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Slovakian Optical Sensor for HAMR Objects Cataloguing and Research

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Abstract

Slovakia became the 9th ESA European Cooperative State in 2015 and the first calls to action for the Plan for European Cooperating State (PECS) were announced shortly after. The Department of Astronomy and Astrophysics, a part of the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI CU), won the call and an activity with a main goal to transform a 0.7-m Newton telescope (AGO70) dedicated to amateur astronomical observations to a professional optical system for regular support of the space debris tracking and research has started. The transformation includes the necessary hardware and software modifications to the existing solution. The presented activity has been performed in cooperation with the Astronomical Institute of University of Bern (AIUB).

The AGO70 has been installed at the FMPI's Astronomical and Geophysical Observatory in Modra, Slovakia (AGO) in fall 2016. There are several predefined objectives to be accomplished within the activity. First, it was imperative to adapt the low-level telescope control for the needs of space debris tracking. Second, the image processing software must have been developed in a modular way. The observation planning has been formulated according to the AGO70 system's hardware limitations with focus on GEO, GTO and GNSS like orbits. To verify the system's capabilities, the whole activity is concluded with an observation campaign measuring AIUB's HAMR (High-Area-to-Mass-Ratio) objects and public TLE objects. The quality of the system's output is monitored by the AIUB via its state-of-the-art epoch bias and astrometric accuracy analysis routines.

Keywords: optical sensor, development, SST, space debris, image processing

1. Introduction

In this work we describe the AGO70 system's parameters. We discuss our modular image processing pipeline and its components and their validation. We also present the adapted observation planning, as well the detailed description of the system's products. We analyze the results of the observations campaign performed for several AIUB/ESA (HAMR) and GEO/GTO objects with a focus on the orbit determination (orbital elements and their change over time), the light curve analysis (apparent period extraction and change over time) and the description of surface properties trough the relative color indices.

1.1 ESA PECS activity

ESA Plan for European Cooperating States (PECS) is an activity dedicated to help candidates to prepare for a full ESA membership. Slovakia was the 9th state to join ESA PECS. The first ESA PECS call to action was in 2015 and first contracts, including the one with Faculty of Mathematics, Physics and Informatics of Comenius University in Slovakia (hereafter FMPI CU), have been signed in spring 2016.

Since the beginning of ESA PECS for Slovakia, three ESA PECS calls have already taken place. The ministry responsible for the PECS activities is the Slovak Ministry of Education, Science, Research and Sport. In Spring 2018 the 3rd call to action was finalized and winners were announced during the year. More than dozen of candidates applied to this call.

1.2 Consortium members

FMPI CU is a prime in the presented activity. It is a Slovak academic entity with a wide range of experience in astronomy, mostly in meteor and minor planets (NEAs, MBAs), and their astrometry and photometry. FMPI has a comprehensive experience in the hardware development of the all sky optical systems and software development for the telescope tasking and image processing.

The Astronomical Institute of the University of Bern (Switzerland) (AIUB) is the sub-contractor in the presented activity. The responsibilities of AIUB were mainly focused on space debris physical and dynamical properties and on optical measurements of space debris. AIUB operates three of its own optical telescopes (Swiss Optical Ground Station and Geodynamics Observatory), including development of object planning and image processing software. AIUB is maintaining its own space debris catalogue.

2. AGO 70-cm telescope

The main instrument of the activity was a Newton design telescope with a very thin 700 mm parabolic mirror from Alluna optics supported by gravity actuator (hereafter AGO70). The focal length of the system is 2962.0 mm. The installation of the AGO 70-cm Newton telescope was performed at the end of September 2016 (see Fig. 1). The whole process consisted from several steps including mount installation (Fig. 1a, 1b), tube placement (Fig. 1c) and primary mirror set up (Fig. 1d). AGO70 is shown in Fig. 2. Image was taken after the installation, in Spring 2017.

