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AGO70 telescope: demonstration of passive optical system supporting SLR tracking of space debris on LEO

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Motivation

- Two Lines Elements (TLEs) for LEO with positions errors up to 1 km, which translates to few arc-min for a ground-based sensor (active or passive)
- For SLR to track TLE object requires time to get the detection, searching around the predicted position on sky, loosing time because of the poor predictions
- With optical passive sensors with wider FoVs higher probability to track the object (including debris) and to improve its orbit to be hand-over to SLR

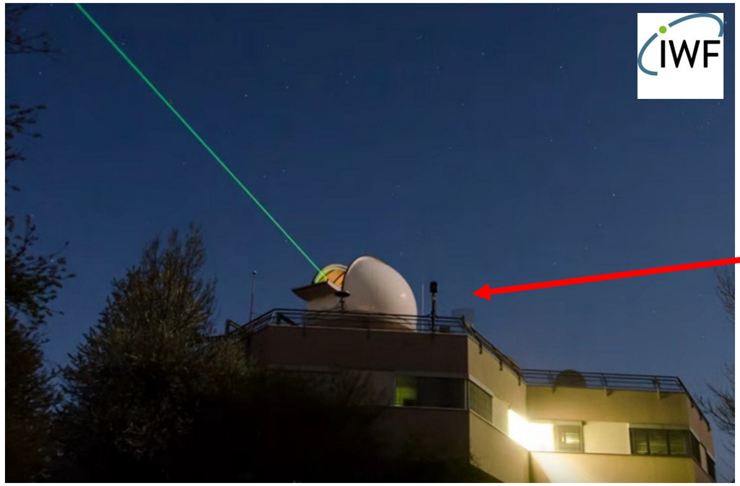
Instrumentation

www.sdlcd.space-debris.sk

- Two instruments have been used, AGO70 telescope and Graz SLR station

- Graz SLR:
  - 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), 532 nm wavelength.
  - 100 Hz / 3 ns / 200 mJ per shot laser, 532 nm wavelength.
  - The telescope used for SLR has a 10 cm transmit telescope, and a 50 cm receive telescope in Cassegrain configuration.

Operator	FMPI
Telescope	AGO70
Telescope design	Newton
Mount	Equatorial (Open fork)
Camera	CCD FLI-ProLine KAF-1001E
Dimension	1024x1024
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/px]	1.67



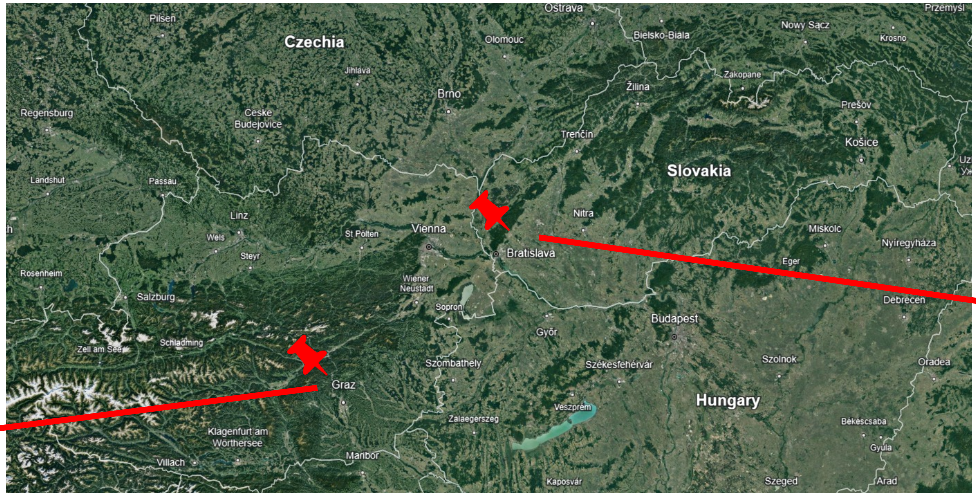


Fig. Graz SLR station AGO70 telescope situate in Graz, Austria

Fig. AGO70 telescope situated in Modra, Slovakia

Data acquisition and data provision chain

- The whole processing consist of several steps, some automated and some required human-in-the-loop which contributed to the time latency for the data delivery

