The Solaris-Panoptes Global Network of Robotic Telescopes and the Borowiec Satellite Laser Ranging System for SST: A Progress Report

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ABSTRACT

We present an update on the preparation of our assets that consists of a robotic network of eight optical telescopes and a laser ranging station for regular services in the SST domain. We report the development of new optical assets that include a double telescope system, Panoptes-1AB, and a new astrograph on our Solaris-3 telescope at the Siding Spring Observatory, Australia. Progress in the software development necessary for smooth SST operation includes a web based portal and an XML Azure Queue scheduling for the network giving easy access to our sensors. Astrometry24.net our new prototype cloud service for fast astrometry, streak detection and measurement with precision and performance results is also described. In the laser domain, for more than a year, Space Research Centre Borowiec laser station has regularly tracked space debris cooperative and uncooperative targets. The efforts of the stations' staff have been focused on the tracking of typical rocket bodies from the LEO regime. Additionally, a second independent laser system fully dedicated to SST activities is under development. It will allow for an increased pace of operation of our consortium in the global SST laser domain.

1. INTRODUCTION

The Polish SST (PL-SST) consortium is composed of two public research institutions from the Polish Academy of Sciences, Nicolaus Copernicus Astronomical Center (NCAC) and Space Research Center, two Polish companies Sybilla Technologies, Cillium Engineering and a non-profit research foundation Baltic Institute of Technology. The European partners include the company Baader Planetarium GmbH (Mammendorf, Germany), and scientists from The Open University (UK), the Max Planck Institute for Extraterrestrial Physics (Garching, Germany) and the Radboud University (Nijmegen, the Netherlands). W currently jointly operate 8 robotic optical telescopes in both hemispheres under the name Solaris-Panoptes network [1] and the Borowiec Laser Ranging Station of the Space Research Center. The Solaris component [2,3,4] is composed of four autonomous observatories located at the South African Astronomical Observatory (Solaris-1 and Solaris-2), Siding Spring Observatory, Australia (Solaris-3) and Complejo Astronomico El Leoncito, Argentina (Solaris-4). The Panoptes component utilizes available observing time of 4 telescopes (northern hemisphere, [1]) owned by The Open University, Max-Planck-Institut für Extraterrestrische Physik and Baader Planetarium on the base of separate agreements on providing SST observations. Below we present an update on the development of our SST assets in the hardware and software domains.

2. OPTICAL TELESCOPES

Fig. 1 Solaris-3 at the Siding Spring Observatory (Australia) upgraded with an astrograph (ASA Astrosysteme H-series, 8 inch, f/2.8) and a sCmos camera (Andor Zyla 5.5).

In May 2017, during a maintenance visit to the Siding Spring Observatory, we have installed a new astrograph on the existing Solaris-3 setup (Fig. 1). The astrograph is an ASA Astrosysteme H-series, 8 inch, f/2.8. It is equipped with a sCmos Andor Zyla 5.5 camera. The camera has a 2560 x 2160 detector with 6.5 um pixels and max QE of 60%. It offers 30 fps with the global shutter. With the focal length of 560 mm, the astrograph and camera offer a 1.7 by 1.4 deg field of view with 2.4 arcsec pixels. The instrument was commissioned on a number of LEO targets to ensure the capability to precisely track even the fastest targets. After the commissioning, the astrograph is now used for regular SST campaigns (Fig. 2).

In August 2017, Baader Planetarium GmbH has delivered a complete set of equipment: optics, mount and the 3.5-m clamshell dome to the Baltic Institute of Technology for the Panoptes 1AB telescope (Fig. 3). Panoptes-1AB is a double system composed of a unique 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m Planewave telescope. The installation and the first light are expected in Q4 2017. The telescope will be initially installed in Gdynia (Poland) for R&D purposes and first on sky tests and later relocated to most likely the southern hemisphere. With a KAF16803 based camera, TEC300VT will offer a stunning 5x5 deg (7 deg across, 4.4"/pixel) field of view. The 0.5-m f/6.8 Planewave will provide a 37' x 37' field of view (52' across, 0.54"/pixel). Panoptes 1AB will be fully dedicated to SST.

