# Utilization of CubeSat nanosatellites as reference objects for evaluating the ballistic coefficients of low-altitude satellites

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**Abstract**

Currently, a large number of 1U CubeSats have been launched, which allows them to be used as reference objects for determining the ballistic coefficient of other objects in close orbits. In this paper, we propose technique of utilization of CubeSat nanosatellites as reference objects for evaluating the ballistic coefficients of low-altitude satellites. This technique was verified on a 3U CubeSat SamSat-218D developed at Samara University. The evaluated ballistic coefficient corresponds to the theoretical estimations. This result can be used in the future to analyse the mode of spatial motion.
**Keywords:** 1U CubeSats, ballistic coefficient, atmosphere, PION, SamSat-218D

## 1. Introduction

Traditionally, models of the density of the upper atmosphere are refined by analysing the deceleration of spacecraft, for which standard spherical objects with known masses and sizes are usually used. With the help of ground-based orbital monitoring stations, observations are made and the motion parameters of such satellites are calculated. Based on these data, the density of the atmosphere at the satellite flight altitude is estimated, which is then used to improve the accuracy of the spacecraft motion forecast at the same altitude level. Samara University introduced this technology from 1989 to 1992 by launching the PION series of six spherical satellites.

Recently, small spacecraft of the nano- and pico- classes have been actively developed. Over the past 10 years, more than 1000 CubeSats have been launched, developed by both universities, small innovative companies, and large companies that launch CubeSat constellations. A significant part of the launched CubeSats belongs to the CubeSat class, the satellites of which have standard dimensions and mass, for which the average ballistic coefficient can be analytically estimated with sufficient accuracy.

In this paper, we propose to use 1U CubeSats as reference objects for estimating the ballistic coefficients of spacecraft moving in the same altitude range. To do this let's consider some features of the motion of CubeSats in low orbits are described in [1].

1) The value of the ballistic coefficient of a CubeSat is more than that of a satellite with large dimensions and mass (with the same bulk density), which leads to a decrease in its lifetime in orbit. It makes possible, given the small planned duration of the active work of the CubeSat (usually from six months to a year), to use low orbits effectively and to avoid clogging of near-Earth space.

2) The angular acceleration of a CubeSat due to the aerodynamic moment is much more than that of a satellite with large dimensions and mass (for the same values of the relative static stability margin and bulk density). This expands the range of heights at which the aerodynamic moment acting on the CubeSat is significant and can be used to passively stabilize along the velocity vector of the centre of mass.

3) The value of the ballistic coefficient of a CubeSat substantially depends on its orientation. The following formula expresses the relationship between the ballistic coefficient of a CubeSat and its orientation [2]:

$$\sigma(\alpha,\varphi) = c_0 \tilde{S}(\alpha,\varphi) S / m,$$

where $\alpha$ – angle of attack; $\varphi$ – angle of proper rotation; $c_0$ – the drag coefficient, which can take values from 2 to 3 depending on the physical properties of the gas and the surface of the CubeSat (for design studies is assumed to be

2.2); $S$ – characteristic area; $m$ – CubeSat mass; $\tilde{S}(\alpha, \varphi)$ – the projection area of a 1U CubeSat on a plane perpendicular to the velocity vector, divided to the characteristic area:

$$\tilde{S}(\alpha, \varphi) = (|\cos\alpha| + k_s \sin\alpha(|\sin\varphi| + \cos|\varphi|))/S,$$

where $k_S = 1$ – the ratio of the area of one of the side surfaces to the characteristic area.

To analyse the angular motion of a CubeSat, for the case when the angular velocity of its own rotation is close to uniform, the expression for the ballistic coefficient can be averaged by the angle of proper rotation:

$$\sigma(\alpha) = c_0(|\cos\alpha| + \frac{4k_s}{\pi}\sin\alpha)S/m.$$

The ratio of the maximum ballistic coefficient to the minimum is 1.73, the average projection area of a 1U CubeSat is 0.01447.

## 2. Formulation of the Problem

Using the information on 1U CubeSats height changing (trajectory measurements), as well as data on its design parameters (mass, inertia moments, aerodynamic characteristics) and the results of theoretical studies of the CubeSat movement dynamics [3] it is possible to estimate the changes in the ballistic coefficient of the spacecraft under study.

