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Earth-Mars Transportation Opportunities: Promising Options for Interplanetary Transportation

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Promising options for interplanetary travel between the Earth and Mars are considered. An evolving mission design is proposed based on modularity, reusability, and commonality of the hardware. A transportation system construction plan is described in the Earth-Moon environment emphasizing a building-block approach that maximizes reusability and commonality by using fly-back boosters for launch to low-Earth orbit, and using the hydrogen-oxygen fuel tank as the basic unit of construction. As part of the overall strategy, semi-cyclers are introduced to augment chemical rockets and aerobraking techniques in a manner that reduces the overall rocket fuel requirements. Semi-cyclers use a propulsion system to stay at one body for a period of time, but uses only gravity assist flybys of the other body. The transporation system will utilize three semi-cyclers to provide regular access to and from Mars. Analysis has been performed for each three synodic year period beginning in 2007 and continuing through 2046. After all three vehicles are operating, a vehicle will arrive at Mars and stay in the vicinity for about seventeen months and then leave for Earth. Nine months later another semi-cycler will arrive at Mars and stay seventeen months, and so on. At the Earth, all three vehicles will fly by within the space of about three and a half months (one on its first, one on its third and one on its fifth encounter), then less than a year later two will come by again (one on its second and one on its fourth encounter) in the space of less than two months, then in less than another year all three will come by again, and so on. A transportation infrastructure in the Mars environment is considered with a focus on the use of Phobos or Deimos as a staging base.

1 Introduction

When considering promising options for interplanetary travel between the Earth and Mars, we quickly find our transportation system design constrained by the "challenges" posed by the gravity field at the boundary points. At one end, the Earth's gravity well is deep and launching massive payloads from the Earth's surface is expensive. Current launch costs are about \$20 million per metric ton to low-Earth orbit. The problem is that overall mission costs are roughly proportional to the initial mass required in low-Earth orbit, and currently, the cost estimates for human exploration are too high to support a *sustained* presence at Mars. In the 1950's, Wernher von Braun proposed a mission architecture in which 37,200 metric tons were required in low-Earth orbit to support a manned Mars mission [1]. Significant progress has been made since then to reduce the required initial mass in orbit for a human mission to Mars. How much mass is needed depends on the mission architecture. The latest NASA Reference Mission v4 (1999) requires about 437 metric tons delivered to low-Earth orbit, of which about 250 metric tons is fuel for the Mars transfer[2]. The NASA Reference mission calls for three spacecraft (unmanned cargo lander, habitiat lander,

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and a crew transfer vehicle). The cargo spacecraft and habitat are launched first, and upon successful arrival, the crew transfer vehicle takes the astronaut team to Mars. And in the end, all this effort is required to land *one* team of astronauts on the surface. In theory, every twenty-six months another team of astronauts can be delivered to the surface using the same transportation system architecture, but requiring all new transportation vehicles.

At the other end of the space route, the gravity well of Mars is shallow and cannot completely capture an incoming spacecraft from Earth. This makes it necessary to either ferry fuel to Mars for a propulsive capture manuever, to use the Martian atmosphere (i.e., aerobraking) to reduce the vehicle speed, or to use a combination of propulsive and aerobraking maneuvers. These propulsion challenges are well-known and have been studied extensively for many years. An interesting comparion of the propulsive options (chemical, nuclear electric, aerobraking, etc.) for a manned Mars tranportation system was reported by Braun and Blersch [3]. In *The Mars Project*, Dr. von Braun suggested using chemical rockets exclusively for his proposed Mars mission transportation system, although he recognized that future developments in propulsion technology might lead to better mission designs. Most recent human exploration mission plans include a combination of chemical rockets and aerobraking; however, they require producing large amounts of fuel on the surface of Mars for the return trip home [7].

As part of the overall strategy for promising interplanetary transportation systems, it is reasonable to consider ways to *augment* the chemical rockets and aerobraking techniques in a manner that reduces the rocket fuel requirements. We believe that the key is the creative use of gravity-assist manuevers. The use of gravity-assist began with the Pioneer 10 fly-by of Venus in 1974, and found its most elegant use during the Voyager "tour" of the solar system in the late 1970's and early 1980's. Extensions of the gravity-assist concept lead to the notion of *circulating trajectories* or *cyclers* [4]–[6]. In the ideal sense, these circulating trajectories move among two or more bodies in a nearly repeatable manner for an indefinite period of time, requiring only small navigation maneuvers to control the trajectory. Cycler orbits are known to exist, but the big question is how can we best use them? In this paper, we introduce a *semi-cycler* as a more modest approach that uses a propulsion system to stay at one body for a period of time, but uses only gravity assist flybys of the other body. Thus, the central figure in our proposed interplanetary transportation system is a semi-cycler "bus" transporting crew and supplies to and fro. As you will see, our system actually consists of three semi-cyclers phased to provide consistent and repeatable routes and timing.

