Go Negative" - commands the MCU to move the motors in the negative direction direction,
- **ENABLE** -- enables the MCU,
- **DISABLE** -- disable the MCU,
- **WRITE** -- writes to the EEPROM (allows to modify several parameters.

LLTC (Low-Level Telescope Control) interfaces between the user and the many hardware components of the telescope itself -- had to be adapted to include interface with the MCU as well. As with the previous control unit, MCU is able to be controlled directly by the user by choosing a slewing direction (East/West, North/South) and inputting a value corresponding to a desired apparent velocity. This functionality serves well if the observer wants to slew the telescope from one point to another. However, in order to observe space debris objects, for example LEOs, which might appear to be accelerating and decelerating rapidly during the observation window, a more complex approach was required.

For this case, SCH software was developed which is engine responsible to calculate the tracking rates of objects by using SGP4 model and TLE data [1]. SCH allows the observer to prepare a complex observing scenario. All it requires are object's COSPAR number, start and end of the observing period, and step resolution. Resulting JSON file, which is output of SCH, contains necessary information to observe the object - the angular rates in RA and DEC at each time step. LLTC parses the JSON, converts the RADEC rates to frequencies and relays the information to the MCU at the proper time, separately to RA axis and separately to DEC axis. The result of SCH, LLTC, MCU, and the interface between them is AGO70 able to keep desired object in its field of view during its observation window. This is demonstrated in the Fig. 2 where are shown three FITS images acquired by AGO70 for objects Sentinel 3B (18039A) during night 25th of March 2021. FITS were acquired by using exposure time 0.05s and C filter. Mean altitude of Sentinel 3B object's orbit is 810 km above the Earth surface.

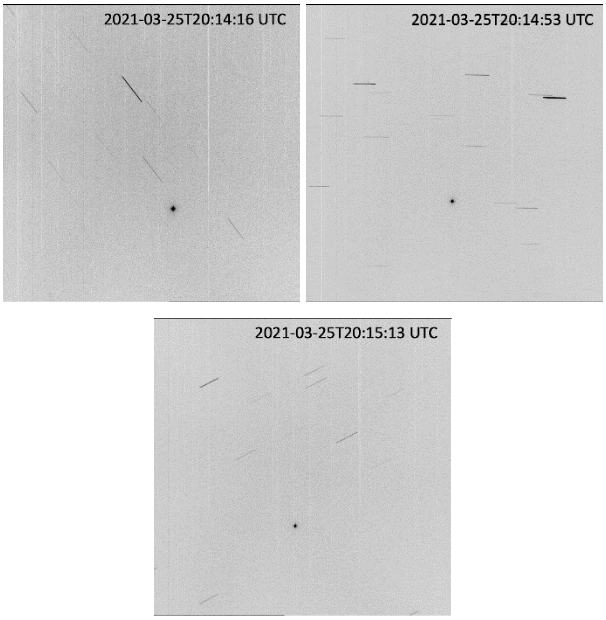

Figure 2. Three FITS images acquired for Sentinel 3B (18039A) by AGO70 on 25th of March 2021. Compilation of 3 frames, exp = 0.05s, filter C

To secure that the data are compatible with European services such as ESA's Expert Centre [2] or European Commission's EU SST service [3] the output of IPS processing is tracklet in format following international CCSDS TDM standards [4].

3 LEO ASTROMETRIC DATA REDUCTION

Astrometric data are acquired either for objects of interest or for calibration objects such as ILRS cooperative satellites. IPS allows to perform segmentation and astrometric reduction of the LEO FITS frames. DVS allows to validate system's data quality once calibration objects are observed. TLEI allows to create improved TLE, ephemerides, which can be used for more efficient tracking with SLR sensors.

3.1 Image Processing System IPS

A comprehensive overview of the IPS used to process frame series produced by AGO70 is described in [5].

In general, IPS pre-processes the frame series, performs segmentation and astrometric reduction, creates tracklets and formats the output. LEO processing uses the same logic, but with small, but crucial, differences.

