Trajectory Design for the Phobos and Deimos & Mars Environment Spacecraft

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The presented trajectory design and analysis was performed for the Phobos and Deimos & Mars Environment (PADME) mission concept as part of a NASA proposal submission managed by NASA Ames Research Center in the 2014-2015 timeframe. The PADME spacecraft would be a derivative of the successfully flown Lunar Atmosphere & Dust Environment Explorer (LADEE) spacecraft. While LADEE was designed to enter low-lunar orbit, the PADME spacecraft would instead enter an elliptical Mars orbit of 2-week period. This Mars orbit would pass by Phobos near periapsis on successive orbits and then raise periapsis to yield close approaches of Deimos every orbit thereafter.

I. Introduction

This paper presents a trajectory design capable of placing the Phobos and Deimos & Mars Environment (PADME) spacecraft[1,2] in an elliptical Mars orbit with successive low-altitude (2 to 10 km) passes/flybys of Phobos and Deimos and with relatively low flyby speeds. A similar trajectory design was presented by Tolson et al.[3] in 1976 and by Diehl et al. [4] in 1978, both with regard to an extension option for the Viking 1 mission; the Viking 1 spacecraft performed 14 flybys of Phobos within an altitude range of 89-213 km, which yielded mass and density measurements of Phobos[5]. ALADDIN proposed an interesting trajectory that would performs flybys of Phobos and Deimos[6], although this trajectory is not compatible with the PADME mission (discussed later).

For about the same amount of ΔV needed by the LADEE spacecraft to enter low-lunar orbit (LLO), the PADME spacecraft is able to enter an elliptical Mars orbit with ≈2-week period. This 2-week cadence allows for operational flexibility and planning between flyby (science) events, and the ability to expend little ΔV to raise periapsis to (near) Deimos distance to begin the Deimos cycler orbit phase. By adjusting the apoapsis altitude of the elliptical Mars orbit, resonance with Phobos and Deimos is achieved, with a total of 16 Phobos and 9 Deimos flybys yielded by the trajectory designed for the PADME spacecraft, with details presented herein.

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II. Assumptions & Constraints

There were several requirements and constraints that significantly influenced the trajectory design for the PADME spacecraft, as summarized in Table 1. The ΔV requirement (No. 2, Table 1), constrains the minimum orbit energy of the captured Mars orbit, while science-related requirements significantly influence the Phobos and Deimos flyby strategy.

The primary software tool used for the presented trajectory design and analysis was STK/Astrogator, which utilized an 8th/9th order Runge-Kutta numerical integrator for orbit propagation within a force model that included an N-body gravity field (Sun, Earth, Moon, Mars modeled as gravity fields with the remaining major planets modeled as point masses), thermal and solar radiation pressure, and atmosphere models at both Earth and Mars. The best available shape models were utilized for both Phobos and Deimos (from Gaskell and Thomas, respectively) given the close-approaches designed into the presented trajectory.

Table 1. Description of Trajectory-Influenced Requirements and Constraints

Requirement Number	Description of Requirement or Constraint	Requirement Imposed by
1	PADME Spacecraft will launch as a primary payload from NASA Kennedy Space Center (KSC)	LAUNCH
2	1,205 m/s Maximum ΔV capability of the spacecraft	PROPULSION
3	Enter a Mars orbit in resonance with Phobos and Deimos	SCIENCE
4	Target resonance trajectory to yield low altitude passes of Phobos and Deimos (between 2 and 10 km)	SCIENCE & NAVIGATION
5	At least eight Phobos and eight Deimos flybys must occur with a speed < 1.5 km/s	NEUTRON SPECTROMETER
6	At least two Phobos flybys must occur with a close-approach speed > 2 km/s (for Deimos, > 1 km/s)	DUST DETECTION
7	All but one Phobos flyby must have the spacecraft close-approach (nadir projection onto Phobos' surface) occur in direct sunlight	LIGHTING
8	Exactly one Phobos flyby must have the spacecraft close-approach (nadir projection onto Phobos' surface) occur on the terminator	LIGHTING
9	All but three Deimos flybys must have the spacecraft close-approach (nadir projection onto Phobos' surface) occur in direct sunlight	LIGHTING
10	Exactly three Deimos flybys must have the spacecraft close-approach (nadir projection onto Phobos' surface) occur on the terminator	LIGHTING
11	Maintain direct line-of-sight with the Earth during every close-approach of both Phobos and Deimos	COMMUNICATIONS
12	Establish opportunity for viewing (within 50 km) of pre-determined target on a sunlit equatorial region of Phobos at multiple positions (at least 3) along its orbit with true anomaly span > 45 deg	LIBRATION SCIENCE
13	Equally balance the latitude/longitude of the close-approaches for both Phobos and Deimos	GRAVITY SCIENCE

III. Trajectory Design

The following section outlines the trajectory design, mission extension options, and future launch opportunities. Libration measurements of Phobos' orbit and gravity field measurements of both Martian moons are also discussed.

A. General Trajectory Design

The presented trajectory assumes a launch on August 3, 2020, the opening of the optimal 21-day launch period. Both Phobos and Deimos cycler orbit phases are shown together in Fig. 1 (left), which also shows a zoomed in image near periapsis to focus on science events (bottom right) and a Phobos inertial view that shows all of the relevant flyby paths.

It can be seen from Fig. 1 that after the initial Mars-orbit insertion, the Mars periapsis is incrementally raised to encounter Phobos off-periapsis (Fig. 1, A), which allows the chance for a relatively large range of libration measurements of Phobos' orbit and gravity measurements of the moon's gravity field (when combined with future measurements).

After seven such Phobos encounters at 2.27 km/s flyby speed (including a warm-up encounter at 10 km flyby altitude), periapsis is raised to obtain more diverse libration and gravity science field measurements, now at lower flyby speeds of 1.45 km/s (Fig. 1, B). After four such flybys, periapsis is raised once again to increase the quality of the science data set, with five Phobos passes at 1 km/s (three flybys before a solar exclusion zone blackout window and two afterward, Fig. 1, C). A summary table of the selected flyby sequence is shown in Table 2, where it is seen that all Table 1 requirements are met.

