Orbital Operations for Phobos and Deimos Exploration

Mark S. Wallace,[1] Jeffrey S. Parker[2], Nathan J. Strange[3], and Daniel Grebow[4]
Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, 91011

One of the deep-space human exploration activities proposed for the post-Shuttle era is a mission to one of the moons of Mars, Phobos or Deimos. There are several options available to the mission architect for operations around these bodies. These options include distant retrograde orbits (DROs), Lagrange-point orbits such as halos and Lyapunov orbits, and fixed-point stationkeeping or "hovering." These three orbit options are discussed in the context of the idealized circular restricted three body problem, full-dynamics propagations, and a concept of operations. The discussion is focused on Phobos, but all results hold for Deimos.

Nomenclature

x	=	Position along the Phobos-Mars line ($-x$ toward Mars), relative to Mars/Phobos barycenter
z	=	Position out of the Phobos orbit plane ($+z$ along angular momentum), relative to barycenter
y	=	Completes the right-hand frame from x and z
$\dot{x}, \dot{y}, \dot{z}$	=	First time derivative of the x, y, and z coordinates
$\ddot{x}, \ddot{y}, \ddot{z}$	=	Second time derivative of the x, y, and z coordinates
μ	=	Phobos/Mars mass ratio
r_1	=	Distance to Mars
r_2	=	Distance to Phobos
$\bar{r}$	=	Position along the Phobos-Mars line ($-\bar{r}$ toward Mars), relative to Phobos center
$\bar{h}$	=	Position out of the Phobos orbit plane ($+z$ along angular momentum), relative to Phobos center
$\bar{v}$	=	Completes the right hand frame from $\bar{r}$and$\bar{h}$.
$\dot{\bar{r}}, \dot{\bar{v}}, \dot{\bar{h}}$	=	First time derivative of the $\bar{r}$, $\bar{v}$, and $\bar{h}$ coordinates
$\ddot{\bar{r}}, \ddot{\bar{v}}, \ddot{\bar{h}}$	=	Second time derivative of the $\bar{r}$, $\bar{v}$, and $\bar{h}$ coordinates
ω	=	Phobos orbital rate
ΔV	=	Propulsive change in velocity
M	=	State-transition matrix over one full period, or monodromy matrix
λ_k	=	Eigenvalue of the monodromy matrix M

Note: Phobos is used in this description, but the nomenclature applies equally to Deimos.

I. Introduction

ONE of the deep-space human exploration activities proposed for the post-Shuttle era is a mission to one of the moons of Mars, Phobos or Deimos. Phobos and Deimos provide a logical bridge between human asteroid missions and Mars surface missions. Many of the exploration systems developed for asteroid missions can be applied to Phobos and Deimos missions and the in-space transportation system needed to reach Phobos and Deimos can be applied to later Mars surface missions. In addition, Phobos and Deimos can provide a location for base to support Mars surface missions and a platform for rapid-tempo telepresence activities on the surface of Mars.

There are several options available to the mission architect for operations around small bodies such as Phobos and Deimos. These options include distant retrograde orbits (DROs), Lagrange-point orbits such as halos and Lyapunov orbits, and fixed-point stationkeeping or "hovering." The three-body dynamics and non-spherical gravitation of the moons drive certain options to be more desirable than others. Direct orbits are infeasibly unstable due to Mars tides and the non-sphericity of the moons. Rectilinear hovers are very fuel intensive due to the Mars

[1] Mission Design Engineer, Mission Design and Navigation Section, M/S 301-121, AIAA Member
[2] Mission Design Engineer, Mission Design and Navigation Section, currently an Assistant Research Professor at the University of Colorado, Boulder, CO, 80309, AIAA Senior Member
[3] Mission Design Engineer, Mission Design and Navigation Section, M/S 301-121, AIAA Member
[4] System Engineer, Mission Systems Concepts Section, M/S 301-170S, AIAA Member

tidal forces. DROs and Lagrange orbits are feasible, however, requiring little or no fuel to maintain. For brevity, we will focus our discussion on Phobos, but all results hold for Deimos.

The classic dynamical system for the Mars-Phobos system is the circular restricted three-body problem[1] (CR3BP), as represented in equation 1. Recall that in these coordinates, Mars is at the $+\mu$ location along x and Phobos is at the $-\mu$ location along x. The units are canonical (Phobos-Mars distance in length, Phobos orbit period in time).

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} x + 2\dot{y} - \frac{1-\mu}{r_1^3}(x+\mu) - \frac{\mu}{r_2^3}(x+\mu-1) \\ y - 2\dot{x} - \frac{1-\mu}{r_1^3}y - \frac{\mu}{r_2^3}y \\ -\frac{1-\mu}{r_1^3}z - \frac{\mu}{r_2^3}z \end{bmatrix} \tag{1}$$

Because the mass ratios (μ) for Deimos and Phobos are so small[2], 1.7e-8 and 2.8e-9, respectively, the Clohessy-Wiltshire (CW) equations[3] (Eq. (2)) can also offer insight, particularly for trajectories relatively far from Phobos. The CW equations are thus the dimensioned form of the CR3BP with μ set to zero and the coordinate system shifted from the Mars-Phobos barycenter to the Phobos center.

$$\begin{bmatrix} \ddot{\bar{r}} \\ \ddot{\bar{v}} \\ \ddot{\bar{h}} \end{bmatrix} = \begin{bmatrix} 3\omega^2\bar{r} + 2\omega\dot{\bar{v}} \\ -2\omega\dot{\bar{r}} \\ -\omega^2\bar{h} \end{bmatrix} \tag{2}$$

