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ORBITAL TRANSFER TECHNIQUES FOR ROUND-TRIP MARS MISSIONS

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The human exploration of Phobos and Deimos or the retrieval of a surface sample launched to low-Mars orbit presents a highly constrained orbital transfer problem. In general, the plane of the target orbit will not be accessible from the arrival or departure interplanetary trajectories with an (energetically optimal) tangential burn at periapsis. The orbital design is further complicated by the addition of a high-energy parking orbit for the relatively massive Deep Space Vehicle to reduce propellant expenditure, while the crew transfers to and from the target orbit in a smaller Space Exploration Vehicle. The proposed strategy shifts the arrival and departure maneuvers away from periapsis so that the apsidal line of the parking orbit lies in the plane of the target orbit, permitting highly efficient plane change maneuvers at apoapsis of the elliptical parking orbit. An apsidal shift during the arrival or departure maneuver is approximately five times as efficient as maneuvering while in Mars orbit, thus significantly reducing the propellant necessary to transfer between the arrival, target, and departure orbits.

INTRODUCTION

A round-trip mission to Mars presents a particular set of orbital challenges. A well-known issue for human missions is that the ΔV-optimal orbits for Mars arrival are generally out-of-plane for departure, significantly increasing total mission mass.[1] Further the optimal planes of the interplanetary trajectories do not necessarily coincide with the plane of the target orbit (near equatorial for Phobos and Deimos), requiring additional maneuvers to complete a round-trip mission to Mars.[1,2,3] The inclusion of an intermediate parking orbit to stage a Deep Space Vehicle (DSV) further complicates the design of orbital transfers at Mars because the parking orbit should allow efficient transfers from both the incoming and outgoing trajectory as well as the target orbit.[4,5,6] Typically, the ΔV of the DSV is kept to a minimum, suggesting low periapsis, long period parking orbits to minimize the ΔV from the high energy interplanetary trajectories and the captured parking orbit. A less massive Space Exploration Vehicle (SEV) provides the additional ΔV to transfer down to the target orbit and back to the elliptical parking orbit.[7,8] The overall propellant consumption is thus reduced by staging ΔV off the relatively massive DSV onto the smaller SEV. Efficient orbital transfers that account for the relative geometry of the arrival, departure, and target orbits enable significant mass savings from this mission architecture.

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BASELINE SCENARIO

The 2033 short-stay Mars opportunity provides a baseline mission to examine representative orbit transfer requirements (Figure 1). This trajectory has an arrival V_∞ at Mars of 3.7 km/s, 13.8 deg declination, and 6.6 deg right ascension. The departure V_∞ has a magnitude of 6.0 km/s with 12.8 deg declination and -0.8 deg right ascension. The stay time would be 60 days. The crew would arrive in a relatively massive (say 60 t) deep space vehicle (DSV) and enter an orbit that is generally not in plane with the target orbit. Part of the crew could then use a smaller space exploration vehicle (SEV, e.g. a 10-t pod) with propulsion stages to transfer to the destination orbit and back via a series of optimized transfers. The crew would then rendezvous with the DSV, which maneuvers into the departure plane before performing trans-Earth injection. Two mission scenarios are considered: 1) exploration of Phobos or Deimos (equatorial orbits) and 2) retrieval of an orbiting sample from an inclined, precessing 500 km altitude circular orbit.

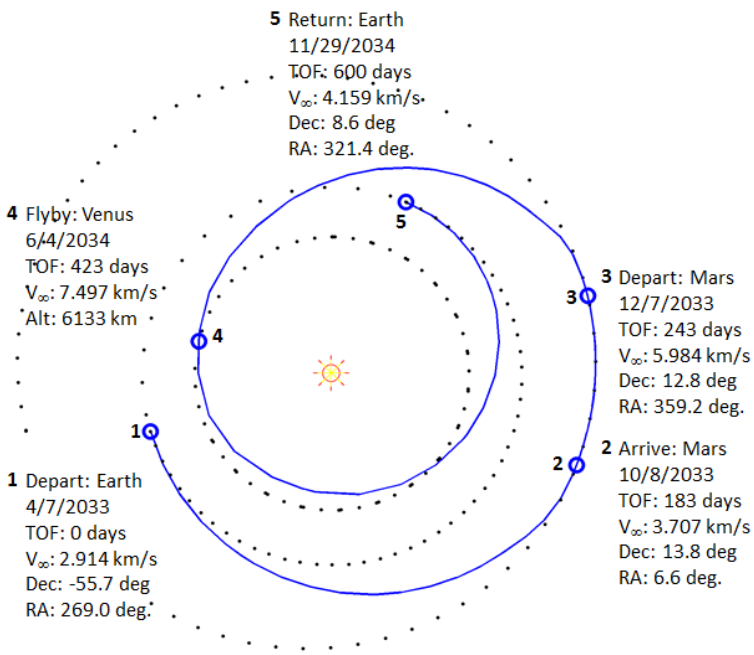

Figure 1 Baseline round-trip mission launching in 2033 with 60-day stay in Mars orbit.

TRANSFER TECHNIQUES

Because the DSV would be much more massive than the SEV, the trajectory optimization stresses minimization of the DSV ΔV. The largest maneuvers for the DSV are Mars orbit insertion and trans-Earth injection, and these maneuvers are minimized by parking the DSV in an orbit with a low periapsis and long period (e.g. 250 km altitude and one-sol period). The minimum ΔV to enter and depart this orbit is achieved with tangential burns at periapsis, however this minimum is usually unattainable because the arrival and departure orbits do not share the same plane. As shown in Figure 2, the cheapest way to reorient the arrival orbit to the departure plane is to either shift the line of apsides at arrival or departure or to "twist" the orbit along the line of apsides. These maneuvers are orthogonal and thus provide a large range of potential orbit orientations when combined. By aligning the apsides of the arrival and departure orbits, the ΔV for the DSV is generally minimized for round-trip Mars missions.

In order for the SEV to reach its target, it must first transfer to the plane of the target orbit, which is also generally not aligned with the arrival orbit of the DSV. If the arrival and departure orbits are designed with the additional constraint of placing their line of apsides in the plane of the target orbit, then the additional ΔV for the SEV to reach its target can be minimized. In this case the SEV simply rotates its orbit along the line of apsides (red line in Figure 2) until it is in the target plane. The circular target orbit is achieved by raising periapsis and then circularizing at the target orbit altitude. At the conclusion of the target orbit mission, the SEV reverses this process to rendezvous with the DSV in the departure orbit for Earth return.