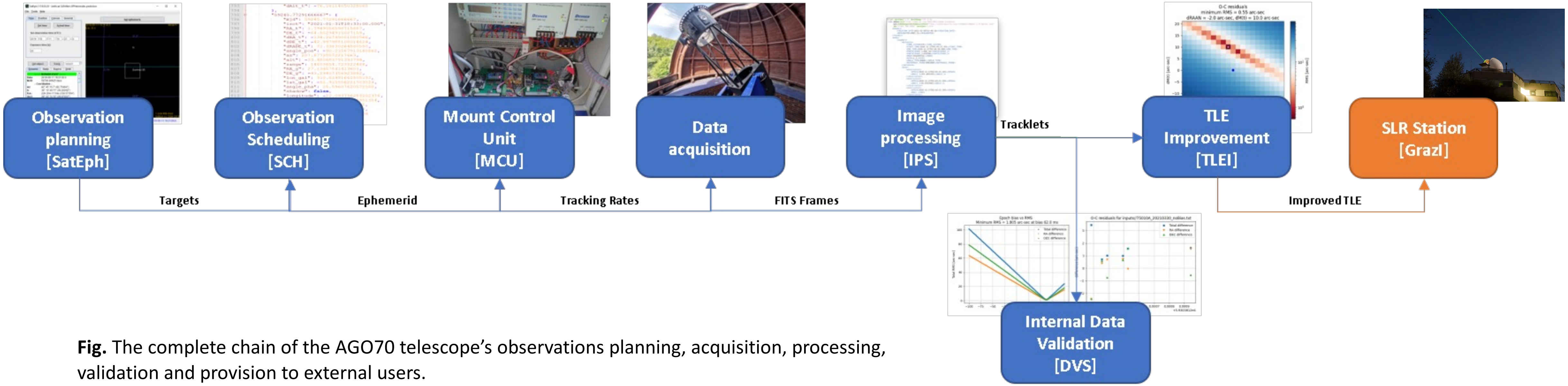


Fig. The complete chain of the AGO70 telescope's observations planning, acquisition, processing, validation and provision to external users.

