Using intermediate NRHOs for phasing with the Lunar Gateway in future lunar exploration missions.

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Abstract – The European Space Agency (ESA) is working on a future exploration architecture which would ensure delivery of cargo and crew to Low Earth Orbit (LEO), the Lunar Gateway, and the Lunar Surface. An effort that will not only contribute to resupplying the International Space Station while still in commissioning, but also create a bridge towards the next LEO space ventures. It will also supplement the Artemis program from NASA in accessing the Moon. A key element of future lunar exploration is the Lunar Gateway, located on a Near Rectilinear Halo Orbit (NRHO), permitting a stopping point for preparation and rest before lunar surface missions. Given the peculiarity of its orbit, and the launch constraints from Europe's spaceport, reaching it directly from Earth is challenging and requires a certain phasing, which in turn limits the available launch windows. These windows are indeed rather narrow, requiring the Moon to be close to the nodal crossings and the Gateway to be properly phased. This paper presents a solution to this problem, by injecting the spacecraft on an intermediate NRHO and then performing phasing manoeuvres to insert on the Lunar Gateway NRHO. Such strategy allows to decouple the Earth-Moon transfer problem from the Gateway rendezvous, since the phasing on the intermediate NRHO is free. This is done by designing and optimising trajectories between NRHOs in the Circular Restricted Three-Body Problem for the most efficient cost or time of transfer, identifying the different solution families, and then testing them with a full ephemeris model. Finally, the paper investigates how to extend the initial transfer solutions between the intermediate NRHO and the Lunar Gateway NRHO by studying transfers where a loitering time is spent on the intermediate NRHO, until the right configuration for a low cost or low time transfer is found. These solutions will allow for lunar missions to have flexibility in getting to the Gateway and overcome launch windows limitations deriving from the Gateway's phasing.

I. INTRODUCTION

The European Space Agency is setting its course for the Moon, not only through the Argonaut program, but also through a long-term strategy to build up capabilities that would ensure delivery of cargo and crew to LEO, the Gateway, and the lunar surface. Due to the specificities of the NRHO and the constraints given by the launch location, targeting the Gateway directly from Earth leads to constraints in the transfer, which in turn, impacts the launch windows. This paper will discuss how to mitigate this constraint by allowing the spacecraft to arrive on a first intermediate NRHO before making its final transfer to the Gateway orbit.

Section II will give more details on the background for this phasing problem while Section III and IV will show the results of the study in a restricted dynamical model and in an ephemeris model respectively. Section V will review the results on the strategy to employ to reach the Gateway with an equatorial launch.

II. BACKGROUND

The Gateway will be located on an NRHO around the Moon with a period of 6.56 days. While these types of orbits are easily accessible when launching from KSC, a launch from Europe's spaceport in French Guyana (Centre Spatial Guyanais, CSG) located near the equator is quite different. Launching from CSG, a maximum performance LTO inclination will always be lower than the inclination of the Moon orbit and therefore launch opportunities only occur twice per month, when the Moon crosses the Earth's equatorial plane [1]. This reduces drastically the launch opportunities as the Moon position on arrival needs to be at the intersection of the Moon and transfer orbital planes for the transfer to be possible, i.e., very close to the lunar line of nodes. A second constraint is added by the phasing of the Gateway on its orbit, which shall be suitable for rendez-vous upon arrival of the spacecraft on the NRHO. This even further constrains the launch opportunities, which need to satisfy both the lunar and the Gateway phasing constraints.

A. *Phasing strategy*

The proposed solution is to have the spacecraft arrive on an intermediate NRHO, one with a different orbital period than the Gateway, and wait until the optimal phasing before performing the transfer to the Gateway. The following nomenclature is employed:

- Intermediate NRHO: an NRHO of different orbital period than the one of the Gateway NRHO.
- Transfer time: time on the transfer arc between two NRHOs.
- Loitering time: waiting time spent on the intermediate NRHO before transferring to the Gateway NRHO.
- Phasing time: total or sum of the loitering and transfer time of flight.