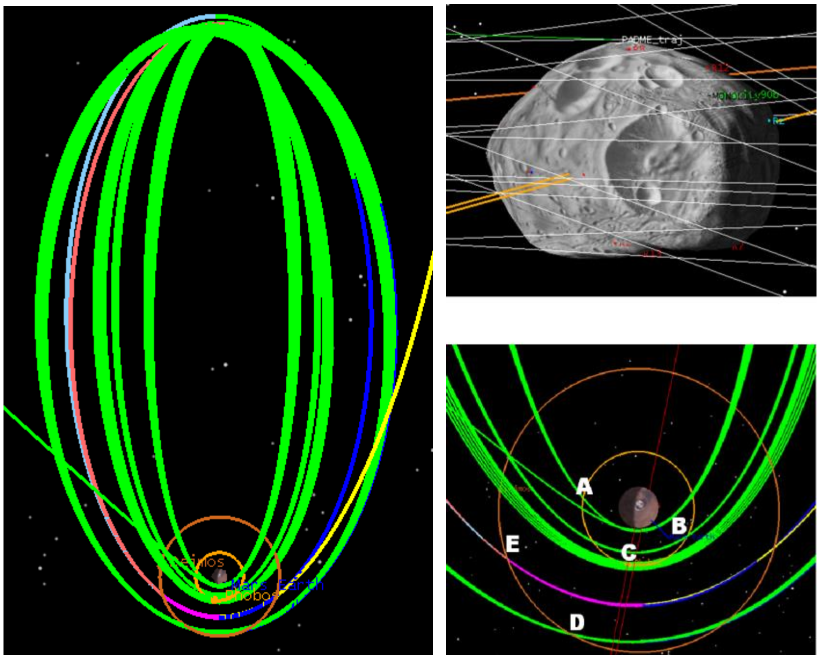
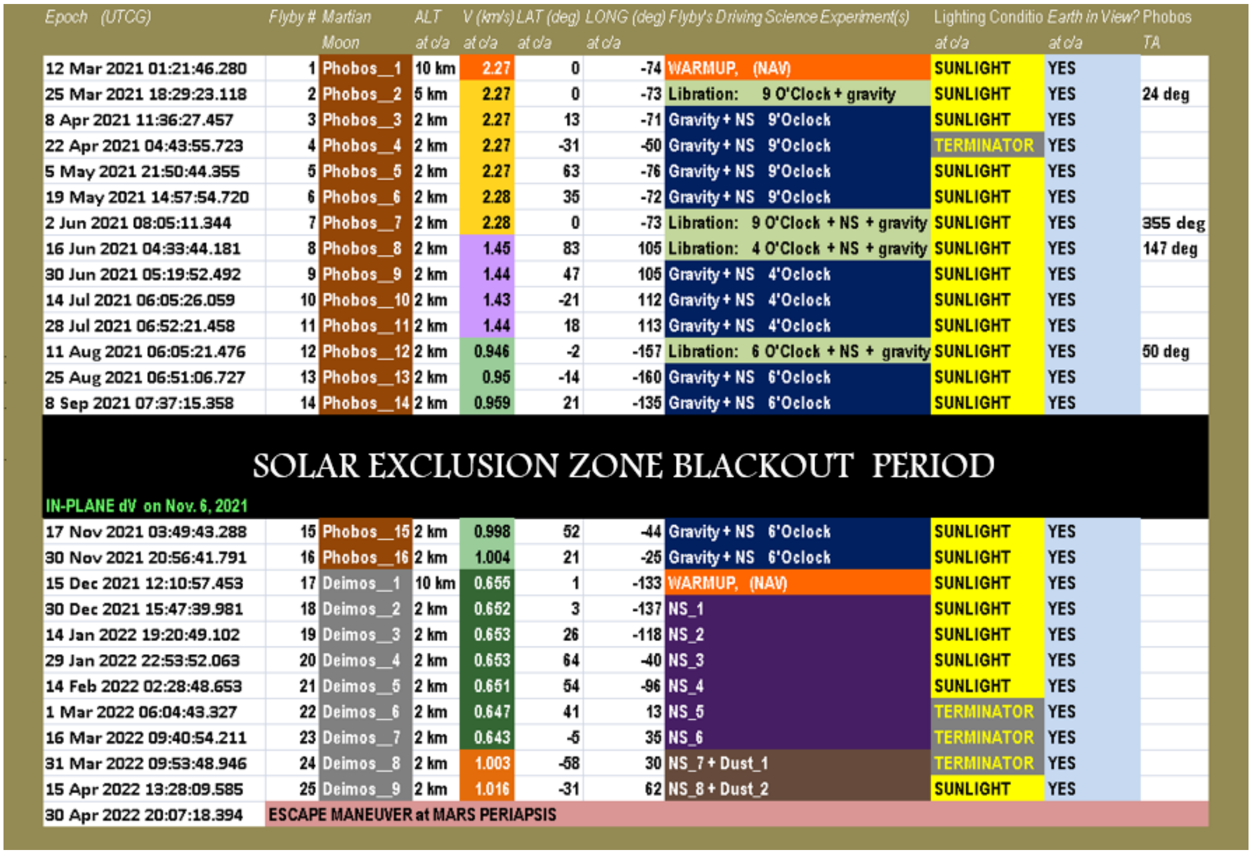


Figure 1. Phobos & Deimos Cycler Orbit Sequence. *Trajectory shown in the Mars inertial frame (left and bottom-right images) and in the Phobos inertial frame (top-right image).*

The largest maneuver to enter the required Phobos/Deimos resonance orbit is the Mars orbit insertion, which required 649 m/s (highest injection ΔV requirement throughout the 21-day launch period). This injection maneuver was fine-tuned to vary the orbit period to yield the required Phobos/Deimos resonance orbit with 2-week period (apoapsis altitude of ~230,000 km). The second largest maneuver was calculated as 59 m/s to "switch gears" from the Phobos to Deimos cycler orbit, where nine Deimos flybys are planned at two Mars periapsis altitudes (Fig. 1, D and E). It is of note that the ALADDIN concept did not require a "gear-switch", as their orbit was designed to pass by both Martian moons during each orbit, although at the expense of a significant increase in the flyby speed of Deimos; the same trajectory can be used for opportunities with high arrival declinations at Mars (discussed later). Given the relatively low ΔV requirement to reach the first Phobos flyby, the Mars periapsis altitude was increased to improve the readings from the neutron spectrometer data.

Varying the Mars periapsis to meet the libration science requirements for the Phobos cycler sequence totaled 58 m/s, with the additional ΔV dedicated to cycler orbit maintenance (approximately 2 m/s per Phobos or Deimos cycle/flyby, assuming a fixed Mars periapsis altitude) and 58 m/s for the Mars-escape disposal maneuver. This yields a total ΔV requirement of 935 m/s which meets the 1,205 m/s total ΔV constraint and allows 270 m/s (22.4%) for navigation, margin, extension mission opportunities, etc. It is of note that direct transfers for future Mars launch periods in 2022 and 2024 were analyzed as backup opportunities and were both shown to be compatible with the presented PADME mission concept. The total ΔV requirement calculated for these launch periods was less than the maximum-allocated 1,205 m/s (discussed in a later section).

