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Inspiration Mars 2018 Free-Return Opportunity

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All Mars free-return trajectories to Earth are found over this century, which are comparable to the Inspiration Mars mission. Trajectories are found emphasizing the desirable characteristics of a short total time-of-flight (TOF), low launch energy, and low Earth arrival entry speed. These trajectory characteristics are chosen such that the mission is feasible for human space-flight using current technology. It turns out that the 2018 trajectory outlined in the Inspiration Mars mission is the best opportunity this century, an occurrence that warrants investigation. A time-free ephemeris model is constructed allowing the Earth-Mars relative geometry to be arbitrarily chosen, revealing what conditions create trajectories similar to the 2018 opportunity. Insight to where desirable trajectories occur comes from analyzing radial distance plots of trajectories existing this century. The most desirable free-return trajectories occur when launched around Earth's perihelion, while also arriving around Mars's perihelion.

Nomenclature

E	= Eccentric anomaly, rad
e	= Orbital Eccentricity
n	= Mean motion, rad/s
V	= Velocity, km/s
V_∞	= Hyperbolic excess velocity, km/s
C_3	= Square of Earth launch hyperbolic excess velocity, km^2/s^2
t_p	= Time past perihelion, s
Subscripts	
Arr	= Earth arrival

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I. Introduction

Mars has been a destination of interest for human space-flight for over half a century [1-15]. Due to the orbital positions of Earth and Mars, it is found that a launch date set in early 2018 is the best opportunity for a human free-return mission to Mars this century. The 2018 trajectory, found by Patel et al. [10], became a main source of motivation for Inspiration Mars, a proposed human free-return mission to Mars made by Dennis Tito et al. [13]. Tito and his colleagues selected one of the trajectories on January 5, 2018, and performed a successful high-fidelity numerical integration to confirm its existence. This trajectory was selected due to its 'fast' time of flight (TOF), low Earth launch energy and low Earth re-entry speed.

The question then arises as to how often these types of trajectories exist, and whether or not another desirable opportunity like the 2018 trajectory exists sometime nearby in case the 2018 one cannot be launched. The metrics used in evaluating a desirable opportunity is the Earth launch energy and re-entry speed such that the mission can be flow using current technology. It turns out that the TOF, which is usually of concern to human missions, remains around 500 days for all the candidates of this type of mission, so it is not given any weight in the decision process. Opportunities similar to 2018 occurs approximately every 15 or 17 years, however the 2018 trajectory demonstrates to be superior overall.

II. Methodology

A. Broad Search Using Satellite Tour Design Program (STOUR)

The Satellite Tour Design Program (STOUR), capable of designing interplanetary missions using patched conics, was designed by engineers at JPL [16]. STOUR was then made fully automated by Williams [17] and Longuski et al. [18], finding every interplanetary trajectory with only a few user inputs written on a scripted file. The STOUR program can find rapid Mars free-return trajectories using by stepping through the user-specified launch dates and launch energies. The results are then consolidated, and the desirable trajectories are selected with low launch energies and low re-entry speeds.

After compiling all of the trajectories found using STOUR, the results are filtered based on the launch energy (C_3) and arrival speed (V_{Arr}). Using the 2018 opportunity as the baseline, the desirable trajectories are ones that possess a similar C_3 and V_{Arr}.

B. Radial Distance Plots and the Time-Free Ephemeris (TFE)

Radial distance plots of Earth, Mars, and the spacecraft's positions exhibit trends to provide low Earth launch and re-entry energies. The good trajectories tend to depart Earth at its perihelion, and intercept Mars at its perihelion. The departure from Earth and swing-by of Mars at their closest approaches to the Sun makes sense, as the most energy is transferred to a spacecraft with respect to the Sun when the body is travelling its fastest. Each synodic period of Earth and Mars is approximately two and one-seventh years; the synodic period varies due to the relative inclinations and nonzero eccentricities of the two planets. When these variations are small compared to the 2018 opportunity, a similar desirable trajectory exists.

To gain further insight to when a desirable Mars free-return trajectory exists, a time-free ephemeris model is constructed to see exactly which relative Earth-Mars positions are ideal. The time-free ephemeris model is an ephemeris built under the pretense that the positions of Earth and Mars can be at any position at any given time along their heliocentric paths. A further assumption imposed, is that the heliocentric paths of Earth and Mars remained fixed, and their orbital elements do not change due to perturbations from other planets. The aforementioned radial distance plots give insight where to search for desirable trajectories along Earth's and Mars's orbital paths.

The trajectories found using the TFE have C_3 and V_{Arr} that are as good, or are better than the 2018 opportunity. It is then possible to see the necessary relative geometry that Earth and Mars must have for these "best-case" free-return trajectories.

III. Results

A. Best Case Mars Free-Returns Found this Century

The STOUR program was used to find launch dates for Mars free-return trajectories over this century, logging all candidates that had launch energies below 43 km^2/s^2, Mars fly-by altitudes greater than 200 km, and Earth re-entry speeds less than 14.5 km/s, based at 100 km altitude (these numbers are denoted as Inspiration Mars, or IM constraints from now on). Figure 1 shows the output from STOUR with a search ranging from January 1, 2000 to December 31, 2099. The step size in Earth launch V_∞ ranged from 6 km/s to 7 km/s with a step size of 0.1 km/s, however only results set by the above constraints are shown on the plot.