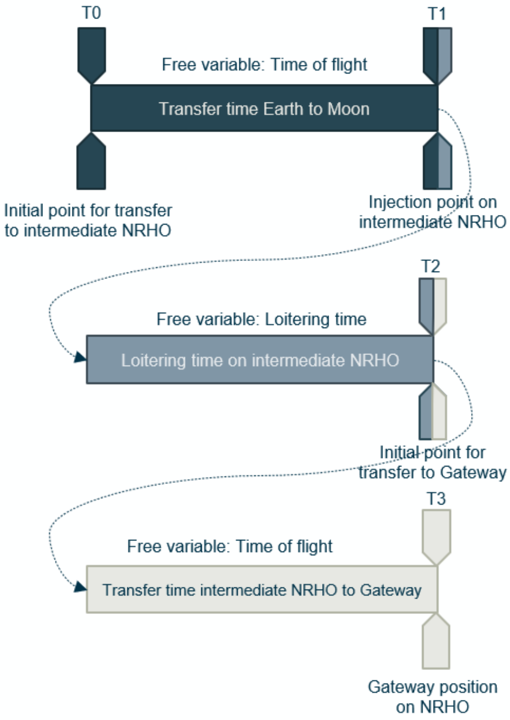

Fig. 1. Timeline for transfer between LEO and Gateway NRHO.

Additionally, the sequence of main events to be considered for the final trajectory is depicted in Fig. 1 where:

- T0 represents the initial point in LEO/LTO from which the Earth-Moon transfer will begin, given a free time of flight T1-T0. The optimisation of the Earth-Moon transfer is not considered in this paper.
- T1 shows the injection point on the intermediate NRHO, having a different orbital period than the Gateway.
- T2 represents the initial point of transfer from the intermediate NRHO to the Gateway, where the time between T1 and T2 is the loitering time.
- T3 shows the position of Gateway after the transfer, where T3-T2 is the transfer time between the intermediate NRHO and Gateway. Note that T3-T1 is the total phasing time composed of the loitering time and the transfer time.

B. *Dynamical Models*

In this paper, two different dynamical environments will be used:

- The Circular Restricted Three-Body Model, useful for preliminary analyses which require a simplified model, but cannot rely on Keplerian dynamics.
- A full ephemeris model, considering the point mass gravities of the Earth, the Moon, and the Sun, with their real motion taken from JPL DE432 ephemeris.

The Earth-Moon trajectory design is performed in the full ephemeris model.

The study of the phasing between two NRHOs will be done in the dynamics of the circular restricted three-body problem (CR3BP). This problem is posed when a negligible mass (m_3) is under the gravitational force of two primaries (m_1 and m_2) [2]. The equations of motion are described in a rotating frame where x-axis is directed from the largest primary m_1 to the smaller one m_2. The y-axis is perpendicular to the x-axis in the orbital plane of the primaries and the z-axis completes the coordinate system by pointing out of the xy-plane. This is called a synodic system [2]. The mass parameter can be defined such that:

$$\mu_{1,2} = \frac{m_{1,2}}{m_1 + m_2}$$

where $\mu_1 = 1 - \mu$ and $\mu_2 = \mu$. This allows to pose the Lagrangian dimensionless equations of motion in the synodic frame such that:

$$\ddot{x} - 2\dot{y} = \Omega_x$$
$$\ddot{y} + 2\dot{x} = \Omega_y$$
$$\ddot{z} = \Omega_z$$

where Ω_x, Ω_y and Ω_z are the partial derivatives of the potential function:

$$\Omega(x, y, z) = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{r_1} + \frac{\mu}{r_2} + \frac{1}{2}\mu(1-\mu)$$

where $r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2}$ and $r_2 = \sqrt{(x-1+\mu)^2 + y^2 + z^2}$ are the distances of the negligible mass from the primaries.

C. *Earth-Moon Transfer Geometry and Cost*

There are two types of direct transfers to reach the intermediate NRHO from Earth. The first one shown in Fig. 2 shows direct transfers between the Earth and the

NRHO. The second one in Fig. 3 shows a transfer which includes a powered lunar gravity assist (LGA) before reaching the NRHO.

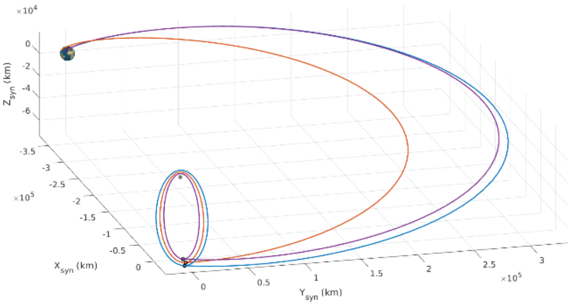

Fig. 2. Direct transfers to NRHOs with different orbital period (blue = 7.5 days, red = 7 days, purple = 6.5 days) in the Earth-Moon rotating frame [3].

