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FAST EARTH-MARS ROUNDTRIP TRAJECTORIES TO REDUCE HEALTH AND SAFETY RISKS FOR CREWED MISSIONS

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The extended mission duration of a crewed Mars mission compounds integrated risks to crew health and safety. Shortening mission duration would therefore have a direct impact on reducing many human health and performance risk factors. This paper describes trajectory feasibility analyses performed to examine trajectory options for a fast crewed mission to Mars. Studies were conducted to examine options with short overall mission durations ($\leq$ 400-day roundtrip) and options that focus on minimizing astronaut time in deep space, while allowing for longer Mars surface stays. Trade studies were performed to determine Δv requirements for a range of launch dates, Mars orbit periods, Mars stay times, and Earth-to-Mars flight time maxima. The implications of a Venus gravity assist are also described. The analyses presented here build on and specifically aim to optimize and address key concerns of assumptions made in previously published studies of fast crewed Mars missions.

INTRODUCTION

Crew health and safety is a fundamental concern for human space flight. Health and safety risks increase with both mission duration and distance from Earth. For example, for a notional 730-day Mars mission, NASA Integrated Medical Model (IMM) estimates suggest a likelihood greater than 1-in-90 of loss of crew life [1]. However, for a crewed mission to Mars, an innovative mission design can mitigate health and safety risks. In particular, reducing the time the crew spends in deep space reduces health risks from key factors whose effects accumulate over time, like exposure to radiation and microgravity.

This paper describes trajectory feasibility analyses performed by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's (GSFC) Navigation and Mission Design Branch to examine trajectory options for a fast crewed mission to Mars [1]. In these analyses, *fast* is allowed to take on two meanings:

1. A short overall roundtrip mission duration ($\leq$ 400 days). This is referenced as mission type 1 throughout the paper.
2. A short amount of astronaut time spent specifically in deep space (i.e., not on the surface of Earth or Mars). This is referenced as mission type 2 throughout the paper.

For mission type 1, a 400-day roundtrip is significantly shorter than typically proposed crewed Mars missions, which often require astronauts to spend 700+ days away from Earth. For mission type 1, we also examine the implications of additionally restricting the Earth-to-Mars flight time because of the benefits of "back-loading" crew time in space. For example, if a crew emergency were to occur during cruise, it is preferable that the crew be on their way to Earth — and ground-based assistance — rather than en-route to Mars.

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All other things equal, decreasing the Earth-to-Mars cruise time reduces the likelihood of a crew emergency happening during this time.

In mission type 2, the overall roundtrip mission duration is allowed to exceed 400 days, which can allow for the combined Earth-to-Mars and Mars-to-Earth transit times to be less than the corresponding transit times for mission type 1. There are two primary motivations for examining mission type 2 in addition to mission type 1. First, some of the most significant deleterious health effects, such as radiation exposure and microgravity exposure, accumulate less rapidly when an astronaut is on the surface of Mars than when they are in deep space. As a result, a 600-day roundtrip that spends 200 days in deep space and 400 days at Mars may be preferable to a 400-day roundtrip that spends 350 days in deep space and 50 days at Mars from a crew health and safety perspective. (These round numbers are merely used to illustrate the concept and are not intended to be representative of specific mission designs.) The second motivation is that longer Mars stay times can significantly reduce fuel requirements for astronaut transit. A longer Mars stay time allows for the crew to wait at Mars for the relative positions of Earth and Mars to align such that a fast Mars-to-Earth transit can be achieved for less fuel than if the Mars stay time is more strictly constrained. Additionally, a longer Mars stay time allows for orbital perturbations to naturally evolve the orbits of Mars-orbiting assets required for the Mars-to-Earth trip (e.g., the crew habitat) such that a reorientation maneuver of the assets' orbit to align themselves with the Mars departure asymptote is likely to require significantly less Δv than if the Mars stay time were more strictly constrained [2, 3].

Regarding food and other supplies needed for the crew, a shorter cruise time may allow for fewer supplies to be transported on-board with the crew to and from Mars. The longer duration spent on the Martian surface will require more supplies at Mars; however, such supplies can potentially be sent in separate launches well in advance of the crewed mission, decreasing the maximum mass required to be carried in any single trip.

A summary of the advantages and disadvantages of minimizing crew time spent in deep space as compared to minimizing overall roundtrip mission duration is presented in Table 1.

Table 1: Potential advantages and disadvantages of minimizing crew time in deep space while increasing time spent at Mars (mission type 2).

Advantage	**Disadvantage**
Shorter time in microgravity	Longer total mission durations
More time available for in situ study of Mars	More resources required at Mars
Fewer resources required in transit	Increased reliability/maintenance requirements on assets at Mars
Lower total Δv requirement for crew's trajectory to/from Mars	Increased multiple health risk due to longer mission duration
Longer time at Mars allows for increased mission schedule flexibility and margin for activities at Mars	

The analyses presented here build on previously published work to develop fast crewed Mars trajectories, while specifically aiming to further optimize and address key concerns with assumptions made in the earlier publications [4–6].

The trade studies described in this paper are focused on Δv requirements and do not make any assumptions regarding the use of a specific propulsion system, including currently unavailable technologies, like Nuclear Thermal Propulsion (NTP). This work is intended to lay the groundwork for further analyses into fast Mars transfer options that examine the concept(s) of operations that may be required to achieve the trajectories described here.

This analysis was performed subsequent to a technical interchange meeting (TIM) with members of the NASA Mars Architecture Team (MAT) in which the authors of this paper attempted to gain a better understanding of realistic values for relevant parameters that could be applied to this study [7]. The authors fully acknowledge that the work of the MAT encompasses a broader scope than trajectory design alone, and the information presented in this paper is not intended to represent a direct competition to MAT studies. Rather, the analysis discussed here is intended to provide a basis for discussion and a groundwork for future analyses into fast Mars transfer options.

METHODS

For this study, GSFC's software tool Evolutionary Mission Trajectory Generator (EMTG) was used for trajectory optimization, with the objective of minimizing end-to-end mission Δv [8–12]. EMTG was used because of its suitability for broad, early-phase trade studies. The scenario was modeled as described in the following bullets. These bullets specifically describe modeling parameters for trade studies of mission type 1, but were also used for trade studies of mission type 2 except where specified in later descriptions.

- The objective function of the optimization is the minimization of end-to-end mission Δv, including contributions from Earth departure, Mars capture, Mars orbit reorientation, Mars departure, Earth arrival, and any intermediate deep-space maneuvers (DSMs). One important note to make is that, in the problem formulation described in the following bullets of this list, EMTG incorporates the Earth-departure maneuver into the objective function as the v_∞ achieved by the Earth departure maneuver. This v_∞ is not necessarily the same as the Δv required to achieve the v_∞. As a result, the actual total mission Δv is not necessarily the same as the objective function evaluated by EMTG. See the next bullet for further details on Earth-departure maneuver assumptions used in the calculation of total mission Δv, as presented in the results of this paper.

