

Gravitational Science with LISA Pathfinder

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Abstract. We investigate the potential of conducting interesting gravitational science experiments with LISA Pathfinder, by executing well defined de-orbiting manoeuvres following the nominal mission. Preliminary work suggests that the residual control authority of the micropropulsion system is sufficient to follow trajectories that cross the region surrounding the Sun-Earth saddle point, and also include one or multiple Earth flybys. Crossing the saddle point region may allow tests of Modified Newtonian Dynamics (MOND), while the flybys may potentially shed some light on the so-called flyby anomaly. We present some sample trajectories and discuss the limitations of the current model. Finally, we discuss the work required to take these ideas from the proof of principle presented here, to a concrete proposal for an extended mission.

1. Introduction

The LISA Pathfinder (LPF) spacecraft, currently being built as a technology demonstrator for the future gravitational wave observatory LISA, has the potential to be in itself a very valuable tool to conduct gravitational experiments in the Solar System.

Some of the main properties of relevance for the discussions that follow are:

- DC free-fall quality of $\approx 10^{-9} \text{ms}^{-2}$ (limited by spacecraft self-gravity)
- Free-fall quality of $\approx 10^{-13} \text{ms}^{-2}/\sqrt{\text{Hz}}$ around 1mHz
- Gravity gradiometer sensitivity $\approx 10^{-14} \text{s}^{-2}/\sqrt{\text{Hz}}$ around 1mHz

A comprehensive discussion of what LPF has to offer as a laboratory for gravitational experiments is provided in [1]. In that reference, several possible gravitational experiments, including tests of Modified Newtonian Dynamics (MOND), are mentioned. It has been pointed out recently that MOND could be tested around gravitational saddle points within the Solar System [2]. Nominally, LPF will be placed in a Lissajous orbit around L1, and possible effects due to a theory such as MOND at that location are estimated to be very small [2].

Here, we look at the potential to execute de-orbiting manoeuvres from the nominal LPF orbit around L1, such that the spacecraft is sent back closer to Earth. The possible trajectories that the spacecraft would then follow include some that cross the region around the Sun-Earth saddle point, and all of them include a single or multiple Earth flybys.

Trajectories crossing the region around the saddle point could be used to test MOND, while the Earth flybys could potentially be used to shed some light on the so-called flyby anomaly [3].

2. Targets for LISA Pathfinder Trajectories

2.1. Modified Newtonian Dynamics

For the Sun-Earth system, and ignoring all other gravitational perturbations, the saddle point is located around 2.59×10^8 m from Earth, along the Earth-Sun line. According to [2], anomalous gravitational gradients in excess of 10^{-13} s^{-2} will be experienced within a MOND “bubble” of semi-major axis 766 km (perpendicular to the Earth-Sun line), and semi-minor axis 383 km (along the Earth-Sun line). Such gradients, if applied at appropriate frequencies, are certainly within LPF’s sensitivity.

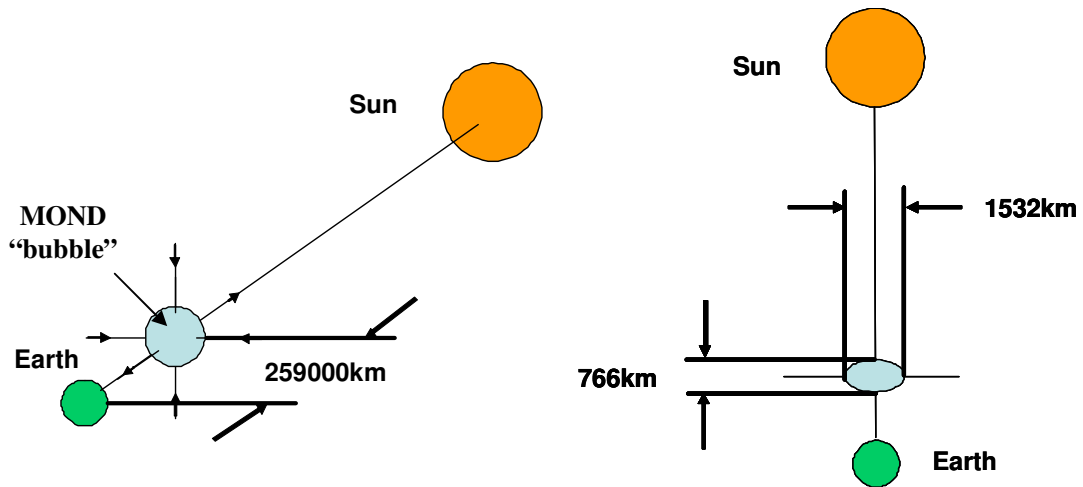


Figure 1 Schematic location and size of LPF target region (MOND “bubble”) for MOND tests. Relative dimensions are not to scale.