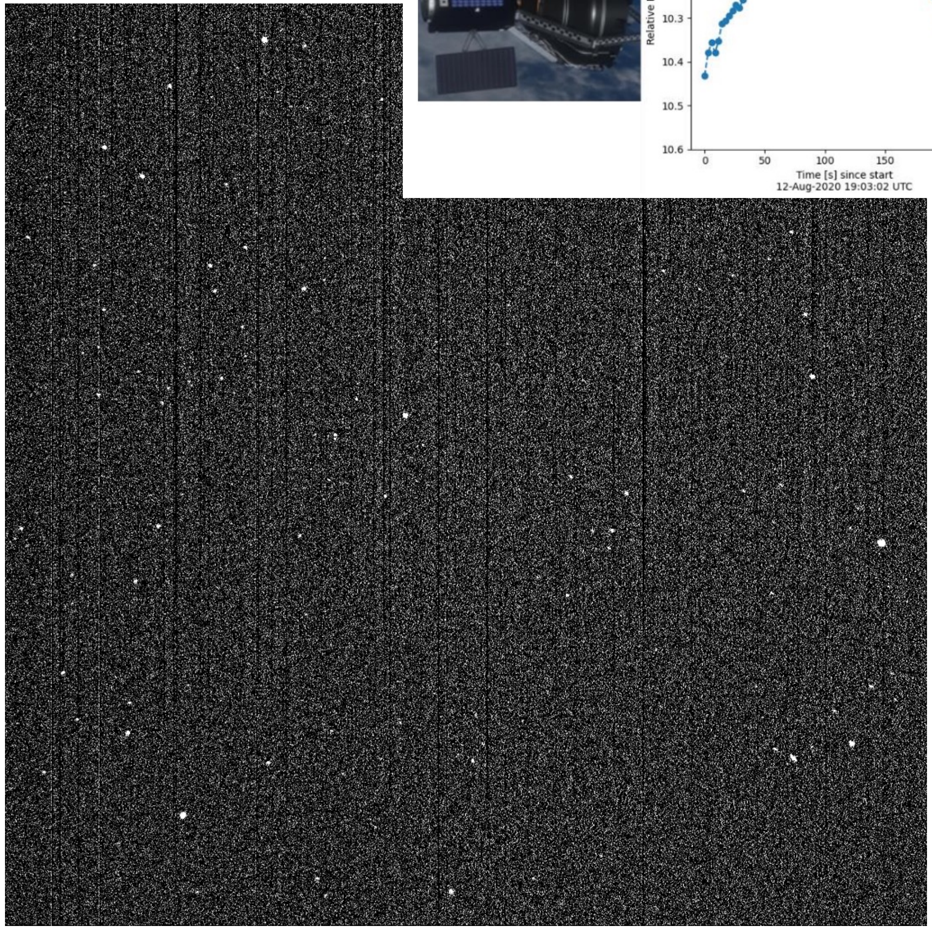
Scheduling and Mount Control Unit

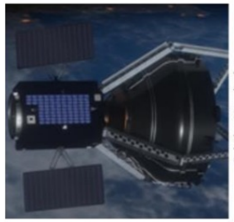
- **Scheduling - SCH –**
  - The Scheduling SW is responsible for the calculation of the detailed ephemeris information for the selected target.
  - The output contains all necessary information for the telescope tasking as tracking rates and also the geometric parameters of the observation, which are 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 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).
  - Communication protocols were 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.





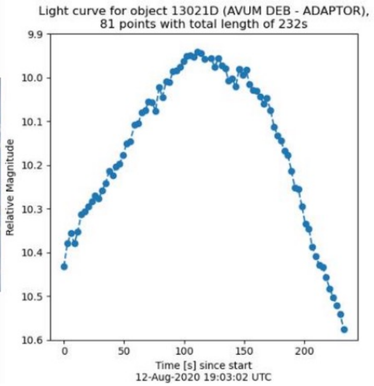
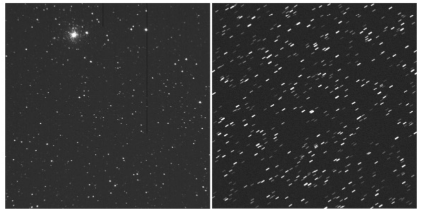
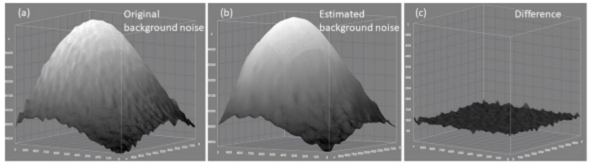


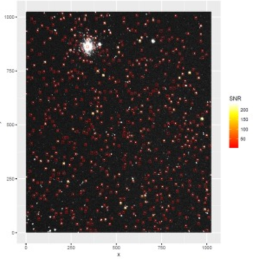
Fig. – Compilation of 118 FITS frames of AVUM DEB (ADAPTOR) (13021D) acquired by AGO70 during night 2020-08-12. Used R filter and exposure time of 0.1 s. Mean altitude ~ 731 km.

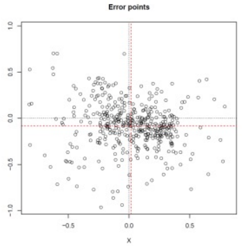
Image Processing System

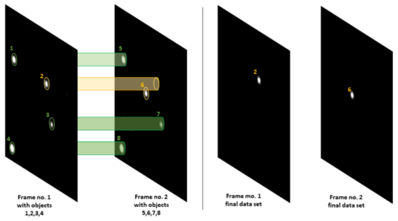
- In total, there are 9 image processing elements (IPEs) in the pipeline, each with its own role:
  - star field identification,
  - image reduction,
  - background estimation and subtraction,
  - objects search and centroiding (segmentation),
  - astrometric reduction,
  - masking,
  - tracklet building,
  - object identification,
  - data format transformation.











