Acta Astronautica 114 (2015) 65–78

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Launch and deployment of distributed small satellite systems ☆

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ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form
14 April 2015
Accepted 18 April 2015
Available online 29 April 2015

Keywords:
Small satellites
Constellation deployment
Nanosatellite
CubeSat
Nodal precession
Earth–Moon Lagrange point L_1

ABSTRACT

The rise in launch and use of small satellites in the past decade, a result of improved functionality through technology miniaturisation and alternative design philosophies, has spawned interest in the development of distributed systems or constellations of small satellites. However, whilst a variety of missions based on constellations of small satellites have been proposed, issues relating to the launch and deployment of these distributed systems mean that few have actually been realised. A number of strategies have been proposed which enable multiple small satellites comprising a constellation to be launched together and efficiently separated on-orbit, thus reducing the total cost of launch. In this paper, two such strategies which have the potential to significantly increase the viability of small satellite constellations in Earth orbit are investigated. Deployment using natural Earth perturbations to indirectly achieve plane separations is analysed using a developed method and compared to deployment utilising the Earth–Moon Lagrange point L_1 as a staging area prior to return to LEO. The analysis of three example missions indicates that these two strategies can facilitate the successful establishment of small satellite constellations in Earth orbit whilst also reducing propulsive requirements, system complexity, and/or cost. The study also found that the method of nodal precession is sensitive to the effects of orbital decay due to drag and can result in long deployment times, and the use of Lunar L_1 is more suitable for constellation configurations where several satellites are present in each orbital plane.

1. Introduction

A growing interest in the use of distributed systems or constellations of small satellites has been generated following the rise in popularity of small satellites, especially in the past decade. This growth in the use of small satellites has been primarily driven by the miniaturisation of electronics and sensors [1] and the availability of commercial-off-the-shelf components with increasing capability, significantly reducing the cost of hardware development. The access-to-orbit and economy of these spacecraft is also improved through availability of secondary payload launch opportunities [2,3], especially for small satellites which conform to standardised form factors such as CubeSat [4].

In recent years, the launch of successful small satellite missions, particularly nanosatellites, with valuable engineering/technology demonstration (e.g. CanX-6/NTS [5], STRaND-1 [6]), scientific (e.g. O/OREOS [7], GeneSat-1 [8]), military (e.g. SMDC-One [9], SENSE-1), and commercial

☆ This paper was presented during the 65th International Astronautical Congress in Toronto.

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http://dx.doi.org/10.1016/j.actaastro.2015.04.015
0094-5765/

(e.g. WNISAT-1 [10]) capabilities has now demonstrated the utility of this class of spacecraft in independent operation.

The use of small satellites in constellations has also been successfully demonstrated by a number of microsatellite-class missions, including the Disaster Monitoring Constellation (DMC) and RapidEye Earth observation missions and the ORBCOMM [11] satellite communications system.

The demonstration of small platform capability and constellation operation has recently resulted in the generation of larger multi-plane constellations of smaller satellites. Two such examples of this new generation of small satellite constellation are the Planet Labs [12] (Flock-1a: 28 satellites, Flock-1c: 11 satellites) and Skybox Imaging (24 satellites) Earth observation constellations which are currently in the process of being launched.

A further value proposition of small satellite constellations, resulting from their lower cost of platform development, is the ability to be launched in larger numbers and perform many simultaneous and distributed measurements or observations. A key feature of multi-plane systems of these satellites is increased temporal resolution of collected data (i.e. shorter revisit times) over single-plane or *string-of-pearls* configurations. Furthermore, the presence of multiple satellites in each orbital plane can facilitate a more graceful degradation of system performance on the occasion of individual satellite failures [13].

A variety of novel missions benefiting from these capabilities have been proposed in the fields of meteorology [14]; climate-science [14,15]; disaster warning and detection [16–18]; atmospheric, magnetospheric, and ionospheric measurement/observation [14–17,19,20]; and gravity and other Earth sciences [15]. Multi-satellite interplanetary exploration missions and constellations in orbit about other central bodies utilising small satellites are also being considered [16,17,21].

However, the current launch paradigm of secondary payload manifesting of small satellites limits the ability of these constellations to be successfully deployed into orbit. In particular, the lack of control on launch schedule and destination orbit prohibits the use of multiple secondary launch opportunities by constellations which require accurately coordinated orbits and multi-plane configurations. This issue is further compounded by technology, mass, and volume constraints on propulsion system capability to maintain low development and manufacturing costs and comply with launch vehicle regulations. These constraints can be particularly restrictive for the smaller nanosatellite and picosatellite class platforms which are therefore typically limited in their ability to individually manoeuvre into their mission orbits [1,4,22].

In order to enable the cost-effective realisation of small satellite constellations a number of deployment strategies have been proposed which allow the launch of a complete multi-plane constellation on a single vehicle with satellite distribution occurring on-orbit. Currently, the FORMOSAT-3/COSMIC mission is the only example of a multi-plane small satellite constellation to be deployed from a single launch vehicle.

This paper investigates two deployment methods for constellations with multi-plane configurations and the ability of these methods to facilitate the establishment of these systems in low Earth orbit (LEO). Through the use of a developed methodology, described in detail in Section 4, the relative effectiveness of deployment using natural Earth perturbations and the Earth–Moon Lagrange point L_1 are considered for different constellation missions.

2. Launch of small satellites

The absence of sufficiently small or inexpensive launch vehicles for the delivery of small satellites to orbit presents a significant barrier to the development of small satellite missions given their typically smaller budgets and development time-scales. This issue of access-to-orbit is somewhat addressed by secondary payload launch opportunities, where satellite operators can either share launch vehicle capacity through clustering or rideshare agreements, or utilise excess capacity on a commissioned launch of a larger satellite, a practise termed piggybacking. Unless arranged through a launch programme (e.g. NASA CubeSat Launch Initiative and Educational Launch of Nanosatellites) with provided or subsidised launch, the cost of secondary payload opportunities is generally greater than the specific cost ($/kg) of the launch vehicle itself [23]. However, these opportunities still allow small payloads to achieve access-to-orbit at a significantly lower total expense than an independently commissioned launch.

The use of secondary payload opportunities is limited by the lack of control on the launch schedule and destination orbit of the vehicle, both controlled by the requirements of the primary payload or determined by a compromise between the payload operators in a rideshare launch. As a result, satellites launched as secondary payloads need to be flexible with regard to the orbit in which their mission can be performed. For some missions, this flexibility may not be feasible or may be too costly to embed in the system design.

Further restrictions on the launch of small satellites utilising secondary payload opportunities can include the requirement to be compatible with a certain class of deployment mechanism (e.g. P-POD, X-POD, ISIPOD), reducing the level of certification required by the secondary payloads by isolating them from the launch vehicle and primary payload [4]. This can further constrain the mass and volume of the satellite and any provision for deployable surfaces such as solar arrays or wireless communication antennae. Constraints on volumes and pressures of stored propellant, nominally to protect the primary payload, can also limit the capability of on-board propulsion systems, further restricting the ability of the secondary payloads to manoeuvre into more suitable or favourable mission orbits.

A number of new launch vehicles aiming to address the microsatellite and nanosatellite launch capability gap are currently in varying stages of development. The payload capability of these vehicles ranges from 12 to 300 kg with specific launch costs in the range of current secondary payload opportunities. Notable examples include the Virgin Galactic LauncherOne which will be air-launched from the WhiteKnightTwo carrier aircraft and will have a capacity on the order of 225 kg to LEO [24], a 10 kg payload launcher deployed from the XCOR Aerospace Lynx Mk.III suborbital