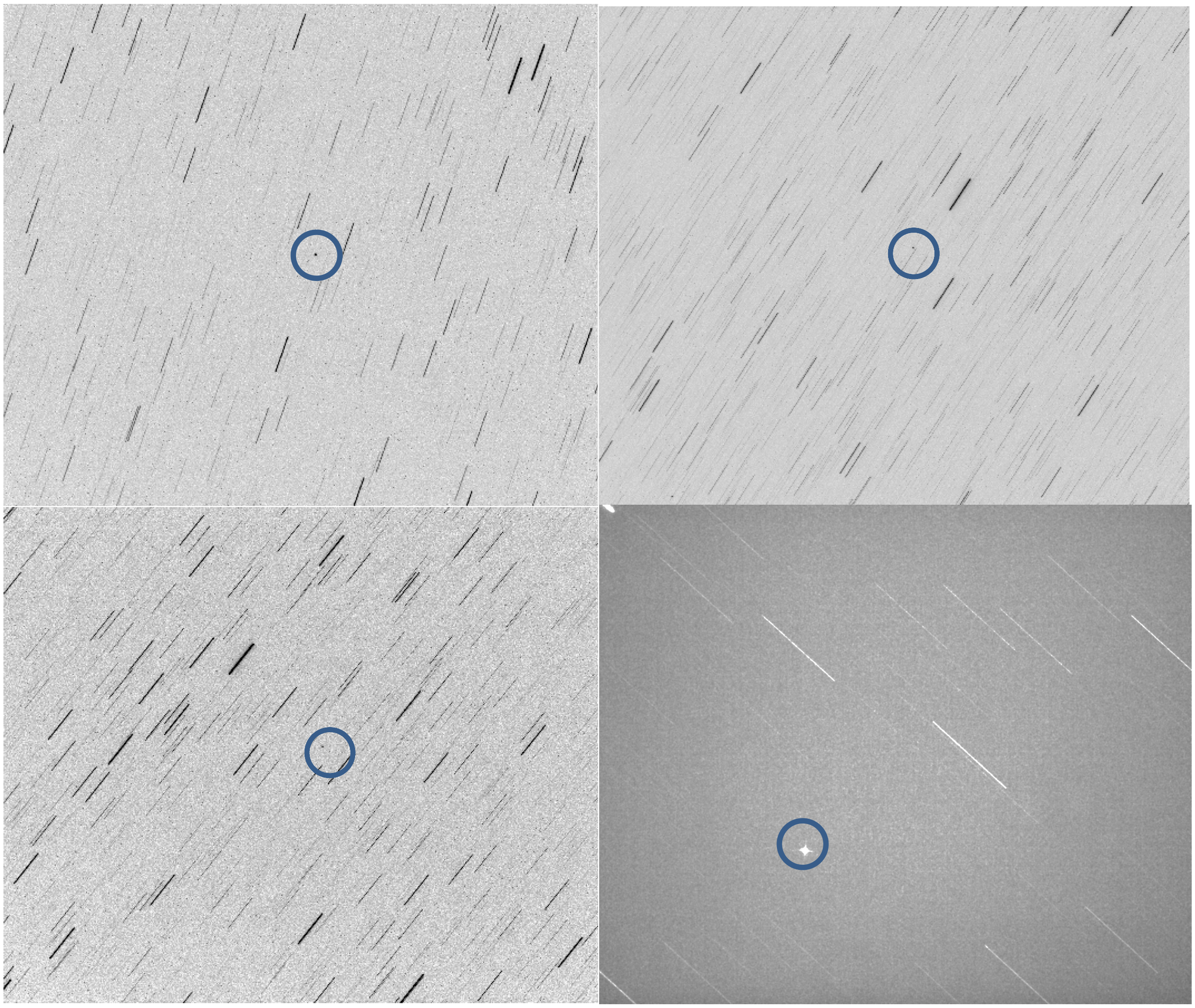

Fig. 2 A sample of commissioning (lower right corner) and regular campaign data (remaining images) from the new astrograph (8 inch ASA f/2.8 + sCmos Andor Zyla 5.5) on the Solaris-3 telescope. The commissioning data is a 0.5 sec exposure of Hinode (LEO, ~700 km), the remaining images are 10 sec exposures of Cosmos 2475, Cosmos 2492 and GPS BIIF 6. The field of view is 1.7x1.4 deg and the pixel size is 2.4 arcsec.

3. BOROWIEC SATELLITE LASER RANGING SYSTEM

Laser space debris tracking

In August 2016 Space Research Centre of PAS (SRC BORL station) has launched regular tracking of space debris (cooperative – defunct satellites and uncooperative targets – rocket bodies) in the frame of Space Debris Study Group (SDSG) of International Laser Ranging Service (ILRS) by means of high-energy laser Continuum Surelite III. This laser operates with 10 Hz repetition rate, 3-5 ns pulse width and 450 mJ pulse energy for 532 nm [5,6]. Up till now 350 full passes (without interleaving) of space debris targets (246 cooperative and 104 uncooperative) were performed. Fig. 4 presents a sample pass of rotating defunct TOPEX/Poseidon with many single good returns (2235), with min.-max distance to the target 1926 – 2207 km. The RMS for this pass is 43.96 cm.

Fig. 3 The new Panoptes 1AB telescope. Left: before shipment on the premises of Baader Planetarium GmbH (Mammendorf, Germany). Right: after delivery of the telescope and the clamshell dome, partly unpacked at a lab of the Baltic Institute of Technology. The sensor is composed of a unique 0.3-m f/1.44 TEC300VT-7DEG astrograph and a 0.5-m Planewave telescope on a GM4000 mount. FLI16803 cameras will be used with the TEC300VT and 0.5-m telescopes.

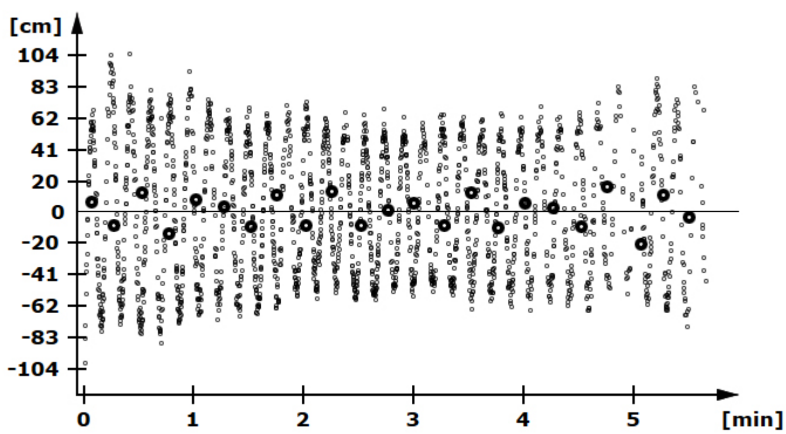

Fig. 4 The standard deviations and normal points after polynomial fitting for TOPEX/Poseidon (a sample pass).

Fig. 5 refers to the Russian rocket body SL-14 R/B (NORAD 17912). It is an example of one of the least efficient passes with 43 residuals accepted by the post-processing software. The RMS is 44.09 cm even though the target is quite large with RCS 4.83 m^2. The distance to the target was 703 km (min.) – 1369 km (max). Likely, the main reason of the limited efficiency is a low P_{AVG} power of our space debris laser. This parameter should be increased significantly, at least several times to the value of 20 W and more, with hHz repetition rate and pulse energy ≥ 100 mJ for 532 nm.