It turns out that the types of trajectories satisfying the IM constraints appear every 15, and sometimes 17 years, with the best appearing in late 2017/early 2018. Since the synodic period of Earth and Mars is roughly two and one-seventh years, the inertial geometry repeats every seven synodic periods, or 15 years. Due to the nonzero inclinations of Mars and nonzero eccentricities of both Earth and Mars, the "best-case" missions can appear one synodic period later, creating the occasional 17-year time increment.

Out of the 100-year search, the seven trajectories listed in Table 1 are the trajectories found this century that closely match the 2018 opportunity, with the second entry representing IM mission. The trajectory closest to the IM mission is the last entry corresponding to a launch in 2097–a date far off, where hopefully humans will not just be performing free-return flybys of Mars. The first entry, the most recent free-return trajectory closest to the IM mission in 2000 portrayed a high C_3 which violated the upper bound of 43 km^2/s^2 set by the IM constraint, as well as a high V_{Arr}. The next best Mars free-return occurs about 15 years later from 2018, in late 2032,

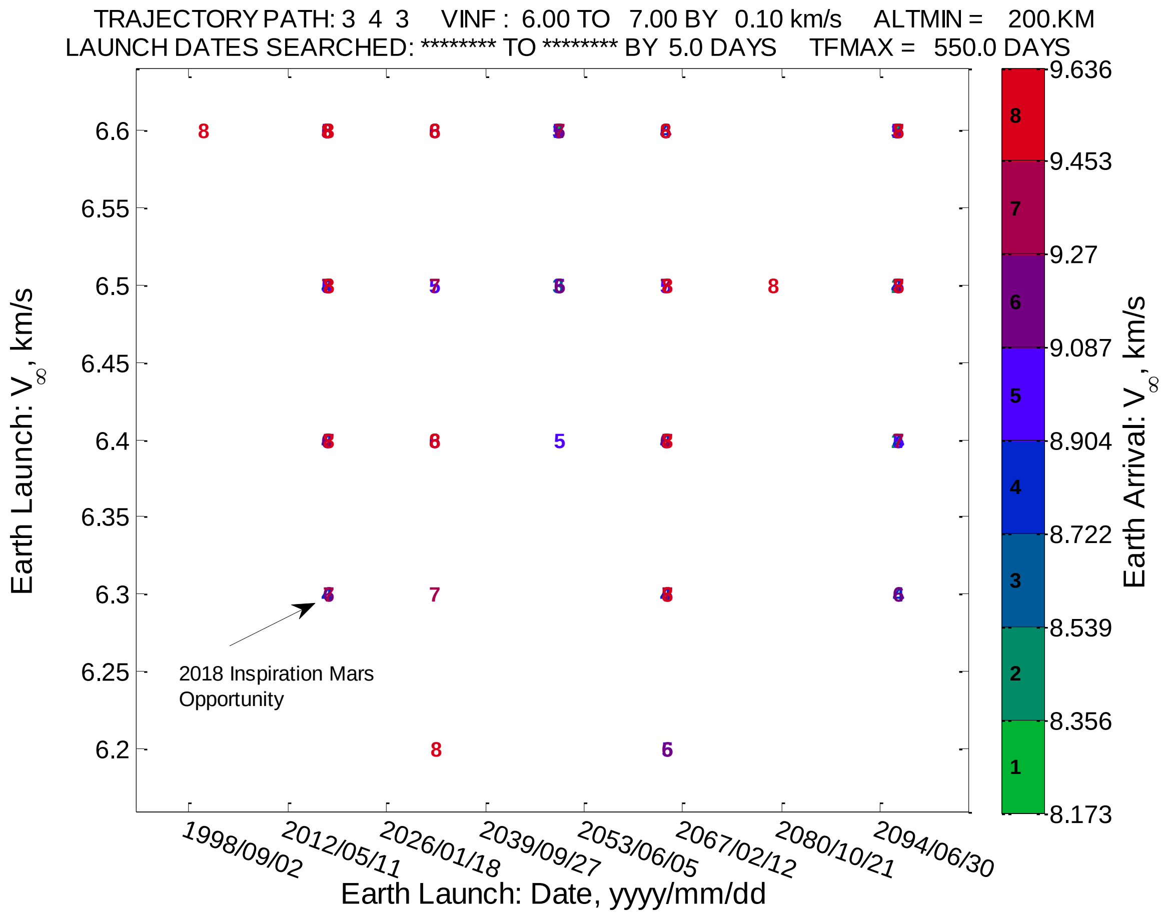

Figure 1. Mars free-return trajectories found using STOUR spanned over this century (01/01/2000 – 12/31/2100). Each trajectory displayed satisfies the IM constraints of C_3 less than 43 km^2/s^2, Mars fly-by altitudes greater than 200 km, and Earth re-entry speeds less than 14.5 km/s.