The CR3BP dynamics yield numerous periodic orbit types that remain in proximity to the secondary body (Phobos or Deimos, in this case). Four families of interesting periodic orbits for this study are the family of Lyapunov orbit, the Vertical Lyapunov (or just "vertical") orbit, halo orbits, and distant retrograde orbit, all of which are depicted in Figure 1. The Lyapunov, Vertical, and Halo orbits are all nearly centered on the two proximate Lagrange Points, L_1 and L_2. These orbits are unstable, and oscillate in-plane, out-of-plane, and both in- and out-of-plane, respectively. The DRO, on the other hand, is stable and, as we will show, this is a very useful property.

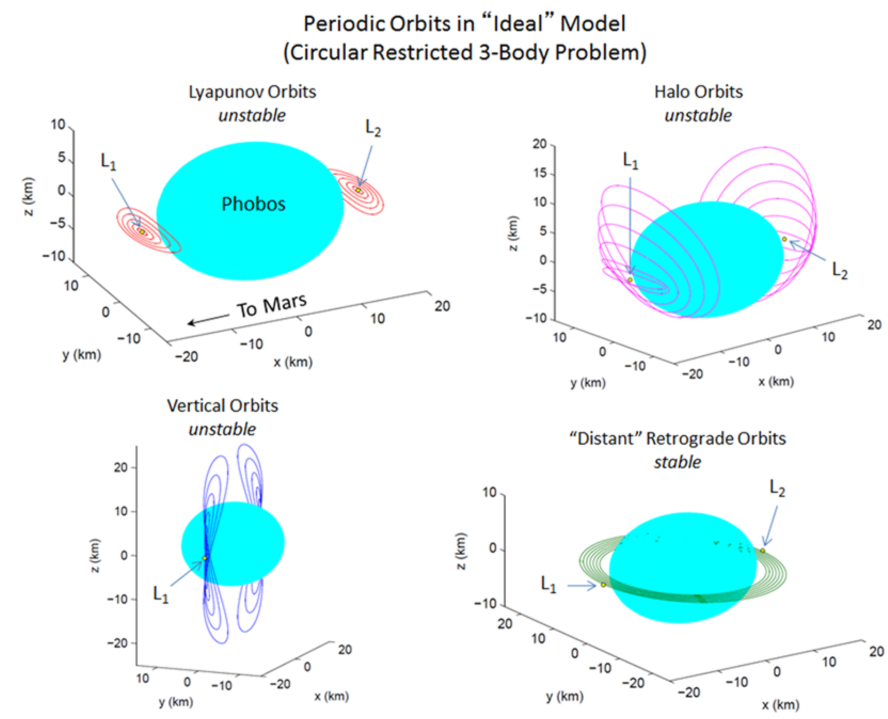


Figure 1. Periodic orbits in the Circular Restricted Three-Body Problem, with the coordinates shifted to be Phobos-centered. The blue ellipsoid is the circumscribing ellipsoid for the Phobos shape model.

The CR3BP and CW equations offer useful insights, but there are other forces at work in real applications. However, neither Phobos nor Deimos are in the perfectly circular orbits required by those equations, though Deimos gets closer. Phobos has a mean eccentricity of 0.01511 and Deimos has an eccentricity of 0.00024 (Ref. 2). In addition to this shortcoming in the dynamical systems, there are other perturbations, such as solar radiation pressure, "third body" gravitation (e.g. the Sun, Jupiter, the other moon), and the non-spherical gravitation of Mars and the proximate moon. Indeed, these last two perturbations have noticeable effects on the orbits of Phobos and Deimos themselves. Fortunately, these perturbations of the classic dynamics can be readily addressed via numerical integration of the underlying real dynamics and their forces. Unfortunately, there are other sources of noise in the dynamics that are unavoidable.

Every spacecraft has some state and acceleration uncertainty. Thrusters for desaturating momentum wheels are never perfectly balanced, spacecraft outgas (and human-class spacecraft are notoriously noisy in this regard), and the forces are imperfectly modeled. For example, the infinite series used to model non-spherical gravity must be truncated and thermal, solar, and albedo radiation forces depend on shape and reflectivity models that are imperfect. These, and other effects such as measurement noise mean that the operators of a spacecraft never know exactly where the spacecraft is. Though, with optical-navigation, body-relative states can be very well known indeed.[4] Even if the initial state and all external forces could be perfectly known, the spacecraft will experience maneuver execution errors. Phobos and Deimos proximity architectures must be responsive to these operational realities

II. Orbit Types

Given the CR3BP and CW equations, and considering the realities of flying a spacecraft, how, then, does one design a mission architecture for Phobos and Deimos exploration? The essential building blocks of an architecture are the potential orbits and trajectories the proposed mission could fly. We divide these trajectory types into three classes: hovering, Lagrange-Point orbits, and orbits. The first two classes generally remain over one spot on the surface of Phobos or Deimos. The hovers have their primary motion toward and away from the body, while the Lagrange Point orbits have a large transverse (either in- or out-of-plane) component. They can be thought of as being very constrained in their motion relative to the latitude and longitude of their sub-spacecraft point. The orbit types, on the other hand, are not so constrained. They, in concept, either cover the entire longitude space (for non-polar orbits) or the entire latitude space (for polar orbits), or both.

