HIGH EFFICIENCY ROBOTIC OPTICAL TRACKING OF SPACE DEBRIS FROM PST2 TELESCOPE IN ARIZONA

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ABSTRACT

We present a new, high-efficiency optical satellite sensor: Poznań Spectroscopic Telescope 2 (PST2). PST2 is the newest addition to a larger instrument: Global Astrophysical Telescope System, composed of two optical telescopes: no. 1 in Poland and no. 2 in Arizona. PST2 is based on Planewave CDK700 using direct-drive motors that are capable of fast slewing and limited satellite tracking up to 15°/sec. One of its foci is equipped with a high frame-rate global electronic shutter Andor iXon3 EMCCD camera. By using a local GPS-based time server the cameras shutter timing is provided with an accuracy better than 10ms relative to UTC time scale. The telescope is controlled by a dedicated software system, created at the Astronomical Observatory of Adam Mickiewicz University (AO AMU), that has been recently upgraded specifically for satellite tracking. A semi-automatic data processing system has also been implemented for astrometry and orbital analysis using AO AMU internal solutions, as well as GEODYN II software packages. PST2 observations of LEO targets show that the instrument is able to deliver over 50 astrometric positions over 10s with a typical accuracy better than 1 arcsec and switch to a different satellite every 40 seconds during the observing run. The orbital analysis of PST2 data shows that residuals with RMS better than 1 arcsec are often acquired also for multiple consecutive observations of the same satellite.

Keywords: space debris; orbit determination; robotic telescope.

1. INTRODUCTION

Poznań Spectroscopic Telescope 2 (PST2) is a part of the Global Astrophysical Telescope System (GATS) network. The instrument is located in Winer Observatory in Arizona, USA (31°39′56.08" N, 110°36′06.42" W, 1515.7m). PST2 is a fully robotic 0.7m diameter, 4.54m focal length telescope, model CDK700 on azimuthal direct-drive fork mount, manufactured by Planewave. Its control software allows non-sidereal tracking in both axes with user pre-selected constant rates up to 15°/s.

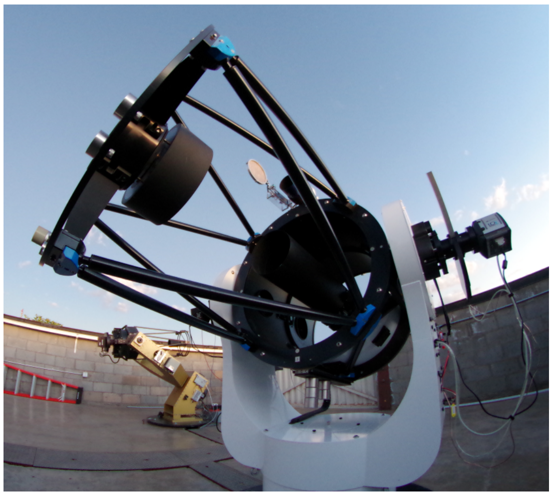

Figure 1. PST2 70 cm telescope of Poznań Observatory located in Winer Observatory in Arizona, USA.

While PST2 was primarily designed for stellar spectroscopy, it also proved its ability, after appropriate software modifications, to preform high quality SST observations. The telescope can now be used to observe any kind of satellite and space debris objects, including LEO, MEO, GEO and HEO, using two different observation modes: sidereal tracking and non-sidereal satellite tracking.

Photometry and astrometry measurements are recorded using Andor iXon3 888 EMCCD camera with global electronic shutter, mounted in the telescope's photometric focus. The camera's field of view is 10′x10′, it provides a very sensitive electron-multiplying (EM) mode and fast frame rate (up to 6 frames per second with 2x2 binning). The combination of iXon camera with a fast tracking 0.7m telescope, makes it a perfect tool for observations of even very faint and fast Earth orbiting targets.

PST2 telescope is controlled by a custom designed software. Every peace of equipment is individually managed by a Linux daemon-like multi-threaded program.

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Each daemon is controlled by a dedicated FIFO queue in MySQL database. The master program is constantly monitoring and orchestring all instruments on the basis of user requirements for a given night. The software allows to program a whole night of space debris observations in advance and constantly delivers up-to-date status through a web-based interface or terminal based low bandwidth client software.