Table 2. Summary of Phobos and Deimos Flyby Characteristics



Epoch (UTCG)	Flyby #	Martian Moon	ALT at c/a	V (km/s) at c/a	LAT (deg) at c/a	LONG (deg) at c/a	Flyby's Driving Science Experiment(s)	Lighting Conditio at c/a	Earth in View? at c/a	Phobos TA
12 Mar 2021 01:21:46.280	1	Phobos__1	10 km	2.27	0	-74	WARMUP, (NAV)	SUNLIGHT	YES	
25 Mar 2021 18:29:23.118	2	Phobos__2	5 km	2.27	0	-73	Libration: 9 O'Clock + gravity	SUNLIGHT	YES	24 deg
8 Apr 2021 11:36:27.457	3	Phobos__3	2 km	2.27	13	-71	Gravity + NS 9'Oclock	SUNLIGHT	YES	
22 Apr 2021 04:43:55.723	4	Phobos__4	2 km	2.27	-31	-50	Gravity + NS 9'Oclock	TERMINATOR	YES	
5 May 2021 21:50:44.355	5	Phobos__5	2 km	2.27	63	-76	Gravity + NS 9'Oclock	SUNLIGHT	YES	
19 May 2021 14:57:54.720	6	Phobos__6	2 km	2.28	35	-72	Gravity + NS 9'Oclock	SUNLIGHT	YES	
2 Jun 2021 08:05:11.344	7	Phobos__7	2 km	2.28	0	-73	Libration: 9 O'Clock + NS + gravity	SUNLIGHT	YES	355 deg
16 Jun 2021 04:33:44.181	8	Phobos__8	2 km	1.45	83	105	Libration: 4 O'Clock + NS + gravity	SUNLIGHT	YES	147 deg
30 Jun 2021 05:19:52.492	9	Phobos__9	2 km	1.44	47	105	Gravity + NS 4'Oclock	SUNLIGHT	YES	
14 Jul 2021 06:05:26.059	10	Phobos__10	2 km	1.43	-21	112	Gravity + NS 4'Oclock	SUNLIGHT	YES	
28 Jul 2021 06:52:21.458	11	Phobos__11	2 km	1.44	18	113	Gravity + NS 4'Oclock	SUNLIGHT	YES	
11 Aug 2021 06:05:21.476	12	Phobos__12	2 km	0.946	-2	-157	Libration: 6 O'Clock + NS + gravity	SUNLIGHT	YES	50 deg
25 Aug 2021 06:51:06.727	13	Phobos__13	2 km	0.95	-14	-160	Gravity + NS 6'Oclock	SUNLIGHT	YES	
8 Sep 2021 07:37:15.358	14	Phobos__14	2 km	0.959	21	-135	Gravity + NS 6'Oclock	SUNLIGHT	YES	
SOLAR EXCLUSION ZONE BLACKOUT PERIOD IN-PLANE dV on Nov. 6, 2021										
17 Nov 2021 03:49:43.288	15	Phobos__15	2 km	0.998	52	-44	Gravity + NS 6'Oclock	SUNLIGHT	YES	
30 Nov 2021 20:56:41.791	16	Phobos__16	2 km	1.004	21	-25	Gravity + NS 6'Oclock	SUNLIGHT	YES	
15 Dec 2021 12:10:57.453	17	Deimos__1	10 km	0.655	1	-133	WARMUP, (NAV)	SUNLIGHT	YES	
30 Dec 2021 15:47:39.981	18	Deimos__2	2 km	0.652	3	-137	NS_1	SUNLIGHT	YES	
14 Jan 2022 19:20:49.102	19	Deimos__3	2 km	0.653	26	-118	NS_2	SUNLIGHT	YES	
29 Jan 2022 22:53:52.063	20	Deimos__4	2 km	0.653	64	-40	NS_3	SUNLIGHT	YES	
14 Feb 2022 02:28:48.653	21	Deimos__5	2 km	0.651	54	-96	NS_4	SUNLIGHT	YES	
1 Mar 2022 06:04:43.327	22	Deimos__6	2 km	0.647	41	13	NS_5	TERMINATOR	YES	
16 Mar 2022 09:40:54.211	23	Deimos__7	2 km	0.643	-5	35	NS_6	TERMINATOR	YES	
31 Mar 2022 09:53:48.946	24	Deimos__8	2 km	1.003	-58	30	NS_7 + Dust_1	TERMINATOR	YES	
15 Apr 2022 13:28:09.585	25	Deimos__9	2 km	1.016	-31	62	NS_8 + Dust_2	SUNLIGHT	YES	
30 Apr 2022 20:07:18.394	ESCAPE MANEUVER at MARS PERIAPSIS									

B. Libration Science Measurements of Phobos' Orbit

Four Phobos flybys are specified as providing opportunities for libration science; however, libration imaging can occur on any flyby that passes within 50 km of a sunlit region of Phobos' surface. Three of the four specified libration flybys allow for two surface regions separated by more than 50 degrees of longitude along the equator to be imaged, which is not required but significantly helps improve science quality and allows redundancy in meeting the libration science requirement consisting of at least 3 measurements of the same equatorial surface region spanning greater than 45 degrees in true anomaly of Phobos' orbit. Given Phobos' rotation property of being tidally locked with Mars, the trajectory design varies the Mars periapsis to allow for different arrival geometries (i.e., varying B-planes) at Phobos.

The second flyby from Table 2 yields the 1st libration measurement located at 0 degrees latitude and 160 degrees west longitude on the surface of Phobos (Fig. 2). Given the 2.27 km/s Phobos flyby speed at this time in the sequence, the spacecraft spends 21-seconds within 50 km (and within view) of this targeted surface location (Fig. 3). On this same flyby, the spacecraft also images another location on Phobos' surface so as to yield two acceptable sets of libration measurements. This second equatorial imaging location is located at 108 degrees west longitude (0, -108). The PADME spacecraft would spend a total of 27 seconds within 50 km of (0, -108), with a close-approach altitude of 6.5 km. The true anomaly at this Phobos position is 24 degrees (Fig. 1, A).

After seven such Phobos encounters at 2.27 km/s flyby speed (including a warm-up encounter at 10 km flyby altitude), The largest maneuver to enter the required Phobos/Deimos resonance orbit is the Mars orbit insertion, which required 649 m/s; this corresponded to the highest ΔV requirement throughout the optimized 21-day launch period associated with a launch from NASA Kennedy Space Center. The second largest maneuver was calculated as 59 m/s to “switch gears” from the Phobos to Deimos cycler orbit, where nine Deimos flybys are planned at two Mars periapsis altitudes (Fig. 1, D and E). It is of note that the ALADDIN concept did not require a “gear-switch”, as its orbit was designed to pass by both Martian moons with a fixed Mars periapsis. However, such an orbit yields a significantly higher flyby speed of Deimos; still, there are applications relevant to the PADME spacecraft when the arrival declination upon Mars arrival is relatively high (discussed in the “*Future Launch Opportunities to Mars*” subsection). Given the relatively low ΔV requirement to reach the first Phobos flyby, the Mars periapsis altitude was increased to improve the readings from the neutron spectrometer data.

