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Mars Free Returns via Gravity Assist from Venus

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The safety of the crew is the top priority for human exploration of Mars. If an unexpected emergency occurs, a free-return trajectory can bring the spacecraft back to the Earth without a large trajectory correction maneuver. Such mission-abort scenarios are analyzed by searching for various Mars free-return trajectories, including gravity assist from Venus en route. Thorough investigations of Earth–Mars–Earth, Earth–Mars–Venus–Earth, and Earth–Venus–Mars–Earth sequences are made for the 15-year launch window beginning in 2010. Out of this study, a Mars–Venus free-return abort option, which satisfies the energy and time-of-flight constraints of NASA's Design Reference Mission in January 2014, is discovered. If aerogravity assist (consistent with the capability of the Design Reference Mission vehicle) is employed at Mars, the abort option can be improved over pure gravity assist at Mars in terms of more launch opportunities and lower time of flight. The planned mission date in January 2014 is remarkably fortuitous because the Mars–Venus abort trajectory only repeats every 32 years.

Nomenclature

C_D	=	drag coefficient
C_L	=	lift coefficient
g	=	acceleration due to gravity at Earth's surface, 9.80665 m/s^2
P	=	orbital period, years
r_p	=	periapsis, astronomical units
V_∞	=	hyperbolic excess velocity, km/s
α	=	angle of attack, deg
ΔV	=	change in velocity, km/s

Introduction

VARIOUS mission and trajectory designs have been proposed to achieve the first human mission to Mars.[1–17] The chief concern in all proposals is how to minimize the exposure of the crew to the hazardous space environment, while keeping the propellant costs at an acceptable level. The problem falls into the classic one, familiar to all mission designers: Minimize some combination of flight time and ΔV propellant expenditure. Because of the energy and phasing constraints, Mars trajectory options naturally fall into two fundamental categories, often referred to as long-stay missions and short-stay missions.

The long-stay mission, or conjunction-class mission, keeps ΔV cost low by using near-Hohmann transfers for both inbound and outbound arcs (Fig. 1). For low ΔV missions, outbound and inbound transits take about 250 days each, although a modest increase in launch ΔV reduces the time of flight (TOF) to as few as 100 days.[1,11] The phasing requires a relatively long stay time of 500–600 days at Mars.

The Mars stopover can be reduced to about 30–90 days for a total mission duration of 400–650 days, if a type 2 transfer (transfer angle greater than 180 deg) is used for either the outbound or inbound leg. Such a mission is referred to as short-stay mission, or opposition-class mission (Fig. 2). The high ΔV requirement of a type 2 transfer can often be reduced by a Venus gravity assist en route.

NASA's current study for sending humans to Mars, known as the Design Reference Mission (DRM),[11,12] uses the long-stay mission profile. The split mission strategy breaks the mission elements into cargo and piloted flights, so that cargo will be transferred on a low-energy, long-transit-time trajectory, whereas the crew will be flown on a higher energy, short-transit-time trajectory. Two cargo missions in 2011 will consist of one flight containing the Earth return vehicle (ERV) and a second flight containing a cargo lander with a propellant production plant, power systems, an inflatable habitat, and an ascent vehicle. The piloted vehicle would be launched in 2014 and spend approximately 180 days on a fast-transit trajectory to Mars. After a 500-day or so stopover, the crew would spend approximately 180 days on the return trip to the Earth.

The first human mission to Mars will require a number of complex systems, and a failure in any of them could result in the loss of the crew. If an unexpected emergency occurs, the mission may be aborted to save the astronauts. In the Apollo program, free-return trajectories served as a mechanism to safely bring the spacecraft back to the Earth without a large trajectory correction maneuver. In this paper, we investigate such abort options for the case of Mars. We approach the problem both analytically and numerically. A graphical technique based on Tisserand's criterion gives insight into how such gravity-assist paths can be discovered. We also make use of two software tools, the satellite tour design program (STOUR)[18–22] and the mission design and analysis software (MIDAS),[23] which employ a patched-conic method to propagate trajectories and treat gravity assist as impulsive.

Mars Free-Return Trajectories

For one-way trips between the Earth and Mars, Hohmann transfers are the most desirable from the energy point of view. However, Hohmann transfers between Earth and Mars have an orbital period of 1.42 years and do not permit a free return after one complete revolution because the Earth would not be in the correct position. We analyze Mars free returns by searching for Earth–Mars–Earth (EME) trajectories and assess their application in current plans for the first human mission. Because the inertial geometry of the two planets repeats every 15 years, trajectories are sought over a 15-year period starting in 2010. The launch opportunities for free-return missions repeat every 2.14 years, which is the synodic period of Earth and Mars.[16]

The EME trajectories found in our search using STOUR are shown in Fig. 3, where we plot the round-trip TOF (in years) vs arrival V_∞ (in kilometers per second). We limit the search to a total TOF of 3 years because a typical human Mars mission does not exceed 3 years. Each number shown in the plot represents a mission, where the numbers 1, 2, 3, 4, 5, and 6 in the plot correspond to launch $V_\infty = 3, 4, 5, 6, 7,$ and 8 km/s, respectively. (Because our objective at this point is to observe the overall trends, the readability of some of the numbers is of little concern.)

