Analysis of Distant Retrograde Orbits in the Earth-Moon System

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***Abstract* – The study of Distant Retrograde Orbits has been a subject of interest from the proposal of the Asteroid Redirect Robotic Mission by NASA, but it has been the development of the Artemis Program and the fulfilment of its first mission what has led to new studies on the subject. The presented work explores the characteristics of DROs and their applications for their potential use in the development of future interplanetary missions. First, a complete characterisation of the DRO family and its bifurcations in the Earth-Moon system, modelized as a Circular Restricted 3-Body Problem, is presented. In this step, it was detected that period tripling DROs are unstable, thus presenting stable and unstable manifolds which offer low-cost connections with other regions of space.**

Then, the manifolds of these neighbouring orbits are evaluated as connection trajectories between the Earth and the Cislunar environment. Using this approach, the complete journey consists of a transfer arc from the Earth to a manifold, a coasting phase along the manifold and a final transfer from the manifold to the final orbit. The selection of the manifold and the injection and departure points from it, allows to optimise the DV while allowing for a certain control of the time of flight. The obtained results show that with a DV of 290,3 m/s it is possible to reach the target orbit in 15,5 days.

Moreover, these natural trajectories, studied in a Patched-CR3BP model with the Sun-Earth system, offer the possibility to find cheap trajectories to escape the Lunar vicinity. By applying this approach, a trajectory to reach Mars has been designed using a transfer from the departure orbit to a manifold of a P3DRO in the Earth-Moon system, a transit phase through L2 of the Sun-Earth system, a coasting phase, and a final transfer towards Mars. It has been observed that the cost to escape the Earth-Moon vicinity is below 250 m/s, without having significant limitations on the choice of the departure date.

In consequence, the use of manifolds has proved its effectiveness: while benefitting from the stability of DROs, connections with other parts of the Earth-Moon system are easily designed with low transfer costs. These transfers between a DRO and a manifold were computed using a continuation method from a target point on the natural path, to one on the target trajectory. In addition, this method has been evaluated for the computation of transfers between a DRO and an NRHO, validating it with other results of the bibliography. This work is finally completed with a study of the station-keeping cost in a more realistic force model and the analysis of the trajectory followed by ARTEMIS I.

I. INTRODUCTION

With the evolution of computer sciences, the study of complex dynamical systems became a reality, and a new type of low-energy trajectories, which exploit the gravitational interactions between three or more bodies, were discovered. These discoveries are key for the reduction of the fuel consumption, allowing an increase of the payload and a consequent improvement in the scientific objectives of space missions. One of the first missions to use this new approach was the Genesis Discovery Mission, whose goal was to collect solar wind samples and return them back to Earth. To achieve this goal, a prove had to be placed in an orbit far away from the Earth for a period of about two years to collect samples and then return to the Earth. All this mission was completed without any deterministic manoeuvre, just some corrections along the path. Obviously, this success created great interest in the study of these complex dynamical systems, reaching up to the consideration of the trajectories conceived using this approach for the design of more ambitious missions, like the Distant Retrograde Orbit used for the Artemis missions to bring humanity back to the Moon.

The interest woken up by these new missions has motivated the project which is presented in this paper. The goal of this study is to analyse the Distant Retrograde Orbit family in the Earth-Moon system to identify their characteristics and explore their feasibility for future missions. To do this, their accessibility from Earth, their stability, and their utility to serve as a hub for future interplanetary missions are evaluated. To maintain a complete view of the analysis, the research focuses on the features of interest for mission analysis in Phase 0/A. All these studies are framed in the Restricted Three-Body Problem, and to study this model, the *SEMpy* library, which is being developed by the Space Advanced Concept Laboratory (SaCLaB) in ISAE-

SUPAERO, will be used. Moreover, it is intended to implement some of the developed solutions into the library to improve the catalogue of tools it provides.

Before starting with the presentation of the work done here, some previous studies on this subject will be presented. Different works have been published in the conception of the Artemis mission like the ones in [1], [2] and [3]. Additionally, DROs have been deeply studied in the works of [4], [5] and [6]. Regarding mission design in the cis-lunar environment there are two groups of previous studies that are relevant for the presented subject: on one side, studies on Earth-Moon trajectories like the ones presented in [7], [8], [9], [10] and on cis-lunar transfers as in [11], [12] and [13]; and on the other, works devoted to interplanetary missions like [14] and [15].