Segmentation contains the most important adjustments. Namely, the sweep algorithm has been replaced by contour finding. Contours are abstract objects which are formed from close proximity pixels exceeding a pre-defined intensity level. Each contour's center pixel's location is sent into the centroiding algorithm which finds or corrects the Centre of Gravity iteratively. Contour finding improved the detectability of segmentation on LEO series, and relatively improved performance. On the other hand, intensity level is a sensitive variable needed to be changed accordingly to a frame's quality.

Additionally, Segmentation now includes a deciding algorithm calculating shape of an object. The information whether a frame object is a point or a streak is then passed into the final output file.

Directly correlated to the point-streak determination is the next adjustment in Masking. When in LEO mode, Masking removes all the frame objects that were determined to be streaks (note: these are from definition stars which are not needed anymore after plate solving). Moreover, if there is more than one point, Masking leaves only the brightest point (with the highest intensity). This simple, but effective, solution stems from the observational strategy of LEO at AGO70.

After the aforementioned changes, input of Tracklet Building is one frame object per frame, which are easily correlated into a tracklet and send for further processing.

3.2 Data Validation System DVS

AGO70 system performance can be validated by using measurements of calibration targets, objects with using Consolidated Prediction Format (CPF) via International Laser Ranging Service (ILRS) [6]. This is done by internal Data Validation System (DVS). Basic principle of the system is to calculate the ephemerides by using available CPF predictions and compared these to angular measurements acquired by AGO70. By varying observation time, e.g., within interval of -100 ms to 100 ms, we search for the smallest observed-minus-calculated (O-C) residuals. Once the minimum is identified, we identified the epoch bias of the system. Additionally, the minimum RMS also provides information about the best astrometric accuracy that system can reach.

Example of DVS in practice is shown in Fig. 3. We used 6 measurement points of Starlette (75010A, 7646), which is cooperative cannonball-like satellite on orbit with mean altitude of 963 km, to search for the epoch bias value for which system reaches minimum RMS between CPF predictions and measurements. Analysis revealed that this the case for epoch bias of 60 ms, which is consistent with our previous findings [7].

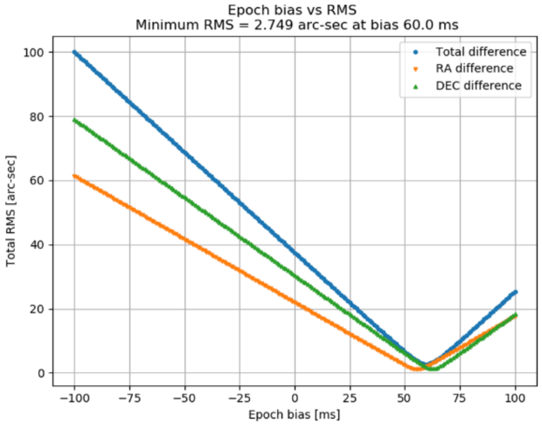

Figure 3. AGO70 epoch bias of +60 ms identified by DVS system. For analysis used has been tracklet (6 points) of geodetic cannonball satellite Starlette (75010A) observed by AGO70, start of series at 2021-03-30T19:29:41.254

3.3 TLE Improvement software TLEI

One of the AGO70's objectives is to provide to SLR stations in real-time the improved predictions based on the acquired angle measurements. This is done with internal tool TLE Improvement (TLEI). The basic logic behind the TLE improvement to be performed by AGO70 system and be provided to the SLR stations is plotted in Fig. 4. Once the FITS images are acquired by the AGO70 system, they are sent to the IPS system. This system performs segmentation and astrometric reduction and extract the astrometric measurements of the LEO object. Obtained data are provided to the TLEI S/W which will modify the TLE data, TLE data used for the pointing determination, by iteratively alternating TLE parameters right ascension of ascending node (*RAAN*) and mean anomaly (*M(t)*), until the smallest residuals between O-C positions are reached. Improved TLE with smallest O-C is selected and sent to the SLR station for ephemeris prediction calculation.

