CIS-LUNAR TRANSFER VEHICLE: MISSION ANALYSIS FOR AN ESA TRANSFER VEHICLE TO THE GATEWAY

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ABSTRACT

Discussions between ESA and NASA identified the development and deployment of a lunar orbital platform gateway concept, called the Gateway, as an intermediate step towards human deep space travel. In order to fulfil the new exploration objectives, the study of a Cis-Lunar Transfer Vehicle concept has been performed at Airbus Defence and Space under the supervision of ESA. This paper summarizes the mission analysis that has been conducted to support preliminary system design, payload mass estimation and mission timeline for the investigated mission architecture and for the system trade-offs. In particular, launch, transfer and phasing options are designed and optimized in a high-fidelity model. Finally, the feasibility and robustness of these options under realistic operational requirements are analysed and the overall mission performance is assessed and traded providing a broad scope of future transfer options from Earth to the Gateway.

1 INTRODUCTION

In 2018, the International Space Exploration Coordination Group proposed international agreements on space exploration: expand human presence into the Solar System, with the surface of Mars as a common driving goal and prepare for space exploration missions beginning with the ISS and continuing to the lunar vicinity, the lunar surface, then on to Mars. The development and deployment of a lunar orbital platform gateway concept, called the Gateway, has been proposed as an intermediate step towards deep space travel. The Gateway would be placed in a Near Rectilinear Halo Orbit (NRHO) [1]. The NRHO has been identified as a suitable orbit for fulfilling the various mission requirements [2] and has been recently reached by NASA's CAPSTONE spacecraft to pave the way for future missions [3]. The Gateway would, for instance, host crews on their way to the Moon surface or serve as an assembly point for the various elements of lunar landers.

To fulfil some of these exploration objectives, the study of a Cis-Lunar Transfer Vehicle (CLTV) concept has been performed at Airbus Defence and Space (ADS) under the supervision of the European Space Agency (ESA): in its initial configuration, the CLTV would be an unmanned expendable space transport vehicle designed for logistic servicing of the Gateway. It provides the capabilities of delivering pressurized and unpressurized cargoes to the Gateway and serves for the Human Landing System (HLS) Refuelling. One of CLTV's mission scenario consists in using the Ariane 6 launch services and then performing orbit transfer to the Gateway's NRHO. Once this orbit is reached, the CLTV performs autonomously all the operations until docking to the Gateway.

In order to support the architecture trade-off and selection, a set of constraints and requirements were defined by the Agency, covering various mission objectives, target payload mass, launch vehicles and timeline requirements. Based on these requirements, a set of architectures were investigated with the objective of providing useful information for a mission architecture and system trade-off and defining one or more transfer baseline. In particular, 1) the launch options – launch into *Lunar Transfer Orbits* (LTO) or into Earth bounded orbits such as GTO, the impact of the launch inclination and launch epoch and 2) transfer types – from short transfers to the NRHO with and without powered gravity assist to long low-energy transfers – are optimized and assessed in a high-fidelity tool, LEMONADE (Lunar transfEr MissiON Analysis and Design). Finally, the feasibility and robustness of these transfer and phasing options under realistic operational requirements are analysed and the overall mission performance (payload delivery, transfer duration, launch window, etc …) is assessed and traded providing a broad scope of future transfer options from Earth to the Gateway.

2 MISSION OVERVIEW and KEY DRIVING REQUIREMENTS

2.1 Cis-Lunar Transfer Vehicle Mission Overview

Candidate missions for the CLTV study have been identified by the Agency and, as a part of a precursor activity, they have been preliminary screened to create families of potentially similar missions. Then, they have been prioritized on the basis of criteria covering the maturity of the corresponding scenario, the programmatic interest for Europe, and the required critical technologies. Four main groups of missions emerged from this initial trade-off:

- A: Logistic missions (dry cargo, propellants) to cis-lunar orbit infrastructure, in particular the Gateway being developed in NRHO.
- B: Missions in support to the establishment and resupply (module delivery, cargo delivery/return, refuelling, AOCS and re-boosting, resource module) of an autonomous LEO Free Flyer/ Habitat.
- C: Missions enhancing European autonomy (support to cargo delivery to the Moon surface, support to a Moon sample return mission, instrumentation delivery to LLO).
- D: In-orbit servicing missions aiming at an orbiting space vehicle/debris (satellite repair/ improvement and life extension).

These four group of missions have been analysed in 2021 by ADS in the frame of a Phase A-B1 study on behalf of ESA. The proposed design approach was to develop the CLTV core vehicle for both Reference Missions (Group A). Then, based on the proposed CLTV definition, the system design addressed the main evolutions required for the Application Missions, listed in Groups B, C and D. While all mission groups were covered by the mission analysis, this paper focuses on the Group A missions, with 1) a cargo mission to the Gateway and 2) a HLS refuelling mission.

2.2 Cis-Lunar Logistic Mission Key Driving Requirements

The logistic missions in support to Moon human exploration are considered the Reference Missions for the CLTV design. They are also the performance drivers, due to the Ariane 6 capability [4]. Both reference missions are targeting the Gateway, which will be a fully integrated spacecraft from an operation point of view. The operations concept will be markedly different from the ISS, with extended periods of un-crewed operations from ground and intense, short periods of crew presence that require 24/7 ground support.

In order to assess the mission architecture and vehicle design, a number of mission requirements have been provided by the Agency. A small subset of the most critical requirements relevant to the mission analysis of the logistic missions is reported below:

- The CLTV shall be launched by the Ariane 64 launch system, possibly with improved performance or by the heavy version of a commercial launch system (refuelling mission only), into a LTO – initial baseline – or an elliptical transfer orbits (e.g. GTO).
- The mission launch period shall start at the end of 2026 and goes beyond 2030.
- A monthly (possibly bi-weekly) launch window of 5 consecutive days shall be available.
- The mission shall be able to target an infrastructure in cis-lunar orbit.
- The mission shall deliver 1) 3.4 tons of dry cargo and 0.6 ton of unpressurised cargo accommodated outside the pressurized cargo module for the cargo mission and 2) 6 tons of storable bi-propellants for the refuelling mission.
- The CLTV shall perform injection in the selected orbit, phasing with its infrastructure destination, rendezvous and docking to the selected port.
- Duration between CLTV cargo on ground loading and cargo delivery to Gateway shall be - when needed - less than 5 weeks (*timeline requirement*).

For this study, the selected cis-lunar infrastructure is the Gateway and its orbit is assumed to be a 9:2 synodic repeat period, meaning that 9 revolutions are completed in two mean synodic months, which leads to a period of ~6.56 days. This orbit is called hereafter the *Gateway-NRHO* (or *G-NRHO*) to differentiate it from other NRHO.