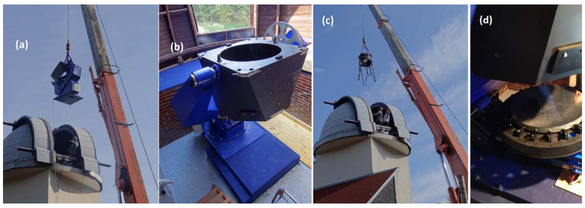

Fig. 1. Installation of the AGO70's mount, tube and primary mirror in the AGO upper dome on September/October 2016

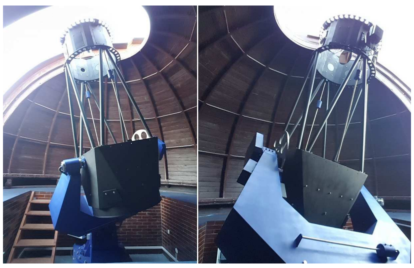

Fig. 2. AGO70 after installation at AGO. Spring 2017

AGO70 is equipped with a FLI Proline PL1001 Grade 1 CCD camera with 1024x1024 pixels and 24 µm pixel size. The download time of an unbinned full-frame image is around 1 second. Color photometry is possible due to a filter wheel containing Johnson-Cousins filters, namely BVRI and Clear. The parabolic primary mirror is placed in the focal length of 2962.0 mm. The resulting FOV of the system is 28.5' x 28.5' and its iFOV is 1.67"/pix.

Concerning the hardware, the mount tracking capabilities are exceptional; however, at the same time, the AGO70's Astro Electronic FS2 control unit has several limitations in tracking rates. Therefore, the nominal tracking rates at AGO70 are sidereal and GEO tracking. Additionally, other combinations are possible in RA and DEC directions, namely 0.25x, 1xSD, 4xSD, 16xSD and 64xSD (SD=sidereal tracking = 15"/s).

Low-level telescope control (LLTC) was developed to unify all the communication with basic systems. LLTC can communicate with the FS2 control unit, CCD camera, dome and filter wheel. LLTC also reads the mount encoders for real-time pointing corrections.

3. Observation campaign, general overview

There were 48 nights of observations in total, 20 nights in 2017 and 28 nights in 2018. We acquired 332 hours of observations, 127 hours in 2017 and 205 hours in 2018, and we collected 124,762 FITS LIGHT frames, 49,633 frames in 2017 and 75,129 frames in 2018. The specific number of acquired frames per given night can be seen in Fig. 3. The vast majority of data was acquired for astrometry, photometry and color photometry. The figure depicts only the number of LIGHT frames. Calibration frames were also acquired but omitted in the statistics.

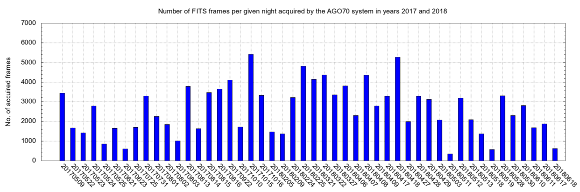

Fig. 3. Number of FITS LIGHT frames acquired by AGO70 system during years 2017 and 2018. Total amount per given night/date

4. Observation campaign, astrometry

Part of the observation campaign focused on astrometric measurements was performed to demonstrate the AGO70's capabilities for space debris/SST cataloguing.

4.1 Target list

We distinguished two types of targets for the astrometric observations - the global navigation satellite system (GNSS) objects and AIUB/ESA objects. GNSS objects are active satellites belonging to either GPS (Global Positioning System) or GLONASS (Globalnaja navigacionnaja sputnikovaja sistěma) navigation systems.

AIUB/ESA is a class of objects which were discovered during routine GEO, GTO and Molniya surveys performed by AIUB and ESA with the ESA's Space Debris Telescope (ESASDT) the 1-m Zeiss telescope located at the Optical Ground Station (OGS) at the Teide Observatory at Tenerife, Spain [1],[2]. These surveys have been taking place for more than 15 years and hundreds of objects have been discovered so far. However, due to the different perturbations which influence the object's orbit, most of them were lost over time.

4.2 Observation strategy and data reduction

The planning of the observations and calculation of the telescope pointing was performed by using FMPI's JAVA suit tool SatEph software. SatEph consists from several free packages and from own algorithms. The basic components of the software are packages containing Simplified General Perturbations SGP [3] and two-line elements (TLE) which can be loaded into the program.

