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Nanosatellites Triangle Formation Flying For Terrestrial Gamma-Ray Flashes and Transient Luminous Events Study

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Abstract

Terrestrial gamma-ray flashes (TGF) and transient luminous events (TLE) are the energetic phenomena at the Earth atmosphere. TGFs are supposedly caused by high-energy electrons accelerated by intense electric fields produced during thunderstorms. TLEs, such as sprites, jets, elves, etc. that are commonly occur above thunderstorm clouds. To study these transients we propose to use a group of small satellites at LEO equipped with gamma- and UV-radiation detectors. To better locate TLEs and the source of TGF, we propose to use three satellites that will ideally form the unilateral triangle in projection onto Earth surface. The length of the triangle side at the mission begin have to be equal to 1000 km, but due to the mission requirement there must be a possibility to reduce it up to 100 km. In addition, there are requirements imposed to the attitude control system: UV-sensor sensitive axis must be pointed to the nadir with the accuracy better than 10 degrees, and the accuracy of attitude determination must be better than 1 degree. The mission could be implemented by using TNS-0 micro-satellite platform, with the satellite mass of 5 kg for a prism form-factor. The micro-satellite will be equipped with magnetotorquers for the attitude control, while magnetometer and sun sensors are used for the attitude determination. Downlink to the ground stations is provided by using GlobalStar communication system. The initial orbital configuration is provided by Progress cargo vehicle. The triangle configuration is formed due to the differences in micro-satellites longitudes of the ascending node and phase shift along the orbit. Active relative motion control is provided by changing the satellites' attitude, which leads to a difference in atmospheric drag that affects the satellites.

Keywords: relative motion control, atmospheric drag control

1. Introduction

It is supposed that energetic phenomena called Terrestrial gamma-ray flashes (TGF) arise in the upper atmosphere due to particular type of thunderstorm activity (intracloud discharges). TGFs were originally discovered in a BATSE experiment [1]. After that, TGFs has been observed by several low-orbit satellites: the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [2], the Fermi Gamma-Ray Space Telescope [3], the Astrorivelatore Gamma a Immagini Leggero (AGILE) satellite [4]. Several experiments devoted to TGF observations have been implemented in Russia [5], [6].

Extensive research of TGFs have revealed some particular features: TGFs typically last from a fraction of to a few milliseconds and exhibit a hard energy spectrum. In addition the last observations provide evidence that there is a connection between TGFs and general transient luminous emissions (TLEs). However, there are still no clear interpretation and mathematical model of TGFs and TLEs. Study of transient atmospheric events is important for understanding their physical nature and theoretical models. Observations and detection of TGF source can provide us information about particles acceleration mechanisms in thunderstorm electric fields. As for TLEs, most of phenomena such as Sprites, Jets and Elves, occur above thunderstorm clouds. Nevertheless, some events were observed far from thunderstorm areas. The nature of such transients is still unknown.

The vast portion of TGFs is accompanied by very-low-frequency radio signals that could be detected by the World Wide Lightning Location Network (WWLLN) [7]. The TGF geolocation is possible by searching correlations with WWLLN triggers. When the radio signal from lightning is detected by several ground-based WWLLN stations, the coordinates of its source can be found using triangulation. If there are no WWLLN stations in the detecting area, one can assume that the source lies within the limits of a cone with an opening angle of 60 degrees relative to the nadir direction.

The possible alternative approach that could provide accurate localization of TGF source is based again on the triangulation technique but applied for observations of the selected thunderstorm area from different satellites. Such a method is particularly useful for cosmic gamma-ray burst source detection. In the case of TGFs it needs at least three satellites that should be spaced at a distance of several hundred kilometers for orbits with altitude about 400–600 km. If such conditions are satisfied, the GPS time accuracy is enough to determine satellites TGF signals time delay. That localizes thunderstorm area in limits of tens of kilometers.

The crucial point in understanding of TGFs is confirming or refuting their connection with the given thunderstorm or lightning. The aforementioned technique of triangulation is enough for TGF source identification, but it is insufficient to guarantee the identification of TGF itself given a thunderstorm cloud. The latter demands an improvement of the angular resolution by at least a factor of 10. The solution for the problem can be achieved by gradually changing the distance between satellites in a group.