II. THEORETICAL FRAMEWORK

The studies presented in this project are framed, mainly, in the Circular Restricted Three-Body Problem, as it is an appropriate model to study the Earth-Moon environment because the orbit of the Moon is almost circular (mean eccentricity of 0.0549), and as at the first phases of mission design it allows to find results which do not exist in the commonly used Two-Body problem. It must also be said that for some parts of the project, other models will be used, as the patched-CR3BP model to study trajectories from the Earth-Moon system to the Sun-Earth one, and the ephemerides model to perform a more realistic study of some trajectories. In the CR3BP, the motion of the spacecraft is defined by the system of differential equations presented in (1), where the pseudo-potential is defined as $\overline{U} = -1/2\,(x^2 + y^2) - (1-\mu)/r_1 - \mu/r_2 - 1/2\,\mu(1-\mu)$:

$$\begin{cases} \ddot{x} - 2\dot{y} = -\frac{\partial \overline{U}}{\partial x} \\ \ddot{y} + 2\dot{x} = -\frac{\partial \overline{U}}{\partial y} \\ \ddot{z} = -\frac{\partial \overline{U}}{\partial z} \end{cases} \quad (1)$$

This set of equations describe a non-integrable problem, so, to find the trajectory, from a given initial state, it is necessary to integrate the equations numerically. As these equations are Hamiltonian and independent of time, they have an energy integral of motion. This result is commonly redefined as the Jacobi integral or Jacobi constant [16]:

$$C = -\left(\dot{x}^2 + \dot{y}^2 + \dot{z}^2\right) - 2\overline{U}(x, y, z) \quad (2)$$

It is also important to understand how the final state is modified due to a variation in the initial state. Considering only the linear terms of this variation, it is possible to define the state transition matrix as the matrix which gives the linear relationship between small initial and final displacements. The State transition matrix is computed solving the following differential equations with the initial conditions $\Phi(t_0, t_0) = I_n$:

$$\dot{\Phi}(t, t_0) = Df\left(\overline{x}(t)\right)\Phi(t, t_0) \quad (3)$$

Among the different utilities of this matrix, one of the most important ones is to compute predefined trajectories. Providing an approximation of an initial state defining a desired trajectory, it is possible to use the STM to correct this approximation to get the initial state that after a certain time gets to a desired final state. An application of this method is for the computation of periodic orbits, starting from analytic result or using a continuation schema to generate a complete family.

A. *Periodic orbit analysis*

The study of the stability of an orbit is no more than the analysis of the effect of a small perturbation over time. The state transition matrix gives the linear relation between a small initial perturbation and the final displacement caused by it after a certain time. For an orbit, as this matrix is integrated over its period, it is renamed as the Monodromy matrix of the orbit.

$$M \equiv \Phi(T, 0) = \frac{\partial \Phi(T; \overline{x}_0)}{\partial x_0} \quad (4)$$

To understand if a perturbation will decay or grow over time it is necessary to analyze the eigenvalues of this matrix. Due to its properties, these eigenvalues come in conjugated and reciprocal pairs, and at least one of these pairs has a value of one. As the remaining four will appear in two reciprocal pairs, every stable one implies an associated unstable one, implying that the linear instability in this system can be of order zero, one, or two, that is, the number of pairs of eigenvalues out of the unity circle.

Although stability is a fixed parameter for an orbit, it can change along orbits of the same family. A family of periodic orbits is a group of periodic solutions which share a common hodograph, which is a continuous curve in the phase space (six dimensional in the CR3BP). By varying a parameter like the Jacobi constant and moving along the hodograph, the eigenvalues also change continuously, which can lead to variations of the order of linear instability. A point along the hodograph at which the stability changes is recognised as a bifurcation point. To find these bifurcations, Broucke introduced the stability diagram for the CR3BP in 1969, and Howard and Mackay generalised it in 1987 [17]. First, for each orbit of the family, the parameters α and β are calculated.

$$\begin{cases} \alpha = 2 - \mathrm{Tr}(M) \\ \beta = \frac{1}{2}[\alpha^2 + 2 - \mathrm{Tr}(M^2)] \end{cases} \quad (5)$$

Then, from the characteristic equation of the Monodromy matrix and the definition of the bifurcations, it is possible to define the curves, which when intersected indicate the existence of a bifurcation.

Table 1. Formulas to find bifurcations.

