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Effect of Departure Delays on Manned Mars Mission Selection

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This study determines the effect on the initial mass in low Earth orbit (IMLEO) of delaying departure from Mars and Earth by 5, 15, and 30 days, once a nominal mission to Mars has been selected. Additionally, the use of a deep-space maneuver (DSM) is considered in order to alleviate the IMLEO penalties. Three different classes of missions are analyzed, using chemical and nuclear thermal propulsion systems in the 2000–2025 time frame: opposition, conjunction, and fast-transfer conjunction. The results indicate that Mars and Earth delays can lead to large IMLEO penalties. Opposition and fast-transfer conjunction-class missions have the highest IMLEO penalties, upwards of 432.4 and 1977.3 metric tons (mt), respectively. Conjunction-class missions, on the other hand, tend to be insensitive to Mars and Earth delays, having IMLEO penalties under 103.5 mt. As expected, nuclear thermal propulsion had significantly lower IMLEO penalties than chemical propulsion. The use of a DSM does not significantly reduce the penalties. The results of this study can enable mission designers to incorporate the influence of off-nominal departure conditions of the interplanetary trajectory in the overall conceptual design of a Mars transfer vehicle.

Nomenclature

I_{sp}	= specific impulse, s
L/D	= lift-to-drag ratio
TMI	= trans-Mars injection date
TOF	= total time of flight, days
TOF_{DSM}	= time of flight to deep-space maneuver, days
TOF_{in}	= inbound time of flight (Mass-Earth leg), days
TOF_{out}	= outbound time of flight (Earth-Mars leg), days
TOF_{s}	= time of flight to swingby, days

Introduction

EARLY in the next century, National Aeronautics and Space Administration (NASA) has plans for a human mission to Mars. Many recent studies have produced preliminary scenarios for various trajectory options to Mars, ranging from fast excursion to long-surface-stay missions.[1–7] These studies have identified nominal Earth departure opportunities in the 2000–2025 time frame, typically utilizing chemical and nuclear thermal propulsion systems. These identified missions have total trip times between 1 and 3 years with stay times at Mars ranging from 30–90 days for the fast excursion missions to 500–600 days for the long-surface-stay missions.

Studies have also been performed to consider the effect of off-nominal conditions, such as abort possibilities for the nominal missions that were identified, in case problems arise while on transit to Mars.[5,8,9] However, problems may arise after the transfer vehicle has established orbit around Mars, or while the transfer vehicle is still in Earth orbit before departure. In such a case, delays may occur that do not allow the use of the nominal Mars or Earth departure dates. This outcome could have a drastic effect on the overall mission profile (i.e., encounter dates), and hence the initial mass of the transfer vehicle in low-Earth orbit (LEO).

This study determines the effect of delaying departure from Mars and Earth, once a nominal mission has been selected. In particular, the effect on the initial-mass-in-low-Earth-orbit (IMLEO) of the vehicle is investigated. Additionally, this study ascertains the usefulness of adding a deep-space maneuver (DSM) and/or a Venus swingby to the interplanetary trajectories in reducing the penalties associated with the delays in the Earth and Mars departure dates.

Background

In this study, three different classes of missions are analyzed: opposition, conjunction, and fast-transfer conjunction. The opposition-class missions are characterized by having total trip times of approximately 500 days with Mars stay times on the order of 30–90 days; the conjunction-class missions have total trip times on the order of 1000 days with Mars stay times around 500–600 days. The fast-transfer conjunction missions have total trip times similar to the conjunction-class missions; however, their transfer times are much shorter (on the order of 100 days). For this reason, fast-transfer conjunction missions are of interest because the crew's exposure to zero g and the space radiation environments are minimized.[5]

Nominal opportunities for performing Mars missions between 2000 and 2025 for all three classes of missions are obtained from Refs. 4 and 6. The opposition- and conjunction-class missions are obtained from a list of baseline opportunities from Ref. 4, and the fast-transfer conjunction-class missions are obtained from a list of opportunities from Ref. 6. From these lists, two opportunities from each class (opposition, conjunction, and fast-transfer conjunction) are selected; that is, a good and a poor opportunity based on total ΔV, total trip time, transit time, and Mars stay time. In all, six nominal opportunities are chosen.