## 3. Technique for using 1U CubeSats as Reference Objects for Determining the Ballistic Coefficient of Low-Altitude Satellites

Satellite orbit perturbations caused by the action of aerodynamic acceleration $\Phi$, for a circular orbit, are described by the well-known formula [3]:

$$\dot{r} = 2r\sqrt{\frac{r}{\mu}}\Phi, \tag{1}$$

where $r$ – current radius vector; $\mu$ – Earth gravitational parameter; $\Phi = -\sigma q$ – disturbing aerodynamic acceleration; $q = \rho V^2/2$ – velocity head; $\rho$ – atmosphere density; $V = \sqrt{\mu/r}$ – flight speed.

1) Selection a group of 1U CubeSats in orbits close in inclination and altitude range to the spacecraft under study.
2) Calculation an average ballistic coefficient for each CubeSat in the group:

$$\sigma_m = c_0\left(\frac{8}{\pi^2} + \frac{2}{\pi}\right)\frac{S}{m}. \tag{2}$$

3) Checking the selected group of CubeSats for the possibility of being a single reference object for the studied spacecraft. To do this, from a set of TLE files for each CubeSat, the value of the product of density and ballistic coefficient observed in flight is estimated.

$$(\sigma\rho)_{ro} = -\frac{\dot{r}}{\sqrt{\mu r}}.$$

4) Estimation of the density of the atmosphere by dividing the found value by the average ballistic coefficient calculated for the known design parameters of the CubeSat. If the obtained density values are close in magnitude, then the selected satellites can be used as a single reference object:

$$\rho = \frac{(\sigma\rho)_{ro}}{\sigma_m}. \tag{3}$$

5) Using a dynamic model of the atmosphere $f_{MODEL}$, the estimate of the density of the atmosphere for the orbit of the reference object is recalculated to the height of the spacecraft under study:

$$\rho^* = f_{MODEL}(h)\cdot\rho. \tag{4}$$

6) Similarly to the third step, for the studied space object from a set of TLE files, the product of density and ballistic coefficient is determined, which is divided by the value of the recalculated density estimate obtained in the previous step.

$$\sigma_{ns} = \frac{(\sigma\rho)_{ns}}{\rho^*}. \tag{5}$$

The result is the estimated ballistic coefficient of the spacecraft under study.

## 4. Results

Since 2014, CubeSats have been developed at the Samara University. The SamSat-218D CubeSat [4] of the CubeSat 3U format is the first CubeSat developed by students and scientists of Samara University. On April 28, 2016, it became a participant of the first launch campaign from the Vostochny cosmodrome, and simultaneously with two other satellites (MVL-300 and Aist-2D) was launched into orbit with an inclination of 97.3 deg and an average height of 486 km using the Soyuz 2.1a launch vehicle. SamSat-218D was designed to improve number of technological and educational tasks. First of all, it was intended for testing the orientation control algorithms of CubeSats. How-ever, since launching into orbit, it was not possible to establish communication with CubeSat. The main parameters of SamSat-218D are shown in Table 1.

Table 1. The main parameters of SamSat-218D

| Parameter | Value |
|---|---|
| Deployment method | Deployer developed by Progress Rocket Space Centre |
| Orbital parameters | |
| − Sun synchronized orbit with average altitude, km | 490 |
| − Inclination, deg | 97.3 |
| − Deployment angle, deg | 80 |
| Mass, kg | 1.82 |
| Inertia moments, kg $m^2$ | 0.00402; 0.01422; 0.01454 |
| Static stability margin, m | 0.06 |

Due to first step of proposed technique, we selected four 1U CubeSats from Nanosats Database [5] with parameters closed in inclination and altitude range to SamSat-218D. Parameters of these CubeSats are shown in Table 2. Let's look at the trajectory measurements of these CubeSats together with SamSat-218D. Fig. 1 shows the changes in the height of their orbits. The information is based on the processing of data from the NORAD TLE files [6]. The considered time interval (from April 28, 2016 till October 05, 2021) corresponds to a decrease of solar activity, which leads to a decrease in the density of the upper atmosphere and the height reduction rate.