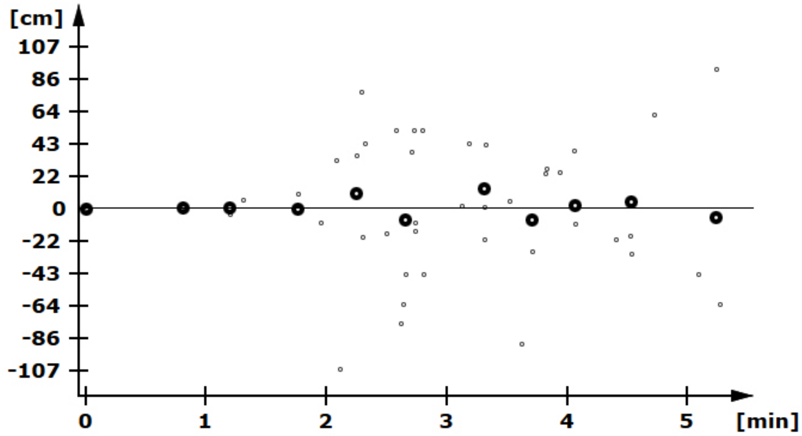

Fig. 5 The standard deviations and normal points after polynomial fitting for a Russian rocket body, SL-14R/B, (NORAD 17912, a sample pass).

New SLR system

In 2017 SRC BORL station started to develop a second independent SLR system ANNA (day/night mode) with passive optical equipment (Fig. 6,7). It is based on the second Cassegrain with 26" mirror (65cm). The telescope is a twin to the first one. Is also equipped with an 8" (20 cm) Maksutov preview telescope. The mount is an azimuth-elevation one with high speed servo motors. Each axis has a <1arcsec hardware resolution with a tracking speed >20deg/s. The telescope and all subsystems (external devices such roof, laser, ADSB) are controlled by a Linux platform with the developed software for control, management, acquisition and data classification (GTK, C#). All data are stored in a MySQL database. Time synchronization is ensured through a link to the cesium fountain (125 m, 410 ft) and a GPS source (in a backup mode). In 2017, the system will be equipped with two fast optical CMOS cameras.

Fig. 6 The Second 26" Cassegrain on a AzEl mount.

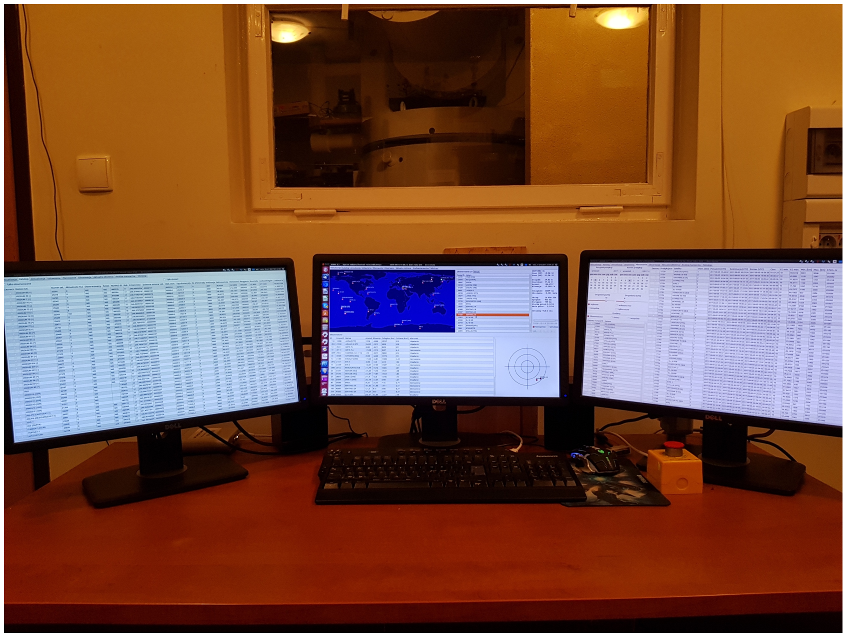

Fig. 7 Operator desk with ANNA software. ANNA Management Software ensures (1) visualization of orbital situation in a RT and simulation mode, (2) passes prediction, (3) orbital data analysis (current and historical: orbital parameters, graphs), (4) observing scheduling, (5) acquisition of SLR data, optical data and environmental parameters (i.e. weather), (6) automatic dependent surveillance broadcast monitoring (shutter), (7) Doppler communication module, (8) stare and chase mode (in progress, [7]), (9) close-up analysis (in progress), (10) Event Timer support.

4. SOFTWARE

4.1 Astrometry24.net

Astrometry24.net[1] (hereafter A24N) is an astrometric web service capable of finding and measuring streaks for SST and NEO programs. The primary objective of the A24N project is to provide a laboratory proven prototype of a reliable and highly-scalable, cloud-based IT solution that allows to detect streaks on provided frames. The tool is accessible by the end users through two interfaces:

a) a cross-platform web-based application with modern, responsive UI
b) programmatically through a RESTful API to ground, optical observatories and datacentres.

It makes use of state-of-the-art IT technologies and specifically developed detection and analysis algorithms, utilizing existing cloud premises, which allow for Service Level Agreement (SLA) up to 99.9%. The solution is available on-demand, with optimized load balancing, depending on the actual usage. This leads to a cost-balanced, future-ready approach. Such a service as A24N has the potential to play an important role in a European, real-time and autonomous network for detection of hazardous objects orbiting Earth.

To achieve this goal, we are developing algorithms and services that will allow robust astrometry on the types of image frames that fall into one of the following three categories:

a) all objects on the frame are point sources,
b) one object is a point source, the other objects are streaks,
c) one or more objects are streaks, all other are point sources.

