MISSION DESIGN ASPECTS OF EUROPEAN ELEMENTS IN THE INTERNATIONAL SPACE EXPLORATION FRAMEWORK

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Abstract: *In the context of the international space exploration coordination group ESA defines the framework for its possible future contribution to an infrastructure that will enable us to explore the solar system in situ in a much more direct way than today. From a mission system design point of view the exploration scenario relies heavily on the exploitation of the dynamical properties of the Earth-Moon system. Here we look into the mission system aspect of a reference scenario that comprises the elements of a captured mini-asteroid on a distant retrograde orbit around the Moon, as well as visiting vehicles from the Earth. The motivation for the analysis of the associated transfers in the Earth-Moon system is the requirement for ESA to provide propulsive elements for the initial missions of the most likely visiting vehicle (Multi Purpose Crew Vehicle, based on hardware from the European Autonomous Transfer Vehicle). For that vehicle the first two missions will go to a distant retrograde orbit around the Moon, the particular properties of which as well as the relevant transfer strategies are explored here.*

Keywords: *mission design, exploration, three-body-problem, roadmap, Moon*

1. Introduction

The leading roadmap [1, 2] for the mid-term exploration of the solar system calls for the capture and retrieval of a small asteroid from near Earth space into a loosely bond orbit around the Moon. Near–term operational tests of transfer vehicles, in particular the NASA Multi-Purpose Crew Vehicle (MPCV) will fly operational tests to this destination. Currently two test missions are scheduled for 2017 and 2012, referred to Exploration Mission 1 and 2 (EM-1 and EM-2), respectively. ESA is involved as a supplier of the service module for the MPCV, the European Service Module (ESM) for those missions [3]. In support of the associated ESA programme, the mission design of EM-1 and EM-2 is reviewed with the objective to anticipate the evolution of requirements, in particular the Δv budget and manoeuvre schedule.

As a target for EM-1 and EM-2 currently a distant retrograde orbit (DRO) around the Moon is foreseen [4], which is also the planned destination for the captured asteroid. A DRO is a planar solution of the idealised circular restricted three- body problem (CR3BP), which has been investigated deeply in literature [5, 6]. A spacecraft on a DRO follows a path around the Earth that seems elliptic around the Moon due to the 1:1 resonant interaction with the Moon. DROs possess properties (flat local potential, high orbital energy) similar to the libration point orbits. Those can be exploited for the design of transfers. A multiple shooting algorithm also produces these orbits in the full ephemeris model. In the lunar orbital plane periodic DROs can be found at various sizes (see figure 1). We refer to the size of the orbit as “amplitude”, because the motion in the CR3BP is more analogous to a two-dimensional oscillation than to Keplerian orbital motion. Usually, the amplitude is in the order of the distance from the Earth-Moon Libration point (EML_2) to the Moon [7]. However, small DROs have a smooth transition to in-plane retrograde Keplerian lunar orbits.

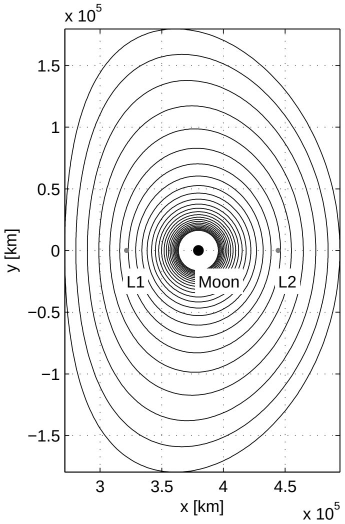

Figure 1. Family of distant retrograde obits in the synodic frame of the Earth Moon system.

