LOW LEO OPTICAL TRACKING OBSERVATIONS WITH SMALL TELESCOPES

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ABSTRACT

In 2018 the 6 Remote Observatories for Asteroid and Debris Searching (6ROADS) and the Astronomical Observatory of Adam Mickiewicz University (AO AMU) performed a joint observing campaign of low LEO objects – very fast targets, difficult to observe for optical SST sensors. Two small, highly automatic telescopes have been used during the campaign: 0.7m RBT/PST2 in USA (AO AMU) and 0.4m Solaris Observatory in Poland (6ROADS). We present the analysis of astrometric data collected during the campaign, which includes the quality of objects' orbital parameters, determined from observations, as a function of the observation arc length, number of astrometric observations and force models taken into account in orbit determination. In particular, the influence of the atmospheric drag perturbations is analyzed in terms of the applied atmospheric model and the area to mass A/M ratio of the observed object.

Keywords: LEO optical observations, orbit determination, SST.

1. INTRODUCTION

In this work we present the results of an optical LEO cubesats campaign conducted in May and June 2018 with two sensors. This is an extension and update to the results presented in [2] We selected targets that are among the smallest Earth satellites for which there are available TLE orbits. These satellites are usually on low LEO orbits, with proper motions between 200 and 2000 arcsec/s, and are therefore considered among the most difficult targets for optical SST. Aditionally, due to significant influence of the Earth's atmosphere on their motion, they are also more demanding in terms of orbital analysis.

Due to their small size, the observed brightness of cubesats is typically between 10 and 14 mag. In optical tracking observations these targets are detectable even with relatively small sensors. In optical survey they are very difficult to detect and would require wide-field optical systems combined with very low noise cameras and special algorighms, such as presented by [1]. AO AMU is currently building optical survey SST sensors equipped with 0.3m f/1.0 OTAs that should be capable to lower the detection threshold for unknown low LEO targets to about 0.2m in size [3].

LEO tracking is also challenging when it comes to image timing. For these targets a sub-millisecond accuracy in determination of exposure beginning and end time is necessary in order not to harm astrometric accuracy of final results. A typical astronomical CCD camera equipped with a mechanical shutter is not able to deliver required timing accuracy and homogenity over the entire image. Global electronic shutter or frame-transfer cameras are strongly preferred. A direct hardware connection with a timing device also seems necessary. Our measurements, comparing a GPS based hardware timestamps to a GPS synchronised PC software timestamps for Andor iXon3 camera, show that a difference of up to 10 milliseconds can be observed.

2. EQUIPMENT DESCRIPTION

Two different sensors were used for all observations. First is Solaris (Fig. 1) telescope (6ROADS), a 0.3m f/4 remotely controlled instrument located in Cracow (Poland). It is a component of 6ROADS global network of telescopes. It was equipped with QHY174M-GPS - the first commercially available global shutter camera with a built-in circuit using GNSS receiver for PC-independent image timing. Timestamps are embedded in the header of every frame recorded and claimed to have $10^{-6}s$ precision. The sensor allows stable satellite tracking at distances down to 600 km from the observer.

The second sensor used in presented campaign is Roman Baranowski Telescope / Poznań Spectroscopic Telescope 2 (RBT/PST2) (Fig. 2), which is a component of AO AMU's Global Astrophysical Telescope System. The sensor is located in Arizona (USA) and equipped with Andor EMCCD iXon3 frame-transfer camera. Exposure start times were recorded using camera's electronic shutter-out signal, which was directly sent to our custom

