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Effects of a Venus Swingby Periapsis Burn During an Earth-Mars Trajectory[1]

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Abstract

Interplanetary missions were analyzed that utilize the gravity-assist orbital transfer technique to increase mission capabilities. Ordinarily, this swingby maneuver provides a non-propulsive change in the spacecraft heliocentric energy that can reduce the amount of propellant needed to complete an interplanetary mission. For certain planetary orientations, incorporating a single propulsive maneuver at the periapsis of the swingby trajectory can decrease the mission propellant requirement. This decrease results in a reduced initial vehicle mass in low-Earth orbit (from one- to 28- percent lower than for the unpowered swingby maneuvers in one-third of the cases investigated). This study analyzed the feasibility of using a powered swingby to reduce the initial vehicle size for an excursion class Mars mission during the 2010-2025 time frame.

Introduction

In the 1960's, NASA examined the feasibility of a manned mission to Mars. Recently, interest in this mission has been renewed [1, 2], and interplanetary analyses have been conducted to update the original data base and to include new mission concepts. Since one of the constraints on initial manned missions is a low total trip time, interest has focused on the use of a Venus gravity assist during one leg of the transfer to reduce trip time as well as total propellant usage [3]. Ordinarily, this planetary swingby maneuver provides a non-propulsive change in the spacecraft's heliocentric energy which can reduce the amount of propellant needed to complete an interplanetary mission. By incorporating a propulsive maneuver at the periapsis of the planetary swingby trajectory, the mission's overall propellant requirement, and thus the initial vehicle mass in low-Earth orbit (LEO), can be reduced. This study analyzed the feasibility of using a powered

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Venus swingby to minimize the initial vehicle size for an excursion class manned Mars mission during the 2010-2025 time frame.

The excursion class mission has a low round-trip time with a short stay time at Mars (on the order of 30-90 days) [3]. The missions examined in this study range from 1 to 2 years in duration with an outbound swingby of Venus and a 60-day stopover at Mars. A characteristic of the excursion class mission trajectory is that one leg is a slower, more efficient transfer, while the other is faster, but less efficient (i.e., efficient in terms of propellant usage). In many cases, a gravity-assist maneuver is used to improve the efficiency of the faster leg. That is, an unpowered swingby can be used to increase the efficiency of the outbound (Earth-to-Mars) leg by increasing the spacecraft's heliocentric velocity and thus its energy.

Other papers have addressed the powered swingby option [4–6]. Gobetz investigated single impulse hyperbolic-to-hyperbolic orbital transfers [4]. He noted that (1) mission flexibility increases by including a propulsive maneuver during the swingby, (2) a transfer at periapsis is close to the optimum transfer point, and (3) the hyperbolic transfer can be analyzed as a two-dimensional problem in the swingby planet's frame of reference. Walton, Marchal, and Culp also studied hyperbolic-to-hyperbolic orbital transfers, but their analysis included more than one impulse during the swingby [5]. Their study classified the types of transfers for the minimum velocity increment (ΔV) maneuver for given hyperbolic excess velocity vectors. Like Gobetz, the authors noted that the powered swingby problem is planar in the planet's frame of reference; in addition, they determined that the single impulse transfer was the best for a majority of the transfers. Hollister and Prussing analyzed the advantages of a powered Venus swingby in comparison with direct and unpowered Venus swingby trajectories to Mars [6]. They developed a method for determining the availability of a Venus swingby based on Earth-Venus-Mars angular relationships. Also, Hollister and Prussing concluded that the savings (in terms of reduced mission ΔV) obtained using the powered swingby over the unpowered swingby option is small.

Swingby Mechanics

The gravity-assist orbital maneuvering technique changes the spacecraft's interplanetary trajectory by altering its heliocentric velocity as it closely flies by a planet. The mechanics of a typical unpowered outbound swingby is shown in Fig. 1. In a two-body analysis, the planet's gravity is the only acceleration acting on the vehicle during the swingby. Upon entering the swingby planet's sphere of influence (SOI), the spacecraft's heliocentric velocity ($\mathbf{V}_{s/c_1}$) may be separated into two components—the heliocentric velocity of the planet ($\mathbf{V}_p$) and the spacecraft's velocity relative to the planet ($\mathbf{V}_{rel_1}$). In order to satisfy conservation of energy, the magnitude of the velocity relative to the planet upon exiting the SOI must equal that entering the SOI

$$V_{rel_1} = V_{rel_2}\,.$$

During the hyperbolic pass, the relative velocity vector of the vehicle is rotated through an angle (K) referred to as the bend angle. The magnitude of the relative velocity vector at the SOI and the closest approach point (periapsis distance,