- The spacecraft departs Earth using a zero sphere of influence (ZSOI), patched-conic launch assumption. An analytic approximation of the Δv required for Earth escape from periapse of a highly elliptical Earth orbit (periapse altitude = 300 km, apoapse altitude = 318,622 km) is included in the overall Δv total for the mission to approximate the Δv required for Earth escape. Launch vehicle and/or Δv requirements for placing the spacecraft in the initial highly elliptical orbit are *not* included in the results presented here.

- The spacecraft cruises to Mars. During the Earth-to-Mars cruise, the spacecraft is allowed to perform one DSM. The cruise flight time is either unconstrained or constrained to be $\leq$ 60 days, $\leq$ 90 days, or $\leq$ 120 days. The motivation to trade constraints on the Earth-to-Mars flight time in addition to the overall 400-day mission-duration maximum is that, all other factors equal, it is preferable to minimize the Earth-to-Mars transfer time rather than the Mars-to-Earth transfer time. Doing so helps minimize crew risk by placing larger amounts of crew time in deep space later in the mission (i.e., closer to Earth return and Earth-based aid) rather than earlier during the mission.

- At Mars arrival, the spacecraft performs a maneuver at periapse to capture into a 2.5-sol- or 5-sol-period orbit at Mars with a periapse altitude of 250 km. The capture orbit is constrained to have an inclination of 35 deg relative to the true-of-date Mars equatorial frame to allow the crew to reach a landing site with a latitude up to ±35 deg. The orbit size and inclination were selected to be consistent with the assumptions made by the NASA MAT, which were communicated to the authors during a TIM [1,7].

- The spacecraft is required to remain in Mars orbit for approximately 10, 15, or 20 sols (i.e., an integer multiple of the period of the capture orbit). The orbit of the spacecraft at Mars is modeled explicitly, as opposed to the ZSOI, patched-conic modeling of Earth departure. In other words, the central body used for the two-body gravity model switches from the Sun to Mars once the spacecraft enters Mars' sphere of influence (SOI). Once at Mars, Mars is modeled as a gravitating body that the spacecraft orbits, not a point in space that the spacecraft intercepts (as was done in [4,5]). The spacecraft is allowed to perform one maneuver while in Mars orbit to align the spacecraft for its eventual Mars departure maneuver. The central body switches back from Mars to the Sun when the spacecraft exits Mars' SOI. The modeling of additional elements of a full concept of operations (CONOPS) is beyond the scope of the work presented here. Examples of such elements include rendezvous with pre-placed assets in Mars orbit and the maneuvers of the crew vehicle to move to and from the surface of Mars.

- After staying in Mars orbit for the required amount of time, the spacecraft performs a maneuver near periapse (between -5 deg and 5 deg true anomaly) to place it on a trajectory back to Earth.

- The spacecraft cruises to Earth. During the Mars-to-Earth cruise, cases were modeled in which the spacecraft performs no gravity assists or one Venus gravity assist (VGA). The spacecraft is allowed to perform one DSM between each body encounter. The inclusion of a VGA as a trade parameter for the Mars-to-Earth journey was based on the results of a lower-fidelity trade study performed by the authors, which suggested that a VGA during the Mars-to-Earth journey could reduce overall Δv requirements for missions launched during portions of the launch period considered by this trade study. Conversely, the lower-fidelity study suggested that a VGA during the Earth-to-Mars journey would not reduce overall Δv requirements, so a VGA during the Earth-to-Mars journey was not included as a trade parameter in the study used to produce the results presented here.

- Earth arrival is modeled as a ZSOI patched conic intercept with the Earth. As with Earth departure, an analytic approximation of a maneuver at periapse to capture the spacecraft into a highly elliptical Earth orbit (periapse altitude = 300 km, apoapse altitude = 318,622 km) is included in the overall Δv total for the mission to approximate the Δv required for Earth capture. From there, the mission may go a few different directions that were not investigated explicitly in this study. For example, after Earth capture, the crew may enter directly into Earth's atmosphere via an entry capsule (e.g., Orion), or perform additional maneuvers to rendezvous with other assets (e.g., Gateway) before returning to Earth, possibly using a new vehicle obtained at the rendezvous point.

- All trajectory segments are modeled as conics (i.e., two-body, point-mass gravity) for computational speed.

- All propulsive maneuvers (i.e., DSMs, capture/departure maneuvers) are modeled as instantaneous Δv maneuvers.

- The beginning-to-end duration of the type 1 mission is constrained to be 400 days or less.

The trade parameters for the study of mission type 1 trajectories are summarized in Table 2.

Table 2: Trade parameters for mission type 1: $\leq$ 400-day roundtrip trade study.

Trade parameter	Value(s)
Launch date	Jan. 1, 2035 – Dec. 31, 2037
Mars orbit period (sols)	2.5, 5
Time in Mars orbit (sols)	10, 15, 20
Total mission duration (days)	$\leq$ 400
Earth-to-Mars flight time (days)	$\leq$ 60, $\leq$ 90, $\leq$ 120, unconstrained
Gravity assists	None or VGA during Mars-to-Earth journey

An important point to clarify is that the time spent in Mars orbit is not the same as useful crew time spent on the surface of Mars. In general, the more time spent in Mars orbit, the more time the crew can spend on the surface, but the precise correlation depends on multiple factors, including Mars parking orbit period (2.5 sols or 5 sols for this study), surface arrival/departure CONOPS, and overall risk posture. For example, one possible CONOPS involves capturing into Mars orbit at periapse, then having the crew depart the interplanetary vehicle at the first Martian apoapse to then land on the surface near the periapse of the parking orbit. In this CONOPS, a full orbit period passes before the astronauts land on the surface. If the process is reversed to depart the surface (i.e., the ascent vehicle departs the surface when the interplanetary vehicle is near periapse to rendezvous near apoapse, followed by a Mars departure burn at the next periapse), then another full orbit period is required to depart the Mars system after the crew has left the surface of Mars. Thus, if this CONOPS were to be used, 10 sols spent by the interplanetary vehicle in Mars orbit does not actually provide any surface time for the astronauts if the orbit period is 5 sols, and a more aggressive

CONOPS is required to make possible crew surface time. Another option is to decrease the size of the Mars parking orbit, thereby providing additional periapses and apoapses in the same absolute amount of time. However, as discussed later when comparing the Δv requirements for the 2.5-sol and 5-sol Mars orbit cases, this comes with the drawback of requiring additional Δv to capture/escape at Mars with the interplanetary vehicle. Direct entry and/or departure to/from the Martian surface are alternative CONOPS elements that could increase time on the surface.