These cases correspond to the following observing approaches:

a) sidereal tracking and classical astronomical imaging of celestial objects,
b) tracking an object with non-sidereal rate that moves relative to the background stars on the image frame, causing the background stars to form streaks,

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[1] Sybilla Technologies (prime) and Cilium Engineering (subcontractor) conduct the activity which is funded by the European Space Agency under the contract no. 4000119510/17/D/SR.

c) tracking the background stars with sidereal rate reveals moving objects that are visible as streaks on the image. Multiple streaks may be visible especially on large field-of-view images taken with long exposure time.

No similar web-based service is available on the market. The closest competitor is the US service Astrometry.net. However, this service cannot detect and measure positions of the objects responsible for streaks. The service is available for beta testers and we encourage people interested in the tool to contact us for access to test accounts.
The web-based interface is a strong point of the service and can be used for different algorithms, not only developed by the authors, for extraction, feature classification and filtering, catalogue matching, plate solving and image distortion modelling. The effort necessary for adding new or existing algorithms should be minimal and require only the translation of the input and output interfaces. The user interface is presented in Fig. 8 and 9. These two figures show synthetic data with properties similar to the existing ESA's Optical Ground Station (pixel scale, frame size, noises) in two typical usage scenarios, the first one with plate solving of data with sidereal tracking with streaks and the second one where the image quality and data are investigated by the experienced user to check some non-standard frames which are not reduced automatically, ranging from background noise analysis, systematics, to point source and streak shapes and SNR measurement.

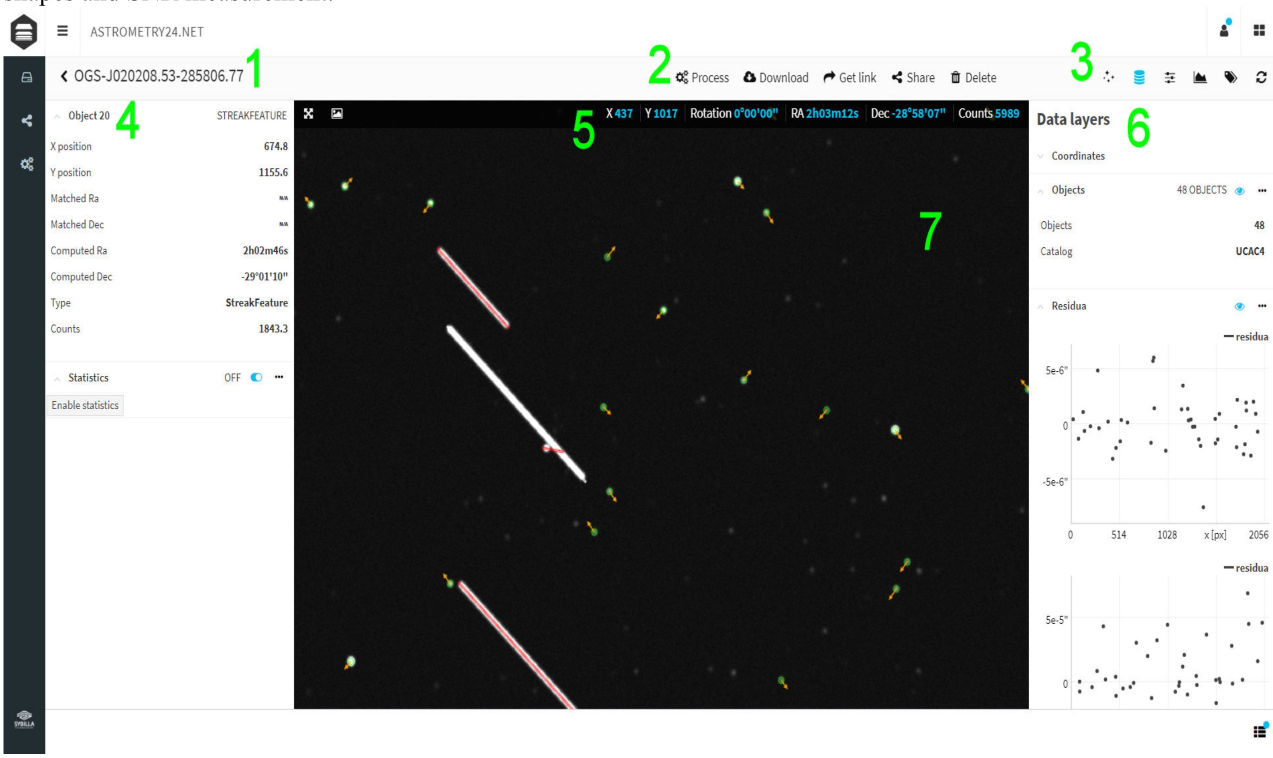

Fig. 8 Example view from A24N web service user interface, where the user can see results of the astrometric solution. 1 – path (in this case root) with file name and back arrow allowing for browsing of the directories with the data; 2 – a list of typical tasks which may be executed by the user: "Process" - astrometric processing of the data file by file or in batch with predefined or customized in the web configuration, "Download" – download of the image data, "Get link" – obtaining link to the file, "Share" – sharing the file with other users, groups or making it public, "Delete" – deleting file; 3 – a list of icons representing selection of the content of the right data panel: "Processing" – displaying the current processing state or result, multiple results may be associated with the same file, "Data layers " – selection of the layers which should be displayed: detected features and/or residua, "Image setting" – a set of parameters for displaying the image, ranging from colour selection to orientation and scaling, "Image analysis tools" – a list of projections which the user has added to the image analysing the data with line or rectangle cuts, "Metadata" – searchable list of FITS keywords; 4 – left side data panel showing the information on the currently selected object; 5 – information bar with the cursor current position in pixels, Right Ascension, Declination and count rate; 6 – content of the data layer selection on the right data panel with residua section expanded showing the list of residuals in Right Ascension and Declination; 7 – acquired data displayed according to the selected scales, which can be rotated, zoomed in or out. Orange circles represent point sources matched with the reference catalogue, red circles- point sources without matching, green and read rectangles denote streaks matched and not matched with catalogue, respectively. White highlight is used to show

currently selected feature. Orange arrows show the distortions, i.e. they to the place where a given source should be if the catalogue data were fully accurate.