Two observing modes have been implemented: sidereal tracking and satellite tracking. In sidereal tracking mode the telescope points at given coordinates a few seconds before the satellite passes through and starts a series of frames. Using this mode it was possible to detect even small ($\sim$ 20 cm) LEO targets. In satellite tracking mode the telescope also points at the given location in advance, but then starts tracking at a selected, constant rates in RA and Dec. This mode boosts the sensitivity of the telescope even further, allowing to observe smaller objects and for longer periods of time. Both types of observations can be repeated many times during the satellite's passage over the observatory.

2. HIGH EFFICIENCY PERFORMANCE

The first test observations of satellite objects with PST2 proved very promising, as it turned out the telescope's hardware configuration is appropriate for an optical SST sensor. After slight modification of the control software, further performance tests of PST2 system also proved its outstanding efficiency. The main factors in play here are:

The PST2 prooved to be a very efficient optical satellite sensor due to several factors.

The key factors to build an efficient optical satellite sensor are as follows.

- fast direct drive mount; Using direct drive technology, it is possible to track targets with very high speeds up to tens of degrees per second with a very high precision. Such speeds are important during observations of satellite objects on low Earth orbits (LEO objects) since a typical astronomical telescopes can not track objects moving faster than tens of arcsec per sec. The velocities of these objects in the sky are typically greater than a few hundreds of arcsec per sec. Moreover, fast slewing of the telescope decreases the time between pointing at consecutive objects.

- Andor iXon 3 EMCCD detector; This camera seems to be perfect for satellite and space debris astrometric observations in almost every aspect. Its electron-multiplying (EM) mode allows to enhance the signal-to-noise ratio and use very short exposure times. This feature enables tracking very faint, fast targets (even $10cm$ LEO satellites) and allows to record images with a number of reference stars. Furthermore, such short exposure times of the order of $50 - 100ms$ ensure that star trails in images taken during satellite tracking are short, which helps to reduce inaccuracies characteristic for astrometry of very long star trails.

- high accuracy time registration; Observations of Earth's satellite objects require high accuracy of time registration. Especially in case of LEO objects, good quality astrometric measurements require time registration accuracy of the order of 1 ms or even better. To maintain the best possible accuracy, PST2 utilizes the time signals from a GPS time server localized on-site in Winer Observatory inside the local network.

- global electronic shutter; The opening/closing time of typical mechanical shutters used in astronomical CCD cameras is of the order of 30-150 ms. The moment of shutter opening and closing is measured in these cases with accuracy comparable to opening time. For targets in LEO orbits, such error in time measurement results in in-orbit position error of tens of meters. In case of PST2, the photometric/astrometric camera is equipped with a global electronic shutter, which "opens" and "closes" immediately which helps to deliver image timing with the accuracy of the order of 10ms and ensures the same exposure time for each pixel.

- optimal observing strategy; To perform highly efficient observations of LEO objects it is necessary to use an optimized scheduler. A dedicated planning software has been created at AO AMU for this purpose. It calculates ephemeris using the SGP/SDP propagator. Initial orbits of satellite objects are based on USSSTRATCOM TLE catalogue. Our planning software optimizes the observing schedule, minimizing the "dead time" between pointing at consecutive targets. It also takes into account various parameters, such as the telescope mount speed and acceleration, meridian and altitude limits, tracking speed limits, stellar field density, bright stars proximity, as well as individual satellite requirements, such as target priority, passage outside of the Earth's shadow, length of image series and number of observations required per satellite passage.

3. ASTROMETRY AND REDUCTION

Astrometry of fast moving artificial satellites is a challenging task. Depending on the observing mode (sidereal tracking or satellite tracking), one needs to compare either point-shaped images of stars with the satellite's image in the form of a trail, or star trails with a point-shaped satellite image. Measuring positions of trails results in higher position errors than in the case of typical point-shaped PSFs. Moreover, the set of reference stars in each image in satellite tracking mode is different.

Given no easily available software fitting our needs, a dedicated software suite for the astrometry of satellite objects has been developed in AO AMU, consisting of a number of tools, each designed for a different task.

The first step in our astrometric procedure is detection of any objects present in an image and listing their flux weighted pixel positions. In this step an initial selection of objects is also performed: objects too close to image edges or merged, as well as hot pixels are rejected. A photometric signal and shape is also calculated for further analysis.

In the next step, the software identifies stars found in the image using an astrometric catalog. By default, Gaia DR1 catalog is used, but the software also allows the use of other catalogs. Two parameters are necessary in this step: an accurate image scale and (at least roughly) estimated RA, Dec coordinates of the center of the image. The minimum number of reference stars required for astrometry is 3, but 4 or 5 are usually used, because overdetermination allows us to estimate astrometric errors. Since the field of view of PST2's imaging camera is small, the number of reference stars in the images is sometimes too low for identification or astrometry. With our scheduler, however, it is possible to select only dense star fields along the satellite's track, so this limitation is no longer a problem.

