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Invited Paper

Deploying a single-launch nanosatellite constellation to several orbital planes using drag maneuvers

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ABSTRACT

This paper proposes a method for deploying a nanosatellite constellation to several orbital planes from a single launch vehicle. The method is based on commercially available deorbit devices that are used to lower the initial orbit, and that are discarded after the correct altitude has been reached. Nodal precession of the right ascension of the ascending node at different altitudes results in spreading the orbital planes of the satellites. Maneuvering all satellites to a similar final altitude freezes the relative separation of the orbital planes. Calculations and simulations of the method are presented, and the results indicate that with a launch of 6 satellites to an initial 800 km sun-synchronous orbit, orbital plane separation of approximately 30° between each satellite can be achieved within 5 years, with each satellite in its own final 600 km orbital plane. Such a constellation could provide continuous global coverage, while requiring only one launch vehicle. Due to the timescales required by the method, it is best suited for nanosatellite missions designed for long lifetimes. Possible applications of such constellations are also discussed.

1. Introduction

Constellation applications are currently one of the focus points of CubeSat and nanosatellite research. Constellations of small satellites can achieve global coverage of the Earth with high spatial and temporal resolution. Additionally, system robustness is increased as small, low-cost satellites can be made redundant, reducing the performance degradation in case of a single satellite failure [1,2]. Potential constellation applications include scientific and commercial Earth observation, disaster monitoring, telecommunications, navigation, and AIS [3] and ADS-B [4] monitoring.

Small satellites are cost-efficient to develop and launch. Launch costs often constitute a major part of the budget of any CubeSat mission, and often they are the single biggest expense. Developing a CubeSat constellation with several different orbital planes is currently either very expensive, if each satellite is launched on a dedicated launch vehicle, or unpredictable, if each orbit would need to be achieved by waiting for suitable piggy-back launch opportunities [5]. Research has focused on differential drag maneuvers that can be used to modify the relative position of satellites on the same orbital plane, achieving a constellation that shares the same orbital plane [6]. However, true global coverage with high temporal resolution cannot be achieved within only one orbital plane.

In this paper, a method is presented for deploying a nanosatellite constellation launched on a single launch vehicle to several different orbital planes. The method uses commercially available deorbit devices that are used to place the satellites at different orbital altitudes, resulting in a cumulative separation of orbital planes over time.

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After the desired orbital plane separation has been reached, the satellite orbits are again adjusted to have the same orbital altitude, nearly freezing the orbital plane separation.

2. Background

2.1. Orbit perturbations

For modelling the satellite orbits in this paper, force models for the Earth's gravity, atmospheric drag, and lunisolar gravity are used. This approach is suggested in [7] for long-term low Earth orbit (LEO) satellite orbit simulations.

The most important perturbation for this paper is the precession of the right ascension of the ascending node (RAAN) due to the oblateness of the Earth. When taking only the J_2 gravitational term into account, an approximation for the nodal precession in radians per orbital period T can be expressed as

$$\frac{d\Omega}{dt} = -3\pi \frac{J_2 R_E^2}{p^2} \cos i \tag{1}$$

where

$$p = a(1-e^2). \tag{2}$$

For Keplerian orbits, the orbital period T is (in seconds)

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}. \tag{3}$$

Here a is the semi-major axis, R_E is the equatorial radius of the Earth, i is the inclination, e is the eccentricity, and μ is the Standard Gravitational Parameter for the Earth [8]. Values given in Table 1 are used in this paper.

In sun-synchronous orbits (SSO), this precession is utilized to cause the RAAN to change at the same rate as the Earth orbits the Sun. This results in continuously predictable lighting conditions, as the satellite always crosses the equator at the same local time. This is especially useful for remote sensing satellites. The specific value for nodal precession, which is required for sun-synchronous orbits, is usually achieved by combining suitable altitude and inclination with near-zero eccentricity. For example, for an 800 km SSO with zero eccentricity, the required inclination is approximately 98.57°. Many secondary payload opportunities for CubeSats target sun-synchronous orbits. The final orbit provided by a launch vehicle is decided based on the requirements for the main payload.

The second most important perturbation is due to atmospheric drag. Equation (4), the drag equation, can be used to estimate the drag force F_D encountered by a satellite traveling through Earth's atmosphere:

$$F_D = \tfrac{1}{2}\rho v^2 C_D A \tag{4}$$

Here ρ is the atmospheric density, v is the velocity relative to the atmosphere, C_D is the drag coefficient, and A is the cross-sectional surface area of the satellite. The drag coefficient can be difficult to estimate, but an approximate value $C_D \approx 2.5$ can often be used [8].

The satellite designer can affect the parameters C_D and A. Larger drag coefficient or larger surface area will result in greater drag force. The cross-sectional area of a 3U CubeSat without deployable surfaces can be up to around 0.03 m^2. However, the drag area can be greatly increased by using a deployable drag sail. While a CubeSat would normally remain at 800 km orbit for decades, a drag-based deorbit device can deorbit the satellite within a few years. However, atmospheric density and thus the available drag force at a given altitude is highly dependent on solar activity. Current and predicted solar activity is an important consideration for a mission based on the method presented in this paper.

Another perturbation worth consideration is the lunisolar gravitational perturbation caused by the presence of the Sun and the Moon. The main effect is changing the orbital inclination of the satellite over long periods of time [8].

Table 1
Values for constants used in this paper.

Parameter	Value
J_2	$1.081874*10^{-3}$
μ	$3.986004418*10^{14}$ m^3/s^2
R_E	6,378,137 m

2.2. Deorbit devices

As the amount of CubeSats in LEO has increased, more effort has been directed toward methods of removing future CubeSats from above approximately 640 km orbits that violate the 25-year rule for orbital life. Deorbit devices based on increasing the drag area of the satellite have become available on the market. AEOLDOS, a 3 m^2 drag area CubeSat deorbit device with 0.4U volume and 0.372 kg mass is described in [9]. The device is shown in Fig. 1. Other drag-based deorbit devices with similar performance are described in [10,11], and [12].

Such a deorbit device is deployable only once, and it will continue to decelerate the satellite until it re-enters the atmosphere. However, the concept in this paper assumes that the deployed deorbit device can be discarded by ejection after a desired orbital altitude – for example 600 km – has been reached. Discarding the deorbit device returns the drag area of the satellite to a value close to what it was before deploying the deorbit device. The orbit of the deorbit device itself will continue to decay rapidly, while at 600 km the orbital lifetime of the nanosatellite itself can still be close to at least a decade.

Another required system for the proposed nanosatellite is an active magnetic attitude control system with enough torque-generation capability to counter disturbance torques caused by air drag in order to maintain a stable attitude after the drag sail has been deployed. However, such active magnetic attitude control systems are already very common in CubeSats.