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Identification of new orbits to enable future mission opportunities for the human exploration of the Martian moon Phobos ☆

Mattia Zamaro *, James D. Biggs [1]

Advanced Space Concepts Laboratory, University of Strathclyde, 75 Montrose Street, G1 1XJ Glasgow, United Kingdom

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ABSTRACT

One of the paramount stepping stones towards NASA's long-term goal of undertaking human missions to Mars is the exploration of the Martian moons. Since a precursor mission to Phobos would be easier than landing on Mars itself, NASA is targeting this moon for future exploration, and ESA has also announced Phootprint as a candidate Phobos sample-and-return mission. Orbital dynamics around small planetary satellites are particularly complex because many strong perturbations are involved, and the classical circular restricted three-body problem (R3BP) does not provide an accurate approximation to describe the system's dynamics. Phobos is a special case, since the combination of a small mass-ratio and length-scale means that the sphere-of-influence of the moon moves very close to its surface. Thus, an accurate nonlinear model of a spacecraft's motion in the vicinity of this moon must consider the additional perturbations due to the orbital eccentricity and the complete gravity field of Phobos, which is far from a spherical-shaped body, and it is incorporated into an elliptic R3BP using the gravity harmonics series-expansion (ER3BP-GH). In this paper, a showcase of various classes of non-keplerian orbits is identified and a number of potential mission applications in the Mars–Phobos system are proposed: these results could be exploited in upcoming unmanned missions targeting the exploration of this Martian moon. These applications include: low-thrust hovering and orbits around Phobos for close-range observations; the dynamical substitutes of periodic and quasi-periodic Libration Point Orbits in the ER3BP-GH to enable unique low-cost operations for space missions in the proximity of Phobos; their manifold structure for high-performance landing/take-off maneuvers to and from Phobos' surface and for transfers from and to Martian orbits; Quasi-Satellite Orbits for long-period station-keeping and maintenance. In particular, these orbits could exploit Phobos' occulting bulk and shadowing wake as a passive radiation shield during future manned flights to Mars to reduce human exposure to radiation, and the latter orbits can be used as an orbital garage,

Abbreviation: 2B, Two-Body; 2B-P, Perturbed Two-Body; 3B, Three-Body; 2BP, Two-Body Problem; 3BP, Three-Body Problem; AEP, Artificial Equilibrium Point; BCBF, Body-Centered Body-Fixed; CR3BP, Circular Restricted Three-Body Problem; CR3BP-CA, Circular Restricted Three-Body Problem with Constant Acceleration; CR3BP-GH, Circular Restricted Three-Body Problem with Gravity Harmonics; ER3BP, Elliptic Restricted Three-Body Problem; ER3BP-GH, Elliptic Restricted Three-Body Problem with Gravity Harmonics; Ef.D., Effective Dose; GCR, Galactic Cosmic Ray; GH, Gravity Harmonic; GNC, Guidance, Navigation and Control; IM, Invariant Manifold; LP, Libration Point; LPO, Libration Point Orbit; MRP, Mars Radiation Pressure; OE, Orbital Element; PO, Periodic Orbit; PRP, Phobos Radiation Pressure; QPO, Quasi-Periodic Orbit; QSO, Quasi-Satellite Orbit; R3BP, Restricted Three-Body Problem; R4BP, Restricted Four-Body Problem; SEP, Solar Electric Propulsion; SEPE, Solar Energetic Particle Event; SOI, Sphere of Influence; SRP, Solar Radiation Pressure; SS, Sun-Synchronous; VDCO, Vertical-Displaced Circular Orbit

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* Corresponding author. Tel.: +44 141 574 5025.
E-mail addresses: mattia.zamaro@strath.ac.uk (M. Zamaro), james.biggs@strath.ac.uk (J.D. Biggs).
[1] Tel.: +44 141 574 5011.

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requiring no orbital maintenance, where a spacecraft could make planned pit-stops during a round-trip mission to Mars.