Next, we calculate astrometric positions of all objects detected in the processed image using Turner's method. Typically, the accuracy of astrometry achieved this way is of the order of 0.5 arcsec, which results from exposure times too short to average the effect of seeing, and from other limitations, such as differences in PSFs between stars and tracked satellite objects.

Finally, having measured the positions of all objects in all images in the series, the last part is to identify which object in the images is the observed satellite. The algorithm developed at AO AMU is designed to deal with both cases: sidereal tracking and satellite tracking, searching either for a target moving along a straight path, or a nearly stationary object in the image. The observing mode used is automatically detected.

4. ORBIT DETERMINATION

Precise orbit determination of satellites has been performed with the use of the NASA/GSFC GEODYN II software [1]. The initial orbital elements of observed satellites have been taken from USSTRATCOM NORAD TLE Satellite Catalog. The mean elements were transformed from TLE to osculating elements with the use of an algorithm based on the Hori-Lie perturbation theory in the version of Mersman [2]. Next, the osculating elements were propagated to the moment of the first observation with the use of Poznan Orbit Propagator STOP - software developed at AO AMU [3].

The following force model has been taken into account:

- Earth gravity field: GRACE Gravity Model 03 (GGM03) up to 80 x 80 degree and order;
- Third body gravity: Moon, Sun and all planets with the use of DE403 JPL Ephemerides;
- Earth and ocean tides;
- Solar radiation pressure, including Earth's shadow effects;
- Atmospheric drag with NRLMSISE-00 model of the atmosphere.

Fitted orbits were compared with observations to check the internal consistency and estimate accuracy of our sensor.

5. OBSERVING CAMPAIGNS

In order to confirm the usability of an optical sensor for astrometric observations of satellite objects it is necessary to carry out a series of observations. Consequently, observations were conducted with PST2 during several observing campaigns in 2016 – 2017.

5.1. Lageos 2

To confirm the ability to track objects with high precision, series of observations of the geodetic satellite Lageos 2 were carried out. Lageos 2 is a satellite with very well defined orbital parameters. During a single pass over Winer Observatory, 6 series of observations were taken, each resulting in a total of about 400 astrometric positions. Based on these observations, it was possible to calculate and improve the orbit of the satellite. The adjusted elements are very close to the elements known a priori, but there are some significant differences and the improved orbit fits better to observed astrometric positions of the satellite. Figures 4 and 3 show the orbit alignment errors to fixed positions. It is worth noting that the errors usually do not exceed 1 arcsec. The resulting orbit fit is at the level of RMS = 0.44 in declination and 0.93 in right ascension. Note that the right ascension O-C residual is dependent on $\sin \delta$, so the actual RMS is even better. A sample image with Lageos 2 satellite is presented in Fig 2. Since the motion of Lageos in the sky is fairly slow, it is difficult to distinguish from stars. The observed satellite is visible in the central part of the image, slightly towards the bottom left.

5.2. Midas 5 Deb

In June 2016 a low MEO space debris number 273 was observed. Several series of images were collected during two consecutive passes over Winer Observatory on

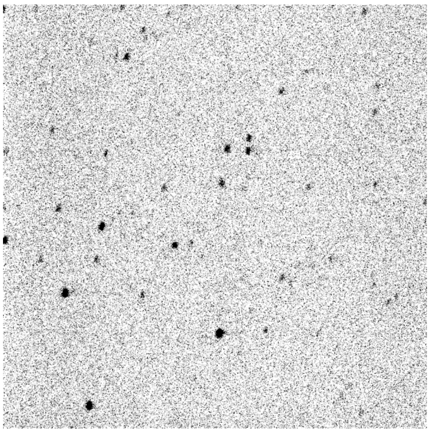

Figure 2. A single image of Lageos 2 take with PST2 using exposure time of 0.05 sec.