Table 1 Mars free-return trajectories this century that display Earth launch energies and Earth entry speeds comparable to the Inspiration Mars 2018 opportunity[‡‡]

Earth Launch Date (mm/dd/yyyy)	C_3 (km^2/s^2)	V_{Arr} (km/s)
11/11/2000	43.6	14.5
12/25/2017	40.2	14.0
12/08/2032	38.4	14.4
01/23/2050	41.0	14.1
12/20/2064	39.1	14.1
11/17/2079	42.3	14.4
12/22/2096	41.0	14.0

with a lower C_3 of 38.4 km^2/s^2, but higher entry speed of 14.4 km/s. It is clear from Table 1 that the IM trajectory in 2018 (represented by the second entry) is the best found this century in terms of its V_{Arr}. In terms of metrics, V_{Arr} is weighted a bit more over C_3 due to limitations in current technology. According to SpaceX, the Falcon Heavy, advertised to be launched sometime in 2014, will be able to propel 13.2 tons to Mars which is sufficient for the

[‡‡] The entry occurring on 01/01/2018 is the trajectory closest to the trajectory announced by Tito et al. [13].

estimated payload mass for the Inspiration Mars mission. The entry speed limitation is more of a critical design factor since current technologies can handle entry speeds of about 14.5 km/s or less; thus the lower the entry speed, the more desirable the trajectory.

B. Radial Distance Plots

Radial distance plots are constructed to identify trends in the planets' positions that make the trajectories desirable. Over a specified time period, the radial distance of Earth, Mars and the spacecraft's trajectory with respect to the Sun are plotted allowing a visualization of the where on the planets' orbits the spacecraft is performing the flybys.

Figure 2 shows the three best free-return opportunities this century. The first plot is an opportunity in late 2017 (within the same launch window as the nominal IM mission) with the lowest launch energy (C_3) and entry speed. The second plot is about 47 years later in late 2064, and the third plot, at the end of the century, in late 2096, are comparable to the nominal IM mission, but all have higher entry speeds.

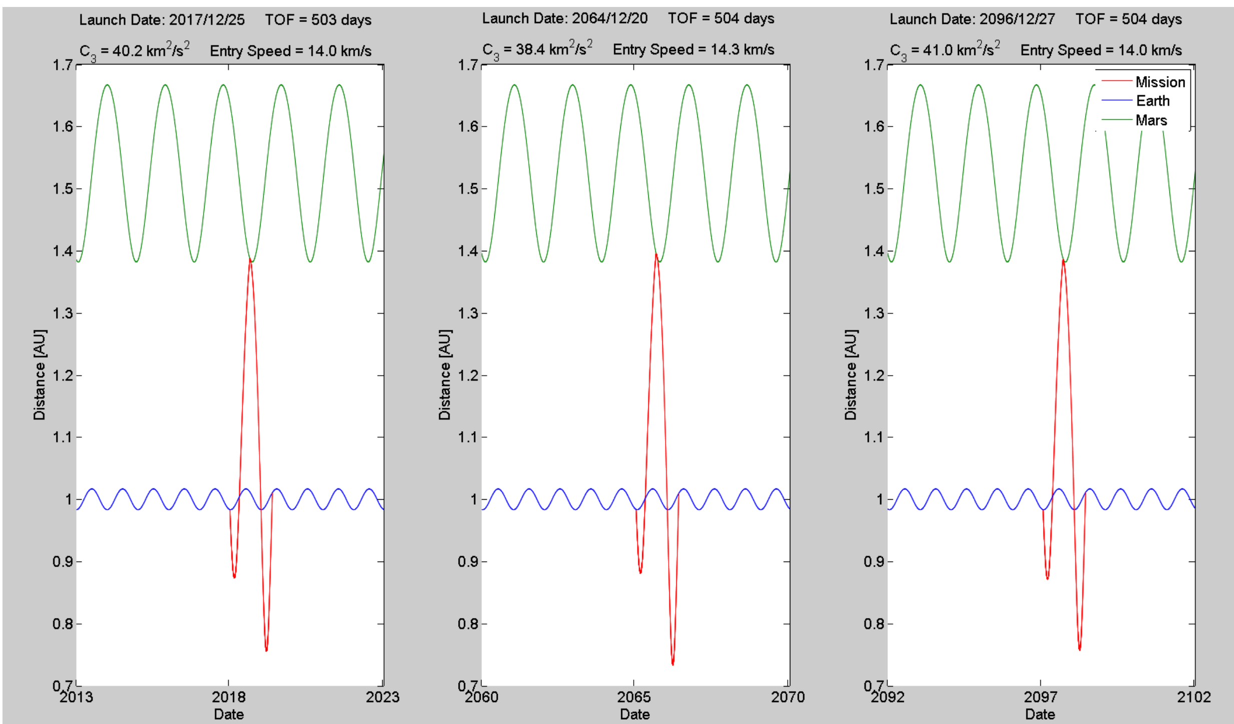

Figure 2: Similar desirable free-return opportunities to Mars. The first graph is the 2018 trajectory, and the other two are trajectories with similar characteristics, one occurring in 2064, and the other in 2096.

