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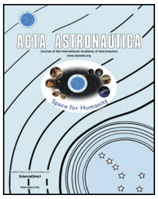

Mission analysis for Earth to Mars-Phobos distant Retrograde Orbits

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ABSTRACT

This paper focuses on the trajectory design for missions destined to explore Mars and/or Phobos departing from Low Earth Orbit (LEO) and arriving into a Mars-Phobos Distant Retrograde Orbit (DRO). Lunar DROs are also briefly explored as an alternative departure location. A Mars-Phobos DRO is a relatively stable environment which would make both the surfaces of Mars and Phobos available for a reasonable propellant expenditure. This paper presents the methodology used to compute LEO to Mars-Phobos DRO trajectories and results regarding required C_3 at launch, v_∞ at arrival, Time-of-Flight (TOF), and total ΔV for various Mars-Phobos DROs using full ephemeris planetary data. The results show that propellant-optimal trajectories from LEO to a specified Mars-Phobos DRO could be used as a staging location between Mars and Phobos. Assuming that refueling is available at the targeted DRO, LEO to Low Mars Orbits (LMO) trajectories would have higher total ΔV due to the additional stop at the Mars-Phobos DRO. However, the aforementioned trajectories would have lower Initial Mass in LEO (IMLEO) and thus a lower gear ratio thanks to the added “pit stop” located at the given DRO. This results in a lower overall spacecraft dry mass that needs to be launched into space from Earth's surface.

1. Introduction

Phobos is the largest of Mars' two moons with an approximate size of 13.4 × 11.2 × 9.2 km and is shaped somewhat like a potato [1]. Phobos is significantly smaller than its parent planet, and the ratio of Phobos' mass to Mars' mass is on the order of 10^{-8}. As a reference, Phobos' orbital parameters of interest that were considered for the work presented in this paper are listed in Table 1. An additional simplification was made for the analysis presented and it was assumed that Phobos' orbital inclination with respect to Mars' equator was small enough to be considered to be zero. Additionally, Phobos' Sphere Of Influence (SOI) is below its physical surface. As a result, it is theoretically impossible to orbit Phobos in the classical Keplerian sense. Alternatively, modeling the dynamics of Mars and Phobos using the Circular Restricted Three Body Problem (CR3BP) having the planet and the moon as the primary masses, it is possible to compute periodic orbits in the vicinity of Phobos. Most of these orbits, such as Lyapunov and halo orbits, are too unstable or come dangerously close to Phobos, some as close as hundreds of meters from the surface of the Martian moon [2]. Nevertheless, stable periodic orbits that are “far enough” from Phobos' surface exist. One family of such orbits is represented by “Distant” Retrograde Orbits (DROs). The term “distant” here is used loosely since Mars-Phobos DROs are still relatively close to Phobos, on the order of tens or hundreds of kilometers from the moon's surface. Sample Mars-Phobos DROs are shown in Fig. 1.

In this and all following figures, Phobos is plotted as an ellipsoid of size 13.4 × 11.2 × 9.2 km, or a scaled version of it when noted. Additionally, L_1 and L_2 correspond to the Lagrange points 1 and 2 of the Mars-Phobos system.

Mars-Phobos DROs exist due to third-body effects and are periodic solutions of the CR3BP of a system in which Mars' and Phobos' gravitational attractions are taken into account. A Mars-Phobos DRO can be viewed as a staging location for robotic and human explorations of Mars and Phobos exploration. In fact, due to its vicinity with Phobos, such “Distant” Retrograde Orbits make Phobos' surface accessible at a ΔV cost less than a few tens of m/s, depending on the chosen DRO [3]. Logistics considerations in space exploration include the locations of on-orbit refueling stations and in-situ resource utilization (ISRU) plants. Recent studies have shown that the use of such in-space infrastructures would make space exploration more effective, affordable, and sustainable, thus avoiding having to bring along all of the necessary materials, including propellant, for deep space missions [4–6]. Using 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 [7,8]. Studies to use lunar DROs have been proposed and details can be found in Ref. [9]. Similar to Earth's Moon, interests in using the Martian moons for human missions can be found in the extensive technical

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Table 1
Phobos' orbital parameters of interest with respect to the Mars Mean Equatorial (MME) inertial reference frame [1].

Parameter	Value
Semi-major Axis	9376 km
Eccentricity	0.0151
Inclination	1.093 deg

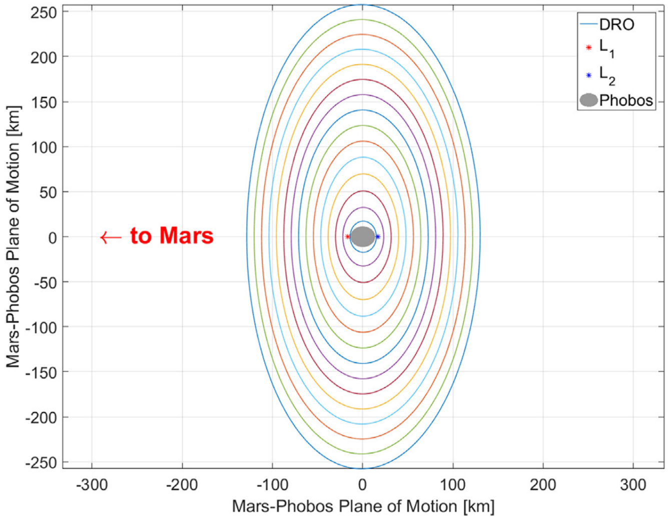

Fig. 1. Sample Mars-Phobos DROs in the Phobos-centered rotating reference frame.