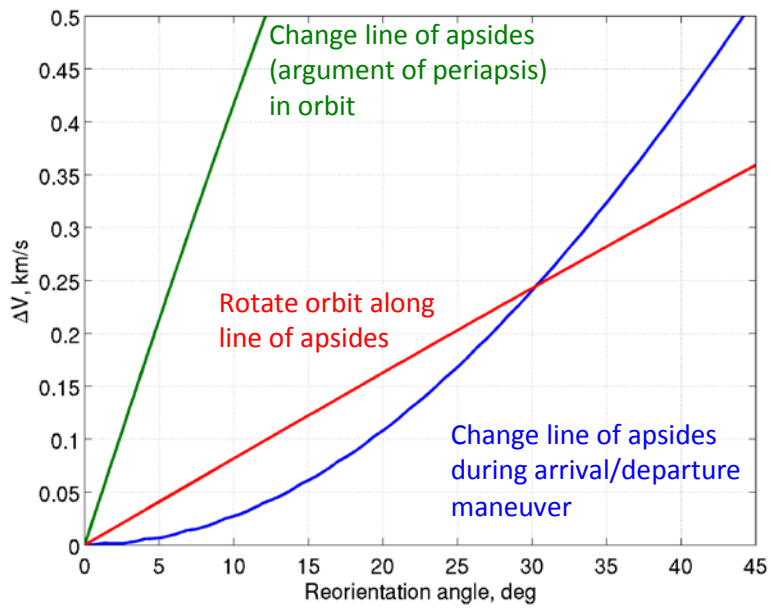

Figure 2 Relative cost of orbit reorientation techniques.

Phobos and Deimos

An example transfer sequence to Phobos is shown in Figure 3 where the arrival orbit, the departure orbit, and the transfer orbit all share a common periapsis with different inclinations. This geometry is possible by changing the line of apsides at the arrival and departure maneuvers (non tangential maneuvers) and by transferring between orbits by rotating along the common line of apsides. In this case the transfer orbit also requires a maneuver to raise periapsis from the arrival orbit (low periapsis for efficient capture) up to Phobos altitude. For the example trajectory shown in Figure 3 the ΔV for the DSV is 4.935 km/s and the ΔV for the SEV is 1.616 km/s. The ΔV for the SEV to transfer to Deimos from the same capture orbit is 1.282 km/s. For comparison, the Hohmann transfer ΔV for a round trip between Phobos and Deimos is around 1.5 km/s.

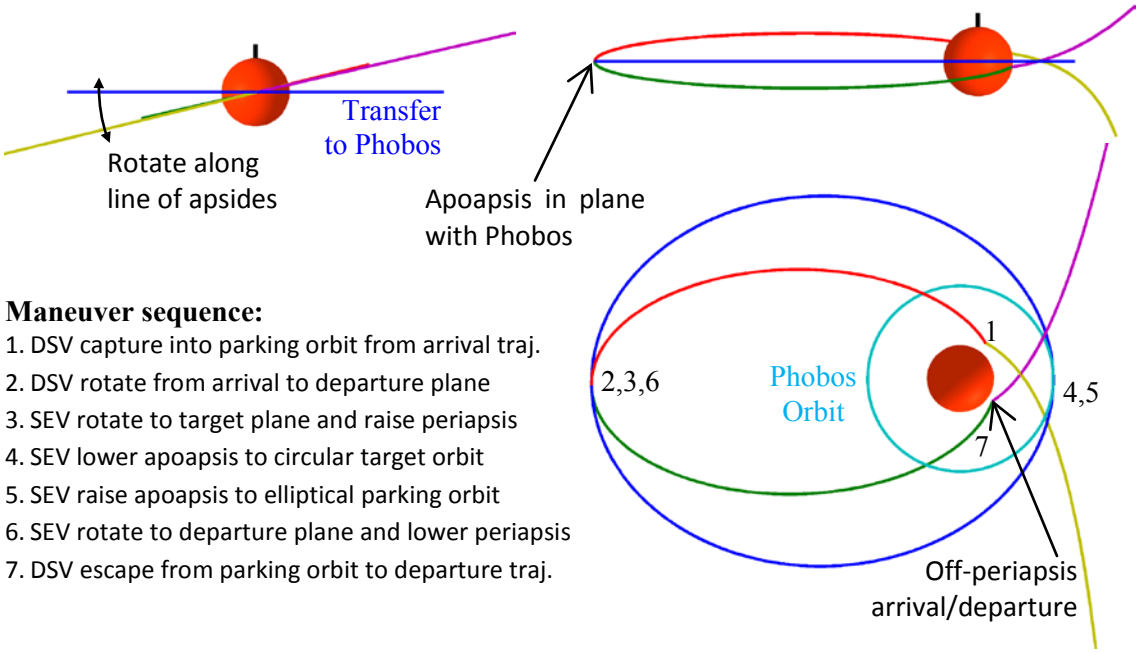

Figure 3 Example transfer to Phobos.

The general characteristics of the maneuver sequence depicted in Figure 3 are investigated by applying the transfer strategy to short duration (500–800 day round trip) Mars missions. The arrival and departure conditions for opposition class trajectories from 2020 through 2070 are presented in Table 1. These V_∞ vectors correspond to trajectories designed for relatively low injected mass to low-Earth orbit (including the Earth departure maneuver) and a 60-day stay time at Mars. Table 2 contains the ΔV of each maneuver for the DSV at Mars along with the orientation of the parking orbit. The total ΔV for the DSV is found in the second column of Table 2, and the portion of the ΔV due to non-ideal geometry is tabulated in the third column. The additional ΔV from the ideal minimum is generally larger than the reorientation maneuver ΔV at apoapsis (column five) because the capture and escape maneuvers (columns four and six) also change the orbital geometry by shifting the line of apsides. The orientation of the parking orbit before and after the reorient maneuver is defined by the right ascension of periapsis (at a node in the target orbit plane) and inclination of the arrival and departure orbits (which share a common line of apsides). The inclinations in Table 2 are generally near the equator to provide low-ΔV transfers to Phobos and Deimos. Table 3 contains the breakdown of maneuvers for the SEV to transfer to Phobos or Deimos. The total ΔV, as well as the additional ΔV from an ideal geometry (i.e. zero relative inclination), is generally smaller for the SEV than for the DSV, suggesting that most of the non-coplanar ΔV has been placed on the DSV.