For each of the six opportunities, baseline missions are generated utilizing chemical (CHEM) and nuclear thermal propulsion (NTP) systems for the following scenarios: 1) all propulsive, 2) propulsive Earth departure, Mars arrival, and Mars departure stages, and Earth direct entry, and 3) propulsive Earth departure stage, Mars aerobraking, propulsive Mars departure stage, and Earth direct entry. In calculating these trajectories, specific impulses I_{sp} of 480 and 925 are used for CHEM and NTP, respectively, along with the vehicle and mission characteristics shown in Table 1.[10] As seen in Table 1, two different Mars excursion vehicle (MEV) masses are used. For the conjunction and fast-transfer conjunction missions, a heavier MEV mass is used to allow for the longer stay-time requirement at Mars than in the opposition-class missions. Therefore, the MEV mass for the conjunction and fast-transfer conjunction missions is calculated by scaling the dry-mass estimates of the affected subsystems from Ref. 11 to accommodate the longer stay time at Mars, and then determining the necessary ascent and descent propellant requirements. Additionally, the tankage and the aerobrake masses are assumed to be 10% of the propellant mass and 15% of the payload mass, respectively. Also, an upper limit on the entry

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Table 1 Vehicle and mission parameters

Vehicle	Mass, kg
Transfer vehicle Habitation module[10]	55,000
Earth return capsule[10]	6,000
Mars excursion vehicle:	
Opposition Mission[11]	76,000
Conjunction and fast-transfer conjunction missions	145,000
Mission	
Periapsis altitude (for all parking orbits)	500 km
Parking-orbit eccentricities:	
Initial Earth orbit	0.000
Mars parking orbit	0.809
Final Earth orbit	0.000
Earth entry velocity limitation	14.5 km/s
Mars entry velocity limitation	10.0 km/s
Mars and Earth atmospheric interface altitude	125 km

velocity at Mars and Earth of 10 and 14.5 km/s, respectively, is imposed for the Mars aerobraking and Earth direct entry scenarios. Previous studies have indicated that, for aerobrakes with an L/D of 0.5, higher entry velocities may pose entry corridor width and deceleration limit problems.[12,13]

Once the nominal missions are identified, delays to their Mars and Earth departure dates are considered in order to determine their effect on the IMLEO of a transfer vehicle. Departure delays of 5, 15, and 30 days were imposed at both Mars and Earth to simulate any problems that may arise while preparing for departure, such as the occurrence of a solar flare, dust storms on the Martian surface delaying ascent, or mechanical difficulties. For the Mars departure delays, the outbound leg to Mars follows the nominal trajectory. However, the inbound leg is allowed to vary so that an optimal Earth return trajectory can be obtained. For the Earth departure delays, the entire round-trip trajectory (i.e., all encounter dates except for the Earth departure date) is allowed to vary so that the optimal trajectory to Mars can be determined for the new Earth departure date. After the effect of these Mars and Earth departure delays is determined, an analysis is performed to assess the usefulness of including a DSM and/or a Venus swingby to aid in the reduction of the penalties (IMLEO) associated with these delays. In this analysis, a DSM and/or a Venus swingby are considered to supplement both the outbound (Earth-Mars) and inbound (Mars-Earth) legs of the delayed trajectories. All the analysis in this study is performed using the patched-conic option of the Interplanetary Program to Optimize Simulated Trajectories (IPOST).[14]

Results

Table 2 shows the baseline trajectory parameters (i.e., encounter dates) for the all-propulsive, Earth direct entry, and Mars aerobraking and Earth direct entry scenarios taken from Refs. 4 and 6 using CHEM. Because of the volume of data, only the chemical-propulsion results for four of the mission opportunities listed in Table 2 are presented in this article. However, all of the NTP results, along with the results for the other mission opportunities, are given in Ref. 15. As seen, the IMLEO varies from approximately 600 to 2800 metric tons (mt), depending on the mission scenario. Additionally, the entry velocities at both Mars and Earth are within the limits imposed for all missions except for the 2010 opposition-class and 2016 a fast-transit conjunction-class missions. In Refs. 4 and 6, the listed opportunities were obtained by optimizing the total mission ΔV and not the IMLEO of the transfer vehicle. Therefore, these baseline missions are reoptimized (producing Table 3) by permitting the encounter dates to vary so that the IMLEO of the transfer vehicle can be minimized.