2. Problem statement and equations of motion

In order to provide the necessary measurements three satellites must form a triangle (preferably close to the unilateral one) in the near-equatorial region. At other parts of orbit satellite configuration is not important. We can obtain this triangle using the following formation. Two satellites are on the same circular orbit but shifted by Argument of Latitude (AOL). The third satellite is located at the circular orbit with the same radius but shifted by small amount of the Longitude of the Ascending Node (LAN) (see Fig. 1).

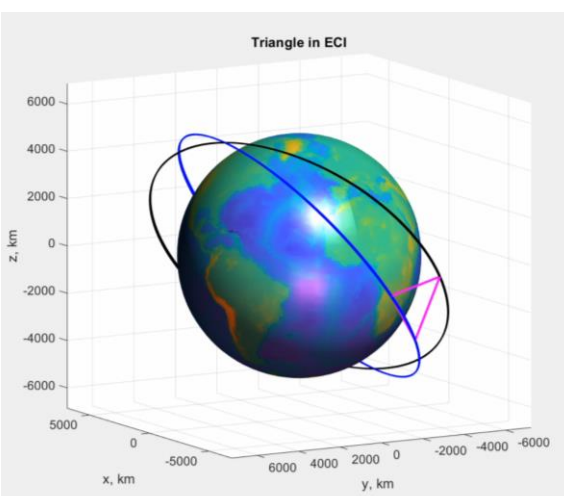

Fig. 1a. Proposed satellite orbits (near equator)

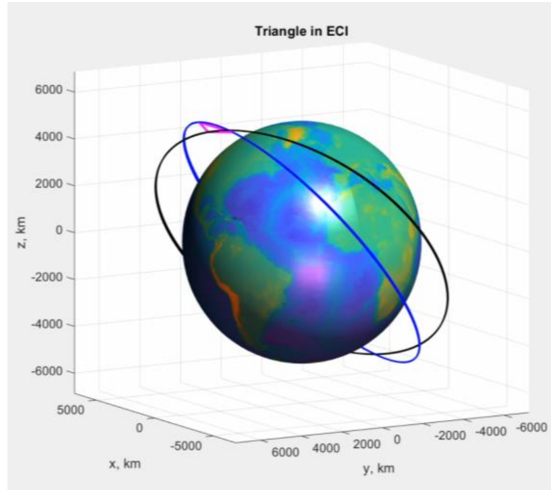

Fig 1b. Proposed satellite orbits (upper part of orbit)

This kind of relative orbit satisfies the main mission requirement and allow us to provide measurements in the region of interest. However, we also must be able to change the triangle size during the mission (expected lifetime is about a year) from initial 1 000 km to 100 km. In order to do that we are utilizing the natural dynamics.

We suppose that satellites are moving under the influence of central newtonian gravity field, J2 perturbation and atmospheric drag. Equations of motion then are [8]

$$\ddot{\mathbf{r}} = -\mu \frac{\mathbf{r}}{r^3} + \mathbf{a}_{J_2} + \mathbf{a}_{atmo}$$

Where

$$\mathbf{a}_{J_2} = \delta \frac{\mathbf{r}}{r^5}\left(5\frac{z^2}{r^2} - 1\right) - 2\frac{\delta}{r^5}\left(0, \quad 0, \quad z\right)^T,$$

$$\delta = \frac{3}{2} J_2 \mu R_E$$

$$\mathbf{a}_{atmo} = -\rho \mathbf{v} v C_x \frac{S}{m}$$

Here μ is Earth gravitational constant, J_2 corresponds to the J2 harmonic coefficient, R_E is the Earth radius, ρ is the atmospheric density, $v = |\mathbf{v}|$ is the satellite velocity w.r.t. the atmosphere, C_x is the ballistic coefficient, S is the satellite area, m is the satellite mass.

