LEO cubesats tracking with a network of Polish optical SST sensors

Krzysztof Kamiński, Edwin Wnuk, Justyna Gołębiewska, Mikołaj Krużyński, Monika K. Kamińska

Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland,

Michał Żołnowski, Marcin Gędek

6 Remote Observatories for Asteroids and Debris Searching, ul. Godebskiego 55a, 31-999 Kraków, Poland,

Rafał Borek

Polish Space Agency, ul. Powsińska 69/71, 02-903 Warszawa, Poland

ABSTRACT

LEO satellite tracking has traditionally been a domain dominated by radars. Recent advancements in optical detectors and telescope mounts are gradually changing this situation. Direct drive motors made telescope mounts software limited devices that recently became capable of tracking even the fastest satellites and slewing from target to target within several seconds. Low readout noise, large light sensitive area, high frame rate sensors made short exposures much more efficient than with traditional CCDs. New cameras are capable of delivering usable data with both satellite target and numerous reference stars with exposure times as short as 0.01s. We present results of an observing campaign performed by the collaboration of Astronomical Observatory of Adam Mickiewicz University (AO AMU) and 6 Remote Observatories for Asteroids and Debris Searching (6ROADS). The campaign has been conducted in the first half of 2018, using sensor types recently introduced in astronomical cameras: (1) electron multiplying CCD (Andor iXon3), and (2) global shutter CMOS (QHY174M-GPS). The latter is equipped by the manufacturer with a built-in circuit that uses GNSS receiver for accurate image timing. Andor camera images timing was made using an external GNSS-based event clock. LEO cubesats, selected for the campaign, are considered one of the most challenging target types for optical SST sensors. This is because of the combination of their relatively low apparent brightness, fast angular velocity an short observing window. Our observations have been performed using two highly automatic small telescopes located on two continents: 0.3m Solaris telescope in Poland (6ROADS) and 0.7m Poznań Spectroscopic Telescope 2 in Arizona (AO AMU). The quality of astrometric results and orbital solutions has been evaluated and the potential of small optical sensors for tracking LEO cubesats and even smaller targets is discussed.

INTRODUCTION

Fast proper motions and relatively dim apparent brightness make LEO cubesats challenging targets for optical SST sensors. The plot of sky movement rate of all TLE catalog LEO targets visible outside the Earth's shadow during five nights from a single location, with respect to altitude above the horizon, is presented in Fig. 1. It is clear that even for low elevation observations of these targets short exposure time, as well as large field of view, are preferred. This implies that a high sensitivity detector with negligible noise level is necessary, rendering CCD less favorable for such purposes. The other aspect necessary to be addressed is accurate image timing and uniform image exposure. Typical mechanical shutters have opening and closing times of the order of a few tens of milliseconds. This leads to inconsistencies in exposure start and stop times, which can be only partially mitigated based on the analysis of shutter blade movement in front of the imaging detector. Much better solutions, also in terms of reliability, are an electronic global shutter or a frame-transfer sensor, which can also be accurately synchronized with an external time reference source. If all possible sources of timing noise are mitigated, exposure timing accuracy of the order of 0.1ms may be achieved, which is considered sufficient for SST observations of LEO targets.

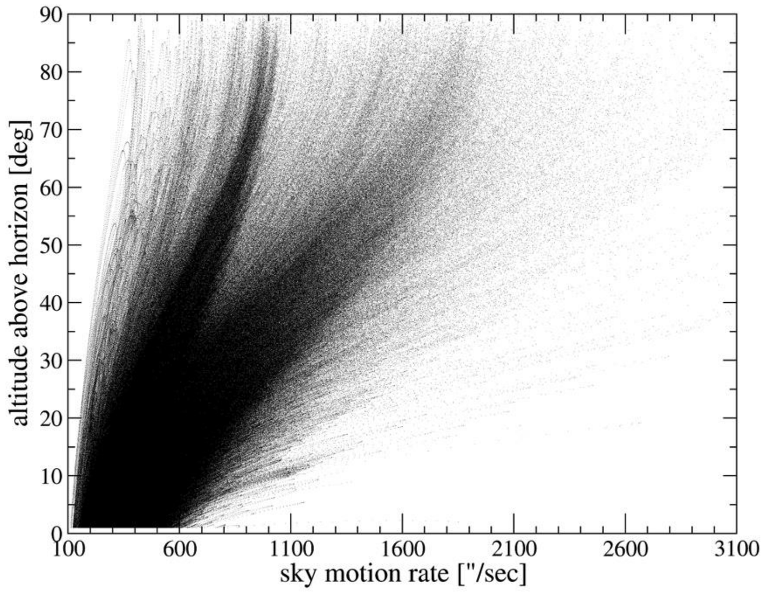


Fig. 1. Observed sky motion rates of all TLE catalog LEO satellites for a single observatory with respect to altitude above the horizon.