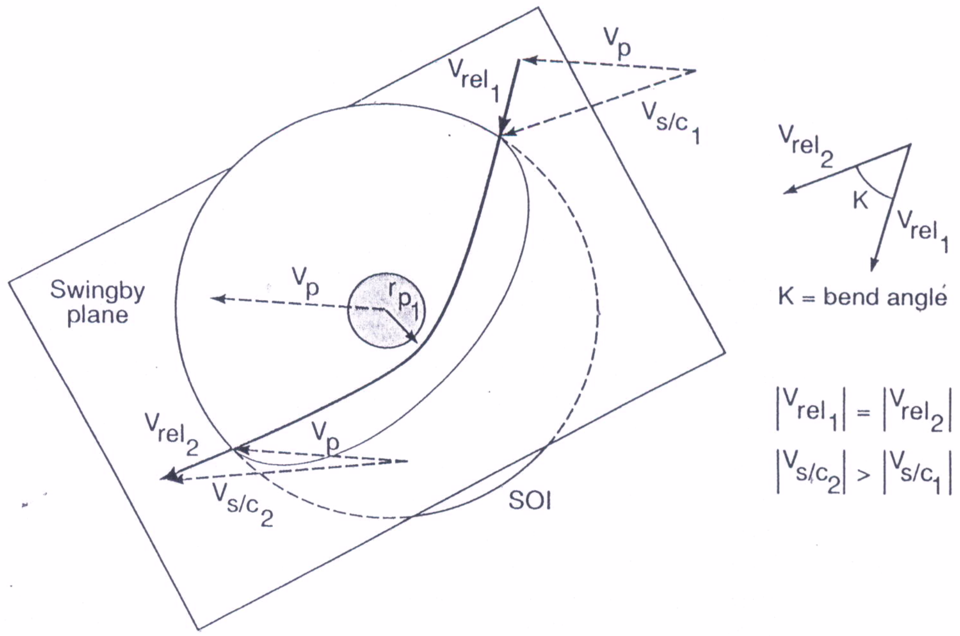

FIG. 1. Unpowered Swingby.

r_{p_1}) during the swingby dictate the size of the bend angle for a given planet. At the exit of the SOI, the relative and planet velocity vectors are recombined. For this outbound swingby, the spacecraft's heliocentric velocity ($\mathbf{V}_{s/c_2}$) rotates and increases in magnitude.

Adding a propulsive maneuver during the swingby will affect this scenario. When the spacecraft reaches periapsis of the planetocentric hyperbolic orbit, a burn will cause the vehicle to transfer to a different hyperbolic orbit. This new orbit not only changes the amount that the relative velocity vector rotates but can also alter the magnitude of that vector. This single, periapsis burn can allow a more efficient orientation of the relative velocity vector to attain a desired heliocentric velocity vector. Thus, a propulsive maneuver provides the trajectory designer with greater control over the spacecraft heliocentric trajectory.

The periapsis burn can be in a direct or retrograde direction, as shown in Figs. 2 and 3, respectively. The direct burn occurs in a direction to increase the relative velocity; whereas a retrograde burn reduces the relative velocity at the SOI exit. An important parameter shown in both Figs. 2 and 3 is the angle (α) between the periapsis velocity vector, $\mathbf{V}_1$, (which is tangent to the incoming hyperbolic orbit at periapsis) and the ΔV vector. Figure 2 shows a positive α, direct burn case, while Fig. 3 illustrates a negative α, retrograde burn scenario. Note that, both the direct and retrograde burn can have either a positive or negative α burn angle.

In Fig. 2, path one would be followed for an unpowered swingby; path two is the hyperbola transferred onto after a direct, positive α burn at the periapsis of

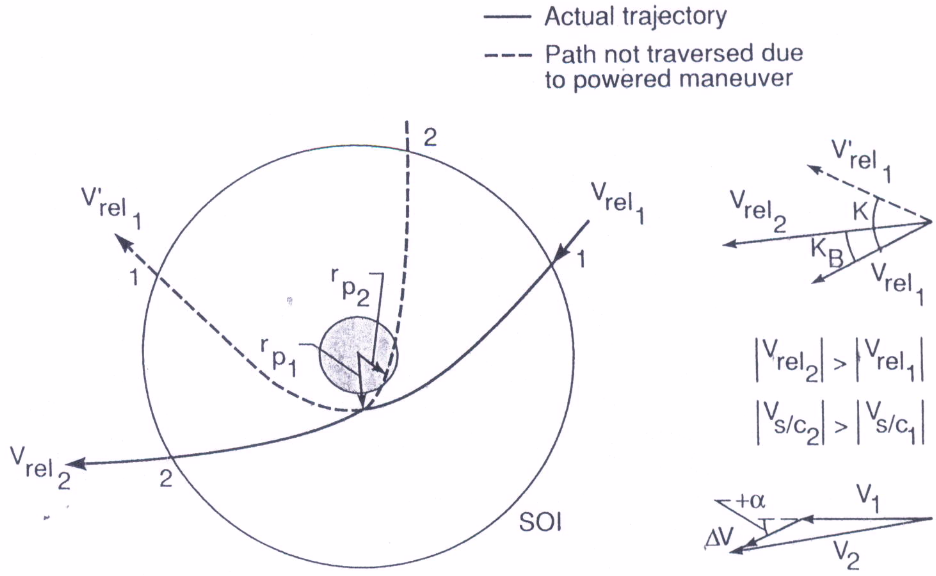

FIG. 2. Effect of Direct, Positive α Propulsive Maneuver.

path one (r_{p_1}). Because of the positive α, the bend angle of the powered swingby, K_B, is less than that for the unpowered swingby. Note that for a positive α burn (either direct or retrograde burn case), the periapsis of the actual trajectory will