One of the main challenges of the CLTV mission is to achieve the target for delivered payload mass considering the launch vehicle requirement. Indeed, while the Ariane 64 version will be able to inject heavy payload into LTO, this launcher is still under development and there are some uncertainties on its performance[1] and penalty associated with a high declination escape. Also, the initial baseline transfer option is a *fast transfer*, which is compatible with the mission duration requirement but provides an achievable cargo dry mass under the required target. Such constraint reflects into a series of system level trades to get closer to the payload target with respect to standard approach:

- Performing alternative transfer strategies: e.g. leveraging stable/unstable manifolds, using resonances with the moon or near-ballistic low energy transfers. The latter option has been considered as a transfer option that would offer a significant improvement in payload mass, in exchange of increased transfer durations – exceeding the cargo delivery to Gateway timeline requirement. Also, low-energy transfers might induce higher cost of operations with durations increasing from typically a few weeks to a few months, and involve dealing with distances from Earth up to circa 1.5 million km. This has an impact on the vehicle configuration, mainly the communication subsystem.

[1] In this study, A64 was assumed to deliver ~10 tons in LTO, slightly above the current expected performance [4]

- Staging: depending on the launch vehicle performance and on the CLTV propulsion system, one option is to use staging i.e. injecting the CLTV into a less energetic transfer orbit – e.g. a GTO – and let the CLTV perform the Trans-Lunar Injection (TLI) manoeuvre.
- Using Electrical Propulsion (EP): this option presents a clear benefit in terms of propellant mass but increases the operations duration, by a factor similar to the low-energy transfer option. Moreover, it implies a significant EP and Power system mass, partly counterbalancing the benefits. In addition, another difficulty is the management of induced flexible modes in rendezvous, and accommodation of large solar arrays at Gateway docking. As a consequence, only Chemical Propulsion transfers are assumed in this paper.

The selection of the orbit transfer and phasing options are the primary drivers for both the achievable payload mass and timeline requirements. Therefore, in order to propose a variety of system design options, transfer and phasing from Earth to NRHO starting from different injection orbits have been optimized for *fast* and *low-energy* transfers and are respectively described in §3 and §4.

3 FAST TRANSFERS to the NRHO and PHASING with the GATEWAY

3.1 Transfer Opportunity Analysis

A simplified feasibility analysis is performed in order to understand the nature, duration and frequency of the launch opportunities for transfers to the Gateway-NRHO. For a launch trajectory close to the equator, launch opportunities are expected to occur twice per (draconic) month: at the Moon's ascending and descending nodes relative to the Earth's equator, repeating every 27.2 days. At each node crossings, there are a consecutive number of days for which transfers to the Moon, and as a consequence, transfers to the Gateway-NRHO, are possible, as seen with opportunity maps for Earth to Moon transfers – see Figure 3-1.

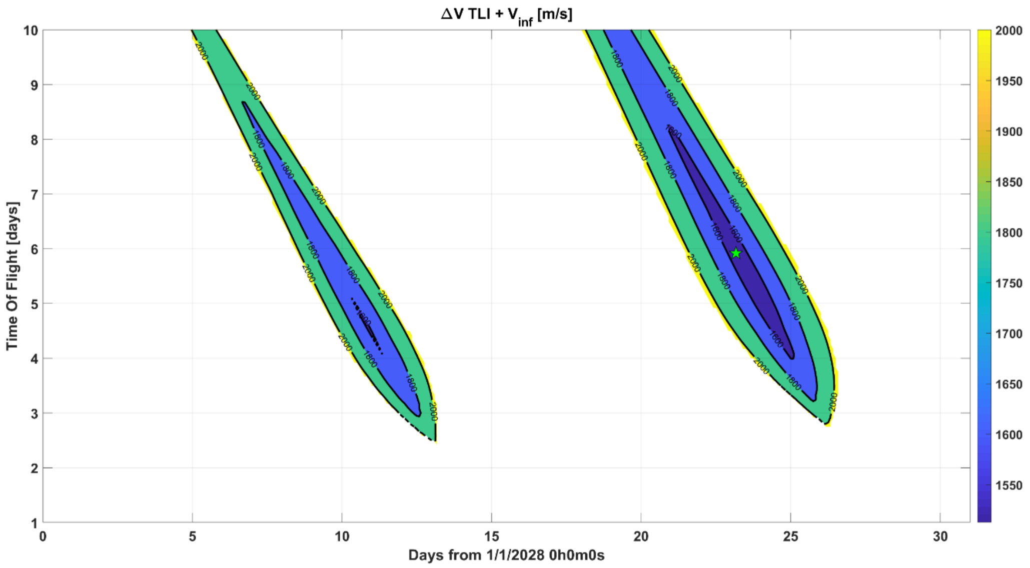

Figure 3-1: Sum of TLI ΔV and arrival v-infinity (below 2000 m/s) from GTO and Time of Flight for Lunar Transfers in January 2028

The initial orbit is supposed to be an Ariane 6 GTO for which the RAAN can be fully optimized, assuming the lift-off time is unconstrained. Starting from a GTO, a TLI ΔV is required to reach the LTO; this manoeuvre is either performed by the launcher (baseline) or by the CLTV – hence this analysis covers both launch scenarios. The TLI epoch window covers the month of January 2028, chosen for illustration. Because of the quasi-monthly period of the Moon, studying one full month provides insights applicable to other months. The required TLI ΔV, v-infinity at arrival and the time of flight are then computed for each day. The metric used to identify launch opportunities is the sum of TLI ΔV and v-infinity, where v-infinity is the norm of the velocity difference between the Moon and the CLTV at lunar encounter in a patched conics model. In Figure 3-1, only solutions for which the sum of TLI ΔV + v-infinity below 2000 m/s are kept.

The following conclusions can be drawn:

- Every draconic lunar month, there are two families of solutions: the Lunar Descending Node solutions and Lunar Ascending Node transfers. When accounting for the geometry at lunar encounter (v-infinity), the total cost depends on the orbit of the Moon at the mission epoch. For a mission scenario in 2028, the Lunar Ascending Node is more favourable.
- The optimum time-of-flights are between 5 to 6 days.
- For a given solution family: there are solutions below 2000 m/s for ~8 consecutive TLI dates but each of these solutions arrives in the vicinity of Moon at the same day +/- 1 day. This arrival dates correspond to the epoch where the Moon crosses the equatorial plane.
- The arrival date can be adjusted by a few hours up to a full day in exchanged of a ΔV penalty ranging from a few tens of m/s up to a few hundreds of m/s.

In practice, the Longitude of Ascending Node is fixed for a given flight program, which means the RAAN is linked to the epoch and cannot be freely chosen at any TLI epoch as assumed before. Therefore, the continuous family of solutions depicted in Figure 3-1 is not available in reality. Taking into account the relationship between the RAAN and the TLI epoch, each continuous family splits into discrete solutions, slightly degraded with respect to the continuous case.