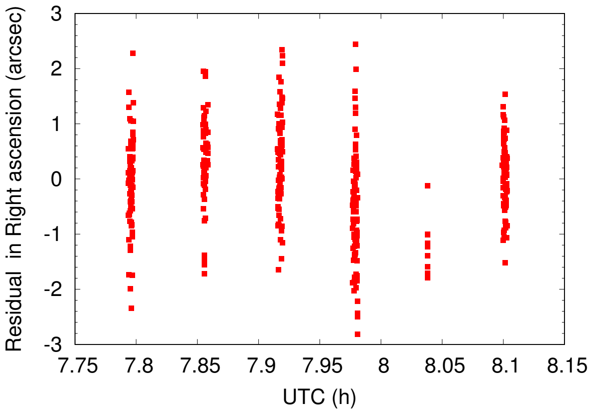

Figure 3. RMS in right ascension for Lageos 2

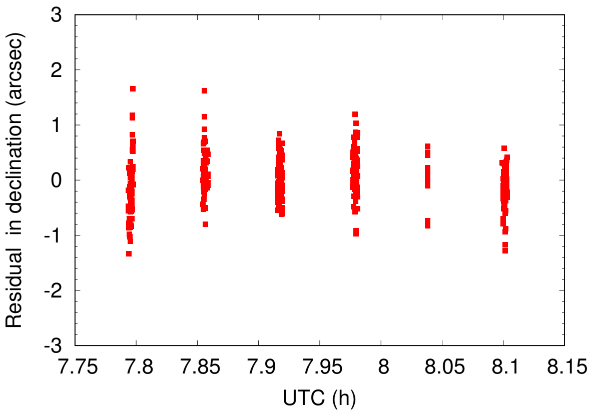

Figure 4. RMS in declination for Lageos 2

the same night. The exposure time was set to 0.1s resulting in a relatively short stellar trails (Figure 5). The observations were fitted with a single orbit as presented in Figures 7 and 6. The estimated RMS in R.A. was 2.1 arcsec and in Dec was 1.5 arcsec.

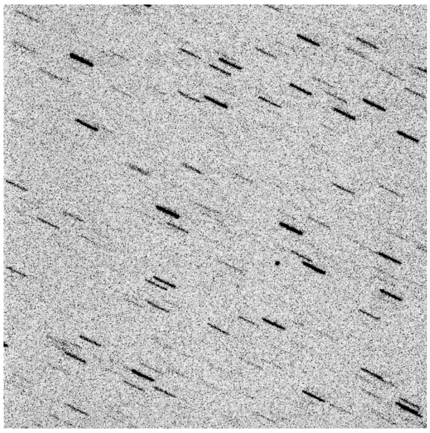

Figure 5. Single image of Midas 5 Deb take with PST2 using exposure time of 0.1 sec.

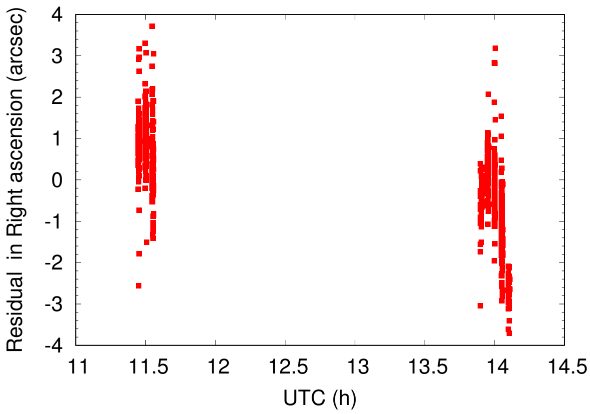

Figure 6. Residuals in right ascension for Midas 5 satellite observed with PST2 telescope.

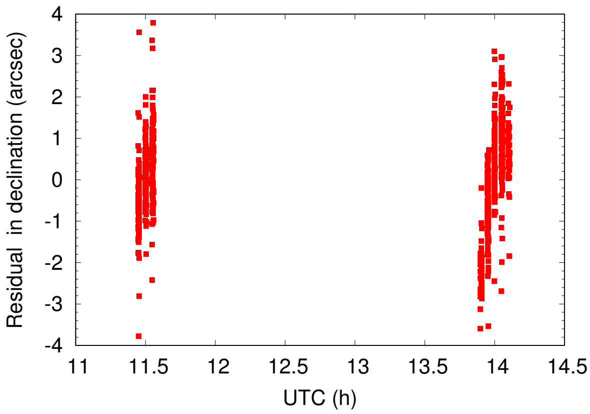

Figure 7. Residuals in declination for Midas 5 satellite observed with PST2 telescope.