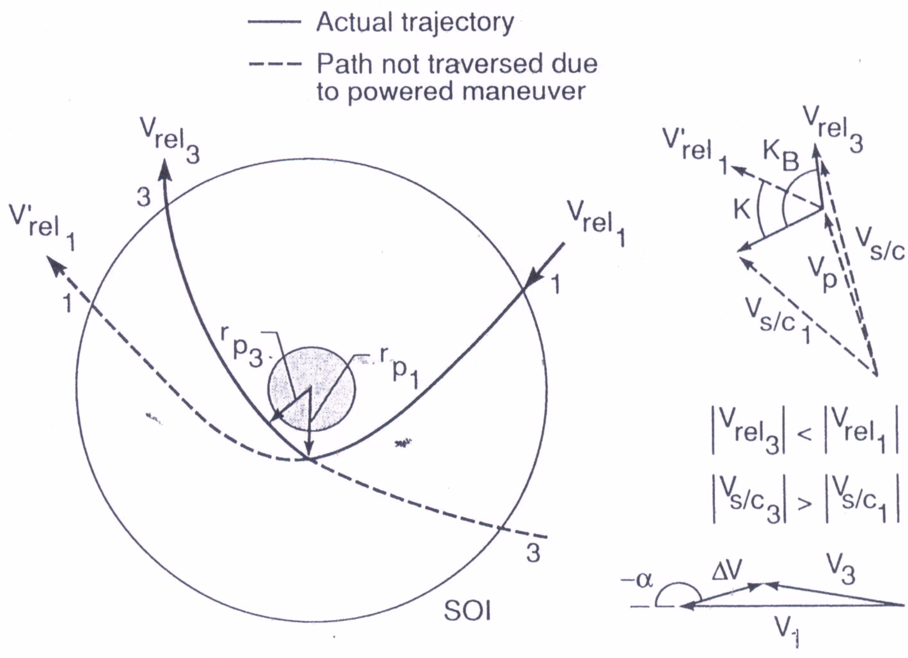

FIG. 3. Effect of Retrograde, Negative α Propulsive Maneuver.

always be the position at which the burn was applied, r_{p_1} in Fig. 2. However, the apparent periapsis of path two, r_{p_2}, can be forced below the actual surface of the planet.

The significance of this fact can be shown using a hypothetical scenario. Suppose path two could properly rotate (bend) the relative velocity vector (to provide the desired heliocentric velocity) via an unpowered swingby. Since the periapsis of this swingby trajectory is below the planet's surface, this path can not be used. Thus, a physical limitation exists (the planet's surface) on the closest approach point. However, a powered swingby could transfer the spacecraft onto the proper exit orbit without ever passing through the actual periapsis of the exit orbit. Therefore, the powered swingby can be used to alleviate the spacecraft's closest approach point restriction at the penalty of increased propellant mass.

A retrograde burn, which reduces the spacecraft's relative velocity, may be necessary for a trajectory that requires an increase in the heliocentric velocity. Since the main purpose of the powered swingby is the reorientation of the relative velocity vector to achieve a desired heliocentric velocity vector at the SOI exit, regardless of the change in its magnitude, a retrograde maneuver is conceivable. In Fig. 3, path one is again the hyperbola which would be travelled if the swingby was unpowered; path three is the trajectory followed after a retrograde, negative α burn. In this case, the magnitude of the relative velocity has been reduced, and the powered bend angle is greater than the unpowered bend angle. Also, note that the periapsis of the swingby is not encountered until after the burn, r_{p_3}; thus, there is a physical limitation for a negative α burn maneuver for either retrograde or direct burns.

Approach

Three major assumptions were made in this analysis. First, only two-body (unperturbed) motion was modelled between the spacecraft and the Sun. That is, for the interplanetary trajectory, only motion between planetary SOIs was simulated. Second, the entire swingby maneuver, including the periapsis burn, was considered instantaneous during the interplanetary analysis. Third, all velocity changes in the mission were considered impulsive.

The objective of this investigation was to minimize the initial LEO weight for an excursion class, manned, all propulsive Mars mission that uses an outbound Venus swingby. Table 1 lists the characteristics of the baseline vehicle and mission used for this study. The original outbound (Earth-to-Mars) scenario involved (1) a propulsively attained velocity increment (ΔV) for departure from Earth orbit, (2) an unpowered Venus swingby to increase the spacecraft's heliocentric velocity, and (3) another propulsive maneuver to place the spacecraft into orbit at Mars (Fig. 4). The second phase of this trajectory was changed to include a propulsive maneuver during the swingby; also, additional tankage and propellant were added to the baseline vehicle to accommodate the Venus burn. The efficient return leg (4 to 5 in Fig. 4), which included a propulsively attained Earth arrival ΔV, was not modified. All three legs (Earth-Venus, Venus-Mars, and Mars-Earth) were modelled using a patched conic approach.