A. Hovering

Hovering could potentially be performed at any location, and with enough fuel expenditures, certainly could be. However, those expenditures can quickly become prohibitive. We consider the problem of hovering using the CW equations, as it produces a lower-bound on the fuel requirements; the addition of the moon's gravity will only add to the cost, as it acts in the direction of motion and must be countered propulsively in a rectilinear hover.

The first location of interest is the pole of Phobos or Deimos. This is the simplest of the CW equations to consider, the $\bar{h}$ direction, which has a closed-form solution independent of the other two coordinates. In this closed form solution, the spacecraft will experience simple harmonic motion into and out of the plane, moving through the center of Phobos twice per Phobos orbit. It is in an orbit about Mars at the same distance as Phobos, but with a slightly different inclination, and this presents the main challenge to a rectilinear hover over the pole. In order to prevent a collision with Phobos, the spacecraft must propulsively change the node of its orbit to be alternately ahead of and behind Phobos in its orbit at least twice per orbit. A convenient estimate of the DV required to achieve this can be determined by determining the value of out-of-plane acceleration in Eq. (2) and expressing the result in m/s/day. For Phobos, maintaining a station 10 km above the north pole (19.2 km from the center of Phobos), neglecting the gravity of Phobos, requires 86 m/s/day. Deimos, being further out, requires only 4.4 m/s/day, but again, these values neglect the gravity of the bodies in question.

Hovers over leading and trailing faces of Phobos are slightly more complicated, as they exist with no maintenance in the CW equations if there is no along-track velocity relative to Phobos and the radial position is zero ($\dot{\bar{v}} = 0, \bar{r} = 0$), regardless of the value of the along-track position. However, a spacecraft placed in that position will experience some acceleration in the along-track direction due to the gravity of Phobos. The effect of this acceleration on a spacecraft in a trailing position is to increase the semi-major axis relative to Mars, which will reduce the orbital period about Mars and cause the spacecraft to drop back, but not before it falls toward Phobos; a 20 km initial altitude at the trailing position will be reduced to 16 km before the fall-back occurs. In this example, the semi-major axis increases from Phobos's 9376 km to 9441 km, and the spacecraft drifts back at a rate of 2100 km/day. This effect must be countered by reducing the spacecraft semi-major axis below that of Phobos to force it to drift back toward Phobos.

Table 1: Trailing-position hovers at Phobos can be very expensive, very large, or both. These data were generated for a two-maneuver return to a stationary point 20 km above the trailing face.

Duration	Fuel Used	Min Alt	Max Alt
0.2 day	59 m/s/day	15.3 km	27 km
0.4 day	39 m/s/day	10.3 km	122 km
0.6 day	27 m/s/day	9.6 km	570 km

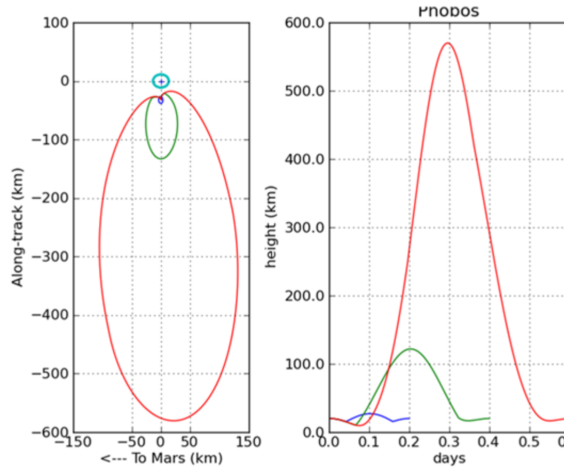


Figure 2. Two-maneuver return trajectories to a 20 km altitude station above the trailing edge of Phobos quickly become very large and smaller trajectories are very expensive both in terms of fuel and operational tempo

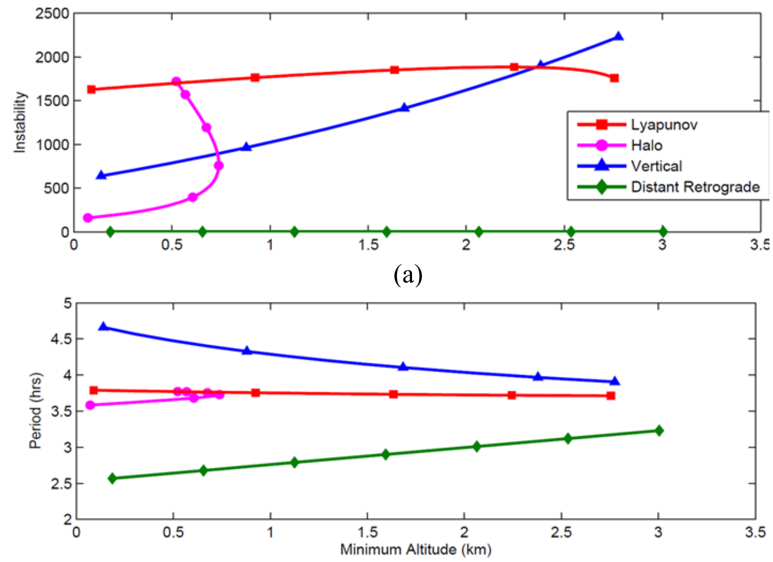
A series of fully-integrated trajectories showing the departure from a point 20 km above the trailing edge of Phobos and a two-maneuver return to the original state are shown in Figure 2, assuming three different total durations: 0.2, 0.4, and 0.6 days, in blue, green, and red, respectively. As can be seen in Figure 2 and Table 1, this strategy, even after optimizing the ΔV, results in large fuel expenditures, rapid operational tempos (maneuvers every few hours), and large departures from the station. Deimos trajectories are much more compact and cheaper. Even at a one-day duration, the maximum altitude is less than 90 km and the ΔV requirement is 6 m/s/day. At 12 hours, the maximum altitude is 35 km and the ΔV is 9 m/s/day. In either case, should the return frequency be equal to that of the orbit period about Mars, it is a very simple issue to add, for negligible additional ΔV, a small out-of-plane component to add the harmonic motion discussed in the previous paragraph.

