AIAA SPACE 2011 Conference & Exposition
27 - 29 September 2011, Long Beach, California

AIAA 2011-7140

Comparison of Deimos and Phobos as Destinations for Human Exploration and Identification of Preferred Landing Sites

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A human mission to one of the two moons of Mars has been suggested as an easier precursor before a mission to land on Mars itself. Astronauts would explore the moon in person and teleoperate rovers on the surface of Mars with minimal lag time, returning samples to Earth. Lockheed Martin evaluated such a mission as part of its Stepping Stones sequence of missions in the spirit of the "Flexible Path" approach advocated by the Augustine Committee. In this paper, we compare Deimos and Phobos as potential destinations, including trajectory design, communications access to Earth and the Martian surface, solar illumination, expected radiation environment, planetary protection issues, and physical access to and from the Martian surface. While prior mission concepts have tended to focus on Phobos, we conclude that Deimos is the better destination for an early teleoperation mission largely because it is farther from Mars than Phobos. This reduces the required mission ΔV by 400 m/s, provides longer communications access and line of sight to 15 deg higher latitudes on the Martian surface, and reduces the frequency and cumulative duration of eclipses by Mars so that a solar powered mission is easier on Deimos than on Phobos. Using a shape model of Deimos, we performed global lighting and communications access analysis and determined that there are two specific regions on Deimos which are the most favorable landing sites. Small areas along the North and South arctic circles on the Mars-facing side of Deimos experience a continuous view of Mars, continuous sunlight for up to ten months during polar summer, and continuous line of sight to Earth during most of the sunlit season. These sites are centered near 60° N 0° W, and 51° S 7° E. A timeline for a mission to these two sites is provided for the 2033-2035 opportunity. This is the easiest opportunity during the next few decades because optimum Earth-to-Mars orbital geometry will likely coincide with the phase of the solar activity cycle that provides the most protection from galactic cosmic rays, reducing the effective radiation dose. During this mission, the crew would land at the southern hemisphere site first, during the middle of the southern summer season. After a four month stay, the crew would depart the surface of Deimos to orbit for 50 days during the equinox and eclipse season, when lighting is unfavorable at any location on the Deimos surface. At the beginning of northern summer, the crew would land at the northern site and stays for ten months before returning to Earth. In this way, the crew can explore both hemispheres of Deimos without requiring advanced power systems.

Nomenclature

GPS	= Global Positioning System
LH_2	= Liquid Hydrogen
LOX	= Liquid Oxygen
mSv	= milliSievert
ΔV	= Change in velocity

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I. Introduction

THE idea that astronauts might visit the moons of Mars, Phobos and Deimos, before Mars itself is older than the Space Age. In a 1951 non-fiction book on space travel, Arthur C. Clarke speculated that because of their low gravity "these tiny Moons may well be the first extra-terrestrial bodies, next to our own satellite, on which human beings will ever land."[1] Later advocates such as Singer[2], Landis[3], Lee[4], and others have developed concepts and rationales for Phobos-Deimos ("PhD") missions. Typical mission objectives include exploration of the moons themselves, exploitation of possible in-situ resources such as water ice, and teleoperation of robots on the surface of Mars. Astronauts on the Martian moons could operate rovers on the surface of Mars with minimal speed-of-light lag and high bandwidth, which may be much more efficient than controlling them from Earth. In a speech in April 2010, President Obama announced a new space exploration plan which includes visiting an asteroid by 2025 and then "by the mid-2030s, I believe we can send humans to orbit Mars and return them safely to the Earth. And a landing on Mars will follow."[5] Though the speech did not mention Phobos or Deimos specifically, they may be visited during the Mars orbital mission.

Lockheed Martin has previously developed a series of human exploration mission concepts nicknamed Stepping Stones. These include missions to explore the lunar farside from the second Lagrange point, and the Plymouth Rock asteroid mission.[6] In light of recent interest in Phobos-Deimos missions, we decided to examine the feasibility of an austere mission to one of the Martian moons. The resulting Red Rocks mission concept follows the same philosophy of minimizing difficulty in an effort to reduce cost which have used in other Stepping Stones missions. We therefore focused on determing ways to make a solar-powered (rather than nuclear) spacecraft viable and to minimize delta V and radiation exposure.

II. Comparison of Deimos and Phobos

Phobos and Deimos are both small, irregular objects comparable in size to the largest terrestrial mountains. Their origins are debated and their composition uncertain. They may be captured D-type asteroids, or remnant debris ejected from early large impacts on Mars (similar to the formation of Earth's Moon), or material left over from when Mars first accreted. Both moons are tidally synchronized to Mars so that the same side faces the planet at all times. Both moons have nearly circular orbits very close to their parent planet within a few degrees of the equatorial plane. The orbit of Deimos is just beyond Mars's geosynchronous orbit altitude. For comparison, its orbit altitude is similar to the orbit used by Earth's GPS satellites. Phobos is even closer to Mars, with an orbital period only one quarter that of Deimos. The orbit altitudes of these moons determine several of the parameters which are key to this study, including communications access to Mars and solar lighting. Relevant parameters are provided in Table 1 below and discussed in more detail in subsequent sections. For comparison the table also includes data on two other potential mission orbits: a low altitude orbit and Mars geostationary orbit.

Table 1. Comparison of Phobos, Deimos and potential spacecraft orbits

	Low Mars Orbit	Phobos	Mars Geo-stationary Orbit	Deimos
Dimensions (triaxial radius)	-	13 x 11 x 9 km	-	8 x 6 x 5 km
Mean orbit radius	3797 km	9377 km	20462 km	23460 km
Mean orbit altitude	400 km	5980 km	17065 km	20063 km
Orbit mean inclination (relative to equator)	Any	1.1 deg	0.0 deg	2.4 deg
Orbit period	1.97 hr	7.7 hr	24.6 hr	30.2 hr
Orbital velocity	3.37 km/s	2.13 km/s	1.45 km/s	1.35 km/s
Maximum eclipse duration	42 min	54 min	78 min	84 min
Max eclipse % of orbit period	35%	12%	5%	4.6%
Eclipse season duration		228 days		83 days
Average night duration	-	3.8 hr	-	15.1 hr
Max visible latitude on Mars	Inclination+26.5	69.8 deg	80.4 deg	84.1 deg
Max latitude with 5 deg horizon mask	Inclination+22	64.8 deg	75.5 deg	80.2 deg
Two-way light time to nadir point on Mars	3 ms	40 ms	114 ms	134 ms
Duration of line-of-sight to Mars equatorial site	Depends on inclination	4.2 hrs	Continuous (or none)	59.6 hrs
Time between communications passes	Depends	6.9 hrs	-	71.8 hrs
Apparent angular size of Mars	126.9 deg	42.5 deg	19.1 deg	16.7 deg

A. Communications Access to Mars and to Earth

If a primary function of a Martian moon mission is for astronauts to teleoperate robots on the surface of Mars then the differences in communication capability from the two moons to the surface are significant. Because of Deimos's higher orbit it moves more slowly than Phobos and an antenna on Deimos can communicate with assets over a larger swath of Mars. Assuming that a communications antenna on the Martian surface may have a 5 degree elevation mask due to terrain on the horizon, then astronauts on Phobos would have line of site communications to a rover up to 64.8 degrees latitude on Mars whereas from Deimos they could control assets up to 80.2 deg latitude. Phobos-based astronauts could directly communicate with most of Mars, but not the polar regions. For example, the landing sites for the Phoenix (68.3 N) and Mars Polar Lander (76 S) missions are only in line of sight from Deimos and not Phobos.