To summarize, when interpreting the results presented here:

- For a 5-sol capture/parking orbit:
  - A 10-sol stay in Mars orbit requires a CONOPS different from the "traditional" CONOPS described in the previous paragraph or a smaller Mars parking orbit to allow non-trivial crew surface time.
  - A 15-sol stay in Mars orbit results in 5 sols of crew surface time, assuming the CONOPS described in the previous paragraph.
  - A 20-sol stay in Mars orbit results in 10 sols of crew surface time, assuming the CONOPS described in the previous paragraph.
- For a 2.5-sol capture/parking orbit:
  - A 10-sol stay in Mars orbit results in 5 sols of crew surface time, assuming the CONOPS described in the previous paragraph.
  - A 15-sol stay in Mars orbit results in 10 sols of crew surface time, assuming the CONOPS described in the previous paragraph.
  - A 20-sol stay in Mars orbit results in 15 sols of crew surface time, assuming the CONOPS described in the previous paragraph.
- For all cases, depending on risk posture, a smaller Mars parking orbit may also be required to yield desired crew surface time.
- For a given Mars orbit stay time, the amount of crew surface time could be increased by decreasing the size of the Mars parking orbit, at the cost of increasing the Δv required to capture/escape at Mars and possibly increasing the Δv required to reorient the orbit at Mars.

Modifications for Longer Stay-Time Trajectories (Mission Type 2) For mission type 2, a few modifications to the above methods are made.

- Longer Mars stay times are used as specified in Table 3.
- Maneuvers to reorient the capture orbit at Mars are not computed. Modeling the orbit at Mars for the extended stay-times considered would require propagations for many revolutions about Mars, which can be challenging for EMTG to compute rapidly and would significantly slow down the large trade study analysis. Arrival and departure maneuvers are calculated analytically, assuming periapse maneuvers in the $\pm v$ direction (using the same methodology used to compute maneuvers for Earth orbit departure and arrival). Maneuver sizes for Mars orbit orientation changes are assumed to be similar or less than those computed for mission type 1 due to the longer Mars stay times [2].
- No VGAs or any other gravity assists (GAs) are considered. Only direct transfers from Earth to Mars and from Mars back to Earth are analyzed.
- The launch date search is truncated (see Table 3) to capture just one Earth-Mars synodic period. The full 3-year span of launch dates considered for mission type 1 is not necessary with Earth and Mars being the only two bodies of interest (i.e., no GAs).

- Only 5-sol Mars orbits are considered. Due to the long stay time, there is less of a need for a shorter Mars orbit to enable realistic CONOPS.

Table 3: Trade parameters for Mission Type 2: Longer Mars Stay Times.

Trade parameter	Value(s)
Launch date	Jan. 1, 2035 – Feb. 28, 2037
Mars orbit period (sols)	5
Earth-to-Mars ToF (days)	0-125, 125-150, 150-200, 200-300
Mars Stay Time (days)	0-180, 180-360, 360-540, 540-720, 720-900
Mars-to-Earth ToF (days)	0-125, 125-150, 150-200, 200-300

RESULTS

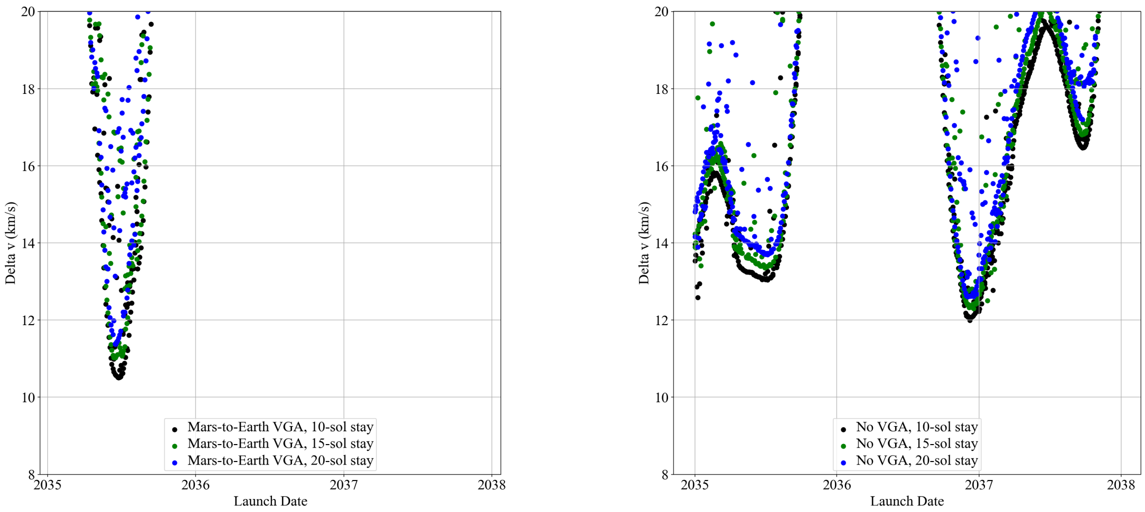
Mission Type 1: 400-Day Roundtrip Trajectories: Unconstrained Earth-to-Mars Flight Time

This section describes candidate trajectories whose Earth-to-Mars flight time is not specifically constrained, though the total mission flight time is constrained to be less than 400 days. Figures 1 and 2 show Δv as a function of launch date for the launch period investigated for the 5-sol and 2.5-sol parking orbit cases, respectively. The different marker colors in the figures represent different Mars orbit stay times. Heliocentric views of the overall minimum-Δv trajectories with round trips $\leq$ 400 days found in the trade study are given in Figure 3.

When examinging Figures 1 and 2, it is clear that not every point solution represents the global minimum Δv requirement for a given launch date due to the presence of "stray" markers. Nevertheless, broad trends are visible, and several comments may be made about the data:

- There are multiple local minima in the figures: There is a local minimum in June/July 2035 both for the no-VGA case and the Mars-to-Earth VGA case; there is a local minimum in December 2036 for the no-VGA case; and there is a local minimum in September 2037 for the no-VGA case (one Earth-Mars synodic period after the June/July 2035 opportunity).
- The overall lowest-Δv cases found are for the Mars-to-Earth VGA scenario using a June/July 2035 launch. The smallest Δv values are given in Table 4.
- If no VGA is allowed, then the overall lowest-Δv cases are found during the December 2036/January 2037. The smallest Δv values are given in Table 5.
- Thus, for the launch period considered, the lowest-Δv trajectory with a Mars-to-Earth VGA requires on the order of 1.5 km/s less Δv than the lowest-Δv trajectory found with no GAs.
- As expected, increasing the Mars orbit stay time from 10 to 20 sols increases the Δv requirement. The "penalty" for increasing the stay time by 5 sols varies but is on the order of several hundred m/s.
- Also as expected, a shorter Mars parking orbit period increases the Δv requirement.

