NATURAL RECOVERY OPTIONS FOR FAILED TRANSFERS TO THE SUN-EARTH LIBRATION POINTS WITH THE EXAMPLE OF GAIA

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ABSTRACT

The libration points of the Sun-Earth system are attractive destinations for astrophysics missions that require a stable thermal environment and rigid orbit geometry. In the recent past those missions have been implemented as survey missions on large-amplitude quasi-halo orbits, that also allow a free transfer from injection by the launcher onwards, or as scanning missions on small-amplitude Lissajous orbits that require an insertion manoeuvre onto the stable manifold of the target orbit. All those missions exploit the benign environmental conditions and low transfer cost of this mission options. Looking at the concrete mission example of the scanning mission Gaia, we find that the transfers to those target orbits provide another advantage: a free recovery option from a failed transfer.

The stable manifold of both large and small libration orbits intersect with the Moon's orbit at a lunar phase of approximately 300°. If the injection by the launcher fails in the typical way of providing too low an apogee (typical target values to reach the libration point range from 0.9×10^6 to 1.5×10^6km depending on transfer strategy), the spacecraft will be stranded on a highly elliptical Earth orbit with an inertially fixed apse line roughly pointed towards the anti-Sun direction (i.e. 360° lunar phase, full Moon). Since the Sun-Earth line moves at 1° per day, the apse line will be at 300° Moon phase after two months. If maneuvering capability on board the spacecraft is retained, careful phasing to reach apogee at this position will allow a gravity assist manoeuvre to jump onto the stable manifold of the target orbit with a low cost in Δv.

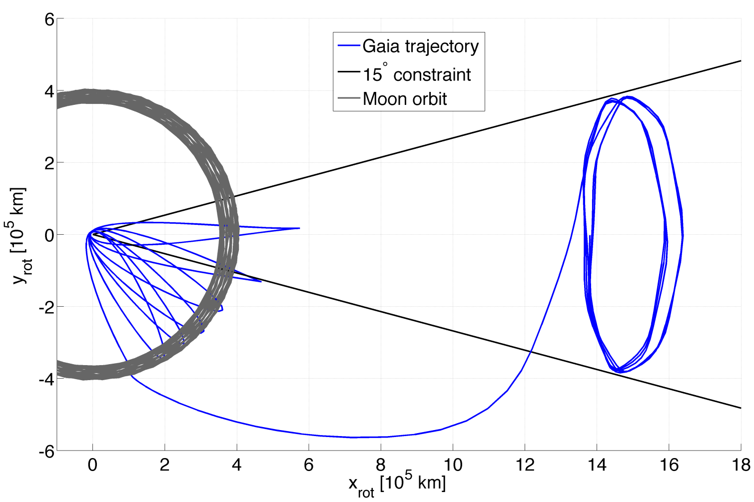

Figure 1: Recovery transfer for a failed injection case of Gaia launched on Dec 20th, 2013.

Here we present the case of a recovery of the Gaia mission from a hypothetical failed transfer injection below the target apogee radius of 958,569 km. We parameterise the initial orbit with the achieved apogee radii between 1.0×10^5 to 7.4×10^5 km. For performances above the parameter range (corresponding to launcher under performance in terms of perigee velocity of less than $12 ms^{-1}$) Gaia will have enough Δv to correct the error with a manoeuvre 48h after injection.

The transfer is constructed by working backward from a valid lunar gravity assist towards the launch epoch. An interesting aspect in the construction is the requirement to avoid a lunar encounter one month before the planned gravity assist. This is a challenge for the Gaia case due to the close proximity of the initial orbit to the ecliptic plane and thus to the lunar orbital plane. This is an issue at least for small amplitude missions that are required to target into the ecliptic plane. Our avoidance strategy is to phase the intermediate orbits such that the Moon passes through the apse line when the spacecraft is near perigee. For the total transfer to work the backward phasing must match the injection state (identical to the reference injection state besides the too low apogee radius) in elements and epoch. This requires an inclination change and perigee raise manoeuvre as early as possible. Later manoeuvres merely adjust the apogee radius in order to achieve the required phasing towards the lunar gravity assist. An important feature of these transfers is that there is no deterministic manoeuvre at the perigee prior to the lunar gravity assist. According to earlier works this allows to avoid time-critical navigation activities on the arc between the perigee and the Moon.

With this strategy and the the Δv budget of Gaia of maximum $235 ms^{-1}$ (impulsive) the transfer towards the target orbit can be recovered for apogee radii as low as 2.2×10^5 km, which corresponds to a under performance of the launcher in terms of perigee velocity of $125 ms^{-1}$. It should be kept in mind that this analysis is limited in two aspects: (a) only eclipses and the target orbit angular size have been considered as operational constraints – limitations of manoeuvre direction and duration have not been taken into account, and (b) in order to provide a smooth parametric analysis of the transfer as a function of the apogee radius, the transfer was not optimised for each case individually, but merely the initial apogee was adjusted to target towards a reference phasing sequence. The consequence of the limitation (a) is that more deep, short-term analysis will be needed in the unlikely case such a scenario is required for the recovery, and limitation (b) means that possibly more optimum solution exist, making even apogee radii below 2.2×10^5 km recoverable. The hard limit will be 1.2×10^5 km, below which so much Δv must be spent for the initial apogee raising that the lunar gravity assist cannot be reached within the budget given.

We have found a natural recovery transfer that should be considered for any libration point mission due to the improved mission success probability even in the case of severe launcher underperformance. The feasibility of this approach as nominal mission design scenario depends on the trade between optimising the final payload mass and operational complexity. For large amplitude target orbits this option will be less effective due to the accessibility of the stable manifold from the near-Earth environment, so that the difference between the direct transfer and the transfer through lunar gravity assist will mainly be the difference in perigee velocity for apogee radii of the Moon orbit and $\sim 1.5 \times 10^6$ km, which is $\sim 60 ms^{-1}$.