Because Phobos moves so quickly it has short communications passes of 4 hours to sites on Mars (changing slightly with latitude) compared to more than 2.5 days duration from Deimos. However, the gaps between passess would also be much shorter. Phobos passes over a site on Mars every 11.1 hours, while opportunities from Deimos occur on a 131 hour cycle. The relative merits of short but frequent communications (Phobos) vs long communications passes with long gaps (Deimos) will depend on the concept of operations for surface assets. However, a given site at 30 deg latitude on Mars is in view from Deimos 45% of the time, but only 38% of the time from Phobos, giving Deimos a distinct advantage.

Though speed of light latency is greater from Deimos than Phobos, it should not be a significant impediment to teleoperations from either moon. Two-way speed of light lag is 40 ms from Phobos and 134 ms from Deimos. On Earth, surgeons perform remote surgery with longer latency. The speed of light lag is short enough that hardware latency may be a larger contributor to total communications latency than the distance to Mars.

Sites on Deimos also have more frequent direct line of sight communications to Earth than from Phobos, because as viewed from Deimos, Mars does not occult the Earth as frequently. From appropriate locations on Deimos it is possible to have many months of continuous Earth communications.

B. Lighting Conditions and Eclipses

The moons of Mars have their polar axes aligned within a few degrees of Mars' polar axis, which is tilted 25° to the ecliptic. Phobos and Diemos therefore have distinct seasons and lighting conditions, which coincide with the Martian seasons. Like Earth and Mars, but unlike the Moon, they have a summer season in which the Sun is high in the sky and a winter season when it is low in the sky. In high latitude regions, the Sun can remain visible continuously during summer and may set for many days during winter, as on Earth. Northern hemisphere summer for Martian moons lasts significantly longer than southern hemisphere summer because Mars' orbit is eccentric and apohelion occurs during northern summer. Martian dust storm season generally occurs during southern summer when Mars is closer to the Sun, a scheduling issue relevant for missions which operate assets on the Martian surface.

Because Phobos and Deimos orbit close Mars they also have eclipse seasons. Eclipses of the Sun by Mars occur repeatedly during the period when the line of intersection between the moon's orbit plane and the ecliptic points toward the sun. Since the orbit plane is roughly the Mars equatorial plane, eclipses occur around the time of Mars' vernal and autumnal equinoxes. Each eclipse season for Phobos lasts about 228 days, whereas the Deimos eclipse seasons are only 83 days long because Deimos orbits much farther from Mars. Maximum eclipse duration on Phobos is only 54 minutes, or 12% of the orbit period. Since eclipse occurs during the middle of the local day for the Mars-facing side of the moon, the combination of eclipse and night time can add up to a maximum of 62% darkness over the orbit period. On Deimos peak eclipse duration is longer, 84 minutes, but constitutes a smaller fraction of the orbit period, and there are many fewer eclipses. It will be difficult to operate a solar powered spacecraft on either moon during the equinoxes at peak of eclipse season, but during the rest of the year Deimos is better illuminated than Phobos.

For purposes of this paper, we define summer to be the period after the vernal eclipse season ends and before autumnal eclipses begin, rather than the astronomical definition beginning at solistice and ending at equinox. Dates and durations for the summer seasons analyzed in this paper are given in Table 2.

Table 2. Dates and duration of summer sunlight season between eclipse seasons

	Phobos Southern Hemisphere Summer	Phobos Northern Hemisphere Summer	Deimos Southern Hemisphere Summer	Deimos Northern Hemisphere Summer
Start	9/22/2033 11:09 AM	8/10/2034 9:32 AM	7/20/2033 9:54 AM	5/30/2034 4:32 PM
End	12/21/2033 6:27 PM	1/1/2035 6:51 AM	3/2/2034 1:46 PM	3/23/2035 8:14 PM
Duration	90 days	144 days	225 days	297 days

C. Sample return

Returning one or more samples of Martian rocks to Earth has been a major goal of planetary scientists for decades. Some advocates of a human Phobos / Deimos mission have suggested scenarios in which a robotic sample return system sends Martian samples from one or more sites on Mars to one of the moons rather than directly back to Earth. Astronauts would bring back the samples in their return vehicle, perhaps only after testing them for biological activity or sorting them to select the best samples. While it may seem that Phobos would be easier than distant Deimos for a Mars sample retun rocket to reach, this is only partly true. Because the moons orbit in the equatorial plane, a sample carrier launched from a non-equatorial Martian site must perform a plane change to soft-land on either moon. The delta V to Phobos is lower than Deimos from sites on Mars below 40 deg latitude, but is lower to Deimos from higher latitude sites. Delta V data are presented in Figure 1 assuming that samples are launched due east from the sample site into a low Mars orbit at 200 km altitude and inclination equal to the site latitude. They then use a simple elliptical transfer from low Mars orbit to the destination moon with a plane change at apoapse. The delta V penalty for higher latitude sites could be reduced using a longer, more complex three-burn bielliptic transfer. However, past studies for robotic sample return Mars Ascent Vehicles have usually found it necessary to keep the vehicle as simple as possible to stay within landing mass and packaging constraints, so we have limited this assessment to the simpler transfer trajectory. For comparison, the delta V required to deliver a sample container directly to Earth is also shown, assuming a hyperbolic excess velocity (V infinity) of 3 km/s and a low departure declination. These assumptions are consistent with feasible Earth return trajectories during the May 2035 return opportunity.

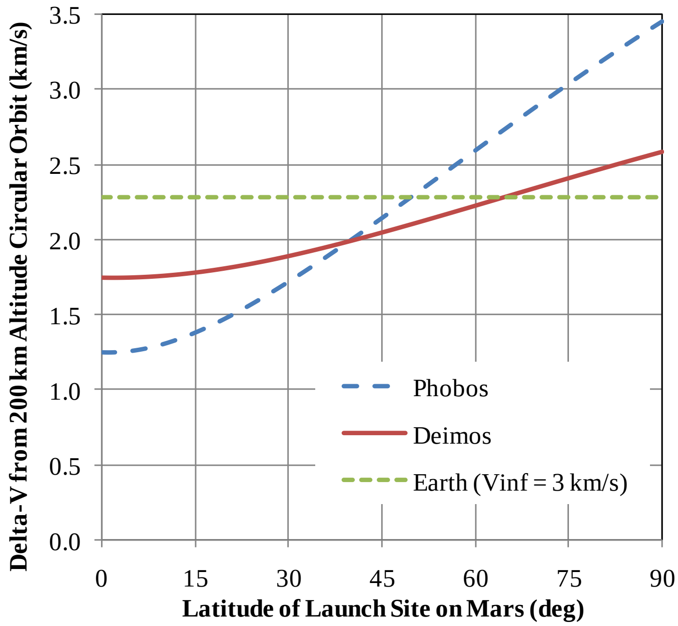

Figure 1. Delta V required to reach Phobos or Deimos from low Mars orbit as a function of surface launch site location.