3.2 Fast Transfers to NRHO Trade-Off

Fast transfers to NRHO were considered as the initial baseline by ESA, with two possible options:

- Option with a two-burn sequence near the moon: first, (1) a lunar *Powered Gravity Assist* (PGA) is performed, followed by (2) the *NRHO Orbit Insertion* (NOI) sequence. A sample transfer is shown in Figure 3-2.
- Option without PGA but with NOI performed around NRHO aposelene: a large ΔV is required (>700 m/s) but this single burn is likely to be less sensitive to manoeuvre errors.

Operational complexity is increased when using gravity assists – in particular because of the short duration between the PGA and the NOI. Also, errors induced by the PGA and strong dynamics need to be accounted for, e.g. by design of a dedicating phasing strategy. However, transfers with PGA can be designed with total deterministic ΔV as low as 450 m/s (w/o margin, larger ΔV required depending on the launch date) and therefore provide a larger payload mass delivery compared to transfers without PGA. It was therefore decided that transfers with PGA would be baseline fast transfer option. The detailed manoeuvre sequence becomes:

- A *Trans-Lunar Injection* (TLI) performed by the launcher (or by the CLTV): after the TLI, the CLTV is in LTO with an apogee near the Moon.
- A *Moon Targeting Manoeuvre* (MTM) performed by the CLTV. This manoeuvre is done typically less than 2 days after the TLI and has a deterministic and a stochastic component: a) the deterministic component accounts for the differences between the LTO provided by the launcher program and the date-specific LTO required to target the lunar condition prior the gravity assist; b) the stochastic component accounts for launcher injection errors.

- A PGA manoeuvre performed by the CLTV typically between 3 and 8 days after the TLI at the closest approach to the Moon. A conservative minimum altitude constraint (1000 km) is applied to this manoeuvre in order to guarantee a collision-free trajectory for the CLTV.
- A NOI manoeuvre, performed by the CLTV and typically scheduled between 4 and 10 days after the TLI (i.e. about 2 days after PGA), allowing sufficient time for tracking and telecommand. After this manoeuvre, the CLTV is Gateway-NRHO or a Phasing-NRHO. These options will be further discussed §3.3.

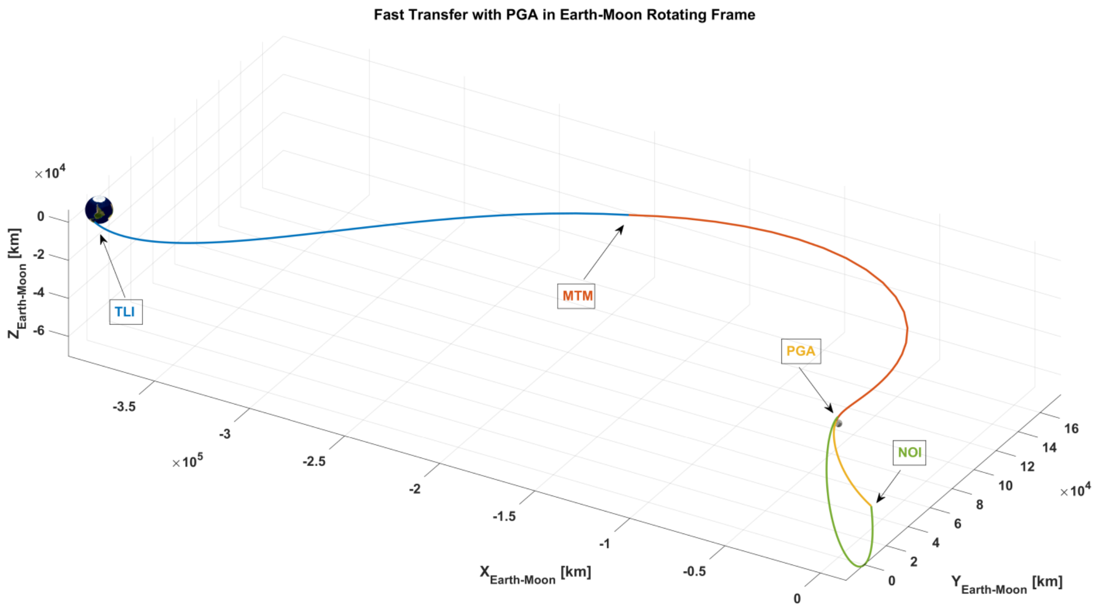

Figure 3-2: Short Transfer Baseline: Sample Transfer with PGA in the Earth-Moon Rotating Frame[2]

Assuming injection orbits with an inclination of 6 deg and unconstrained transfers (i.e., the phasing with the gateway is ignored and the minimum duration between PGA and NOI is unconstrained) the deterministic transfer ΔV (MTM + PGA + NOI) were optimised over a full cycle of 18.6 years. The total ΔV and time of flight for the month of January 2028 are shown in Figure 3-3 keeping solutions with total ΔV lower than 600 m/s. The following conclusions can be drawn, although, one shall keep in mind that these results are launch-epoch dependant:

- For each set of transfer solutions with ΔV below 600 m/s, there are 6 consecutive launch date opportunities, followed by 7 consecutive days without launch opportunities. This cycle repeats providing two sets of 6 consecutive launch dates per lunar month.
- The lowest achievable transfer ΔV is around 450 m/s
- The time of flights range between 4 and 10 days with a ΔV-optimal duration of ~7 days.
- The NOI epochs (arrival date) are the 17th of January 2028 (for the Descending Node solutions) and the 30th of January 2028 (for the Ascending Node solutions), i.e. separated by half a lunar period and with arrival date variations of roughly half a day.

[2] EMRF: The X-axis is pointing from Earth to Moon, the Z-axis is oriented towards the orbital momentum vector of the Earth-Moon system and the Y-axis completes the right-handed frame. Here, the frame is centred on the Moon.