Clearly, when considering promising options for future interplanetary travel, it seems sensible to search for innovative approaches to reducing the mass requirements for the mission and to reducing the launch costs, both of which support *practical* and *sustained* human exploration of Mars[1]. The key to success is to evolve the mission design based on modularity, reusability, and commonality of the hardware. In this paper, we propose to construct a transportation system in the Earth-Moon environment in a "building-block" fashion that maximizes reusability and commonality by using fly-back boosters for launch to low-Earth orbit, and using the hydrogen-oxygen fuel tank as the basic unit of construction of the transportation vehicle. Our ideas touch the issues of space tourism, lunar exploration, preparation for Mars exploration, and ultimately, provides what we think is a promising interplanetary transportation system for sustained exploration of Mars.

This paper is organized as follows. Section 2 describes our ideas for constructing the semi-cycler vehicle in a building-block manner that initially provides access to space for tourists. In Section 3 we show that semi-cycler trajectories do indeed exist, and we describe a scenario in which a series of three semi-cyclers can be used to establish a regular "bus" schedule. We conclude the paper in Section 4, where we discuss ideas for the transporation system in the Mars environment. The idea of using Phobos or Deimos as a staging point is investigated.

[1] A good summary of the status of human exploration of Mars can be found in the collection of articles comprising the "Special Report: Sending Astronauts to Mars" in *Scientific American*, March 2000.

2 Near-Earth Transportation Infrastructure

The near-Earth transportation infrastructure should be constructed in a building-block fashion and eventually evolve into an efficient Earth-Mars transportation system. We envision the utilization of fly-back boosters supplemented with resuable main engines (which are recovered after use) to serve as the main launch system. The fly-back boosters would also serve other NASA missions to low-Earth orbit. The main building component of the cycler is the hydrogen/oxygen tank used during the launch. Once on-orbit, we connect the hydrogen tank and the oxygen tank (both are contained within the outer external tank structure) with a tunnel, and we connect the oxygen tank to the payload with a tunnel. The version of the launch system depicted in Figure 1 utilizes two fly-back boosters. At the top of the launch system is the payload which contains the "node" which will serve as the docking port, power service station including solar panels, heat disposal, and main computer facility for cycler managment. The node is illustrated in Figure 2. The node provides multiple docking ports for visiting vehicles.

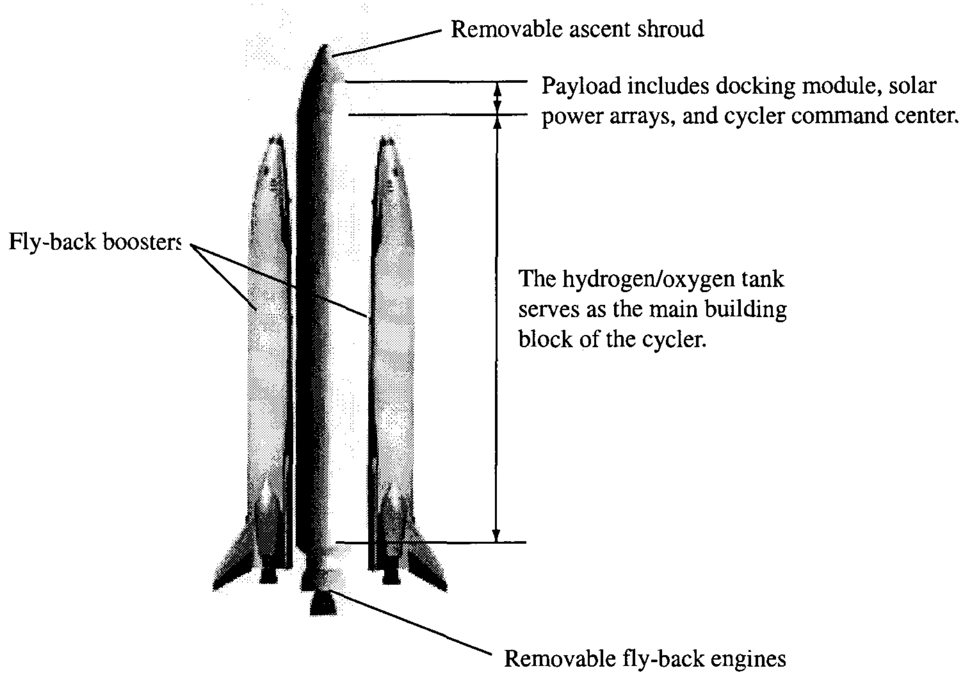

Figure 1: Semi-cycler first element with launch system.

Although the idea of using external fuel tanks as the core of a "space station" is not new, our proposed configuration illustrates a novel use of the empty tank. As in previous proposals, out transportation vehicle living and working space would be created within the voluminous interior of the external tank pressure vessel, and the transportation vehicle would be designed for modular expansion.