D. Additional Considerations

1. Planetary Protection

Current planetary protection guidelines consider Phobos and Deimos to be inhospitable habitats for Earth life and therefore do not levy any requirements to prevent forward contamination (transmission of Earth microorganisms to another world). Missions to Mars orbit must still prevent accidental contamination of Mars itself, such as by a mission failure which results in accidental Mars impact. Backward contamination (bringing alien life to Earth) requirements for the moons are still being studied, due to the possibility that rocks carrying Martian life could be ejected from Mars by cratering events and impact on Phobos or Deimos. In this scenario, material is energetically more likely to end up on Phobos than Deimos. However, we do not expect a difference in requirements between the two moons to be a strong influence on mission planning. Planetary protection requirements for a human mission to either moon will be far easier than for missions to the Martian surface.

2. Radiation environment

Early in our investigation we expected that appropriate sites on Phobos might offer a reduced radiation environment compared to Deimos because Mars would fill more of the sky, blocking cosmic rays and solar particles. However, the differences are small. Landing on either moon provides shielding from half the sky due to the bulk of the moon, and perhaps more if the landing site is in a crater or other depression. But, Mars fills only 3.4% of the 4 pi steradian sky as seen from Phobos, vs 0.5% as seen from Deimos. So, differences due to proximity to Mars are likely to be smaller than differences due to local terrain. In either case, using a moon for radiation shielding is beneficial, and can reduce cosmic ray effective dose by on the order of 150-300 mSv compared to staying in high Mars orbit. (This negelects a small but unquantified increase due to albedo neutrons from the surface.)

III. Identifying Landing Sites on Deimos and Phobos

In order to make a low-cost teleoperation mission feasible, we hoped to find locations on Deimos or Phobos where solar power is readily available and the surface of Mars is visible simultaneously. The following section describes the method and results of the search.

A. Analysis Methods

We used Version 9.2.1 of Satellite ToolKit (STK) software from Analytical Graphics Inc. (AGI) to perform the lighting and access analysis presented in this paper. In order to capture the effects of local terrain on the lighting and Mars access we created terrain models for both Phobos and Deimos. We used raw elevation data for the moons which was created by Dr. Peter Thomas and which we obtained from the NASA Planetary Data System repository.[7] The Phobos model contained elevation data points spaced at 2 deg increments in latitude and longitude and the Deimos spacing was 5 deg. Using a process recommended by AGI, we converted the shape files into STK terrain files and applied them to the respective central body definitions for Deimos and Phobos provided within STK. We verified that we had correctly incorporated the maps and shape models and could accurately calculate surface lighting by reproducing Viking images from similar viewing angles on the dates the images were taken. This testing revealed that the data sources and STK model used different conventions for east and west longitudes, which we corrected.

We used the STK Coverage tool to compute lighting and Mars access for locations on each moon. In order to obtain accurate access results for the full visible disk of Mars or the Sun and not simply their centroids, we placed a network of facilities on the surface of both the Sun and Mars to define points which were evenly spaced geographically. We grouped the facility networks into a ‘constellation’ on each of the two bodies. For the facility network on the Sun, the access constraints of the constellation were set so that access to any one of the facilities constituted access to the constellation, and therefore line of sight to the sun. Effectively, this counts a location on Deimos or Phobos as having sunlight if part of the sun’s disk is visible above the local horizon, or if the location is in the penumbra of Mars. Because we wanted to know which places on the moons had access to the full Martian disk (and because the moons are much closer to Mars than the Sun), it was necessary to constrain access to the Mars facility constellation to only count when there was access to the maximum number of facilities that could be viewed from that moon's distance. This number was determined by running a quick access report to the constellation from each moon and noting the maximum number of facilities that that particular moon could see over a long period of time. For the analysis presented here, full Mars visibility from Phobos was defined as 8 of 40 facilities visible and 15 of 40 from Deimos. In addition to computing which sites on the moons can see the full disk of Mars, we were also able to calculate which regions had line of sight to fewer facilities and therefore could see only part of Mars.

We performed a lighting analysis to determine the times when the sub-solar point on each moon was above and below that body's equator. These dates corresponded to the two equinoxes. The times of maximum and minimum Sun latitude were also collected to determine the times of the two solstices. We generated an eclipse report for each moon to identify the seasons between eclipses when a site on the moon could potentially have uninterupted access to the Sun. The results presented below cover the time periods defined in Table 2.

In order to create a coverage definition on each moon whose access would be constrained by local terrain features, we created a template facility on each moon. First, the altitude had to be set to "Use Terrain Data". Second, the "AzElMask" option had to be set to "Use Terrain Data" with the "Use Mask for Access Constraint" box checked. Finally, both the "Line of Sight" and "Az-El Mask" boxes had to be checked under basic constraints.

The final step was to create a coverage definition for each moon. The process for each is mostly the same with the only difference being the time intervals and Mars constellation used for access. Within the coverage definition we used a global area of interest with a latitude/longitude point granularity of 4 deg. The point altitude was set to 0 km above the moon’s terrain. Under "Grid Constraint Options", the "Reference Constraint Class" was set to "Facility" with the "Use Object Instance" box checked and the appropriate template base facility highlighted. Under assets, the appropriate Mars constellation was assigned, along with the Sun constellation. For each constellation, the grouping option was set to "Grouped" and the "Use Constraints" box was checked. Finally, the interval start and stop times could be set to correspond with the particular period of interest for the analysis (see Table 2). Several figures of merit can be utilized to yield different access maps. For the lighting and access maps shown in this paper, we set the type to "Coverage Time" and the compute type to "Percent".

B. Deimos Results

Figure 2 shows views of the southern hemisphere of Deimos. There are several regions on the Mars-facing and anti-Mars lobes which are sunlit up to 100% of the time during southern summer, shown in part c of the figure. These could be good landing sites for any solar powered spacecraft. For a mission which will control assets on Mars, the combination of solar power and Mars visibility is desirable. A small region on the Mars-facing lobe combines continuous sunlight and Mars access. It is highlighted in yellow in Figure 2d, and is located at 51° S, 5-10° E. A similar region exists in the northern hemisphere, as shown in Figure 3. It is centered at 60° N and extends several degrees on either side of the 0° longitude line. Coincidentally, this northern region is only a few hundred meters east of where the only high resolution images of Deimos were taken by Viking (such as image 423b62 and 423b63). The Viking images of this area show a smooth surface with muted craters which appear to have been filled in by a deep layer of regolith.