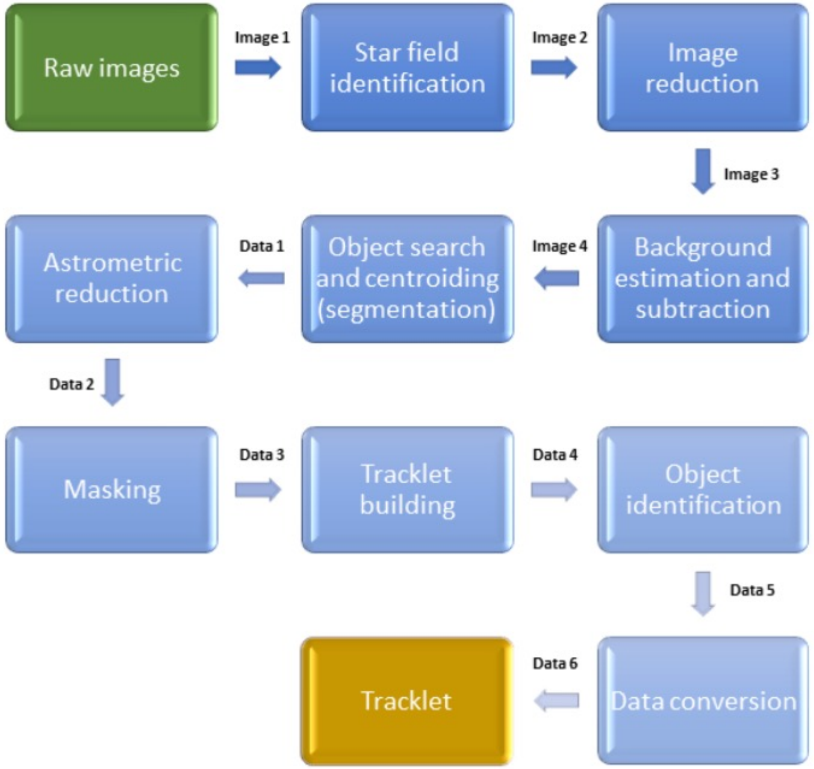


Fig. Simplified diagram demonstrating the interactions and data flows between FMPI's Image Processing Elements (IPEs) used for the AGO70 telescope pipeline for the astrometric and photometric reductions.

TLE improvement and data provision

- The basic approach is to improve two elements of a specific TLE set:
  - mean anomaly M(tTLE) (tTLE 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.

- The mean anomaly M and RAAN corresponding to the minimum of the residuals are then saved as improved TLE (iTLE)

- Data are automatically sent directly to the Graz SLR station through the FTP server.