All of the trajectories in Fig. 2 possess similar characteristics in regards to where they leave Earth and intercept the orbit of Mars. They all seem to leave Earth at or around Earth's perihelion, and arrive close to, but not directly at Mars's perihelion. The case in late 2064 has the spacecraft arrive a bit before Mars is at its perihelion, while the trajectories in late 2017 and 2096 have the spacecraft arrive closer to Mars's perihelion. Due to the relative inclinations and eccentricities of Earth and Mars, it is expected that the spacecraft would not intersect the planets' orbits exactly at their respective perihelia, but rather have other geometries that produce desirable free-return trajectories.

C. Time-Free Ephemeris (TFE)

Due to the relative nonzero inclinations and eccentricities of Earth and Mars, it is difficult to predict when an optimal alignment will occur for a desirable Mars free-return trajectory. However the use of a time-free ephemeris tells where the planets would need to be for these trajectories. The trends of an Earth departure around its perihelion and a Mars fly-by around its perihelion appear to be common in the radial distance plots of the desirable trajectories, so they are used as the general search regions in the time-free ephemeris model.

The TFE works much the same way that STOUR does, except that the ephemeris used to describe the positions of Earth and Mars is user-defined. The planets' orbital elements are assumed to be constant and frozen on the date that the 2018 trajectory occurs. Lambert arcs are computed between the planets using a V_∞-matching algorithm to compute free-return trajectories. In this way, if the two Lambert arcs computed from Earth to Mars and from Mars to Earth possess the same V_∞ at Mars's arrival and departure, then a free-return trajectory exists. Then, if the trajectory has desirable C_3 and V_{Arr} characteristics, it is logged while others are discarded.

Mars's and Earth's positions around the Sun are user-specified by adjusting the constant found by integration resulting in Kepler's Equation, t_p, or time past periapsis

$$n\left(t - t_p\right) = E - e\sin E \tag{1}$$

where n is the planet's mean motion, t is the current time, E is the eccentric anomaly, and e is the eccentricity. By adjusting t_p, the planet's position can be computed by iteratively solving (1) for E. With both the planets' positions and a user-input TOF, Lambert arcs between the planets are computed.

The first solution space searched in the TFE included hard constraints on the positions of Earth and Mars where they are both set to lie at their respective perihelia. A constraint was also imposed on the Mars arrival arc where the trajectory ended at the Lambert arc's aphelion, as suggested by the radial distance plots. Since there are three inputs to the Lambert arc algorithm (assuming zero revolutions about the Sun), and three imposed constraints, only one unique solution for the outbound arc is available. Since Earth was assumed to start at its perihelion, we propagate its trajectory forward in time, computing lambert arcs with corresponding V_∞ of departure from Mars. Unfortunately, no free-return trajectories exist for any TOF input to the lambert algorithm, as illustrated in Fig. 3.

Figure 3 illustrates how the V_∞ (or C_3) matching algorithm works, which is incorporated into STOUR and the TFE. For each V_∞ of arrival at Mars computed from the first Lambert arc from Earth to Mars, the second leg of Lambert arcs are computed with varying TOFs, with their associated V_∞ of departure at Mars. If the dashed line and the solid line intersect at one or more points, then the V_∞ of arrival and V_∞ of departure match, and a free-return trajectory exists, and the corresponding TOF is computed using a root-solving technique. In the TFE, a secant method is used to solve for the roots, since the two guesses required for such a method are each less than a day from the actual solution.

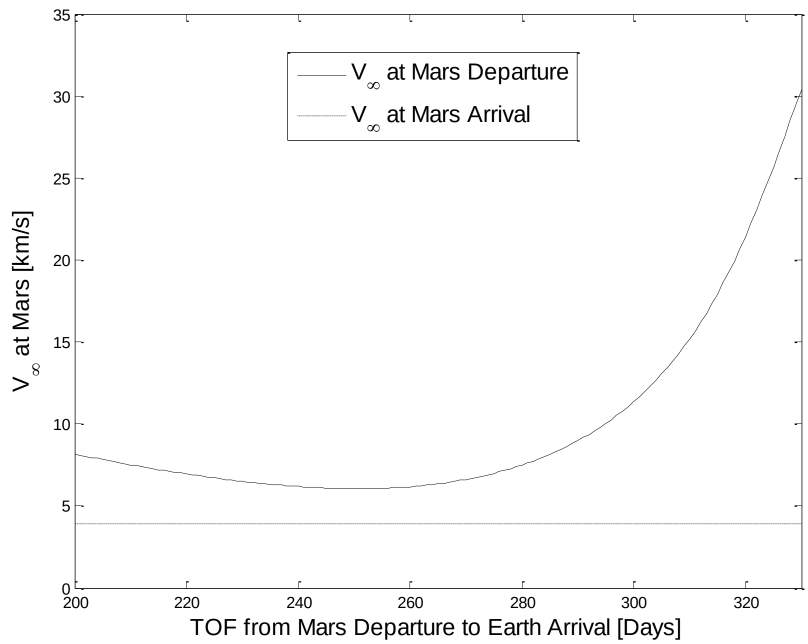

Figure 3. A plot showing the possible V_∞'s of departure at Mars versus the V_∞ of arrival when Earth and Mars are located at their respective perihelia. If the solid and dashed lines intersect, then the V_∞ of arrival and V_∞ of departure match, and a free-return trajectory exists.