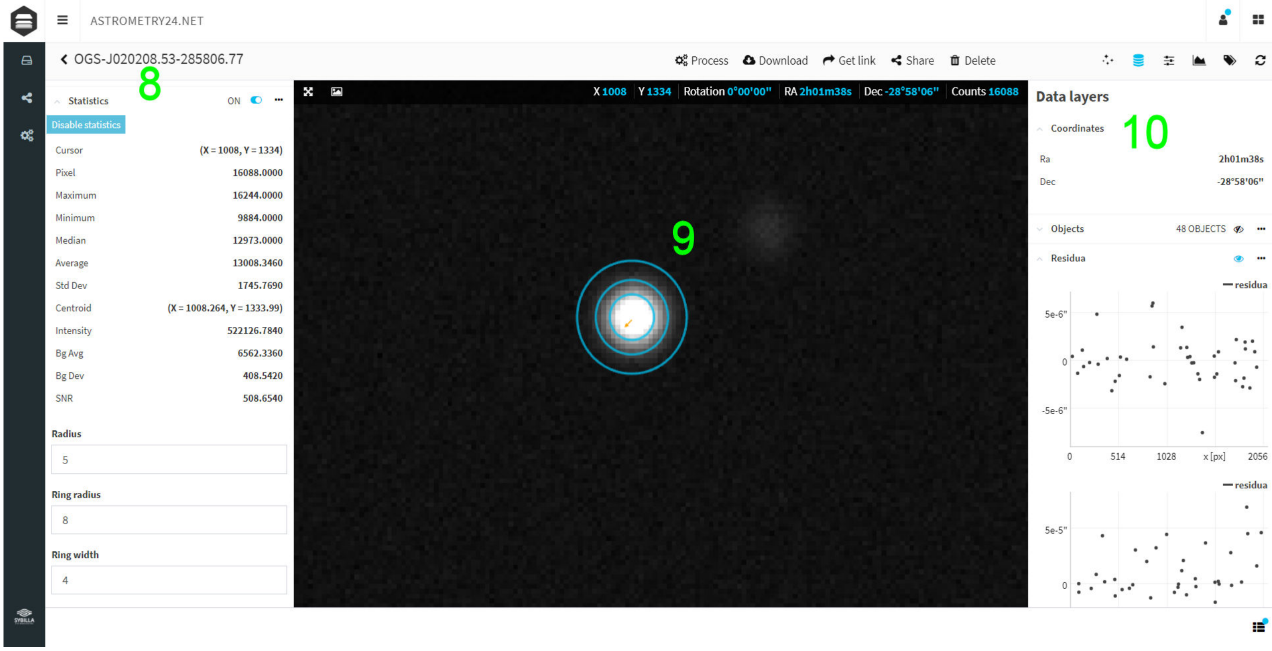

Fig. 9 Detailed analysis in the web interface of the point source from the test frame. 8 – shows the statistical data under the cursor, the cursor's shape is changed to circle with annulus, with configurable sizes of the circle radii, gap and annulus width, similar tool is available for rectangles and can provide following statistical data: cursor position in pixels, centroid position, pixel value, minimum, maximum, median, standard deviation, sum of the counts and average for circle data and average, standard deviation for the annulus. Signal-to-noise ratio is calculated for the source, on the basis of summed counts from the circle minus background average divided by the photon noise being square root of the counts in the circle; 9 – area displaying the acquired data with cursor overlay showing for which part of the frame the statistics are calculated, updated live with the cursor movement; 10 – right panel displaying the calculated frame centre, options to switch on and off objects overlay and graphs showing residuals.

Tests

We have performed tests using our "template matching" astrometric algorithm (hereafter A24N-TM) and Astrometry.net on both real and synthetic data. Local configuration of our solvers is exactly the same as the configuration in the web service. The comparison of A24N and Astromerty.net used only the web based services. Synthetic data has been generated on the basis of OGS real data, with the same binning (2x2), same linear distortions parameters, rotation, pixel scale, background level and background noise. The processing machine for the web version of A24N-TM is Azure Standard D13 (8 cores, 56 GB memory, Intel Xeon CPU E5-2660, 2.2 GHz, 16x500 IOPS, Input/output operations per second, 400GB SS, 780 EUR per month) virtual machine.

Tab. 1 summarizes the test results performed on a real data set. The achieved accuracy is comparable for the two tools, with slightly better result from A24N-TM in terms of median RMS but with two frames not solved and solved by Astrometry.net.

Tab. 1 Comparison of A24N-TM algorithm and Astrometry.net test results from a real data set. The high maximum RMS for A24N-TM comes from the not matched frames.

METRIC	**A24N - TM**	**Astrometry.net**
Total number of frames	131	131
Solved frames	125	127
Solved frames	95.42%	96.95%

Max RMS ["]	397.37	6.70
Min RMS ["]	0.07	0.16
Median RMS ["]	0.38	1.03

A summary of the test results obtained with the A24N and Astrometry.net applied on synthetic data are presented in Tab. 2. A total of 100 frames have been generated with a background level of 6000 and σ = 60 with OGS-based parameters (pixel scale 0.69384 ‘’/px, binning 2x) starting at RA = 01:01:54 and DEC = -66:34:14 and sky-scanning with a step of 0.2 degrees in RA and DEC. Dense fields were avoided (separation of objects larger than 10 pixels), as well as fields with very bright object which would saturate quickly.

Tab. 2 Comparison of A24N-TM and Astrometry.net test results from a synthetic data set.