Figure 1. Solaris telescope

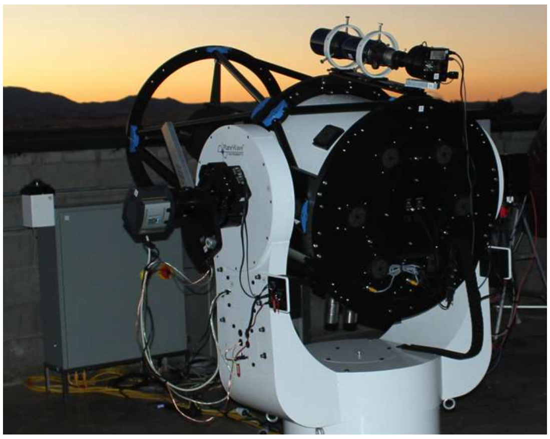

Figure 2. RBT/PST2 telescope

built timing device based on ATmega32u4 controller and NEO-7M GPS module. We found this timestamp source to be more precise than the camera software generated exposure timestamps and used it throughout the project.

3. 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. 1

4. ORBIT DETERMINATION

Precise orbit determination of observed LEO satellite objects – cubesats – was performed with the NASA/GSFC

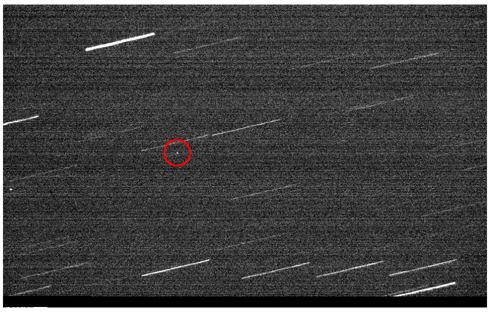

Figure 3. AeroCube 7C image from Solaris telescope.

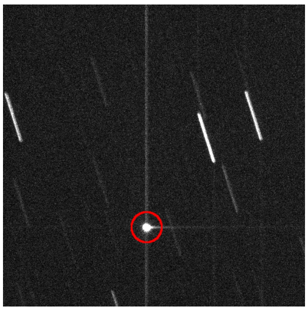

Figure 4. Popacs 2 image from RBT/PST2 telescope.

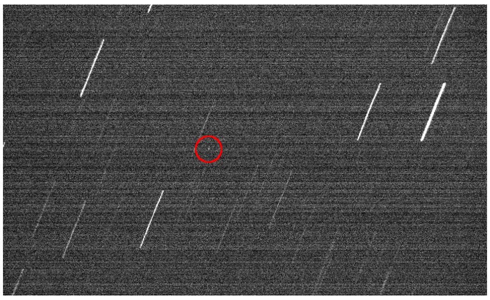

Figure 5. UKube 1 image from Solaris telescope.

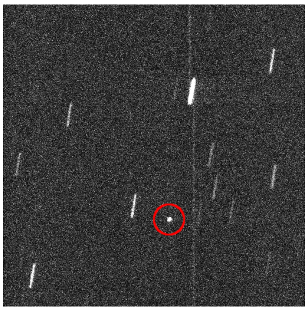

Figure 6. UKube 1 image from RBT/PST2 telescope.

Table 1. Dates of observations of selected targets. Not all observations were later useful for astrometry due to insufficient number of reference stars.

Target	Solaris	RBT/PST2
Popacs 2	May-28	May-24 / Jun-03
UKUBE 1	Jun-08	May-23 / Jun-13
AeroCube 7C	May-25 / May-29	May-25 / May-27

Table 2. Targets description. alt. = average altitude above the Earth's surface. 1U = cube $10x10x10cm^3$.

Target	NORAD	size	alt[km]
Popacs 2	39269	ø=10cm	824
UKUBE 1	40074	3U	624
AeroCube 7C	43043	1.5U	455

GEODYN II software [4] 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 [6]. 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 AO AMU [7]. 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 three different models of the Earth's atmosphere available in GEODYN:
  - MSIS empirical drag model;
  - Jacchia model;
  - French Drag Model.

Fig. 7 show the example results of orbital analysis in the case when Solaris and RBT/PST2 observations were fitted together. Considered object is UKUBE 1. The time span covered in this case is 5.39 days. 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 amount 5.0" in right ascension and 4.6" in declination.