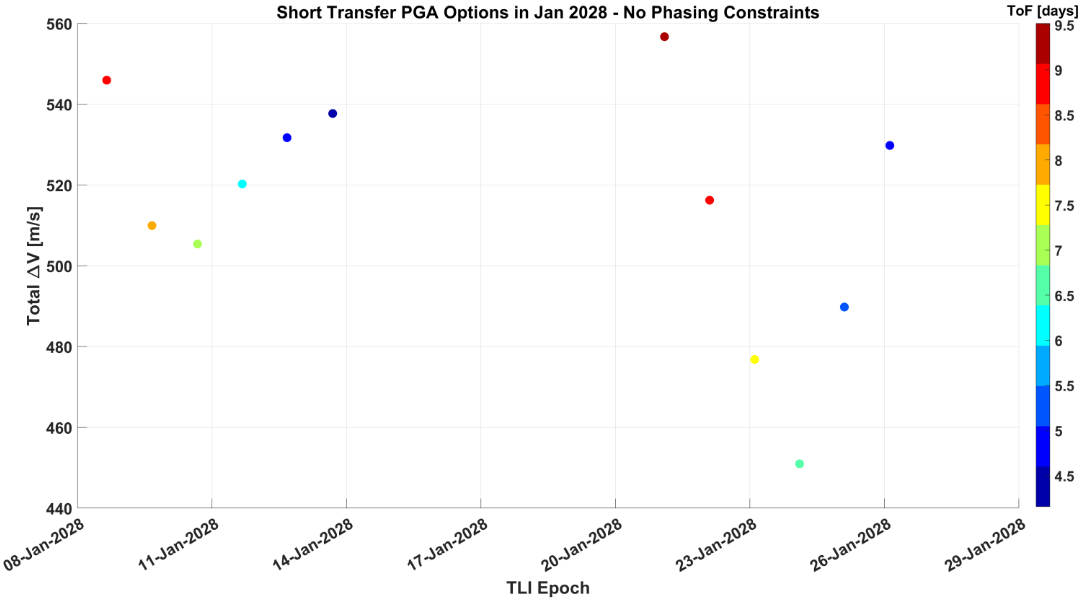

Figure 3-3: Total ΔV and Time of Flight for the Unconstrained Transfers with PGA in January 2028. The left (resp. right) group of solutions represents the descending (resp. ascending) node transfers.

Finally, a ΔV budget campaign assessment has been performed in order to inform the payload mass delivery requirement:

- Deterministic ΔV over the period 2023-2041: it was shown that ΔV repeat periodically with the Moon's argument of periapsis precession (9 years) and its longitude of the ascending node regression (18.6 years).
- Injection from LTO but also GTO and SSTO have been considered, taking into account for gravity losses.
- High inclination injection: injection from high inclination at iso launcher performance does not provide significant ΔV reduction.
- Guidance analysis: a guidance analysis has been performed (1000 samples) taking into account launch injection errors, navigation errors and manoeuvre errors. *Trajectory Correction Manoeuvres* (TCM) are implemented in between the deterministic manoeuvres to correct for these errors.

3.3 Phasing with the Gateway Trade-Off

The logistic missions require a rendezvous with the Gateway which imposes arriving at a given epoch at the moon and have the CLTV properly phased with the Gateway. The initial baseline proposed by the Agency consisted to perform orbit transfer to the NRHO and directly targeting the Gateway position (so-called *direct* transfers with NOI in the vicinity of the Gateway's location). Unfortunately, these transfers offer only a limited number of short launch windows per year. Indeed, changing the arrival time or location of the NOI in order to phase with the Gateway induce large ΔV penalty – the Gateway has a long orbital period of ~6.56 days, which prevents to find ΔV-acceptable direct transfers for long period of times.

Because of the payload mass delivery requirement, transfer and phasing must avoid large ΔV penalty which occurs when the NOI location coincides with the Gateway location. These conditions depends uniquely on the (fixed) Gateway period, the launch window frequency (also fixed by requirement and about twice per lunar draconic month) and the NOI epoch window. The ESOC team has identified circa 4 sets of 4 consecutive launch dates in 2023, considering a ΔV limit at 650 m/s – showing that direct transfers cannot meet both payload mass delivery and launch opportunities requirements at the same time. Moreover, such trajectories do not provide safe initial conditions for the rendezvous with the Gateway, due to the large dispersions of the PGA and NOI manoeuvres and the too short time span between them to correct their dispersions. It is therefore proposed to use *phasing orbits* (which could be in practice L1 and/or L2 Halo orbits, lunar orbits, etc …). For the study, we proposed to use L2 southern NRHOs, belonging to the same family of the Gateway-NRHO, as this option offers a good compromise between phasing ΔV and duration. Therefore, the transfer/phasing architecture can be summarised:

1. *Phasing-NRHO Insertion* (*P-NOI*) at the optimum insertion time (to optimise ΔV) illustrated in Figure 3-4 (left) with Phasing-NRHOs at periselene altitude of 5000 and 7000 km.
2. Loitering into the Phasing-NRHO until *Orbit Phasing Transfer* (*OPT*) is possible – drawback: increase timeline duration.
3. Orbit Phasing Transfer – two manoeuvres: *Phasing-NRHO Departure* (*P-NOD*) and *Gateway-NRHO Insertion* (*G-NOI*), with the objective of targeting the initial condition for Gateway rendezvous initialisation – illustrated in Figure 3-4 (right).

By decoupling the launch and the Gateway phasing problem, this approach enables two launch opportunities per lunar month for a limited additional ΔV. Moreover, the added loitering time can be used to correct for the large dispersions induced by the PGA and NOI manoeuvres. The expected downside is a longer overall transfer phase, from launch to rendezvous interface point.

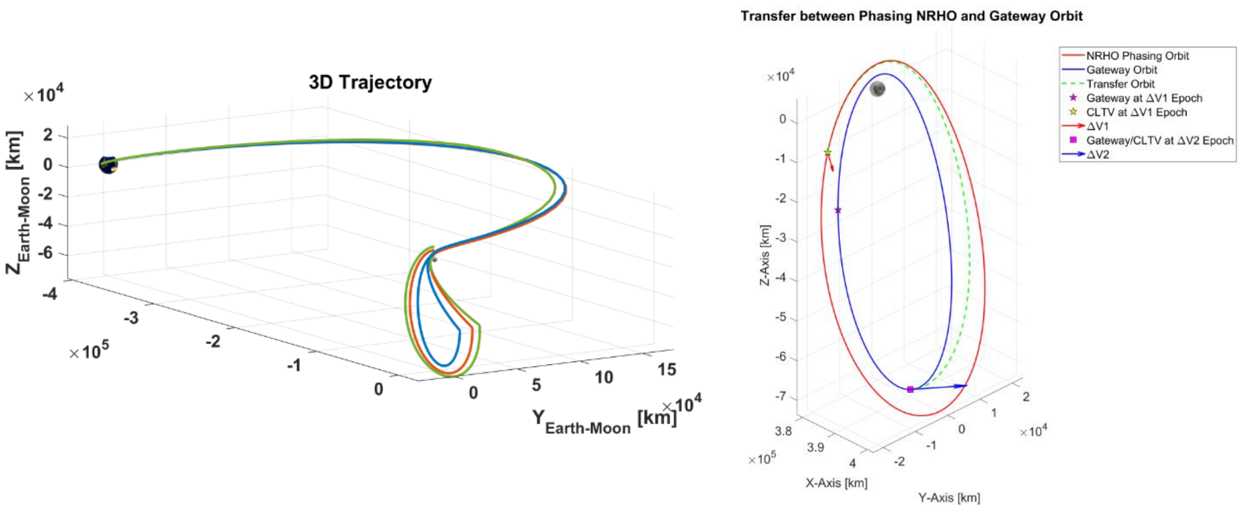

Figure 3-4: (Left) Sample Transfers to the Gateway (blue) and P-NRHO (5000 km in red, 7000 km in green) and (Right) Sample OPT from a P-NRHO to the G-NRHO

Figure 3-5 gives the maximum phasing duration as a function of the period of the selected Phasing-NRHO, assuming phasing orbits with periods greater than the Gateway period. It shows that contained maximum phasing duration (in the range of 1 or 2 months maximum) are obtained with Phasing-NRHO periods larger than 7.4 days. The larger the period, the shorter the phasing but the larger the minimum ΔV required for the Orbit Phasing Transfer.