The initial vehicle configuration is depicted in Figure 3a. In this case, we utilize a gravity-gradient stabilized orientation to help with attitude control, and to provide a stable orientation for "tourists" that may be on-board, since the first version of the semi-cycler can serve as a "hotel." Like Skylab and the International Space Station, this early facility will be zero "g." However, it will have better facilities for visitors than the early space stations designed for engineering and science experiments. The next stage of development of the semi-cycler vehicle will address the desires of those tourists who wish to go to the Moon (not landing, though!).

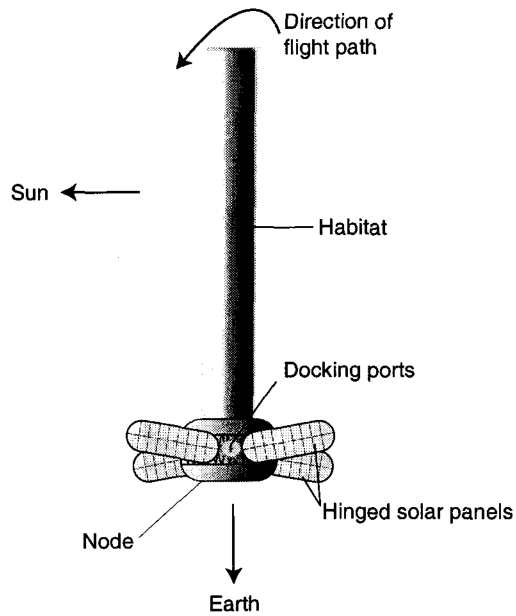

Figure 2: The first semi-cycler vehicle in gravity-gradient stabilized attitude.

The build-up of the semi-cycler vehicle occurs in stages. A second external tank can be added, as well as a nuclear power supply. We envision that these components will be tethered to the main body which is now spinning. A pressurized elevator provides access to the power station and second habitat. With the spinning motion we obtain a level of artificial gravity. This is essential for future long duration use of the semi-cycler for the Earth-Mars trajectories. Ultimately, other habitats can be attached to the vehicle.

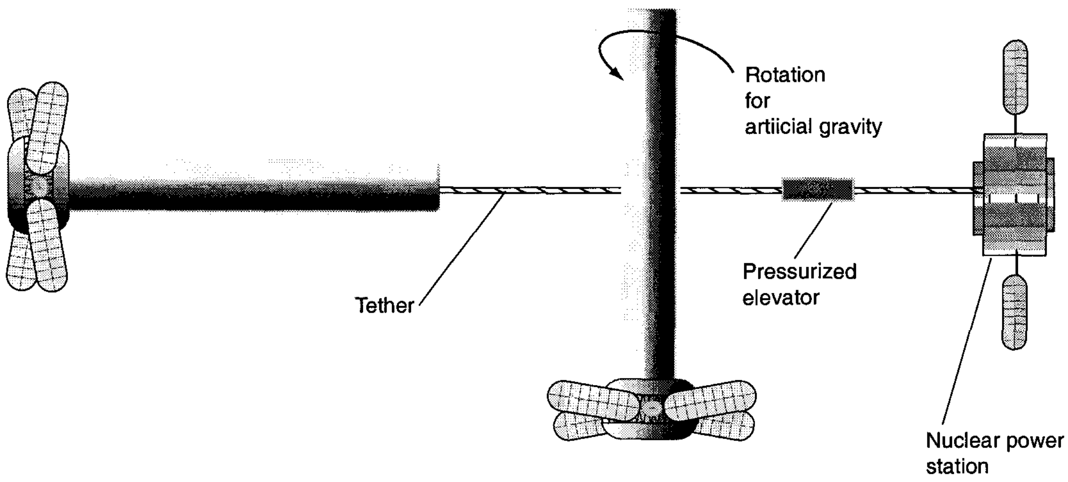

Figure 3: A complete semi-cycler on-orbit.

The plan would be to construct three semi-cyclers (actually these would be cyclers since these trajectories exist in the Earth-Moon system). The first cycler would be used for "space tourism." The second would be used as a lunar cycler, and the third as an "exploration" vehicle, most likey stationed at L1 (in the Earth-Moon system). These three cyclers would serve as the prototype for the Mars transportation infrastructure.

3 Semi-Cyclers

The concept of the *semi-cycler*, introduced here, is a more modest approach that uses a propulsion system to stay at one body for a period of time, but uses only gravity assist flybys of the other body. This saves the propellant needed for multiple missions of the standard conjunction class that use propulsion to depart low orbit and achieve terminal orbit at each body for each encounter.