Tables 4 and 5 show the overall minimum-Δv trajectories found for the cases with and without a VGA, respectively. For 10-sol Mars orbit stay times, additional details are given for the minimum-Δv cases in Table 6. These trajectories are also plotted in Figures 3a and 3b, respectively. One observation from these additional representations of the data is that the minimum-Δv trajectory with a VGA takes the spacecraft marginally within Venus' orbit (Figure 3a), and even the no-VGA trajectory takes the spacecraft to approximately Venus' orbital distance from the Sun (Figure 3b). The 400-day roundtrip necessitates passing inside Earth's orbit, and a spacecraft designed for such a mission concept must be outfitted with appropriate thermal shielding to ensure the safety of the spacecraft and the astronauts onboard. On the other hand, maximum solar distances



(a) Δv as function of launch date for 5-sol Mars parking orbit, with VGA.

(b) Δv as function of launch date for 5-sol Mars parking orbit, without VGA.

Figure 1: Δv as function of launch date for 5-sol Mars parking orbit, with and without VGA.

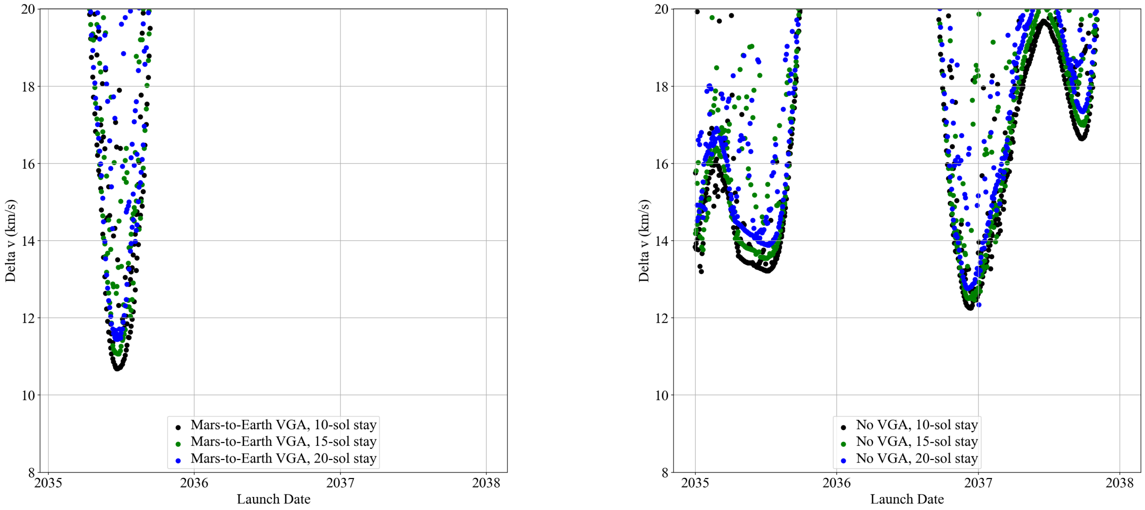
are approximately equal to Mars' orbital distance; greater solar distances are generally incompatible with the short flight time requirement.

Another observation, from Table 5, is that the minimum-Δv solution for a 20-sol stay with no VGA and a 2.5-sol Mars parking orbit is *less* than the minimum-Δv solution for a 15-sol stay with no VGA and a 2.5-sol Mars parking orbit. This is incongruent with the general trends presented in Figures 1 and 2, in which increasing Mars orbit stay time results in an increase in Δv requirements. The explanation for this result is the inconsistency between the EMTG objective function and the total mission Δv as reported in this paper. The 20-sol, 2.5-sol-orbit-period, no-VGA trajectory uses a much larger Earth departure v_∞ than the 15-sol, 2.5-sol-orbit-period, no-VGA trajectory, but the former requires less Δv to perform subsequent maneuvers than the latter. At the same time, the difference between the Δv values required to achieve the Earth-departure v_∞ values is smaller than the v_∞ difference itself. Thus, this is an example of a case in which optimization of the EMTG objective function results in a different trajectory than would optimization of total Δv as reported in this paper.

Table 4: Minimum-Δv trajectories, VGA during Mars-to-Earth transfer, for $\leq$ 400-day roundtrip trade study.

Mars orbit stay time	Mars parking orbit period	Launch date	Earth-to-Mars flight time	Total Δv
10 sols	5 sols	6/25/2035	132 days	10.507 km/s
15 sols	5 sols	6/17/2035	127 days	11.023 km/s
20 sols	5 sols	6/17/2035	126 days	11.377 km/s
10 sols	2.5 sols	6/23/2035	131 days	10.684 km/s
15 sols	2.5 sols	6/25/2035	130 days	11.072 km/s
20 sols	2.5 sols	6/23/2035	128 days	11.443 km/s

Figures 4 and 5 show total Δv as a function of Earth-to-Mars flight time. In addition to the stray data points providing further verification that additional optimization is possible for some cases, it is clear that all local minima previously described have an Earth-to-Mars flight time well over 100 days (approximately 125 days for the minimum-Δv VGA case).



(a) Δv as function of launch date for 2.5-sol Mars parking orbit, with VGA.

(b) Δv as function of launch date for 2.5-sol Mars parking orbit, without VGA.

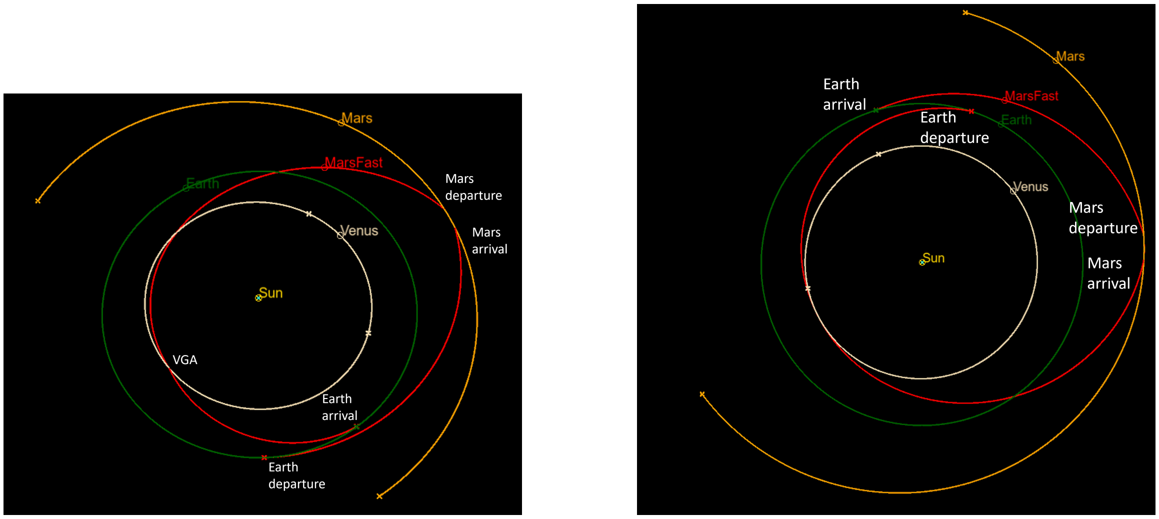
Figure 2: Δv as function of launch date for 2.5-sol Mars parking orbit, with and without VGA.