Finally, hovering over the sub-Mars or anti-Mars points of Phobos is very expensive for the same reason that the pole hovers are: the motion due to Mars tides dominate. Consider the case of a spacecraft in a stationary position above the sub-Mars point of Phobos. This spacecraft must orbit Mars at the same rate as Phobos (thus possessing the same semi-major axis) and have a radius less than that of Phobos. There must then a horizontal component to its velocity, as the lower radius position must move faster than Phobos, and a rectilinear trajectory relative to Phobos is impossible naturally. The natural motion of the spacecraft (absent Phobos's gravity, again), would be the classic two-by-one CW ellipse, a modified version of which is the distant retrograde orbit. It could be propulsively accomplished by thrusting toward Phobos, effectively decreasing the acceleration due to Mars's gravity such that the smaller orbit has the same period as the larger one. Using Eq. (2), if the initial conditions are set to zero, except for $\bar{r}$, the acceleration simplifies to $3\omega^2\bar{r}$ in the anti-along-track direction. For a station 10 km above the sub-Mars point (23.4 km from the center of Phobos), the required DV is 315 m/s/day, plus the effect of Phobos gravity. As the station gets closer to the Phobos-Mars Lagrange points, the contribution to the acceleration due to Phobos's gravity becomes large enough that the various Lagrange point orbits become possible.

B. Lagrange-Point Orbits

Given that rectilinear hovers are prohibitively expensive, other options need to be explored. The previous discussion allowed only motion in a rectilinear direction (or relatively small variations about it). If larger departures from the station are acceptable, sub- and anti-Mars stationkeeping becomes possible through the use of Lagrange point orbits. The CR3BP permits the existence of five fixed point solutions, namely, five places where a satellite may be placed such that the gravity of Mars and Phobos (or Deimos) balance with the spacecraft's orbital motion. This is the case for any three-body system, including the Earth-Moon and Mars-Phobos systems. For the case of the Mars-Phobos system, the L_1 point lies between Mars and Phobos, only 16.6 km from the center of the moon and only 3.1 km from the surface. The L_2 point is on the far side of Phobos and only 20 meters further from the surface.

The Lagrange point orbits: Lyapunov, Vertical, and Halo, are unstable. The stability of the orbits indicates how quickly a trajectory will depart from the nominal baseline periodic orbit in the presence of a small perturbation, and without orbital maintenance maneuvers. Instability does not, however, imply that the cost for orbital maintenance is high. On the contrary, it has been demonstrated that the ΔV costs to remain close to the nominal orbit are quite small.[5,6,7] Stability as well as orbital period play an important role in determining the frequency of the stationkeeping maneuvers. There are many ways to gain insight into the stability properties of the orbits considered for this investigation. A first order analysis of the stability is available from the periodic orbit theory in the CR3BP, and ultimately stability is verified with simulations in the full-ephemeris model. In the CR3BP, knowledge of the eigenstructure of the state-transition matrix integrated over one full period, or the monodromy matrix M, offers insight to the behavior of trajectories in the neighborhood of the periodic orbit. Given a small variation from the reference orbit, the eigenvalues λ_k measure the rate of departure of the initial variation. For periodic orbits, two eigenvalues are always equal to one, corresponding to both modes along the periodic orbit itself and its orbit family. Of four remaining eigenvalues, if $|\lambda_k| < 1$, then λ_k corresponds to a stable mode, and likewise, for $|\lambda_k| > 1$, the associated mode is unstable. If λ_k is complex, then, additionally, the matching eigenvectors can be used to determine the frequency of toroidal motion in the vicinity of the reference orbit.



(a)

(b)

Figure 3. (a) Instability and (b) orbit period for orbit families in CR3BP plotted versus minimum geodetic Phobos altitude.

The largest $|\lambda_k|$ is important for this study, since it indicates the mode with the greatest rate of departure from the baseline periodic orbit. For each orbit in Figure 1, the maximum $|\lambda_k|$ and period are plotted versus minimum geodetic orbit altitude over the course of one revolution (see Figure 3). Geodetic altitude is computed assuming Phobos is a triaxial ellipsoid, locked in the stable orientation with respect to Mars orbit. Since there is a negligible difference between altitude, stability, and period between the L_1 and L_2 orbits, the data in Figure 3 is representative of both L_1 and L_2 families. The orbits with the highest minimum altitude, roughly 2.7 km, are the Lyapunov and vertical orbits that are closest to the libration points. These orbits are the smallest in size, since they bifurcate from the libration point. They also possess the greatest instability as well as the smallest period, approximately 4 hours, which factor into the frequency of maneuvers required for stationkeeping. As the Lyapunov and vertical orbits increase in size, the minimum altitude gets smaller until eventually intersecting the surface of Phobos. Similarly, for halo orbits the minimum altitude increases with orbit size up to 0.7 km, and then decreases until the family intersects Phobos. As expected, for DROs, minimum altitude and period monotonously increase with orbit size.