The maneuver breakdown in Table 2 and Table 3 is optimized to minimize the sum of the DSV and SEV ΔV, which may not be optimal from a mass standpoint because the DSV could be much more massive than the SEV. An alternative maneuver breakdown is provided in Table 4 and Table 5 where the ΔV of the DSV is minimized while neglecting the cost of the SEV. In this case the DSV ΔV can be reduced dramatically (e.g. by 800 m/s in 2020) at the expense of an increase in SEV ΔV. The most dramatic changes occur when the inclination of the parking orbit is retrograde and the SEV must nearly reverse direction at apoapsis to transfer to the target orbit (as

in Figure 4). The overall ΔV for the DSV remains low because both the arrival and departure orbits are retrograde.

A key design variable for the reorientation ΔV is the speed near apoapsis of the parking orbit, where lower speeds generally lead to lower ΔV. Examples where the apoapsis speed is lowered by increasing the period of the parking orbit to three sols (from one sol) are provided in Table 6 and Table 7. This design provides the greatest benefit to the SEV ΔV (e.g. over 800 m/s in 2020), though the DSV ΔV also decreases. The SEV ΔV is still generally larger in Table 7 than in Table 3, but the maneuver combination in Table 6 and Table 7 could provide an overall lower mass design. However, these longer period orbits provide a transfer opportunity only once every three sols, whereas the shorter period orbits have more frequent transfer opportunities. Thus the mass benefits must be balanced against the operational constraints.

An alternative, less complex strategy, is to transfer the just the DSV to the target orbit, forgoing the need for a SEV. When the target orbit is circular, the orbit transfer geometry simplifies greatly because the line of nodes of the arrival, departure, and parking orbits no longer need to align. The arrival and departure apses reorient by entering and departing the circular orbit at different longitudes, and decoupled apoapsis maneuvers can rotate the DSV into and out of the target orbit plane. However, in this case the ΔV for the DSV increases significantly, thus requiring more propellant mass to complete the mission. From Figure 5 this "DSV only" scenario generally requires more mass for missions to Phobos when the DSV is a few times more massive than the SEV (60 t versus 10 t in Figure 5). Further mass savings are possible by completely minimizing the ΔV for the DSV and transferring more of the mission ΔV to the less massive SEV.

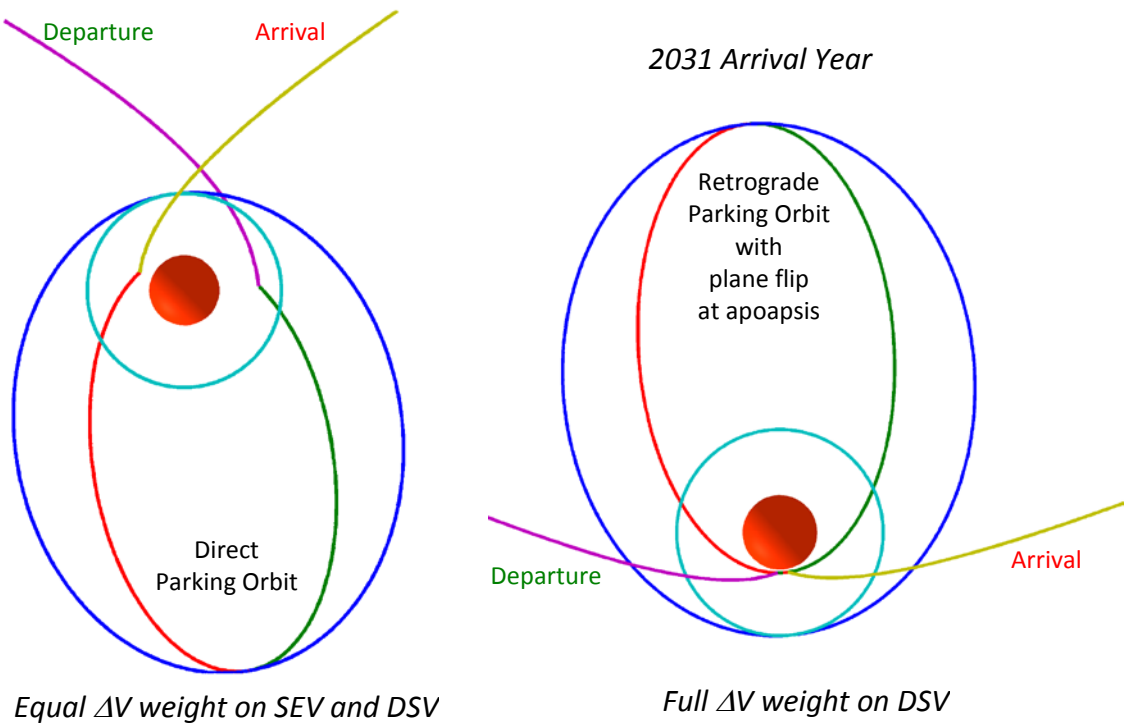

Figure 4 The optimal orbit orientation can change dramatically based on relative mass of the Deep Space Vehicle and Space Exploration Vehicle.