There are two large families of trajectories for TOFs of around 2 and 3 years, where the Earth-arrival V_∞ have two local minima of

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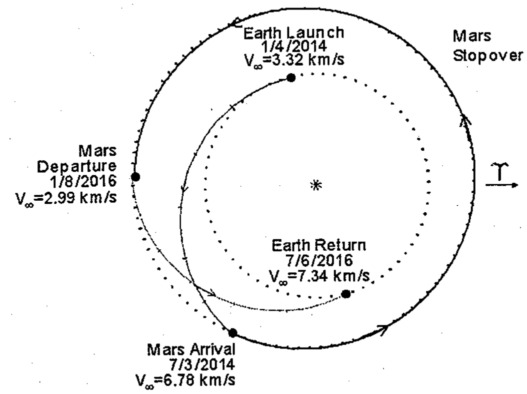

Fig. 1 Long-stay mission profile. (Tick marks denote 30-day increments.)

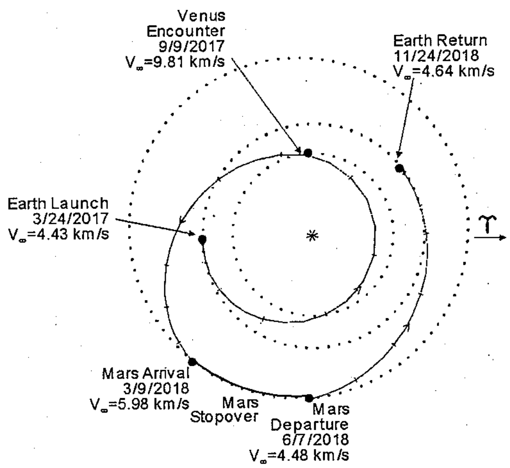

Fig. 2 Short-stay mission profile. (Tick marks denote 30-day increments.)

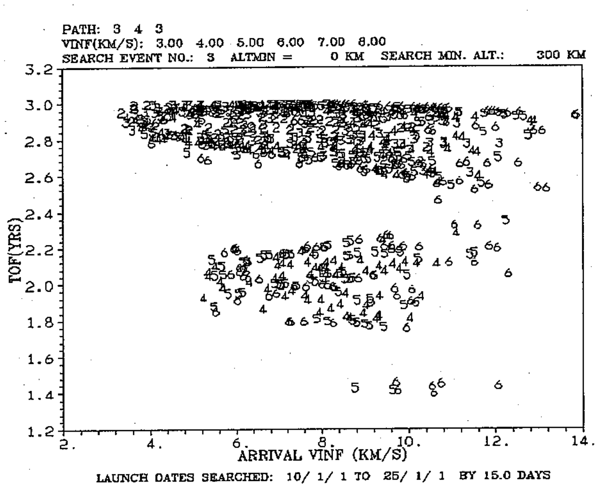

Fig. 3 EME energy–TOF relationships.

approximately 5 and 3 km/s, respectively. We also observe a small family of trajectories, where launch V_∞ of 7 and 8 km/s (the numbers 5 and 6 in the plot) achieve a short TOF of about 1.4 years. In the 2-year TOF family, the lowest discrete launch V_∞ presented in Fig. 3 is 6 km/s (which means the minimum launch V_∞ required is between 5.00 and 6.00 km/s), whereas in the 3-year TOF family, the required launch V_∞ is less than 4 km/s. Figure 3 contains missions with Earth-arrival V_∞ as high as 14 km/s. Our initial searches do not restrict Earth-arrival V_∞ because the arrival velocities can be reduced with

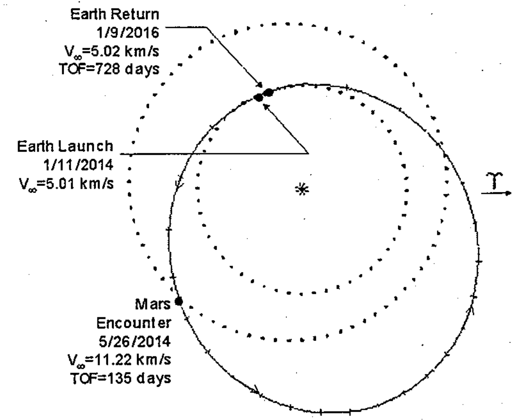

Fig. 4 Minimum ΔV EME free return with 2-year period. (Tick marks denote 30-day increments.)

propulsive maneuvers, aerobraking, or a combination of both, and mission constraints on arrival V_∞ could differ significantly (compared to constraints on launch V_∞) from one mission to another.

Nevertheless, V_∞ at both launch and arrival should be as low as possible. Collision orbits (which assume no gravitational perturbation from Mars) have the minimum energy requirement for launch and arrival at Earth when the Earth-to-Earth TOF are integer multiples of Earth years.[16,17,24] Collision orbits are subsets of free returns, where the total ΔV cost is locally minimized as TOF approaches 2 and 3 years. We note that the 3-year TOF family includes collision orbits with periods of both 1.5 and 3.0 years, where the low-energy 1.5-year period provides low ΔV cost (but the spacecraft must revolve twice about the sun before returning to Earth) and where the high-energy 3.0-year period achieves fast one-way transits.