In order to verify the accuracy and performance of two cameras, which might be considered promising candidates for small LEO tracking sensors, we decided to perform a joint campaign using two sensors: Solaris operated by the 6 Remote Observatories for Asteroids and Debris Searching (6ROADS) and Roman Baranowski Telescope / Poznań Spectroscopic Telescope 2 (RBT/PST2) operated by the Astronomical Observatory of Adam Mickiewicz University. Both cameras (Tab. 1) are characterized by a combination of parameters which are essential in SST domain, but quite unique for astronomical cameras.

manufacturer	QHY	Andor
mode	174M-GPS	iXon3 888
detector type	front-illuminated CMOS	back-illuminated CCD
detector size	1920×1200 pix	1024×1024 pix
pixel size	5.86μm	13μm
readout noise	3-5e^-/pix	<1e^-/pix in EM mode
max QE	78%	95%
air cooling	-40 °C	-75 °C
max full-frame frame rate	138 fps	9 fps
readout type	global shutter	frame transfer
image timing	internal GNSS receiver	external GNSS receiver or PC
binning used	1×1	2×2

Tab. 1. Basic parameters of cameras under investigation.

EQUIPMENT

6ROADS used 0.3m f/4 CT12 Orion Optics UK Newtonian telescope (Fig. 2), which is a part of the 6ROADS Company network. The sensor is located in the suburbs of Cracow in Poland. It is equipped with QHY174M-GPS global shutter camera with a built-in circuit using GNSS receiver for PC-independent image timing. Time stamps are embedded in the header of every frame recorded. The optical tube is mounted on German equatorial mount Bisque Paramount MX, allowing stable satellite tracking at distances down to 600 km from the observer.

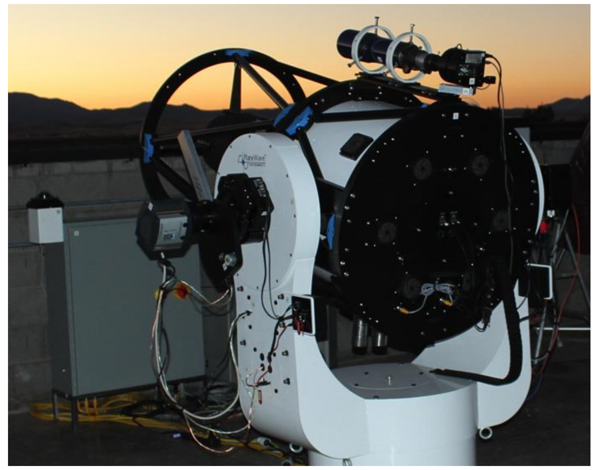
 

Fig. 2. Solaris telescope to the left, RBT/PST2 telescope to the right.

AO AMU used 0.7m Planevawe CDK700 telescope (Fig. 2), which is a part of the Global Astrophysical Telescope System[1]. The sensor is located in Winer Observatory in Arizona. It is equipped with Andor EMCCD iXon3 frame-transfer camera, connected with a PC using a proprietary interface and a dedicated PCI card. All images were acquired using IR-blocking filter to limit the fringing effect on its back-illuminated sensor. To measure the exposure start times we used electronic shutter-out signal, which was directly sent to our custom built timing device based on ATmega32u4 controller and NEO-7M GPS module. Each frame was also independently timed with our own PC software which is built using Andor Linux SDK library. The PC controlling the camera was synchronized over a local area network (with latency <1ms) with a GPS-based NTP server. We found that there is a systematic shift between the exposure start time registered using those two methods, varying from -5 to -20ms (Fig. 3). The exposure time from our timing device was always delayed compared with the time registered by the PC software. We attribute this shift to the delay occurring between the moment PC software sends the start exposure command and its actual execution by the camera. This delay is probably the time necessary for the camera to finish the CCD cleaning cycle, which is continuously repeated between exposures to keep the shutter-less detector free of unwanted signal. We decided to use our GPS timing device as the primary source of time measurements.