We distinguish three types of observation strategies at AGO70 depending on the speed rates used during the measurements acquisition, namely: observations with sidereal tracking, observations with GEO tracking and observations with object tracking. Sidereal tracking is used in cases when the target is a bright object, e.g. brighter than 14-15 mag in R filter (Johnsons-Cousins filter). In this case we used very short exposure times, specifically 0.1s and 0.2s, to achieve that the target objects, as well star objects, appear as points on the exposed images. For this type of observation strategy, it is important to have enough dense star fields because fainter stars will be lost within the background. This observation strategy was used for the majority of astrometric measurements acquisition. Examples of composite images of series acquired for GNSS objects (left) and AIUB/ESA object (right) are shown in Fig. 4 below.

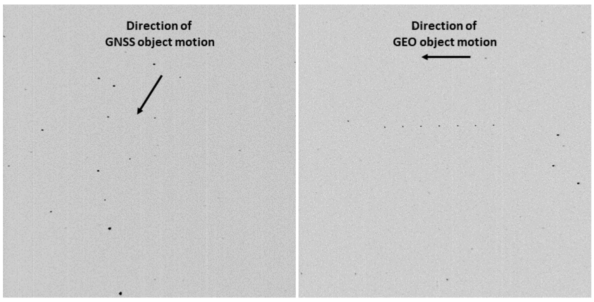

Fig. 4. Frames containing composites of images for GPS satellite (10022A) (left, a composite of 4 frames) and object E16022A (right, a composite of 7 frames) acquired by the AGO 70cm telescope during sidereal tracking. Exposures of 0.1s / R filter and 0.2s / R filter, respectively, were used.

Because the processing pipeline was under development during the activity (panel "Processing pipeline") we used Astrometrica tool [4] for astrometric reduction. Astrometrica is a commercial standalone software provided by an amateur astronomer Herbert Raab. It is a well-established tool in the astronomical community for astrometry measurements of celestial objects. It performs image segmentation, field identification and astrometric reduction.

4.3 System validation

Since 1992 the AIUB operates the Center for Orbit Determination in Europe (CODE) [5]. One part of the CODE's products are refined navigation satellites' orbits. The satellites' positions can be known for an exact moment to an order of few millimeters/centimeters. Thanks to such high precision one can use the data as the ground-truth for the satellite's positions, e.g. in ECI (Earth-Centered Inertial). The ECI coordinates can be transformed to the local equatorial RADEC which are then compared to the measured positions of the GNSS satellite. The output of the AIUB's routine are then the O-C (Observed - Calculated) residuals.

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.

As seen in Fig. 5, the analysis revealed that data quality varied over the investigated period, reaching astrometric accuracy between 0.8-0.9 arc-sec for the best period (May and June 2018) and 10.3 arc-sec for the worst period (April 2018). This discrepancy could not be explained to the date of this publication. However, any interference to the hardware or software could cause such a change in the data quality and several different improvements toward AGO's H/W and S/W were performed during the observation campaign.

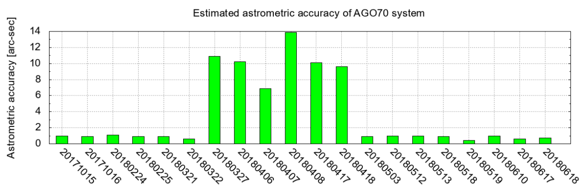

Fig. 5. Estimated astrometric accuracy of AGO70 system. Data obtained from AGO70's GNSS measurements processed by AIUB.

4.4 Orbit improvement, cataloguing support

In total, 14 AIUB/ESA objects observed by AGO70 for more than 3 days were processed for the orbit improvement. This has been done by AIUB by using the SATORB software, an orbit determination software which is part of the CelMech program suite [6]. The force model of the software includes all relevant forces and perturbation such as Earth's geopotential with spherical harmonics to degree and order 12 and gravitational perturbations from the Sun, Moon, Earth tides, corrections due to general relativity, direct radiation pressure (Sun only) and eclipses (Earth, Moon).