3. Reference orbit construction and maintenance

Atmospheric drag affects mostly in-plane motion of the satellite, and hardly affects its out-of-plane motion (i.e. it does not change inclination and LAN). However, main effect of J2 harmonic is the orbit precession, which can be described as

$$\dot{\Omega}_{LAN} \approx -10\left(\frac{R_E}{a}\right)^{\frac{7}{2}} \cos i \quad \left[\frac{\deg}{\mathrm{day}}\right]$$

Here a is orbit major semiaxis, i is the inclination. Note that if major semiaxes are different, it would lead to fast formation degradation – satellites will fly away from each other. Therefore, all the satellites must rotate at the same height. If inclinations of the orbits are different, it would lead to a different precession rates, i.e. "distance" between orbits would change. This fact is utilized to ensure the necessary change of the triangle size: at the inclination of 51.7 degrees (similar to the International Space Station inclination) difference of about 0.2 degrees would be sufficient to change the triangle size from initial 1 000 km to 100 km in a year.

Change of triangle sides length is ensured by utilizing atmospheric drag control [9]. We are going to use the TNS-0 nanosatellite platform (see Fig. 3), which is close to the 3U CubeSat. Therefore, by changing the satellite attitude we can change the its cross-section area, which would lead to the different accelerations caused by atmosphere.

Since this is just a preliminary study, at this moment we do not consider the attitude control problem. We suppose that for any moment of time it is possible to set satellite cross-section to any value from the interval $\left[S_{min}, S_{max}\right]$, i.e. to any value between the minimum and maximum possible area.

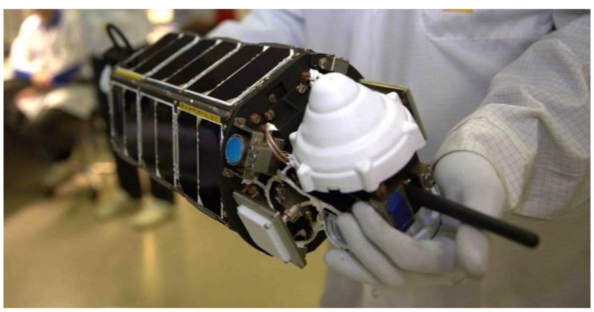

Fig. 3. TNS-0 nanosatellite platform

To control the triangle side length, which is actually almost the same as the difference between satellites' AOLs, we propose simple control algorithm. Let the first satellite cross-section area is always set to

$$S_1 = \frac{S_{min} + S_{max}}{2}.$$

This way we ensure that two other satellites can produce an acceleration in both directions, i.e. they can either get to the first satellite or fly away from it. In order to maintain the necessary AOL shift between the satellites the following proportional-derivative algorithm is used (example for the shift between the first and second satellites):

$$S_2 = S_1 + k_\omega \left(n_1 - n_2\right) + k_u \left(u_1 - u_2 - u_{ref}\right)$$

Here n_k is the mean motion (i.e. mean orbital angular motion) of the k-th satellite, u_k is the AOL, u_{ref} is the reference AOL shift, k_ω, k_u are control coefficients. In addition, if S_2 goes beyond the given boundary $\left[S_{min}, S_{max}\right]$, it is cut to fit within it.

4. Simulation

In order to test suggested control techniques the following mission was simulated. Three satellites are at the initially circular orbits, height is 500 km. Inclination is 51.7 degrees for two satellites on the same orbit, and 51.46 degrees for the third satellite. Satellites are shifted by AOL and LAN in such a way that initially they form a unilateral triangle in the equator region. Atmospheric density calculated using Russian GOST model and includes information about night/day cycle, year season, solar activity etc. Atmosphere moves with the Earth, so its velocity is

$$\mathbf{V}_{atmo} = \boldsymbol{\omega}_E \times \mathbf{r}.$$

We consider two scenarios: high solar activity (launch in 2013) and low solar activity (launch in 2019). Satellite mass is 4.8 kg, $S_{min} = 0.0275\ \mathrm{m}^2$, $S_{max} = 0.05\ \mathrm{m}^2$. Simulation time is 15 months. Satellites cross-section area is updated once per revolution.

The first case simulation is presented in Fig. 4. As we can see, in 15 months satellites height decreased for almost 150 km. Simulation also shown that after another month the satellites hit the surface. For the most part of the simulation controller was able to maintain the necessary triangle form and size. The only problem appeared at the end part of simulation, when the triangle size become too small (blue triangle corresponds to the initial one, black to the current one). Also, satellites areas are near the mean value, which means that the necessary orbital motion control is rather small.