The Orbit Phasing Transfer from a candidate Phasing-NRHO to the Gateway-NRHO has two local optima: 1) the first burn (P-NOD) is performed near aposelene and 2nd burn (G-NOI) near periselene and 2) the first burn is performed near periselene and 2nd burn near aposelene (case illustrated in Figure 3-4 - right).

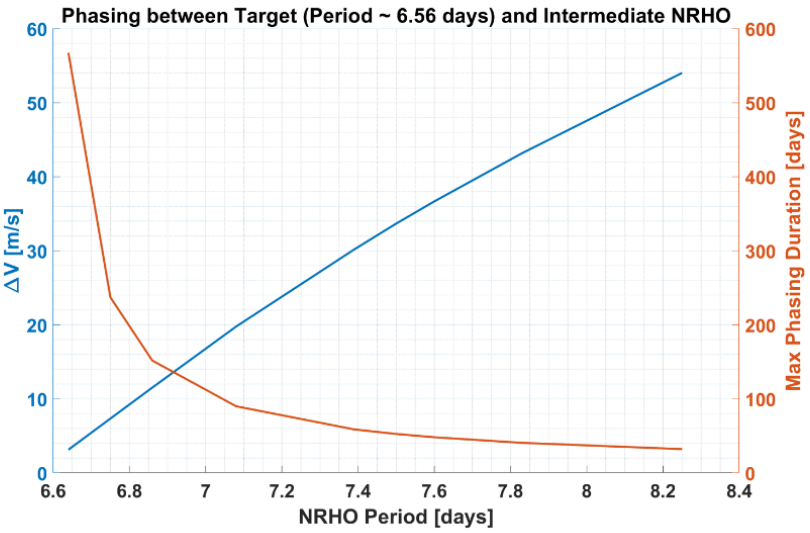

Figure 3-5: Maximum Phasing Duration and Minimum OPT ΔV as a function of the P-NRHO Period.

Figure 3-6 shows that, assuming a Phasing-NRHO with periselene altitude of 7000 km, a small ΔV penalty (~ 15 m/s) enables to locate the G-NOI at any point in the Gateway-NRHO which might be convenient to prepare for the rendezvous. This property is used to extend the Launch Window to the fullest as described hereafter.

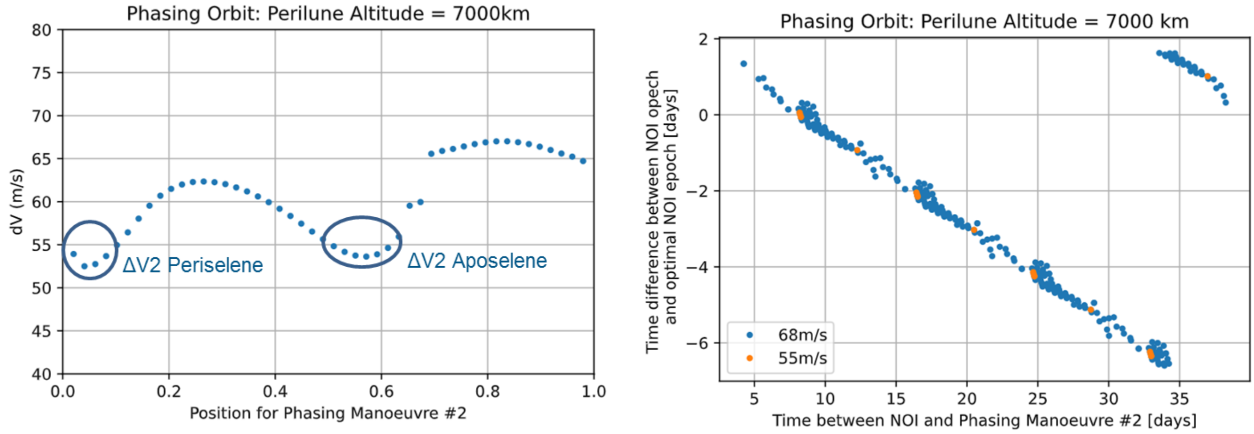

Figure 3-6: (Left) Orbit Phasing Transfer ΔV for Varying ΔV2 Position from Periselene (0) to Aposelene (0.5) and (Right) Relationship between Phasing Duration and Time Difference Between Direct Phasing NOI Epoch and Actual NOI Epoch

Assuming unconstrained launch opportunities to the Phasing-NRHO and loitering during N days until favourable phasing configurations occur, the OPT can be performed either: a) constraining the total ΔV allocation and/or G-NOI location or b) being fully unconstrained.

In the case a) the Orbit Phasing opportunities become discrete and one must have to constrain the transfer to the Phasing-NRHO to be able to phase with the Gateway in less than a month – thus reducing the number of launch opportunities. However, if b) the OPT is unconstrained, allowing for larger ΔV (a maximum of 68 m/s in our example) and having the G-NOI located freely on the Gateway-NRHO. In that case Figure 3-6 (right) shows that it is possible to phase with the Gateway by waiting the appropriate amount of phasing time regardless the initial conditions when arriving on the P-NRHO (P-NOI). A maximum of 28 days enables to fully cover one Gateway-NRHO period, i.e. all initial phasing configurations. Said otherwise, if one allocates 68 m/s and 28 days for the loitering time, it is possible to benefit from all possible launch opportunities i.e. 2 per lunar month, compared to the initial ~4 launch opportunities per year without phasing orbits.

Qualitative Phasing-NRHO Trade-Off and Selection

When selecting the Phasing-NRHO, a dedicated trade-off can be performed. A preliminary list of criteria is proposed hereafter:

- Phasing/loitering duration: NRHO period below ~7.4 days might be ruled out because of their long synodic period wrt the Gateway
- ΔV budget: a reduced transfer+phasing ΔV budget is obviously favourable. Here, all proposed options have comparable ΔV budget.
- Communications and Eclipses: steer for the choice of a resonant synodic Phasing-NRHO
- Orbit Stability: impact on insertion manœuvre, need for post-NOI manœuvre etc…

Resonant orbits, such as the 9:2 NRHO selected for the Gateway, are interesting candidate options: since their period and the duration of the mean synodic month (29.53 days) are a rational number ratio, these orbits are such that the trajectory as seen in a Sun-Earth rotating frame and therefore the lighting conditions after a integer number of orbits is nearly repeated, which can be used to design (almost) eclipse-free orbits [5].