Specifically, a Mars–Earth semi-cycler would depart from a Mars orbit (requiring a propulsive ΔV maneuver), flyby the Earth five times over four years and return to Mars and enter a Mars orbit (requiring a propulsive ΔV maneuver). This entire process, plus a stay time at Mars, would take three Earth–Mars synodic periods (approximately 6.4 years) and then be repeated. By having three such vehicles, each beginning one synodic period after the other, a vehicle is leaving Earth for Mars each synodic period and another is leaving Mars for the Earth each synodic period.

Other scenarios involving either two or three synodic periods are possible, but the one described above allows the short transfer times Earth-to-Mars and Mars-to-Earth ($\approx$180 days or less) that are desirable for human crewed missions. The above scenario also has reasonably low approach and departure velocities at Mars and reasonable flyby velocities at the Earth. This should allow feasible transfer of crews at each terminal planet and cargo transfer during the Earth flybys.

3.1 Simple Analysis

First, a simplified analysis for the three synodic period case using circular co-planar orbits for the orbits of Earth and Mars was performed. The assumptions are as follows:

1. Earth and Mars in circular co-planar orbits
2. Earth period = 1 year
3. Mars period = 1.875 yr. which implies a synodic period = 2 1/7 years
4. Transfer time (both Mars-Earth and Earth-Mars) constrained to 180 days (i.e. fast type I transfer.)
5. Five Earth flybys (four years transfer time E1E5) which implies a Mars stay time = 526 days
6. Minimum capture/departure ΔV at Mars calculated as transfer to/from interplanetary trajectory from/to Mars centered parabola with 300 km altitude periapsis.

With these assumptions the results are:

1. V_∞ at Mars = 3.40 km/s which implies a capture/departure $\Delta V \approx 1080$ m/s
2. V_∞ at Earth = 5.52 km/s (reasonable for 4 one-year transfers)
3. The choice of Earth flyby altitudes is flexible, but are of the order of 10,000 km to 30,000 km.

3.2 Conic Analysis

A more realistic analysis using the actual ephemerides of Mars and the Earth was performed. The spacecraft trajectory is modeled with heliocentric conic arcs connecting the planetary bodies and instantaneous V_∞ rotation occurring at the planetary flybys (a technique commonly known as "point-to-point conic V_∞ matching" or also as "zero-sphere patched conic" analysis). This level of analysis frequently gives good preliminary indications of the dynamics and parameters of interest.

This analysis has been performed for each three synodic year period beginning in 2007 and continuing through 2046. These results are summarized in Table 1. The "Opportunity" column identifies the Mars departure and arrival years. Thus "07-12" leaves Mars in July 2007, flies by Earth in January of 2008, 2009, 2010, 2011, 2012 and returns to Mars in July 2012. The Mars departure date, first Earth flyby date and Mars return dates are shown along with the associated V_∞'s. The minimum Mars departure and arrival ΔV's are calculated under the same assumptions as for the simple analysis above and represent the minimum cost to leave and enter some sort of "loose" Mars parking orbit. The Earth flyby V_∞ is also shown. Since the five Earth flybys are separated by one year each, the spacecraft heliocentric orbit is resonant with the Earth. This gives significant freedom in the flyby characteristics, but generally they can be chosen to be in the region of 5,000 km to 20,000 km.

From Table 1, sequences for each of the three required vehicles can be constructed. For example, start vehicle 1 from Earth in 5/2/2016 (opportunity "11-16"), arrive at Mars in 10/28/2016, insert into Mars orbit, leave Mars in 3/19/2018 (opportunity "18-23") and arrive Earth 9/15/2018, re-encounter Earth 9/15/2019, 9/15/2020, 9/15/2021, 9/15/2022, and 9/15/2023, arrive Mars 3/13/2023, insert into Mars orbit, etc. Vehicle 2 would start from Earth in 6/28/2018 (opportunity "13-18"). Vehicle 3 would start from Earth in 8/11/2020 (opportunity "16-21"). After all three vehicles are operating, a vehicle will arrive at Mars and stay in the vicinity for about 17 months and then leave for Earth. Only about nine months later another will arrive, stay 17 months and so on. At the Earth, all three vehicles will fly by within the space of about 3 1/2 months (one on its first, one on its third and one on its fifth encounter), then less than a year later two will come by again (one on its second and one on its fourth encounter) in the space of less than two months, then in less than another year all three will come by again, and so on.

3.3 Optimal Integrated Analysis

Two specific cases have been studied with JPL numerically integrated optimization software. Realistic trajectories from Mars departure through five Earth flybys to Mars arrival including all important gravitational perturbations were studied for the "16-21" and "24-29" opportunities.