Type of bifurcation	**Formula**
Tangent	$\beta = -2 - 2\alpha$
Secondary Hopf	$\beta = \frac{\alpha^2}{4} + 2 \; with \; -4 < \alpha < 4$
Period doubling	$\beta = -2 + 2\alpha$
Period tripling	$\beta = 1 + \alpha$
Period quadrupling	$\beta = 2$
Period quintupling	$\begin{cases} \beta = \frac{\alpha}{2\cos\left(\frac{4\pi}{5}\right)} - \frac{\cos\left(\frac{8\pi}{5}\right)+1}{\cos\left(\frac{4\pi}{5}\right)} \\ \beta = \frac{\alpha}{2\cos\left(\frac{8\pi}{5}\right)} - \frac{\cos\left(\frac{16\pi}{5}\right)+1}{\cos\left(\frac{8\pi}{5}\right)} \end{cases}$

From these expressions it is possible to build the stability diagram, in which the white region indicates a linear instability of order zero, the grey, of order one, and the black, of order two. From this diagram it is also possible to observe which bifurcations cause a change in this linear instability.

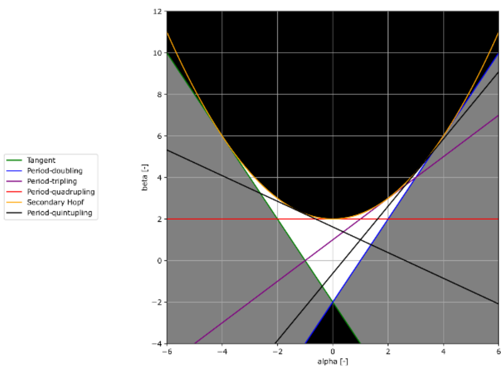

Fig. 1. Broucke stability diagram.

Once the bifurcation points have been found, it is possible to start a new continuation schema, in a direction determined by the pair (or pairs for the secondary Hopf type) of eigenvalues causing the bifurcation, to obtain the new family originated.

B. Invariant manifolds

A manifold is a trajectory which tends/departs, asymptotically, towards/from a periodic orbit. In autonomous systems, e.g. in the CR3BP, these manifolds are invariant because their position in the phase space is fixed in time. These structures only exist for unstable orbits, as the asymptotic departure from a periodic orbit is associated with an eigenvalue of its Monodromy matrix with a modulus greater than one. In opposition, the asymptotic approach to a periodic orbit is associated with eigenvalue that has a modulus smaller than one.

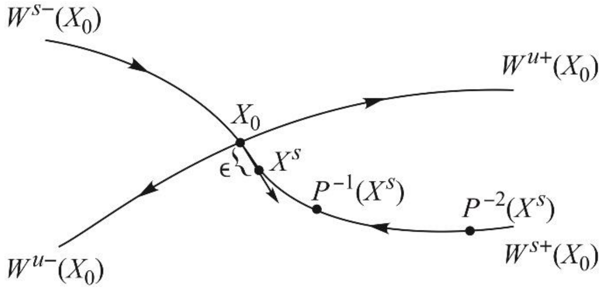

Fig. 2. Process to approximately compute invariant manifolds of a periodic orbit [16].

The approximate computation of a manifold is performed introducing a perturbation in a point X_0 in the direction of the normalised eigenvector associated to the unstable eigenvalue, $Y_u(X_0)$, and in the direction of the normalised one associated to the stable eigenvalue, $Y_s(X_0)$:

$$\begin{cases} X_u(X_0) = X_0 \pm \epsilon Y_u(X_0) \\ X_s(X_0) = X_0 \pm \epsilon Y_s(X_0) \end{cases} \quad (6)$$

This asymptotic behaviour makes them interesting for the design of low-energy transfers, but they also make it possible to identify different types of motion in space, making it possible to predict the behaviour of trajectories without having to propagate them.

III. ANALYSIS OF THE DRO FAMILY

DROs are periodic orbits characterised for presenting a planar retrograde motion in the xy-plane around the second primary of the system. These orbits extend from Low Lunar Orbits up to larger orbits which have a 1:1 resonance with the second primary, which are commonly known as Quasi-Satellite Orbits.