Two solutions were generated for 14 AIUB/ESA objects. For the first solution only AIUB data was used for orbit improvement, while for the second solution we included AGO70 data in the calculation as well. The results in the form of total residuals in astrometric position, calculated vs measured, can be seen in Fig. 6. The figure plots RMS measured for solution without (red empty circle) and with AGO70 measurements (green filled circle).

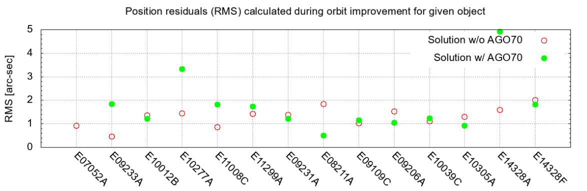

Fig. 6 - Position residuals (RMS) as calculated during AIUB's orbit improvement routine performed with CelMech tool. Plotted are solutions when AGO70 system data were not included to the processing (red) and were they were included to the processing (green).

5. Observation campaign, photometry

Instrumental photometry is performed in order to obtain the object's apparent rotation rate and phased light curve which is partially a function of the object's shape and surface reflective properties. Instrumental photometry is also an intermediate product for the absolute photometry.

5.1 Target list

The light curves were acquired for two types of objects - public catalogue objects monitored by the USSTRATCOM (United States Strategic Command) and AIUB/ESA objects.

5.2 Observation strategy and data reduction

The planning of the observations and calculation of the telescope pointing was performed by using FMPI's JAVA suite tool SatEph. We acquired series acquisition when generally, about 150-200 frames were acquired per series with exposure time from 1.0s to 5.0s, depending on the signal of the target. To decrease the total size of acquired data in most cases, we acquire subframes with 256x256 pixels. Example of a photometric image series (its composite) is plotted in Fig. 7.

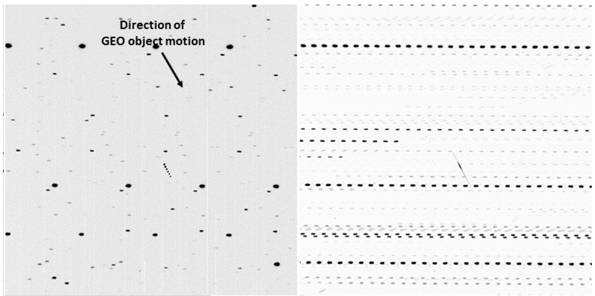

Fig. 7 - Images containing composite of frames for rotating defunct GEO satellite Echostar 3 (97059A) (left and right, composite of 6 and 130 frames, respectively) acquired by the AGO70 system during GEO tracking. Used were exposure of 1.3s / R filter.

To obtain a light curve from the acquired series we had to perform several steps. First, we performed image reduction to reduce the LIGHT frames by subtracting master DARK frame and master FLAT FIELD. This step was performed by the tool AstroImageJ (AIJ) [7], public domain, Java-based, software for astronomy image processing. Second, construct the light curve by extracting the instrumental magnitude values of the objects from the calibrated frames. This was also performed by AIJ. Third step is to extract the apparent rotation period from the time series, a light curve. For this step we used our own tool for frequency analysis. The principle is based on work published in [8].

5.3 FMPI's light curve catalogue

During 48 nights of observation campaign we acquired 339 light curves for 148 individual objects. Acquired light curves have been used to build up an FMPI's internal catalogue for further scientific purposes. From 148 observed objects 30 were spacecraft (S/C), 83 were upper stages (R/B), 22 were catalogued debris objects (DEB) and 13 were AIUB/ESA objects.

For more than 55% of all observed objects we could extract their apparent rotation periods; these were marked s *rotator* in Fig. 8 where we plot the overall statistics of the FMPI's light curve catalogue. *Stable/Slow* stands for objects with slow or no rotation, while *Unknown* stands for light curves we could not process.