The second flyby specified for Phobos libration science corresponds to the 7th Phobos flyby seen in Table 2. The flyby speed is 2.28 km/s which yields a 21-second viewing opportunity within 50 km of the (0, -160) libration target; the close-approach altitude above (0, -160) was calculated as 10.9 km. For the (0, -108) libration target, more time (26 seconds of total time) is spent within 50 km; the spacecraft reaches its close-approach altitude of 3.4 km and is then able to continue viewing (0, -108) on its outbound trajectory. Phobos’ true anomaly for this flyby is 355 degrees given 29 degrees of natural precession since the second flyby (Fig. 1, A).

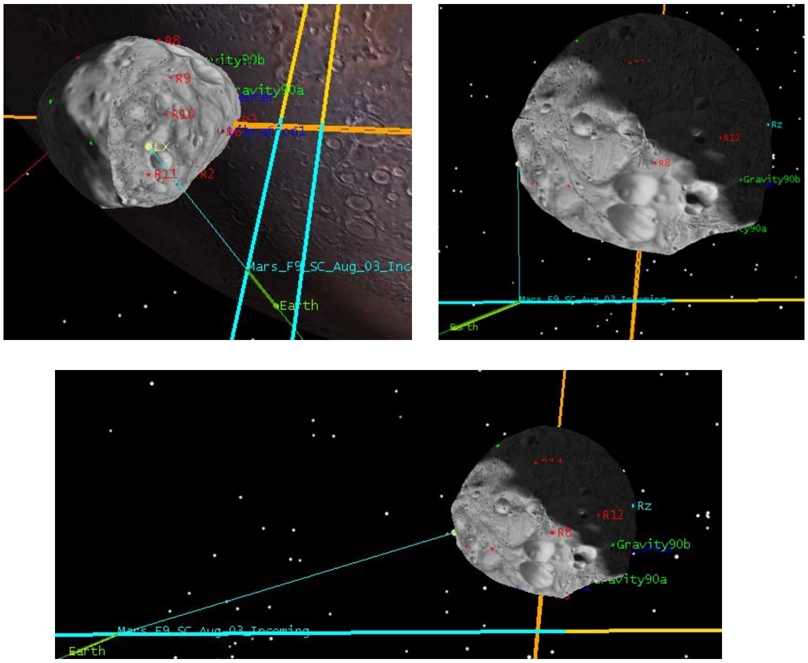
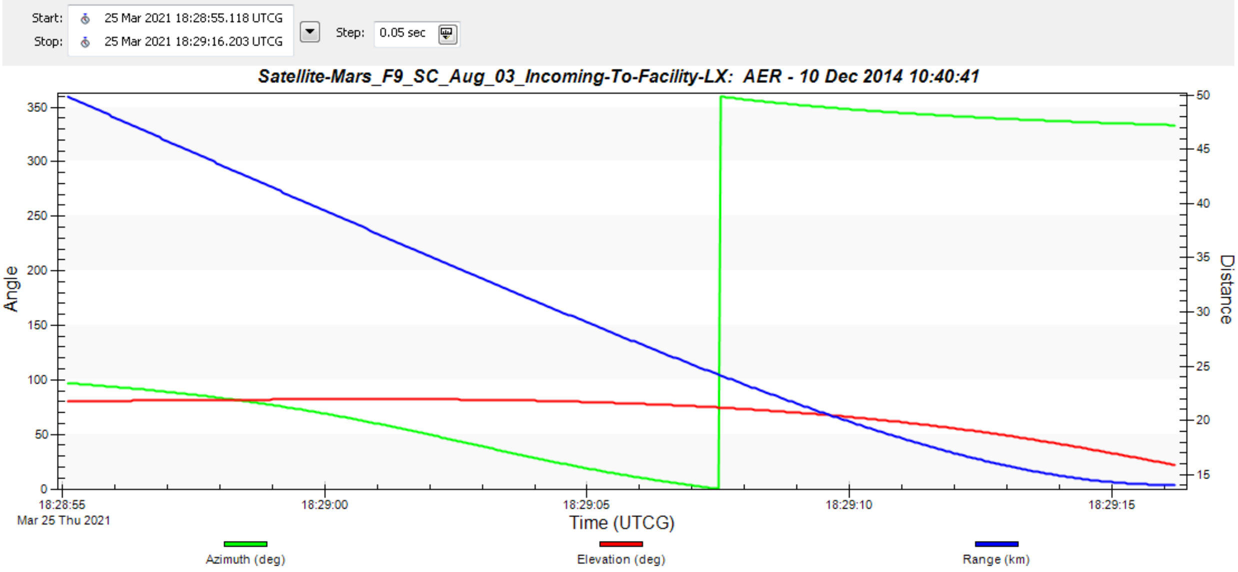


Figure 2. Libration Measurement for 2nd Phobos Flyby. *Surface Target chosen for imaging on this flyby: (0 degrees, 160 degrees west).*

During the third libration-specified Phobos flyby (this is the 8th Phobos flyby per Table 2), the (0, -108) libration target is in shadow, thus no viewing opportunity of this target is possible during this flyby. However, the (0, -160) libration target is in direct sunlight and provides an important opportunity to acquire a libration measurement on the outbound of the trajectory (i.e., after reaching Mars periapsis: Fig. 1, B). This opportunity is important, since it significantly increases the range of sampled Phobos’ true anomaly values by adding 147 degrees to the data set for the (0, -160) target. As the flyby speed is reduced to 1.45 km/s, the viewing opportunity window is longer (compared to the previous libration measurements), with a total of 32 seconds of viewing time spent within 50 km of (0, -160). The close-approach altitude above (0, -160) was calculated as 13 km.

The fourth specified libration flyby is the 12th Phobos flyby. The associated flyby speed is the lowest among any specified libration flybys, at 0.946 km/s since it occurs closest to Mars periapsis (Fig. 1, C). The (0, -160) libration target is within 50 km of the PADME spacecraft for 65-seconds, the longest viewing opportunity calculated. The close-approach altitude above (0, -160) was calculated as 2.1 km. The (0, -108) libration target is also imaged on this flyby at 0.946 km/s speed within a 58-second viewing window within 50 km of this libration target. The close-approach altitude above (0, -108) was calculated as 7.8 km. The true anomaly of Phobos’ orbit was 50 degrees for this flyby.