1. Introduction

Since the discovery of Phobos and Deimos in 1877, the two natural satellites of Mars have become increasingly interesting astronomical objects to investigate. Phobos is closer to Mars than Deimos and almost double its size, but despite this, they are very similar, since they share common physical, orbital and geometrical features. Their origin is still largely unknown [1,2], and is currently debated to have been either an asteroid capture by Mars, or coalescence from proto-Mars or Solar System material, or even accretion of material from Mars ejected from its surface after an impact with a previous small body. This puzzle is supported by the mysterious composition of these moons inferred from infrared spectral analysis: due to their relative low density and high porosity, they could hide a considerable amount of iced water [2], which is an attractive in situ resource that could be exploited by human missions. In addition, it is speculated that the Martian moons' rocks could provide evidence of alien life [3]. Phobos has some unique characteristics that make it also astrodynamically interesting. The low altitude of its orbit around Mars has produced speculation on its evolution: due to its tidal interaction with Mars, its altitude is currently decreasing, which means Phobos will eventually crash into Mars or break up into a planetary ring [4].

Due to its proximity to Mars, Phobos is currently of great interest for future missions to the Red Planet. During its Ministerial Council Meeting of November 2012, ESA confirmed post-2018 mission concepts: the Mars Robotic Exploration Programme would include a mission (Phootprint) to return back to Earth a sample from Phobos [5,6]. Another sample-and-return mission to this moon is currently proposed by NASA Innovative Advanced Concepts team, that will use two CubeSats propelled by a solar sail and joined by a tether mechanism [7]. In addition, NASA has identified a mission to Phobos as a key milestone to be achieved before bringing humans to Mars [8–11], since the absence of atmosphere on Phobos and Deimos makes landing and take-off easier for a manned spacecraft than on Mars. Therefore, the Martian moons could be exploited as outposts for astronauts: Phobos' proximity and fast orbital period can provide a relay for robotic exploration on Mars, and protection from space radiation hazards for manned spacecraft orbiting Mars (Phobos' bulk and shadow shielding the spacecraft). At the beginning of 2013, with the development of a new rover platform for the exploration of minor bodies, consisting of robotic hedgehogs, it has been reported that NASA is taking into consideration a mission (Surveyor) to Phobos as a test-bed for this new technology [12].

The purpose of this paper is to present a breakdown of different kinds of orbits that could be exploited in future space missions to Phobos. In [13], a collection of different options that a spacecraft can use to orbit around Phobos is discussed, and their properties are preliminarily assessed in the framework of the three-body dynamics. This paper builds on this approach by expanding the computation to all the available orbits within each class of trajectories, refined in more tailored models of the relative dynamics, and by computing a broad range of their properties for space engineering applications. These results will become useful for the ultimate selection of the operative orbits in the mission design loop to plan the exploration of Phobos.

The outline of this paper is as follows. Section 2 introduces the reader to the physical environment connected to the orbital dynamics and constraints of a spacecraft in the vicinity of Phobos. The following Sections 3–6 showcase each of the different kinds of orbits around this moon, such as hovering points using Solar Electric Propulsion (SEP); Vertical Displaced Circular Orbits with low-thrust; natural Libration Point Orbits and their Invariant Manifold trajectories, and their artificial equivalent with constant low-thrust; Quasi-Satellite Orbits around Phobos. Section 7 provides a summary of the different solutions focusing on their applications in space missions to Phobos. Section 8 concludes the paper suggesting their potential usefulness in a real-world mission scenario.

2. Preliminary analysis for a space mission around Phobos

In this section we introduce the basic design aspects of the dynamics and physics of a spacecraft in orbit of Phobos.

2.1. Physical and astrodynamical characteristics

The immediately noticeable characteristics of Phobos are its small size (even smaller than some asteroids) and its irregular shape: in particular the surface is marked by a dense texture of grooves and by several big craters, one of them, named Stickney, is by far the largest and is located on the face of the moon pointing towards Mars. Phobos has an almost circular and equatorial orbit around Mars, and it rotates with synchronous period and almost zero-tilt with respect to its orbital motion. The low altitude of its orbit is lower than that required for a Mars-synchronous rotation: Phobos rises from the West more than three times a day as seen from Mars' surface near its Equator, whereas near the poles Phobos is never seen, since it is always under the horizon. Table 1 presents a summary of the physical and orbital parameters of Mars and Phobos that have been used in the analysis of the orbits undertaken in this paper.