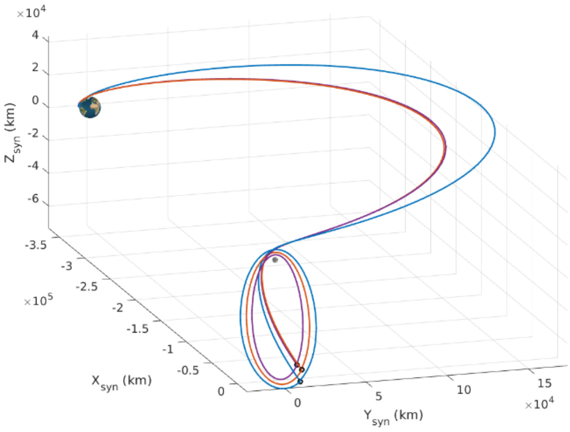

Fig. 3. Transfers with LGA to NRHOs with different orbital period (blue = 7.5 days, red = 7 days, purple = 6.5 days) in the Earth-Moon rotating frame [3].

The cost of a powered LGA transfer can be as low as 500 m/s with a time of flight of ~6-7 days as shown in Fig. 4.

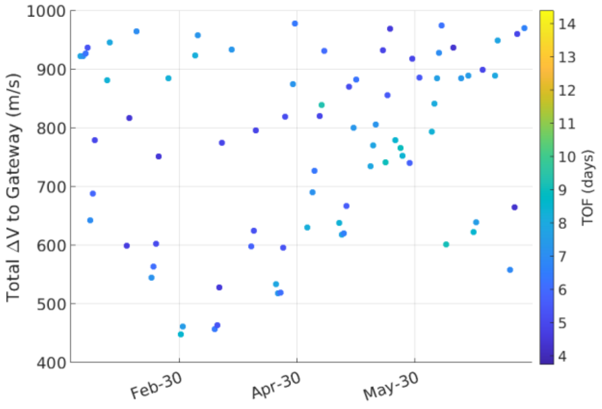

Fig. 4. Transfer cost to the Gateway with LGA from equatorial LTO.

Note that the plot is saturated to 1000 m/s, discarding excessively expensive solutions. Optimal solutions are found when both the lunar and Gateway phasing constraints are satisfied, otherwise, a significant Δv penalty is required.

Low-energy transfers to the Gateway (e.g. employing the Weak Stability Boundary) are not considered in this study. Given their long time of flight, it is reasonable to assume that such transfers won't need the presented phasing strategy, and the time of arrival to the Gateway can be freely tuned during the transfer.

III. PHASING SOLUTIONS IN CR3BP

A. *Total phasing time analysis*

Due to the constraints explained in Section II, it is possible that a spacecraft arriving from the Earth-Moon transfer would not be in the optimal phasing configuration for a direct transfer to the Gateway NRHO. Thus, the loitering time on the intermediate NRHO needs to be analysed. The phasing time will depend on where the spacecraft injects on the intermediate NRHO, when arriving from Earth, and from where it will depart to transfer to the Gateway NRHO. These points of injection, departure and arrival on the orbit can all be defined by the quantity mean anomaly, which is defined as the angle between the point on the orbit and the periselene. The periselene will therefore be considered at 0° and the aposelene at 180°. The mean anomaly can be used to quantify the arrival position of the spacecraft on the intermediate NRHO in Fig. 3 where, assuming an optimal transfer to the NRHO with a powered LGA, the mean anomaly at injection on the intermediate NRHO is 80°.

The study is built by initially performing a large search, to determine all the possible transfers between an intermediate NRHO and the Gateway NRHO. To determine the cost of transfer and time of flight for all possible configurations of transfer, a three-dimensional grid was created with each variable: time of flight (TOF), departure point from intermediate NRHO and arrival point on the Gateway NRHO. Using the set of all the transfer solutions found to reach the Gateway orbit from the intermediate NRHO, the phasing time for the trajectory can be determined. The approach to solving this problem is to work backwards. The position of the Gateway on its NRHO is known, the time to transfer from the intermediate NRHO to the Gateway NRHO is also known and the time from the injection point on intermediate NRHO to departure point for the transfer can be calculated.