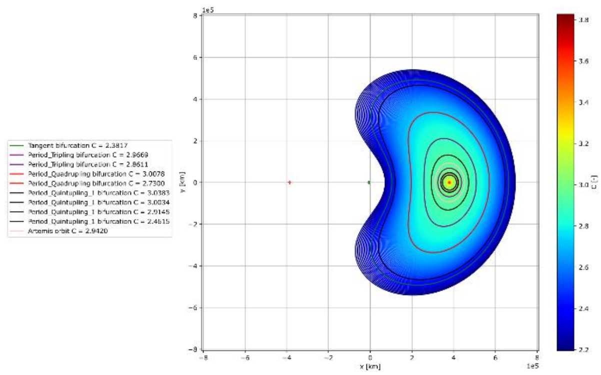

Fig. 3. DRO family in the Earth-Moon system.

Observing the DRO family, as the Jacobi constant decreases, the size of the orbits grows, which agrees with the fact that a lower value of this parameter means a higher level of energy. It is also possible to observe the evolution of the shape of the orbits in the synodic frame as they grow. In the closest region of the Moon, they keep an almost circular shape. However, as they get further from it, they start to be more affected by the attraction of the Earth, giving them an elongated shape, reaching up to the equilateral equilibrium points for the Earth-Moon system. Finally, the theoretical orbit used for the Artemis I mission is also presented. This orbit has a Jacobi constant of 2,942, a period of 13,71 days and encloses both, L1 and L2.

One of the most important properties of this family is that almost all the orbits are linearly stable. Only the ones with lowest values of Jacobi constant, after the appearance of the tangent bifurcation, are slightly unstable. Using the Broucke stability diagram it is possible to evaluate the stability of DROs and find the 9 bifurcations of this family.

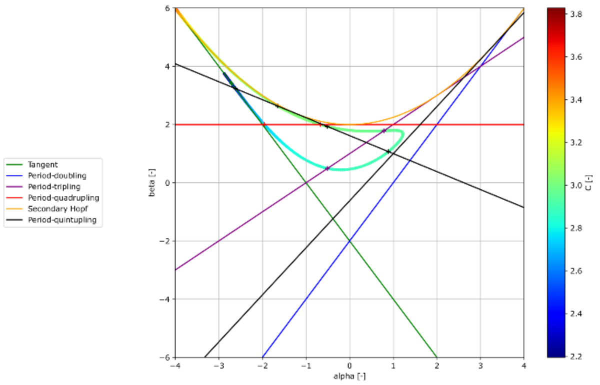

Fig. 4. Broucke stability diagram.

Studying the intersection of the hodograph of the DRO family and the different lines it is possible to find the points at which the different bifurcations occur (as its was done for the Jupiter-Ganymede system in [5]).

Table 2. Bifurcations of the DRO family.

Type of bifurcation	**Jacobi constant**
Tangent	2,38
Perio quintupling	2,46
Period quadrupling	2,73
Period tripling	2,86
Perio quintupling	2,91
Period tripling	2,97
Perio quintupling	3,00
Period quadrupling	3,01
Perio quintupling	3,04

Among the different bifurcations, the most interesting one is the period tripling bifurcation which appears for a Jacobi constant of 2,97. The orbits of this bifurcating family are unstable, meaning that they have manifolds linking the DRO neighbourhood with other regions of space.

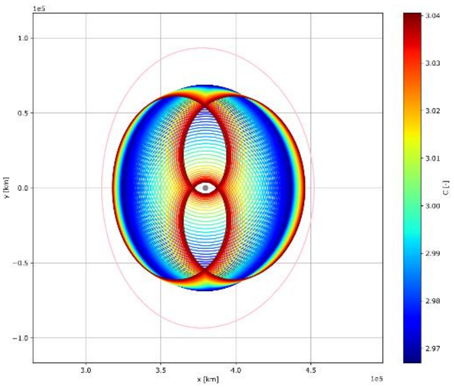

Fig. 5. Period tripling bifurcating family.

The manifolds of these orbits have trajectories much more chaotic than libration point orbits. To study the regimes of motion between realms it is much more recommendable to use these libration point orbits as it was done in the design of a low-energy transfer to the Moon in [16].