The southern polar region of Deimos offers an interesting potential storage location for missions with an Earth return stage using cryogenic propellants. The south polar region is a depression between two large lobes which shadow the south pole. During southern summer the south pole receives sunlight during only parts of the day, and no sunlight at all during winter (see Figure 2c). It is also shielded from thermal energy emitted by Mars. The south polar region of Deimos may be one of the coldest places in the Martian system. Furthermore, the average surface gravity on Deimos is roughly 0.004 m/s^2. This is similar to the low acceleration used to settle propellant in cryogenic propulsion stages such as Centaur today. Settling the propellant separates warm ullage gas from colder liquid, which simplifies thermal management, venting, and mass measurement. The south polar region of Deimos may be a good location to store a cryogenic return stage during the many months that the crew stays in the Martian neighborhood.

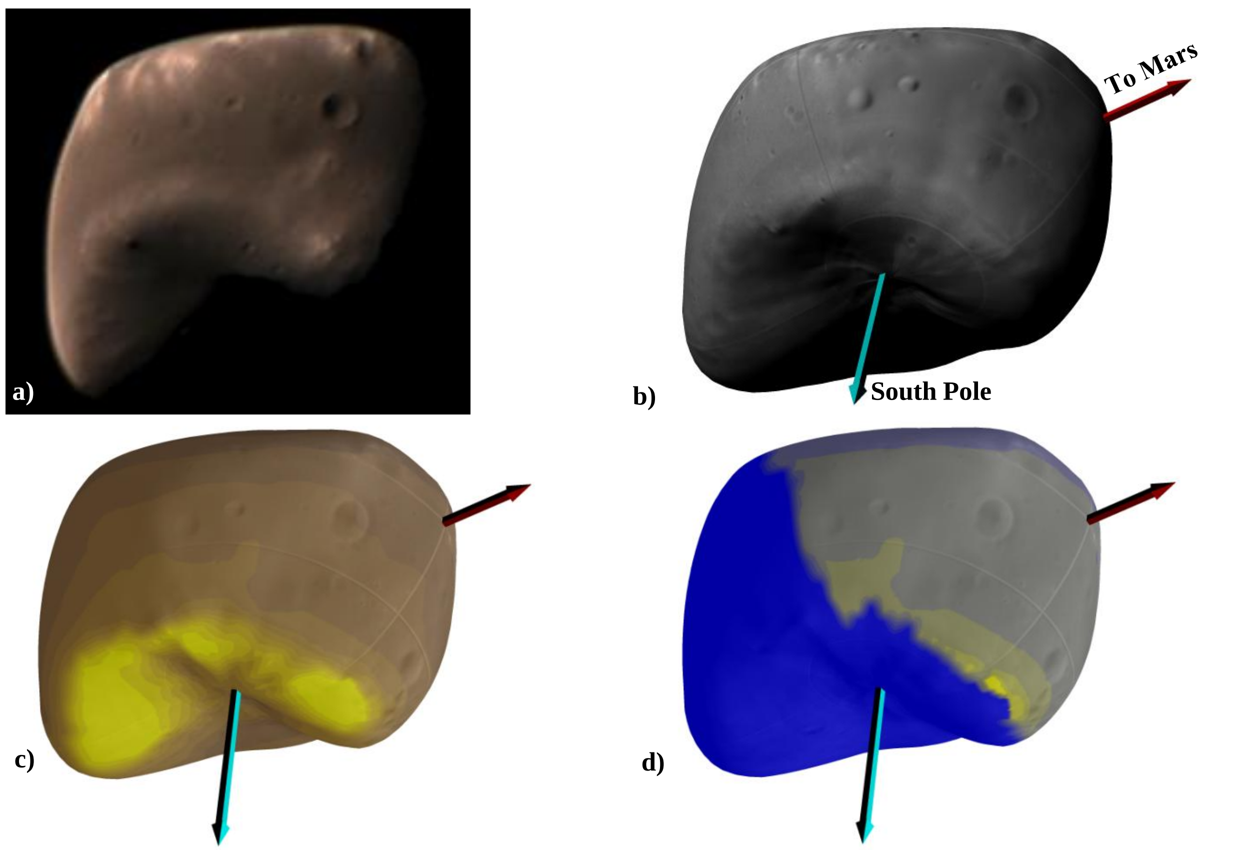

Figure 2. Southern hemisphere of Deimos. a) Composite of Viking Orbiter images F355B51 to B59, courtesy NASA/JPL/Emily Lakdawalla. b) Digital model used for this analysis in similar orientation and lighting to the Viking image. c) Regions of Deimos southern hemisphere highlighted yellow experience sunlight during up to 100% of the southern summer. d) Region of Deimos which can continuously see both the Sun and full Mars shown in yellow, and blue indicating either Sun or Mars is not visible.

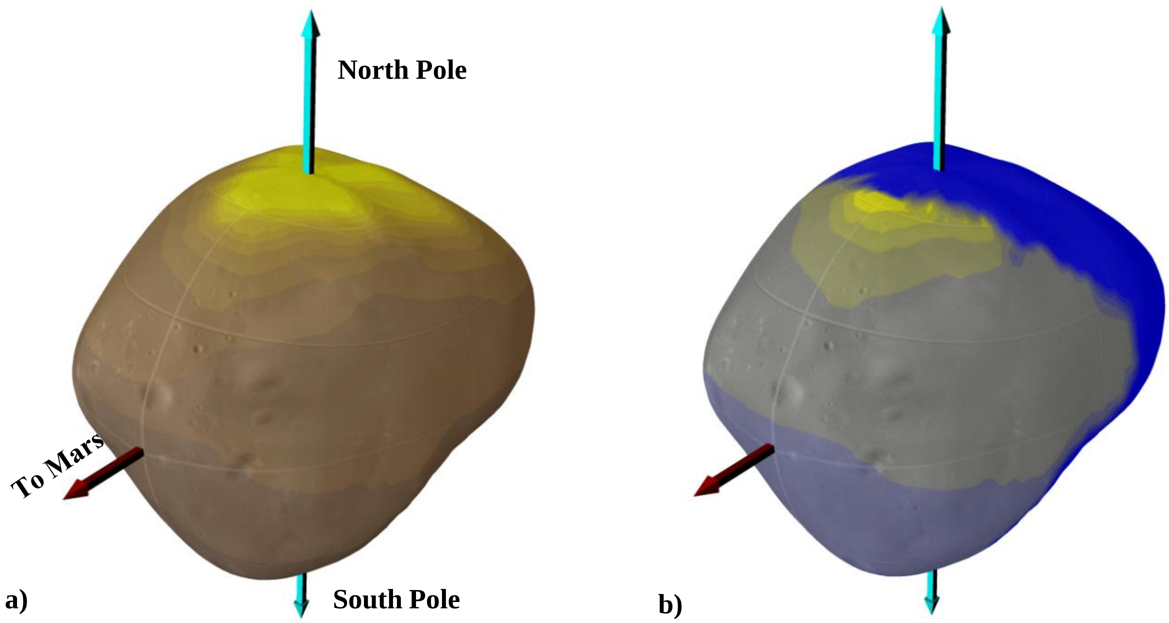

Figure 3. Northern Hemisphere of Deimos. a) Regions which experience sunlight up to 100% of the northern summer indicated in yellow. b) Region of Deimos which can continuously see both the Sun and full Mars shown in yellow, and blue indicating either Sun or Mars is not visible.