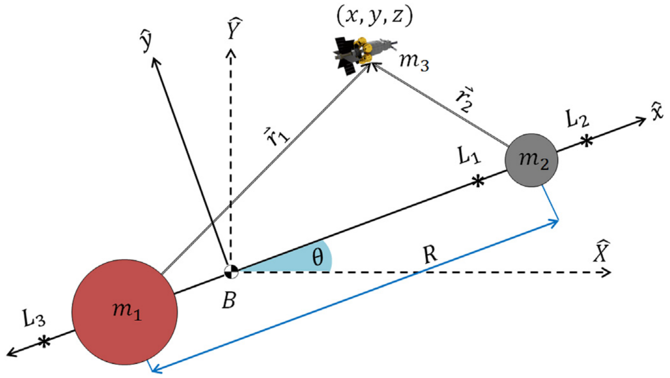

Fig. 2. Geometry of the CR3BP. $\hat{X}\hat{Y}\hat{Z}$ is inertial while $\hat{x}\hat{y}\hat{z}$ is rotating. $\hat{Z}$ and $\hat{\boldsymbol{z}}$ are aligned with each other and point out of the paper. m_1, m_2, and m_3 represent Mars, Phobos, and a spacecraft respectively. The collinear equilibrium points, L_1, L_2, and L_3, are also shown.

Table 2
CR3BP parameters for the Mars-Phobos system [1,13].

Parameter	Value
Mass ratio, λ	1.6610×10^{-8}
Semimajor axis (1 LU), km	9376
Time constant (1 TU), s	4387
Orbital period of the primaries (2πTU), hours	7.657

NASA reports as early as 1985, while more detailed preliminary design strategies for using the moons of Mars as intermediate locations for human Mars explorations are provided in more recent technical publications [10,11]. Equivalently to how one drives a car and does not bring along all of the fuel they will ever need, but rather stops at gas stations to refuel, adding an additional intermediate step between Earth and Mars at a Mars-Phobos DRO would allow future missions to be able to refuel and, in case of emergency, utilize such stop as a “safe haven” or use it for contingency plans. Additionally, in-orbit spacecraft assembly could take place at such intermediate stop since the final spacecraft size and mass are not affected by launch vehicle constraints.

The work presented in this paper is aimed at laying out the mission analysis of the main phases necessary to transfer from LEO to arrive at a prescribed Mars-Phobos DRO. Numerical and graphical sample results are included in order to show the general Concept of Operations (ConOps) for such sequence of transfers. Ballistic and low-energy solutions to Mars-Phobos DRO insertions exist, but require particularly accurate and timely targeting and repeated close encounters (fly-bys) with Phobos at altitudes less than 10 km. This results in savings on Mars arrival ΔV [3]. On the other hand, the sequence of maneuvers proposed in this paper does not require targeting to be as accurate and keeps the spacecraft at a safer position, i.e. further away from possible impacts with Phobos' surface for the majority of the time until orbit insertion is performed at the desired DRO. The analysis presented here is carried out starting with typical mission design parameters like required characteristic orbital energy, C_3, at launch, v_∞ at arrival, Time-of-Flight, and total ΔV in order to correctly target the DRO insertion upon arriving into Mars' SOI. The paper starts with a general analysis of Mars-Phobos DROs in Section 2. Transfers from LEO to Mars' SOI are well-characterized in the literature and are thus only briefly discussed, while the Mars Arrival ConOps is explained in detail in Section 3. Here, the main maneuvers needed to arrive from Mars' SOI to insert into a Mars-Phobos DRO are laid out. Further detailed analysis and sample results are provided throughout the paper and summarized in Section 4, where lunar DROs are also briefly considered as a departing location from the Earth-Moon system to target Mars' SOI. Lastly, Section 5 draws conclusions on this work.

The Earth to Mars-Phobos DRO trajectory analysis presented in this paper was supported by the following assumptions:

- ΔVs are treated as impulsive maneuvers.
- The dynamics of Mars and Phobos are developed using the Circular Restricted Three Body Problem (CR3BP) model, with mean distance between the primaries of 9376 km and mass ratio, $\lambda = \frac{m_{Phobos}}{m_{Phobos} + m_{Mars}}$, of 1.6610×10^{-8}.
- Patched conics are used for interplanetary orbital transfers between Earth and Mars.
- Secular perturbations of other planetary bodies are neglected within Mars' SOI; however, the planetary ephemerides of Earth and Mars are provided by JPL DE 430 and are used for the interplanetary portion of the mission [12].

2. Mars-Phobos DROs

DROs are in general characterized by the so-called x-amplitude A_x, i.e. the largest distance from the smaller primary's center (Phobos) in the x-direction of the xyz triad that composes the rotating frame of reference of the orbiting primaries in the CR3BP. In fact, it is typical to work in the CR3BP using a coordinate system xyz which generates a rotating reference frame whose origin corresponds to the barycenter B of the primary masses, m_1 and m_2, as shown in Fig. 2. The third mass, m_3, represents a spacecraft and is assumed to have negligible mass, i.e. m_3 does not affect the orbits of m_1 and m_2. $\vec{r_1}$ and $\vec{r_2}$. are the position vectors from m_1 to m_3 and from m_2 to m_3 respectively.

In non-dimensional form, the characteristic length of the CR3BP is the semimajor axis of the system of primaries, R. Using the non-dimensional mass ratio $\lambda = \frac{m_{Phobos}}{m_{Phobos} + m_{Mars}}$. Thus, the resulting non-dimensional canonical length and time units (LU and TU) for this dynamical system can be represented as listed in Table 2.

A sample Mars-Phobos DRO with A_x amplitude of 300 km is shown