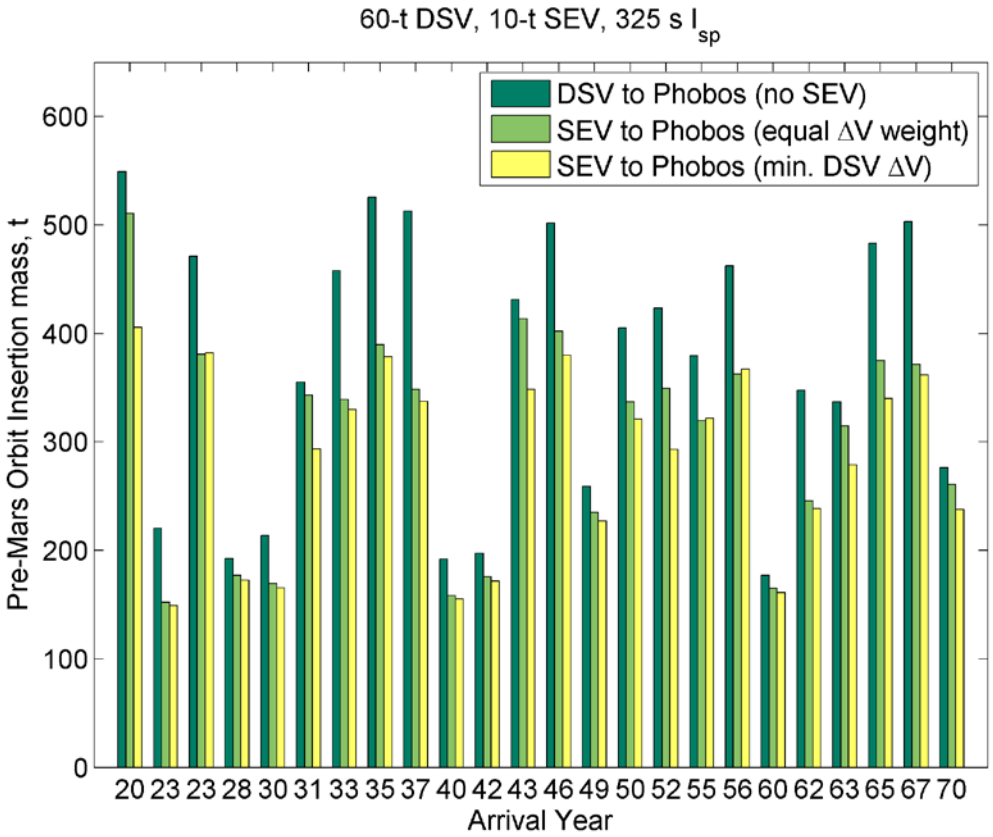

Figure 5 The addition of a Space Exploration Vehicle can significantly reduce the mass for missions to Phobos.

Table 1 Mars arrival and departure vectors for short duration (opposition class) missions 2020–2050.

Mars Arrival	Traj. Type[a]	Arrival V_∞, km/s	Arrival RA,[b] deg.	Arrival Dec., Deg.	Departure V_∞, km/s	Departure RA, deg.	Departure Dec., Deg.
12/11/20	EMVE	4.545	124.06	10.98	6.208	45.99	26.69
04/20/23	EME	3.018	-176.10	-18.33	3.198	-85.77	-20.11
06/23/24	EVME	6.712	28.37	10.13	3.322	12.01	7.66
08/11/28	EME	3.239	-11.10	-20.59	2.869	76.74	43.43
10/10/30	EME	3.466	32.23	12.27	2.767	129.83	38.59
01/08/31	EVME	5.427	-151.11	-5.15	3.711	157.19	6.49
10/14/33	EMVE	3.890	5.69	1.23	6.226	0.44	8.51
06/26/35	EVME	5.912	-30.57	-10.76	4.790	-39.57	-15.15
05/16/37	EVME	6.308	-46.45	-26.78	3.872	-15.30	-31.86
06/19/40	EME	2.642	-156.51	-31.08	3.203	-51.50	-4.41
08/08/42	EME	2.709	-117.19	-15.71	3.542	-7.32	9.00
10/02/43	EVME	5.720	138.48	23.66	4.229	78.32	6.04
08/17/46	EMVE	4.400	-44.63	-2.83	6.209	-63.43	-27.30
02/17/50	EME	4.770	149.60	23.19	2.829	-115.72	-12.64
03/19/50	EVME	5.743	-101.06	-25.31	3.761	-125.22	-12.67
12/03/52	EMVE	3.746	95.61	17.72	5.823	50.12	29.04
06/25/56	EVME	5.907	41.70	4.14	3.384	25.99	-5.23
07/05/56	EVME	6.453	27.64	11.12	3.521	14.87	10.52
08/13/60	EME	2.908	-7.10	-20.61	2.675	92.53	43.62
11/01/62	EME	5.348	58.30	25.75	2.891	141.56	31.66
01/10/63	EVME	5.424	-150.39	-6.59	3.402	165.78	2.83
10/16/65	EMVE	3.989	24.39	7.30	6.321	-2.09	11.83
06/28/67	EVME	5.789	-29.71	-9.92	4.734	-35.96	-14.16
04/03/70	EMVE	3.207	174.88	-6.31	4.800	147.76	31.90

[a]EMVE has a Venus flyby on the return (Mars-Earth) leg; EVME has a Venus flyby on the outbound (Earth-Mars) leg; and EME has no Venus flybys during the round-trip Mars trajectory.

[b]Mars right ascension and declination are in Mars equator and equinox of J2000 frame.

Table 2 Deep Space Vehicle transfers for 250 km x 1 sol parking orbits with equal weighting on DSV and SEV ΔV.

	DSV ΔV, km/s					Parking Orbit Orientation,[b] deg.		
Mars Arrival	Total	Difference from ideal[a]	Capture	Reorient	Escape	Periapsis right asc.	Arrive inc.	Depart inc.
12/11/20	6.47	1.20	2.95	0.06	3.53	-24.8	20.6	28.0
04/20/23	2.32	0.05	1.16	0.00	1.23	141.9	26.3	26.3
06/23/24	5.32	0.42	3.85	0.02	1.52	-73.1	10.3	7.7
08/11/28	2.81	0.60	1.25	0.61	1.04	-61.6	26.0	54.9
10/10/30	2.63	0.34	1.47	0.26	0.98	-9.2	18.2	50.6
01/08/31	5.08	0.96	2.99	0.11	2.04	98.7	5.5	7.6
10/14/33	5.15	0.30	1.75	0.06	3.43	-82.5	1.2	8.6
06/26/35	5.47	0.26	3.18	0.04	2.35	-127.1	10.8	15.2
05/16/37	4.98	0.07	3.40	0.05	1.64	-124.7	27.3	33.4
06/19/40	2.50	0.42	0.93	0.29	1.36	164.8	44.0	7.4
08/08/42	2.88	0.57	1.04	0.33	1.59	-151.1	26.8	15.0
10/02/43	5.72	1.05	3.17	0.14	2.47	28.6	25.0	7.9
08/17/46	5.70	0.53	2.14	0.20	3.45	-141.2	2.8	27.8
02/17/50	3.71	0.55	2.33	0.40	1.09	101.5	29.9	20.4
03/19/50	4.96	0.56	3.11	0.11	1.82	156.4	25.8	12.9
12/03/52	5.23	0.78	2.03	0.08	3.19	-25.1	20.4	29.9
06/25/56	4.79	0.48	3.22	0.08	1.55	-59.1	4.2	5.2
07/05/56	5.16	0.35	3.63	0.01	1.60	-72.5	11.3	10.5
08/13/60	2.57	0.63	1.07	0.65	0.94	-52.4	27.9	58.9
11/01/62	3.77	0.16	2.75	0.07	1.05	7.8	32.0	40.5
01/10/63	4.79	0.85	2.92	0.08	1.84	104.3	6.8	3.2
10/16/65	5.49	0.50	1.96	0.04	3.57	-78.5	7.5	12.2
06/28/67	5.32	0.24	3.08	0.03	2.30	-124.8	10.0	14.2
04/03/70	4.27	0.89	1.56	0.31	2.45	71.8	6.5	32.7

[a]Minimum ΔV for coplanar transfers.
[b]Parking orbit orientation is given in Mars equator and equinox of J2000 frame.