As was pointed out above, there is significant freedom in the choice of Earth flyby parameters. Specifically the first earth flyby must rotate the V_∞ from the Earth approach orientation to an orientation that has essentially the same V_∞ magnitude and a direction which when combined with the Earth's velocity around the Sun results in a heliocentric period of one year. The locus of possible V_∞ directions that satisfies these conditions is a ring that is the intersection of a sphere with radius equal to the Earth's velocity magnitude and a sphere with radius equal to the V_∞ magnitude and centered on the tip of the Earth velocity vector. The second, third and fourth Earth encounters must rotate the V_∞ vector around this ring and then the fifth Earth encounter rotates the V_∞ vector off of the ring to the direction of departure which will accomplish the final Earth-Mars transfer.

The amount of rotation (ν = bend angle) that a given Earth encounter can accomplish, is related to the V_∞ (V_I) magnitude and radius of closest approach (R) by:

$$\sin\left(\frac{\nu}{2}\right) = \left(1 + \frac{RV_I^2}{\mu}\right)^{-1}$$

where μ is the gravitational parameter of the Earth.

The opportunity "16-21" has one of the lowest V_∞'s at the Earth encounters as well as at Mars departure and arrival, while opportunity "24-29" has the highest V_∞ at the Earth and so would be expected to be the most challenging in terms of possible flyby limitations. These two cases thus might be expected to bound the behavior of the other opportunities. The trajectories and relative positioning of Earth and Mars for "16-21" opportunity are illustrated in Figure 4. The four Earth fly-by's are not discernable in Figure 4 due to the relative scaling mismatch, but they occur at very nearly one-year intervals beginning in 8/12/2017. Tables 2 and 3 compare the flyby

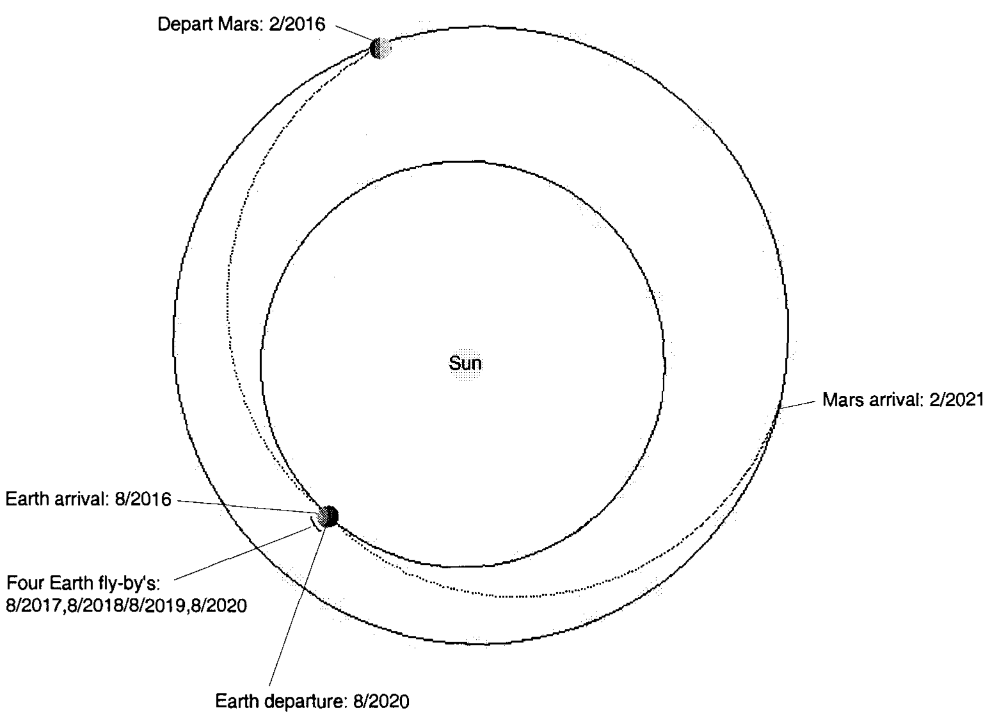

Figure 4: The "16-21" trajectory showing relative locations of Earth and Mars at departure and arrival times.

characteristics of the conic and integrated analyses for the "16-21" and "24-29" cases. The Mars dates were fixed at the values chosen in the conic study, while the Earth flyby times were allowed to vary to accommodate the real world dynamics. The agreement is quite close with the major difference being that the gravitational influence of the Earth affects the trajectory everywhere, not just near the flyby. This results in the time between Earth encounters being slightly less that one year with the effect being larger for the lower V_∞ case. Small deterministic maneuvers between the Earth flybys (of order 2-10 m/s) are required due to the resonant character of the encounters. This is consistent with experience in Galileo and Cassini trajectory design of resonant orbits. Although not required, the altitudes of the second, third and fourth Earth flybys are chosen to be equal for convenience (this is equivalent to making equal incremental rotations around the V_∞ ring described above).