The second solution space searched in the TFE kept the constraints that Earth and Mars remain at their respective perihelia, but no requirements on the Lambert arcs. In this way, the total TOF for the free return trajectory was split between the Earth departure leg and the Earth arrival leg. Since the 2018 opportunity is approximately 500 days, the first Lambert arc was allotted a flight time around half that, that stepped from 200 to 300 days in one-day increments. The second leg's flight-time was varied from the first leg's flight-time, subtracted from a maximum allowed total TOF, set to 530 days. This was the range that all feasible IM-like free-return trajectories would be located. With the one-day steps between flight-times of the first leg, seven free-return trajectories were found and are listed in Table 2, while the Heliocentric plot of the trajectories are presented in Fig. 4, centered in the J2000 reference frame.

Table 2 Mars free-return trajectory characteristics from the TFE with Earth and Mars set at their respective perihelia

C_3 (km^2/s^2)	Entry Speed (km/s)	TOF (days)
55.3	14.0	525.1
54.2	14.0	523.5
53.0	13.9	521.8
51.9	14.0	519.9
50.8	13.8	517.5
49.7	13.8	514.5
48.7	13.7	509.8

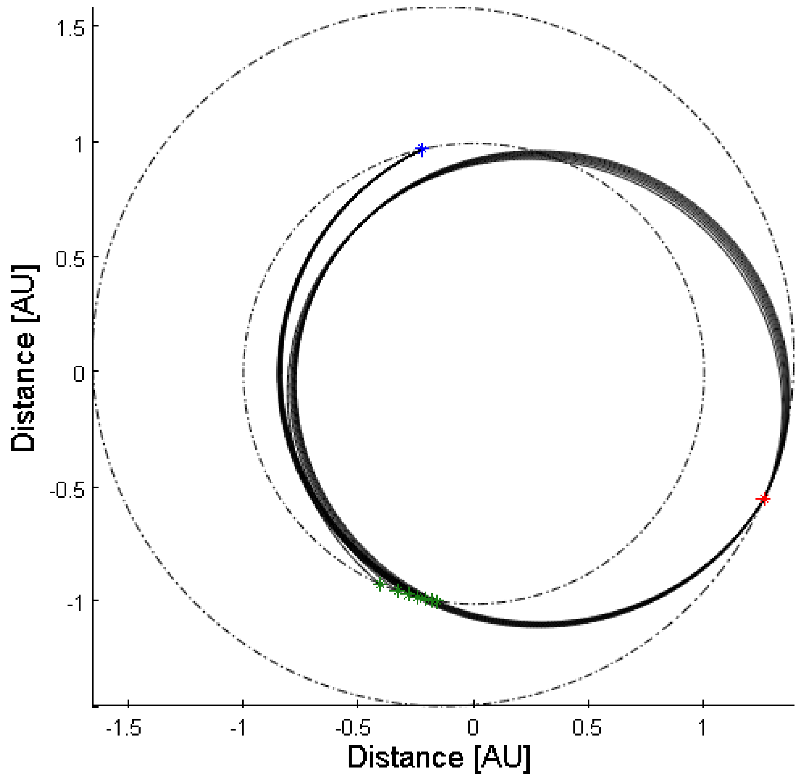

Figure 4. Mars free-return trajectories where Earth and Mars are fixed at their respective perihelia, and no constraints are imposed on the transfer arcs. The blue star indicates Earth launch, the red star indicates the Mars fly-by and the green stars are the possible Earth arrivals.

The trajectories found in the second solution space exhibit the low arrival speeds congruent with the 2018 opportunity, however possess higher launch energies which are not within the bounds of the IM-constraints. These cases are not ideal for human missions due to the need for higher payload masses, meaning more fuel required during launch.

Since no other information could be gathered by leaving Earth and Mars at their respective perihelia, the next step is to move Earth and Mars around their perihelia to find the relative geometry that produces desirable trajectories.

This solution space of the TFE and the desirable Mars free-return trajectories are constructed, moving Earth's and Mars's relative positions by adjusting the time past perihelion, t_p. Earth at departure is moved around its perihelion by $t_{p,E}$ = ±40 days while Mars at its arrival is moved around its perihelion by $t_{p,M}$ = ±50 days, and all free-return trajectories are found using the aforementioned V_∞-matching technique, with one-day increments in the transfer time between Earth launch and Mars arrival. Those free-return trajectories possessing IM-like characteristics or better are retained, while all others are discarded.