It was determined that the minimum cost of transfer will have a higher total phasing time and the solutions with a lower total phasing time will have a higher cost of transfer. There is a trade-off between cost and time of transfer.

B. *Transfer study*

It is possible to compute the minimal cost of transfer between any intermediate NRHO and the Gateway NRHO. In Fig. 5, the transfer solutions depending on the period of intermediate NRHO can be found. The period of the Gateway NRHO is marked as a vertical blacked dashed line. Intuitively, the minimum cost of transfer is achieved when the difference between the intermediate NRHO period and the Gateway period is smallest. The cost then increases regardless of whether the intermediate NRHO period increases or decreases. It can be noted that only the minimum ΔV solutions are shown here for the optimal phasing. There exists a full range of solutions when varying the cost of transfer (ΔV), the time of flight and the phasing between the two orbits.

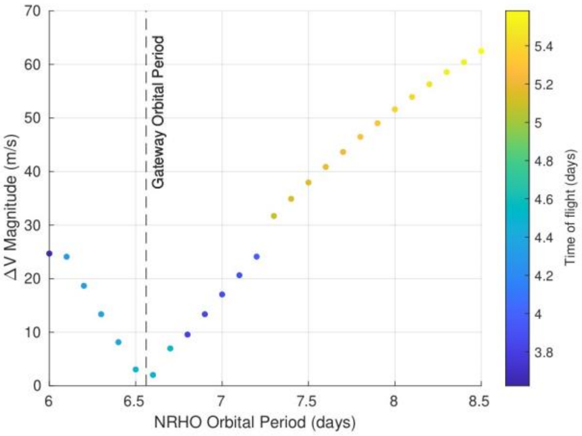

Fig. 5. Cost of transfer between each intermediate NRHO and the Gateway orbit.

C. *Multiple revolution transfer study*

So far in this paper, only transfers shorter than the period of the Gateway NRHO have been used to perform the transfer between an intermediate NRHO and the Gateway NRHO. Multiple revolution transfers can be investigated by giving a grid of time of flight as input to simulate the transfer. In Fig. 6, transfers with a time of flight between 0.5 and 25 days were calculated. Multiples of the Gateway orbit period are shown as vertical black dashed lines. A global search was performed using different initial guesses, this allowed to find at least two solutions per time of flight for a transfer between a 7-day period NRHO and the Gateway orbit.

For a deeper understanding, the *x*-axis in Fig. 6 is divided into four intervals:

- 0 days to 1 Gateway period (T_{GW})
- 1 T_{GW} to 2 T_{GW}
- 2 T_{GW} to 3 T_{GW}
- 3 T_{GW} to 4 T_{GW}

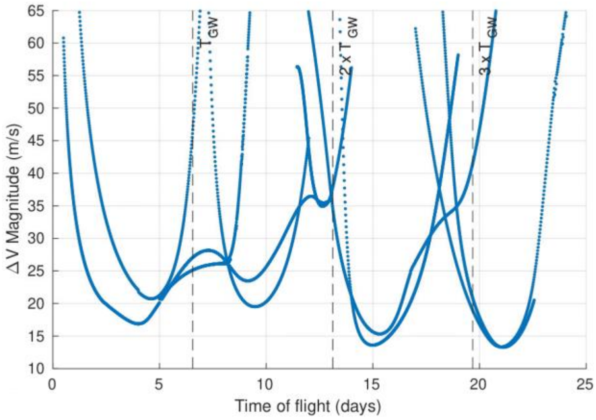

Fig. 6. Cost of transfer over a transfer time grid of 0.5 - 25 days for a transfer between a T = 7 days intermediate NRHO and the Gateway orbit.

For each interval, there is a minimum cost for transfer with an associated time of flight where the most expensive transfer minimum occurs between 1 T_{GW} and 2 T_{GW}. A transfer in the interval of 0 days to 1 T_{GW} will be less expensive than between 1 T_{GW} and 2 T_{GW} however the cost of transfer minima after 2 T_{GW} are always lower than the minima prior to 2 T_{GW}. Practically this means when a spacecraft injects on the intermediate NRHO after the Earth-Moon transfer, there are multiple solutions for a low-cost transfer and if there are no time constraints, particularly low-cost transfers can be taken. This could be explained by the presence of manifolds departing from NRHOs allowing for cheaper transfer costs but higher flight time. Additionally, it can be noted that the minima are always in-between multiples of T_{GW}, having a shape similar to Hohmann transfers.