Interestingly, the orbital velocity on a DRO increases with amplitude, while of course the orbital velocity on a Keplerian orbit decreases with circular radius (see Figure 2). DROs are sufficiently high up in the gravitational well of the Earth-Moon system, so that a transfer of a 100 tonne class near Earth mini-asteroid is feasible. On the other hand they provide the mission system design benefits of an orbit in the Earth-Moon system, like a libration orbit around the far side Earth-Moon Libration point (EML_2), which are:

- Low orbit maintenance cost ($< 10\,\mathrm{m\,s^{-1}\,y^{-1}}$)
- Low Δv connection to orbits in the Sun-Earth system
- Low Δv connection to near-Earth interplanetary space
- Direct injection transfer from the lunar surface
- Low transfer times from Earth ($\approx 8\,\mathrm{d}$)
- Small direct insertion manoeuvre from Earth ($\approx 600\,\mathrm{m\,s^{-1}}$)
- Even lower insertion cost options from Earth using lunar gravity assist ($\approx 300\,\mathrm{m\,s^{-1}}$, see below)

In particular the final point has some bearing on the exploration system design. Large elements of an exploration infrastructure need to be launched from Earth using highly efficient cryogenic chemical propulsion, which is known to have a system mass penalty on the transfer time due to off-boiling. A conceivable system design would exploit the time separation between early high Δv trans lunar injection (TLI) and a later low Δv orbit insertion using a combination of a cryogenic departure stage and a destination stage with storable propellants.

2. The DRO Family

There are different approaches to construct a DRO around the Moon [7]. Here we use a simple numerical approach with propagation in the full ephemeris model. A propagation is started at the x-axis of the synodic frame, in which the Earth is at the origin and the Moon's orbital plane is the x-y-plane with x pointing from the Earth to the Moon. In that frame the other two position coordinates are initially equal to zero. In velocity there is only a non-zero component in the negative y-direction. With the initial velocity v_y as the free parameter a matching algorithm is employed to search for a matching after propagation to the next x-z-plane

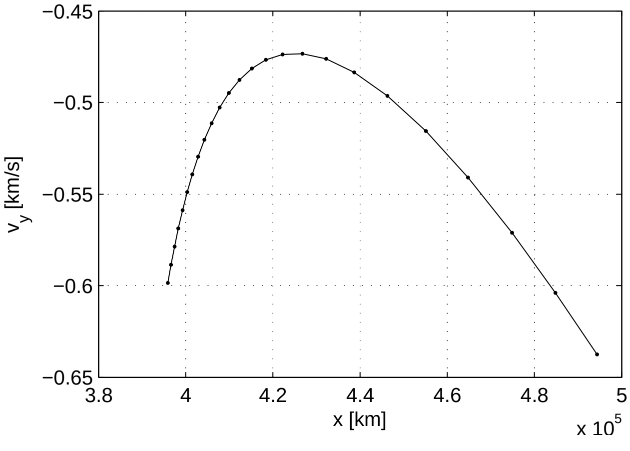

Figure 2. Orbital velocity at the x-z-plane crossing.

crossing. This algorithm converges quickly for x-coordinates starting from zero altitude above the Moon surface to $> 100,000\,\text{km}$ from the centre of the Moon.

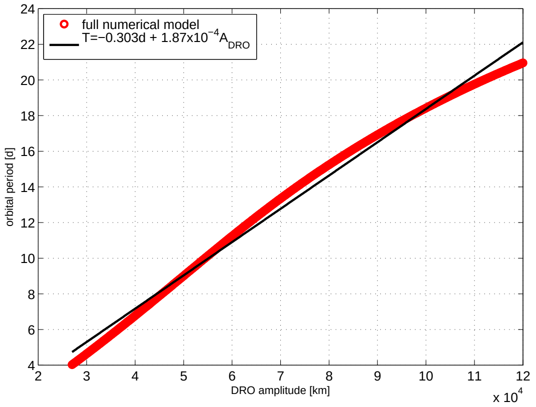

Figure 3. Evolution of the orbital period of DROs as a function of amplitude from the full numerical model compared with a linear fit. The parameters of the fit are provided in the legend.

This family of in-plane DROs is visualized in figure 1. An interesting feature is that there is a smooth transition from DROs with amplitudes below $60,000\,\text{km}$ that have orbital velocities decreasing with decreasing amplitude to retrograde circular Kepler orbits that have orbital velocities increasing with decreasing orbital radius.

