Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 54 (2014) 1838–1857

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Zero, minimum and maximum relative radial acceleration for planar formation flight dynamics near triangular libration points in the Earth–Moon system ☆

F.J.T. Salazar [a,*], J.J. Masdemont [b], G. Gómez [c], E.E. Macau [d], O.C. Winter [a]

[a] UNESP-Grupo de Dinâmica Orbital e Planetologia, Guaratinguetá, SP 12516-410, Brazil
[b] Departament de Matemàtica Aplicada I, ETSEIB-UPC, Avda. Diagonal 647, 08028 Barcelona, Spain
[c] Departament de Matemàtica Aplicada i Anàlisi, UB, Gran Vía 585, 08007 Barcelona, Spain
[d] Instituto Nacional de Pesquisas Espaciais, Av. dos Astronautas 1758, São José dos Campos, SP 12227-010, Brazil

Received 6 April 2014; received in revised form 17 July 2014; accepted 20 July 2014
Available online 26 July 2014

Abstract

Assume a constellation of satellites is flying near a given nominal trajectory around L_4 or L_5 in the Earth–Moon system in such a way that there is some freedom in the selection of the geometry of the constellation. We are interested in avoiding large variations of the mutual distances between spacecraft. In this case, the existence of regions of zero and minimum relative radial acceleration with respect to the nominal trajectory will prevent from the expansion or contraction of the constellation. In the other case, the existence of regions of maximum relative radial acceleration with respect to the nominal trajectory will produce a larger expansion and contraction of the constellation. The goal of this paper is to study these regions in the scenario of the Circular Restricted Three Body Problem by means of a linearization of the equations of motion relative to the periodic orbits around L_4 or L_5. This study corresponds to a preliminar planar formation flight dynamics about triangular libration points in the Earth–Moon system. Additionally, the cost estimate to maintain the constellation in the regions of zero and minimum relative radial acceleration or keeping a rigid configuration is computed with the use of the residual acceleration concept. At the end, the results are compared with the dynamical behavior of the deviation of the constellation from a periodic orbit.

Keywords: Formation flight of satellites; Zero Relative Radial Acceleration; Earth–Moon system; Circular Restricted Three Body Problem; Stable Lagrangian points; Residual acceleration

1. Introduction

The concept of Satellite Formation Flying (SFF) means to have two or more satellites in orbit such that their relative positions remain constant or obeying a certain dynamical configuration along the trajectory (Sholomitsky et al., 1977; Battrick, 2000; Bristow et al., 2000; Burns et al., 2000; Ticker and Azzolini, 2000; Fridlund and Capaccioni, 2002). This concept involves the control over the coordinated motion of a group of satellites, with the goal of maintaining a specific geometric space configuration between the elements of the cluster (Sabol et al., 2001). It allows that a group of low cost small satellites, arranged in a space formation flying, operate like a large 'virtual satellite'. This formation will have many benefits over single satellites, including simpler designs, faster build

☆ This template can be used for all publications in Advances in Space Research.

* Corresponding author. Tel.: +55 12 981015572.
E-mail addresses: e7940@hotmail.com (F.J.T. Salazar), josep@barquins.upc.edu (J.J. Masdemont), gerard@maia.ub.es (G. Gómez), elbert.macau@inpe.br (E.E. Macau), ocwinter@gmail.com (O.C. Winter).

http://dx.doi.org/10.1016/j.asr.2014.07.018
0273-1177/

times, cheaper and unprecedented high resolution (Kapila et al., 2000). Over the past decade, numerous formation flying missions have been conceived. The Laser Interferometer Space Antenna (LISA) is a proposed mission, whose objective is to observe astrophysical and cosmological sources of gravitational waves of low frequencies, goal that could be possible using three identical spacecraft flying in a triangular constellation, with equal arms of 5 million kilometers each (Peterseim et al., 2000). Another example is the PRISMA formation flying and rendezvous technology mission, launched successfully on June 25, 2010, into a Sun synchronous orbit at approximately 750 km altitude (Persson et al., 2006; Gill et al., 2007; Hellman et al., 2009; Persson et al., 2010). PRISMA mission consists of two spacecraft: Mango and Tango, with a total mass of about 200 kg, and its primary purpose is to demonstrate formation flying and rendezvous technology, not only in terms of Guidance, Navigation and Control software and algorithms, but also in terms of instruments and operational aspects (e.g., small rocket engines and Micro Electro Mechanical Systems). Another interesting formation flying mission is the New Worlds Observer (NWO) (Cash et al., 2009). NWO consists of a large telescope and an occulter spacecraft in tandem at about 50,000 km apart. The two spacecraft would be flying at the Earth–Sun L_2 Lagrangian point or in a drift-away solar orbit. Its purpose is to discover and analyze terrestrial extra-solar planets. The NWO planned launch date is about 2018.