Table 3 Space Exploration Vehicle transfers for 250 km x 1 sol parking orbits with equal weighting on DSV and SEV ΔV.

	Phobos SEV ΔV, km/s				Deimos SEV ΔV, km/s			
Mars Arrival	Total[a]	Difference from ideal[c]	Leave Parking	Return Parking	Total[b]	Difference from ideal[c]	Leave Parking	Return Parking
12/11/20	1.78	0.20	0.30	0.35	1.42	0.15	0.54	0.58
04/20/23	1.81	0.23	0.34	0.34	1.44	0.17	0.57	0.57
06/23/24	1.62	0.03	0.25	0.24	1.29	0.02	0.50	0.50
08/11/28	2.03	0.44	0.34	0.56	1.64	0.37	0.57	0.78
10/10/30	1.94	0.36	0.28	0.53	1.57	0.30	0.53	0.75
01/08/31	1.60	0.02	0.23	0.24	1.28	0.01	0.49	0.50
10/14/33	1.60	0.01	0.23	0.24	1.28	0.01	0.49	0.50
06/26/35	1.65	0.07	0.25	0.27	1.32	0.04	0.51	0.52
05/16/37	1.87	0.28	0.35	0.39	1.49	0.22	0.58	0.62
06/19/40	1.84	0.26	0.48	0.24	1.48	0.21	0.70	0.50
08/08/42	1.74	0.16	0.34	0.27	1.39	0.12	0.58	0.52
10/02/43	1.70	0.12	0.33	0.24	1.35	0.08	0.57	0.50
08/17/46	1.71	0.13	0.23	0.35	1.36	0.09	0.49	0.58
02/17/50	1.79	0.21	0.37	0.30	1.43	0.16	0.59	0.54
03/19/50	1.72	0.14	0.34	0.26	1.37	0.10	0.57	0.51
12/03/52	1.79	0.21	0.30	0.37	1.43	0.16	0.54	0.59
06/25/56	1.59	0.01	0.23	0.23	1.28	0.01	0.49	0.49
07/05/56	1.63	0.05	0.25	0.25	1.30	0.03	0.51	0.50
08/13/60	2.07	0.49	0.35	0.59	1.68	0.41	0.58	0.81
11/01/62	1.96	0.37	0.38	0.45	1.57	0.30	0.61	0.67
01/10/63	1.59	0.01	0.24	0.23	1.28	0.01	0.50	0.49
10/16/65	1.62	0.04	0.24	0.26	1.30	0.03	0.50	0.51
06/28/67	1.64	0.06	0.25	0.27	1.31	0.04	0.50	0.52
04/03/70	1.75	0.17	0.24	0.39	1.40	0.13	0.50	0.61

[a]Includes 1.13 km/s to enter and depart Phobos orbit.
[b]Includes 0.29 km/s to enter and depart Phobos orbit.
[c]Minimum ΔV for coplanar transfers.

Table 4 Deep Space Vehicle transfers for 250 km x 1 sol parking orbits with full weighting on DSV ΔV.

	DSV ΔV, km/s					Parking Orbit Orientation,[b] deg.		
Mars Arrival	Total	Difference from ideal[a]	Capture	Reorient	Escape	Periapsis right asc.	Arrive inc.	Depart inc.
12/11/20	5.61	0.34	2.16	0.13	3.33	169.9	164.9	148.8
04/20/23	2.32	0.05	1.12	0.00	1.20	141.9	26.3	26.3
06/23/24	5.01	0.11	3.70	0.02	1.30	119.8	169.9	172.0
08/11/28	2.80	0.59	1.21	0.59	1.01	-64.1	25.2	56.3
10/10/30	2.63	0.34	1.39	0.28	0.96	-13.6	16.9	53.3
01/08/31	4.24	0.11	2.66	0.10	1.48	-81.8	174.5	172.4
10/14/33	5.15	0.30	1.72	0.06	3.37	-82.5	1.2	8.6
06/26/35	5.47	0.26	3.13	0.03	2.31	-127.1	10.8	15.2
05/16/37	4.98	0.07	3.33	0.05	1.60	-125.7	27.2	33.6
06/19/40	2.49	0.41	0.91	0.32	1.27	169.9	47.4	6.7
08/08/42	2.87	0.57	1.02	0.33	1.53	-149.2	28.0	14.4
10/02/43	4.88	0.20	2.89	0.15	1.84	-157.3	154.0	172.7
08/17/46	5.40	0.23	1.94	0.19	3.28	31.1	177.1	152.6
02/17/50	3.71	0.55	2.27	0.38	1.05	101.7	30.0	20.3
03/19/50	4.54	0.14	2.92	0.09	1.53	-15.9	154.6	166.6
12/03/52	4.53	0.08	1.50	0.07	2.95	154.5	159.5	150.2
06/25/56	4.49	0.19	3.07	0.08	1.35	131.1	175.9	174.6
07/05/56	4.92	0.11	3.50	0.00	1.42	119.4	168.9	169.1
08/13/60	2.57	0.63	1.03	0.63	0.91	-55.1	26.8	60.7
11/01/62	3.77	0.16	2.67	0.08	1.02	5.4	31.2	41.7
01/10/63	4.03	0.08	2.65	0.08	1.30	-75.5	173.2	176.8
10/16/65	5.04	0.05	1.66	0.03	3.35	94.5	172.2	168.1
06/28/67	5.32	0.24	3.03	0.03	2.26	-124.8	10.0	14.2
04/03/70	3.77	0.39	1.22	0.30	2.25	-115.8	173.3	147.9

[a]Minimum ΔV for coplanar transfers.
[b]Parking orbit orientation is given in Mars equator and equinox of J2000 frame.