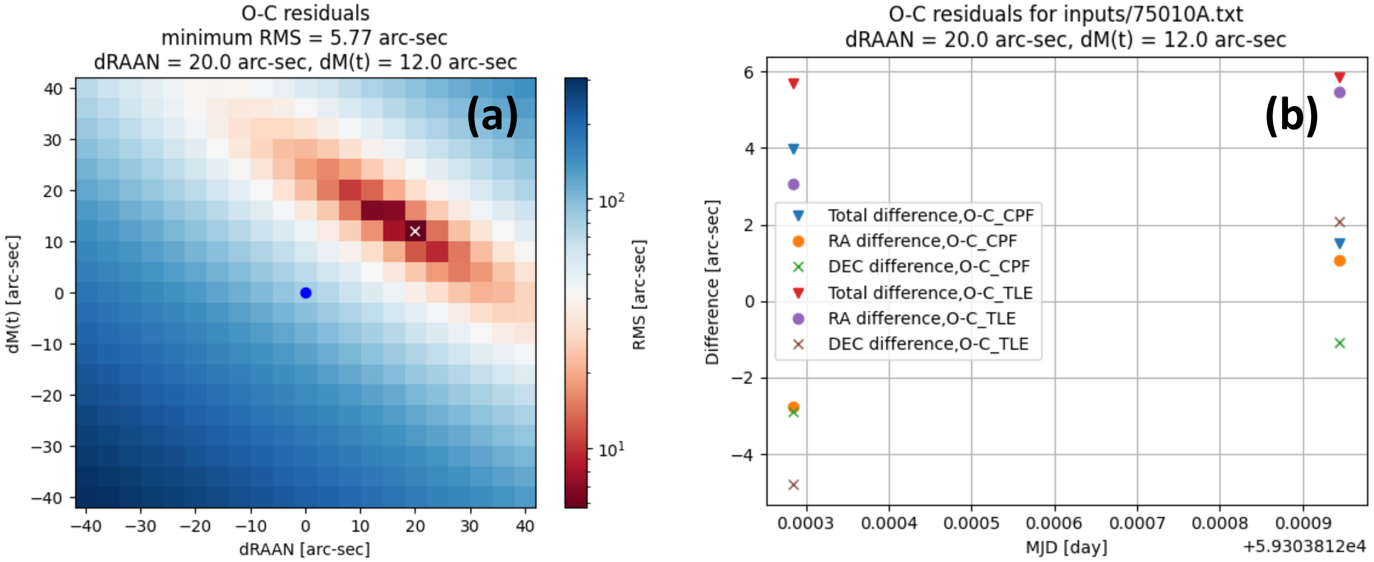
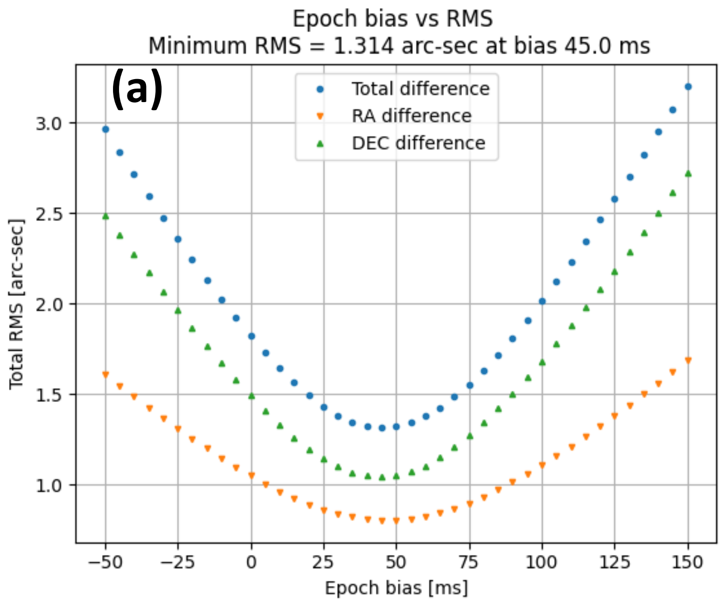


Fig. Output diagrams generated by TLEI S/W. Plotted is the search heatmap dRAAN vs dM(t) (a) and O-C residuals between observed and data calculated from improved TLE and from CPF (b).

Data validation

- AGO70 and its all subsystems needed to be validated before the campaign.

- For validation we are using Data Validation System (DVS) S/W where compared are the very high accuracy predictions/positions (O-C analysis) (GNSS, ILRS objects) with the measurements



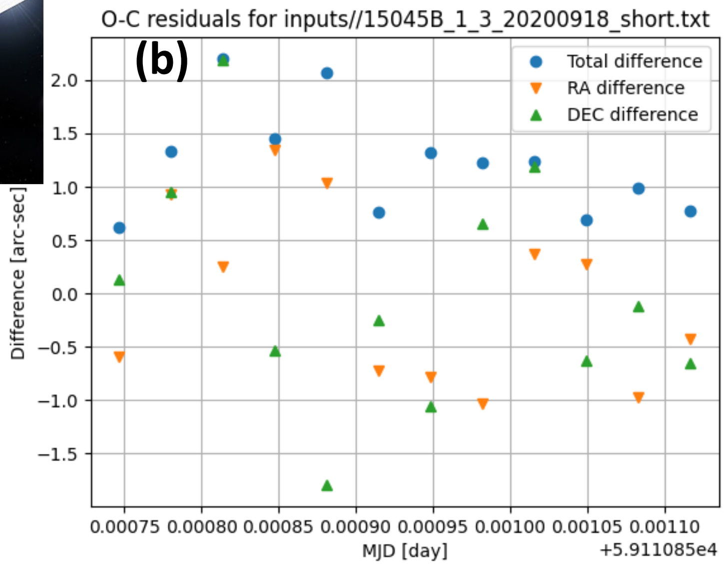


Fig. Results of the internal Data Validation Suite (DVS) for object GALILEO 10 (206) (NORAD 40890, 2015-045B) observed by AGO70 during night 2020-09-18. (a) RMS of RA, DEC and total residuals as function of epoch bias. (b) O-C assuming used measurements and found epoch bias value.