TABLE 1. Baseline Vehicle and Mission Characteristics

Vehicle	
Mars drop off weight, lb	166,000
Earth return weight, lb	135,000
Structural weight, lb	10% of propellant weight
Engine specific impulse(I_{sp}), sec	480
Mission	
Periapsis altitude, km (for all parking orbits)	500
Parking orbit eccentricities for	
initial Earth orbit	0.000
Mars parking orbit	0.807
final Earth orbit	0.838

For this initial evaluation of the hypothesis that a powered swingby could be used to decrease the initial LEO weight, 22 unpowered swingby cases were simulated with the Swingby Stopover Optimization Program (SWISTO) [7]. (See Table 2.) These unpowered swingby missions were the minimum initial LEO weight cases for each particular Earth departure date. In this investigation, the vehicle efficiency boundary was defined as an initial LEO weight of less than 6.75 million pounds; that is, all missions with initial vehicle weights less than 6.75 million pounds were efficient, all others were inefficient. As seen in Table 2, a wide range of unpowered swingby missions were examined. To bracket this study, initial LEO weights ranged from extremely efficient (less than 3.5 million

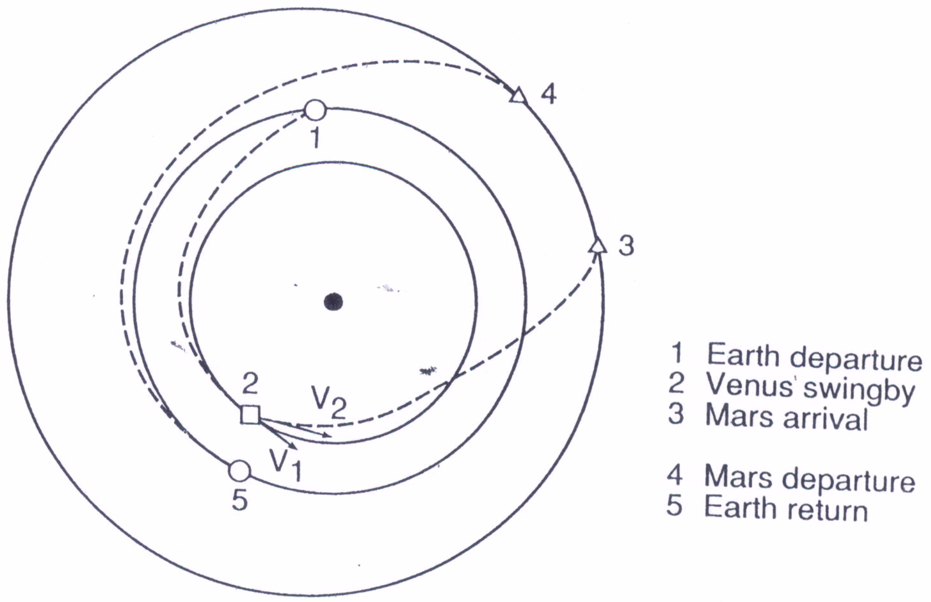

FIG. 4. Earth-Mars Outbound Swingby Mission.

TABLE 2. Unpowered Swingby Cases Studied

Earth Departure		Venus Swingby		Mars Arrival		Mars Departure		Earth Arrival		Initial LEO Weight
Date	V_∞(km/s)	Date	V_∞(km/s)	Date	V_∞(km/s)	Date	V_∞(km/s)	Date	V_∞(km/s)	(lb × 10^6)
11/9/2010	6.836	5/11/2011	12.116	9/23/2011	6.200	11/22/2011	5.622	6/26/2012	4.246	4.43
11/20/2010	5.394	5/7/2011	10.759	9/28/2011	5.751	11/27/2011	5.901	6/29/2012	4.380	3.46
1/20/2011	10.661	5/16/2011	13.990	9/28/2011	6.244	11/27/2011	5.901	6/29/2012	4.380	10.36
1/25/2011	11.446	5/18/2011	14.624	9/28/2011	6/363	11/27/2011	5.901	6/29/2012	4.380	13.35
3/1/2017	7.920	9/19/2017	13.318	2/10/2018	8.163	4/11/2018	2.688	10/23/2018	3.261	5.90
3/6/2017	5.773	9/13/2017	11.138	2/16/2018	7.468	4/17/2018	2.804	10/24/2018	3.300	3.60
6/5/2017	11.140	9/27/2017	14.295	4/23/2018	6.240	6/12/2018	4.778	11/29/2018	4.959	10.64
6/10/2017	12.253	9/27/2017	15.103	4/3/2018	6.366	5/21/2018	3.894	11/14/2018	4.124	13.70
8/15/2021	5.414	3/24/2022	6.128	8/23/2022	6.039	10/22/2022	5.179	7/21/2023	7.793	4.49
9/29/2021	8.651	12/20/2021	16.294	6/28/2022	8.157	8/27/2022	4.210	5/5/2023	3.805	7.89
10/4/2021	8.313	12/23/2021	15.965	7/3/2022	7.997	9/1/2022	4.369	5/10/2023	4.009	7.29
11/25/2021	7.423	1/15/2022	12.742	7/18/2022	7.217	9/16/2022	6.102	3/27/2023	3.075	6.10
12/25/2021	13.461	1/31/2022	10.664	7/30/2022	6.805	9/28/2022	6.828	4/11/2023	3.771	37.14
8/21/2023	6.359	2/19/2024	12.442	6/18/2024	7.191	8/17/2024	3.587	4/14/2025	3.453	3.92
8/26/2023	6.279	2/22/2024	12.460	7/8/2024	6.632	9/6/2024	4.052	4/14/2025	3.408	3.57
9/15/2023	5.102	2/17/2024	11.141	7/4/2024	6.372	9/2/2024	3.725	5/12/2025	2.831	2.74
9/20/2023	5.339	2/17/2024	11.200	7/3/2024	6.404	9/1/2024	3.685	5/14/2025	2.827	2.83
9/25/2023	5.643	2/18/2024	11.349	7/7/2024	6.374	9/5/2024	3.866	5/12/2025	2.818	2.97
9/30/2023	6.063	2/19/2024	11.538	7/6/2024	6.430	9/4/2024	3.814	5/12/2025	2.822	3.16
10/21/2023	8.301	2/24/2024	12.868	7/13/2024	6.717	9/11/2024	4.121	5/8/2025	2.899	5.02
11/5/2023	10.785	2/26/2024	14.489	7/4/2024	7.331	8/27/2024	3.753	3/30/2025	4.392	10.58
11/10/2023	11.727	2/27/2024	15.162	6/23/2024	7.663	8/22/2024	3.659	3/25/2025	4.788	15.45