A comparison of the Earth-Mars transfer architecture between the semi-cycler and the NASA Mars Reference Mission, as shown in Table 4, suggests that the semi-cycler concept can provide similar performance to an intermediate energy conjunction class "fast transfer" orbit in terms of transit time and Mars surface stay time. Constraining the semi-cycler one way transit times to 180 days in the previous analysis does not impose a significant ΔV penalty. In Table 4, note that the surface stay for the semi-cycler 16-21 is based on a previous cycler/Mars rendezvous on 9/6/14. The surface stay for the semi-cycler 24-29 is based on a previous cycler/Mars rendezvous on 3/13/23.

4 Mars Transportation Infrastructure

Once delivered to the vicinity of Mars, a cargo vehicle and its human occupants could detach from the cycler and insert itself into Mars orbit. Alternatively, if a problem were to occur during the

Table 1: Conic Analysis

Opportunity	Mars Departure Date	Mars V-inf (km/s)	Min. Mars Depart. DV	Earth Arrival Date	Earth V-inf (km/s)	Mars Arrival Date	Mars V-inf (km/s)	Min. Mars Arrival. DV
07-12	07/24/07	4.77	1.96	01/20/08	8.27	07/17/12	4.40	1.71
09-14	09/12/09	4.30	1.64	03/11/10	8.56	09/06/14	4.63	1.87
11-16	11/04/11	4.72	1.93	05/02/12	6.82	10/28/16	4.78	1.97
13-18	12/30/13	5.12	2.21	06/28/14	4.90	12/24/18	3.55	1.17
16-21	02/13/16	3.82	1.33	08/11/16	4.28	02/06/21	2.72	0.72
18-23	03/19/18	2.67	0.69	09/15/18	4.46	03/13/23	4.46	1.75
20-25	05/10/20	4.10	1.51	11/06/20	5.38	05/04/25	5.04	2.16
22-27	07/04/22	4.90	2.06	12/31/22	7.59	06/28/27	4.53	1.80
24-29	08/23/24	4.42	1.72	02/19/25	8.72	08/17/29	4.46	1.75
26-31	10/14/26	4.46	1.75	04/12/27	7.67	10/08/31	4.85	2.02
28-33	12/08/28	5.09	2.19	06/06/29	5.49	12/02/33	4.18	1.56
31-36	01/29/31	4.55	1.81	07/28/31	4.46	01/23/36	2.71	0.71
33-38	03/04/33	2.76	0.74	08/31/33	4.30	02/26/38	3.73	1.28
35-40	04/19/35	3.44	1.10	10/16/35	4.83	04/12/40	5.04	2.16
37-42	06/13/37	4.80	1.98	12/10/37	6.72	06/07/42	4.75	1.95
39-44	08/05/39	4.64	1.87	02/01/40	8.53	07/29/44	4.38	1.69
41-46	09/24/41	4.31	1.65	03/23/42	8.32	09/18/46	4.73	1.94
43-48	11/16/43	4.88	2.04	05/14/44	6.32	11/09/48	4.64	1.87
46-51	01/11/46	5.01	2.13	07/10/46	4.70	01/05/51	3.19	0.96

Table 2: Integrated Analysis—Opportunity "16-21"

	Integrated Analysis				Conic Analysis		
	Date	**Time**	**V_∞ (km/s)**	**Altitude (km)**	**Date**	**Time**	**V_∞ (km/s)**
Mars	02/13/16	12:00	3.809	300	02/13/16	12:00	3.82
Earth1	08/12/16	20:23	4.218	9000	08/11/16	12:00	4.28
Earth2	08/12/17	4:51	4.228	18000	08/11/17	18:00	4.28
Earth3	08/11/18	17:28	4.231	18000	08/12/18	0:00	4.28
Earth4	08/11/19	8:27	4.239	18000	08/12/19	6:00	4.28
Earth5	08/10/20	0:37	4.230	18892	08/11/20	12:00	4.28
Mars	02/06/21	12:00	2.717	300	02/06/21	12:00	2.72

Table 3: Integrated Analysis—Opportunity "24-29"

	Integrated Analysis				Conic Analysis		
	Date	**Time**	**V_∞ (km/s)**	**Altitude (km)**	**Date**	**Time**	**V_∞ (km/s)**
Mars	08/23/24	23:31	4.432	300	08/23/24	23:31	4.42
Earth1	02/19/25	16:09	8.766	5235	02/19/25	23:31	8.72
Earth2	02/19/26	20:06	8.751	5235	02/20/26	5:31	8.72
Earth3	02/19/27	23:44	8.752	5235	02/20/27	11:31	8.72
Earth4	02/20/28	3:24	8.749	5235	02/20/28	17:31	8.72
Earth51	02/19/29	7:21	8.766	5233	02/19/29	23:31	8.72
Mars	08/17/29	23:31	4.475	300	08/17/29	23:31	4.46