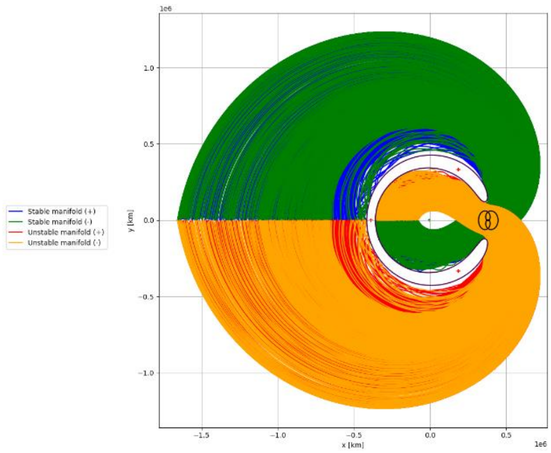

Fig. 6. Trajectories of the manifolds of a P3DRO with C = 3,0405.

For the work being currently developed, manifolds of period tripling DROs will be used as pre-designed trajectories to transit between realms.

IV. TRAJECTORY DESIGN AND APPLICATIONS

The previous analysis provided the main characteristics of the DRO family and its bifurcations, making it now possible to focus on the main question of this work: "for which applications are DROs suitable?". To answer it, the first study consists of an exploration of the transfers between orbits in the neighbourhood of DROs. Later, the strategies to reach these orbits from the Earth environment and the opportunities they might offer for interplanetary journeys are explored. Finally, an estimation of the station-keeping costs for a vehicle placed in a DRO is carried out. In all these studies, the orbit selected from the DRO family is the one used for Artemis I (unless otherwise stated).

A. *Transfers in cis-lunar region*

Although an analytical solution exists for the transfer problem in Keplerian dynamics, in the CR3BP this is not the case, so a Two Point Boundary Value Problem must be solved using a shooting algorithm. One requirement for this approach to work is to have a good initial guess to start the shooting algorithm. The most used method to generate this initial guess is based on the solution of Lambert's problem. This approach works well in the regions where the first primary dominates the gravitational attraction, but when the trajectories run through regions perturbed by the interaction of both primaries this strategy becomes less efficient.

Here, a method based on the progressive perturbation of the natural trajectory until the desired point is attained has been implemented. If no manoeuvre is performed, the particle will follow its natural path, but if it is desired that it gets to a point slightly separated from that path, the natural trajectory will be a good initial guess for the targeting process. This differential correction can be integrated into a continuation scheme, using the previously corrected solution as an initial guess for the next step, until the final desired point is achieved. In the next figure it is possible to see the initial point (x_0) and the final point (x_d), as well as the initial trajectory of the particle and the final one. To start the continuation schema, the closest point to the final one is found in the initial trajectory ($x_{d,0}$). Then, segment connecting these two states is divided in n points ($x_{d,i}$). At each step, the initial velocity is corrected to reach $x_{d,i}$ and with the results obtained, the initial guess for the next step is predicted. This is repeated until the final point is reached.

The presented algorithm makes it possible to find a solution between two points for a given transfer duration, but to find the cheapest way to connect two orbits it is necessary to optimise the initial and final points, and the ToF. To achieve this goal, an optimiser (Nelder-Mead algorithm) of the *SciPy* library [18] has been implemented.

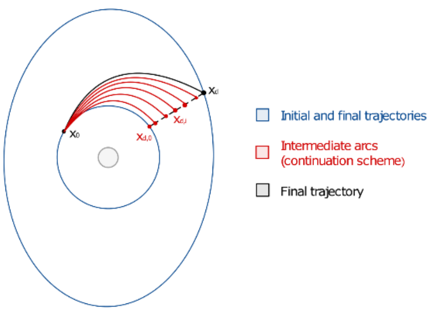

Fig. 7. Continuation scheme used in the transfer problem.

Once the method has been explained it is possible to introduce the different cases that have been studied. The first of the studied cases is the transfer between two trajectories in the DRO region in a given time of flight. The Artemis I orbit is chosen as the final trajectory, and as Period-tripling DROs have manifolds which provide a transport path between different regions of space, the transfer cost departing from one of these orbits is evaluated. To evaluate the worst-case scenario, the selected Period-tripling DRO is the one with the most different Jacobi constant (3,0405) with respect to the one of the target orbit (2,9420). As a reference case, a transfer between two DROs with the stated values of Jacobi constant is also presented.