pounds) to extremely inefficient (over 35 million pounds), but most of the missions studied were under 11 million pounds.

These 22 cases were then altered to have powered Venus swingbys, and the initial vehicle weights in LEO were compared. The baseline (unpowered) Earth departure and Mars arrival dates, and therefore their positions, were held constant while the swingby date was modified. By moving the swingby date, the required heliocentric velocity vectors at Earth, Mars, and Venus were changed, thus varying the velocity increment required at these planets. From the ΔV information at Earth and Mars, candidate powered swingby dates were chosen based on initial LEO weight calculations before the ΔV at Venus was determined. That is, if the initial LEO weight (for the powered swingby) was greater than the baseline (unpowered swingby) initial weight prior to the calculation of the required ΔV at Venus, then the unpowered swingby for the Earth departure date could not be improved upon via a powered swingby. However, for cases in which the initial LEO weight (prior to determining the ΔV at Venus) was less than the baseline weight, the Program to Optimize Simulated Trajectories [8] (POST) was used to minimize the required ΔV at the periapsis of the swingby (since POST can optimize ΔV while constraining several parameters, such as periapsis altitude). From this ΔV information, the actual weight in LEO for that swingby date was determined and compared to the baseline. The periapsis burn was allowed to occur in any direction, as long as the relative velocity vector at the exit of the SOI gave the proper outgoing heliocentric velocity vector. The swingby date which resulted in the lowest initial vehicle weight in LEO was chosen for each Earth-departure/Mars-arrival date combination tested.

Results

For eight of the 22 cases simulated, the powered swingby on a different flyby date resulted in a lower initial LEO weight than the unpowered case. Table 3 summarizes the reduced weight cases. The weight reductions for these eight cases ranged from 1 to 28 percent. The 17-percent case (12/25/2021 Earth departure) was an extremely inefficient unpowered swingby case, and any improvement in the ΔV at Mars and Earth greatly lessened the initial LEO weight. Most of the remaining cases were reduced between one and four percent. The last case in Table 3 was the unpowered swingby with the lowest initial LEO weight to be improved upon.

When the interplanetary trajectories of the seven improved cases with reasonable initial LEO weights were compared, five were noted as having a similarity in their transfer geometry. (See Fig. 5.) The Earth-Venus transfer angle was approximately 300 degrees, and the Venus-Mars angle was about 100 degrees. These cases also had a similar relationship in their transfer time, Earth-Venus around 190 days and Venus-Mars around 135 days. In each of these cases, the swingby was moved to an earlier date for the powered flyby. By examining the trajectory associated with one case, the reason for the earlier swingby date becomes more obvious.

For the 3/1/2017 Earth departure unpowered swingby trajectory (Fig. 6), the angle between the spacecraft's and Earth's velocities at departure forces the

TABLE 3. Reduced Weight Cases

	Earth Departure			Venus Swingby				Mars Arrival			Initial LEO Weight	
Swingby Mode	Date	ΔV (km/s)	V_∞ (km/s)	Date	ΔV (km/s)	$V_{\infty in}$ (km/s)	$V_{\infty out}$ (km/s)	Date	ΔV (km/s)	V_∞ (km/s)	(lb × 10^6)	Reduction* (%)
U**	11/9/2010	5.140	6.836	5/11/2011	0.000	12.116	12.116	9/23/2011	3.309	6.200	4.429	—
P		4.739	6.055	5/6/2011	0.528	11.313	10.657		3.158	6.010	4.297	3.0
U	3/1/2017	5.753	7.920	9/19/2017	0.000	13.990	13.990	2/10/2018	4.947	8.163	5.901	—
P		4.038	4.453	8/31/2017	1.006	9.408	7.922		4.697	7.873	4.262	27.8
U	3/6/2017	4.604	5.773	9/13/2017	0.000	13.318	13.318	2/16/2018	4.352	7.468	3.600	—
P		4.323	5.152	9/9/2017	0.352	10.438	9.972		4.300	7.406	3.564	1.0
U	9/29/2021	6.198	8.651	12/20/2021	0.000	14.295	14.295	6/28/2022	4.942	8.157	7.890	—
P		5.745	7.907	12/24/2021	0.593	15.046	15.727		4.872	8.077	7.710	2.3
U	10/4/2021	5.989	8.313	12/23/2021	0.000	6.128	6.128	7/3/2022	4.804	7.997	7.289	—
P		5.529	7.538	12/27/2021	0.618	14.651	15.362		4.706	7.884	7.119	2.3
U	12/25/2021	9.624	13.461	1/31/2022	0.000	10.664	10.664	7/30/2022	3.798	6.805	37.14	—
P		8.499	11.986	2/9/2022	1.612	7.793	9.957		4.063	7.124	30.70	17.4
U	8/21/2023	4.891	6.359	2/19/2024	0.000	15.965	15.965	6/18/2024	4.119	7.191	3.921	—
P		4.479	5.504	1/14/2024	0.662	11.553	10.730		3.844	6.860	3.786	3.4
U	8/26/2023	4.850	6.297	2/22/2024	0.000	12.442	12.442	7/8/2024	3.657	6.632	3.567	—
P		4.447	5.434	2/16/2024	0.683	11.583	10.740		3.330	6.227	3.429	3.9