A summary of the libration science measurements are listed below; it can be seen in Table 3 that the 45-degree range in Phobos true anomaly values sampled (at least 3 measurements) is met for both libration targets despite only one such target needed to meet the relevant science requirement. Specifically, a 152-degree total true anomaly range is acquired for (0, -160) and a 55-degree range for (0, -108).



Start: 25 Mar 2021 18:28:55.118 UTCG
Stop: 25 Mar 2021 18:29:16.203 UTCG
Step: 0.05 sec

Figure 3. Libration Measurement for 2nd Phobos Flyby. *Surface Target chosen for imaging on this flyby: (0 degrees, 160 degrees west).*

Table 3. Summary of Phobos Libration Science Measurements.

Libration Surface Target Coordinates (latitude, longitude)	**Flyby Number from which Measurement is acquired**	**True Anomaly of Phobos' Orbit at Time of Measurement**	**Delta True Anomaly of Phobos' Orbit** (Cumulative values shown for both targets)
(0, -160)	Flyby #2	24 degrees	0 degrees
(0, -160)	Flyby #7	355 degrees	29 degrees
(0, -160)	Flyby #8	147 degrees	152 degrees
(0, -160)	Flyby #12	50 degrees	152 degrees
(0, -108)	Flyby #2	24 degrees	0 degrees
(0, -108)	Flyby #7	355 degrees	29 degrees
(0, -108)	Flyby #12	50 degrees	55 degrees

C. Gravity Science Measurements of Phobos and Deimos

The PADME spacecraft is equipped with a neutron spectrometer that has the ability to obtain mass measurements from both Phobos and Deimos to better understand the gravity field of both Martian moons.

For each gravity science flyby, the coordinates of close-approaches of both Phobos and Deimos by the spacecraft are plotted, with an inertial view of all (nine) Deimos flybys displayed as well (Figs. 4, 5 and 6).

Given the lighting and other constraints, the latitude and longitude of close-approach was balanced as best as possible throughout the Phobos/Deimos cycler orbit sequence. The libration science requirement (No. 12 in Table 1) is coupled with the gravity science requirement (No. 13 in Table 1) since sampling of the Martian moons at different true anomalies given the tidal lock of both moons. Since both libration and gravity science can occur in the same flyby, the coupling of these requirements is met with a single trajectory design feature, namely that of varying the Mars periapsis altitude to yield the necessary measurements at varying true anomalies. The gravity science data shown in Figs. 16 and 17 were deemed sufficient to meet Requirement number 13 in Table 1.

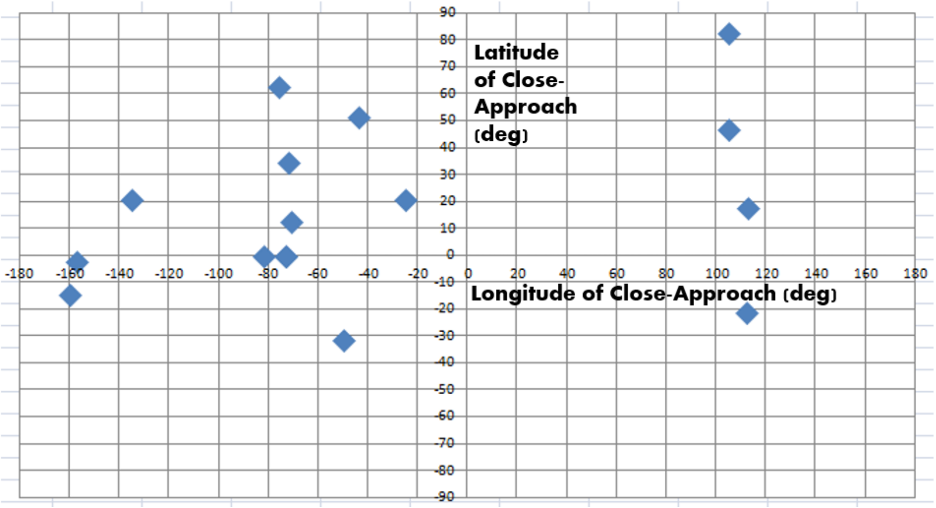


Figure 4. Phobos Gravity Science Measurements. *Latitude & Latitude of close-approach for Phobos flybys (1st warmup flyby of Phobos not shown); X-axis: Longitude, Y-axis: Latitude*

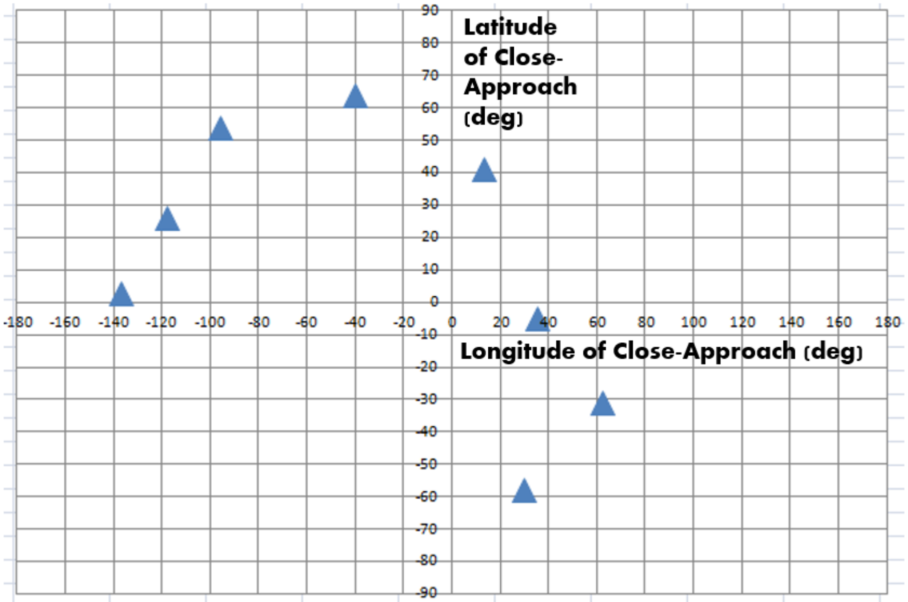


Figure 5. Deimos Gravity Science Measurements. *Latitude & Latitude of close-approach for Deimos flybys (1st warmup flyby of Deimos not shown); X-axis: Longitude, Y-axis: Latitude*