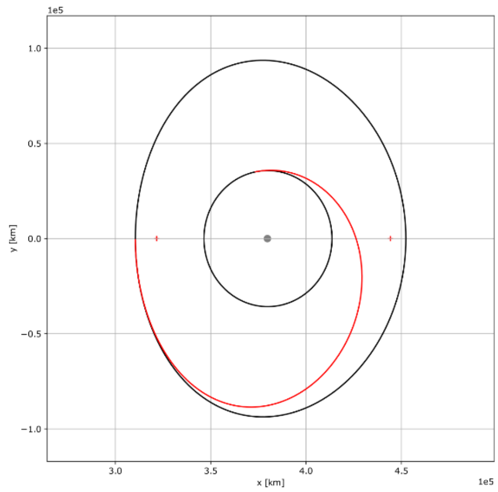

Fig. 8. Optimal transfer between DRO-DRO.

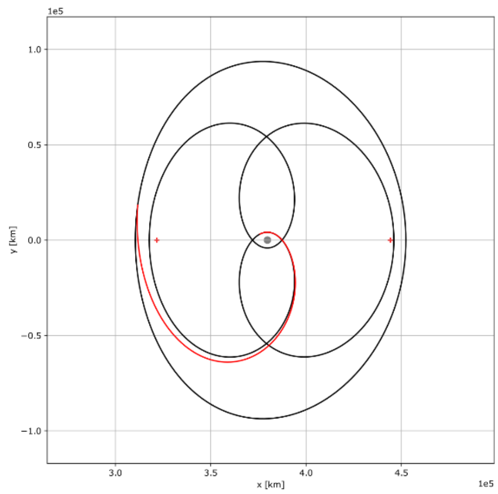

Fig. 9. Optimal transfer between P3DRO-DRO.

Comparing the costs in Table 3, for a transfer between two DROs, when going from one of lower altitude to a higher one, it is required to give a higher impulse at the depart point and a lower one at the arrival, which is logical as the energy must be raised to achieve the target orbit. On the other hand, for the transfer from the Period-tripling DRO to a DRO, the first impulse is really low, which is justified by the fact that this orbit has an unstable manifold, meaning that a small perturbation will make a particle leave it. However, the impulse at the arrival point is much higher to match the energy of the final orbit. In the end the total cost is almost the same. Also, the transfer takes less time when departing from a P3DRO, as this transfer arc is shorter.

Table 3. Cost and time of flight for the two cases.

Transfer	**ΔV_1[m/s]**	**ΔV_2[m/s]**	**ΔV[m/s]**	**ToF[h]**
DRO-DRO	76,7	27,9	104,6	200,8
P3DRO-DRO	3,1	105,4	108,5	139,4

For the development of operations near the Gateway, it is interesting to apply this same method to study transfers linking a 9:2 resonant NRHO to a DRO (in this case one with a period of 12,17 days). In this work only the transfer in one sense is presented, but the invers transfer presents an analogous behaviour. The cost of the optimised transfer is of 188,1 m/s at the departure point and of 265,9 m/s at the arrival. The total transfer has a cost of 454,0 m/s and a total duration of 149,0 h (6,2 days). These results agree with the ones presented in [19]. Moreover, the obtained solution presents an analogous shape to some of the transfers between a northern NRHO and a DRO presented in [9].

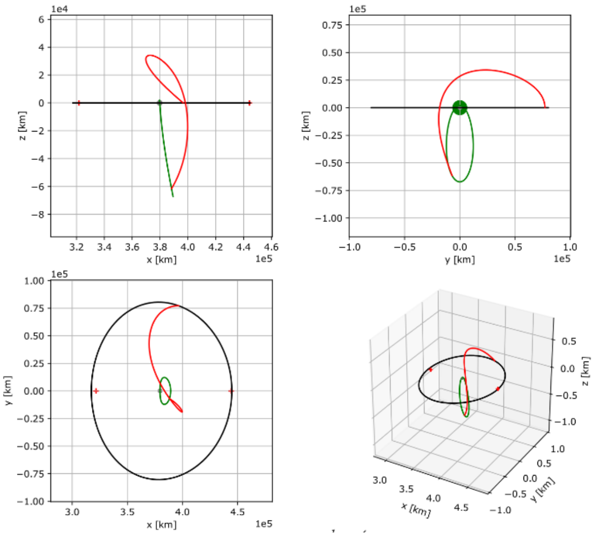

Fig. 10. Optimal transfer between NRHO-DRO.

B. Trans-lunar trajectories

In this part, the analysis of strategies to reach a DRO orbit from the Earth is carried out. In this case, the goal is to reach the Artemis I orbit from a departure point at an altitude of 200 km above the Earth from which the Trans-Lunar Injection is performed. This is a subject of study that has been widely studied, with almost each paper mentioning this kind of orbits in the Earth-Moon system presenting a way to reach them from Earth. An extensive study of multiple strategies was presented in [8], and at the end, the chosen strategy was the close Lunar flyby because it allows for a considerable decrease in fuel consumption.