*Compared with unpowered swingby mode
**U = unpowered; P = powered

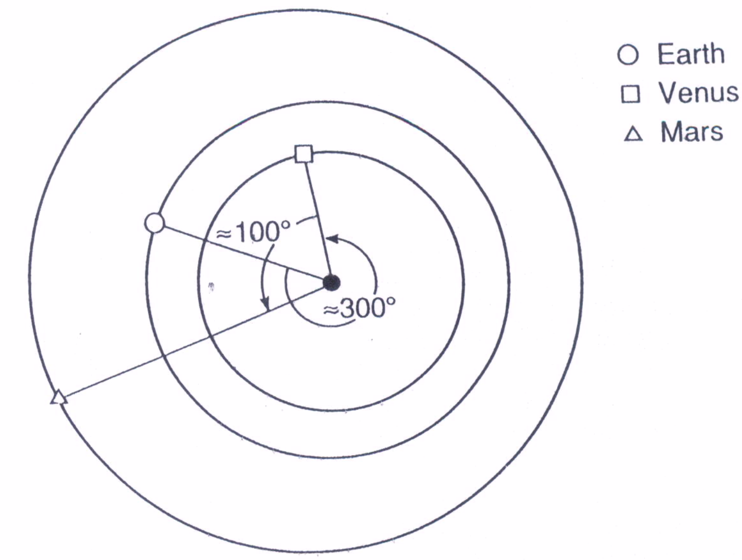

FIG. 5. Earth-Mars Outbound Swingby Transfer Geometry.

spacecraft's velocity relative to Earth to be sizable. However, for the powered case (Fig. 7), the departure velocity angle is greatly reduced, causing the relative velocity magnitude to decrease. Although not as noticeable in these figures, this velocity phenomenon is occurring at Mars arrival as well. Therefore, since the spacecraft's ΔV required at a planet is directly related to its relative velocity at

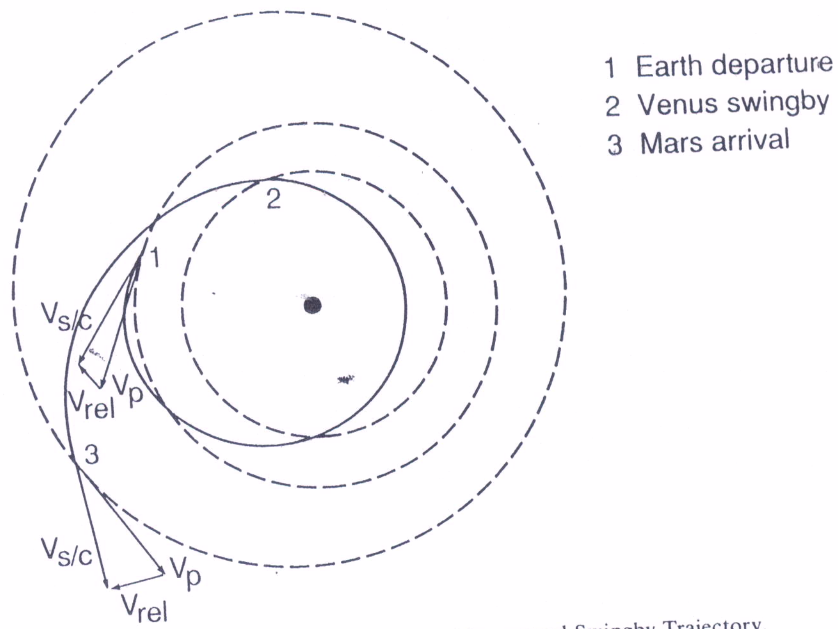

FIG. 6. 3/1/2017 Earth Departure Unpowered Swingby Trajectory.