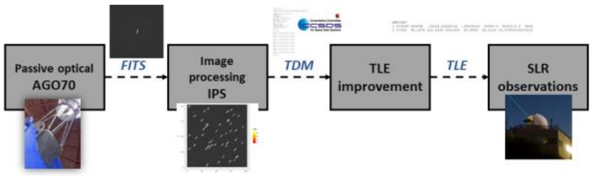

Figure 4. RMS of original (blue point) and improved TLE obtained with TLEI tool (red white cross). For analysis has been used tracklet (2 points) of geodetic

cannonball satellite Starlette (75010A) observed by AGO70, start of series at 2021-03-30T19:29:41.254

TLEI functionality can be demonstrated trough the ILRS cannonball satellite Starelette discussed in previous section. We used two measurement points of Starelette satellite which were acquired 60 s apart. We searched in *RAAN* and *M(t)* interval of ± 40 arc-sec. Fig. 4 depicts the result. We obtained smallest O-C difference for *dRAAN* = 0 arc-sec and *dM(t)* = 24 arc-sec.

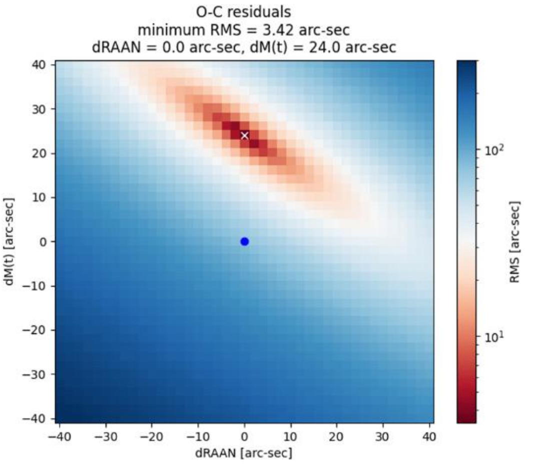

Figure 5. RMS of original (blue point) and improved TLE obtained with TLEI tool (red white cross). For analysis has been used tracklet (2 points) of geodetic cannonball satellite Starlette (75010A) observed by AGO70, start of series at 2021-03-30T19:29:41.254

Fig. 5 depicts angular distances Observed-Calculated (O-C) from previous case which show difference between measurements and CPF predictions (blue triangle) and difference between measurements and improved TLE predictions (red triangle).

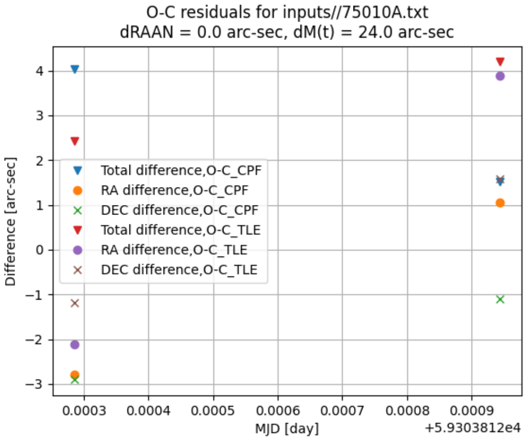

Figure 6. Angular O-C difference between measured and calculated positions. Blue triangles represent O-C with CPF prediction and red triangles represent O-C with improved TLE. For analysis has been used tracklet (2 points) of geodetic cannonball satellite Starlette (75010A) observed by AGO70, start of series at 2021-03-30T19:29:41.25

4 LIGHT CURVES OF LEO OBJECTS

The AGO70 has simultaneously ongoing several programmes [9], including instrumental light curve program. Under this program the light curve catalogue of the space debris objects on High-elliptical and Geosynchronous orbits has been established and is being continuously maintained and extended [7]. The Space Debris Light Curve Database (SDLCD) catalogue contains all relevant information about the target's apparent rotation period at the moment of observation. Estimated apparent rotational period is then used to fold the light curves into the rotational phase functions i.e. relations between rotational phase and targets instrumental magnitudes. This procedure is discussed in detail in [7,8].