The second case is presented in Fig. 5. In this simulation atmospheric density is much lower, so in 15 months satellites height decreased for only about 30 km. Again, for the whole duration of simulation we are able to maintain triangle at the equator region

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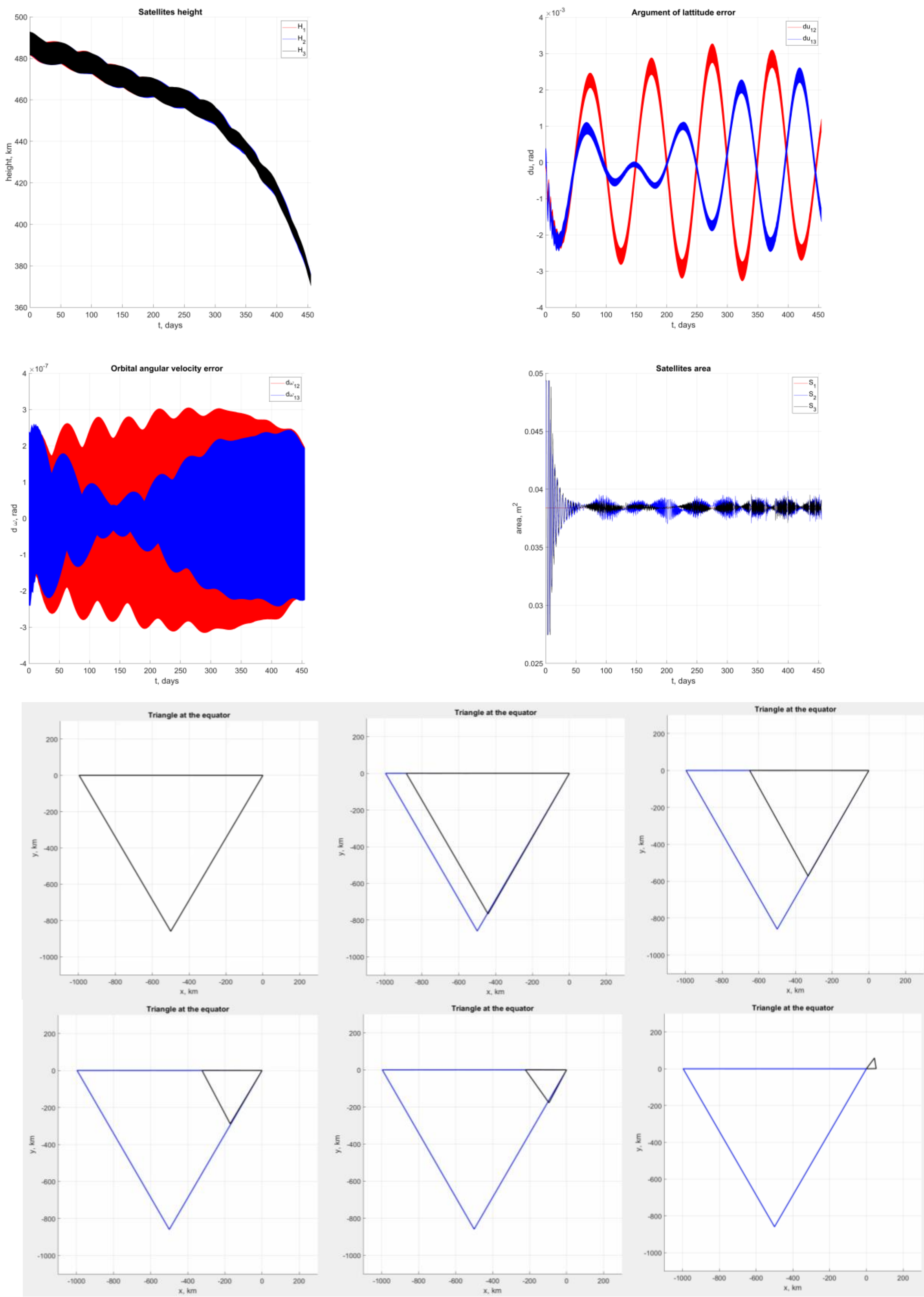