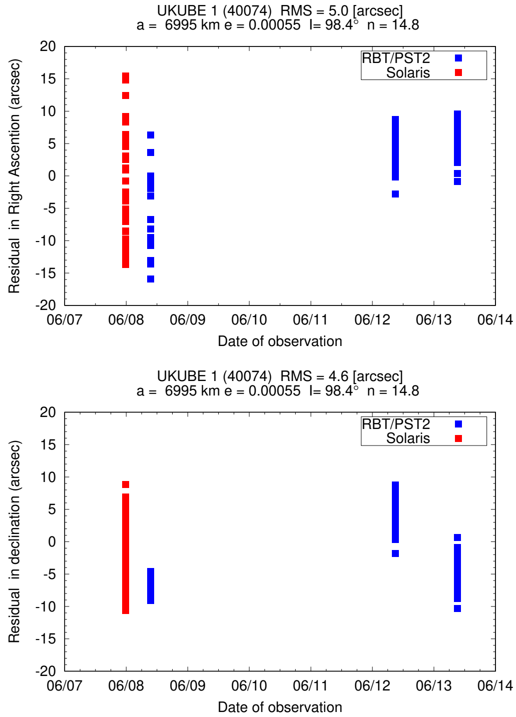

Figure 7. Residuals in right ascension and declination. Object: UKUBE 1, Telescope: RBT/PST2 and Solaris.

4.1. Earth gravity field

GEODYN has been used for orbit determination of the observed objects taking into account different number of geopotential coefficients. The determined root mean square (RMS) values of the residuals in right ascension (α) and declination (δ) for observation of very low (455 km) cubesat AeroCube 7C (43043) from Solaris telescope are presented in Table 3. Table shows the results for different values of maximum degree and maximum order of coefficients used in the gravitational model. These results show that the use of geopotential coefficients up to 60x60 or even 50x50 degree and order is sufficient to model the orbit of this type of satellite on 1 arcsec accuracy level.

Table 3. RMS values of the residuals in α and δ for different value of maximum degree and maximum order of geopotential coefficients. Object: AeroCube 7C (43043), telescope: Solaris

max. degree and order of coefficient	$RMS(\alpha)$ [arcsec]	$RMS(\delta)$ [arcsec]
80x80	1.58	1.99
70x70	1.58	1.99
60x60	1.57	1.99
50x50	1.59	2.01
40x60	1.62	2.05
30x30	2.13	1.98
20x20	10.02	4.93
15x15	22.05	12.58

4.2. Atmospheric drag

The basic equation for aerodynamic drag can be written as [5]:

$$\vec{a} = \frac{1}{2BC}\rho v_{rel}^2 \frac{\vec{v}_{rel}}{|\vec{v}_{rel}|} \quad (1)$$

where ρ is atmospheric density and $\vec{v}_{rel}$ is the velocity vector relative to the atmosphere.

Atmospheric drag strongly depends on the ballistic coefficient of the object [5]:

$$BC = \frac{M}{C_D A} \quad (2)$$

where:

- C_D is the drag coefficient, a parameter that considers the interaction of the atmosphere with the object;
- A is the cross-sectional area of the object;
- M is the mass of the object.

The influence of the atmospheric drag perturbations is analyzed in terms of the applied atmospheric model and the area to mass A/M ratio of the observed object.

Orbit determination of observed objects was performed with the use of GEODYN software taking into account different atmospheric models. The results of orbit fitting for the object AeroCube 7C (43043) with the use of the French Drag Model for different values of the area to mass ratio (A/M) are presented in Table 4. The best orbit fit (1.59 arcsec in right ascension (α) and 2.02 arcsec in declination (δ) on 4 days orbital arc) is for $A/M = 0.0062m^2/kg$. Residuals in right ascension (α) and declination (δ) are presented in Fig. 8.