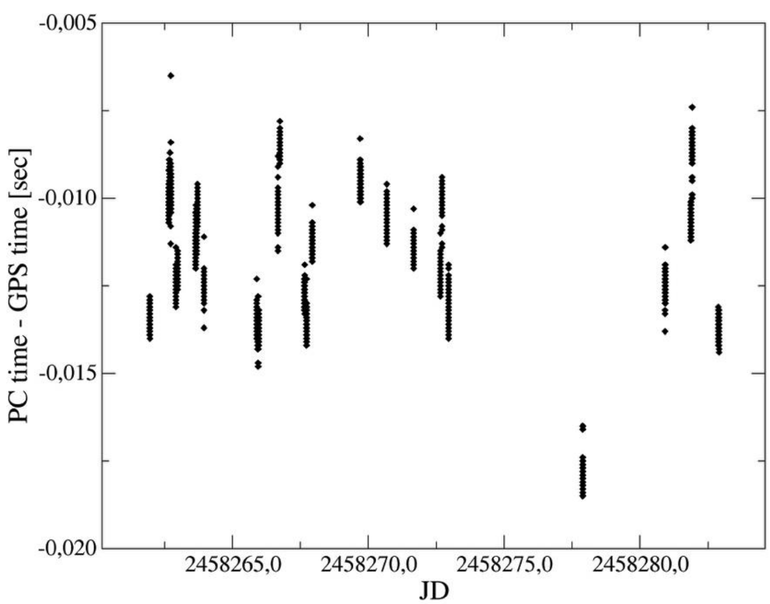
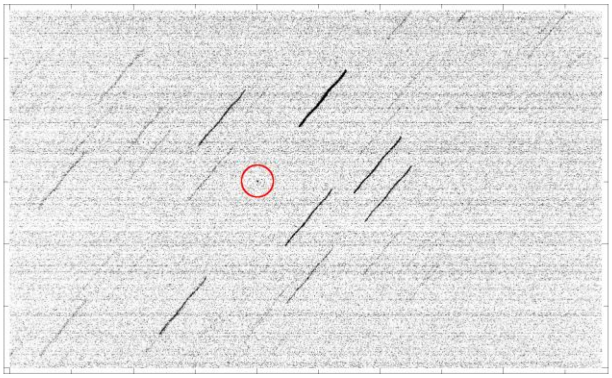


Fig. 3. Differences between exposure start time registered by Linux machine using Andor SDK and the electronic shutter open signal registered by our GPS timer connected directly to the Andor iXon3 shutter-out SMB socket.

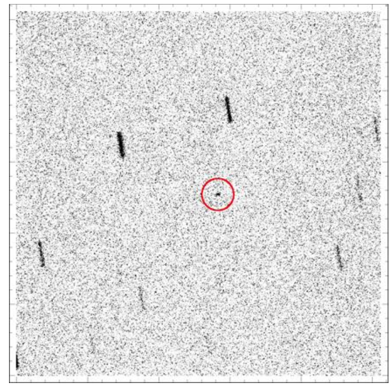
[1] www.astro.amu.edu.pl/GATS

CAMPAIGN

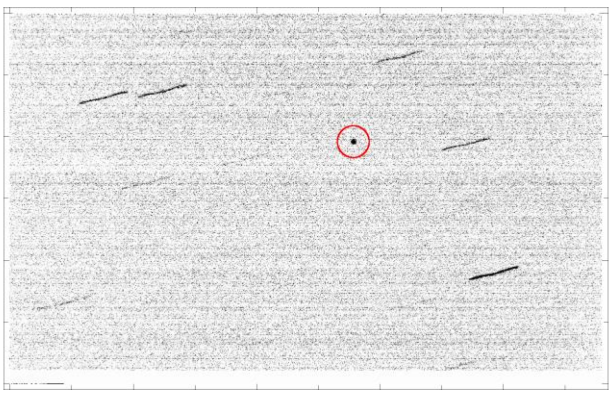
We prepared the campaign by selecting known LEO cubesats which were most frequently visible from both sites in May and June 2018, just before the monsoon season in Arizona. Targets observed during the campaign are listed in Tab. 2.