Figure 5 shows all Mars free-return trajectories found using the TFE. The blue stars, red stars and green stars correspond to Earth launch, Mars fly-by and Earth arrival respectively. The yellow trajectory shows where the IM trajectory lies within the solution space of the TFE. These trajectories illustrate what kind of geometry Earth and Mars must have in order for an IM-like mission to exist. Of course, in reality, Earth and Mars cannot be moved around arbitrarily, and one must wait until the planets are in the proper alignment.

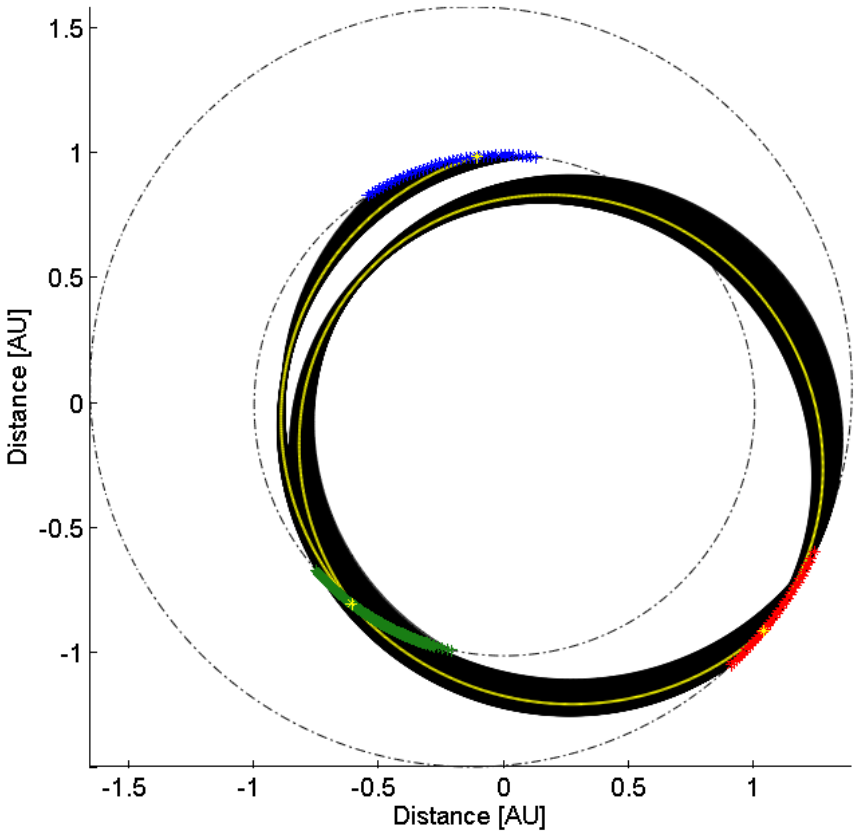

Figure 5. Mars free-return trajectories where Earth departure and Mars arrival are allowed to move in an arcs around their respective perihelia. The blue star indicates Earth launch, the red star indicates the Mars fly-by and the green stars are the possible Earth arrivals. The yellow trajectory corresponds to the 2018 IM opportunity.

D. Launch Window for 2018 Opportunity

The STOUR search results, radial distance plots, and TFE analysis all clearly show that the best-case opportunities are highly sensitive to planetary geometry (and therefore launch date). In fact, simulations in STOUR about the 2018 opportunity (with launch date steps of 1 day and launch V_∞ of 0.1 km/s) show that the 2018 launch opportunity is only available from about 12/19/2017 to 1/3/2018. The results of the STOUR simulation are shown in Fig. 6 with TOF, launch date, and launch V_∞ shown on the vertical axis, horizontal axis, and color bar, respectively. All results in the plot have Earth arrival V_∞ no larger than 9 km/s (entry speed of 12.29 km/s). The plot shows that to achieve this launch window, the launch V_∞ ranges from 6.3 km/s and 6.5 km/s (C3 from 39.7 km^2/s^2 to 42.3 km^2/s^2), and TOF from 502 days to 510 days. To restrict the launch V_∞ to 6.3 km/s and maintain a TOF near 503 days, the launch window is restricted to the lower group of opportunities (shown with index of 1 in the figure), which lasts about one week, from 12/28/2017 to 1/3/2018.