However, there are three complicating factors in the Mars-Phobos system when comparing libration orbit missions to similar missions near the Earth and stability theory. First, since the Lagrange points are so close to Phobos's surface, many of the orbits that are often considered for missions in the Earth's neighborhood impact Phobos's surface. Second, Phobos's asymmetric gravity field plays a much larger role than it does near the Earth. Finally, the dynamics that drive the orbits are related to the orbital period of the smaller body about the larger primary; consequently, orbits about the Mars-Phobos Lagrange points have orbital periods measured in hours rather than weeks (Earth-Moon) or months (Sun-Earth). This significantly impacts the operational schedule for station keeping and surface visibility.

Even with these mission complications, several families of libration orbits stand out as potential destinations for a mission to Phobos. Their characteristics are best represented by considering three classes: planar Lyapunov orbits, vertical Lyapunov orbits, and halo orbits, such as those illustrated in Figure 1, which are illustrated in the CR3BP. The CR3BP is a great planning tool, but in an environment like the Mars-Phobos system, it is prudent to reconstruct the trajectories in a high-fidelity model. Several example orbits from each family have been transferred into a high-fidelity model using a multiple shooting differential corrector.[8,9,10] The general characteristics of these orbits remain the same, but the specifics, e.g., their minimum altitude relative to Phobos, are prone to change.

The model that used here includes a 50x50 spherical harmonic field representing Mars' gravity, a 3x3 field representing Phobos's gravity, point-mass models of the Sun, Earth, Moon, Deimos, Jupiter, and Saturn, and a solar radiation pressure model that assumes the spacecraft's area-to-mass is 0.2 m^2/kg with a solar flux of $1.019794376 \times 10^{17}$ N at 1 AU.

Figures 4-6 show several views of an example orbit from the classes of planar Lyapunov orbit, vertical Lyapunov orbit, and halo orbit, respectively, after differentially correcting the orbits into the high-fidelity model of the system. Each of these is in orbit about the Mars-Phobos L_2 point, though nearly symmetric orbits exist about the Mars-Phobos L_1 point. The L_1 orbits may be beneficial, since they are always between Mars and Phobos, providing communication to the surface of either body. Each of the orbits shown requires no maneuvers whatsoever, except statistical station keeping maneuvers.

Each of the three classes of orbits offers different mission characteristics. The planar Lyapunov orbits, such as that in Figure 4, may be as large or as small about the L_1 or L_2 point. The smaller the orbit is, the more consistently it remains near the Lagrange point – placing it about as far away as one can get from Phobos without requiring maneuvers. Indeed, the example orbit shown in Figure 4 oscillates from 3 to 5 km from the surface. These orbits have the best access to the equatorial region on either side of Phobos, though they do not have good access to the poles of Phobos. The class of vertical Lyapunov orbits, such as that in Figure 5, do offer a way to view the poles of Phobos as well as the equatorial region. The example shown traverses quite a ways out of plane, though it also comes very near the surface of Phobos twice per orbit. The third class of orbits, halo orbits, as illustrated in Figure 6, offers the most coverage of the surface of Phobos. Only a small subset of the entire family of halo orbits does not impact the surface, so there are very few options for the mission designer. But the example shown in Figure 6 is a good choice: it remains above 2 km from the surface at nearly all times, covers the equator very well, and covers other parts of the surface every 3.5 hours or so.