Observation campaign - cooperative

- Example: 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.

- iTLE generated with refined TLE 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.

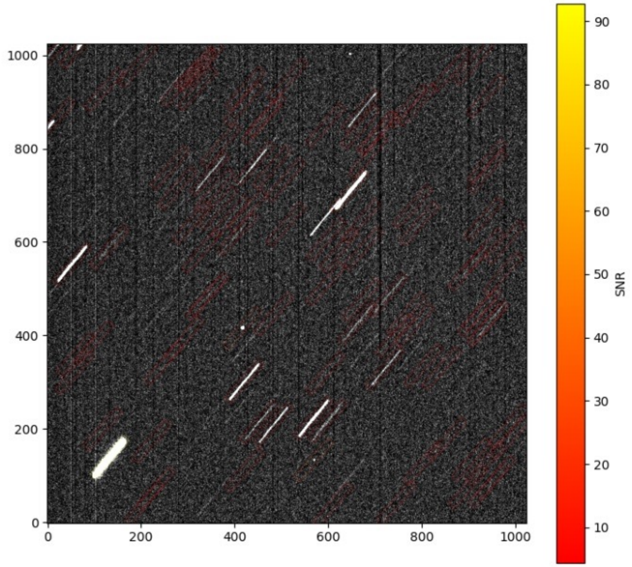


Fig. AGO70 observation frame containing target's position used for TLE improvement

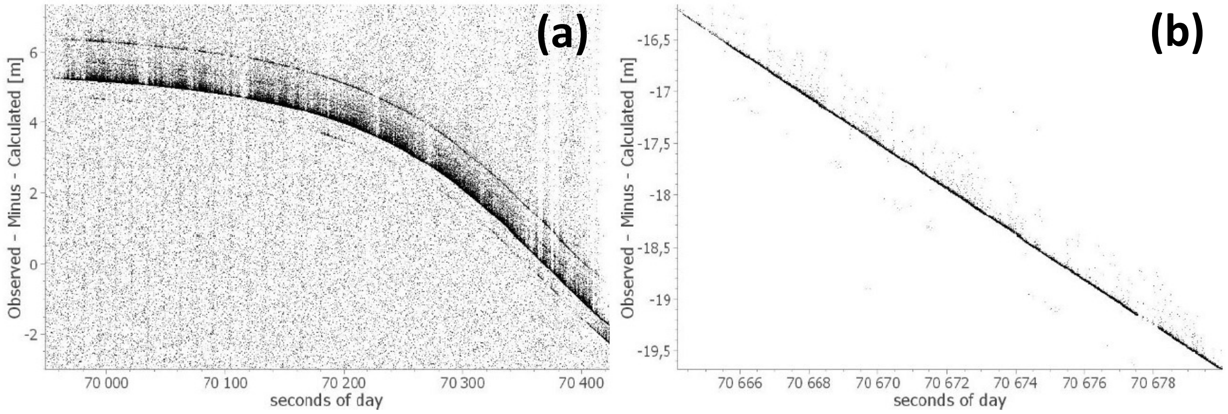
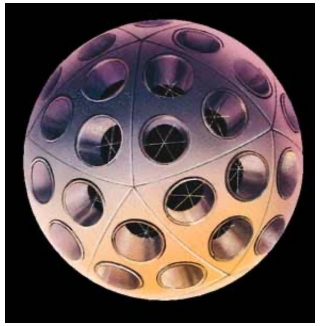


Fig. Object 75010A residuals measured by SLR Graz station. (a) Plotted are residuals obtained by using CPF predictions. (b) Plotted are residuals obtained by using iTLE generated from AGO70's measurements.



