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# Earth-Mars transfers through Moon Distant Retrograde Orbits

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ABSTRACT

This paper focuses on the trajectory design which is relevant for missions that would exploit the use of asteroid mining in stable cis-lunar orbits to facilitate deep space missions, specifically human Mars exploration. Assuming that a refueling "gas station" is present at a given lunar Distant Retrograde Orbit (DRO), ways of departing from the Earth to Mars via that DRO are analyzed. Thus, the analysis and results presented in this paper add a new cis-lunar departure orbit for Earth-Mars missions. Porkchop plots depicting the required $C_3$ at launch, $v_\infty$ at arrival, Time of Flight (TOF), and total $\Delta V$ for various DRO departure and Mars arrival dates are created and compared with results obtained for low $\Delta V$ Low Earth Orbit (LEO) to Mars trajectories. The results show that propellant-optimal trajectories from LEO to Mars through a DRO have higher overall mission $\Delta V$ due to the additional stop at the DRO. However, they have lower Initial Mass in LEO (IMLEO) and thus lower gear ratio as well as lower TOF than direct LEO to Mars transfers. This results in a lower overall spacecraft dry mass that needs to be launched into space from Earth's surface.

## 1. Introduction

Lunar Distant Retrograde Orbits (DROs) are orbits that exist due to third-body effects. Such trajectories are the solutions of the Circular Restricted Three Body Problem (CR3BP) of a system in which Earth's and Moon's gravitational attractions are considered. A DRO is possibly a critical stepping stone, both implicitly and literally, for the next big goal in space exploration: human Mars exploration.

The history of exploration has taught mission designers the importance of logistical considerations for such expeditions. Part of the logistics considerations in space exploration includes the locations of on-orbit propellant depots, in-situ resource utilization (ISRU) plants, and other types of space infrastructure [1]. Multiple recent studies have shown the promising effectiveness of having a propellant depot on the way to or back from the destination [2,3].

Recent interests in asteroid mining and utilizing cis-lunar space as a gateway for deep space robotic and human missions (including Mars missions) have increased the focus on utilizing the Moon and its surrounding as an intermediate step to eventually reach Mars [4,5]. Recently NASA has announced its plan to build a crew tended spaceport in lunar orbit that would serve as a gateway to deep space and the lunar surface [6]. After the establishment of the Deep Space Gateway, the objective is to develop a transport system for human travel that, from the gateway, would reach destinations beyond the Earth-Moon system, including Mars. In the early 2000s, a halo orbit around the Earth-Moon Lagrange point 1 was proposed as a gateway where to mount lunar and interplanetary missions for the OASIS (Orbital Aggregation and Space Infrastructure Systems) study [7]. Earth and lunar departure orbits are analyzed also in Ref. [8], including High Earth Orbits (HEO) with low or high perigee and cis-lunar departure orbits. Such orbits allow spacecraft to obtain the necessary $C_3$ to reach destinations such as Mars and Near Earth Asteroids (NEA) of interest [8].

A DRO has recently been proposed to be one of the most suitable locations to locate space infrastructure. This is due to its orbital stability and ease of access in terms of gravity well [9,10]. For example, a propellant depot can be at a DRO so that a cargo mission can visit that depot to be refueled before heading to its destination. In addition, a space station can also be located at a DRO, which can be used as a maintenance base or safe haven for any unexpected contingencies in cis-lunar space. Moreover, a DRO can be used for the assembly of large spacecraft. This idea is attractive because, e.g., one of the many benefits of in-orbit spacecraft assembly is that the final spacecraft size and mass are not affected by launch vehicle constraints.

In order to realize the above scenarios, an efficient transfer orbit from Earth to Mars via a DRO (or the other way around) is critical. The contribution of this work with respect to the studies available in the

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**Table 1**
Assumed parameters.

| From | To | $\Delta V$ [km/s] | TOF [days] |
|---|---|---|---|
| LEO | LMO | 5.76 | 202 |
| LEO | DRO | 3.82 | 6 |
| DRO | LMO | 3.29 | 206 |

**Table 2**
$\Delta V$ and TOF for each case.

| Scenario | Gear Ratio | TOF [days] | SLS launches |
|---|---|---|---|
| 1 | 13.09 | 202 | 5 |
| 2 | 10.56 | 222 | 4 |
| 3 | 8.43 | 222 | 3 |

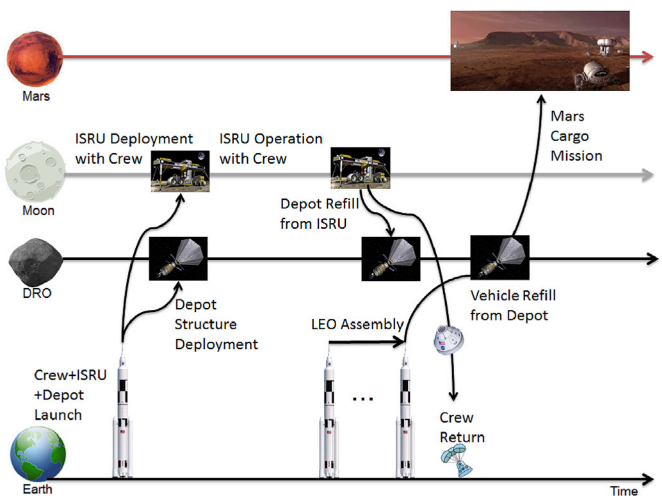


**Fig. 1.** Concept of Operations (ConOps) for an example scenario of using DRO (Icon Credit: NASA, ULA).

literature resides in the study of transfers to and from a lunar DRO to reach Mars. An Earth flyby maneuver is used for departing the DRO to leave the Earth-Moon system in order to optimize the use of propellant within the Earth-Moon system. Thus, necessary $\Delta V$, TOF, mass requirements and porkchop plots for a given synodic period are shown in this paper.