In practice, other Solar System bodies modify both the location and the size of this unperturbed MOND bubble. The dominant effect, due to the Moon, can be estimated as follows: The background terrestrial gradients are of the order of $4 \times 10^{-11} \text{ s}^{-2}$. During a solar eclipse, the Moon would get to within approximately 1.2×10^8 m of the unperturbed saddle point. The gravitational acceleration due to the Moon at that point would then be of the order of $3.4 \times 10^{-4} \text{ ms}^{-2}$, and the true gravitational saddle point (now of the Earth – Moon – Sun system) would shift by approximately $3.4 \times 10^{-4} / 4 \times 10^{-11} \approx 8.5 \times 10^6$ m, or 8500 km, towards the Earth. This is clearly a significant effect.

The effect on the bubble size can be estimated from the lunar gravity gradients, which for the example above are of the order of $6 \times 10^{-12} \text{ s}^{-2}$. This amounts to about 15% of the Earth gradient, and this is also the magnitude of the bubble dimension reduction that can be expected.

For Jupiter, the equivalent saddle point position shift is of the order of 10 km, and the impact on the bubble size is completely negligible.

For the proof of principle sought in this very preliminary work, the shift of the target region as a function of Moon position has not been considered.

2.2. Flyby Anomaly

The so-called “Flyby Anomaly” has now been observed in six Earth flybys, and manifests itself in an apparent change in orbital energy of the satellites before and after close Earth flybys [3]. These satellites were on unbound orbits, with v_∞ ranging between 4 km/s and 16 km/s. The altitudes at closest approach varied from 300 km to 2500 km.

The anomalous energy change, expressed as a change in v_∞ before and after the encounter, is present in both Doppler tracking and ranging data, and is a large effect with signal-to-noise-ratios of up to 10^3 . An empirical expression has been derived for this change as a function of incoming and outgoing geocentric latitudes. To date, there is no known explanation for this effect.

Any de-orbiting manoeuvres as will be described below will inevitably result in LPF executing a single or multiple Earth flybys. Careful tracking of the spacecraft might help to shed some light on the flyby anomaly, or at least could provide some complementary data.

LPF Earth flybys would be characterised by the following properties:

- Flybys would not have $v_\infty > 0$, but $v_\infty \leq 0$ (weakly bound orbits)
- For low altitude, “fast” flybys (1000s – 10000s), free-fall quality around single Test Mass could be significantly better than 10^{-9}ms^{-2} during that time
- Low ($\approx 1000\text{km}$) and high ($> 10000\text{km}$) altitude flybys could be compared
- Geocentric latitudes could be chosen to maximise the effect

In this preliminary work, the main emphasis has been placed on crossing the MOND bubble, and Earth flybys are effectively a “spin-off”.

3. Assumptions regarding LISA Pathfinder

3.1. Modifications to nominal LPF Hardware

None. Although modifications to the micropropulsion system might in principle be of advantage, LPF is deep into its implementation phase and it is much too late to consider any changes now.

3.2. Allowed interference with nominal LPF Mission

None. Again, the primary goal of LPF is to demonstrate the technology for LISA, and it will be assumed that no interference with the nominal mission is allowed. Any extended scientific operations proposed as a result of this work will have to be carried out in an extended phase, once the nominal mission is completed.

3.3. LPF Micropropulsion dV budgets

Simple estimates of the remaining total dV authority at the end of the nominal LPF mission have been carried out. For the FEEP system, total dVs between 6m/s and around 15m/s have been derived. However, it is noted that the FEEP micropropulsion system development is not yet completed.

For the purposes of this preliminary work, a conservative assumption of a total dV budget of 1m/s has been made. The DRS thrusters should also be capable of providing some additional dV, but no assumptions have been made about this.

It is also important to note that trajectory correction manoeuvres for LPF may be limited by factors other than total control authority, and that therefore this assumption is not as restrictive as it may, at first, seem.