We provide lighting maps for Deimos northern summer in Figure 4 and southern summer in Figure 5. They indicate the percentage of time that each location is sunlit, not the lighting at a particular time. Black regions recieve no sunlight, and the brightest yellow regions have continuous sunlight during the summer seasons.

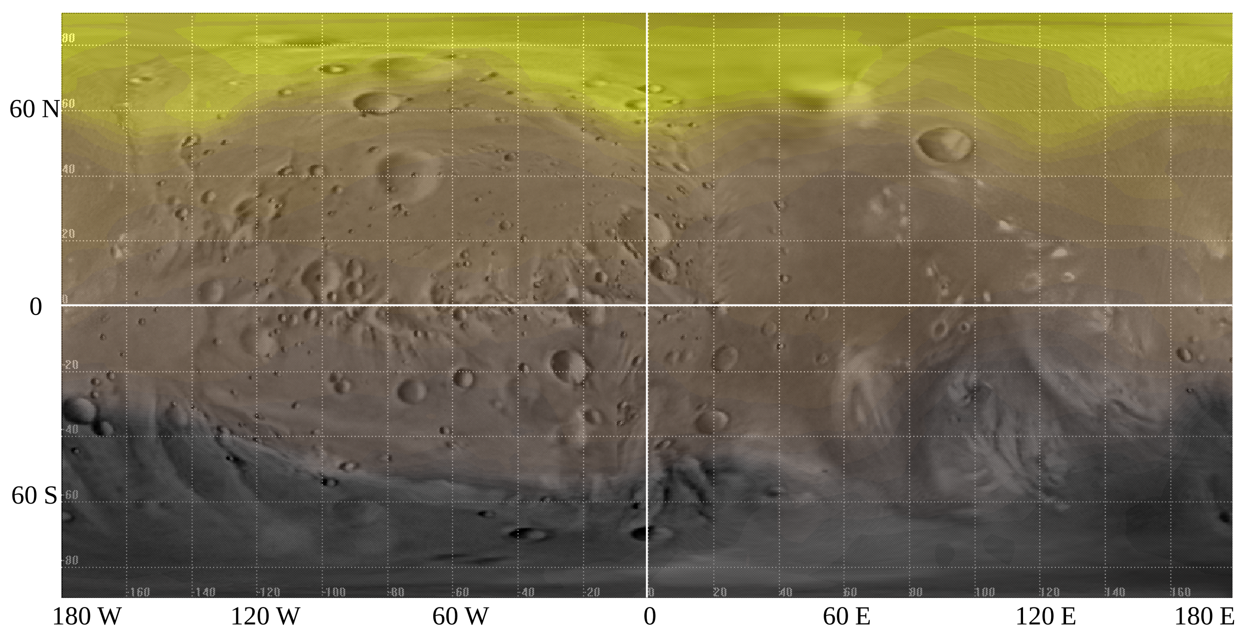

Figure 4. Map of lighting during Deimos northern summer, with yellow indicating continuous sunlight and black indicating no sunlight.

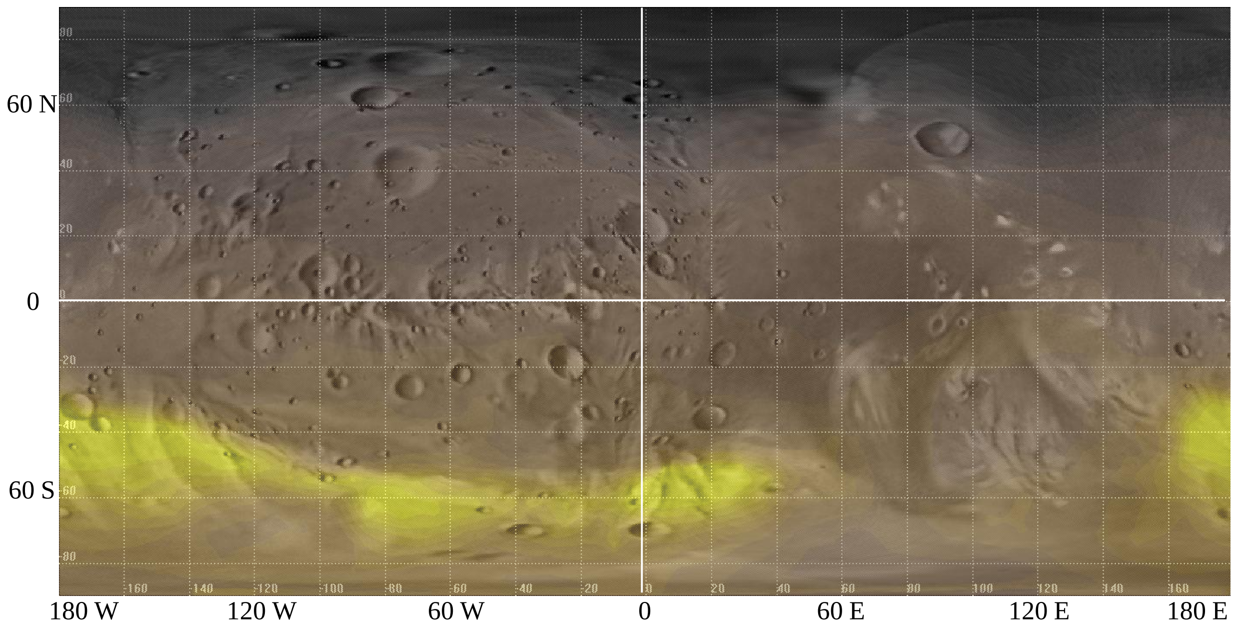

Figure 5. Map of lighting during Deimos southern summer, with yellow indicating continuous sunlight and black indicating no sunlight.

Figure 6 combines the illumination and Mars access data on a single map. In this figure, only the regions with 100% continous sunlight during the respective hemisphere's summer season are marked in yellow. The area inside the green boundary can see the entire face of Mars. In the area between the red and green boundaries, Mars would appear on the horizon and only part of its disk would be visible. The two previously identified regions which combine full sunlight and full Mars visbility are quite small. However, larger regions at higher latitudes have continuous sunlight and visibility to part of Mars.