The analysis of LEO to DRO and DRO to Mars trajectories was supported by the following assumptions:

- $\Delta V$ maneuvers are treated as impulsive maneuvers.
- Earth-Moon dynamics is modelled as the Circular Restricted Three Body Problem (CR3BP) using an Earth-Moon mean distance of 384,400 km.
- Patched conics are used for interplanetary orbital transfers.
- Secular perturbations of other planetary bodies are neglected.

The paper starts with an analysis of the role of DROs in Mars missions in Section 2. Transfers from Earth to DRO and from DRO to Mars are presented in Sections 3 and 4 and Section 5 draw conclusions on this work.

## 2. The role of DROs in Mars missions

In order to show the value of a DRO for Mars exploration, a simple numerical example is shown in this section. The considered scenarios assume a cargo mission, which can be a habitat pre-deployment mission preceding human missions. A propellant depot is assumed to be located at a DRO, and here the value of having such a propellant depot is analyzed. More precisely, it is of interest to find the mass savings on the Initial Mass in Low Earth Orbit (IMLEO) by refilling the propellant tanks from the depot at a DRO before departing for Mars. Note that the cases with a depot cannot be simply compared against those without a depot because the depot development and launch costs would need to be considered. Instead, the result would give an indication about how much cost the develop and launch of such a propellant depot would be worth considering its reusability.

With the representative $\Delta V$ and TOF resulted from later analysis, the following scenarios are considered for a Mars mission.

- Scenario 1. Direct transfer from Earth to Mars: the vehicle directly departs from Earth to Mars.
- Scenario 2. Oxygen refill in DRO: the vehicle departs from Earth to the DRO, refills its oxygen tank from a propellant depot in the DRO, and heads to Mars.
- Scenario 3. Hydrogen and Oxygen Refill in DRO: the vehicle departs from Earth to the DRO, refills its hydrogen and oxygen tanks from a propellant depot in the DRO, and heads to Mars.

Note that for both scenarios 2 and 3, an Earth flyby after departing the DRO is considered. The computation is simply based on the rocket equation [11]. The assumed parameters are shown in Table 1, where LMO stands for Low Mars Orbit, and the results are shown in Table 2. The $\Delta V$ and TOF values assume the Earth-Mars synodic period 2035–2036. Chemical engines with a specific impulse ($I_{sp}$) of 450 s is assumed as the vehicle propulsion system. The refill operation is assumed to take 10 days. To represent the IMLEO reduction, the gear ratio is shown, which is defined as the ratio of IMLEO to the mass that arrives at Low Mars Orbit (LMO). In addition, the number of launches is shown assuming the equivalent payload as NASA Design Reference Architecture 5.0 cargo pre-deployment mission (40 mT on Martian surface [12]) and the launches by the 130 mT Space Launch System (SLS) Block 2.

The results show that stopping at the DRO "gas station" would provide the propellant necessary for part or all of the rest of the journey to Mars, which would effectively reduce the propellant mass and the size (and therefore mass) of the tanks that need to be launched from Earth. Thus, a smaller number of launches or smaller rockets could be used for the same payload mass to be sent to Mars. In the above case, the total spacecraft mass can be reduced by more than 35%, so the number of launches can be reduced from five to three, which can save on launch cost and time significantly. (Note that the current schedule for SLS launch frequency is only once a year.)

An example scenario of utilization of propellant depot in a DRO and lunar ISRU for a Mars cargo mission is shown in Fig. 1. The first launch is a crewed mission that delivers the ISRU plant to the lunar surface and the propellant depot to a DRO. During the ISRU operation period, the human crew maintains the ISRU plant and performs science missions at the same time on the lunar surface. After the ISRU propellant generation, the obtained propellant is delivered to the propellant depot in the DRO, and the human crew returns to Earth. In the meantime, the Mars cargo is launched and assembled in LEO, stops in a DRO to get refilled, and heads to Mars to deliver the cargo (e.g. habitat pre-deployment for later crew missions). Note that in this scenario, the propellant depot is assumed to be refilled by ISRU, but there are other possibilities for the usage of propellant depots [3]. This scenario provides an example of how DROs can be used for Mars exploration, which thus motivates this research to design trajectories around a DRO.

## 3. Earth - Lunar DRO transfer

No closed form solution for the DRO in the CR3BP exists. A collection of positions and velocities for points along the orbit can however be obtained by implementing a shooting method. The shooting method propagates the motion of a point in the CR3BP from one of the approximate initial conditions (position and velocities) that can be derived from