Table 4. RMS values of the residuals in α and δ for different value of A/M. French Drag Model. Object: AeroCube 7C (43043), telescope: Solaris

A/M $[m^2/kg]$	$RMS(\alpha)$ [arcsec]	$RMS(\delta)$ [arcsec]
0.0058	6.09	3.44
0.0059	4.76	2.91
0.0060	3.48	2.46
0.0061	2.35	2.11
0.0062	1.59	2.02
0.0063	1.87	2.13
0.0064	2.90	2.42
0.0065	4.15	2.82
0.0066	5.47	3.29
0.0070	10.92	5.52

Table 5. RMS values of the residuals in α and δ for different value of A/M. MSIS Model. Object: AeroCube 7C (43043), telescope: Solaris

A/M $[m^2/kg]$	$RMS(\alpha)$ [arcsec]	$RMS(\delta)$ [arcsec]
0.0060	16.90	7.54
0.0065	11.29	5.07
0.0070	5.81	2.88
0.0072	3.72	2.25
0.0074	1.96	1.97
0.0075	1.59	2.02
0.0076	1.91	2.19
0.0077	2.69	2.45
0.0080	5.69	3.57
0.0090	16.45	8.22

Results of similar calculations with the use of the MSIS dynamical model are presented in Table 5. In this case the best fitting is for $A/M = 0.0075m^2/kg$.

The values of RMS in right ascension and declination for the same set of observations and for the same value of $A/M = 0.0075m^2/kg$, but for different atmospheric models are presented in Table 6.

Similar analysis has been performed for the object BeeSat1 (35933) with the use of observations from 10 days orbital arc taken by RBT/PST2 telescope in Arizona. The orbit determination was performed for different parts of the whole orbit arc (2 or 3 days long arcs) with the use of MSIS dynamical model. For particular arcs (for the same satellite) different values of A/M ratio are needed

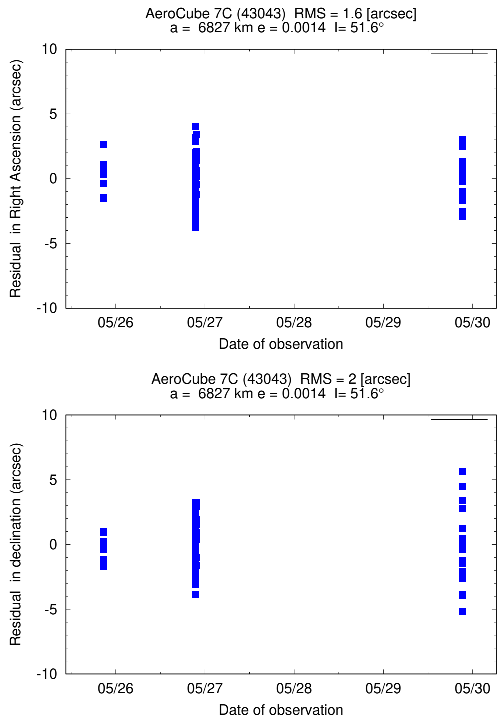

Figure 8. Residuals in right ascension and declination. Object: AeroCube 7C (43043), telescope: Solaris. French Drag Model.