METRIC	**A24N - TM**	**Astrometry.net**
Total number of frames	99	99
Solved frames	99	91
Solved frames	100.00%	91.92%
Max distance of frame centres ["]	5.40E-04	6.43E+01
Min distance of frame centres ["]	9.18E-07	1.63E-05
Median distance of frame centres ["]	8.80E-06	6.24E-05

The synthetic data test is a very good test scenario, where all factors responsible for final accuracy are under our control. We decided that the linear elements for distortions will be sufficient and fair for comparison of the algorithms and their performance. More complex distortions are possible but with our knowledge about the real model the advantage would result in an unfair treatment of Astrometry.net algorithm.

A24N-TM excels in all fields. The parameters are well within the expected limits. The accuracy could be slightly improved with PSF sampling instead of centroid calculation and of course with increased SNR of point sources. We are reaching the numerical precision of double type which is 1E-13 but after several numerical operations the errors accumulate and the precision of 1E-10 is a more likely limit of the used double type. 1E-10 is 0.13 milliarcsecond. If the higher precision is required we will have to switch to decimal 128-bit type which offers 28-29 precision (significant digits). Quite puzzling are 8 frames not solved by the Astrometry.net and some frames with definitely bad solution. This may also require a fine tuning of Astrometry.net. This is a clear sign that in general special care should be taken for the customization of the algorithm’s parameters per usage scenario and per instrument.

The final test was conducted only with A24N-TM as it involved streak detection and their measurements. To our knowledge, no other code available on the market can do that. The synthetic data always contained three streaks aligned along the same angle but of various length, position and brightness (peak intensity between 6000 and 24000). The overview of the results is presented in Tab. 3.

Tab. 3 Comparison of A24N-TM with the ground truth data from synthetic frame generator.

METRIC	**A24N - TM**
Total number of frames	99
Solved frames	99
Solved frames	100.00%
Max RMS ["]	3.64
Min RMS ["]	0.04
Median RMS ["]	0.08
Number of streaks in the frame	3
Number of found streaks	366

Number of correct identifications	280
Percent of correct identifications	76.50%
Number of false identifications	86
Percent of false identifications	23.50%
Min distance for streaks centres ["]	0.01
Max distance for streaks centres ["]	40.68
Median distance for streaks centres ["]	0.19

Calculated streak centre for the feature extracted from the synthetic frame has an accuracy two times worse than the RMS for the point sources matched with the reference catalogue. Taking into account that the distance on a sphere is calculated slightly differently than the RMS and is on average 1.5 times larger, the difference is much smaller. However, the middle point is calculated from the beginning and end of the streak and the error of their position doubles in the worst-case scenario and is responsible for the worse result. Number of false detections and missing detections of real streaks show the importance of the extraction method and have the highest priority during the remaining development time before the final tool release.

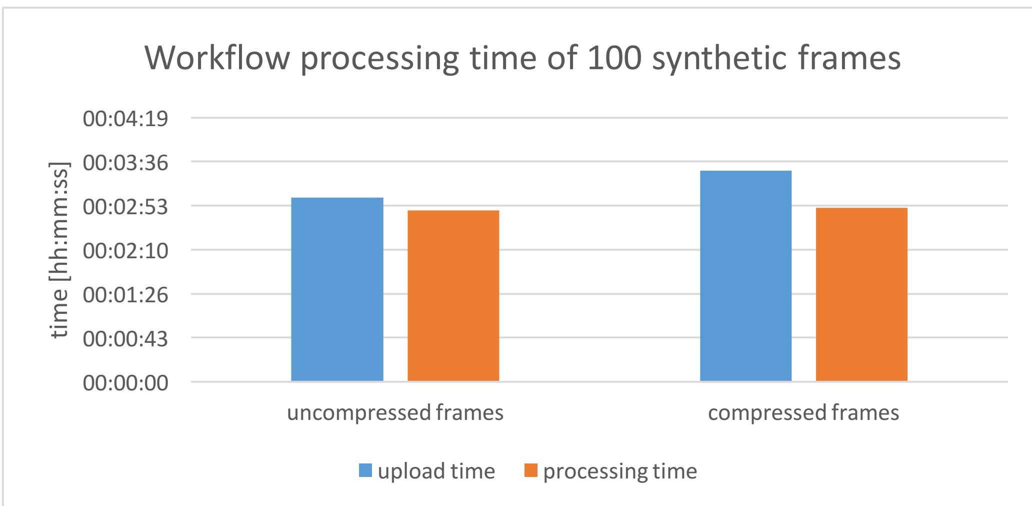

Fig. 10 Comparison of upload and processing time for 100 frames that are compressed on-the-fly and frames that are left uncompressed