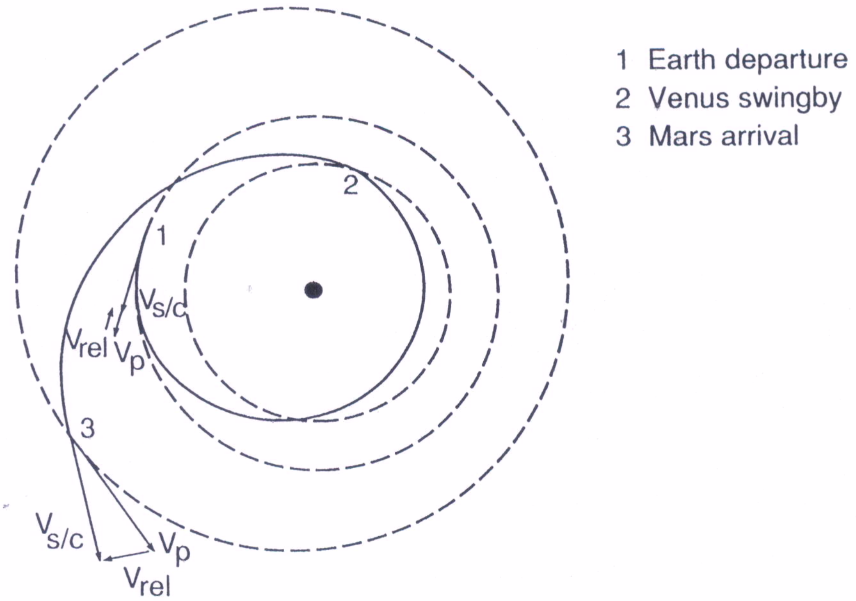

FIG. 7. 3/1/2017 Earth Departure Powered Swingby Trajectory.

that planet's SOI, a reduction in the velocity increment necessary at Earth and Mars results in this case. However, as the swingby date is moved, the ΔV required at Venus increases.

The effect of changing the planetary orientation on the ΔV can also be seen in Fig. 8, which shows the ΔV at Earth, Venus, and Mars and the initial LEO weight at various Venus swingby dates for the aforementioned powered swingby case (3/1/2017 Earth departure). In Fig. 8, the unpowered swingby occurs on 9/19/2017. Notice the larger Earth and Mars velocity increments for that date, whereas the Venus ΔV is zero. As the swingby is moved earlier, the ΔV at Earth and Mars decreases, and the Venus ΔV increases (as is expected based on Figs. 6 and 7). Therefore, by balancing the ΔV required at Earth, Mars and Venus, an optimum swingby date in terms of initial LEO weight can be chosen (in this case 8/31/2017).

The other two cases (of the previously mentioned seven improved cases) had a similar, but transposed, transfer geometry and time ratio. These cases had an Earth-Venus transfer angle (in degrees) and time (in days) of about 75, while the Venus-Mars angle and time were around 260 degrees and 190 days, respectively. A similar phenomenon as that described above occurred in this case. The difference was that the swingby date was moved later than the baseline unpowered date to produce a more efficient transfer.

Table 4 lists transfer trajectory information and swingby burn information on the seven baseline cases with reasonable initial LEO weights. As indicated previously, the symbol α represents the angle between the periapsis velocity vector (tangent to the incoming hyperbola at periapsis) and the ΔV vector in the swingby plane. From the table, five cases appear to burn nearly tangential to the

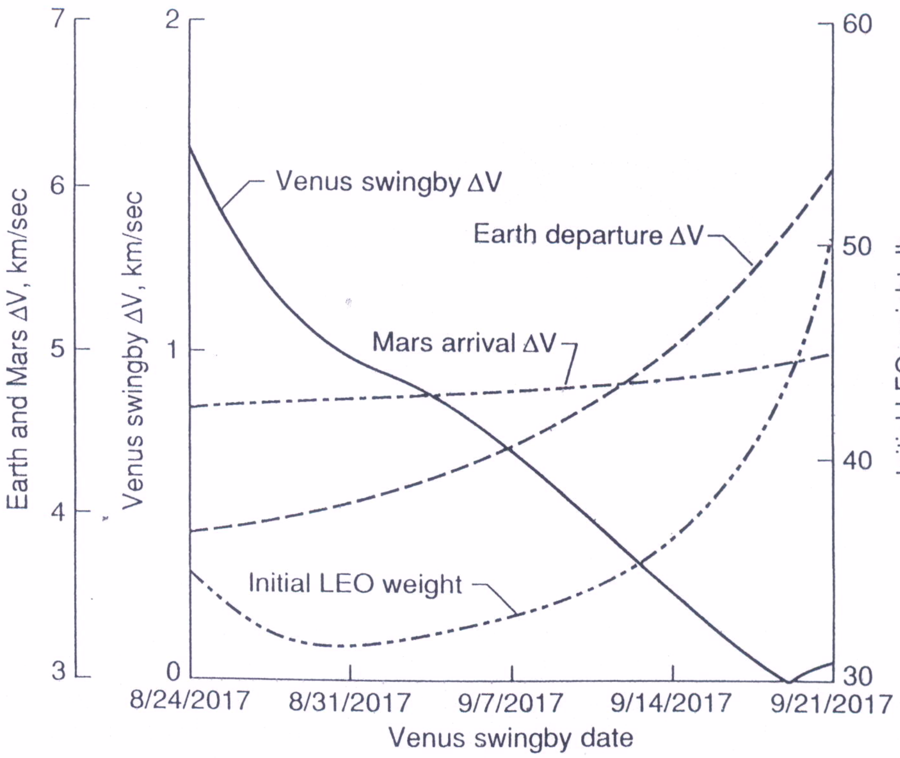

FIG. 8. Relationship Between Initial LEO Weight and Outbound Leg ΔVs for the 3/1/2017 Opportunity.

incoming hyperbola; also, five cases have retrograde maneuvers. Two swingbys have a negative α burn angle.