Table 5: Minimum-Δv trajectories, no VGA during Mars-to-Earth transfer, for $\leq$ 400-day roundtrip trade study.

Mars orbit stay time	Mars parking orbit period	Launch date	Earth-to-Mars flight time	Total Δv
10 sols	5 sols	12/8/2036	258 days	11.990 km/s
15 sols	5 sols	12/18/2036	244 days	12.295 km/s
20 sols	5 sols	12/3/2036	253 days	12.600 km/s
10 sols	2.5 sols	12/11/2036	257 days	12.256 km/s
15 sols	2.5 sols	12/21/2036	236 days	12.470 km/s
20 sols	2.5 sols	1/2/2037	217 days	12.346 km/s

Table 6: Trajectory characteristics for minimum-Δv trajectories for 10-sol Mars orbit stay times, for $\leq$ 400-day roundtrip trade study.

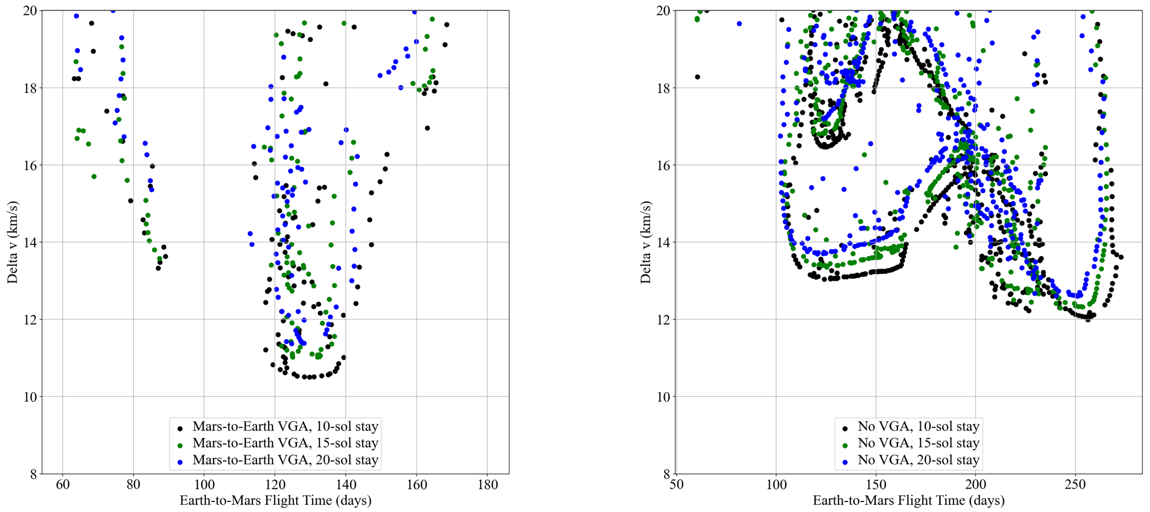
Trajectory characteristic	With VGA, 5-sol orbit	With VGA, 2.5-sol orbit	Without VGA, 5-sol orbit	Without VGA, 2.5-sol orbit
Dates				
Earth departure date	6/25/2035	6/23/2035	12/8/2036	12/11/2036
Mars orbit capture date	11/4/2035	11/2/2035	8/24/2037	8/24/2037
Mars orbit departure date	11/14/2035	11/12/2035	9/3/2037	9/3/2037
Earth arrival date	7/29/2036	7/27/2036	1/12/2038	1/15/2038
Timespans				
Earth to Mars capture (days)	132	131	258	257
In Mars orbit (sols)	10	10	10	10
Mars departure to Earth arrival (days)	258	258	132	133
Total mission duration (days)	400	400	400	400
Maneuvers (km/s)				
Earth departure	0.810	0.825	0.762	0.739
Earth-to-Mars DSM	0.000	0.000	2.728	2.787
Mars capture	2.609	2.731	3.125	3.239
Mars orbit reorientation	0.340	0.479	0.458	0.568
Mars departure	5.660	5.537	3.784	3.869
Mars-to-Earth DSM (no VGA)	N/A	N/A	0.000	0.000
Pre-VGA DSM	0.000	0.000	N/A	N/A
Post-VGA DSM	0.000	0.000	N/A	N/A
Earth capture	1.089	1.112	1.132	1.055
Total Δv	10.507	10.684	11.990	12.256
VGA				
Date	5/13/2036	5/13/2036	N/A	N/A
Altitude (km)	1004	1076	N/A	N/A



(a) Minimum-Δv 400-day round trip solution found with VGA.

(b) Minimum-Δv 400-day round trip solution found without VGA.

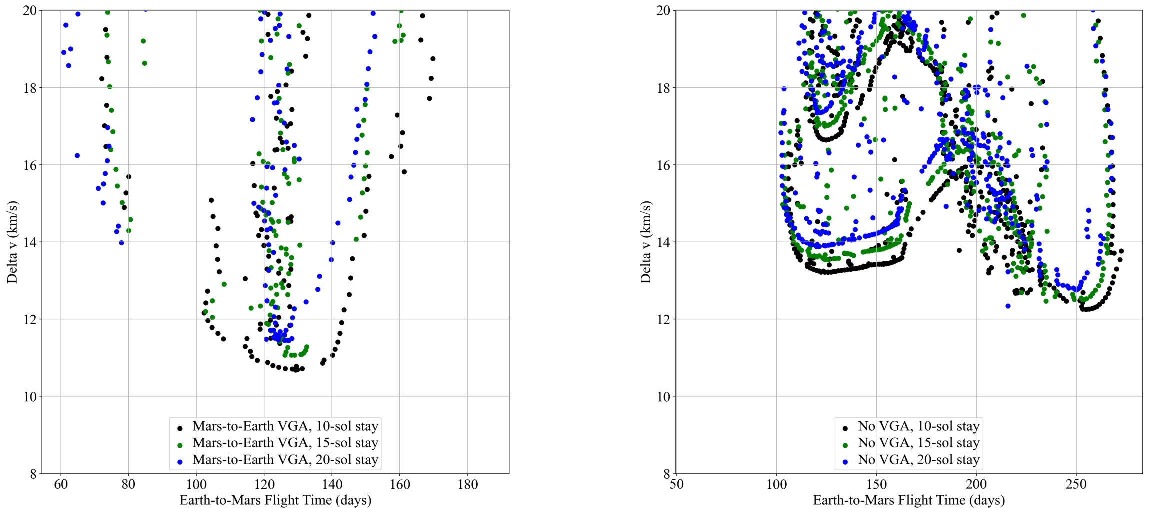
Figure 3: Minimum-Δv 400-day round trip solutions.