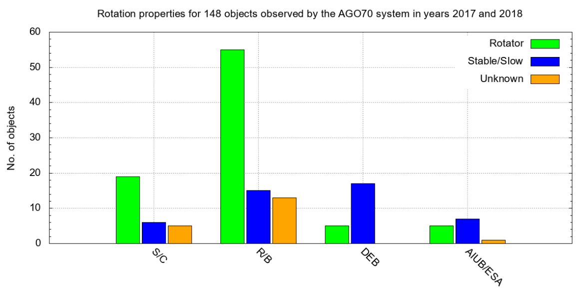

Fig. 8 - Distribution of the objects observed by AGO70 system in years 2017 and 2018 according to their rotation properties and type.

Observed objects were situated on different type of orbits, namely GEO, eGEO, GTO, Molniya and MEO. For more see Tab. 1.

Table 1. Number of observed object's type as a function of orbit type as observed during AGO70's photometry observation campaign.

Type / Orbit	S/C	R/B	DEB	AIUB/ESA
GEO	25	15	17	12
eGEO	1	8	0	0
GTO	0	37	5	1
Mol.	4	13	0	0
MEO	0	10	0	0

6. Image processing pipeline

One of the main goals of the presented activity was to develop image processing elements (IPEs) for the AGO70 system. IPEs are responsible for the image processing and with it related functions. First, we performed a review of existing processing pipelines, e.g., OGS or FMPI/AGO and related algorithms. Then we defined the design of our own pipeline according to the limitations and needs of AGO70's program. Finally, we identified 10 IPEs in our processing pipeline:

a) image reduction,
b) background estimation,
c) objects search and centroiding,
d) star field identification,
e) astrometric reduction,
f) masking,
g) tracklet building,
h) object identification,
i) data format transformation,
j) output data redistribution.

6.1 Image reduction and background estimation

The goal of the image reduction is to remove additive and multiplicative errors from the image pixels. The independent estimate of background noise can simplify the objects search and recognition procedures. Image reduction (IPE-IR) and background estimation (IPE-BE) elements are the first ones applied to the raw LIGHT image. IPE-IR uses well-established routines, while IPE-BE is based on the sigma clipping algorithm [9]. IPE-IR and IPE-BE testing revealed that the results are yielded in real-time. IPE-BE behaved very reliably and it is applicable even for more challenging cases when non-linear background is present in the frame.

IPE-IR and IPE-BE were developed by FMPI during presented activity.

6.2 Object search and centroiding

This element, IPE-SC, is responsible for detection and measurement of frame objects. It is one of the most complex elements and it consists of three major parts:

- search algorithm
- centroiding algorithm [10]
- touch-down algorithm

IPE-SC was developed by FMPI during the presented activity.

6.3 Star field identification and astrometric reduction

For the star field identification (IPE-SI) and astrometric reduction (IPE-AR) we use a script suite Astrometry.net [11]. For the latter, we used the input from IPE-SC and only the plate constants solution function is used.

Except the Astrometry.net suite, all the algorithms of IPE-SE and IPE-AR were developed by FMPI during the presented activity.

6.4 Masking

The masking algorithm (IPE-MR) contains the identification of star frame objects algorithm which is used to find stars in the data by using data sets from different FITS frames with presumably similar star field. By comparing J2000 coordinates of frame objects measured at different frames one can identify static objects, e.g., objects with very low apparent angular velocity. The objects slower than the mentioned threshold are marked as stars and therefore removed from the data set.

IPE-MR was fully developed by FMPI during presented activity.

6.5 Tracklet building and object identification

The IPE Tracklet building (hereafter IPE-TB) is responsible for associating frame objects into a tracklet, consecutive measurements of the same object. The IPE contains two steps to associate frame objects:

- Linear regression algorithm
- Weighting algorithm

Linear regression is a well-known statistical concept. The weighting algorithm provides a weight to each frame object which passed the linear regression. This is done by using two quantities, namely the apparent angular velocity ω and the position angle PA. These quantities are then used to correlate a single measurement into a tracklet.