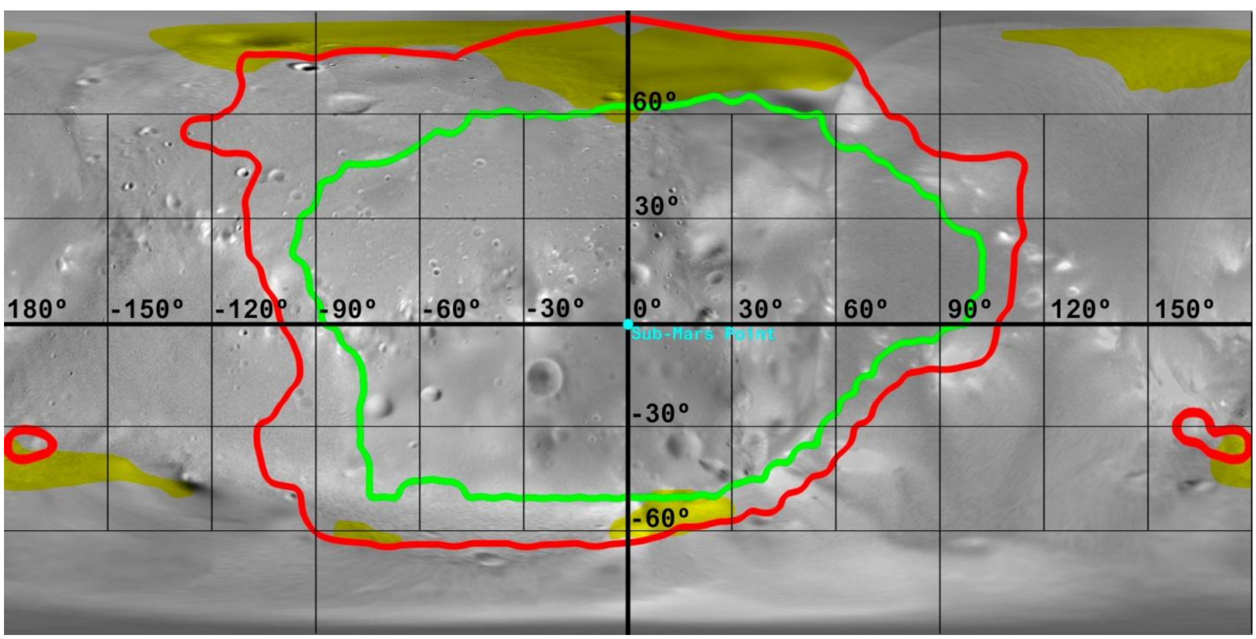

Figure 6. Map of Deimos showing regions of continuous sunlight in yellow. The region inside the green boundary has line of sight to the full disk of Mars, while the region between green and red boundaries has visibility to parts of Mars. Underlying photomosaic courtesy Phil Stooke.

C. Phobos Results

We generated similar results for the analysis of Phobos. Figure 7 shows the regions with continuous sunlight exposure. These regions are larger than on Deimos, with some noticeable gaps in craters. Figure 8 shows the map of Mars access and sunlight regions. There are small regions in the northern hemisphere near the crater Flimnap which have continuous sunlight and full Mars access. These are located at 60° N, near 15° E and 20-30° W. The similar perfect location in the southern hemisphere of Phobos is extremely small . However, because Phobos is so close to Mars, part of the Martian disk would still be visible from the polar regions, even from the far side of Phobos. There are regions of continuous sunlight with access to most of the Martian disk around 40-45° S, mainly to the west of the prime meridian.

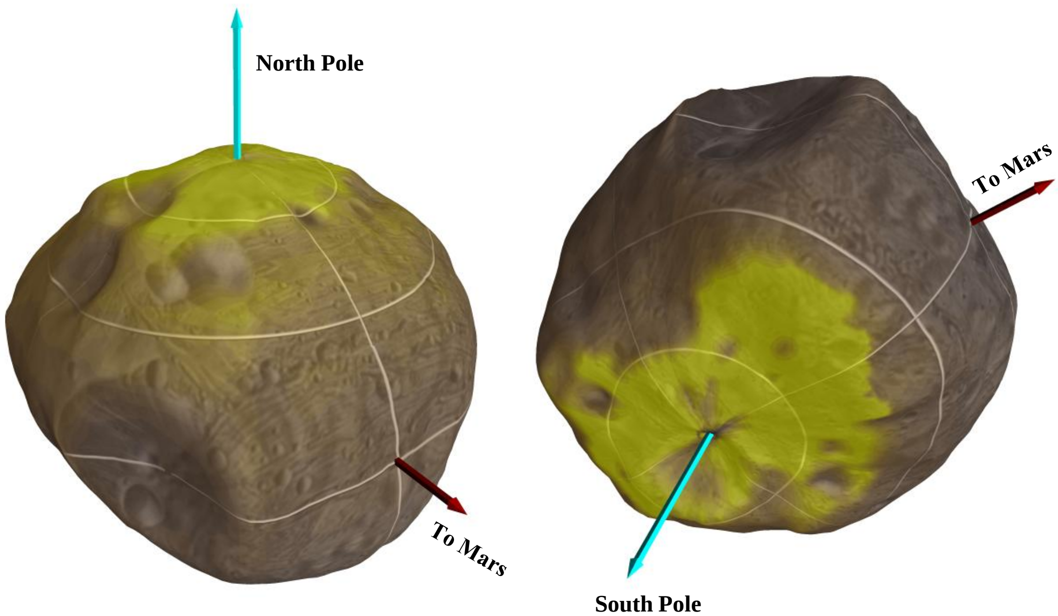

Figure 7. Regions of continuous sunlight on Phobos during northern summer (left) and southern summer (right).

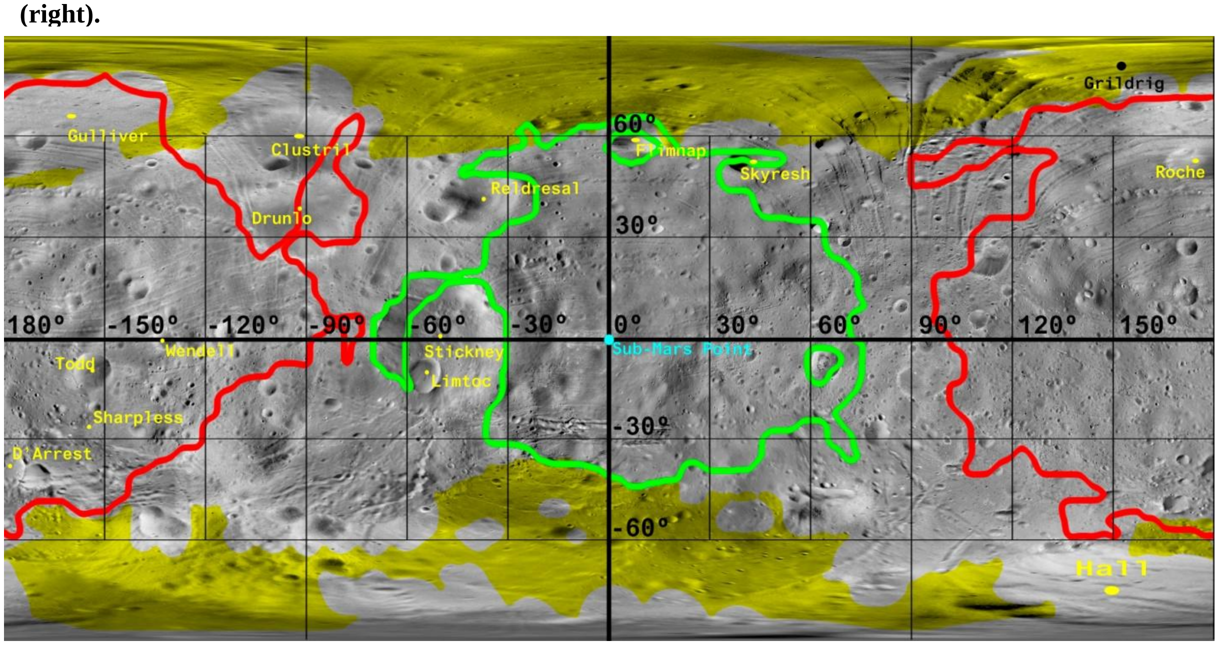

Figure 8. Map of Phobos showing regions of continuous sunlight in yellow. The region inside the green boundary has line of sight to the full disk of Mars, while the region between green and red boundaries has visibility to parts of Mars. Underlying photomosaic courtesy Phil Stooke.