D. *Transfer families analysis*

To visualise the solutions for minimum cost of transfer for any time of flight between 0.5 and 25 days, an algorithm can be created where for each point on the time-of-flight grid (*x*-axis), the minimum value for the cost of transfer (*y*-axis) will be stored. Additionally, it can be of interest to know which point the spacecraft is targeting after the transfer and therefore where the Gateway will have been located.

Fig. 7 shows the position of the Gateway after the transfer for all the minimum transfer solutions over a time grid of 0.5-25 days. The colours represent the position on the arc where the yellow represents the ascending arc (from periselene to aposelene) and the green, the descending arc (from aposelene to periselene).

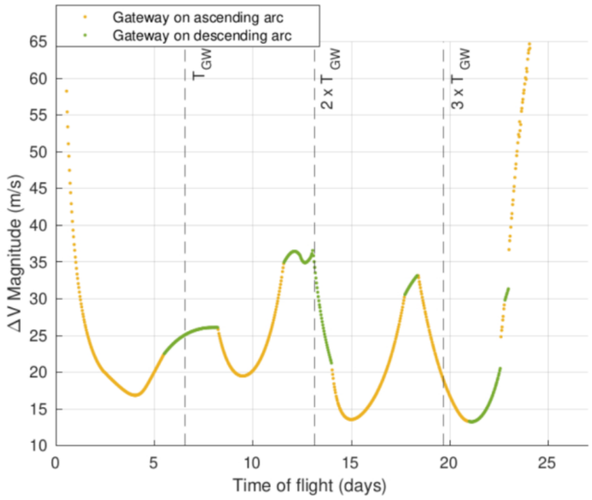

Fig. 7. Minimum cost of transfer over a transfer time grid of 0.5 - 25 days for a transfer between an intermediate NRHO T = 7 days and the Gateway orbit.

The minima cost of transfer corresponding usually to an arrival on the ascending arc of the Gateway NRHO. Such transfer is shown in Fig. 8 where the arrival point of the transfer can be seen as the green circle on the Gateway orbit.

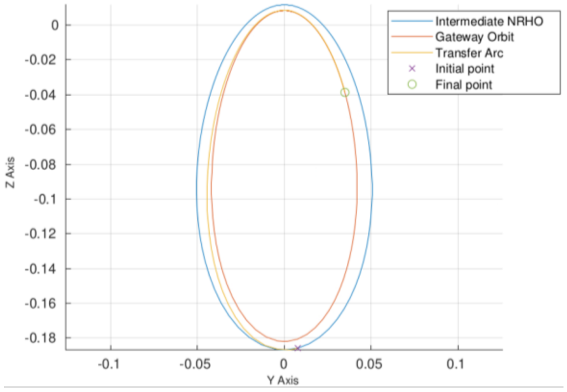

Fig. 8. Type 1 transfer with arrival on ascending arc.

Another family of transfers can be found, as shown in Fig. 9, where the arrival point of the transfer is on the descending arc of the Gateway NRHO.

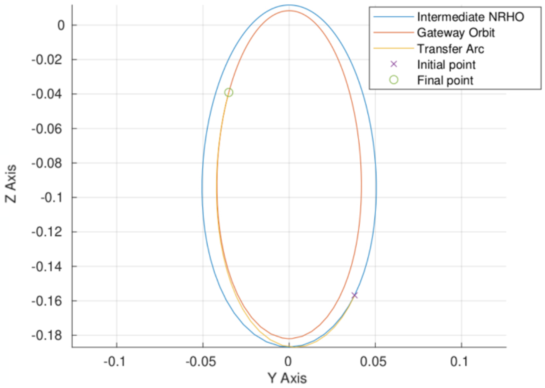

Fig. 9. Type 2 transfer with arrival on descending arc.

IV. PHASING SOLUTIONS IN FULL EPHEMERIS

Having found a solution for the phasing problem in the CR3BP dynamical model, it is important to test it in the full ephemeris model. The problem is slightly different as the position of the spacecraft in space does not repeat at each revolution of the NRHO, as it would in CR3BP, but is dependent on the epoch. A possible way to approach it is to work backwards: the epoch at which the spacecraft will arrive at the Gateway is known, the departure epoch from the intermediate NRHO can be calculated from the time of flight of the transfer arc which will in turn impact the initial epoch of the intermediate NRHO.