An operationally interesting aspect is the orbital period of DROs. Figure 3 shows how the orbital period evolves with orbit amplitude. We present here the full numerical solution to the DRO as obtained with the multiple-shooting algorithm. In the relevant range the orbital period varies with the amplitude in a linear manner. Thus, we can provide a fit that can be used for operational considerations as well as for initial guess in orbit construction. The parameters of the linear fit are given in figure 3. For large amplitude there is a significant deviation of the linear fit by up to $1.2\,\text{d}$.

3. Transfer Options from Earth

3.1. Direct Transfer

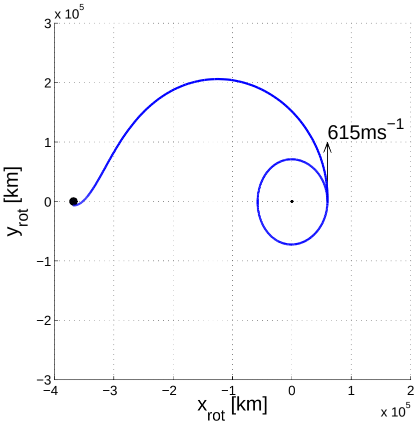

Figure 4. Transfer geometry of an example of a direct lunar transfer orbit to a $60,000\,\text{km}$ distant retrograde orbit (the amplitude of which requires the largest insertion Δv) in the synodic frame with the Moon at the centre.

The most obvious way to transfer from Earth is to use a lunar transfer orbit (LTO) with the apogee as much above the Moon as the amplitude of the DRO relative to the Moon. The insertion into the DRO would then occur tangentially at the x-z-plane crossing providing a low Δv opportunity. The insertion Δv directly into the DRO is thus just a little smaller than that into low lunar orbit (LLO). The travel time is with $5.9\,\text{d}$ also only slightly longer than the minimum energy LTO to LLO. At a distance of $89,000\,\text{km}$ from the centre of the Moon the lunar gravity is sufficiently low to consider the transfer problem a pure Kepler problem. From this point of view the transfer is an ellipse with the apogee at the required DRO amplitude above the Moon's position with a manoeuvre at apogee to raise the perigee to the same distance below the Moon, so that the semi-major axis is the same as the Moon's. A parametric analysis of the full ephemeris propagation and optimisation is shown in figure 5. The minimum insertion Δv as a function of orbit amplitude exhibits an approximately quadratic behaviour with a minimum at amplitudes around $60,000\,\mathrm{km}$. A quadratic fit to the insertion Δv can be used as initial guess for the transfer construction. The coefficients as given in the legend of figure 5.

3.2. Prograde Powered Lunar Gravity Assist

The direct transfers to the DRO suffer from a still substantial insertion Δv requirement, which is only 30% lower than a typical insertion into a classic LLO. The obvious idea is to use the lunar gravity to achieve the perigee raising required to transition from an LTO to the DRO. The trouble with this approach is that the orbital energy of a typical LTO relative to the Moon is in the order of $C_3 \approx +3\,\mathrm{km}^2\,\mathrm{s}^{-2}$, so that the outbound leg of the gravity assist hyperbola cannot be connected to a DRO, which has $C_3 \approx -0.06\,\mathrm{km}^2\,\mathrm{s}^{-2}$. The only solution is to introduce an energy-change manoeuvre at periselenium. Again we construct the transfer from an initial guess and matching algorithm using a multiple-shooting method. One possible solution is shown in figure 6. The trajectory is shown in the *x*-*y* plane of the synodic frame of the Earth-Moon system, which is the Moon's orbital plane. It can be seen from figure 6 how the typical inbound velocity of the gravity assist hyperbola is reduced in the periselenium manoeuvre of $190\,\mathrm{m\,s}^{-1}$, so that the insertion into the DRO can be achieved with $318\,\mathrm{m\,s}^{-1}$. The total $\Delta v = 508\,\mathrm{m\,s}^{-1}$ represents a savings of $122\,\mathrm{m\,s}^{-1}$ relative to the direct transfer. The transfer time is however prolonged by 2.7 to 8.6 d. Operationally speaking this transfer time can still be supported by a human rated system and life support system. The feasibility of a time-critical periselenium manoeuvre at 100 km above the lunar surface is to be established, however.