Table 4: Comparison of Semi-cycler with NASA Reference Missions

Transfer Orbit Architecture	**Earth/Mars Transit Time (days)**	**Surface Stay (days)**	**Mars/Earth Transit Time (days)**	**Total Mission Time (days)**
Semi-Cycler (16-21)	180	525	180	885
Semi-Cycler (24-29)	180	529	180	889
NASA Mars Ref. Mission: Long-Stay Min. Energy (14-16)	254	458	237	949
NASA Mars Ref. Mission: Long-Stay Fast Transit (14-16)	150	619	110	879

interplanetary transfer or during the separation phase, the cargo vehicle could simply remain with the cycler and follow the free-return trajectory back to Earth. After separation from the cycler, direct descent to the surface would be possible, but it may also be possible and desirable to utilize the the Martian satellites Phobos and Deimos in an evolutionary strategy for Mars exploration.

One possible evolutionary strategy for Mars exploration may consist of the following staged sequence of missions leading up to crewed planetary surface exploration. First, a semi-cycler flyby of Mars may be performed, perhaps with an automated test of cargo departure operations, perhaps by delivering cargo to the Martian surface, or conducting a robotic reconnaissance of Phobos or Deimos. Further cargo departure/arrival operations could be tested in earth orbit when the cycler returns. Next, a semi-cycler could be used to deliver a human crew to Mars orbit where a reconnaissance of Phobos or Deimos could be conducted without the risks of a decent to the Martian surface and the subsequent ascent. Benefits and costs of this possibility are discussed below. Before, during, or after the crewed excursion to Phobos or Deimos, tests of Mars descent and ascent hardware could be performed. Crews could also teleoperate robotic surface vehicles from the vantagepoint of Phobos or Deimos in preparation for a crewed planetary surface expedition. The Phobos/Deimos crew could then hitch a ride home on the next cycler, which could also be used to deliver hardware for a future crewed planetary surface mission. Finally, a crewed planetary surface mission could be conducted. In subsequent synodic periods, a new crew could be delivered for further surface exploration and the old crew carried back to Earth, allowing for continued planetary surface exploration. If six cyclers were allowed, then a Mars Direct style approach could be taken and both a new crew and additional backup hardware could be delivered during each synodic period.

4.1 Why Go to Phobos or Deimos?

The question of Phobos and Deimos remains: What are the benefits of utilizing Phobos and/or Deimos in this evolutionary approach to Mars exploration? First, we must justify what Phobos or Deimos bring to this approach. Second, we must consider if it is energetically possible to utilize Phobos and/or Deimos in this architecture.

Phobos and Deimos would be interesting to study in and of their own rights. Both moons are thought to be asteroids nudged into the inner solar system by Jupiter and captured by Mars but they may also originate from the outer solar system. Their low densities (< 2 g/cm3) suggest that Phobos and Deimos may be a mixture of rock and ice. The Phobos 2 probe also reported outgassing from Phobos before the spacecraft was lost. Positioning a habitation on the side of Phobos or Deimos facing Mars would enhance radiation protection from galactic cosmic radiation (GCR). Mars would tend to block some of the background GCR from one direction, and the moon would tend to block some GCR from the opposite direction. Phobos, with its orbit only 6000 km above the Martian surface, would provide more GCR shielding than the more distant Deimos. An appropriately located crater could also be used to further shield the habitation from solar particle events (SPEs). Phobos or Deimos would also provide a vantage point to conduct remote teleoperation of robitic vehicles on the Mars suface. The relatively short sidereal period of Phobos of $\approx$0.32 days might hamper these operations, while the longer period of Deimos of $\approx$1.26 days would enable longer periods of teleoperation without interruption. The presence of a Mars communications network (as has been recently proposed) could also assist in this process.

Figure 5 shows the Deep Space Network (DSN) coverage and sun visibility for a Mars facing habitat on Phobos or Deimos. Typical coverage is shown, and the specific example is taken from the 2/6/2021 12:00 arrival from the "16-21" integrated analysis. A Mars facing habitat is a good location to protect the crew from radiation. This example demonstrates a typical timeline for DSN communications opportunities and sun visibility for a habitat situated on the Mars side of Phobos or Deimos.