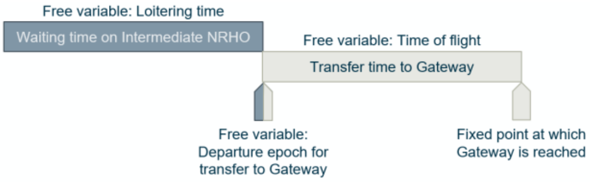

Fig. 10. Depiction of the phasing problem between an intermediate NRHO and the Gateway in full ephemeris.

The problem is setup as follows:

- Free Δv and time of flight of the transfer.
- Free initial and departure epoch for the intermediate NRHO.
- Fix state and epoch for arrival on the Gateway orbit.

Fig. 11 shows an example of such transfer where the departure epoch from the intermediate NRHO is 2029-12-31T03:38:45Z and the arrival epoch at the Gateway is 2030-01-04T12:00:00Z. The period of the intermediate NRHO is 7 days. The time of flight for this transfer is 4.35 days for a cost of 16.7 m/s. This is very similar to the Type 1 transfer seen in Fig. 8 and the cost of transfer is still coherent with the CR3BP solution shown in Fig. 5.

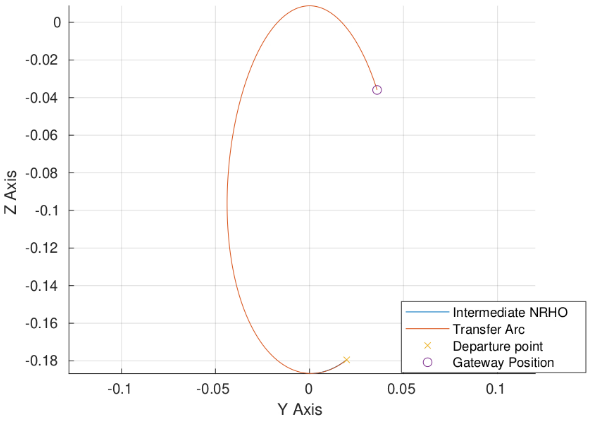

Fig. 11. Transfer between intermediate 7-days period NRHO and the Gateway using full ephemeris model.

The arrival epoch at the Gateway can be varied to understand the relationship between transfer cost and target Gateway position. The Gateway epoch was varied by 0.5 days over a 40-day period, the results are shown in Fig. 12. The shape of the data shows how the configuration for the transfer highly impacts the cost of the latter. Given the current setup of the problem, the transfer cost results higher when the Gateway is at the aposelene, since the transfer departs close to the aposelene, and the solution converges to fast transfers. This is expected to be solved by also considering multi-revolution transfers and by setting up the end-to-end optimization. As the arrival point on the Gateway moves away from the aposelene, the cost of transfer decreases as more optimal transfer configurations are reached.

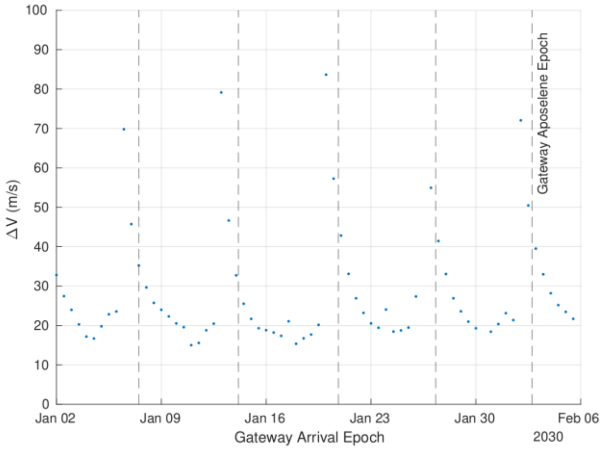

Fig. 12. Cost of transfer for transfers when varying the arrival epoch at the Gateway.