The IPE Object identification (hereafter IPE-OI) is responsible for correlating a tracklet with a catalogue object. There are three parameters used for comparison of the tracklet and the catalogued object, namely angular distance Δ, position angle PA and angular velocity ω. Positions of catalogued objects are determined by using SGP model and TLE data from the catalogue, which can be either public (from www.space-track.org) or internal, e.g. AIUB/ESA TLE catalogue.

IPE-TB and IPE-OI were developed by FMPI during the presented activity.

6.6 Data format transformation

The element IPE-DC converts internal FMPI's tracklet format defined during the presented activity into other formats such as AIUB's OBS, CCSDS TDM [12], Minor Planet Centre (MPC) and Inter-Agency Space Debris Coordination Committee (IADC) light curve format [13]. This helps AGO70 to interface with external systems and institutions such as AIUB, ESA's SST Expert Centre, EU SST, etc.

7. Conclusions

In our paper we present goals and results of the ESA PECS activity for Slovakia called "Development of a Supporting Optical Sensor for HAMR Objects Cataloguing and Research (HamrOptSen)". This is an activity led by the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava (FMPI CU), Slovakia in cooperation with the Astronomical Institute of University of Bern.

The main goal of the activity was to develop a Slovak optical passive system for space debris research and SST applications. We described the properties of the developed 70-cm Newton telescope (AGO70) situated at the FMPI's Astronomical and Geophysical Observatory in Modra, Slovakia (AGO). We discussed the strategies, target lists and results used during extensive observation campaign which took place in years 2017 and 2018 by using AGO70. This campaign was focused on acquisition of astrometric and photometric data to AIUB/ESA and TLE objects.

Large part of the activity was dedicated to design definition and development of the image processing pipeline to be used in AGO70's space debris measurements. The pipeline, as well its image processing elements were presented and discussed.

Acknowledgements

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References

[1] Schildknecht et al., Optical observations of space debris in high-altitude orbits, Proceedings of the 4th European Conference on Space Debris (ESA SP-587), 18-20 April 2005, ESA/ESOC, Darmstadt, Germany (2005), pp. 113-118.

[2] Silha, J., et al., An optical survey for space debris on highly eccentric and inclined MEO orbits, Advances in Space Research, Volume 59, Issue 1, 1 January 2017, Pages 181-192, ISSN 0273-1177.

[3] Vallado et al., 2006. Revisiting Spacetrack Report #3, in: The AIAAAAS Astrodynamics Specialist Conference. American Institute of Aeronautics and Astronautics, pp. 1-88.

[4] Raab, H., Detecting and Measuring Faint Point Sources with a CCD, in Proceedings of the Meeting on Asteroid and Comets in Europe, 2003, May 1-4, 2003.

[5] Villiger, A. and R. Dach (Eds.); 2017: International GNSS Service: Technical Report 2017. IGS Central Bureau and University of Bern, Bern Open Publishing, June 2018.

[6] Beutler G., Methods of Celestial Mechanics, Springer Verlag, Heidelberg, 2005.

[7] Collins et al., AstroImageJ: image processing and photometric extraction for ultra-precise astronomical light curves, arXiv:1601.02622.

[8] Šilha J. et al., Apparent rotation properties of space debris extracted from photometric measurements, In Advances in Space Research, 2017, ISSN 0273-1177.

[9] V. Kouprianov, Distinguishing features of CCD astrometry of faint GEO objects, Advances in Space Research, Volume 41, Issue 7, 2008, Pages 1029-1038, ISSN 0273-1177, http://dx.doi.org/10.1016/j.asr.2007.04.033.

[10] H. Wang et al. Gaussian Analytic Centroiding method of star image of star tracker, Advances in Space Research, Volume 56, Issue 10, 15 November 2015, Pages 2196-2205, ISSN 0273-1177, 2015.

[11] D. Lung et al., Astrometry.net: Blind astrometric calibration of arbitrary astronomical reduction, 2010, The Astronomical Journal, Volume 139, Number 5.

[12] Tracking Data Message, CCSDS 503.0-P-1.0.4, CCSDS, Pink Book, January 2017.

[13] IADC, Information exchange between WG1 and WG2: content and format, Version 5, January 2014.