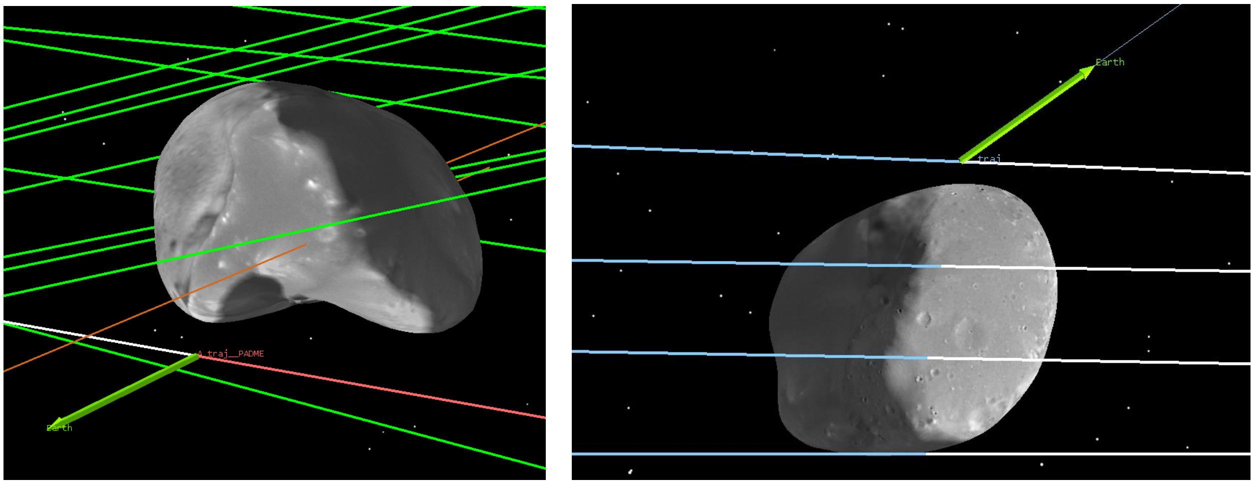


Figure 6. Deimos Flyby Phase: *flybys are shown in separate Deimos-centric inertial frames (left: all flybys shown with edge-on view of the Deimos equatorial plane; right: four flybys shown from view onto the north pole, with better view of the terminator per Req. No. 10 in Table 1).*

D. Disposal & Mission Extension Options

After the ninth and final flyby of Deimos, the disposal plan for the PADME spacecraft is that of heliocentric orbit that does not impact Mars for at least 100 years. To reach this heliocentric disposal orbit, the spacecraft would perform an escape maneuver at Mars periapsis 2 weeks after the final Deimos flyby; the ΔV required for this maneuver was calculated as 58 m/s.

Alternatively, the Mars-escape maneuver can be increased and/or delayed to allow for alignment with an interplanetary target of interest. For purposes of better understanding such mission extension options, both flyby and rendezvous trajectory opportunities to near-Earth objects (NEOs) and Mars-crossing asteroids (MCAs) were calculated using a 2-body force model.

Table 4. Top 8 Asteroid Rendezvous Opportunities for the PADME Spacecraft, *opportunities are sorted by ΔV required for trans-NEO injection from Mars and the NEO rendezvous maneuver.*

Opportunity Number	Asteroid Number (Designation)	ΔV Required for Rendezvous
1	68278 (2001 FC7)	1.14 km/s
2	96631 (1999 FP59)	2.67 km/s
3	256004 (2006 UP)	3.11 km/s
4	162783 (2000 YJ11)	3.75 km/s
5	65803 Didymos (1996 GT)	4.69 km/s
6	363305 (2002 NV16)	4.78 km/s
7	173664 (2001 JU2)	4.82 km/s
8	302871 (2003 HA22)	4.98 km/s

The top 8 asteroid rendezvous opportunities are listed in Table 4, where it can be seen that no opportunity requires less than 1 km/s (many require significantly higher ΔV requirements). Given the 1,205 ΔV requirement imposed by the propulsion system (No. 2, Table 1), the PADME spacecraft can afford to expend about 250 m/s, including the disposal/escape maneuver, for an extension mission option. Thus a rendezvous mission was deemed infeasible for the analyzed launch opportunity.

Mission extension options that entail an asteroid flyby require far less ΔV than the aforementioned rendezvous opportunities. The top 10 NEO flyby opportunities are listed in Table 5; the top 3 opportunities require an injection/escape ΔV less than 250 m/s and are thus feasible options for the PADME spacecraft. The lowest ΔV requirement is associated with the flyby opportunity of NEO 85585 Mjolnir (1998 FG2) which has an estimated diameter of 127 to 284 meters and represents the axe-hammer of the mythological Norse god Thor. A high-fidelity trajectory to Mjolnir was thus calculated and a view of the trajectory at time of NEO close-approach is displayed in Fig. 7. In this trajectory, the PADME spacecraft would wait in Mars orbit until August 3, 2023 (allowing time for more Deimos and/or Phobos flybys) which is when the trans-NEO injection (TNI) maneuver is performed at Mars periapsis. The TNI is the only deterministic maneuver required (including disposal) with a ΔV of 67 m/s calculated via the high-fidelity STK/Astrogator model mentioned in the Assumptions & Constraints section. The flyby of Mjolnir would occur almost 9 months later on April 24, 2024. The close-approach of the flyby can be varied, but was chosen as 1 km for the presented case; the flyby speed of Mjolnir was calculated as 9.5 km/s. After the flyby, the spacecraft would be in a heliocentric disposal orbit without the need to perform a maneuver. The total ΔV requirement yielded was 944 m/s, well within the 1,205 m/s limit.

Table 5. Top 10 NEO Flyby Opportunities for the PADME Spacecraft. *Opportunities are sorted by ΔV required for trans-NEO injection from Mars.*

Opportunity Number	NEO Number (Designation)	ΔV Required for Flyby
1	85585 Mjolnir (1998 FG2)	75 m/s
2	252558 (2001 WT1)	131 m/s
3	203217 (2001 FX9)	227 m/s
4	405212 (2003 QC10)	288 m/s
5	276468 (2003 HQ32)	306 m/s
6	68278 (2001 FC7)	313 m/s
7	385605 (2005 EJ225)	328 m/s
8	172974 (2005 YW55)	342 m/s
9	96189 Pygmalion (1991 NT3)	349 m/s
10	230089 (2000 WP148)	373 m/s

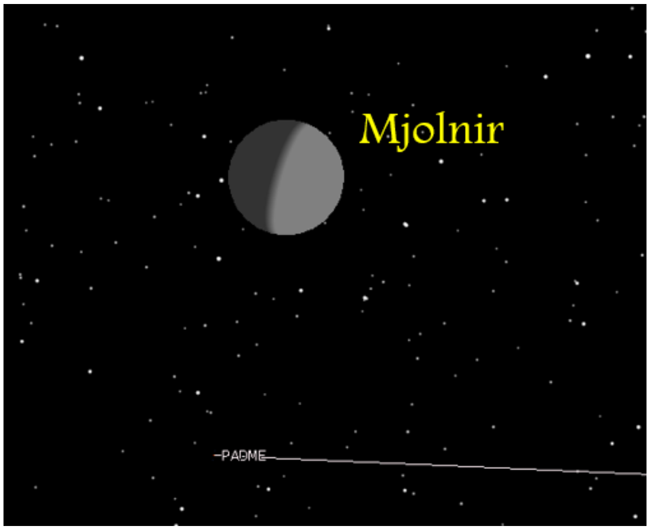


Figure 7. NEO Flyby Opportunity of Mjolnir (Thor's axe-hammer according to Norse mythology). *Flyby epoch of April 24, 2024 with a spacecraft flyby speed of 9.5 km/s with respect to Mjolnir.*