Table 5 Space Exploration Vehicle transfers for 250 km x 1 sol parking orbits with full weighting on DSV ΔV.

	Phobos SEV ΔV, km/s				Deimos SEV ΔV, km/s			
Mars Arrival	Total[a]	Difference from ideal[c]	Leave Parking	Return Parking	Total[b]	Difference from ideal[c]	Leave Parking	Return Parking
12/11/20	3.34	1.76	1.12	1.09	3.03	1.76	1.38	1.35
04/20/23	1.81	0.23	0.34	0.34	1.44	0.17	0.57	0.57
06/23/24	3.39	1.80	1.13	1.13	3.07	1.80	1.39	1.39
08/11/28	2.03	0.45	0.33	0.57	1.65	0.37	0.57	0.79
10/10/30	1.96	0.37	0.28	0.55	1.58	0.31	0.53	0.76
01/08/31	3.39	1.81	1.13	1.13	3.08	1.81	1.39	1.39
10/14/33	1.60	0.01	0.23	0.24	1.28	0.01	0.49	0.50
06/26/35	1.65	0.07	0.25	0.27	1.32	0.04	0.51	0.52
05/16/37	1.87	0.28	0.35	0.39	1.49	0.22	0.58	0.62
06/19/40	1.87	0.28	0.50	0.24	1.51	0.23	0.72	0.50
08/08/42	1.75	0.16	0.35	0.27	1.39	0.12	0.58	0.52
10/02/43	3.36	1.78	1.11	1.13	3.05	1.78	1.36	1.39
08/17/46	3.36	1.78	1.13	1.10	3.05	1.78	1.40	1.36
02/17/50	1.79	0.21	0.37	0.30	1.43	0.16	0.60	0.54
03/19/50	3.36	1.78	1.11	1.13	3.04	1.77	1.37	1.39
12/03/52	3.34	1.76	1.12	1.10	3.02	1.75	1.38	1.35
06/25/56	3.39	1.81	1.13	1.13	3.08	1.81	1.39	1.39
07/05/56	3.38	1.80	1.13	1.13	3.07	1.80	1.39	1.39
08/13/60	2.08	0.49	0.34	0.60	1.69	0.42	0.58	0.82
11/01/62	1.96	0.38	0.37	0.46	1.57	0.30	0.60	0.67
01/10/63	3.39	1.81	1.13	1.13	3.08	1.81	1.39	1.39
10/16/65	3.39	1.80	1.13	1.13	3.07	1.80	1.39	1.39
06/28/67	1.64	0.06	0.25	0.27	1.31	0.04	0.50	0.52
04/03/70	3.35	1.77	1.13	1.09	3.03	1.76	1.39	1.35

[a]Includes 1.13 km/s to enter and depart Phobos orbit.
[b]Includes 0.29 km/s to enter and depart Phobos orbit.
[c]Minimum ΔV for coplanar transfers.

Table 6 Deep Space Vehicle transfers for 250 km x 3 sol parking orbits with full weighting on DSV ΔV.

	DSV ΔV, km/s					Parking Orbit Orientation,[b] deg.		
Mars Arrival	Total	Difference from ideal[a]	Capture	Reorient	Escape	Periapsis right asc.	Arrive inc.	Depart inc.
12/11/20	5.34	0.30	2.02	0.07	3.25	173.0	165.6	147.8
04/20/23	2.10	0.06	1.01	0.00	1.08	141.9	26.3	26.3
06/23/24	4.79	0.12	3.59	0.01	1.19	119.8	169.9	172.0
08/11/28	2.26	0.28	1.09	0.28	0.89	-65.6	24.8	57.2
10/10/30	2.24	0.18	1.24	0.15	0.85	-19.1	15.6	57.1
01/08/31	3.95	0.06	2.54	0.05	1.37	-81.7	174.5	172.4
10/14/33	4.82	0.19	1.56	0.03	3.23	87.4	178.8	171.5
06/26/35	5.09	0.11	2.95	0.02	2.12	57.2	169.2	164.7
05/16/37	4.73	0.05	3.22	0.03	1.48	-127.4	27.1	33.9
06/19/40	2.10	0.25	0.82	0.16	1.12	174.5	51.2	6.1
08/08/42	2.52	0.45	0.95	0.16	1.42	-147.7	29.0	14.0
10/02/43	4.58	0.13	2.78	0.07	1.72	-158.7	153.8	172.8
08/17/46	5.08	0.14	1.82	0.09	3.16	31.2	177.1	152.6
02/17/50	3.30	0.38	2.17	0.18	0.95	102.2	30.2	20.1
03/19/50	4.27	0.10	2.81	0.04	1.42	-16.4	154.6	166.6
12/03/52	4.26	0.04	1.38	0.04	2.83	156.1	159.8	150.0
06/25/56	4.23	0.16	2.96	0.04	1.24	131.4	175.9	174.6
07/05/56	4.71	0.13	3.39	0.00	1.31	119.4	168.9	169.1
08/13/60	2.00	0.30	0.91	0.30	0.79	-56.8	26.2	61.8
11/01/62	3.49	0.11	2.52	0.05	0.91	0.5	29.7	44.5
01/10/63	3.75	0.04	2.53	0.04	1.18	-75.4	173.2	176.8
10/16/65	4.80	0.04	1.55	0.02	3.24	94.8	172.3	168.1
06/28/67	4.98	0.14	2.87	0.02	2.10	59.4	170.1	165.8
04/03/70	3.39	0.24	1.11	0.14	2.14	-116.0	173.3	147.9

[a]Minimum ΔV for coplanar transfers.
[b]Parking orbit orientation is given in Mars equator and equinox of J2000 frame.

Table 7 Space Exploration Vehicle transfers for 250 km x 3 sol parking orbits with full weighting on DSV ΔV.