Thanks to the beforementioned upgrades to the AGO70's system, the light curve acquisition could be extended fast LEO objects. Photometry of these objects is the crucial method for the extraction of necessary data for the planned active debris removal missions of high priority objects i.e. Envisat (02009A, 27386) and Vega AVUM adaptor (13021D, 39162). While AVUM shows stable behaviour, Envisat shows signs of rotation, which is expected for this target. Light curves for both mentioned objects can be seen in Fig. 7-8. Additionally, also light curve of Jason 2 (08032A, 33105) is plotted in Fig. 9, which shows signs of rotation, as well.

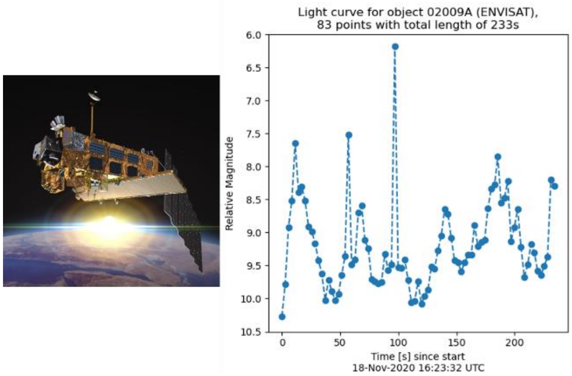

Figure 7. Visualisation of the ENVISAT (02009A, 27386) and its light curve from 18th November 2020 consisting of the 83 points acquire during 233 s long passage

5 SUMMARY AND CONCLUSIONS

AGO70 is operational system able to acquire SST and scientific data for space debris objects situated from LEO to GEO.

Thanks to the Image Processing System IPS adapted to the LEO frames segmentation it is possible to perform extract angle measurements of objects situated at altitude of 750 km. Data Validation System DVS provides information about the data quality. TLE improvement TLEI software improves original TLE data by using acquired measurement points. All AGO70's subsystems allow system to perform real-time improved ephemeris provision to SLR stations to increase their efficiency of tracking to non-cooperative targets.

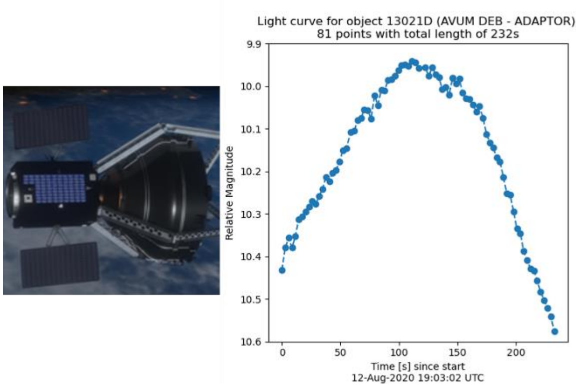

Figure 8. Visualisation of the AVUM DEB-ADAPTOR (13021D, 39162) and its light curve from 12th August 2020 consisting of the 81 points acquire during 232 s long passage

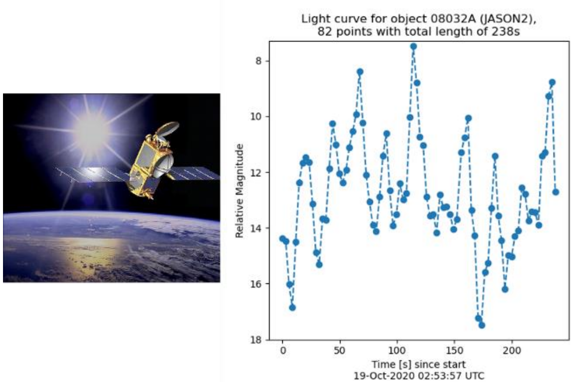

Figure 9. Visualisation of the JASON 2 (08032A, 33105) and its light curve from 19th October 2020 consisting of the 82 points acquire during 239 s long passage

The next step in the system's development is to demonstrate via observation campaign the capability to track non-cooperative objects on LEO and to provide improved ephemerides to SLR stations in real time fashion to increase their detection capabilities of these objects. Additionally, development of Pointing Model Construction PMC software and installation of a sCMOS camera planned for summer 2021 will introduce the possibility to track the space debris objects during daylight.

6 ACKNOWLEDGMENTS

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