For various reasons, the remaining 14 cases did not result in lower initial LEO weights when the powered swingby option was used. In five cases, the unpow-

TABLE 4. Transfer Trajectory and Swingby Burn Data

Earth Departure Date	Unpowered Swingby				Powered Swingby
	Earth-Venus		Venus-Mars		
	time, days	angle, deg	time, days	angle, deg	α, deg
11/9/2010	183	300	136	104	−159
3/1/2017	202	308	144	104	−168
3/6/2017	191	293	156	116	179
9/29/2021	82	71	190	263	1
10/4/2021	80	70	192	262	1
8/21/2023	182	297	120	97	178
8/26/2023	180	296	137	105	178

ered swingbys were extremely efficient (initial LEO weights below 3.5 million pounds). Because of time ratio difficulties, five other cases appeared to become less efficient when the swingby date was moved earlier or later than the unpowered date. For example, instead of a 300°-100° transfer angle case having a 190-135 day transfer time ratio (like the reduced weight 300°-100° transfer angle cases), it would have a 135-190 day transfer time ratio; thus, when the swingby date was changed for a better Earth-Venus transfer angle, the Earth-Venus transfer time decreased when it needed to increase. A clear reason why two other cases failed to be improved has not yet been established. The remaining two cases had similar transfer ratios as listed above: one had the 300°-100° angular relationship, while the other was like the 75°-260° ratio. These cases, which were expected to result in lower initial weights, are still being investigated.

POST was also used to determine if the periapsis point was the optimum location at which to perform the single propulsive maneuver. Of the 11 cases tested, all optimized to the periapsis point of the inbound hyperbola (within 1.5 degrees in true anomaly). Nine of these eleven cases were within a few hundredths of a degree in true anomaly of periapsis.

Conclusions

This study focuses on the feasibility of using a powered Venus swingby to reduce the initial low-Earth orbit (LEO) vehicle weight for an excursion class manned Mars mission. Based on this analysis, the powered swingby can not be discounted as an efficient trajectory option. The periapsis burn allows an efficient reorientation of the relative velocity vector not always possible in the unpowered swingby option. When considered as part of the entire Earth-Mars trajectory, the powered swingby combined with more efficient Earth-Venus and Venus-Mars transfers can result in a lower initial LEO vehicle weight (from one- to 28- percent lower than for the unpowered swingby maneuvers in one-third of the cases investigated). Since the Earth departure and Mars arrival dates (positions) were restricted to the unpowered swingby minimum initial LEO weight mission, this study was biased in favor of the unpowered swingby; thus, any reduction in the initial LEO weight by using a powered swingby indicates that the powered swingby mode is definitely the better option for that Earth departure date. Potentially, greater initial LEO weight reduction is possible by allowing the Mars arrival, Mars departure, and Earth arrival dates to change in conjunction with a powered Venus swingby.

The transfer geometry and time relationship discussed in this paper is an indicator of interplanetary trajectories that could benefit from a powered swingby, but is not a definite rule. Because this transfer relationship does not always denote a weight reducing trajectory, the transfer geometry and time relationship must only be a part of the powered swingby picture. Additionally, the powered swingby seemed to have little effect, if any, on an extremely efficient unpowered swingby trajectory case. Thus, only less efficient missions will typically benefit from using the powered swingby option. Finally, the periapsis of the incoming hyperbolic trajectory is close to the optimum single burn point. Therefore, a propulsive maneuver at periapsis is sufficiently optimal for a first-run analysis.

References

[1] "Pioneering the Space Frontier—An Exciting Vision of Our Next Fifty Years in Space," National Commission on Space, Bantaam Books, Inc., May 1986.

[2] RIDE, SALLY K. "Leadership and America's Future in Space—A Report to the Administrator," NASA, August 1987.

[3] BRAUN, R. D. "A Survey of Interplanetary Trajectory Options for a Chemically Propelled Manned Mars Vehicle," AAS Paper No. 89-202, AAS/GSFC International Symposium on Orbital Mechanics and Mission Design, Greenbelt, Maryland, April 1989.

[4] GOBETZ, F.W. "Optimum Transfers between Hyperbolic Asymptotes," *AIAA Journal,* Vol. 1, No. 9, September 1963, pp. 2034–2041.

[5] WALTON, J. M., MARCHAL, C., and CULP, R. D. "Synthesis of the Types of Optimal Transfers between Hyperbolic Asymptotes," *AIAA Journal,* Vol. 13, No. 8, August 1975, pp. 980–988.

[6] HOLLISTER, W. M., and PRUSSING, J. E. "Optimum Transfer to Mars Via Venus," AIAA Paper No. 65-700, AIAA/ION Astrodynamics Specialist Conference, Monterey, California, September 1965; also *Astronautica Acta,* Vol. 12, No. 2, 1966, pp. 169–179.

[7] MEAD, C.W., and JONES, M. F. "Optimization of 'Ephemeridal' Parameters for Minimum Propellant Requirements on Multiplanet Roundtrip Swingby-Stopover Missions," Lockheed Missiles and Space Company/Huntsville Research and Engineering Center, A791436 TM 54/50-189, May 1968.

[8] BAUER, G. L., CORNICK, D. E., and STEVENSON, R. "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)," NASA CR-2770, February 1977.