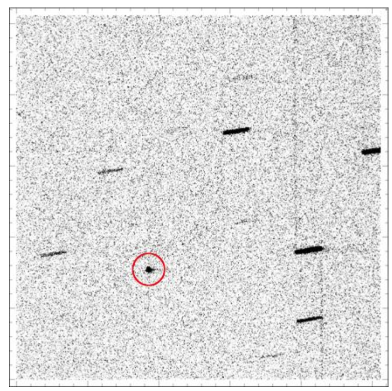
Ukube 1 – 0.21s – 14.2 mag



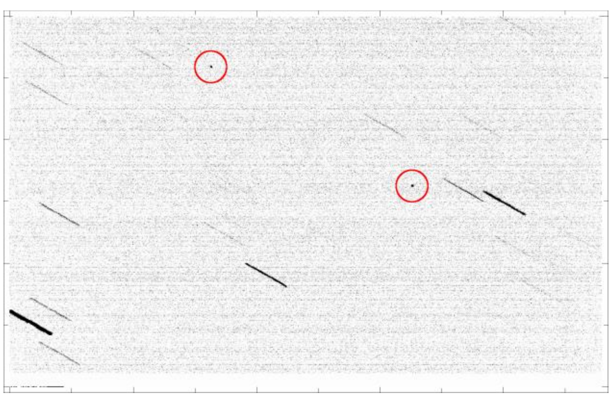
Ukube 1 – 0.05s – 13.9 mag



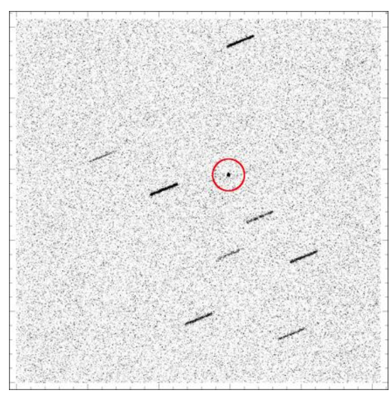
CanX 7 – 0.13s – 9.4 mag



CanX 7 – 0.05s – 10.5 mag



AeroCube 7C – 0.09s – 10.6 mag (left)
AeroCube 7B – 0.09s – 9.8 mag (right)



AeroCube 7B – 0.05s – 13.4 mag

Fig. 4. An example of solved images of LEO cubesats observed throughout the campaign.
Left – Solaris telescope, right – RBT/PST2 telescope. Exposure times and observed magnitudes are also given.
The fields of view are 32'x20' for Solaris and 10'x10' for RBT/PST2.

name	NORAD id	size	alt. [km]	Solaris passes/ images	PST2 passes/ images	Observed by Solaris	Observed by RBT/PST2
BeeSat 1	35933	1U	712	-	9/10600	-	May-23 / Jun-03
Popacs 2	39269	ø=10cm	824	1/172	14/11300	May-28	May-24 / Jun-03
Tigrisat	40043	3U	654	1/721	5/2200	May-29	May-24 / Jun-03
UKUBE 1	40074	3U	624	1/1525	6/4000	Jun-08	May-23 / Jun-13
CANX-7	41788	3U	667	1/527	5/1800	May-28	May-24 / Jun-02
AeroCube 7B	43042	1.5U	455	-	5/2400	-	May-23 / May-27
AeroCube 7C	43043	1.5U	455	3/1413	2/300	May-25 / May-29	May-25 / May-27

Tab. 2. Primary targets observed during the campaign.
alt. = average altitude above the Earth's surface. 1U = cube 10x10x10cm^3.

REDUCTION

The analysis of short-exposure images containing mostly star trails is challenging. For that purpose we used our own software – Poznań Satellite Software Tools (PSST) – which is dedicated to astrometric and photometric analysis of SST optical observations. With this software we are able to calculate accurate image positions of both point-like objects and trails, and identify star fields using the GAIA catalog. All objects moving with respect to stars are identified using the TLE catalog or marked as unknown. The software calculates astrometric positions and photometric brightness and estimates uncertainties. We compared our software with astrometry.net in terms of star field identification success rate. Using exactly the same inputs – pixel coordinates of all objects detected on LEO tracking images – we achieved significantly better results with PSST (Tab. 3).

satellite name	no of images	sensor	avg no of usable stars on images	star trail length	no of solved images		
					astrometry.net		PSST optimized settings
					default settings	optimized settings	
UKUBE 1	999	Solaris	1.9	5'	3	27	36
UKUBE 1	100	RBT/PST2	7.3	0.8'	48	63	87

Tab. 3. Comparison of star field identification performance for a single pass of a satellite.