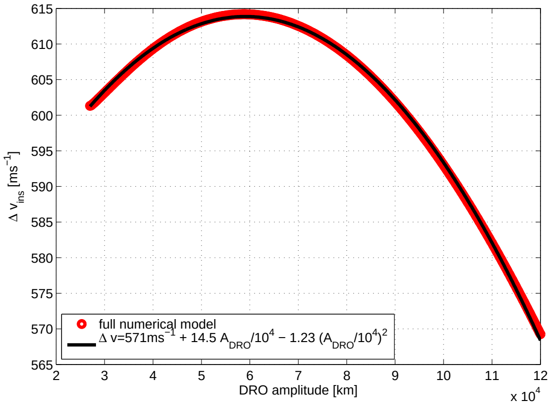

Figure 5. Evolution with target orbit amplitude of the direct insertion Δv into DRO using the full ephemeris multiple shooting optimisation

3.3. Retrograde Powered Lunar Gravity Assist

The prograde powered lunar gravity assist to a DRO has the drawback that the prograde direction of motion must be small enough so that the insertion into the retrograde target orbit does not become too big. Therefore there is a limit to the retrograde direction of the outbound leg before the insertion, making the insertion manoeuvre relatively large. A strategy to mitigate this shortfall is to consider a retrograde transfer, in which the gravity assist hyperbola has an inclination of approximately 180° relative to the *x*-*y*-plane. This allows the hyperbolic outbound leg to be more aligned with the target orbit, significantly reducing the required insertion Δv. A solution based on this strategy is presented in figure 7. The trajectory is shown in the *x*-*y* plane of the synodic frame of the Earth-Moon system,

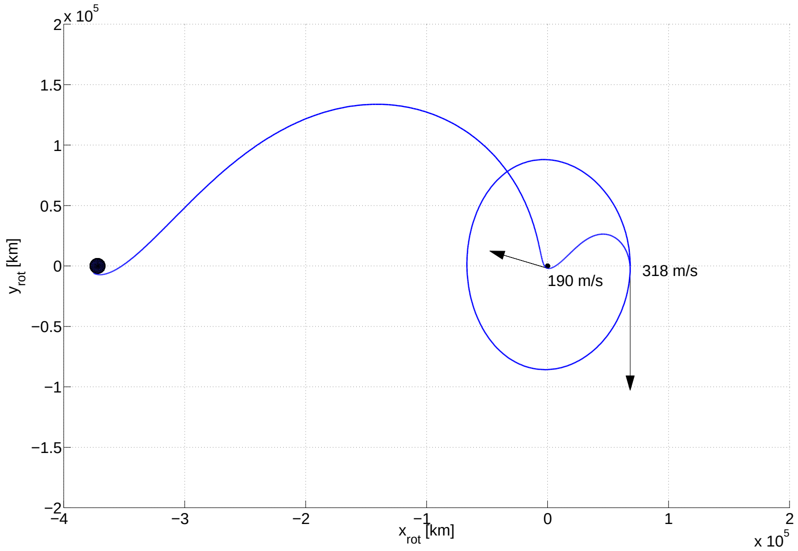

Figure 6. Transfer geometry of a prograde lunar gravity assist transfer to a DRO with $60,000\,\mathrm{km}$ amplitude.

which is the Moon's orbital plane. One aspect of the retrograde lunar gravity assist transfer shown in figure 7 is the longer outbound arc from the Moon. In the solution shown the time from TLI to periselenium manoeuvre is $4.6\,\mathrm{d}$, and the time from periselenium to orbit insertion is $8.9\,\mathrm{d}$. The total transfer time from TLI to insertion into the DRO is $13.5\,\mathrm{d}$. In terms of total transfer Δv the retrograde transfer is the least demanding with $299\,\mathrm{m\,s^{-1}}$. Here the same remarks regarding operational feasibility apply as for the prograde transfer.