(a) Δv as function of Earth-to-Mars flight time for 5-sol Mars parking orbit, with VGA. Earth-to-Mars flight time is unconstrained.

(b) Δv as function of Earth-to-Mars flight time for 5-sol Mars parking orbit, without VGA. Earth-to-Mars flight time is unconstrained.

Figure 4: Δv as function of Earth-to-Mars flight time for 5-sol Mars parking orbit, with and without VGA. Earth-to-Mars flight time is unconstrained.



(a) Δv as function of Earth-to-Mars flight time for 2.5-sol Mars parking orbit, with VGA. Earth-to-Mars flight time is unconstrained.

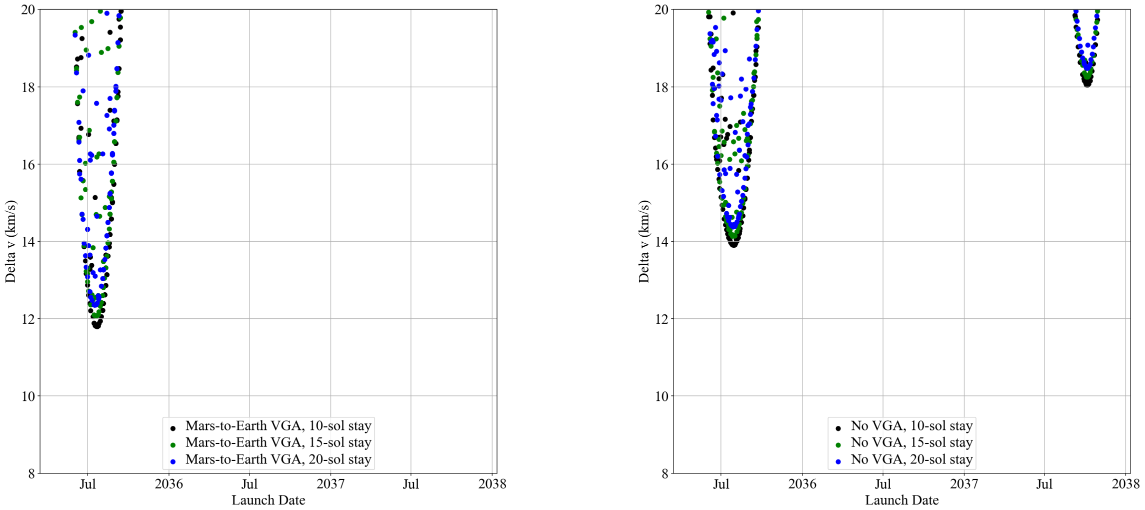
(b) Δv as function of Earth-to-Mars flight time for 2.5-sol Mars parking orbit, without VGA. Earth-to-Mars flight time is unconstrained.

Figure 5: Δv as function of Earth-to-Mars flight time for 2.5-sol Mars parking orbit, with and without VGA. Earth-to-Mars flight time is unconstrained.

Mission Type 1: 400-Day Roundtrip Trajectories: Constrained Earth-to-Mars Flight Time

This section describes trajectories resulting from constraining the Earth-to-Mars flight time to be no greater than 60, 90, or 120 days. As expected based on Figures 4 and 5, the Δv values are greater than for the unconstrained case. For a 60-day Earth-to-Mars flight time, no solutions have been found with a total Δv less than 20 km/s, and no further details of 60-day cases are discussed here. On the other end of the spectrum, the Δv penalty for restricting the Earth-to-Mars flight time to no greater than 120 days is relatively small (on the order of 100 m/s) for the summer 2035 launch opportunities. This is because the Earth-to-Mars flight time for the Δv-optimal case is only marginally greater than 120 days even when the Earth-to-Mars flight time is unconstrained. However, the Δv penalty on the December 2036/January 2037 launch opportunities is much larger because of the 260-day Earth-to-Mars flight time for the Δv-optimal case when the Earth-to-Mars flight time is not constrained. In fact, the summer 2035 launch opportunities require 4 km/s less Δv than the December 2036/January 2037 launch opportunities when the Earth-to-Mars flight time is constrained to 120 days, while the December 2036/January 2037 launch opportunities require less Δv than the summer 2035 launch opportunities when the Earth-to-Mars flight time is unconstrained.

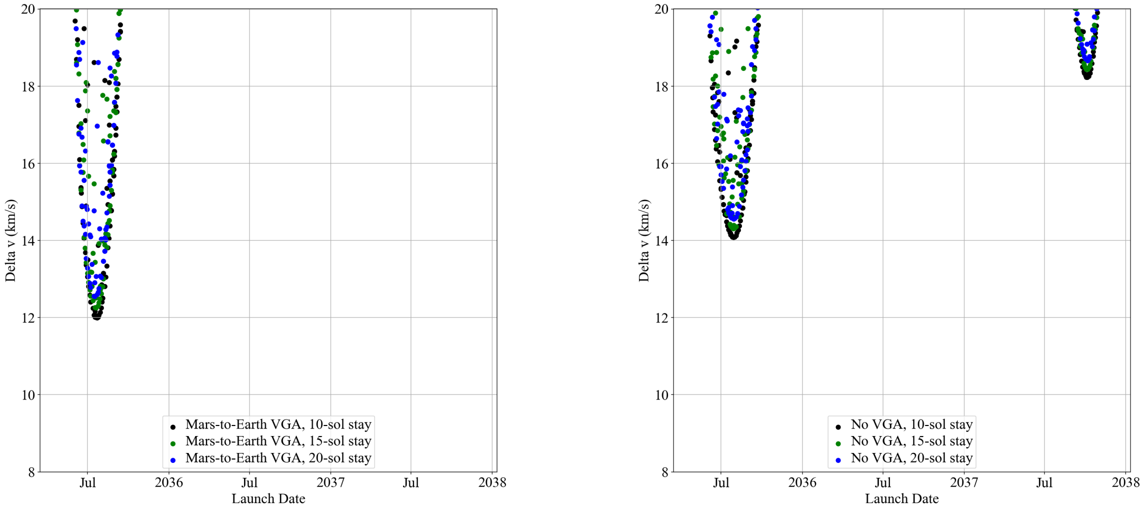
For a 90-day Earth-to-Mars flight time, the Δv penalty grows to 1 km/s for the summer 2035 launch opportunities, with or without a VGA during the Mars-to-Earth leg. The lowest-Δv trajectory found (with a VGA) requires nearly 12 km/s of Δv. The 90-day limited case is shown in Figures 6 and 7.



(a) Δv as function of launch date for 5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, with VGA.

(b) Δv as function of launch date for 5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, without VGA.

Figure 6: Δv as function of launch date for 5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, with and without VGA.



(a) Δv as function of launch date for 2.5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, with VGA.

(b) Δv as function of launch date for 2.5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, without VGA.

Figure 7: Δv as function of launch date for 2.5-sol Mars parking orbit with Earth-to-Mars time of flight no greater than 90 days, with and without VGA.