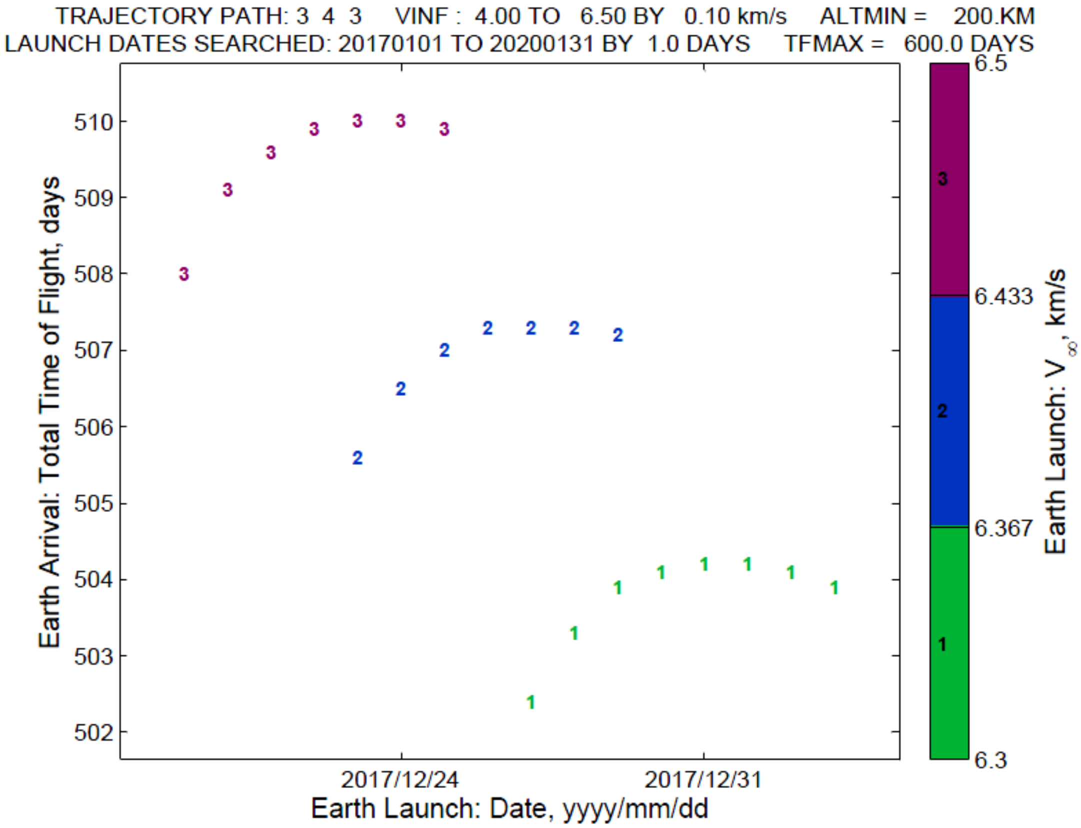

Figure 6. STOUR results showing available launch window for the 2018 opportunity, with TOF, launch date, and launch V_∞ shown on the vertical axis, horizontal axis, and color bar, respectively. Within the resolution of the STOUR search (one-day step in launch date and 0.1 km/s-step in launch *V_∞*), the earliest launch date occurs on 12/19/2017 with launch *V_∞* of 6.5 km/s and the latest launch date occurs on 1/3/2018 with launch *V_∞* of 6.3.

E. Deterministic Maneuvers

Part of the desirability of the 2018 opportunity for Inspiration Mars is that it is a *free* return, and therefore does not require any deterministic maneuvers to return the crew to Earth. Nevertheless, maneuvers are briefly investigated to determine if significant reductions in TOF, launch C3, and/or entry speed can be achieved, for a moderately sized impulsive ΔV. Only powered flybys at Mars are considered for this investigation, and are implemented in STOUR using a subroutine that places the maneuver 3 days after the Mars encounter—effectively increasing the energy change obtained from the Mars gravity assist. A full discussion of how this maneuver is implemented in STOUR is given in detail by Patel [19]. All maneuvers in this investigation are assumed impulsive and allowed a maximum ΔV size of 1 km/s.

Only near-term opportunities around the 2018 launch date are considered in the STOUR trajectory search using steps of 1 launch day and 0.25 km/s launch V_∞. The results show that the maneuver has little to no effect on TOF, as the trajectories found have TOF ranging from 497 days to 510 days—about the same as those found for the ballistic case (with no maneuver implemented). Specifically, to achieve a TOF of 497 days (only a few days shorter than the ballistic case) requires a maneuver size of 0.40 km/s ΔV, and launch V_∞ of 6 km/s.

The launch window was found to expand to as early as 12/14/2017 to as late as 2/5/2018, however many of these opportunities (near the extremes of these dates) require larger maneuver sizes of about 1 km/s. For more moderately sized maneuvers below 0.5 km/s, the launch window was found to be 12/18/2017 to 1/14/2018— still a few weeks longer than the available launch dates for the ballistic case.

The impact of a maneuver on available launch and arrival V_∞ (or launch C3 and arrival entry speed) is shown in Fig. 7. The figure shows the STOUR results with maneuver ΔV, arrival V_∞, and launch $V_{\infty,}$ shown on the vertical axis, horizontal axis, and color bar, respectively. For more moderately sized maneuvers with ΔV below 0.5 km/s, the figure shows that an arrival V_∞ of 8.29 km/s (entry speed of 13.8 km/s) is achievable for a small 65 m/s maneuver, with launch V_∞ of 6.5 km/s (C3 of 42.3 km^2/s^2). Overall, this is not much of a decrease from the ballistic trajectory with 14.0 km/s entry speed (shown in Table 1 with launch date on 12/25/2017), which only requires a C3 of 40.2 km^2/s^2.