4. Targeting the Earth-Sun saddle point from the LISA Pathfinder Lissajous orbit

4.1. Principle

LISA-Pathfinder flies in a large amplitude Lissajous orbit (in fact close to Halo orbit dimensions). Like all such orbits, it is unstable if adversely perturbed from its ideal state. This instability can be exploited to enable the spacecraft to leave the orbit with only a small manoeuvre. A DeltaV applied in a critical direction of 28 deg from the Earth-Sun direction ensures that the spacecraft state reaches an ‘unstable manifold’. This means that over a period comparable with that of the Lissajous orbit, it will strongly diverge from its nominal motion. Possible motions include low energy escape trajectories and also trajectories returning to Earth with a low perigee. The problem to be solved is to find an appropriate manoeuvre after which it is possible to target the Earth-Sun gravitational equilibrium zone.

Following the discussions above, the size of the initial manoeuvre was limited to $\Delta V \leq 1\text{m/s}$. Furthermore, it was decided to propagate the trajectories for a maximum of two years from the initial manoeuvre. Within these constraints, some interesting solutions have been found.

4.2. Orbit Propagation Method

A standard multi-body gravity field numerical integrator was used for the orbit propagation. The software offers the opportunity to include a range of environmental models. Solar radiation pressure was not included in this preliminary work but can also be incorporated later.

It is important to stress that the primary goal of the work here was to show that a family of solutions exists to bringing LPF back to the saddle point following the nominal mission, given the constraints from the micropropulsion system. The existence of this family of solutions will not be affected by any future refinement of the orbit propagation, but the details of the optimum solution certainly will.

4.3. One Parameter Search

The first investigation concentrated on a varying a single parameter, namely the time of departure, while maintaining a constant ΔV magnitude (1m/s) and direction (28 deg from Earth-Sun direction). Some of the resulting trajectories are shown in **Figure 2**:

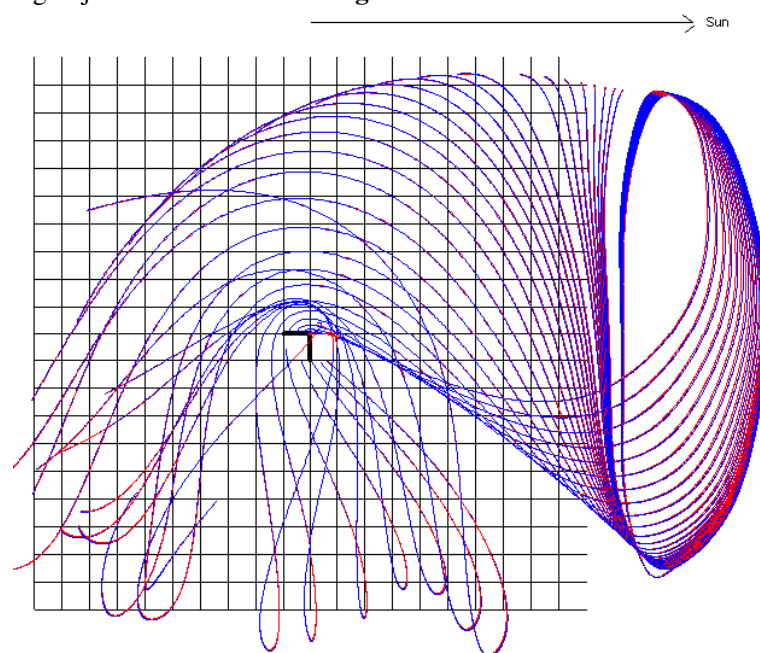


Figure 2 A range of orbits leaving the nominal Lissajous orbit, with a ΔV of 1 m/s. The time application for each trajectory is incremented in 5 day steps. The grid is in the ecliptic using an Earth-Sun rotating reference. Grid squares are 100000km

This initial search showed that the large out of ecliptic motion of the nominal orbit makes it difficult to target the saddle point on the first 'leg' of the trajectory, where the spacecraft starts its return towards Earth. However the subsequent motion after Earth perigee is weakly bound and offers numerous further possibilities to reach the required region.

4.4. Two Parameter Search

A two parameter search was also conducted. The control parameters employed are the time at which the DeltaV is applied and the size of the DeltaV.