IV. Example Mission Design

A. Optimum mission opportunity in 2033 or 2035

The best opportunities to send humans toward Mars will occur in 2033 and 2035, when two important cycles reach simultaneous optima. Because of the eccentricity of Mars's orbit, the round trip delta V from Earth to Mars varies over a 15 year cycle. The 2033 and 2035 opportunities will be at the lowest point in the cycle. This also results in a relatively low Earth reentry velocity, another important parameter in the mission design. Simultaneously, the Sun should be in the most active phase of its 11 year cycle, a solar maximum. During this period the Sun's magnetic field will be strongest, which reduces the flux of cosmic rays entering the inner solar system, thereby reducing the largest radiation risk for the astronauts. We estimate the tissue-averaged effective dose for a Red Rocks mission to be in the range of 650-750 mSv if undertaken during a solar maximum, vs 1100-1250 mSv during a solar minimum. The combination of a low delta V mission opportunity during a low radiation environment should make the 2033 and 2035 opportunities much easier than other years. However, the prediction of solar activity two decades in the future is tentative, especially due to recent anomalies in the current solar cycle. This paper documents mission data for the 2033 departure opportunity, returning in 2035. We have also analyzed the 2035 opportunity as a backup but do not report the results here.

B. Orbit insertion using bi-elliptic transfer

The most efficient way we have identified to reach Deimos and Phobos upon arrival at the Mars system is to use a bi-elliptic transfer. An example for a spacecraft arriving November 4 2033 is shown in Figure 9. The arriving spacecraft would perform a Mars Orbit Insertion burn near periapse of the hyperbolic approach trajectory to capture into a 400 x 75,000 km altitude orbit, with inclination determined by the arrival declination. The MOI burn is adjusted to constrain argument of periapsis near 0 deg for the resulting orbit so that apoasis will occur near the equatorial plane. At apoapsis the spacecraft performs a second burn to raise periapsis to the altitude of the target moon, and simultaneously changes the orbit inclination to the near-equatorial plane of the moon. A third burn then circularizes the orbit. This can be targeted to match the true anomaly of Deimos or Phobos by controlling the initial arrival time of the interplanetary trajectory or adjusting the apoapsis of the initial orbit. The high initial apoapsis of the bi-elliptic method reduces the delta v required for the inclination change. It also allows a lower thrust to weight ratio during the first orbit capture burn than would be required to capture directly into a low Mars orbit. A vehicle thrust to weight ratio at ignition of roughly 0.05:1 is optimal for the capture burn in this scenario.

Using the bi-elliptic technique, the total delta V required from MOI to Deimos is 1822 m/s, compared to 2017 m/s for Phobos. (These figures include estimates for some smaller burns not shown in the figure.) The return to Earth works in much the same way as the arrival, except in reverse, and the difference in delta V is similar. So, the total mission delta V is about 400 m/s lower for a mission to Deimos than Phobos. This is a relatively modest difference – roughly 10% of the delta V conducted near Mars, or 5% of the total mission delta V including the Earth departure. However, we found that the lower delta V for a return from Deimos makes it possible to consider return propulsion systems using propellants with lower specific impulse than LOX/LH_2. This would circumvent the challenge of storing LH_2 for at least 25 months.

The selected apoapsis altitude of 75,000 km is good but not necessarily optimal. Higher apoapsis altitudes can be used to reduce the delta V somewhat. However, this would increase the duration required to rendezvous with the target moon. Using a very high target apoapsis would mean that a slight propulsion underperformance during orbit insertion would leave the spacecraft in a hyperbolic trajectory, which is a safety concern.

Aerobraking could be used to gradually lower the initial apoapsis altitude non-propulsively. However, this does not reduce the propulsive delta V required to rendezvous with Deimos because the required periapse raising burn is larger. It is potentially beneficial for a Phobos mission, and would reduce the total arrival (but not departure) delta V to be similar to the Deimos mission.

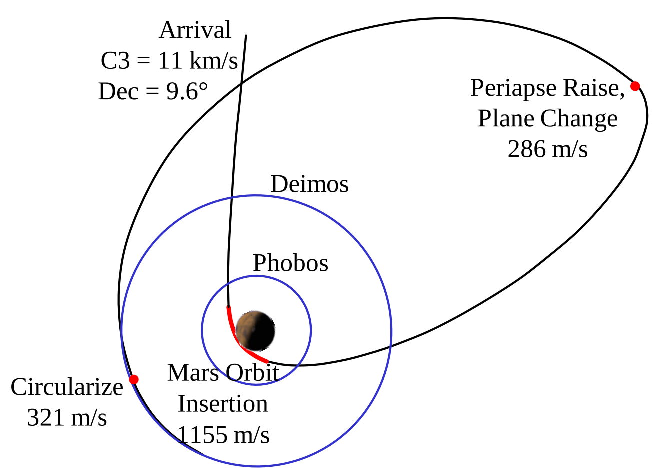

Figure 9. Three burn bi-elliptic orbit insertion maneuver for rendezvous with Deimos

C. Timeline of Proposed Mission

The Red Rocks mission would begin by pre-deploying a Deimos surface habitat and other equipment in 2031, during the opportunity prior to the crew mission. The astronauts would depart Earth in April 2033 and arrive at Mars in November 2033 using a low energy conjunction class trajectory with a 201 day transfer time rather than a sprint trajectory. Upon arrival at Mars the spacecraft follows the three-burn bi-ellpitic transfer described previously, arriving at Deimos four days after Mars Orbit Insertion. November 2033 will be the middle of southern hemisphere summer, so the mission lands first at the southern site identified in section III.B. From here the crew can explore the southern hemisphere of Deimos, nearly all of which could be within range of a one-day EVA. The crew would also teleoperate sample collection rovers on the Martian surface. For the remaining four months of southern summer the landing site experience continuous sunlight. However, as the vernal equinox approaches in 2034, the Sun begins to set briefly each night at the landing site in early March, and eclipse season begins at the same time. The duration of nighttime peaks at 15 hours in April, temporarily making any location on Deimos an inconvenient place for a solar powered mission. Therefore, the astronauts and their spacecraft would depart Deimos before equinox and loiter in Mars orbit nearby for several weeks. Launching from Deimos requires only trivial amounts of propellant and thrust due to its low gravity. In orbit the maximum period of darkness would be less than 90 minutes, due to eclipses. The astronauts could land at the northern landing site in late April 2034, when the polar night would be shorter than the eclipse duration. Eclipse season will continue with diminishing eclipses for another month before permanent sunlight begins at the northern site, after which the site will experience continuous sunlight for the next ten months. Earth will also be in continuous line of sight for more than six and a half months. During this period the astronauts would explore the northern hemisphere of Deimos (Figure 10). The astronauts would depart Deimos in early April 2035 as the next eclipse season begins and Earth drops below the local horizon for an extended period of time. They would spend a few weeks in Mars orbit preparing to return to Earth, with the final Mars departure burn occurring May 7, 2035 for a low energy return. The crew would spend 548 days in the Mars neighborhood and 949 days total in space. Basic mission parameters and timeline are provided in Table 3 and the notional mission is described further in a separate paper[8].