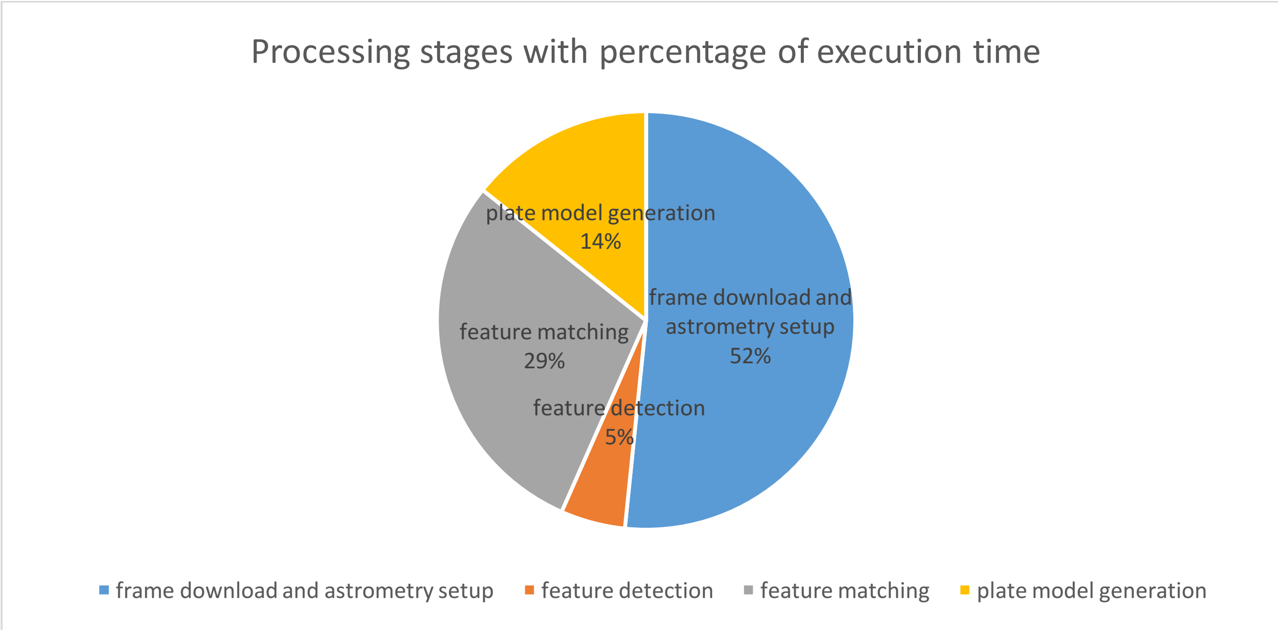

Fig. 11 Pie chart showing how each processing stage contributes to the overall execution time with downloading and preparing astrometry for processing taking up the majority of the time.

Execution times of batch of 100 synthetic frames

Synthetic data were modelled after OGS frames. Each frame is 16 MB of uncompressed data. For the compressed data simple DEFLATE algorithm was used reducing the size approximately by half of the frame size in the average case. The browser implementation of our algorithm has been used.

With the entire batch processed in 5 m 49 s and 6 m 18 s for uncompressed and compressed data, respectively, an average for each frame is 3.49 s and 3.78 s. This is well within the limits of the requirement of the service to be capable of processing 100 frames in 10 minutes.

Execution time as a function of frame size

Since frame download and workflow setup required most of the time they were split up to determine how much each of them contributes to the overall processing time and how the processing times scale with increasing frame size ranging from 1 MB to 20 MB. It was expected that stages other than frame download and feature detection should not scale proportionally to the frame size as other factors are more important for their scaling e.g. number of features and telescope field of view.

In this test, each case was tested with one frame at a time to allow more fine-grained measurement of execution time without interference from other jobs being processed in parallel.

It is apparent that the larger the frame the bigger percentage of the overall execution time is consumed by downloading the data to the processing. Setting up the workflow also scales with the frame size which is caused by reading the raw frame data into matrix consumed by feature extraction.

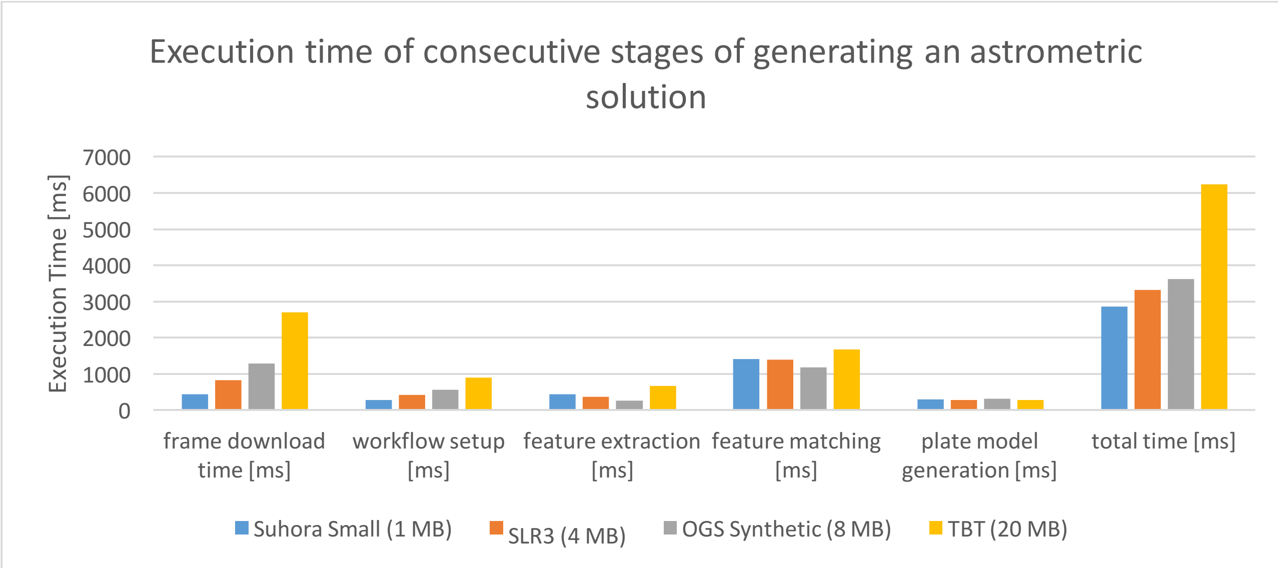

Fig. 12 Execution time of each consecutive stage for each observatory sorted by compressed frame size.

Conclusions

The A24N web service presents an important step in astrometric data processing where the user experience is web based, does not require installation of any third-party software, is always up to date and is easily scalable due to the cloud resources usage. The architecture of the service allows for easy incorporation of new or existing algorithms and will improve user experience where the same familiar layout may be used for multiple algorithms. A24N provide support tools for the investigation of each astrometric processing step in the web interface as well as image statistics analysis. Our solution provides a unified experience and a smooth transition from an automatic batch setup and processing to a non-standard data investigation.