A few candidate phasing resonant NRHO have been investigated during the study, leading to the selection of the 7:2 (resp. 4:1) NRHO, for which the maximum phasing durations is circa 3 weeks (resp. ~2 months), with a period of ~8.5 days (resp 7.4 days) with a maximum OPT ΔV of ~75 m/s (resp. ~40 m/s).

Using Multiple Phasing Orbits for Relaxing the RdV Box Constraint

Rendezvous initialization – the CLTV must reach, with a given accuracy, a rendezvous box interface located at a given orbital position on the Gateway-NRHO – may induce constraints on the G-NOI location, therefore reducing the launch opportunities. In order to remedy this, it is proposed to use, when needed, not one but several phasing NRHO as illustrated in Figure 3-7. Each phasing NRHO has a different relative drift with the Gateway which increases the opportunities to perform the G-NOI manoeuvre where required. Also, a positive side effect is the individually smaller burns, hence smaller dispersions to recover from.

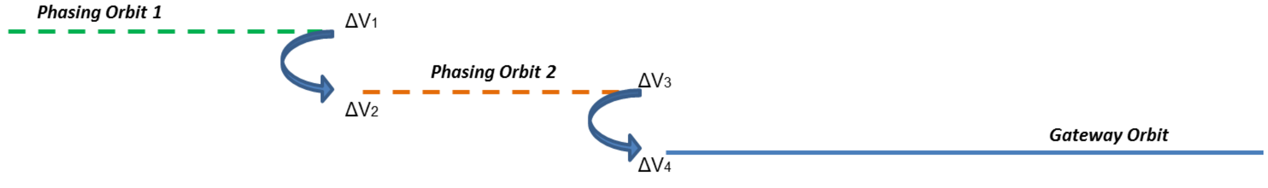

Figure 3-7: Illustration of Using Multiple Phasing NRHO to Rendezvous with the Gateway

4 LOW ENERGY TRANSFERS to the NRHO and PHASING with the GATEWAY

4.1 Analysis of Low-Energy Transfers to NRHO

Low energy transfers (also known as Weak Stability Boundary (WSB) transfers [6] and [7]) use the gravitational pull of the Sun to leverage orbit transfers from Earth to the Moon. During these transfers the spacecraft's distance can be as far as 1 to 2 million km away from Earth. During the first leg of the transfer, the spacecraft leaves the sphere of influence of the Earth until the Sun's perturbation becomes dominant. Then, assuming a proper transfer geometry, the spacecraft returns with a larger perigee altitude and a different orbit plane, with those changes induced by the Sun's perturbation. The perigee altitude and the orbit plane can be tuned in a way to coincide with the Moon's orbit, enabling insertion into a lunar orbit, e.g. in NRHO, where a small insertion manoeuvre (below 20 m/s) can be designed.

Low-energy transfers can be discriminated as *Away* or *Toward* when the apogee is either directed away or toward the Sun direction [8-9]. By comparison with the fast transfers discussed in §3.2, low-energy transfer are typically 3 to 5 months long thus being not compatible with the cargo timeline requirement. Nevertheless, they were considered in the architecture assessment.

As depicted in Figure 4-1 in Sun-Earth Rotating Frame (SERF), the main events of the transfer consist in:

- TLI, either performed by the launcher (injecting the CLTV with an apogee typically between 1 and 2 million km) or by the CLTV itself after injection into an Earth bounded orbit.
- A *Deep Space Manoeuvre* (*DSM*) performed by the CLTV typically several weeks after the TLI and at a large distance from Earth. In practice, several DSM may be performed (in particular in case the transfer geometry is not favourable) to adjust for the arrival time.
- A NOI manoeuvre, performed by the CLTV. This manoeuvre occurs typically near the NRHO periselene. After this manoeuvre, the CLTV is assumed to be in the Gateway-NRHO.

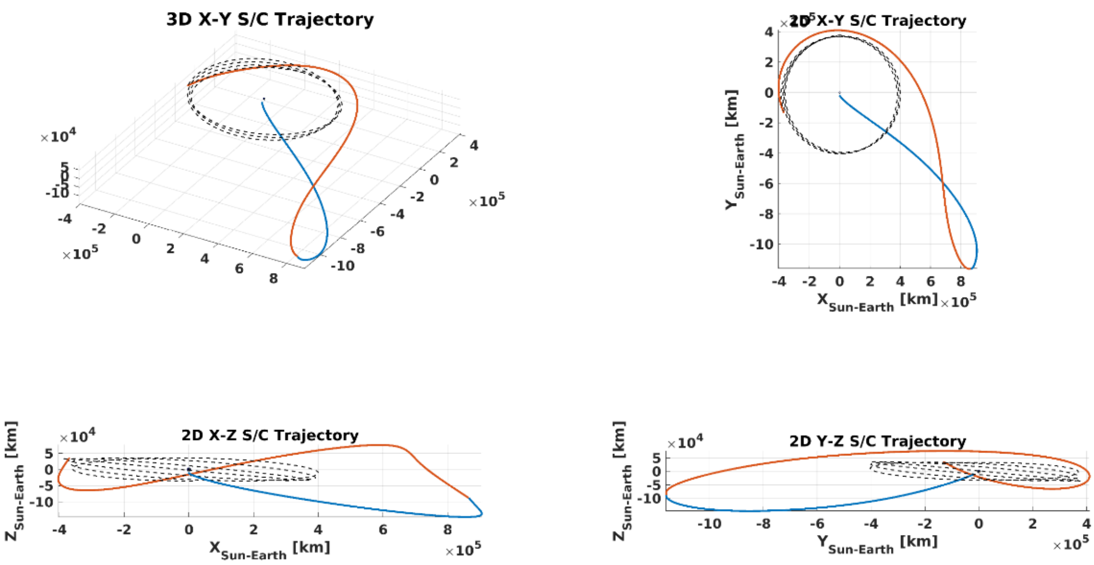

Figure 4-1: Sample WSB "Away" Transfer from LTO to NRHO in Sun-Earth Rotating Frame – Red: TLI to DSM leg, Blue: DSM to NOI leg

In the frame of the CLTV study, thousands of transfers were optimized in the ephemeris model – Earth (J2), Sun and Moon – starting from GTO, SSTO and LTI and targeting the Gateway-NRHO.

In this section, we illustrate different families of low-energy transfers[3] to the Gateway-NRHO for a TLI epoch in January 2028: Figure 4-2 gives the total low-energy transfer duration (top left), the duration between TLI and DSM (top right) and the NOI epoch (bottom). It can be seen that:

- For a fixed TLI date several transfer options are available. These transfers have “short”, “medium” or “long” durations, enabling to target several NOI epoch.
- For each of these options, changing the DSM epoch and NOI ΔV size enable to slightly change the transfer duration, hence the NOI epoch.
- The NOI epochs are roughly separated by one lunar synodic month and NOI ΔV have values between 12 and 18 m/s – lower values are achievable if allowing additional revolutions before insertion.
- There are multiple transfer options per launch date with DSM+NOI ΔV below 100 m/s and almost daily options below 150 m/s.