For the opposition-class missions, the Earth departure, Mars arrival, Venus swingby, and Earth arrival dates are allowed to vary. However, the Mars stay time is fixed at 60 days, because as short a stay time as possible is preferred if the stay time is permitted to vary. For the conjunction-class missions, all the counter dates are allowed to vary, that is, the Earth departure and Mars arrival dates, the length of the Mars stay time, and the Earth arrival date. For the fast-transfer conjunction-class missions, only the Earth departure date and the length of the Mars stay time are allowed to vary, so that their characteristic of having fast transfer legs will be preserved. If the Mars and Earth arrival dates were permitted to vary, the fast-transfer conjunction missions' transit times would lengthen to those of the conjunction-class missions. Thus, the outbound and inbound transit times are fixed. Table 3 shows how the baseline missions are altered when the encounter dates are varied to optimize the IMLEO. Note again that the differences between these results and those of Refs. 4 and 6 are a consequence of using a different optimization function and mission scenario.

As seen in Table 3, the IMLEO is drastically reduced, in most cases, from the baseline missions of Refs. 4 and 6 (see Table 2). The reductions in the IMLEO are more pronounced for CHEM than for NTP, because of its lower I_{sp}. Again, the NTP results are not all shown here because there are so many data, and the reader is referred to Ref. 15 for further information on NTP results. For all missions, however, the earth departure date is altered only by a month or so. The inbound and outbound transit times, along with the Mars stay time, have changed considerably for many missions. However, the net effect is small (for most missions) in that the total mission time remains roughly the same. Note that the transit times for the fast-transfer conjunction-class missions were increased (for the Earth direct entry and the Mars aerobraking and Earth direct entry scenarios) so that the Mars and Earth entry velocities could satisfy the imposed constraints.

Looking at Table 3, chemical propulsion appears very unfavorable for almost all mission classes and mission scenarios. The opposition and fast-transfer conjunction-class missions require a drastically high IMLEO in some cases (upward of 2800 mt), and only the conjunction-class missions seem remotely feasible. Nuclear propulsion, on the other hand, appears quite attractive for all mission classes and mission scenarios, with IMLEOs ranging from 300 to 715 mt. Additionally, replacing a propulsive stage by an Earth direct entry mode or a Mars aerobraking and Earth direct entry mode was always found to reduce the required IMLEO. Aerobraking is shown to have the greatest effect for the fast-transfer conjunction-class missions, because these high-energy transfers require a high velocity decrement for orbital capture.

Once the minimum-IMLEO missions are calculated for each opportunity, the effect of delaying their Mars and Earth departure dates by 5, 15, and 30 days is examined. Tables 4–7 show the results. All the nominal missions calculated in Table 3 for each opportunity are reproduced at the top of Tables 4–7 for comparison.

Mars Delays

Tables 4–7 show the effect of delaying the Mars departure date for the 2013, 2010, 2016, and 2018 opportunities and mission scenarios. The greatest effect is seen for the opposition and fast-transfer conjunction missions. For the opposition-class missions, the increase from the nominal in the IMLEO can be upwards 388.1 mt for the 2013 opportunity (Table 4) and 203.8 mt for the 2010 opportunity (Table 5). Overall, a 5-day delay does not have a significant effect on the IMLEO, but any further delays can lead to drastic consequences. For this opportunity, NTP was able to absorb the penalty in IMLEO significantly better than CHEM; however, a large delay (30 days) may still pose a problem. For the fast-transfer conjunction-class missions, the increase in the IMLEO over the nominal mission can be as high as 698.0 mt for the 2016 opportunity (Table 6). The trends produced by the fast-transfer conjunction-class missions are very similar to those of the opposition-class missions. That is, a 5-day delay at Mars does not impose a significant penalty; however, a longer delay leads to excessive IMLEO increases. Again, as expected, NTP has significantly lower penalties than CHEM, but long delays may still pose a problem (see Ref. 15).

The conjunction class missions are only slightly affected by the delays in the Mars departure date. The largest penalty in the IMLEO is only around 19.6 mt for the 2018 opportunity (Table 7), with respect to the nominal. Furthermore, Mars departure delays up to 30 days have very little effect on the IMLEO. For this mission class, NTP showed only minor advantages over CHEM in absorbing any IMLEO penalties. Since conjunction-class missions rely on low energy transfers, Mars departure delays are shown to

Table 2 Baseline trajectory parameters for CHEM missions optimized by total mission ΔV