The overall success rate of star field identification for Solaris and RBT/PST2 is not very high, since most images did not contain enough stars necessary to independently identify the star field (minimum 5 stars were required). In some cases the centroids of star trails were significantly shifted from the geometric central positions, therefore we implemented a pixel weighting algorithm which reduced this effect and improved the identification efficiency. For RBT/PST2 the primary limiting factor was its small field of view, for Solaris its small aperture and less sensitive camera. Overall, we collected 2171 astrometric positions with an average position uncertainty estimated at the level of 0.68" for Solaris and 0.40" for RBT/PST2.

ORBIT DETERMINATION

Precise orbit determination of observed LEO satellite objects – cubesats – was performed with the NASA/GSFC GEODYN II software [1] applied to astrometric observations in the form of right ascension and declination data. The initial orbital elements of observed satellites were taken from USSTRATCOM NORAD TLE Satellite Catalog. The TLE mean elements were transformed to osculating elements with the use of an algorithm based on the Hori-Lie perturbation theory in the version of Mersman [2]. The osculating elements were propagated from the TLE epoch to the moment of first observation with the use of Poznan Orbit Propagator STOP — software developed at the Astronomical Observatory of Adam Mickiewicz University [3]. The moment of the first observation was the epoch of osculating elements obtained from GEODYN calculations with the use of given set of astrometric observations.

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 the Earth's shadow effects;
• Atmospheric drag with MSIS empirical drag model of the Earth's atmosphere.

During the analysis it turned out that it was crucial to use an accurate cross-sectional area to mass ratio (A/m) parameter value. The initial values of the A/m parameter have been calculated based on sizes and masses of the selected satellites and later adjusted until minimum residuals were found. The final values of A/m found during the analysis were:

- AeroCube 7B: A/m = 0.0067 m^2/kg
- UKUBE 1 : A/m = 0.013 m^2/kg
- CANX-7: A/m = 0.88 m^2/kg

The orbit determination for observed cubesats has been performed separately for Solaris and RBT/PST2 telescopes, as well as together for all observations from these two sensors.

The determined root mean square (RMS) values of the residuals in right ascension and declination for observations from a single sensor did not exceed 3". Example residuals for CANX-7 observed with RBT/PST2 are presented in Fig. 5. For the time span covered – 1 day – we obtained excellent RMS below 1" in both right ascension and declination.

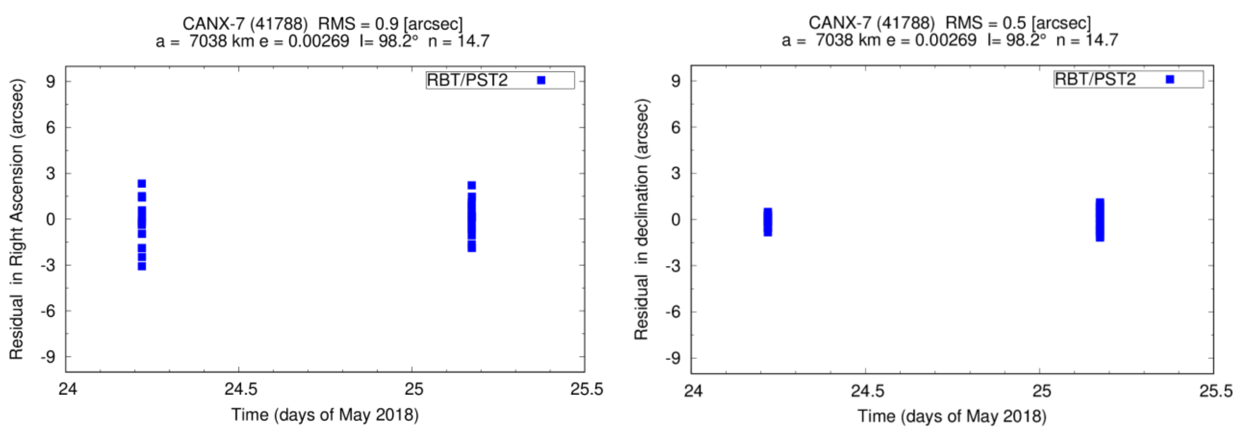


Fig. 5. Residuals in right ascension and declination for the orbital fit of CANX-7 observed with RBT/PST2.