The resulting miss distances, as a function of time of application relative to an arbitrary reference, are shown in **Figure 3**:

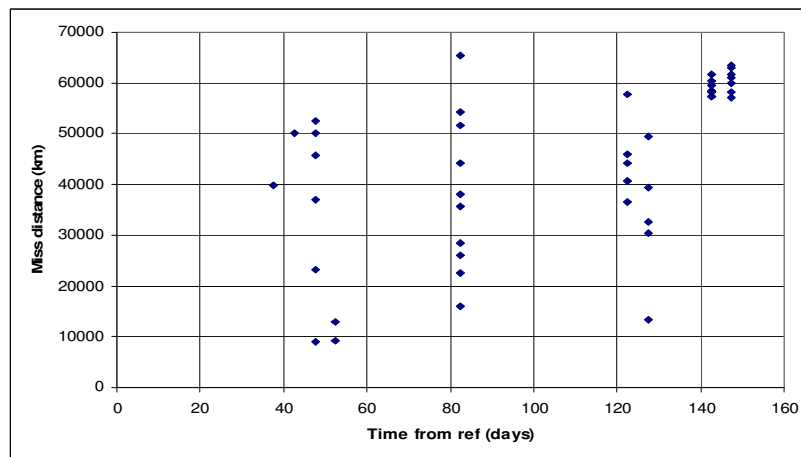


Figure 3 Target miss distance using a coarse 2 parameter set.

The coarse search indicates some clustering of low miss distances with time at which the manoeuvre is made, relative to an arbitrary reference.

As can be seen, some solutions have target miss distances smaller than 10000km, and with fine tuning miss distances of around 5000km can be achieved for selected cases. In view of the shift of the target region as a function of Moon position, as well as the uncertainty in the orbit propagation itself, no attempt was made at reducing this distance further.

4.5. Example Trajectories

As an illustration of what is possible, some selected trajectories from the two parameter search will be shown here. The solution with the smallest miss distance, around 5000km, is shown in **Figure 4**:

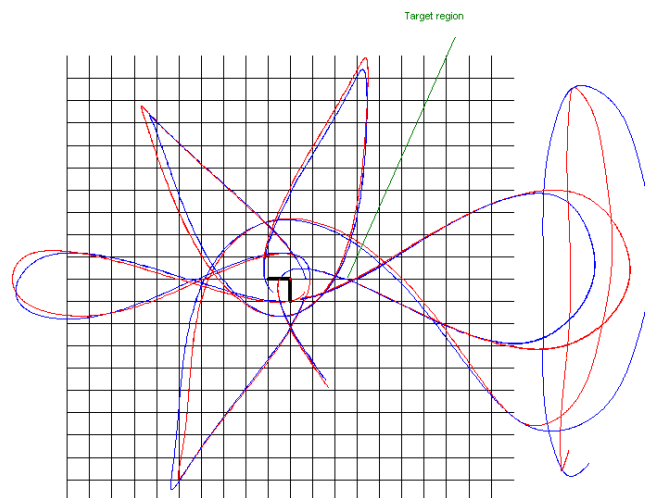


Figure 4 Two parameter solution with smallest miss distance

The time taken to reach the equilibrium region is approximately 480 days after the manoeuvre in the Lissajous orbit, and the initially applied dV is 0.87m/s .
An example of a “fast” transfer is shown in **Figure 5**:

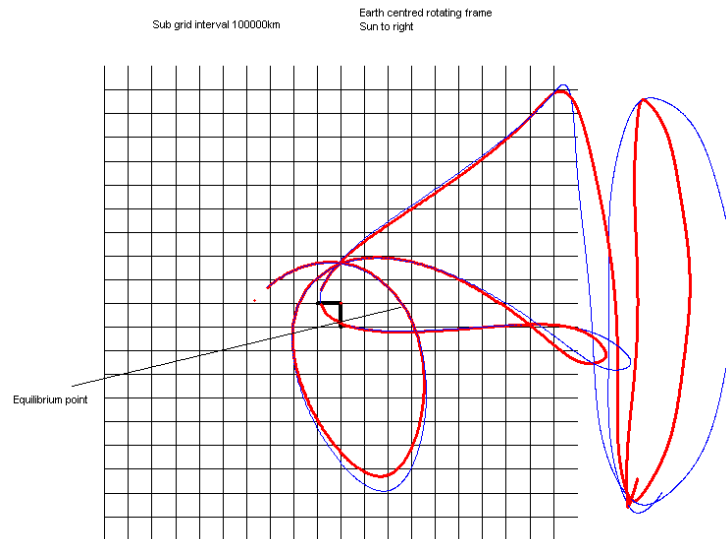


Figure 5 “Fast” transfer from Lissajous orbit to saddle point

The applied dV was 1m/s , and the transfer time was approximately 340 days. The miss distance was 30000km , but could in principle be improved with additional manoeuvres.