TMI	TOF_s, days	TOF_{out}, days	Stay, days	TOF_s, days	TOF_{in}, days	TOF, days	IMLEO, mt
			All propulsive				
Opposition							
11/25/2010	160.5	287.8	60.0	—	361.4	709.2	1995.2
11/20/2013	—	256.3	60.0	147.1	310.7	627.0	898.5
Conjunction							
01/01/2014	—	328.8	382.7	—	300.2	1011.7	905.5
05/17/2018	—	235.0	515.4	—	191.2	941.6	766.2
Fast-transfer conjunction							
04/11/2016	—	120.0	648.0	—	90.0	858.0	2853.2
08/13/2020	—	115.0	652.0	—	107.0	874.0	2511.9
			Earth direct entry				
Opposition							
11/25/2010	160.5	287.8	60.0	—	361.4	709.2	1496.9
11/20/2013	—	256.3	60.0	147.1	310.7	627.0	826.2
Conjunction							
01/01/2014	—	328.8	382.7	—	300.2	1011.7	846.6
05/17/2018	—	235.0	515.4	—	191.2	941.6	728.3
Fast-transfer conjunction							
04/11/2016	—	120.0	648.0	—	90.0	858.0	2331.4
08/13/2020	—	115.0	652.0	—	107.0	874.0	1984.8
			Mars aerobraking and Earth direct entry				
Opposition							
11/25/2010	160.5	287.8	60.0	—	361.4	709.2	640.9
11/20/2013	—	256.3	60.0	147.1	310.7	627.0	612.3
Conjunction							
01/01/2014	—	328.8	382.7	—	300.2	1011.7	601.7
05/17/2018	—	235.0	515.4	—	191.2	941.6	622.5
Fast-transfer conjunction							
04/11/2016	—	120.0	648.0	—	90.0	858.0	1132.4
08/13/2020	—	115.0	652.0	—	107.0	874.0	1114.9

Table 3 Nominal trajectory parameters for CHEM missions optimized by IMLEO

TMI	TOF_s, days	TOF_{out}, days	Stay, days	TOF_s, days	TOF_{in}, days	TOF, days	IMLEO, mt
			All propulsive				
Opposition							
11/27/2010	162.5	330.6	60.0	—	293.6	684.3	1021.7
11/20/2013	—	270.5	60.0	135.0	302.6	633.1	839.5
Conjunction							
12/04/2014	—	294.0	440.5	—	237.4	971.9	742.3
05/10/2018	—	203.5	553.7	—	192.6	949.8	737.8
Fast-transfer conjunction							
04/09/2016	—	120.0	657.5	—	90.0	867.5	2793.5
08/19/2020	—	115.0	644.8	—	107.0	866.8	2463.1
			Earth direct entry				
Opposition							
11/27/2010	162.5	330.6	60.0	—	288.3	679.0	879.8
11/21/2013	—	271.0	60.0	133.5	299.5	630.5	770.4
Conjunction							
12/04/2014	—	294.0	442.5	—	301.6	1038.2	698.5
05/10/2018	—	203.5	552.6	—	191.9	947.9	701.5
Fast-transfer conjunction							
04/09/2016	—	120.0	637.7	—	100.0	857.7	2171.5
08/19/2020	—	115.0	622.5	—	125.0	862.5	1639.1
			Mars aerobraking and Earth direct entry				
Opposition							
11/22/2010	165.0	302.7	60.0	—	315.8	678.6	544.4
12/30/2013	—	209.8	60.0	152.5	315.4	585.2	582.3
Conjunction							
12/26/2014	—	324.5	390.3	—	301.3	1016.1	601.6
05/18/2018	—	240.5	508.4	—	191.9	940.7	622.3
Fast-transfer conjunction							
03/04/2016	—	135.0	659.1	—	100.0	894.1	755.2
08/01/2020	—	115.0	641.2	—	125.0	881.2	905.4

Table 4 Effect of Earth and Mars departure delays for 2013 opposition-class mission with inbound Venus swingby

TMI	TOF_{out}, days	Stay, days	TOF_s, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
			All propulsive				
Nominal							
11/20/2013	270.5	60.0	135.0	302.6	633.1	839.5	
Mars delay							
11/20/2013	270.5	65.0	130.1	280.7	616.2	876.1	36.6
11/20/2013	270.5	75.0	122.0	294.0	639.5	945.7	106.2
11/20/2013	270.5	90.0	109.5	276.4	636.9	1226.4	386.9
Earth delay							
11/25/2013	265.0	60.0	135.5	303.6	628.6	843.5	4.0
12/05/2013	265.3	60.0	126.6	296.6	621.9	885.1	45.6
12/20/2013	222.9	60.0	149.6	319.6	602.5	1007.8	168.3
			Earth direct entry				
Nominal							
11/21/2013	271.0	60.0	133.5	299.5	630.5	770.4	
Mars delay							
11/21/2013	271.0	65.0	129.1	298.1	634.1	794.9	24.5
11/21/2013	271.0	75.0	120.7	284.1	630.1	874.1	103.7
11/21/2013	271.0	90.0	107.9	272.7	633.7	1158.5	388.1
Earth delay							
11/26/2013	268.7	60.0	131.2	296.3	625.1	773.8	3.4
12/06/2013	264.4	60.0	126.4	289.7	614.1	823.3	52.9
12/21/2013	222.7	60.0	148.5	319.5	602.2	913.8	143.4
			Mars aerobraking and Earth direct entry				
Nominal							
12/30/2013	209.8	60.0	152.5	315.4	585.2	582.3	
Mars delay							
12/30/2013	209.8	65.0	147.6	298.2	573.0	585.8	3.5
12/30/2013	209.8	75.0	140.0	304.7	589.5	590.6	8.3
12/30/2013	209.8	90.0	127.3	290.7	590.5	638.3	56.0
Earth delay							
01/04/2014	210.2	60.0	147.5	299.2	569.4	589.8	7.5
01/14/2014	200.3	60.0	147.3	299.2	559.5	608.4	26.1
01/29/2014	179.8	60.0	152.5	315.4	555.2	670.3	88.0