Example residuals for AeroCube 7B observed with the Solaris sensor are presented in Fig. 6. During the time span covered – 3 days – the satellite made 45 revolutions around the Earth. Therefore, the determined RMS is slightly higher than above: 1.7" in right ascension and 3.0" in declination.

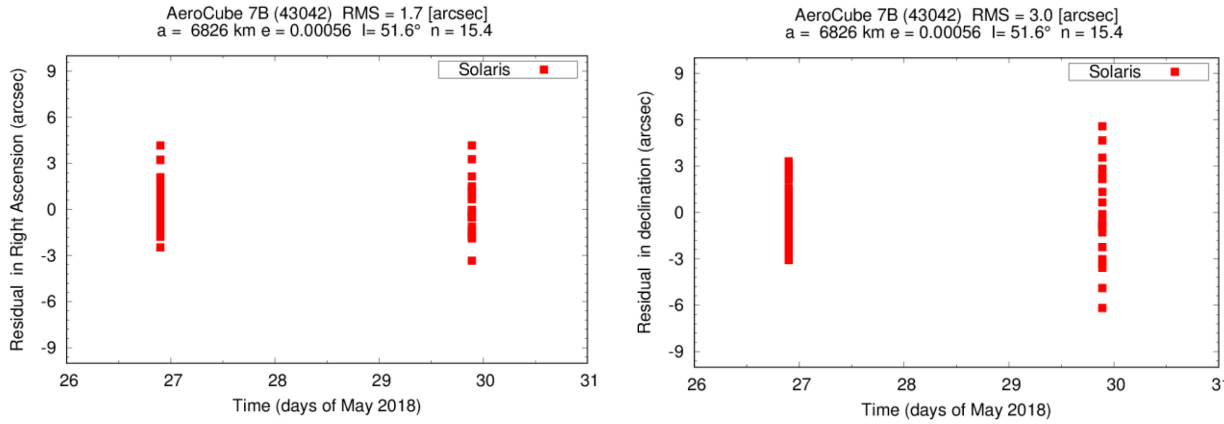


Fig. 6. Residuals in right ascension and declination for the orbital fit of AeroCube 7B observed with Solaris.

Fig. 7 and 8 show the results of orbital analysis in the case when Solaris and RBT/PST2 observations were fitted together. Considered objects are AeroCube 7B and UKUBE 1. The time span covered in this case is 5.72 days for AeroCube 7B and 5.39 days for UKUBE 1. AeroCube 7B completed 88 orbits around the Earth and UKUBE 1 completed 80 orbits around the Earth between the first and last observation. Such a long time span of the observations used for orbit fitting, as well as significant distance between the sensors, can be the reason of quite large systematic deviations of the model from the observations. The determined RMS values of the residuals for AeroCube 7B amount 6.5" in right ascension and 6.5" in declination, while for UKUBE 1 they amount 5.0" in right ascension and 4.6" in declination.

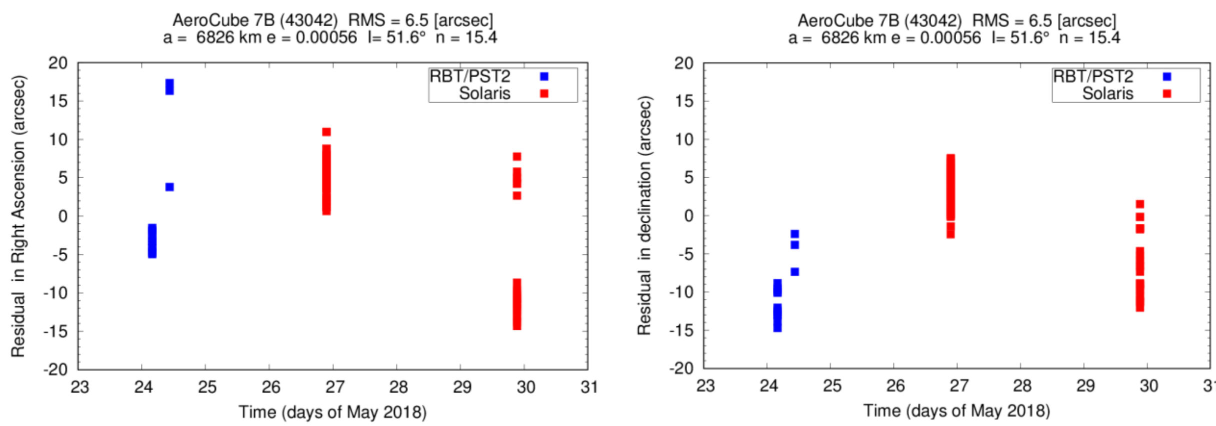


Fig. 7. Residuals in right ascension and declination for the orbital fit of AeroCube 7B observed with both sensors: Solaris and RBT/PST2.

