Feasibility of ultra low thrust transfers in L_1/L_2 Sun–Earth–Moon systems

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Executive Summary

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1 Motivations

The number of spacecraft flying in highly nonlinear gravitational fields is largely increased during the last few decades, and probes orbiting in Lissajous or Halo orbits can be found around both the Lagrangian Points L_1 and L_2 of the Sun-Earth&Moon system.

Recently, another point in space has become more and more appealing, i.e. the Sun-Earth Saddle Point (SP). The increasing interest towards the exploration of this particular region within the Solar System is due to the fact that it represents a suitable location to measure possible deviations from the General Relativity and find scientific evidence for the correctness of other theories, such as the MOND/TeVeS.

The particular location as well as its non-equilibrium nature suggest that SP can be more easily reached by using highly nonlinear orbits, as opportunistic mission extension of spacecraft already about the Lagrangian points. Nonetheless, this introduces some concerns about the applicability in a real scenario, due to the high sensitivity and the limited control authority of these missions. For this reason, a validation analysis is mandatory to assess the feasibility of flying such orbits with a special focus on their navigability.

2 Objectives

The main objectives pursued in this study are:

1. the establishment of techniques and tools to design transfers in highly nonlinear vector fields, having very limited control authority (i.e. ultra low thrust propulsion), and flying through the SP;
2. the development of methods and tools to assess the feasibility of flying such highly nonlinear, limited-control orbits by using real life technologies for both ground and space segment.
3. the application of developed tools to the Lisa Pathfinder mission and the definition of strategies to reach the SP once the primary mission is complete.

To achieve the above mentioned objectives, the following activities have been performed:

- Consolidation of assumptions to be used for the study;
- Development of techniques and tools to identify/find transfers;
- Development of techniques and tools to assess the feasibility of flying the transfers;
- Modeling of real-life capabilities and characteristics of ESA ground and space systems;
- Use the tools to assess the feasibility of the Lisa Pathfinder L1 to SP transfer;
- Generatation of top level requirements on ground and space systems;
- Identification of potential applications for current and future mission concepts.

3 Main Results

3.1 Design tool

The implemented trajectory design tool consists of 4 phases:

1. the exploration phase, where feasible initial solutions are sought by means of a global grid search. Starting from the unstable manifold of L1 and L2 halo orbits, ballistic approaches to the SP are classified. The direct numerical simulation parameters are a) the halo orbit amplitude, b) the S/C initial phase along the halo, and c) the initial epoch. The search provides sufficient degrees of freedom to achieve numerous ballistic SP close passages (with a grid of 96,000 points, roughly 1% of the trajectories came to within 10,000 km of the SP).
2. the optimization phase, the core of the transfer design, where a direct transcription of the dynamics, coupled with a multiple shooting method, is used to tune a series of impulsive maneuvers to precisely target the SP.
3. the finite burn phase, required to translate the optimal impulsive maneuvers into a series of finite thrust arcs, compatible with the engine ultra-low control capabilities.
4. the refinement phase, to tune the thrusting direction of the output solutions in an Earth-centered inertial frame.

3.2 Navigation tool

The navigation tool, specifically designed to deal with these kind of solutions and aimed at assessing the flyability of designed transfers, consists of two main modules:

1. a first module aimed at the preliminary exploration of the computed solutions, the initial pruning of those not compliant with relevant geometric and/or sensitivity constraints, as well as at the computation of visibility windows;
2. a second module, mainly devoted to the simulation of the radiometric data acquisition process, the computation, through a covariance analysis, of the achievable position and velocity knowledge, and finally to the estimation of the required correction maneuvers.

3.3 Application to Lisa Pathfinder

Simulations performed for Lisa Pathfinder confirm that trajectories reaching the SP with a miss distance smaller than 50 km and total time of flight smaller than 1 year can be easily found, without the need for a Moon's gravity assist and requiring less than 1 m/s. Interestingly all the solutions are similar and belong to the same family, due to the relatively high amplitude Lissajous orbit of Lisa PathFinder.

For this kind of trajectories, coverage windows larger than 6 hours are available each day, even by using a single ground station. Covariance analyses show that the achievable level of knowledge accuracy is typically limited by the presence of process and measurements noises. Further enhancements can be achieved by varying the orbit determination frequency, whereas the introduction of additional ground stations leads to limited improvements, which do not justify the increase in operational costs.

Monte Carlo analyses have also been conducted to estimate the size of ΔV_{nav} required to navigate the nominal trajectory. The main outcome is that the feasibility of this kind of transfers might be seriously affected by the amount of ΔV_{nav}, for which very large values can be found, compared with the nominal ΔV (in some cases even an order of magnitude larger).

Finally, some parametric analyses have been carried out to evaluate the effects of the correction maneuver frequency and the object initial distribution on the size of ΔV_{nav}, revealing conditions for which the transfer of Lisa Pathfinder from L1 to SP can be achieved.

4 Conclusions

The major outcomes of the present study are shortly described here:

- A Matlab-based software, ULTIMAT, including tools and methods for the design and the assessment of ultra low-thrust transfers in the Sun–Earth&Moon environment has been developed;
- Transfer to SP are more easily achieved from L1 and from small amplitude Halo orbits;
- Moon perturbation matters, but multiple lunar gravity assists are not beneficial;
- Coupling exist between:
  - SP and Moon motion (depends on L1/L2);
  - departure epoch and phase on Halo;
- Several transfer trajectories from L1 to the SP were found for LPF, all belonging to the same family and therefore very similar in their shape and characteristics;
- Detailed navigation analyses have shown that some limitations exist due to the level of ΔV_{nav} required to keep the spacecraft on the nominal path. In particular, it was found that the sizes of correction maneuvers are highly influenced by:
  - the guidance frequency;
  - the initial dispersion of the spacecraft state;
- Lisa Pathfinder transfer to the SP can be flied using one control maneuver per week, if the initial dispersion is reduced to a value below < 10 km on each position component and < 0.1 m/s on each velocity component.
- For larger initial dispersion values, the size of correction manuevers drastically increases, with a consequent need to reduce the guidance frequency to ensure their proper implementation with the on-board thrusters.

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