Table 2. The list of 1U CubeSats in orbits close in inclination and altitude range to SamSat-218D.

| NORAD | 1U CubeSat | Mass, kg |
|---|---|---|
| 41607 | Swayam COEP | 0.990 |
| 42789 | skCube | 1.056 |
| 43136 | CANYVAL-X | 0.810 |
| 43138 | STEP-1 | 0.969 |

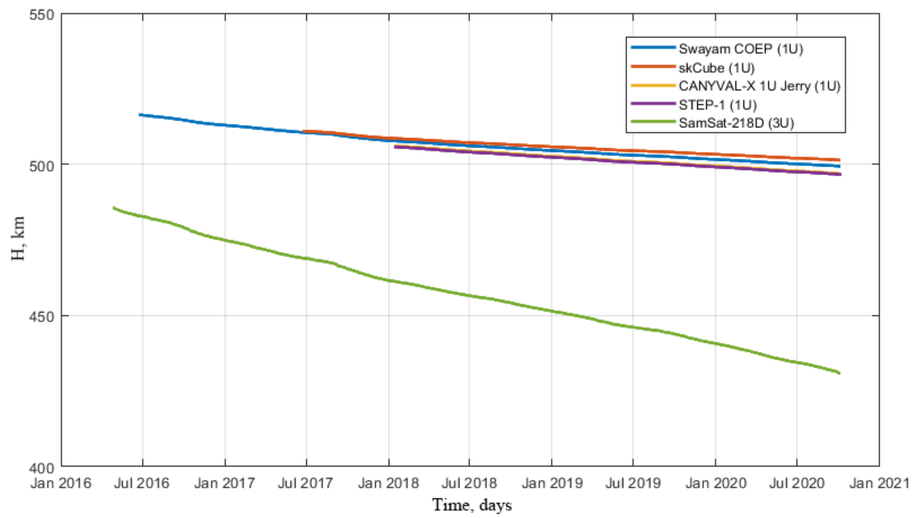


Fig. 1. Altitude plots for 1U CubeSats together with SamSat-218D starting from their launch dates

The time dependence of the ballistic coefficient obtained using the proposed technique is shown in Fig. 2.

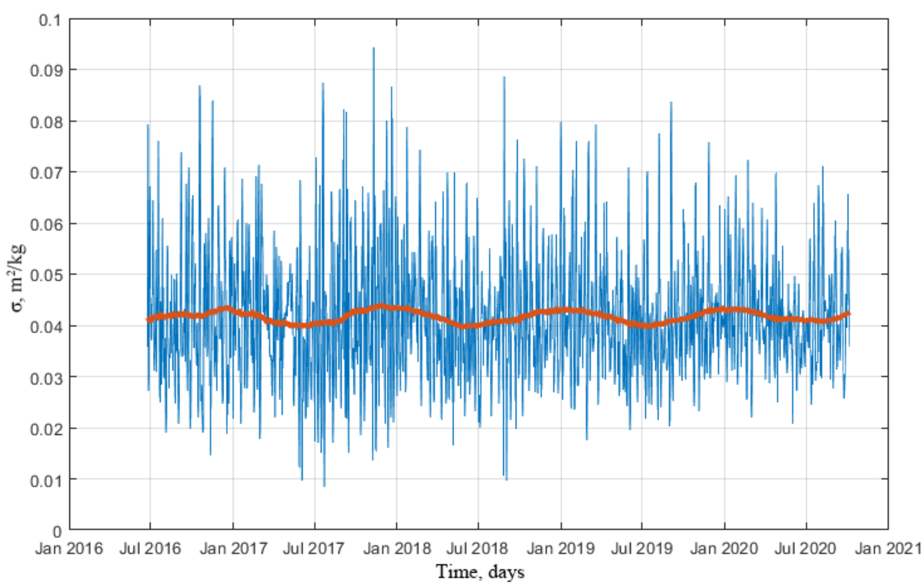


Fig. 2. Estimated ballistic coefficient of SamSat-218D, smoothed by a window 180 days wide.

## 5. Conclusions

This result can be used in the future to analyse the mode of spatial motion of the spacecraft under study. The proposed method for estimating the ballistic coefficient for an unmanaged 3U CubeSat SamSat-218D has been verified. The result showed good agreement with the theoretical estimate of the average ballistic coefficient of the considered satellite.

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