Fig. 4. High solar activity results

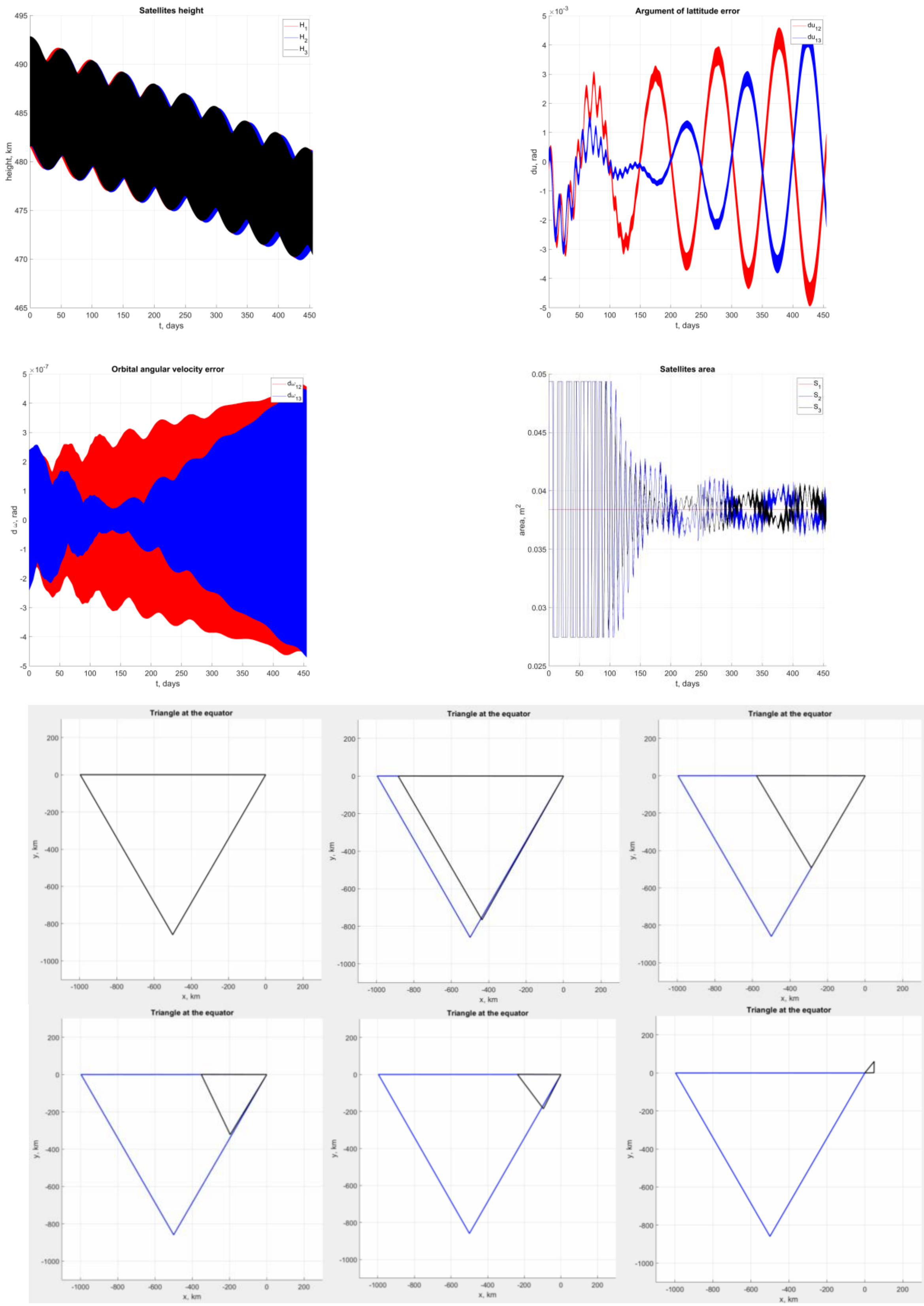

Fig 5. Low solar activity

5. Conclusion

Preliminary study shows that we are able to maintain the necessary triangle formation configuration for more than a year using only fuelless means of orbital control, such as natural dynamics and atmospheric drag. It should be noted that using the suggested approach we can assure change of triangle size during a year. However, we cannot stop its changing: difference in inclination, which causes this change, cannot be compensated using atmospheric drag.

We did not take into account the satellites attitude motion. In future work we are going to consider magnetic attitude control and verify, would it be sufficient to provide the necessary attitude pointing accuracy and cross-section area change, or it would be necessary to install reaction wheels.

6. Acknowledgements

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