Mission Type 2: Short Deep-Space Time, Long Mars Stay Times

As described in the Introduction, an alternative option to strictly enforcing a 400-day total mission duration is to focus on minimizing crew time in deep space rather than minimizing end-to-end mission duration. Benefits of this approach include reducing health risks that accumulate as time in deep space accumulates (e.g., radiation, microgravity), and the potential reductions in total mission Δv attainable by allowing astronauts to spend time on the surface of Mars while Earth and Mars "realign themselves."

The high Δv values found from the previous analyses is driven by the relative positions of Earth and Mars and their orbits about the Sun. Ideally, the crew can wait at Earth until the optimal relative positions of Earth and Mars occur for the trip to Mars. Once at Mars, the crew would then wait until the optimal relative geometries are achieved for the trip back to Earth. If the crew is required to leave Mars quickly enough to return to Earth within 400 days of Earth departure, there is not sufficient time for Earth and Mars to drift into position for an efficient transfer from Mars to Earth. In the previous analyses, the optimal solutions are simply the best that can be done with non-optimal planetary geometries for minimizing Δv, but are necessary if total round trip time is constrained to 400 days. On the other hand, long stay times necessitate the habitats and supplies at Mars must be ready for use with very high confidence for the crew to stay many months to years without the luxury of aborting back to Earth in an emergency. Thus, this concept likely requires extensive testing and development of habitats on the Moon and robotically/remotely on Mars before the crew is sent on such an voyage. (See Table 1 for additional advantages and disadvantages of mission type 2 relative to mission type 1.)

The results from the long-stay analysis are shown in Fig. 8 for trajectories with total mission $\Delta v \leq 20$ km/s. The vertical axis shows total mission Δv, the horizontal axis shows the total cruise duration (i.e., the sum of cruise times to and from Mars), and the color bar shows the stay time at Mars. The vertical bands visible on certain time of flights (TOFs) are due to the optimizer maximizing the allowed flight time up to the constrained maximum value, in order to minimize the total mission Δv. (Maximum TOFs considered are given in Table 3.) For a given point on the plot, the total mission duration is the sum of the total cruise duration and Mars stay time.

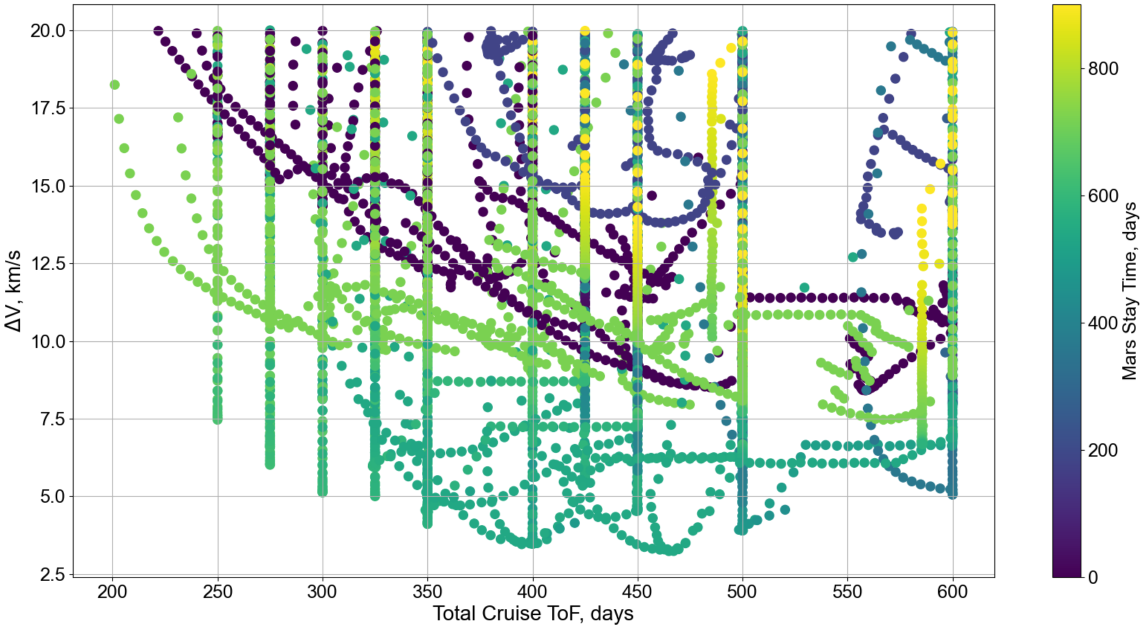


Figure 8: Minimum Δv trade-study results for Mission Type 2: Long Mars Stay Time.

It is immediately apparent from the plot that substantial Δv can be saved and/or total cruise duration can be significantly reduced with this mission type (mission type 2) compared to the 400-day round trip (mission type 1). Some select cases are highlighted in Table 7. For example, for a 395-day cruise, a Δv of only 3.46 km/s is achievable, but requires a 540-day stay time at Mars. Another 200 m/s can be saved if the cruise duration is extended to 465 days; this is the smallest ΔV solution found in the analysis. Of the solutions with $\Delta v \leq 10$ km/s, the minimum cruise duration is 250 days and requires a Δv of 7.5 km/s and a Mars stay time of 888 days. All of the highlighted solutions in Table 7 have a smaller Δv than the 400-day round-trip cases, and all but one have a similar or shorter cruise duration. This observation still holds even if realistic additional Δv (e.g., 500 m/s) is earmarked for Mars orbit reorientation maneuver(s).

Table 7: Select trajectories for mission type 2: short cruise time, long Mars stay time.

Launch Date	Total Cruise Duration	Mars Stay Time	Total Mission Duration	Total Δv
7/5/2035	465 days	540 days	1005 days	3.24 km/s
7/10/2035	395 days	540 days	935 days	3.46 km/s
8/4/2035	372 days	540 days	912 days	4.13 km/s
7/30/2035	275 days	618 days	893 days	6.05 km/s
7/25/2035	250 days	638 days	888 days	7.47 km/s

DISCUSSION AND FUTURE WORK

This feasibility study represents an initial investigation to update and improve upon the fast Mars mission architecture presented in [4] and [5]. The analysis techniques and assumptions used here address some potential concerns with the assumptions made in [4] and [5], such as:

- Stay time at Mars. This analysis increases the Mars stay time, examining cases with stay times in orbit at Mars of up to 20 sols for 400-day round trips and much longer stay times for the type 2 mission concept. The type 2 concept additinoally reduces crew time in deep space and/or total Δv requirements relative to the 400-day round trip mission concept. In addition, this analysis examines Mars parking orbit periods of 2.5 sols and 5 sols, providing insight into the trade between Δv and parking orbit size.
- Earth return. This analysis does not assume direct entry to Earth upon return and includes Δv for capture into a highly elliptical Earth orbit in the overall Δv budget.

