Design and Validation of Ultra Low Thrust Transfers to the Sun-Earth Saddle Point with Application to LISA Pathfinder Mission Extension[§]

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Keywords: Restricted four-body problem, Lagrange point dynamics, low-thrust propulsion, saddle point

Flying in highly nonlinear gravitational fields is becoming more and more appealing due to the unique features that can be achieved in these models (i.e., Lagrange point orbits, ballistic capture, low-energy transfers). These orbits require less Δv than the equivalent high-energy orbits, which is achieved by a wise exploitation of the high sensitivity in initial conditions. This makes it possible for spacecraft characterized by very limited thrust authority to accomplish such transfers. More recently, attention has been paid to the exploration of the Saddle Points (SP) within the Solar System [1]. These are locations where the net gravitational accelerations balance. Regions about the SP present clean, close-to-zero background acceleration environments where possible deviations from the General Relativity can be tested and quantified. In particular, evidence is mounting that the MOND/TeVeS theory can be valid for accelerations below 10^{-10} m/s^2 [2]. Among the SP in the Solar System, the Sun-Earth one seems particularly appealing due to its relatively easy accessibility: it is located at a distance of approximately 258,800 km from the Earth, along the Sun-Earth line, between the Sun and the Earth. Although they seem to be remarkable locations in the Solar System, SP are still unexplored. Their location and the non-equilibrium nature suggest that flying by the SP can be done by using highly nonlinear, under-actuated orbits as opportunistic mission extension of spacecraft already about the Lagrange points. The orbits of interest being highly sensitive and having limited control authority, questions raise about their applicability in real scenarios. For this reason, a validation analysis is mandatory to assess the feasibility of flying such orbits with a special focus on their navigability.

In this paper we present methods and concepts to design and validate the orbits that experience one or multiple passage through the SP. A parametric analysis is first performed to consider spacecraft initially on a number of Lagrange point orbits having different out-of-plane amplitudes. Orbits are first designed in a co-planar, circular restricted four-body problem having the Sun, the Earth, and the Moon as primaries. Preliminary solutions are then later refined in a full-ephemeris, three-dimensional restricted n-body model stated in a roto-pulsating frame, whose dynamics considers also non-gravitational forces. Both impulsive and finite-burn maneuvers are considered. The focus is on solutions with very low Δv budget (1-10 m/s), ultra low thrust (0.1-10 mN), and low/medium resources spacecraft (200-2000 kg). The validation analysis considers instead geometrical constraints (ground station visibility, occultation, conjunction, etc.) as well as sensitivity of the orbit with respect to the maneuvers execution (variations in the thrust magnitude, pointing angle, delay, interrupted burn, etc.). Moreover, a navigation tool has been developed to infer the flyability of the orbits. This carries out the orbit determination process from range and range rate simulated measurements and considers the presence of noises in both the maneuver execution and orbit propagation. The mission extension of LISA Pathfinder is considered as case study. LISA Pathfinder embarks a payload with two free-falling masses whose position is measured through laser interferometry with picometer resolution, which is ideal to experiment the MOND/TeVeS theory. In this case the available estimation for the end-of-operation state is taken as initial condition, and the cold gas propulsion available on the LISA Pathfinder Science Module is considered as primary propulsion. Several mission extension options are designed and validated into a high-fidelity model, and their implementation is discussed.

References

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[§] The work presented in this abstract has been performed within the ESA study ITT 8601 "Feasibility of Ultra Low Thrust Transfers in L1, L2, Sun, Earth & Moon Systems", ESA contract No. 4000118201/16/F/MOS.