4. Possibilities for the Initial MPCV Missions and Operational Implications for the ESM

After having analysed the possible target DROs and transfer options, here we discuss the possible mission design options for the MPCV (of which the ESM is an essential part) in the frame of the EM-1 and EM-2 mission. As discussed in the introduction, the purpose of those mission is the operational preparation of the main exploration missions to near-Earth asteroids stepping up towards a human mission to Mars. An important element in the preparation missions is their amount of forward operational tests that can be achieved in preparation for the later missions. They should not, however, completely without value by themselves. The choice of DRO as a target for EM-1 and EM-2 (the former being unmanned and the latter manned) fulfills this objective. EM-1 can be used to check out and certify the full system for the DRO mission profile including transfer modes, while EM-2 will allow the crew to use the system in order to perform sampling from an asteroid that will have been delivered to a DRO by the asteroid retrieval mission. Thus, after successful completion of EM-1 and EM-2 the SLS and EM-1 systems will have acquired sufficient operational experience, on the basis of which missions like near-Earth asteroid visits, human-assisted robotic lunar sample return, and in the mid-term human missions to Mars can be developed.

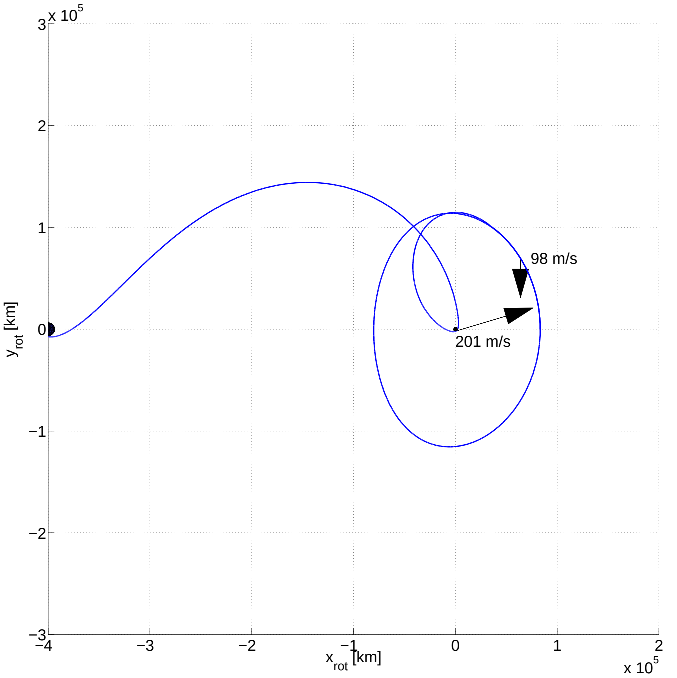

Figure 7. Transfer geometry of a retrograde lunar gravity assist transfer to a DRO with $60,000\,\mathrm{km}$ amplitude.

The mission design of EM-1 calls for a 25 d mission from TLI to reentry with a few days of coast in a DRO around the Moon. One possible mission scenario is depicted in 8 using a prograde powered lunar gravity assist transfer on the Earth outbound leg and a retrograde transfer on the Earth inbound leg. Alternatively the outbound leg could be flown retrograde as well, which will lower the mission Δv, but increase the transfer time (so that either mission will become longer or the coast time on the DRO shorter).

For the example shown in figure 8 the total mission Δv is $534\,\mathrm{m\,s^{-1}}$, which has to be provided by the ESM of the MPCV. While in the capability driven approach of the MPCV system design the peculiarities of the actual mission have little bearing on the system requirements (e.g. the Δv requirement covers all DRMs as specified in the applicable concept of operations), an understanding of the relevant use cases of the system helps to anticipate the requirement evolution. It should be noted that example provided does not constitute a mission Δv budget, but it can act as a DRM, a frame for the operational implementation (scheduling of navigation, commissioning, maneuvering). Table 1 summarises the time-line of the EM-1 mission as depicted in 8.