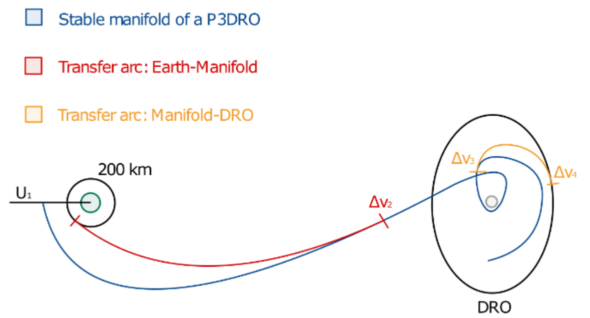

Fig. 11. Implemented strategy to design an Earth-DRO transfer.

The approach followed in this work takes advantage of the existence of manifolds of P3DROs connecting the Earth neighbourhood with the Lunar vicinity. By the insertion of a vehicle in a stable manifold of an orbit, no manoeuvres other than minor corrections will be needed for it to be placed into that orbit. This trajectory is known as a low-energy transfer or ballistic capture. However, due to the inherent qualities of manifolds, this type of trajectories tends to take a considerable amount of time and are therefore too long for most applications. Nevertheless, as they approach a periodic orbit asymptotically, it is possible to perform a transfer arc to place the vehicle in the desired orbit when it is close enough. In fact, it was shown in [13] that there is a trade-off between the manoeuvre cost and the coasting time in the manifold.

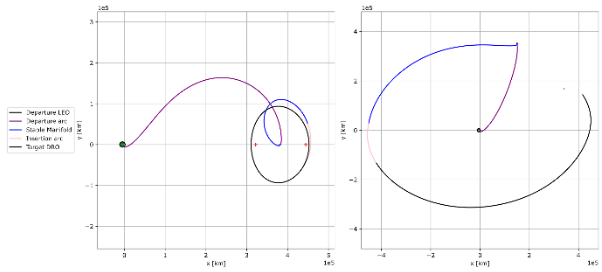

Fig. 12. Complete trajectory in the synodic and in the inertial frames.

The obtained results show that with a ΔV of 290,3 m/s it is possible to reach the target orbit in 15,5 days. These results are similar to the ones obtained with the proposed fly-by and agree with the costs of the already completed mission, Artemis I [20]. The advantage of working with the presented method is that by changing a reduced number of parameters (selected manifold, and insertion and departure points) which have a physical sense in the CR3BP it is possible to obtain a wide variety of solutions which should be suitable for a certain application. What is more, this same method can be applied to a wide number of destination orbits that have manifolds or that have neighboring orbits with manifolds.

C. Interplanetary trajectories

There are various characteristics of DROs that make them a suitable emplacement for a space station which would serve as an outpost from where to leave to other planets or a site where large vehicles to perform long journeys could be assembled. Here, the goal is to show that it is possible to exploit the natural dynamics of the system to design trajectories that escape the Earth-Moon environment with a low transfer cost. Then, the interplanetary phase can be studied with the approach which is more attractive for the designed mission.

Accordingly with the hypothesis that have been adopted along this work, some simplifications have been introduced. First, the orbit of the Moon around the Earth, as well as the orbits of the Earth and Mars around the Sun are considered to be in the same plane. Next, instead of taking into account the gravitational influence of all the bodies at the same time, the studied domain has been divided in three models: the Earth-Moon CR3BP, the Sun-Earth CR3BP and the Heliocentric 2BP.

With these hypotheses, the method applied to study this kind of trajectories starts with the propagation of a certain number of unstable manifolds of a Period-tripling DRO until they intersect with the U2 Poincaré section of the Sun-Earth system. On the other side, stable manifolds of a Planar Lyapunov orbit at L2 in the Sun-Earth system are propagated until the same Poincaré section. With these, it is possible to identify the trajectories that would pass through the neck section at L2 in the Sun-Earth system to leave the Earth-Moon system towards the outer solar system. Then it is possible to connect the manifold with the DRO, on one side, and on the other, the transit trajectory with Mars.