Table 5 Effect of Earth and Mars departure delays for 2010 opposition-class mission with outbound Venus swingby

TMI	TOF_s, days	TOF_{out}, days	Stay, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
			All propulsive				
Nominal							
11/27/2010	162.5	330.6	60.0	293.6	684.3	1021.7	
Mars delay							
11/27/2010	162.5	330.7	65.0	291.8	687.5	1034.8	13.1
11/27/2010	162.5	330.7	75.0	288.0	639.7	1060.7	39.0
11/27/2010	162.5	330.7	90.0	282.2	702.9	1104.2	82.5
Earth delay							
12/02/2010	158.7	340.3	60.0	288.2	688.4	1044.1	22.4
12/12/2010	150.0	340.0	60.0	284.5	684.4	1129.8	108.1
12/27/2010	138.7	341.0	60.0	278.2	679.3	1454.1	432.4
			Earth direct entry				
Nominal							
11/27/2010	162.5	330.6	60.0	288.3	679.0	879.8	
Mars delay							
11/27/2010	162.5	330.6	65.0	280.1	675.7	899.5	19.7
11/27/2010	162.5	330.6	75.0	266.2	671.8	947.3	67.5
11/27/2010	162.5	330.6	90.0	243.0	663.7	1083.6	203.8
Earth delay							
12/02/2010	158.6	339.3	60.0	271.5	670.8	913.5	33.7
12/12/2010	148.0	318.0	60.0	267.9	645.9	1000.5	120.7
12/27/2010	136.6	316.6	60.0	260.6	637.2	1255.7	375.9
			Mars aerobraking and Earth direct entry				
Nominal							
11/22/2010	165.0	302.7	60.0	315.8	678.6	544.4	
Mars delay							
11/22/2010	165.0	302.7	65.0	314.0	681.8	546.3	1.9
11/22/2010	165.0	302.7	75.0	310.3	688.0	550.5	6.1
11/22/2010	165.0	302.7	90.0	292.3	685.0	563.8	19.4
Earth delay							
11/27/2010	160.0	302.4	60.0	314.2	676.6	544.5	0.1
12/07/2010	150.0	289.2	60.0	315.3	664.5	569.4	25.0
12/22/2010	140.0	313.0	60.0	280.2	653.2	698.3	153.9

Table 6 Effect of Earth and Mars departure delays for 2016 fast-transfer conjunction-class mission

TMI	TOF_{out}, days	Stay, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
			All propulsive			
Nominal						
04/09/2016	120.0	657.5	90.0	867.5	2793.5	
Mars delay						
04/09/2016	120.0	662.5	90.0	872.5	2812.6	19.1
04/09/2016	120.0	672.5	90.0	882.5	2960.2	166.7
04/09/2016	120.0	687.5	90.0	897.5	3491.5	698.0
Earth delay						
04/14/2016	120.0	652.5	90.0	862.5	2834.7	41.2
04/24/2016	120.0	642.5	90.0	852.5	3188.2	394.7
05/09/2016	120.0	627.5	90.0	837.5	4770.8	1977.3
			Earth direct entry			
Nominal						
04/09/2016	120.0	637.7	100.0	857.7	2171.5	
Mars delay						
04/09/2016	120.0	642.7	100.0	862.7	2178.0	6.5
04/09/2016	120.0	652.7	100.0	872.7	2228.4	56.9
04/09/2016	120.0	667.7	100.0	887.7	2403.9	232.4
Earth delay						
04/14/2016	120.0	632.8	100.0	852.8	2201.1	29.6
04/24/2016	120.0	622.8	100.0	842.8	2469.7	298.2
05/09/2016	120.0	607.8	100.0	827.8	3682.0	1510.5
			Mars aerobraking and Earth direct entry			
Nominal						
03/04/2016	135.0	659.1	100.0	894.1	755.2	
Mars delay						
03/04/2016	135.0	664.1	100.0	899.1	757.3	2.1
03/04/2016	135.0	674.1	100.0	909.1	774.7	19.5
03/04/2016	135.0	689.1	100.0	924.1	835.4	80.2
Earth delay						
03/09/2016	135.0	654.1	100.0	889.1	759.3	4.1
03/19/2016	135.0	644.1	100.0	879.1	792.1	36.9
04/03/2016	135.0	629.1	100.0	864.1	907.0	151.8