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

Tab. The time and range bias results of the orbit fitting evaluated during post processing

Observation campaign – non-cooperative

- Example: 1973-109B (SL-8 R/B, NORAD 7009) 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. Object started its motion from the North-N.
- 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.
- iTLE generated TLE 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. **Object still tracked even in the shadow.**

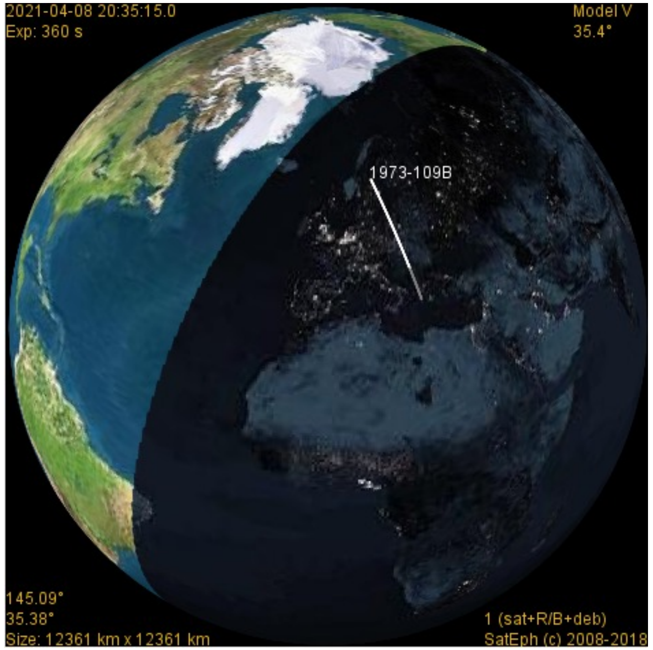


Fig. Passage geometry from AGO location

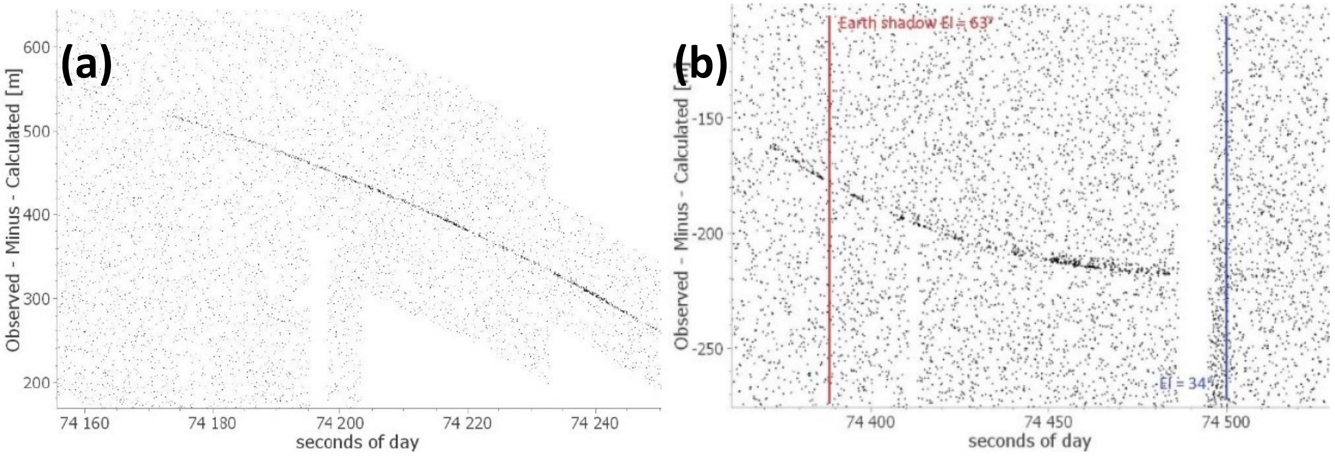


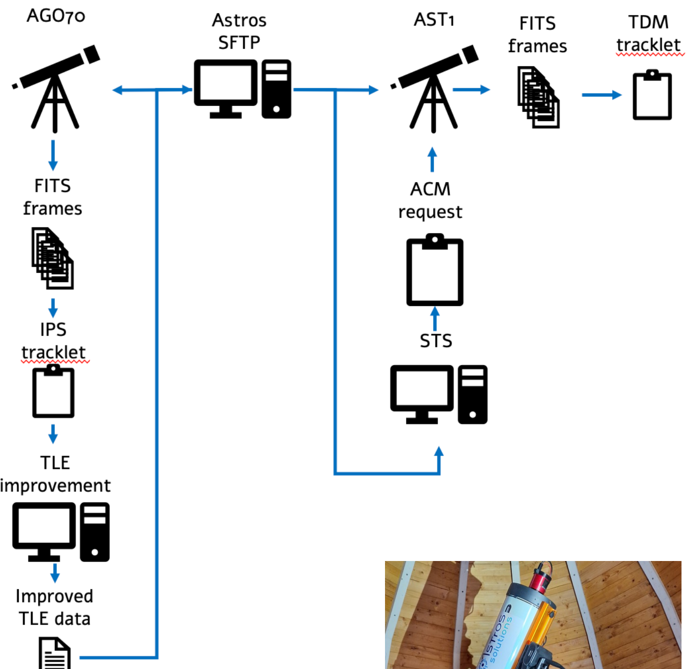
Fig. Object 73109B residuals measured by SLR Graz station. (a) Plotted are residuals obtained by using old TLE predictions. (b) Plotted are residuals obtained by using iTLE generated from AGO70's measurements.

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

Tab. The time and range bias results of the orbit fitting evaluated during post processing

Extension to other systems – Astros example

- AGO70 "Stare&Chase" demonstration in combination of automated SST optical passive sensor operated by Astros Solutions s.r.o. - Task under the activity Iguassu PECS SK P3-SST-III CR02
- AGO70 served as Stare sensor – Astros (AST1) sensor served as Chaser