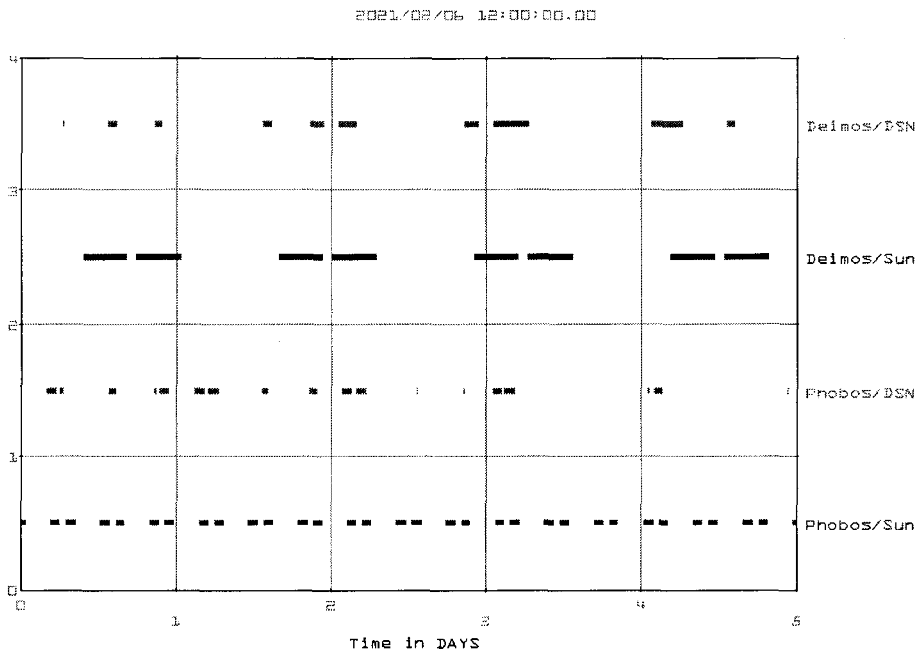

Figure 5: Deep Space Network (DSN) coverage and sun visibility for a Mars facing habitat on Phobos or Deimos.

4.2 Energetics of Going to Phobos or Deimos

One major downside of utilizing Phobos or Deimos in combination with the semi-cycler is the orbital plane changes that would be required. Inclination angles for the Earth/Mars interplanetary transfer ellipses of the semi-cycler are in the range of 0.1-2.3° for the 2007-2027 semi-cycler opportunities. Mars has an obliquity, with respect to the ecliptic plane, of 25.19° while the orbits of Phobos and Deimos have inclination angles, with respect to the equatorial plane of Mars, of 1.08° and 1.79° ,respectively. This necessitates a significant change of the orbital plane between the interplanetary transfer ellipse (arrival or departure) and the desired orbital plane at Mars. During Mars arrival, an early release of the "crew and cargo" vehicle and a minor targeting maneuver at the appropriate time would enable the cargo vehicle to easily match inclination angles of Phobos or Deimos. However, the return trip would be significantly more challenging. An expensive plane change maneuver would be required for the departing "crew and cargo" vehicle to reach the semi-cycler. One option to reduce the costs of such a maneuver would be to carry consumables and other cargo for the trip home onboard the next arriving semi-cycler. In this way, only the crew and a minimal amount of cargo need make the trip from Phobos or Deimos to the semi-cycler departing for Earth.

One strong argument for bypassing Phobos and/or Deimos and heading directly for the Martian surface must be acknowledged: The gravitational environment of Mars is much more conducive to long-term habitation that the low-weight environment of Phobos or Deimos. Missions to Phobos or Deimos would require added physiological countermeasures in comparison to a Mars surface mission; one option might be to utilize artificial gravity systems. On the other hand, a mission to Phobos or Deimos with a variable-g artificial gravity system could be used to validate countermeasures programs for Mars surface exploration.

5 Summary and Conclusions

Promising options for interplanetary travel between the Earth and Mars have been considered. An evolving mission design was proposed based on modularity, reusability, and commonality of the hardware. A transportation system construction plan was described in the Earth-Moon environment using fly-back boosters for launch to low-Earth orbit, and employing the hydrogen-oxygen fuel tank as the basic unit of construction. As part of the overall strategy, semi-cyclers were introduced to augment chemical rockets and aerobraking techniques in a manner that reduces the overall rocket fuel requirements. Semi-cyclers use a propulsion system to stay at one body for a period of time, but uses only gravity assist flybys of the other body. The proposed system will utilize three semi-cyclers to provide regular access to and from Mars. Analysis shows that the semi-cycler achieves conjunction class mission transit times and comparable Mars stay times. Although the semi-cycler cannot match the shorter transit times of the "fast transit" approach, it may be a more economical approach in terms of delivery of usable payload to Mars. The semi-cycler also offers free-return trajectory with 180 day transit time, is ompatible with evolutionary mission approach including the utilization of Phobos or Deimos as an early target of exploration, and possesses the long-term benefits of repeated missions every synodic period.

The semi-cycler represents another step in the evolution of the "cycler" concept. It should be emphasized that this is an on-going "work-in-progress." Closer study of the near-Earth transportation system will undoubtably reveal greater possibilities for increasing modularity and reusability. Further investigations of the near-Mars transportation system, including potential use of Phobos and Deimos, will most probably lead to further improvements in our overall mission design.

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