5.3. Popacs

A telescope dedicated to LEO observations should be able to detect small objects, since the number of low-cost cubesat-type satellites in LEO orbits is constantly growing. In April 2016 Popacs-1, one of three similar $10cm$ white ball-shaped satellites in Low Earth Orbit was observed in satellite tracking mode. 120 images were collected during single pass. A sample image with Popacs-1 satellite is shown in Fig 8. Despite its small size and short exposure time (0.05 sec), the satellite is perfectly visible with SNR at the level of $\sim$ 8. Based on these observations an orbit was fitted, and the distribution of residuals is shown in Figures 10 and 9. The estimated RMS in R.A. was 0.61 and in Dec was 0.98.

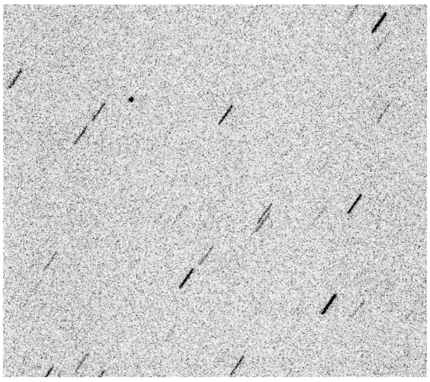

Figure 8. Single image of Popacs-1 satellite take with PST2 using exposure time of 0.05 sec. The dimmest stars detectable have GAIA magnitude at the level of 13.

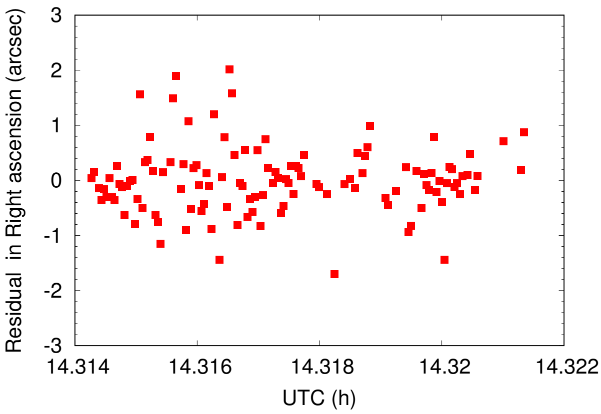

Figure 9. Residuals in right ascension for Popacs-1 observed in 2016 with PST2 telescope.

5.4. PST2 efficiency test

In January 2017 the PST2 telescope performance test was conducted. The observation plan was arranged in order to observe as many satellites as possible, with only short 10-second series of 66 images for each satellite (0.05 sec exposure time). The satellite cycle-time was set to 40 seconds, so the time span of 30 seconds was reserved each time for slewing and preparing for next target observations. The test allowed us to estimate the average telescope efficiency of 60 satellites successfully tracked per hour. Typically in 25% cases the target was outside our

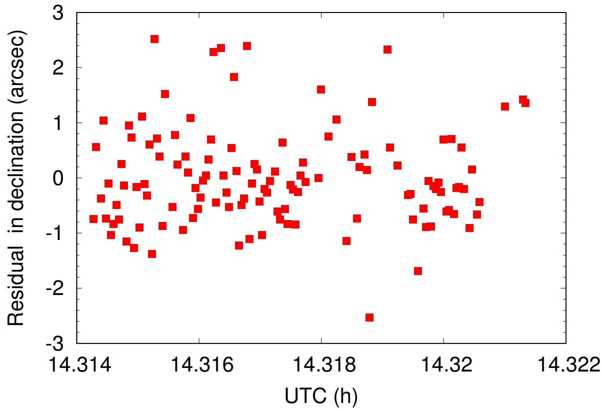

Figure 10. Residuals in declination for Popacs-1 observed in 2016 with PST2 telescope.

small field of view. We suspect that those misses were partly due to the telescope firmware delays when starting non-sidereal tracking (the manufacturer is working to correct this problem), and partly caused by the errors in the TLE catalog used.

6. CONCLUSIONS

The observations made with PST2 telescope show that it can be used for efficient and high accuracy satellite and space debris observations. On average, it is possible to observe one object every single minute, which corresponds to about 300 – 500 objects per night. Moreover, if the ephemeris of the tracked objects was of better quality than the SGP positions based on the TLE catalog, the number of observed satellites during one night may be even higher. The quality of astrometric observations made by PST2 is of the order of 1-2 arcsec even for the most challenging LEO targets. Further improvements in the PST2 efficiency are also possible. We plan to improve the timing accuracy even further, with the ultimate goal of 0.1 millisecond, improve the ephemeris accuracy with algorithms developed in AO AMU and improve the camera's frame rate, which is currently limited by low-end processing power of the industrial PC controlling the imaging camera.

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