With regard to reducing launch V_∞, Fig. 7 shows that maneuvers of at least 0.69 km/s are required to obtain a launch V_∞ of 5.75 km/s (C3 of 33.1 km^2/s^2). Although this is a significant reduction in C3, it comes at the cost of a relatively large maneuver size, and may not provide any reduction in propellant cost. Additionally, the arrival V_∞ that results from such opportunities approach 9 km/s (entry speeds of 14.3 km/s), which (of the trajectories considered in this study) is relatively large. To achieve a launch V_∞ of 6 km/s (C3 of 36 km^2/s^2), maneuvers that are at least 0.21 km/s are required, and result in entry speeds near 14.2 km/s—again, providing very little to no benefit over the purely ballistic best cases.

Overall, this preliminary investigation of impulsive maneuvers suggests that the use of a powered flyby does not provide any significant benefit (if any at all) over the purely ballistic 2018 Mars free-return opportunity.

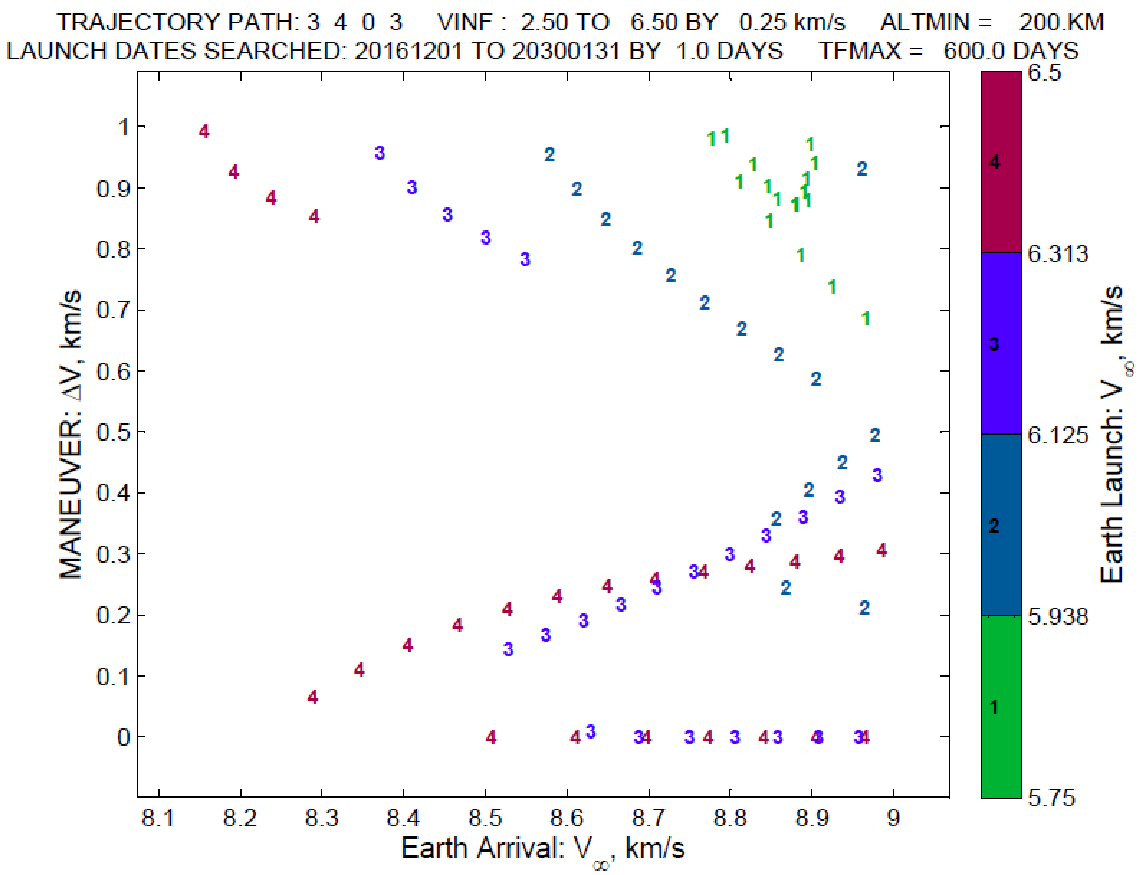

Figure 7. STOUR results showing available opportunities in late 2017/early 2018 with a powered flyby implemented at Mars. The Maneuver ΔV, arrival V_∞, and launch V_∞ are shown on the vertical axis, horizontal axis, and color bar, respectively. The maximum allowed maneuver size for the STOUR search is 1 km/s, with steps in launch date of 1 day, and steps in launch V_∞ of 0.25 km/s.

IV. Conclusion

The study found all the desirable candidate trajectories this century for a Mars free-return mission that are possible using current technology. It was discovered that the one proposed for Inspiration Mars in early 2018 is the best chance we have in this century. Since the next opportunity does not occur for another 15 years in 2032, it emphasizes the urgency for a human mission to Mars in 2018. The TFE shows the relative geometries that Earth and Mars need to possess for an IM-like mission to occur, and similar geometries only occur every 15 or 17 years – a considerable waiting period. Unless a back-up trajectory was found using other gravity-assist sequences, or new propulsive technology is developed to open up other trajectory design spaces, it would mean another long waiting period until another human mission to Mars could be flown.

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