- Night 2022-12-17
  - 2 successful attempts on GNSS target NORAD 40001
  - 1 GTO attempt on CZ-3 R/B target NORAD 40750
- GTO target – qxQ = 302.4 x 16,536.0 km
  - Mean distance during the passage 4500 km

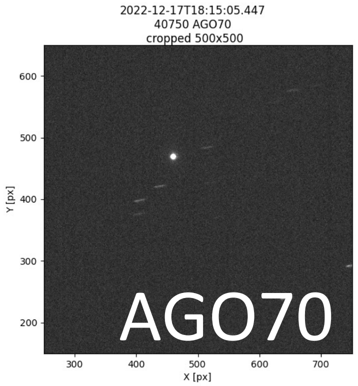


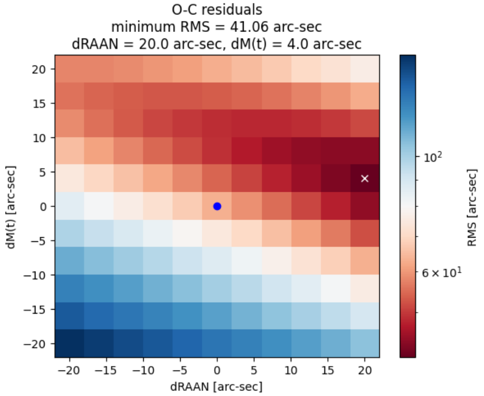
Original TLEs

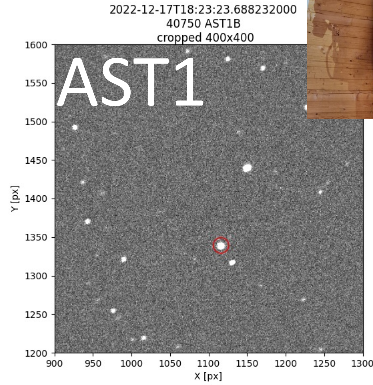
```
0 CZ-3B R/B
1 40750U 15037C   22351.11904813  .00010170  00000-0  19340-2 0  9990
2 40750  54.9653 246.2518 6487824    7.8997 358.1159  4.82625930128828
```

Improved TLEs

```
0 15037C
1 40750U 15037C   22351.11904813  .00010170  00000-0  19340-2 0  9990
2 40750  54.9653 246.2574 6487824    7.8997 358.1170  4.82625930128828
```







Summary

- Developed has been for AGO70 control unit, image processing software and interfaces for the real-time TLE improvement and data handover to SLR station
- All subsystems tested and validated during successful observation campaign conducted in 2021 and in collaboration with IWF and Graz SLR station
- In 2022 the whole system tested also on the private sector’s passive optical sensors (tracking up to 9 deg/s), the whole methodology transferred to private sector to improve latency

Thank you for your attention!

Questions?

www.sdlcd.space-debris.sk

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