5. Conclusion

We have presented the family of distant retrograde orbits in the Earth-Moon system, a weakly bound motion around the Moon at the edge of the lunar sphere of influence, and their use in the frame of the operational preparations for an international space exploration roadmap, for which Europe provides important elements. At the current time the most prominent of those elements is

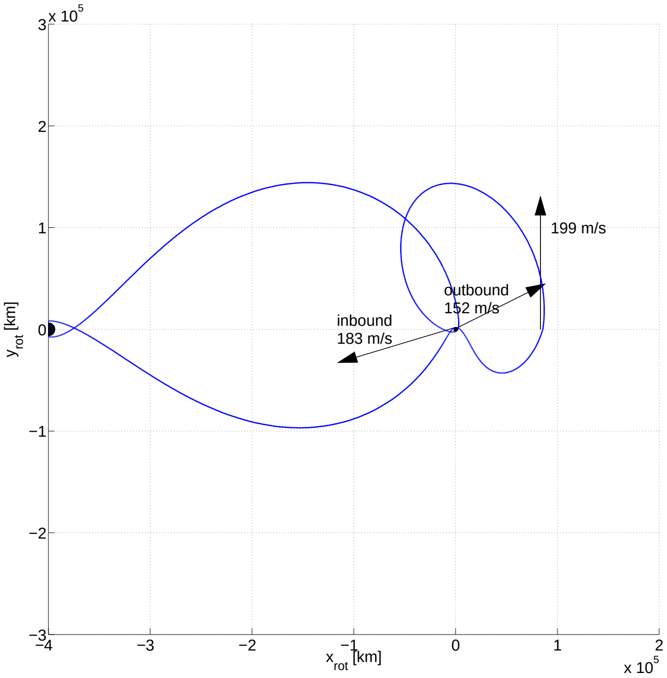

Figure 8. Transfer geometry of a combination of Earth outbound prograde and inbound retrograde lunar gravity assist transfer to a DRO with $60,000\,\mathrm{km}$ amplitude and back. The trajectory is shown in the x-y plane of the synodic frame of the Earth-Moon system, which is the Moon's orbital plane.

event	time [d] relative to TLI	MPCV Δv
TLI	0.0	-
outbound LGA	4.7	$152\,\mathrm{m\,s^{-1}}$
insertion into DRO	8.1	$0\,\mathrm{m\,s^{-1}}$
departure from DRO	15.7	$199\,\mathrm{m\,s^{-1}}$
inbound LGA	20.6	$183\,\mathrm{m\,s^{-1}}$
entry, descent and landing	24.4	-
total		$534\,\mathrm{m\,s^{-1}}$

Table 1. List of events in a mission design representative to EM-1 of MPCV (LGA refers to lunar gravity assist).

the European service module for the multi-purpose crew vehicle. The DROs can be reached through a variety of transfers from LTO: direct, prograde and retrograde powered lunar gravity assist. The one-way transfer Δv ranges from 300 (for the retrograde gravity assist) to $630\,\mathrm{m\,s^{-1}}$ (for the direct), and the one-way transfer times range from 5.9 (for the direct) to 13.5 d (for the retrograde gravity assist). The low insertion Δv into an DRO is of particular interest for a space transportation system that relies on storable propellants, since they provide only moderate specific impulses in the order of 320 s. The DRO is thus a good destination for large infrastructure elements without the requirement of huge amounts of propellant.

The flexibility of the DRO in its amplitude as well as the transfer options open the possibility to flexibly combine the mission elements in order to adjust the mission to the capabilities of the spacecraft and the objectives of the mission. This flexibility is a typical characteristic of weakly bound orbits, of which DROs only one example. Other examples are Earth-Moon libration points [8] and weak stability boundary transfer [9]. While in the capability driven approach of the MPCV system design the peculiarities of the actual mission have little bearing on the system requirements (e.g. the Δv requirement covers all DRMs as specified in the applicable concept of operations), an understanding of the relevant use cases of the system helps to anticipate the requirement evolution. The work presented here is only one step in understanding and exploiting the properties of weakly bound trajectories for exploration. Future work shall consider transfers from the lunar surface and the connections between Earth Moon libration points and DROs. Also, transfers from DROs and libration orbits into interplanetary space, in particular to near Earth asteroids are of high interest. More parametric analyses of the phase space are needed in order to establish worst case Δv budgets and launch windows, in particular for the more elaborate transfers with gravity assist manoeuvres.

The design if future European contributions to the exploration space transportation infrastructure can benefit from the flexible design reference missions involving weakly bound destination orbits like DRO and Earth-Moon libration points.

6. References

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