Table 7 Effect of Earth and Mars departure delays for 2018 conjunction-class mission

TMI	TOF_{out}, days	Stay, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
			All propulsive			
Nominal						
05/10/2018	203.5	553.7	192.6	949.8	737.8	
Mars delay						
05/10/2018	203.5	558.7	189.2	951.4	738.2	0.4
05/10/2018	203.5	568.7	182.6	954.8	741.9	4.1
05/10/2018	203.5	583.7	173.6	960.8	757.4	19.6
Earth delay						
05/15/2018	201.9	550.3	192.6	944.8	740.0	2.2
05/25/2018	198.8	543.4	192.6	934.8	757.1	19.3
06/09/2018	201.1	526.1	192.6	919.8	818.3	80.5
			Earth direct entry			
Nominal						
05/10/2018	203.5	552.6	191.9	947.9	701.5	
Mars delay						
05/10/2018	203.5	557.6	188.4	949.5	701.8	0.3
05/10/2018	203.5	567.6	181.4	952.5	704.9	3.4
05/10/2018	203.5	582.6	172.4	958.5	718.1	16.6
Earth delay						
05/15/2018	201.9	549.2	191.9	943.0	703.5	2.0
05/25/2018	198.8	542.3	191.9	933.0	719.8	18.3
06/09/2018	201.1	525.0	191.9	918.0	778.0	76.5
			Mars aerobraking and Earth direct entry			
Nominal						
05/18/2018	240.5	508.4	191.9	940.7	622.3	
Mars delay						
05/18/2018	240.5	513.4	188.4	942.3	622.6	0.3
05/18/2018	240.5	523.4	181.4	945.3	625.4	3.1
05/18/2018	240.5	538.4	172.4	951.3	637.1	14.8
Earth delay						
05/23/2018	237.1	506.8	191.9	935.8	623.7	1.4
06/02/2018	236.8	497.1	191.9	925.8	633.1	10.8
06/17/2018	242.0	476.9	191.9	910.8	661.0	38.7

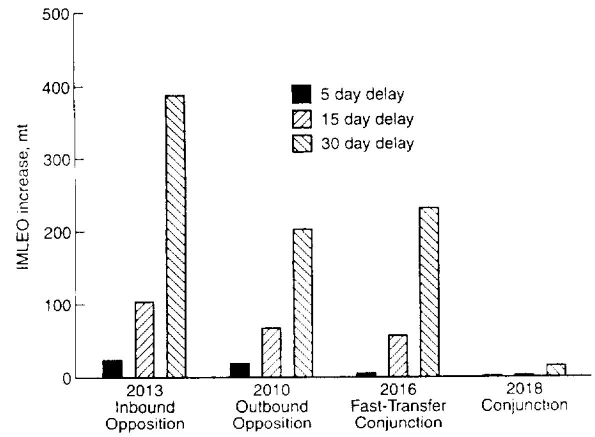

Fig. 1 Earth direct entry—Mars delay (chemical propulsion).

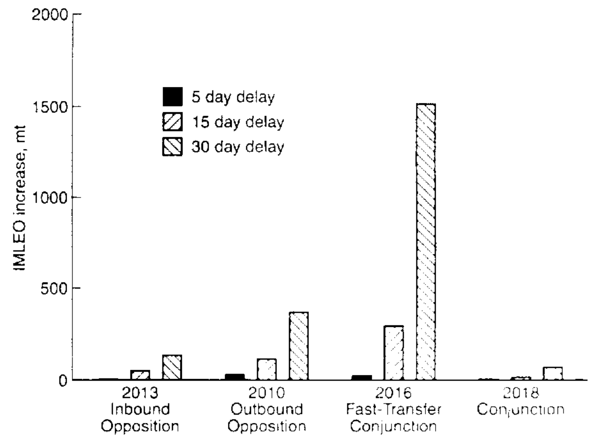

Fig. 2 Earth direct entry—Earth delay (chemical propulsion).

have very little effect. Therefore, slight deviations from the nominal trajectories do not produce significant penalties in IMLEO. Opposition and fast-transfer conjunction-class missions, on the other hand, rely on high energy transfer. As a result, any modifications to their trajectories can lead to excessive increases in the IMLEO.