As a final example of what is possible, **Figure 6** shows a solution that includes a lunar flyby:

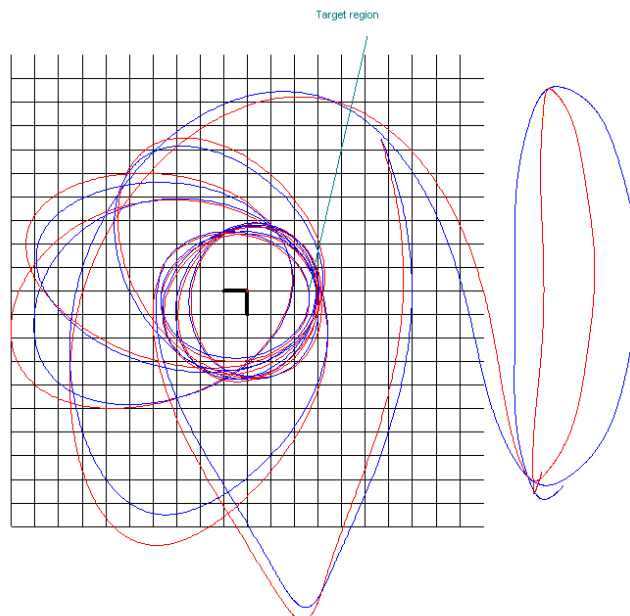


Figure 6 Solution including lunar flyby

A close lunar approach occurs (20000km) which results in the near circular orbit seen in the trajectory. One pass of this trajectory approaches the equilibrium zone with a miss distance of approximately 7000km.

4.6. Frequency Band for anomalous Gravity Gradient Measurements

In general, the LPF spacecraft will cross the region around the saddle point at a speed which is of the order of a few km/s. With a target region size of the order of 1000km, this means that anomalous gravity gradients will be applied for the duration of a few hundred seconds or so. This frequency band constitutes almost an ideal match to the LPF sensitivity.

4.7. Improvements

From a mission analysis point of view, numerous options exist to achieve closer approaches. The principle involves the application of further control parameters, which in general means a second manoeuvre. This could be applied at some time after the first manoeuvre, whilst still close to the initial Lissajous orbit, or at one of the subsequent apogees.

In order to find an optimum solution, it is certainly necessary to better define the target location, and also to refine the environmental models (gravitational and solar radiation pressure) used in the orbit propagation.

5. Conclusions and Future Work

We have shown that in principle, the residual control authority on LISA Pathfinder, following its nominal mission, is sufficient to bring LISA Pathfinder back to cross the region around the Sun-Earth saddle point, following one or more Earth flybys. These trajectories could be used for tests of MODified Newtonian Dynamics (MOND), and perhaps to investigate the so-called flyby anomaly. The speed of the LPF spacecraft is also such that any anomalous effects would be applied in the appropriate frequency band.

Clearly, a significant amount of work is still required, before any concrete proposal for an extended scientific phase can be put forward. The many issues that still need to be resolved include:

- consolidation of dV budgets
- actual MOND bubble position and size as a function of Moon position
- possible constraints from LPF navigation accuracy
- possible constraints from LPF attitude requirements
- possible constraints from test mass re-caging or instrument commissioning
- detailed MOND gravitational gradient signature within target region
- ...

In any event, we believe that the prospect of LISA Pathfinder being used to test gravitational theories is extremely exciting, and certainly deserves to be investigated in some detail.

References

- [1] ESA-SCI (2007) 1: LISA Pathfinder: Einstein's Geodesic Explorer – The Science Case for LISA Pathfinder
- [2] J.Bekenstein and J.Magueijo, Modified Newtonian Dynamics habitats within the solar system, Phys Rev D 73, 103513 (2006)
- [3] J.D. Anderson et al, Anomalous Orbital-Energy Changes Observed during Spacecraft Flybys of Earth, Phys Rev Lett 100, 091102 (2008)