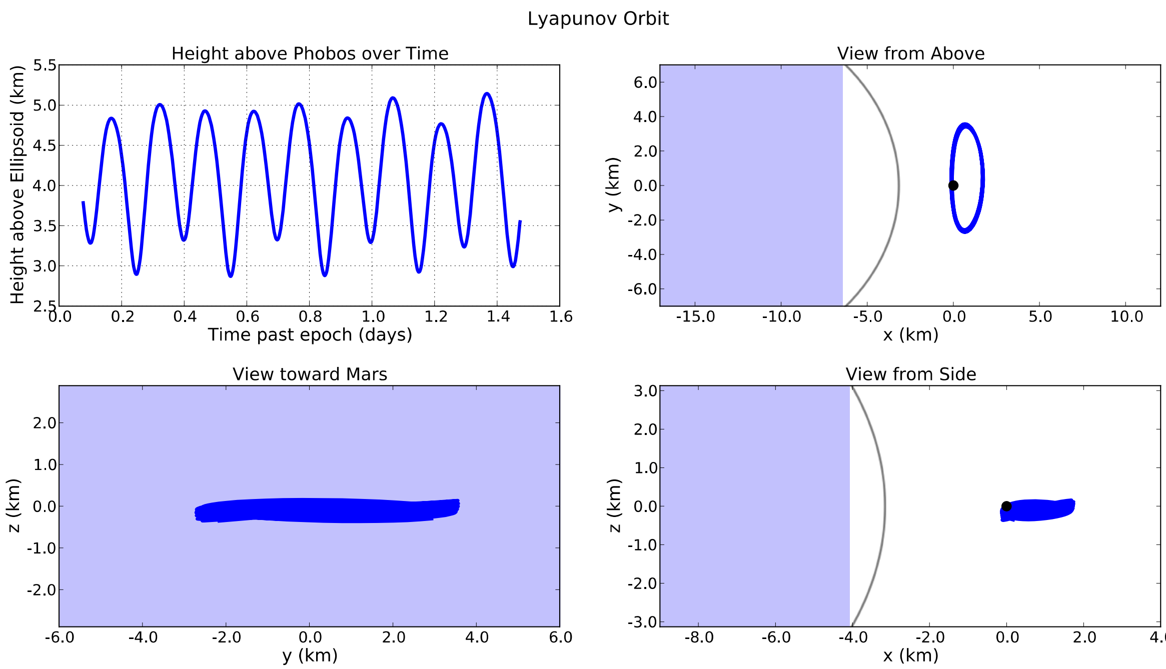


Figure 4. Four perspectives of an example Lyapunov orbit about the Mars-Phobos L2 point in the high-fidelity Phobos system. These views are in the Mars-Phobos rotating frame, centered about the L2 point.

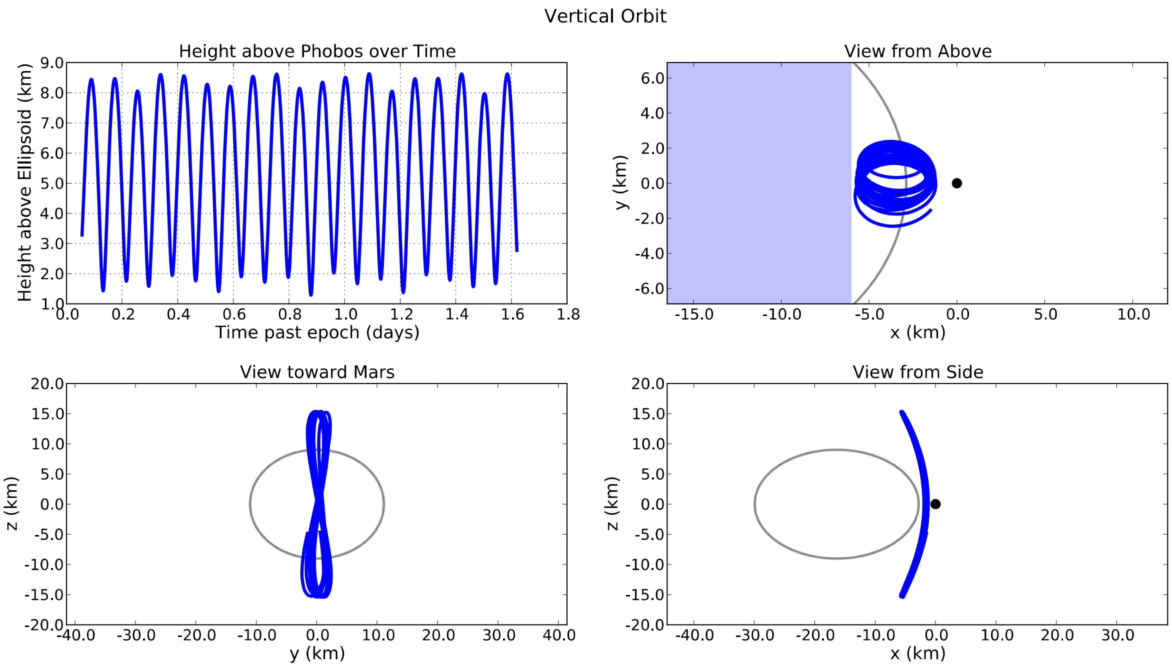


Figure 5. Four perspectives of an example vertical Lyapunov orbit about the Mars-Phobos L2 point in the high-fidelity Phobos system. These views are in the Mars-Phobos rotating frame, centered about the L2 point.