For the opposition-class missions, the IMLEO penalty is lower for outbound Venus swingby trajectories (2010 opportunity) than for the inbound Venus swingby trajectories (2013 opportunity). This outcome is a consequence of opposition-class missions having a high-energy-transfer leg (which includes the Venus swingby) and a low-energy-transfer leg (which does not include the Venus swingby). Therefore, when the high-energy-transfer leg (i.e., with the Venus swingby) is used for Earth return, larger IMLEO penalties result (see Table 4) for any delays in the Mars departure date. If the low-energy-transfer leg is used for Earth return (as in the conjunction-class mission trajectories), lower IMLEO penalties will be produced. Hence, opposition-class missions with an outbound Venus swingby are preferable in connection with Mars departure delays. Figure 1 shows graphically the comparison between the various mission classes for delays in the Mars departure date for the Earth direct entry scenario using chemical propulsion.

Earth Delays

Tables 4–7 also show the effect of delaying the Earth departure date for the 2013, 2010, 2016, and 2018 opportunities and mission scenarios. The results are very similar to the trends observed for delays in the Mars missions. That is, the greatest effect is seen for the opposition and fast-transfer conjunction-class missions; the conjunction class missions are not affected very much. The same reasoning about the efficiency of the transfers applies here as for the Mars delays. For the opposition-class missions, the penalty in the IMLEO can be upwards of 168.3 mt from the nominal for the 2013 opportunity (Table 4), and 432.4 mt for the 2010 opportunity (Table 5). For the fast-transfer conjunction-class missions, the penalty can be as high as 1977.3 mt for the 2016 opportunity (Table 6). Again, a 5-day delay at Earth does not impose a significant penalty; however, longer delays lead to excessive IMLEO increases. These excessive increases occur when the Earth departure date is pushed outside the nominal opportunity to perform that particular mission. As before, NTP has significantly lower penalties than CHEM, but long delays can pose a problem (see Ref. 15).

Once again, the conjunction-class missions were the least affected by the delays in the Earth departure date, as compared to the opposition and fast-transfer conjunction missions. The same reasoning applies here as stated in the Mars delay. The largest penalty in the IMLEO for delays up to 15 days is only around 19.3 mt from the nominal for the 2018 opportunity (Table 7). If the delay in the Earth departure date is longer than 15 days, the penalty in IMLEO can become large. Again, this outcome is the result of the Earth departure date being pushed outside the nominal opportunity to perform that particular delayed mission. As stated before for conjunction-class missions, NTP showed only minor advantages over CHEM in absorbing any IMLEO penalties. Figure 2 graphically shows the comparison between the various mission classes for delays in the Earth departure date for the Earth direct entry scenario using chemical propulsion.

Trajectory Modification

Since the effect of delaying departure from Mars and Earth is significant for many of the nominal missions, an attempt has been made to reduce the penalty in IMLEO by modifying the mission trajectory. The missions are modified by including a DSM, along with adding or removing a Venus swingby, on the inbound and outbound legs of the trajectory. Additionally, the inbound time of flight is allowed to increase. Many combinations of the above scenarios were tried, and the combination producing the largest reduction in the IMLEO penalty is shown. Table 8 gives the results for a few of the missions analyzed that had high IMLEO penalties associated with either a Mars or an Earth delay. The nominal values and the corresponding ones for the delayed Mars of Earth mission are reproduced for comparison.