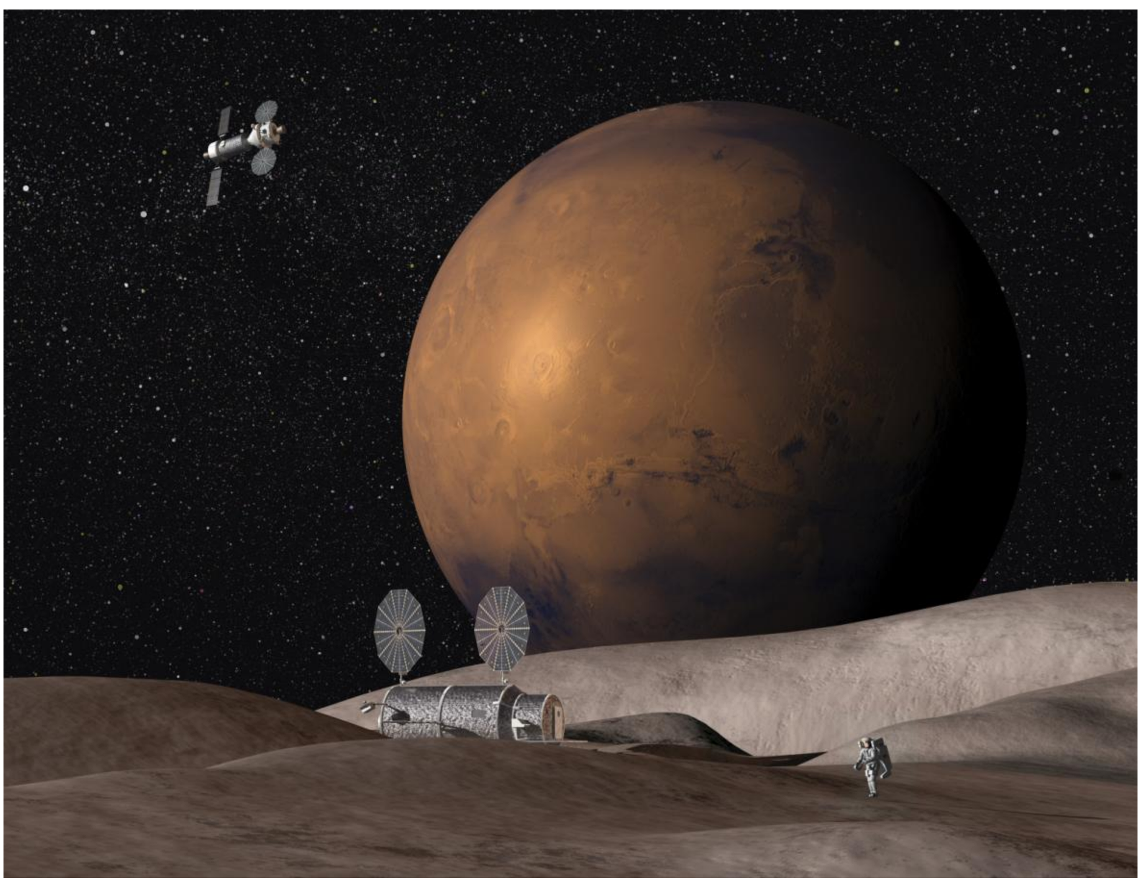

Figure 10. The view from a base at the northern landing site on Deimos

Table 3. Red Rocks mission timeline and maneuver charateristics

Mission Events		Deimos Calendar	
Earth departure date	4/17/2033		
Earth departure C3	9.17 km^2/s^2		
Departure declination	-55.4 deg		
Transfer duration	201 days		
		Eclipse season ends	7/20/2033
		Winter Solstice	11/5/2033
Mars arrival date	11/4/2033		
Arrival declination	9.6 deg		
Arrival C3	11.0 km^2/s^2		
Mars Orbit Insertion ΔV	1155 m/s		
Apoapse manuever ΔV	286 m/s		
Circularization ΔV	321 m/s		
Deimos arrival date,	11/8/2033		
Land at southern site			
Stay time at southern site	114 days		
Depart southern site	3/2/2034	Eclipse season begins	3/2/2034
Loiter in Mars orbit	49 days		
		Vernal Equinox	4/11/2034
Land at Northern site	4/20/2034		
		Eclipse season ends	5/30/2034
Stay time at northern site	373 days		
		Earth-Sun conjunction	8/19/2034
		Summer Solstice	10/27/2034
		Eclipse season begins	3/23/2035
Deimos departure date	4/7/2035		
Apoapse raise manuever ΔV	326 m/s		
Drop periapse manuever ΔV	280 m/s		
Mars departure date	5/7/2035		
Trans-Earth Injection ΔV	1674 m/s		
Trans-Earth C3	8.76 km^2/s^2		
Transfer duration	199 days		
Arrive at Earth	11/22/2035		
Reentry velocity	11.48 km/s		

V. Conclusions

A mission to the moons of Mars may be the least difficult way to begin exploring the Mars system with astronauts. Such a mission can be performed without developing technologies and hardware for advanced propulsion, nuclear power, aerocapture, entry and landing of large payloads, Mars-compatible space suits, advanced energy storage, or other technologies which will be needed for a Mars surface landing. A mission to the Martian moons can still serve as the penultimate step towards an eventual Mars surface mission by developing and demonstrating necessary capabilities such as long term cryopropellant storage, radiation protection, microgravity effects mitigation, regenerative life support, and other abilities needed for long term human spaceflight very far from Earth.

For a solar powered mission to teleoperate assets on the surface of Mars, we concluded that either moon is a viable destination, but Deimos is a superior operating location to Phobos. It offers better communications access to

Earth and Mars, better solar illumination, and lower mission delta V than Phobos. However, a Phobos mission is also feasible, and may be preferred for other reasons, such as the inherent geological interest in Phobos itself.

Acknowledgements

We thank Philip Stooke of the University of Western Ontario for providing his composite maps of Phobos and Deimos, and Emily Lakdawalla of the Planetary Society for allowing us to use her Viking image composite in this paper. Matthew Bitzer, of Analytical Graphics Inc., provided assistance setting up the complex lighting analysis, as well as help with creating the STK terrain files from the shape models of both moons produced by Dr. Peter Thomas of Cornell University. We credit Bernard Kutter of United Launch Alliance with pointing out that the moons' gravity is desirable for propellant settling. Mark Jones built physical globes of Deimos and Phobos which have been invaluable for understanding these moons. Several people at Lockheed Martin contributed to the Red Rocks mission design study, including Al Herzl, Caley Buxton, Jeff Kwong, Razvan Gaza, and Steve Hartmann.

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