Nevertheless, additional design elements discussed in [4] must be evaluated in future work to assess mission architecture feasibility. This list includes:

- Distribution of staging and propellent resources (e.g., propellant depots in cislunar space and/or at Mars) and prepositioning of assets. These elements were integral to the architecture proposed in [4] and make feasible larger end-to-end Δv requirements when compared to architectures that do not use staging or prepositioning.
- Propulsion system selection and design.
- Crew asset design, including interplanetary vehicle/habitat, Mars landing and ascent vehicles, and Mars surface habitat.
- Food and water requirements and distribution.

This list forms part of the multitude of directions in which future work could proceed to increase the realism of the preliminary results presented here and/or further explore the trade space of possibilities for a fast Mars transfer. Many of these activities will necessarily require input from subject matter experts in realms outside of astrodynamics. Possible work includes:

- Investigation of the tradeoffs between crew time spent in interplanetary space vs. time spent at Mars vs. total mission duration, and the impact of the three on the crew's physical and mental health. Such work is necessary to supplement the discussion of flight dynamics differences between mission types 1 and 2 presented in this paper. In other words, the results described in this study indicate that substantial Δv savings are achievable by selecting mission type 2 instead of mission type 1, but further investigation is needed to clarify whether mission type 2 is superior to type 1 from perspectives besides flight dynamics.
- Exploration of additional launch dates. This work examined a 3-year launch period (2035—2037), which covers slightly more than one Earth-Mars synodic period. However, there are differences in Δv requirements from one synodic period to the next, as well as other time-dependent effects, ranging from the physical (e.g., solar cycle, availability of VGAs) to the programmatic (e.g., launch vehicle availability, propulsion system availability, funding profiles) that necessitate the investigation of a longer time period for launches.
- Investigation of launch-period duration requirements for the fast Mars transfer option and comparison with the launch-period duration requirements of alternative architectures.
- Investigation of the risks and benefits of using pre-positioned propellant assets (e.g., in Mars orbit) vs. bringing all resources to Mars at once to determine whether currently available chemical propulsion systems are viable to perform the maneuvers required by a fast Mars transfer.

- Investigation of mission duration constraints between the 400-day value studied in this report and durations of greater than 800 days proposed in alternate architectures.
- Investigation of the effects of different propulsion systems on the trajectories. The work presented here assumes Δv impulses for all maneuvers to simplify the optimization problems. In reality, of course, these maneuvers are finite burns that do not occur instantaneously. Modeling the maneuvers more realistically allows for (1) the estimation of fuel requirements for different propulsion systems and (2) the estimation of the effects of finite burn losses (e.g., the reduction in the efficiency of a maneuver because it does not occur instantaneously at the optimal time). This includes the investigation of the use of cutting-edge or near-future propulsion technologies like NTP.
- Further inclusion of realistic CONOPS constraints. The work presented in this study attempts to approximate some CONOPS constraints, such as the inclination of the Mars orbit to allow the astronauts to achieve a desired landing site. However, there are many potential CONOPS constraints that were not considered in this study. Further refinement of a realistic CONOPS and inclusion of derived requirements on the trajectory is needed to make results directly comparable with those produced by previous studies that were based on a fully developed CONOPS. To give one example, this work did not examine the requirements for a crew "taxi" vehicle at Mars to take the astronauts from the primary interplanetary vehicle to the Mars surface.
- Investigation of the implications of using the Lunar Gateway and possible Mars Gateway as staging areas.
- Investigation of the implications of the trajectory options on the overall mission architecture. Perhaps mostly importantly, this work has not attempted to address how many launches would be required to pre-position assets in the Earth-Moon system and/or at Mars to accomplish a fast crewed Mars mission.
- Investigation of the risks and beneifts of using Earth-Mars cycler trajectories. One of the key trades is that, while cycler trajectories potentially enable multiple missions to Mars using currently available propultion systems with significant propellant savings, these architectures require hyperbolic rendezvous of the crew with an interplanetary vehicle that has been prepositioned on the cycler trajectory. Such a rendezvous is required both at Earth departure and Mars departure, and may require the ability to abort the rendezvous to produce an acceptable risk level.
- Increase modeling fidelity. In particular, the Earth departure and Earth arrival events are modeled using ZSOI patched-conic events and therefore do not represent true flyable trajectories. At the same time, changing the modeling fidelity is unlikely to result in a large change in Δv requirements unless other assumptions also change (e.g., the size of the Earth-return capture orbit).
- Investigation of additional factors that were not the focus of this study, but that may drive aspects of the trajectory design. For example, the mental health of the crew in isolation may play a role in the maximum allowable curise flight time to and from Mars (in addition to restrictions based on exposure to microgravity and radiation). Mental health in isolation may also play a role in crew size — which drives vehicle mass and resource needs in space and at Mars — and how many crew members venture to the Martian surface vs. stay in Mars orbit. These factors could have direct impacts on the trajectory requirements and therefore the feasibility of the mission.

As is evident from the number of items in the above list, the authors readily acknowledge that the contents of this paper do not represent the end of the discussion of fast crewed Mars mission concepts. Rather, due to the very strong crew health benefits of limiting mission duration, and, in particular, time spent in deep space, we wish to stimulate ongoing discussions to fully assess the feasibility of these mission concepts.

CONCLUSIONS

This study presents trajectories obtained by minimizing the Δv required for a crewed mission to Mars with a total flight time no greater than 400 days, with 10-to-20 sols spent in a Mars parking orbit, with orbit periods of 2.5 or 5 sols (mission type 1). This study also describes trajectories that seek to specifically reduce the time spent by the crew in deep space while allowing for the total mission duration to exceed 400 days (mission type 2). The additional time is spent at Mars. The longer-stay-time solutions require much lower Δv due to the realignment of Earth and Mars that occurs while the astronauts are at Mars. A list of future work activities—inside and outside the astrodynamics field—is presented as next steps toward moving from a set of candidate trajectories to more fully fledged Mars mission architectures.

Mission type 1 likely requires prepositioned propellant depots and staging due to the large Δv required. On the other hand, mission type 2 requires increased prepositioned resources for the crew on Mars (e.g., food and habitats) due to the long Mars stay time. The key next step in developing mission type 1 is to estimate the amount of propellent required and identify a feasible staging plan to accommodate it. The key next step for mission type 2 is to assess the amount of crew resources required at Mars and the feasibility of positioning these resources at Mars prior to crew arrival. Mission type 2 is simpler from a trajectory design perspective, but will likely require extensive testing of the Mars habitats and life-support systems on Earth, the moon, and possibly remotely on Mars to ensure that these systems will have an extremely high likelihood of working when the crew arrives for their long stay at Mars. Solving this challenge (and many others) is beyond the scope of this trajectory study, but is essential if the type 2 option is to be considered for flight. Depending on the outcomes of this future work, one of these two mission types may be the best option NASA has to get a human crew to the surface of Mars and return them safely and in good health in a reasonable timeframe.

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