In some cases, the penalty for conjunction- and opposition-class missions can be reduced by adding a DSM. Table 8 shows results for two opposition-class missions in which adding a DSM reduced the IMLEO penalty. The addition of a DSM also reduced the IMLEO penalty for some conjunction-class missions when NTP was used (see Ref. 15). For the 2013 opposition-class mission, adding a small DSM of approximately 0.47 km/s on the outbound leg reduced the IMLEO penalty to 78.7 mt (from 168.3 mt). For the 2010 opposition-class mission, reductions in the IMLEO penalty to 275.2 mt (from 432.4) are obtained by including a DSM. Note the total times of flight for these missions do not change very much on modifying the trajectories. That is, approximately the same Earth arrival date as the nominal mission is obtained. Overall, missions with any delays in the Mars departure date could not be modified to reduce the IMLEO penalty, regardless of mission class (i.e., opposition, conjunction, or fast-transfer conjunction). Only missions with Earth departure delays could be modified to reduce the IMLEO penalty. For the fast-transfer conjunction-class missions, the penalty in the IMLEO could only be reduced by allowing the return time to increase. A reductions in the IMLEO penalty could be achieved, but at the cost of almost tripling the return time, as seen in Table 8. As a result, the favorable characteristics of having fast transfers for this class of missions are lost.

As seen from the results, modifying the mission trajectories by adding a DSM or a Venus swingby can reduce the penalty in IMLEO. However, even with the extra degrees of freedom, the IMLEO of the off-nominal missions could not be brought to or reduced below the nominal mission levels. As a result, planning for delays at Mars or Earth has dramatic consequences for a mission, since sufficient margins will have to be included in the overall design of a Mars transfer vehicle. Furthermore, these results indicate that opposition and fast-transfer conjunction missions appear very unfavorable in terms of IMLEO, because of their sensitivity to departure delays at both Mars and Earth. Modifying these mission classes with a DSM or a Venus

Table 8 Effect of trajectory modification on missions having large IMLEO penalties associated with Mars or Earth departure delays

TMI	TOF_{DSM}, days	TOF_{out}, days	Stay, days	TOF_{s}, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
2013 opposition-class mission (chemical: all propulsive)								
Nominal								
11/20/2013	—	270.5	60.0	135.0	302.6	633.1	839.5	
30-day Earth delay								
12/20/2013	—	222.9	60.0	149.6	319.6	602.5	1007.8	168.3
Adding outbound DSM								
12/20/2013	104.1	235.0	60.0	138.0	318.0	613.0	918.2	78.7

TMI	TOF_{DSM}, days	TOF_{s}, days	TOF_{out}, days	Stay, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
2010 opposition-class mission (chemical: all propulsive)								
Nominal								
11/27/2010	—	162.5	330.7	60.0	293.6	684.3	1021.7	
30-day Earth delay								
12/27/2010	—	138.7	341.1	60.0	278.2	679.3	1454.1	432.4
Adding inbound DSM								
12/27/2010	80.7	136.3	319.5	60.0	286.5	666.1	1296.9	275.2

TMI	TOF_{out}, days	Stay, days	TOF_{s}, days	TOF_{in}, days	TOF, days	IMLEO, mt	Increase in IMLEO, mt
2016 fast-transfer conjunction-class mission (chemical: Earth direct entry)							
Nominal							
04/09/2016	120.0	637.7	—	100.0	857.7	2171.5	
30-day Mars delay							
04/09/2016	120.0	667.7	—	100.0	887.7	2403.9	232.4
Adding inbound Venus swingby							
04/09/2016	120.0	667.7	168.3	393.5	1181.2	2217.4	45.9

swingby did not reduce their IMLEO penalties significantly. Therefore, to avoid excessive penalties in the IMLEO resulting from long Mars or Earth departure delays, conjunction-class missions seem to be the only feasible option available, because of their insensitivity to departure delays at both Mars and Earth. Additionally, nuclear thermal propulsion had significantly lower IMLEO penalties than chemical propulsion. In fact, for some mission scenarios with NTP, the penalty in IMLEO was less than approximately 1 mt. Therefore, the consideration of delays to the Mars and Earth departure dates indicates the use of NTP.

Conclusions

This study determines the effect on the initial mass in low-Earth orbit (IMLEO) of a nominal mission if the departure from Mars or Earth is delayed by 5, 15, or 30 days. For opposition and fast-transfer conjunction missions, the results indicate that a 30-day delay in either the Mars or Earth departure dates can produce high penalties in the IMLEO; increases as high as 432.4 and 1977.3 mt are possible, respectively. Conjunction-class missions, on the other hand, are relatively insensitive to delays in the Mars and Earth departure dates; penalties in the IMLEO of less than 103.5 mt were observed. Nuclear thermal propulsion had significantly lower IMLEO penalties than chemical propulsion. The use of a DSM, along with the addition or removal of a Venus swingby, on the interplanetary trajectories did not significantly alleviate the IMLEO penalties. Hence, this analysis suggests that conjunction-class missions appear to be the only choice for performing human missions to Mars and avoiding IMLEO penalties due to long Mars or Earth departure delays.

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