Finally, and using the study from Section III.A for the loitering time spent on the intermediate NRHO after insertion from the Earth-Moon transfer, it is possible to understand how the transfers determined in the full ephemeris model are compatible with the NRHO Insertion (NOI) epoch. This epoch is calculated using the Lunar Orbit Insertion (LOI) epoch (ie. the epoch where the Moon and transfer orbital planes intersect) and the assumed mean anomaly for the NOI. This serves as initial guess, as a re-optimization of the full problem from LTO to Gateway might deviate from this assumption.

Fig. 13 shows all possible transfers and their compatibility with the NOI epoch. The black horizontal lines illustrate the different possible NOI epochs due to the launch constraints. Compatible transfers with the NOI epochs are shown overlapping or very close to the black lines. It can be noticed that some transfers become possible and compatible with a different NOI epoch when the loitering time is increased by one to two NRHO period.

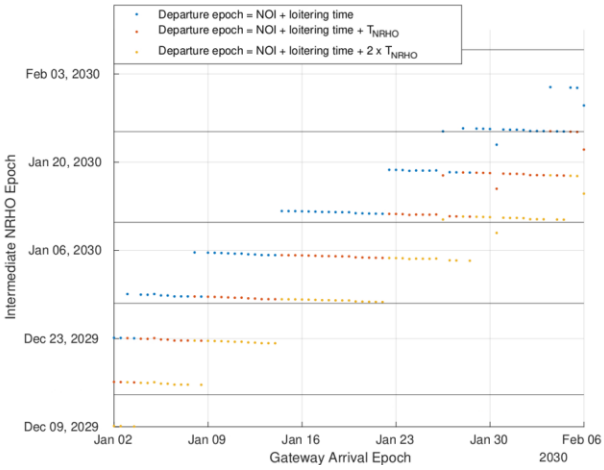

Fig. 13. Transfer possibilities considering the NRHO insertion (NOI) epoch.

This final figure cumulates and highlights all the previous points that have been demonstrated throughout this paper. The phasing problem is complex and even more so when studied in the full ephemeris model. Transfers are possible although the right configuration between the NOI, departure epoch on the intermediate NRHO and the arrival epoch on the Gateway NRHO needs to be well chosen for a solution to be feasible. The loitering time on the intermediate NRHO is crucial for identifying solutions.

V. CONCLUSION

This work has presented the difficulties to reach the Gateway on its NRHO with a launch from equatorial CSG and has shown how using an intermediate NRHO can mitigate the problem and offer more solutions for the launch window.

An Earth-Moon transfer with a powered lunar gravity assist is preferred to reduce the cost of transfer. This was shown to lead to an insertion on the intermediate NRHO at a mean anomaly of 80°. If the optimal departure point for the transfer to the Gateway orbit is known, it is possible to determine the loitering time on the intermediate NRHO before performing said transfer.

A study was performed for multiple revolution transfers and showed that multiple transfers are possible for a single time of flight and that cost of transfer generally decreases with increasing time of flight. The transfer configuration was also identified to have in general two types of transfers with one having an arrival on the Gateway orbit on the descending arc and the other on the ascending arc. The latter usually requiring the lowest cost of transfer.

Finally, solutions were tested in the full ephemeris model where similar cost of transfer and time of flight were found as for the solutions in CR3BP. Under this model, the solutions were constrained by each state being associated with an epoch which led to solutions needing the right configuration between the NOI, departure, and arrival epoch for the solution to be possible. The problem remains complex but the intermediate NRHO is a solution which allows for larger launch windows.

Future studies will be devoted to generalising the phasing problem using intermediate NRHOs with different periods, and to setting up the full optimisation problem from LTO to Gateway, phasing strategy included.

VI. REFERENCES

[1] W. Martens and L. Bucci, *Cis-Lunar Transfer Vehicle (CLTV) - Mission Analysis Guidelines*, European Space Agency, Issue 1, Revision 2, OPS-GFA-TN-125 2021.

[2] F. Bernelli Zazzera, F. Topputo and M. Massari, “Assessment of Mission Design Including Utilization of Libration Points and Weak Stability Boundaries,” European Space Agency, 2004.

[3] L. Bucci, M. Hutton and M. Burnichon, *Human Inspirator Mission Analysis Guidelines*, European Space Agency, Issue 1, Revision 0, OPS-GFA-TN-132, 2023.

[4] W. S. Koon, M. W. Lo, J. E. Marsden and S. D. Ross, Dynamical Systems, the Three-Body Problem and Space Mission Design, 2006.