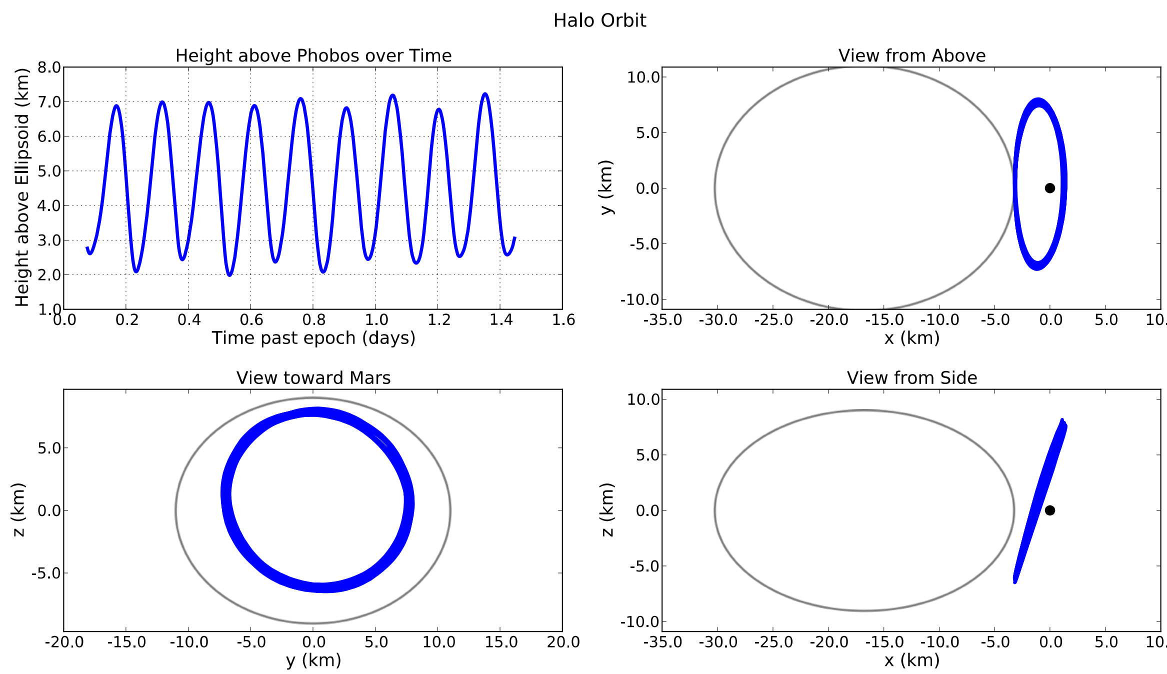


Figure 6. Four perspectives of an example halo orbit about the Mars-Phobos L2 point in the high-fidelity Phobos system. These views are in the Mars-Phobos rotating frame, centered about the L2 point.

The most challenging aspect of the libration orbits is that they are very unstable. A spacecraft placed in one of these orbits will remain on it indefinitely, given a perfect injection. But a small error will grow exponentially. Figure 7 illustrated that a 1 mm/s error in velocity caused the spacecraft to completely depart the orbit after just five hours. A spacecraft can remain on the orbit for very little fuel – on the order of 1 m/s per month – if it performs station keeping maneuvers often enough and accurately enough. Historical missions to libration orbits have required 2-3 station keeping maneuvers every orbit.[11,12] The orbital period of those shown in Figures 4 – 7 is approximately 3.6 – 4.0 hours. This suggests that station keeping maneuvers must be performed every 1.5 – 2 hours, if not more frequently. This is much too rapid for the station keeping to be designed anywhere on Earth; the maneuvers must be designed autonomously[13] or by operators at Mars.

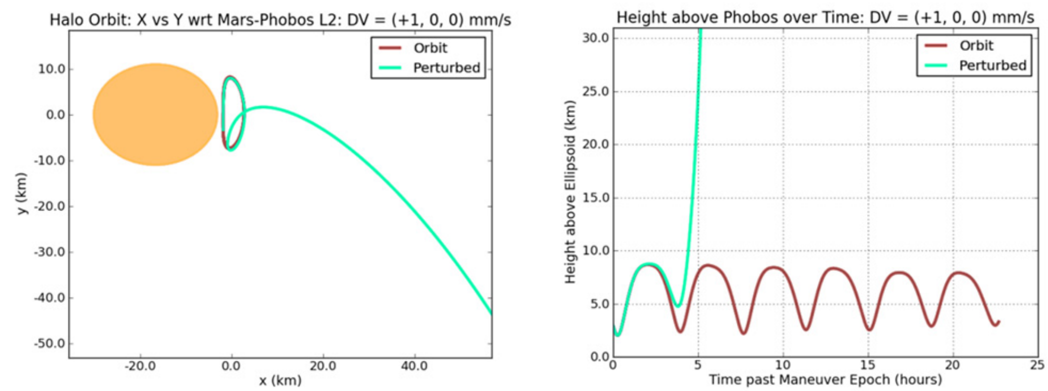


Figure 7. A 1 mm/s disturbance in a Phobos halo orbit will cause the spacecraft to depart on an unstable manifold in less than 5 hours. Depending on the direction of the disturbance, the path could be toward the surface instead of away as depicted, which can be useful for a controlled descent to the surface.

The results of an analysis of stationkeeping requirements for various maneuver frequencies are shown in Table 2. These results are for a vertical orbit, but they are similar for the other types as well. Assuming a 0.5 mm/s maneuver execution error and 1 mm/s uncertainty in the velocity of the spacecraft in the orbit, the position uncertainty and maneuver frequency were varied to determine the ΔV budget required to maintain the orbit. Clearly, the collection of high-precision and timely navigation data is vital to support successful station keeping. Tracking data must be collected nearly continuously. The lower-frequency maneuvers with greater position uncertainty failed to converge on an answer, suggesting that the instabilities caught up with the simulated spacecraft and it either crashed or was ejected. As a point of comparison, 100 meter position error is comparable to that of Artemis at the Moon,[14] and 0.1 to 1.0 meters is achievable with optical navigation techniques. It is likely that tracking data will include radiometric data from one or more beacons on the surface of Phobos, optical tracking of surface features on the moon, radiometric data from other spacecraft either in orbit about Mars or Phobos, and any radiometric data from Earth or the surface of Mars.

Table 2: High-precision navigation and frequent maneuvers are required to maintain a Lagrange point orbit.

m/s/day for Vertical orbit maintenance	Maintenance Period			
	0.5 hours	1.0 hour	1.5 hours	2.0 hours
Position Error: 0.1 m	0.22	0.17	0.29	0.73
Position Error: 1.0 m	0.25	0.22	0.35	1.0
Position Error: 10 m	1.3	1.0	1.9	N/A
Position Error: 100 m	13.8	9.8	N/A	N/A

C. Orbits

The various Lagrange orbits, while very cheap to maintain in terms of ΔV, still require intensive operations as they require maneuvers every few hours. Keplerian-like orbits around Phobos and Deimos are unstable or simply do not exist, given their small size and the strength of the Mars tides.[15] The Phobos and Deimos spheres of influence are 7.3 km and 8.2 km, respectively, which do not compare well with their sizes (radii of 13.4 km and 7.5 km in their largest dimension, respectively). The Phobos sphere of influence is actually contained entirely within the moon, and a Deimos-orbiting spacecraft would have to remain within 0.7 km of the surface to remain within the sphere of influence. As such, a stable Keplerian-like orbit could theoretically exist, but the navigation and orbit control requirements are extraordinary and render such orbits to be undesirable as a low-risk, quiet-operations option.