	Phobos SEV ΔV, km/s				Phobos SEV ΔV, km/s			
Mars Arrival	Total[a]	Difference from ideal[c]	Leave Parking	Return Parking	Total[b]	Difference from ideal[c]	Leave Parking	Return Parking
12/11/20	2.51	0.83	0.54	0.52	2.03	0.82	0.69	0.67
04/20/23	1.79	0.10	0.17	0.17	1.28	0.07	0.31	0.31
06/23/24	2.53	0.85	0.54	0.54	2.06	0.85	0.70	0.70
08/11/28	1.89	0.21	0.16	0.28	1.38	0.17	0.31	0.41
10/10/30	1.87	0.18	0.14	0.28	1.36	0.15	0.29	0.41
01/08/31	2.53	0.85	0.54	0.54	2.06	0.85	0.70	0.70
10/14/33	2.53	0.85	0.54	0.54	2.06	0.85	0.70	0.70
06/26/35	2.53	0.84	0.54	0.54	2.05	0.84	0.69	0.69
05/16/37	1.81	0.13	0.17	0.19	1.31	0.10	0.31	0.33
06/19/40	1.83	0.14	0.26	0.12	1.33	0.12	0.39	0.27
08/08/42	1.76	0.08	0.18	0.13	1.27	0.05	0.32	0.28
10/02/43	2.52	0.84	0.53	0.54	2.04	0.83	0.68	0.70
08/17/46	2.52	0.83	0.54	0.53	2.04	0.83	0.70	0.68
02/17/50	1.78	0.10	0.18	0.15	1.28	0.07	0.32	0.29
03/19/50	2.52	0.83	0.53	0.54	2.04	0.83	0.68	0.69
12/03/52	2.51	0.82	0.53	0.52	2.03	0.82	0.69	0.68
06/25/56	2.53	0.85	0.54	0.54	2.06	0.85	0.70	0.70
07/05/56	2.53	0.84	0.54	0.54	2.05	0.84	0.69	0.69
08/13/60	1.91	0.23	0.17	0.30	1.40	0.19	0.31	0.43
11/01/62	1.86	0.18	0.18	0.23	1.35	0.14	0.32	0.37
01/10/63	2.53	0.85	0.54	0.54	2.06	0.85	0.70	0.70
10/16/65	2.53	0.85	0.54	0.54	2.06	0.84	0.70	0.69
06/28/67	2.53	0.84	0.54	0.54	2.05	0.84	0.70	0.69
04/03/70	2.51	0.83	0.54	0.52	2.04	0.83	0.70	0.67

[a]Includes 1.45 km/s to enter and depart Phobos orbit.
[b]Includes 0.67 km/s to enter and depart Phobos orbit.
[c]Minimum ΔV for coplanar transfers.

Low Mars Orbit

The combination of reorientation maneuvers at apoapsis with off-periapsis arrival and departure is also applicable to targets in low-Mars orbit. Such a scenario could occur if a Mars surface sample was launched to low orbit and part of the crew's mission was to retrieve the sample during their orbital stay. For this type of mission, the orbiting sample container could be in a plane that is inconvenient to reach from the arrival and departure interplanetary trajectories. In Figure 6, the DSV arrives in a plane that permits a near-periapsis arrival maneuver, then rotates to the plane of the target orbit, then rotates again into a plane that permits a near-periapsis departure maneuver.

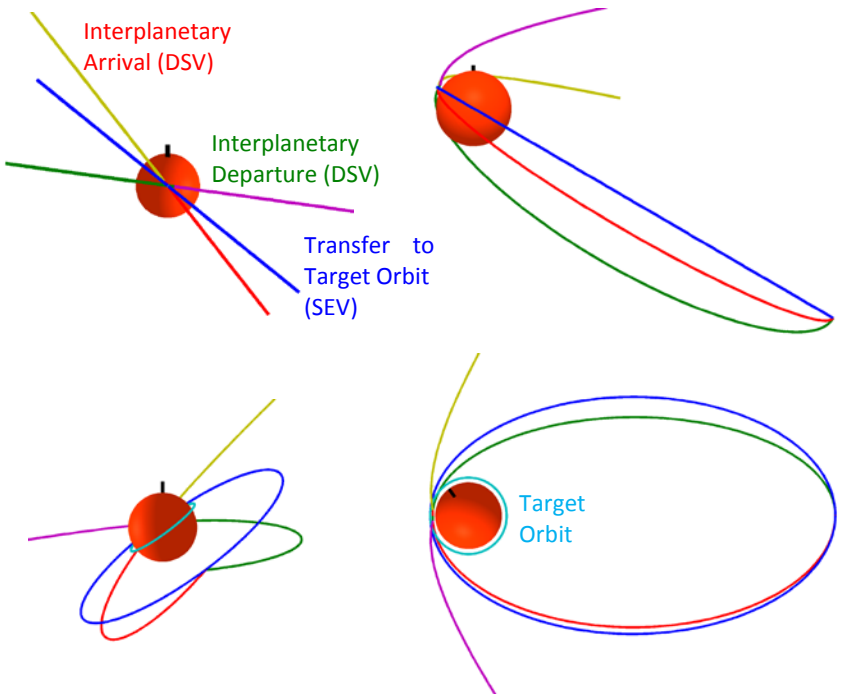

Figure 6 Transfer from arrival interplanetary trajectory to a 500 km, 45 deg orbit, then to departure.

The ΔV for the SEV to achieve a range of target orbits can vary significantly as indicated by Figure 7. The ΔV ranges from 2.3–3.2 km/s depending on the orbit orientation, while the absolute minimum ΔV (from an energy standpoint) is 2.3 km/s. Thus the additional ΔV to account for the arrival and departure orbits is 0–0.9 km/s. The ΔV for the (typically much larger) DSV optimizes to approximately 4.9 km/s regardless of target orbit orientation. The minimum ΔV from an energy standpoint (tangential periapsis burns) is 4.6 km/s, thus the orbit transfer method has minimized additional ΔV to the DSV and places more of the ΔV burden on the smaller SEV.

In all cases the orbit transfer design satisfies the objectives of connecting the arrival V_∞ to the departure V_∞ with the DSV, while connecting the arrival and departure orbits to the target orbit via the SEV. There can be additional ΔV for the SEV to transfer to the target orbit due to the precession of low-altitude orbits. For example, the oblateness of Mars (J_2) causes a 15 degree inclination orbit to precess at around 9 deg/day. Thus the parking and target orbits become 90 degrees out of phase after 10 days, which adds 250 m/s for one-way transfers to an orbit with 15 deg inclination. This penalty is exacerbated at higher inclination orbits, where a 30 deg inclination orbit requires around 1 km/s additional ΔV for out-or-phase transfers as shown in Figure 8. The mitiga-

tion strategy is to either wait until the orbits are 180 deg out of phase (where an apo-twist maneuver is available), or wait an entire precession cycle. While the latter requires less ΔV the additional wait time may be unacceptable for time-constrained missions.