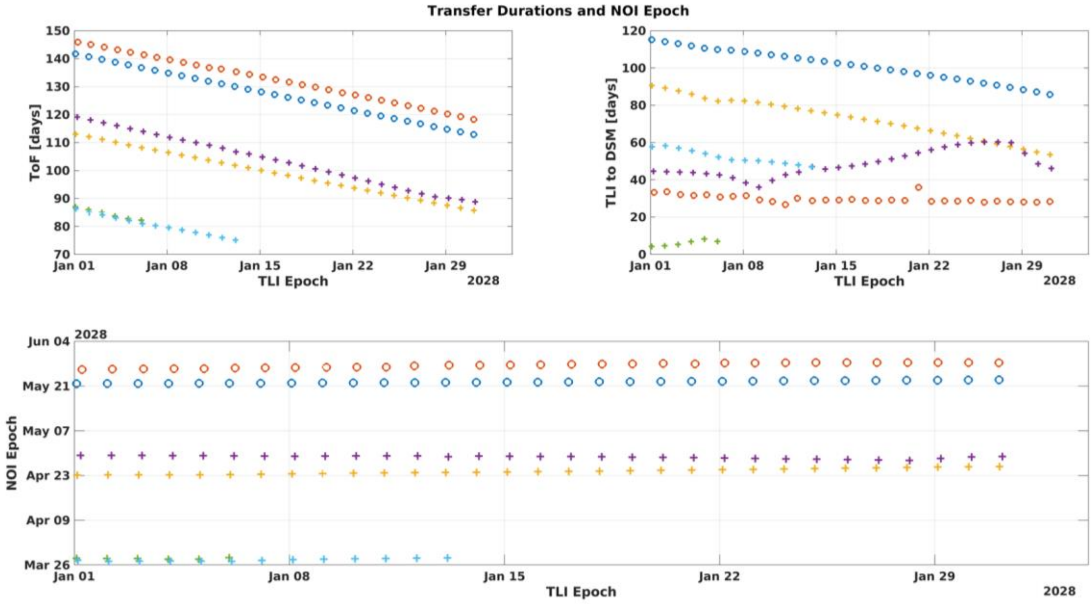

Figure 4-2: WSB Transfer Duration and NOI Epoch

Among the different low-energy transfer trajectory options, the selection is made based on the CLTV mission requirements:

- Launcher performance: shall be compatible with the required c3 injection.
- Payload mass delivery: shall seek for reduced total ΔV.
- Phasing with the Gateway: achievable NOI epoch must coincide with gateway passage.

Furthermore, other criterion such as Earth and Moon eclipse duration or maximum distance to the Earth may be used to select or filter out trajectories.

[3] Transfers with lunar fly-bys are left out on purpose: although they enable additional launch opportunities with reduced launch c3, thus increased payload mass, the propellant budget sizing must considered the least favourable case mass-wise.

4.2 Phasing with the Gateway

In section §4.1, the optimized transfers from Earth (GTO, SSTO, TLI) to the Gateway-NRHO were unconstrained (free NOI epoch/location). However, for a cargo mission, a rendezvous between the CLTV and the Gateway shall be designed. Therefore the NOI epoch or location must be fixed in order to insert the CLTV in a way that the rendezvous can be (quickly) initialised in a safe way. Unlike fast transfers where phasing is achieved with the use of intermediate phasing orbits, it is here proposed to directly aim the rendezvous initial conditions. It is possible to do so by changing the DSM magnitude, orientation or date or by adding DSM. The feasibility of this option is illustrated in Figure 4-3.

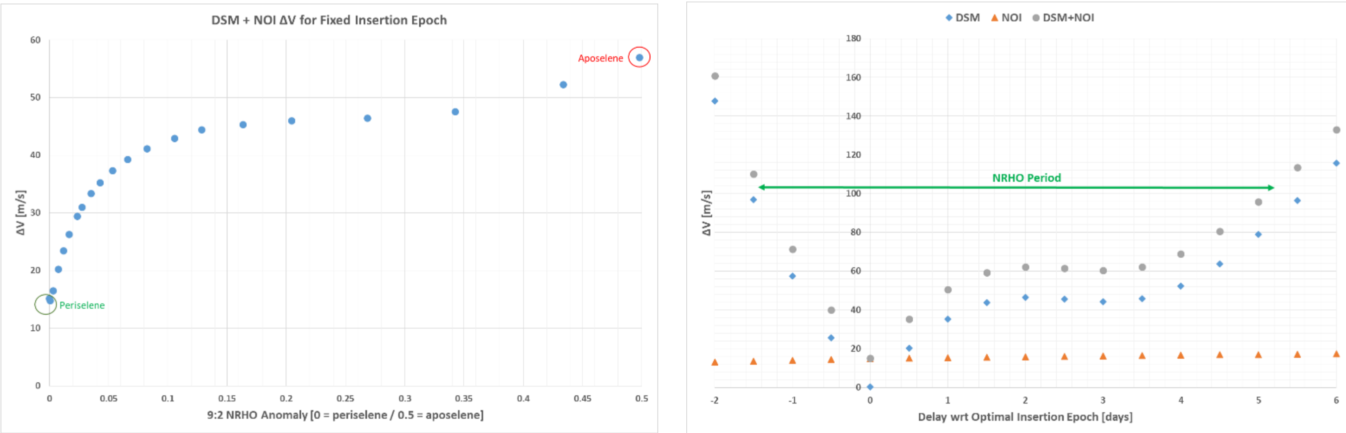

Figure 4-3: Impact of NOI Anomaly (left) and of NOI Epoch for a NOI Located at Periselene (right)

Assuming no additional revolution around the NRHO before insertion, a low-energy transfer targeting the periselene is optimized; then, the NOI location on the Gateway-NRHO is varied from periselene to aposelene. For this nearly-ballistic initial case (DSM ΔV ~ 0 m/s), a provision of ~43 m/s enables to target any anomaly. Figure 4-4 (left) shows the optimal trajectory of this test case targeting the periselene and the trajectory targeting the aposelene.