If instead a flyby opportunity to a Mars-crossing asteroid is desired, the PADME spacecraft has several options; the top 15 MCS flyby opportunities are sorted in ascending order by the ΔV required and listed in Table 6. There are 8 opportunities that require less than 250 m/s of ΔV and are thus within the capability of the PADME spacecraft propulsion system. The MCA that requires the least amount of ΔV is 147431 (2003 JA), with 76 m/s shown as the required for the trans-MCA injection (including disposal) given the 2-body search performed. Once again, a high-fidelity trajectory to 2003 JA (estimated diameter between 900 and 1,800 meters) using STK/Astrogator was calculated. This trajectory is shown in the heliocentric inertial frame (Fig. 8); the spacecraft waits in Mars orbit until September 5, 2023 before performing the injection maneuver, which requires 81 m/s in the high-fidelity, N-body model. After a 30-month heliocentric coast, the spacecraft performs a flyby of 2003 JA at a speed of 4.34 km/s, this time targeted to 1 km from the MCA at close-approach on November 18, 2024. The spacecraft would remain in heliocentric orbit after the MCA flyby to satisfy disposal requirements of avoiding contact with Mars (without the need to perform a dedicated disposal maneuver since the injection also consists of the disposal maneuver). The total ΔV requirement yielded was 958 m/s, well within the 1,205 m/s limit.

Table 6. Top 15 Mars-Crossing Asteroid Flyby Opportunities for the PADME Spacecraft. *Opportunities are sorted by ΔV required for trans-MCA injection from Mars periapsis.*

Opportunity Number	Mars-Crossing Asteroid Number (Designation)	ΔV Required for Flyby
1	147431 (2003 JA)	76 m/s
2	(2014 AG41)	109 m/s
3	(2010 CV185)	148 m/s
4	(2010 KA58)	156 m/s
5	(2012 BU23)	158 m/s
6	(2008 WX51)	159 m/s
7	(2010 GK68)	225 m/s
8	(2012 KU24)	238 m/s
9	(2009 WP192)	276 m/s
10	(2011 FF29)	276 m/s
11	(2010 JH100)	282 m/s
12	(2010 KD1)	286 m/s
13	356948 (2012 VE5)	290 m/s
14	(2007 WA5)	295 m/s
15	(2000 DF8)	297 m/s

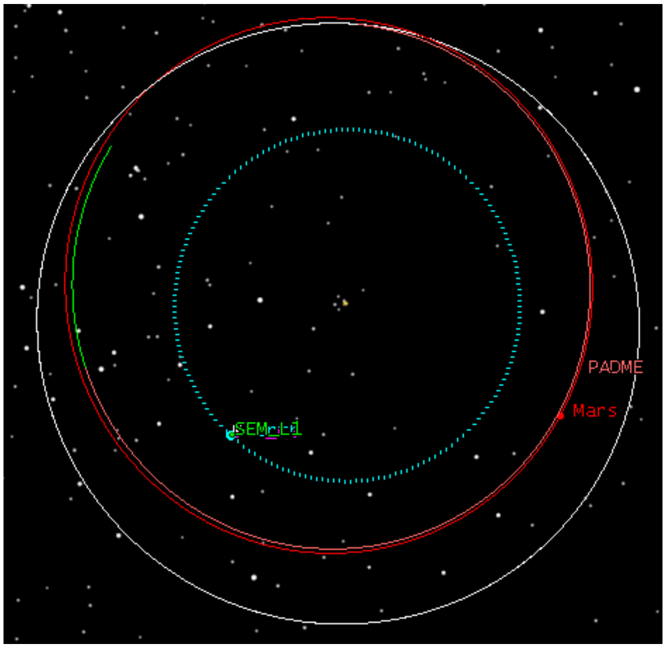


Figure 8. Flyby Opportunity of Mars-Crossing Asteroid. *Transfer shown in the heliocentric inertial frame, 147431 (2003 JA) on Nov. 18, 2024.*

E. Future Launch Opportunities to Mars

Along with the 21-day launch period in August of 2020 for the presented nominal case, launch periods for direct injections occurring in 2022 and 2024 were analyzed as well. The 2024 period was seen to be similar to that of 2020; however, this was not the case for the 2022 period. The major problem for the 2022 injection is the steep arrival declination upon Mars orbit injection. The steep, post-captured Mars orbit is shown in Fig. 9.

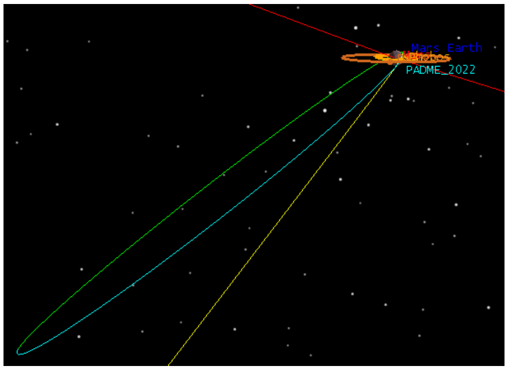


Figure 9. Post-capture Mars orbit for 2022 direct injection opportunity. *View of trajectory is edge on Phobos equatorial frame.*

By extending the apoapsis to the edge of Mars' sphere of influence, solar gravity "lifts" the trajectory toward Phobos' orbit plane far enough away from Mars such that a tolerable out of plane maneuver, with 250 m/s of ΔV, is performed to enter Phobos' plane and thus reduce the Phobos (and Deimos) flyby speeds to tolerable values (Fig. 10). Specifically, the Phobos flyby speeds will remain the same as those presented in the nominal case (about 1 km/s), while the Deimos flyby speed is increased to 1.39 km/s which still satisfies the neutron spectrometer and dust detection flyby speed requirements (Nos. 5 and 6, Table 1).