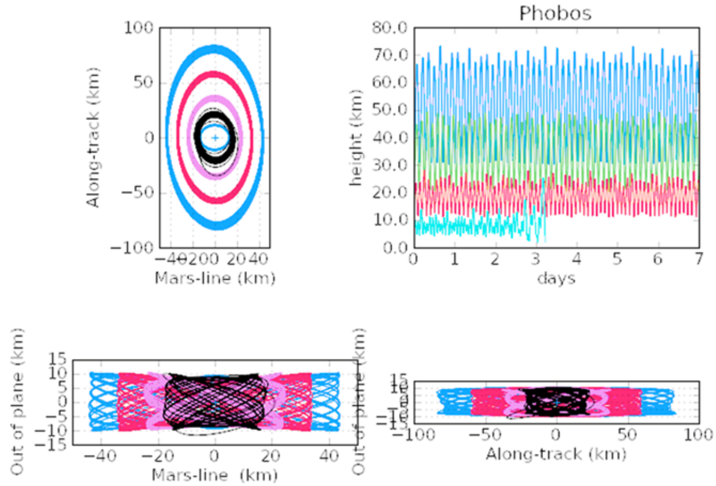


Figure 4. Four DRO trajectories integrated for 7 days, with minimum altitudes varying from 2 to 30 km illustrate the stability of this orbit type. Total lifetimes were over 60 days, except for the 2 km orbit, which collided with Phobos at 3.25 days.

Fortunately, there does exist a trajectory type that combines low altitudes, stability, and ease-of-maintenance: the so-called distant retrograde orbit, or DRO, sometimes referred to as a quasi-satellite orbit, or QSO.[16] The "distant" part of the name is a misnomer in the case of Phobos and Deimos as such orbits can exist very close to the surface of the moons. These orbits have the greatest stability when they lie entirely within the orbit plane, but they can easily incorporate out of plane velocity components, provided they oribt far enough away from the moon, as illustrated in Figure 4. The velocity at the sub- and anti-Mars points for these example orbits varies from 11 to 21 m/s and the orbit period varies from 2.9 to 6.9 hours as the orbit moves out from the 2 km initial altitude to 30 km.

III. Concept of Operations

A human mission to Phobos or Deimos would likely use many of the orbits identified earlier in this paper for different phases of the mission. The DROs could be used as stable home base orbits between more intesive operations in other orbits. The Lagrange point orbits provide options for a mothership to maintain continuous visibility of a crew performing surface exploration in the sub or anti Mars hemispheres of Phobos or Deimos, although this is at the expense of more intensive station keeping. Transitions from the DROs to vertical or halo Lagrange point orbits cost only 10-20 m/s. The unstable manifolds from the Lagrange point orbits would also be useful for efficient transfers from the mothership to the surface and back.

An example scenario for a manned Phobos mission would be for the mothership to arrive at Phobos in a DRO and gradually reduce the altitude to a few kilometers. During this phase the crew could remotely examine the surface of Phobos and verify the state of planned surface excursion sites. After the initial survey, the mothership could transition to a halo orbit about the Mars-Phobos L1 point. A small excursion craft could leave the mothership on an unstable manifold and reach Stickney crater. During the surface mission, the mothership could remain in constant communications with the surface crew. After the surface mission is done, the crew could take a stable manifold trajectory from the surface to the mothership in the halo orbit. The mothership could then transfer from the halo orbit to a DRO where the station keeping requirements are less demanding. A similar scenario at the L2 point could be used for exploration of the anti-Mars hemisphere. For missions to the Phobos North or South poles, a DRO with sufficient altitude could also provide for continuous communications between the mothership and the surface crew.

Another scenario is a combined DRO/Hover scheme. A Phobos DRO with a periapse altitude of 17.8 km has an apoapse altitude of 20 km. At apoapse, above the trailing face, the ΔV required to bring the spacecraft to rest relative to Phobos is only 13 m/s. For that relatively small cost, the spacecraft can enter the leading/trailing hover discussed in Section II.A. Then, performing a 6 m/s maneuver every two hours, the mothership could remain within 30 km of the leading face for the duration of the surface mission. While the mothership is further away and requires more fuel to remain on-station, it does maintain contact with a crew on the leading face, which the halo cannot.

IV. Conclusion

The Phobos and Deimos dynamical environment, while relatively complex, still permits the existence of Lagrange point orbits such as the halo orbit and the stable “distant” retrograde orbit. The DRO is a stable orbit with minimal station keeping requirements and can get very close to the surface. Lagrange point orbits offer continuous line-of-sight with portions of the surface and are ideal for short-term activities such as surface excursions, provided the navigation and maneuver frequency requirements can be met. Fortunately, that is well within the state of the art for autonomous spacecraft. Given the various advantages of the two orbit types, a mission could switch between a DRO “home” orbit and a Halo orbit to support short-term surface missions.

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