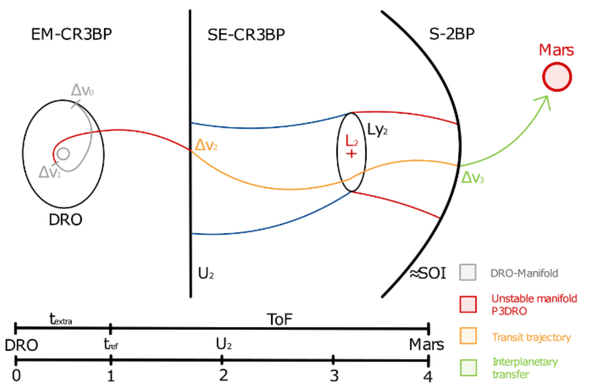

Fig. 13. Scheme of a complete trajectory from a DRO to Mars.

Having presented the process followed, the computed results for a set of trajectories with a defined departure date and time of flight can be evaluated. The reference departure date for the results in following figure is the 01-08-2024 and the total duration of the journey is of 350 days.

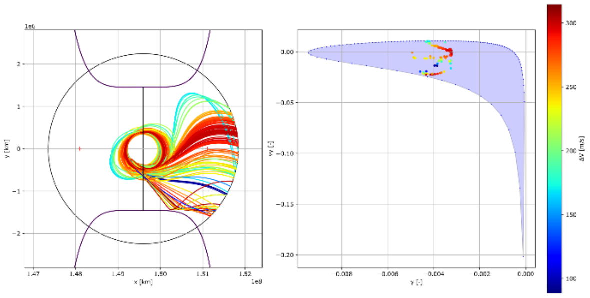

Fig. 14. Escape trajectory from the Earth-Moon system.

Additionally, the evolution of the cost for the dates between 01-02-2024 and 01-01-2025 and a journey duration between 250 and 350 days was evaluated. The obtained results show that the required ΔV to escape the Earth-Moon vicinity is in between 0 and 250 m/s, plus the amount to connect the departure orbit with the manifold which is below 100 m/s. It must be noted that the impulse to raise the transfer up to the orbit of Mars has still to be included, but what this study proves it is possible to leave a DRO towards an interplanetary journey without requiring a great impulse.

D. Station-Keeping analysis

To complete the study of the applications of DROs it is interesting to evaluate the costs of keeping a spacecraft in this orbit for an extended time. First, a theoretical orbit in the CR3BP is converted into a more realistic orbit in the Earth-Moon-Sun ephemerides model. Then, it is propagated for a certain time to check the corrective manoeuvres that should be carried out along time.

The process to get the initial state of the realistic orbits consists in the adjustment of the initial state in the J2000 frame using a Least-Squares minimisation. This computation, conducted for a certain number of orbits ensures that the orbit will stay near the reference one for some time. The adjustment was carried out starting from a duration of half of the period and increased up to four orbits. Then, the computed state was propagated for 100 orbits (3,75 years), showing that the maximum separation during this time was of 10.0000 km.

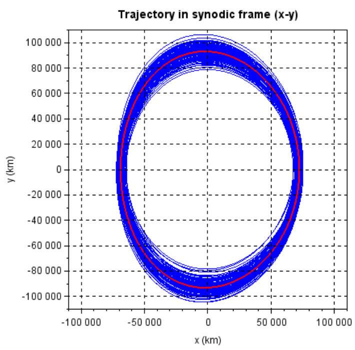

Fig. 15. DRO adjusted in a realistic Earth-Moon-Sun force model (synodic frame).

These results are consistent with the studies presented in [2] which show that the studied DRO can be maintained without any corrective manoeuvre for extended periods of time. However, further studies should be carried on this subject as it is provable that the initial state cannot be achieved with the required accuracy.

V. Conclusions

With the study of the DRO family and its bifurcations it is possible to state that almost all the orbits of the family are linearly stable. Also, although these orbits do not have manifolds, there are some of its bifurcating families in the same region which do, providing paths connecting DROs with other regions of space. Secondly, it has been proven that DROs are a suitable emplacement for a space outpost which might be useful for in-situ resource utilisation or to refuel a spacecraft leaving for distant destinations. This is justified by the following facts: these orbits can be easily accessed from the Earth, manoeuvring between orbits of the family is not expensive, they provide the possibility to escape the Earth-Moon vicinity at a low cost and do not require significant station-keeping manoeuvres. Finally, all these studies developed using *SEMpy* prove that is a convenient tool to study multi-body dynamics.

VI. References

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