Note that the Deimos flybys occur in approximately the same orbit as the Phobos flybys; thus the ALADDIN trajectory design helps reduce the PADME spacecraft's ΔV requirement by eliminating a "gear-switch" and by performing the escape maneuver at a lower Mars periapsis (Fig. 10, bottom-left). Therefore, this 2022 solution becomes marginally feasible as the total ΔV required, including disposal to a 100-year safe orbit (from Mars impact, shown in Fig. 10), was calculated as 1,190 m/s. Optimization of this indirect 2022 solution can further reduce the total ΔV requirement, while a heliocentric broken-plane maneuver and/or a solid stage used for the MOI might eliminate the need for the 230-day post-capture trajectory sequence shown in Fig. 10.

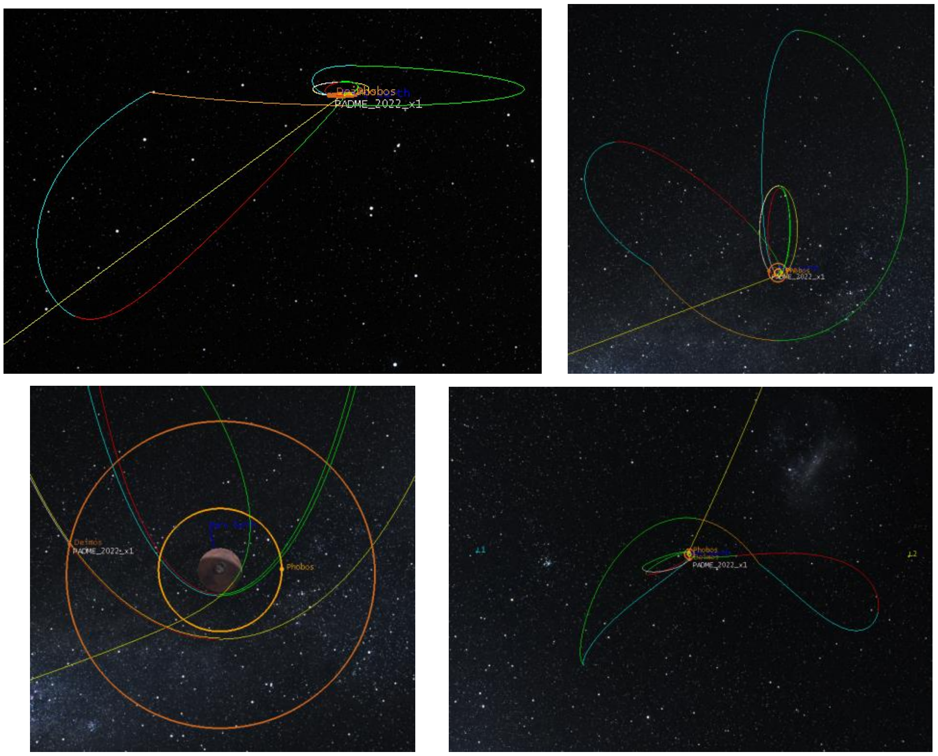


Figure 10. Mars inertial views of the indirect 2022 injection opportunity to the Phobos & Deimos resonance orbit. *Trajectory shown edge-on to the Phobos equatorial plane, (top-left); normal to the Phobos equatorial plane (top-right and bottom-left). Trajectory also shown in the Sun-Mars rotating frame, normal to the Phobos equatorial plane (bottom-right).*

IV. Conclusion

A trajectory design for the PADME spacecraft has been presented that meets all specified constraints and requirements stated in the Assumptions & Constraints section (Table 1).

It has been shown that the PADME trajectory was designed in resonance with the orbit of both Phobos and Deimos (Req. No. 3, Table 1), while launched as a primary payload from NASA Kennedy Space Center (Req. No. 1, Table 1) within the ΔV budget of 1205 m/s (Req. No. 2, Table 1). All flybys have an altitude between 2 and 10 km above their respective Martian moon (Req. No. 4, Table 1), with at least 8 Phobos and 8 Deimos flybys with a close-approach spacecraft flyby speed less than 1.5 km/s (Req. No. 5, Table 1). The dust detection requirement of having two Phobos passes occur at a flyby speed greater than 2 km/s is met by any two of Phobos flyby numbers 1-7 (Req. No. 6, Table 1), while this requirement is met for the last two Deimos flybys (> 1 km/s). The requirement of having (almost) all Phobos and Deimos flyby close-approaches occur in sunlight is met (Req. No. 7 and 9, Table 1), except for the required terminator flyby(s) which is met by Phobos flyby number 4 (Req. No. 8) and Deimos flyby numbers 6, 7, and 8 (Req. No. 10, Table 1). The neutron spectrometer requirement of at least 8 Phobos and 8 Deimos flybys with speed less than 1.5 km/s is met by all 16 Phobos and all 9 Deimos flybys. The requirement of having the Earth in view (Req. No. 11, Table 1) during the close-approach of every flyby is satisfied by all 16 Phobos and 9 Deimos flybys. Finally, Phobos flyby numbers 2, 7, 8, and 12 meet the libration science requirements (Req. No. 12 in Table 1), while the requirement of balanced longitude spacing for gravity science (Req. 13, Table 1) is satisfied by all of the Phobos and Deimos flybys.

With the same ΔV capability of the lunar LADEE spacecraft, the LADEE-derived PADME spacecraft can reach the required Mars orbit for the analyzed 2020, 2022, and 2024 launch periods, with the ability to conduct valuable and cost-effective science of Phobos and Deimos to help better understand the properties and origin of these Martian moons.

Acknowledgments

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References

[1] Lee, P. et al., "PADME (Phobos and Deimos & Mars Environment): A Proposed NASA Discovery Mission to Investigate the Two Moons of Mars," presented at the 46th Lunar and Planetary Science Conference, The Woodlands, TX, March 16-20, 2015.

[2] Lee, P. et al., "Phobos and Deimos & Mars Environment (PADME): A LADEE-Derived Mission to Explore Mars' Moons and the Martian Orbital Environment," presented at the 45th Lunar and Planetary Science Conference, The Woodlands, TX, March 17-21, 2014.

[3] Tolson, R. H., Blanchard, R. C., Daniels, E. F., "Phobos and Deimos Encounter Experiment during the Viking Extended Mission," *Journal of Spacecraft & Rockets*, Vol. 13, No. 1, pp. 19-25, 1976.

[4] Diehl, R. E., Adams, M. J., Rinderle Jr., E. A., "Phobos Encounter Trajectory and Maneuver Design," AIAA 16th Aerospace Sciences Meeting, Huntsville, AL, January 16-18, 1978.

[5] Christensen, E. J., Born, G. H., Hildebrand, C. E., Williams, "The mass of Phobos from Viking flybys," *Geophysical Research Letters*, Vol. 4, No. 12, pp. 555-557, 1977.

[6] Pieters, C., et al., "ALADDIN: Exploration and Sample Return of Phobos and Deimos" 30th Lunar and Planetary Science Conference, 1999.