A configuration of SFF can typically be positioned and maintained in two dynamically distinct scenarios: in a planetary orbit or in outer space (Alfriend et al., 2002). In the planetary orbit scenario the fundamental model is the problem involving two light bodies (satellites), close to each other, that could be in the same orbit or describe orbits of slightly different radii, eccentricities and inclinations around a massive central body, e.g. the Earth. Because the gravitational attraction between the two satellites is negligible, this scenario can be considered like a superposition of two problems of two bodies (Sengupta and Vadali, 2007), where the atmospheric drag and higher-order gravity terms (e.g., J_2) can be considered in the dynamic models of the formation (Carter and Humi, 2002; Humi and Carter, 2006; Sengupta et al., 2007) and, therefore, improving the fidelity of the model. An example of this kind of formation is the pair of satellites Landsat 7 with EO-1, mission designed to enable the development of future Earth imaging observatories that will have a significant increase in performance while reducing cost and mass (Flick, 2012).

In the outer space scenario, involving SFF in the vicinity of a libration point, the fundamental model to study the natural motion of spacecraft relative to each other is the Circular Restricted Three Body Problem (CRTBP) (Hsiao and Scheeres, 2002). The interest of astronomical missions has been to position SFF around the Lagrangian points L_1 and L_2 (Faquhar, 1968; Henon, 1973; Breakwell and Brown, 1979; Howell, 1984; Gómez et al., 2000) or L_4 and L_5. Of particular interest is the stability of the five Lagrangian points. In the case of the three collinear stationary points: L_1, L_2 and L_3, they are always unstable. Whereas the stability of L_4 and L_5 points depends on the mass ratio between the two larger bodies (Danby, 1962; Szebehely, 1967). In important cases like Earth–Moon or Sun–Earth, these points are linearly stable. Moreover, there exists a family of periodic orbits around L_4 and L_5. This stability property makes the fuel required for a spacecraft to maintain its relative position there to be almost zero. Despite this advantage, today there are no missions orbiting L_4 or L_5 points for any celestial pair of primaries. In the case of Earth–Moon system, L_4 and L_5 points could be excellent locations to place space telescopes for astronomical observations or a space station (Schutz et al., 1977). In addition, there is a renewed interest of major space agencies for Lagrangian point colonization. Furthermore, Defilippi (1977) has made a review of the ideas of O'Neill (1974) about building space colonies at the L_4 and L_5 positions. These space stations could be used as a way-point for traveling to and from the region between Earth's atmosphere and the Moon (cis-lunar space).

For the reason that keeping a formation from drifting apart and achieving mission requirements is expected to require significantly more fuel than station keeping a single spacecraft, one of the problems of positioning satellites in formation flying is the cost to maintain them continuously orbiting each other. In particular, missions in the vicinity of the Lagrangian points, considering the scenario of the CRTBP, may be placed in families of halo orbits. All these orbits are inherently unstable (Gómez et al., 1993) and drive the SFF out of its desired configuration. Thereby, a less difficult option is to place the Satellite Formation Flying in the vicinity of Earth–Moon L_4 and L_5 Lagrangian points. Because of their stability properties, less fuel would be spent to keep the formation in its proper configuration.

Previous studies like those by Catlin and McLaughlin (2007) and Wong (2009) on SFF about L_4 in the Earth–Moon system have been analyzed. The motion of formation flying near triangular libration points was studied adopting the CRTBP model and the linearized equations at the equilibrium points. Catlin and McLaughlin (2007) show that formations are possible at the Triangular points on uncontrolled trajectories due to the stability of stationary solutions. On the other hand, Wong (2009) establishes the need for a system control and develops strategies for controlling a spacecraft formation system at the L_4. In the CRTBP scenario, these studies show that velocity change requirements demanded by the control methods would be very small. Thus, Catlin and McLaughlin (2007) and Wong (2009) conclude that nonlinear aspects as well as perturbations forces (e.g. solar gravity, solar radiation pressure) are necessary to provide a more real-world accurate descriptions of motion and control of formation flying around equilateral equilibrium points in the Earth–Moon system.

In this work, we do not adopt the linear model about L_4, we investigate the relative dynamical behavior of satellites with respect to periodic orbits around L_4 and L_5 in the