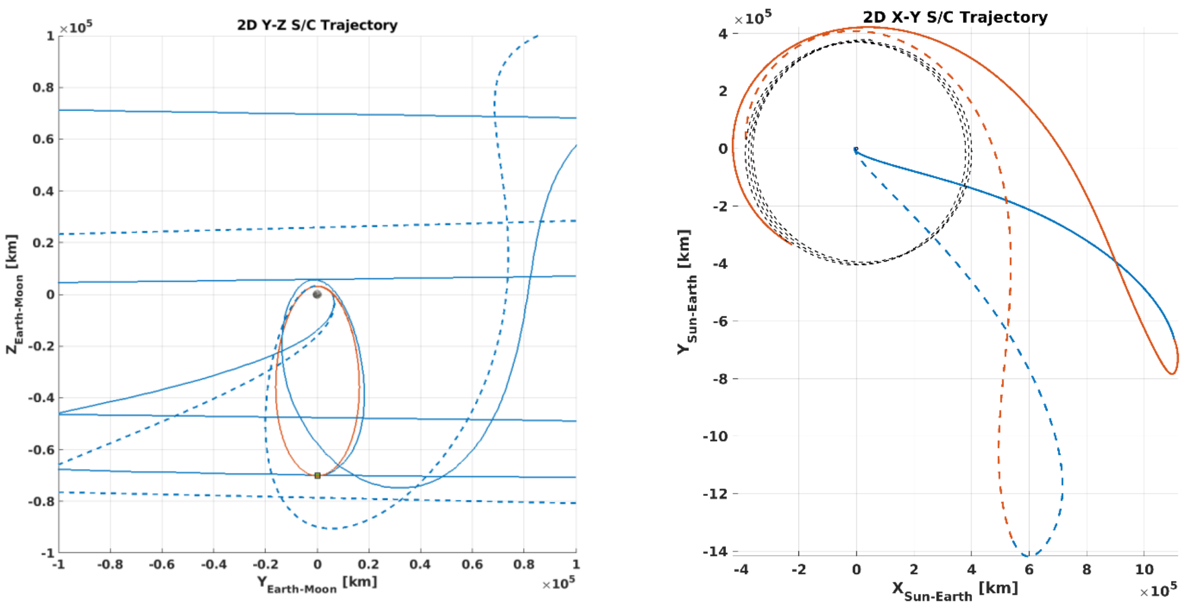

Figure 4-4: (Left) End of Phasing at Periselene (dotted line) and Aposelene in the EMRF, (Right) Trajectory Targeting Periselene at Optimum Date (dotted line) and 5 Days Later in SERF

Now, assuming a NOI located at periselene, the NOI is epoch is varied. Figure 4-3 (right) gives the DSM, NOI and total ΔV over a full NRHO period showing the required additional ΔV contribution to directly phase with the Gateway at periselene. Figure 4-4 (right) shows two trajectories performing NOI at the periselene, one at the optimal epoch (dotted line) and another one 5 days later.

Following the insertion manoeuvre, potential clean-up manoeuvres or manoeuvres to position the CLTV ready for rendezvous might be performed in the following days. It was found that a provision of a few m/s (maximum ~5 m/s) should be sufficient to allow for controlling the along-track drift between the CLTV and the Gateway after the NOI and for correcting the manoeuvre errors and OD uncertainty.

5 ARCHITECTURE ASSESSMENT OVERVIEW

The Mission Architecture is then derived from these key mission analysis results on the one hand, and from additional system or operational considerations on the other hand. The purpose of this section is to illustrate these latter considerations in a non-exhaustive manner and present the resulting overall mission architecture retained in the frame of CLTV phase-A study.

As recalled by section §1, Gateway logistic service proposed by CLTV are twofold, 1) pressurized and unpressurised Cargo to the Gateway and 2) refuelling of the HLS. A first operational constraint may come from the end user, NASA in this study: the duration between cargo loading on ground and cargo delivery to the Gateway shall be less than 5 weeks, meaning a transfer and phasing time below ~30 days, thus enabling flexibility in the definition of dry cargo to support the crew in the Gateway. The low-energy transfer strategy would therefore be excluded – to be confirmed in later stages of the study – as they clearly do not meet this timeline constraint. Therefore, for the Logistic Cargo delivery service, fast transfers (§3) are selected, allowing to deliver about 2.3 tons of dry cargo net mass to the Gateway, assuming A64 launcher, a 5 days bi-weekly launch window and considering propellant/system margins. It is considered at this stage of the study that a phasing sequence of circa 30 days (as proposed in §3.3) – allowing enlarging launch opportunities for a bounded ΔV – is acceptable and not conflicting with the maximum transfer constraint.

Remain for direct transfer the selection of Launcher insertion orbit. Complementary ‘staging’ trade-offs have been performed addressing the opportunity to benefit from better Launcher performance on a less energetic insertion orbit than LTO (e.g. GTO as mentioned in §2.2), to the price of a larger CLTV velocity increment towards LTO. It appears that GTO insertion strategy would promise a higher overall delivered mass on NRHO wrt LTO injection strategy when considering respective Launcher performance gain wrt additional CLTV propellant burnt at iso CLTV dry mass. However, the system dry mass increase to host the additional CLTV transfer propellant – at tank dry mass level as well as at overall Service Module structure level – cancels out the benefit. Therefore, for direct transfer, only LTO injection strategy is retained.

To address the second NRHO service, HLS refuelling is on the other side not constrained by the timeline requirement. Besides, the current CLTV study assumes that the HLS needs storable refuel propellant. Therefore, low-energy transfers are potential candidates for such payload with the only remaining drawback being communications between CLTV at typically 1 to 2 million km from its Control Centre, hence at a range significantly greater than the one of a fast transfer. The need being restricted to command and control aspects in a phase that is rather quiet – coast phase and regular correction manoeuvres at low frequency – far from rendezvous critical operational needs. In this case, TM data rate is decreased so as to avoid oversizing the communication system. With these drawback disappearing, low energy transfers can be selected for refuel propellant delivery on NRHO, enabling significant delivered mass benefits – about 1 ton increase compared to the pressurized cargo figures.

6 CONCLUSIONS

This paper presented the mission analysis activities performed in the frame of the Cis-Lunar Transfer Vehicle Phase A-B1 study by Airbus Defence and Space for the account of ESA. The emphasis is on the Logistic missions to the Gateway, which serve as the main mission scenario for the CLTV.

In order to inform mission architecture and system trade-off, in-house astrodynamics tool LEMONADE (Lunar transfEr MissiON Analysis and Design) was used to perform activities covering transfer and phasing to NRHO from various injection orbits (GTO, SSTO and LTO), propellant budget estimation taking into account navigation and manoeuvre execution errors along with launch window/period requirements. In this paper, the focus is on the transfer options – fast transfers with and without gravity assist, low-energy transfers – and on the phasing strategy options – direct phasing or phasing using intermediate orbits.

Based on the mission requirements, the feasibility and robustness of these options under realistic operational requirements were analysed, paving the way for the CLTV but also for future lunar programs. The overall mission performance was assessed and the following baselines were proposed:

1) for cargo missions: fast transfers using Powered Gravity Assist and targeting a Phasing-resonant NRHO, followed by a loitering period (< 30 days) on one or several intermediate orbits and finally transferring to the Gateway-NRHO once the phasing is achieved.

2) for HLS refuelling missions: low-energy transfers with direct phasing with the Gateway.

When comparing the two baselines, the latter option improves the payload mass delivery by about 1 ton, in exchange of a longer transfer phase.

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