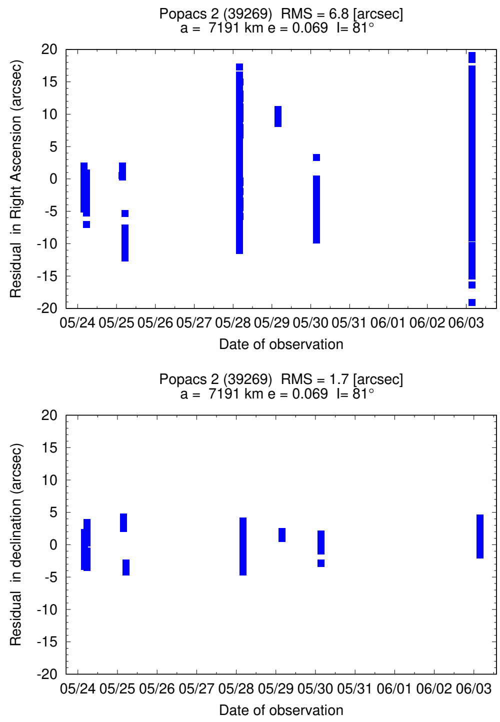

Figure 9. Residuals in right ascension and declination [arcsec]. Object: Popacs 2 (39269), telescope: RBT/PST2.

Table 6. RMS values of the residuals in α and δ for different models of the Earth's atmosphere. Object: AeroCube 7C (43043), telescope: Solaris, $A/M = 0.0075m^2/kg$

Models of the Earth's atmosphere	$RMS(\alpha)$ [arcsec]	$RMS(\delta)$ [arcsec]
MSIS	1.58	1.99
Jacchia	2.25	2.00
French Drag	16.95	8.29

to obtain the best orbital fit. This is a result of changes in time in the applied dynamical atmosphere. The best orbit fit for this satellite for 2 days orbital arc (23 -24 May) is $RMS(\alpha) = 2.37''$ and $RMS(\delta) = 1.97''$ with $A/M = 0.0142m^2/kg$.

4.3. Earth and ocean tides

The influence of the Earth and ocean tides on results of orbit determination from optical astrometric observations of analyzed satellites is negligible. RMS for the object AeroCube 7C (43043) on 4 days orbital arc with $A/M = 0.0075m^2/kg$ and MSIS atmospheric model calculated with the tides taken into account was $RMS(\alpha) = 1.58''$ and $RMS(\delta) = 1.99''$, whereas without tides it was $RMS(\alpha) = 1.58''$ and $RMS(\delta) = 1.98''$.

4.4. Length of orbital arc

The quality of orbit determination process and the accuracy of obtained final orbital elements determined from astrometric observations for LEO satellites depends on many different factors. The length of orbital arc is one of them. RMS of residuals in α and δ is relatively small for short orbital arcs and higher for longer arcs. Difficulties in modelling of disturbing forces (mainly atmospheric drag) are the reason of this situation. Nevertheless, it is possible to determine sufficiently precise one orbit for about 10 days orbital arc. Fig. 9 presents residuals of orbital fitting for the Popacs 2 (39269) satellite (10 cm in diameter sphere object moving at an altitude of 824 km) calculated from 708 observations taken by RBT/PST2 telescope in Arizona in the time span May 24 – June 3 2018.

REFERENCES

1. William A. Dawson, Michael D. Schneider, Chandrika Kamath (2016), Blind Detection of Ultra-faint Streaks with a Maximum Likelihood Method, AMOS 2016 Technical Papers.

2. Kamiński K., Wnuk E., Golebiewska J. et al. (2018),

LEO cubesats tracking with a network of Polish optical SST sensors, AMOS 2018 Technical Papers.

3. Kamiński K., Wnuk E., Golebiewska J. et al. (2018), New Optical Sensors Cluster for Efficient Space Surveillance and Tracking, AMOS 2018 Technical Papers.
4. Pavlis, D. E., Rowlands, D. D., et al. (1998), GEODYN Systems Description, vol.3. NASA Goddard, Greenbelt.
5. Vallado, D.A. (2007), Fundamentals of Astrodynamics and Applications, Third Edition. Hawthorne, CA.: Hawthorne Press.
6. Wnuk, E. (1999), Relation Between Osculating and Mean Orbital Elements in the Case of the Second Order Theory, *AAS paper 99-448, Advances in the Astronautical Sciences*, **103**, 2279-2292.
7. Wnuk, E. (2015), STOP - The Short-Term Orbit Propagator, Kepassa 2015, 28-30 October 2015 Toulouse.