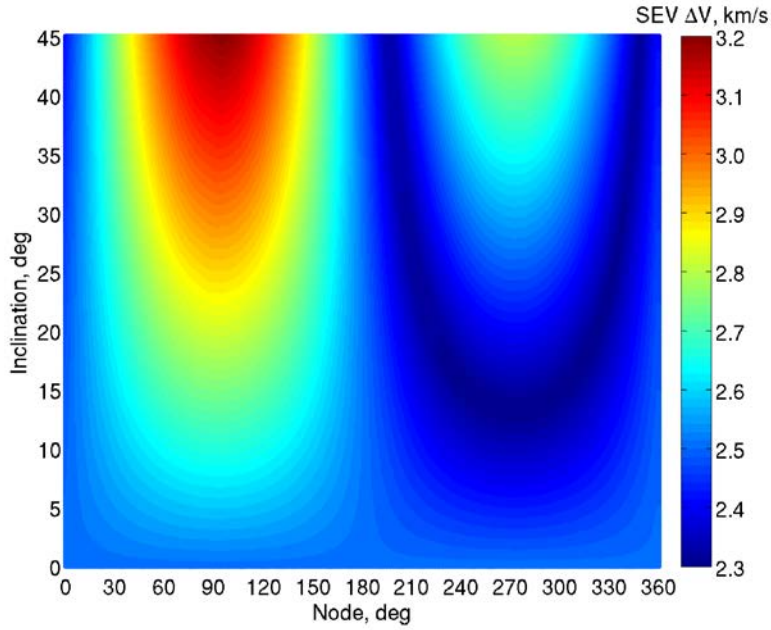

Figure 7 Transfer cost of the SEV to reach potential target orbits at 500 km altitude.

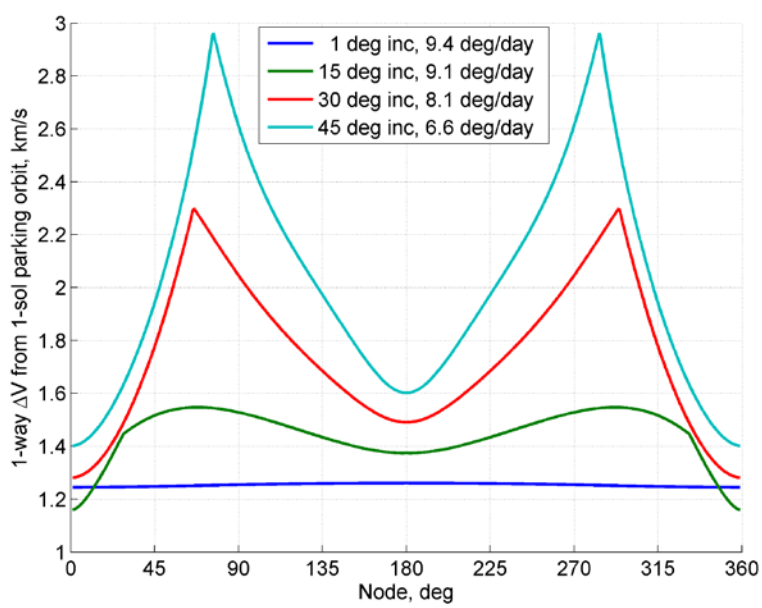

Figure 8 The orbit transfer ΔV varies as a 500-km altitude target orbit precesses.

CONCLUSIONS

The design of efficient parking orbits for round-trip missions to Mars is constrained by the relative orientation of the arrival and departure interplanetary trajectories. This design problem becomes even more constrained when there is also a target orbit at Mars. In general the interplanetary trajectories, parking orbit, and target orbit will not share the same orientation. An effective method to rotate Mars orbits along two axes is to combine off-periapsis arrival and departure maneuvers with twists along the line of apsides at apoapsis. This method permits the use of a less massive Space Exploration Vehicle to rendezvous and return from a low-energy target orbit while a larger Deep Space Vehicle remains in a high-energy parking orbit. The mass-optimal parking orbit design can sometimes be retrograde, but still offers significant mass savings over transporting the Deep Space Vehicle all the way to the target orbit. If the target orbit is inclined, then the choice of parking orbit also depends on the node of the target orbit. Because this node precesses, the optimal transfer becomes time-dependent, and transfers to and from the target orbit may have to delay until the nodes realign. Nevertheless, an efficient combination of apsidal maneuvers provides a specialized technique to match low ΔV Deep Space Vehicle trajectories to any desired target orbit at Mars.

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REFERENCES

[1] Luidens, R. and Miller, B., "Efficient Planetary Parking Orbits with Examples for Mars," NASA TN D-3220, January 1966.

[2] Hoffman, S. J., "Mass Performance Implications of Mars Parking Orbit Selection for Piloted Missions," Paper AAS 91-440, Astrodynamics Specialist Conference, Durango, CO, August 19–22, 1991.

[3] Desai, P., Braun, R., and Powell, R., "Aspects of Parking Orbit Selection in a Manned Mars Mission," NASA TP-3256, December 1992.

[4] Cornick, D. E. and Seversike, L. K., "Optimum Parking Orbit Orientation for a Three-Dimensional Capture-Escape Mission," *Journal of Spacecraft and Rockets*, Vol. 7, No. 7, 1970, pp. 808–813.

[5] Cupples, M. L., and Nordwall, J. A., "Optimal Parking Orbits for Manned Mars Missions," American Astronautical Society, Paper 93-149, Feb. 1993.

[6] Landau, D. F., Longuski, J. M., and Penzo, P. A., "Method for Parking Orbit Reorientation for Human Missions to Mars," *Journal of Spacecraft and Rockets*, Vol. 42, No. 3, May–June 2005, pp. 517–522.

[7] Mulqueen, J. "Manned Mars Mission Transfer from Mars Parking Orbit to Phobos or Deimos," Manned Mars Missions, Working Group Papers, Vol. 1, Section 1–4, May 1, 1986, pp. 154–161.

[8] Foster, Cyrus, " Delta-V Budgets for Robotic and Human Exploration of Phobos and Deimos," Abstract 11-018, 2nd International Conference on the Exploration of Phobos and Deimos, Moffett Field, CA, March 14–16, 2011.