The service reached the alpha state and is available for external testers. The accuracy and precision tested on real and synthetic data shows that the service is already comparable to or better than Astrometry.net. The performance tests showed that the service can process typical real data frames with the speed of one frame per few seconds, depending on their size. With the cloud computing scaling capability, even the throughput of sCMOS camera producing 100 frames per second will not be an issue for the service and only the constant delay of a few seconds will be introduced between the image acquisition and astrometric solution. The performance may be also improved if necessary by segmentation of large frames, algorithms optimization and parallelization of additional fragments of the code.
For the future development, we plan to work on extraction algorithm to include sources with SNR lower than 10, deal with the artefacts (bad pixels, saturation), increase the number of support tools available to users and conduct test deployment taking into account private or hybrid cloud.

4.2 Scheduling

Simple and quick scheduling of satellite observations is important in situations where rapid action is necessary, for example when potential collision is possible or when the contact with satellite has been lost and it is no longer on the expected orbit. Easy scheduling of such observations may also increase the interest of amateur and professional observers usually targeting other objects. Finally, the universal and simple principles of scheduling help in the case of heterogeneous (different hardware, software and primary tasks) observatories to overcome differences and allows for a quick and reliable implementation.

Fig. 13 Web interface for the scheduling of Panoptes-Solaris network. 1 – text field for simple observing program name; 2 – observatory to be the scheduler, selected from the drop-down list, coordinates of the selected observatory are also provided; 3 – how many times the observing program should be repeated; 4 – information on the scheduling mode, if time based the observing program will be automatically repeated within the requested time boundaries, if not time based the observatory will execute the schedule within given limits and once finished will move to next target; 5 – name of the object; 6 – how many times the observations for the object should be repeated; 7 – object search

with autocompletion based on the NORAD number or object's name, 'Sybilla' database contains TLEs published by NORAD and TLEs made available by partners; 8 – first line of TLE, entered manually or automatically when the object is selected from database; 9 – second line of TLE; 10 – visibility graph for selected object showing its altitude within next 24 hours or during the next night, night is marked with dark grey, twilight is marked with light grey colour, orange line shows the object's altitude in time, blue line shows the object's distance to the Moon, red line denotes the altitude limit for the observatory, black line the horizon, vertical green line shows current time; 11 – combo box allowing for selection of the filter available at given observatory; 12 – field for a new filter in the sequence of various filters for a given object, multi filter observations are made possible by adding elements like this; 13 – estimated total time required to execute the program; 14 – buttons allowing for saving the program for use in the future, submitting it immediately to the observatory or cancelling the scheduling.

Within Panoptes-Solaris we use two approaches, one is web scheduling of simple SST observations available for the human user and another one is automated and specialised agent taking the list of TLEs (Two Line Elements) and scheduling them according to the predefined logic (survey, tracking or other). The web interface for the first usage scenario is presented in Fig. and the advanced scheduling concept by a specialized agent in Fig. . The agent is reading the configuration JSON file with a list of data sources (may be a file or an http/https link) and default settings from the configuration file to initialize instance of the specialized scheduler. The observatory may be connected to multiple schedulers at the same time and report progress to all of them or to selected ones. At the same time, it may receive updates and requests from the web user interface. One agent can schedule multiple observatories at the same time to distribute the work evenly or shift it in case of bad weather not allowing one of the observatories to acquire data for a high priority target. External users or entities receive an account with a login and a password to access the system via the web interface and a secret key to access it programmatically. They may also provide their list of targets which will be consumed by the scheduling agents. All communication is encrypted and supports redundancy of agents and communication channels. A complete change of the schedule in the observatory by the automated agent takes less than 10 seconds. Data once obtained is immediately uploaded to the AstroDrive service (our service for data storage, visualisation and analysis) and the astrometric solution for the new frame is available within a few seconds. The format for data exchange is based on JSON and XML description of simple observation or the strategy for processing the given object list. We plan to release to the public the data formats in the first quarter of 2018.

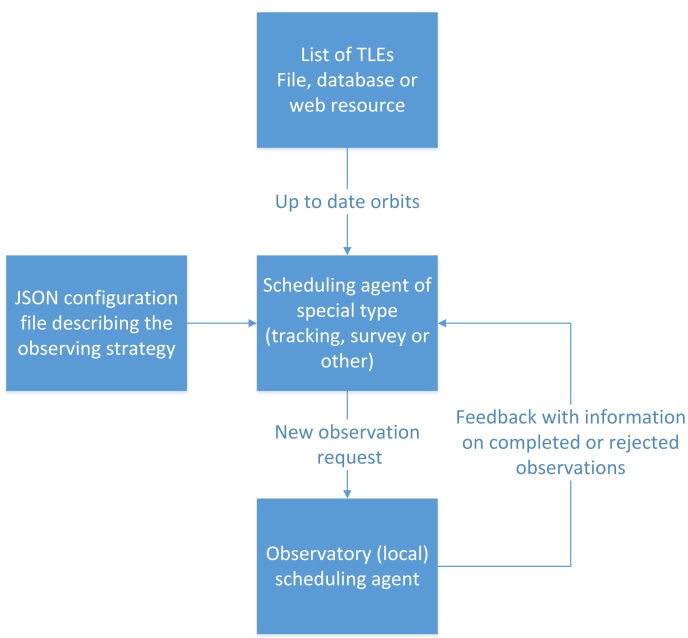

Fig. 14 Advanced scheduling concept based on multiple specialized agents connected to multiple observatories requesting observations and monitoring their progress. External entities may provide a list of targets for existing agents or create their own agents. Each agent and user can have time slots when observations can be scheduled, priorities range which can be used, and the amount of observing time to be used. When no time slot is available or no observing time left, the scheduling agent is no longer able to send new requests. When two agents schedule the same sensor at the same time the priority of the assigned request decides which one will be executed. Local scheduler which is installed

on the computer next to the telescope is a simple unit executing received schedule, advanced and multi sensor scheduling is executed in the Azure Cloud by specialized agents.

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