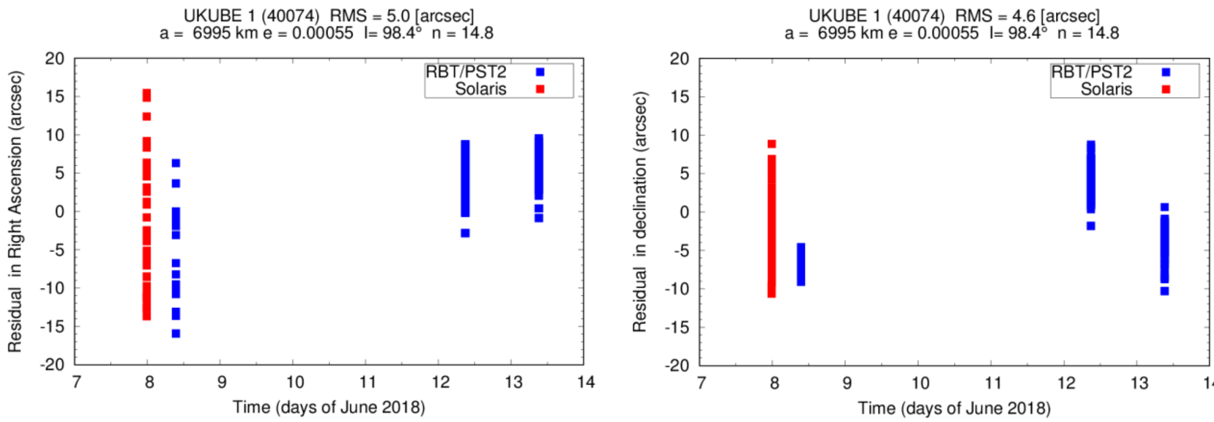


Fig. 8. Residuals in right ascension and declination for the orbital fit of UKUBE 1 observed with both sensors: Solaris and RBT/PST2.

SUMMARY

The presented LEO cubesat observing campaign can be considered mostly successful. We had no problems in detecting all targets with both sensors. For QHY 174M-GPS camera on 0.3m Solaris telescope we found that stars up to 11.0 mag were usable as reference for astrometric analysis with our software. For Andor iXon3 on 0.7m RBT/PST2 telescope this limit was raised to about 12.5. Satellites up to about 14.5 mag were detectable with both sensors with exposure times of 0.2s and 0.05s, respectively. On average only about 9% of all images were astrometically solved. Optics with larger field of view or software capable of using advanced analysis with limited number of stars would significantly improve this result. Almost all images contain at least one clearly detectable star trail, which could potentially be used to combine the images into a mosaic and analyze them together.

Orbital analysis shows that both cameras are fully capable for such demanding tasks as LEO tracking. Orbits fitted for two different passes for individual sensors present low RMS values of residuals: 1.5-3.0" for QHY and 0.5-0.9" for Andor. For Andor camera they are comparable to the astrometric accuracy estimated from statistical analysis of reference stars' residuals. For QHY they are somewhat higher, partly due to larger pixel scale, but still acceptable. This shows that both cameras produce consistent results over several days and do not show random image timing issues. Orbital analysis for combined data from two sites resulted in RMS of the residuals up to 6.5" and systematic shifts up to 15". This can be attributed to sensor offsets, which were not included during the fitting process, but also to the orbital model and fitting limitations. Due to extreme sensitivity of GEODYN II to initial conditions, even our sophisticated method did not allow us to fit all data for all targets. With a more detailed search of initial parameters space it is possible that more observations would be modeled.

Overall, both sensors equipped with both cameras performed reasonably well, proving that not only high-end EMCCD, but also low-end CMOS camera is capable of delivering useful LEO observations of the smallest targets from the TLE catalog.

ACQNOWLEDGEMENTS

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