Figure 4 is an example of a 2-year period Mars free return, in which we use MIDAS to minimize the total ΔV cost (not including ΔV for Mars orbit insertion). We find that no deep-space maneuver is required in the optimized solution, so that all of the ΔV is used for launch from Earth. The minimum ΔV trajectory is very similar to a collision orbit with the values of launch and arrival V_∞ nearly identical (5.01 and 5.02 km/s, respectively). In Fig. 4 we see that the flyby of Mars has little effect on the optimal trajectory. This 2-year EME achieves desirable TOF characteristics: The trajectory takes only 135 days to reach Mars and it brings the crew home 2 years after Earth launch in the event of emergency. A trajectory is not considered a practical abort option unless it can meet constraints for the nominal mission as well. For example, the high Mars approach speed of 11.22 km/s that 2-year EMEs require may be excessive.

Launch energy, trip time, and arrival speeds are considered to be the major competing constraints for NASA's DRM.[13] To minimize both consumable masses and hazards to the crew, the DRM uses 180 days (6 months) as the maximum TOF limit each way. Also, if a free-return option is employed, the crew must reach the Earth within a reasonable time. What a reasonable total TOF is in such a situation is not discussed in the DRM reports because the DRM scenario does not incorporate a free-return abort. According to the DRM,[11] "the Mars transit/surface habitat will contain the required consumables for the Mars transit and surface duration of approximately 800 days (approximately 180 days for transit and approximately 600 days on the surface) as well as all the required systems for the crew during the 180-day transit trip." Our study, therefore, assumes 800 days (or 2.2 years) as the mission abort total TOF limit. Finally, the atmospheric entry speed should be as low as possible to minimize structural mass and g-load on the crew and to maximize the entry corridor.[13] A free-return trajectory's atmospheric entry speed must be as low as possible at Mars for a nominal mission and sufficiently low at Earth for an aborted mission.

When these issues are addressed, we find that all EME trajectories violate at least one of the DRM constraints. For example, although the EME collision orbit with a period of 1.5 years (TOF of 3.0 years) requires slightly lower launch and arrival velocities than DRM's, its 250-day outbound transit time is above the 180-day guideline. In addition, the crew vehicle does not carry enough consumables for a 3-year flight. A 2-year free return has launch and arrival $V_\infty = 5$ km/s and a Mars encounter V_∞ above 11 km/s, both being much higher than values used for NASA's DRM. Likewise, the launch V_∞ and Mars approach speeds for the 3-year period EME are unacceptably high, although the one-way trip time of 111 days is considered desirable.

These considerations may explain the design philosophy that favors the abort to Mars surface[7,11] approach over the (EME) free-return option. We now consider an alternate free return: a scheme with a gravity assist from Venus on the way home.

Mars Free Returns via Gravity Assist from Venus

Lyne and Townsend propose a powered swingby abort with Venus flyby for NASA's Mars DRM.[14] They suggest that, by linking the ERV and the outbound crew vehicle (which are launched in different years in the DRM), the propulsive capability would be enough to perform a powered Mars swingby followed by sequential encounters of Venus and Earth. In the following we search for free returns, which do not require significant modifications, if any, to the DRM.

Mars free returns via gravity assist from Venus can be first analyzed in terms of energy of the available orbit by employing a Tisserand graph (see Ref. 25). In this analysis, the orbits of the planets are assumed to be circular and coplanar. If the spacecraft orbit is also restricted to the same plane, then the shape of its orbit around the sun is defined by its period P and periapsis r_p, and thus represented by a single point in the P–r_p Tisserand graph (Fig. 5). When such an orbit intersects with an orbit of a planet, the V_∞ with respect to the planet can be computed. Collections of such orbits with constant V_∞ are shown as contours in the Tisserand graph. Because the V_∞ magnitude remains constant before and after a flyby, a gravity assist changes the orbit around the sun along these contours. How far a spacecraft can travel along a contour in one flyby is constrained by the minimum flyby altitude allowed. The dots on the contours indicate how much an orbit could be altered in a single gravity assist with a flyby altitude of 300 km. (In Fig. 5, the altitude constraints represented by the distance between the dots are only shown on one of the Venus contours.) Transfers between Venus, Earth, and Mars may exist (from an energy point of view), where contours of two planets intersect.

Figure 5 shows, as expected, that the minimum launch V_∞ required at Earth to reach Mars is approximately 3 km/s. We see this by tracing the 3.0-km/s V_∞ contour for Earth to its intersection with the 3.0-km/s V_∞ for Mars. Similarly, the minimum launch V_∞ at Earth to reach Venus is about 2.5 km/s. We observe that the Earth V_∞ contour of 2.5 km/s would intersect the Venus V_∞ contour at about 2.7 km/s. However, the minimum energy required for Mars–Venus free returns is determined by Hohmann transfers between Mars and Venus, whose V_∞ contours are shown as solid bold lines in the plot. The dashed bold line represents the minimum launch V_∞ contour (of 3.4 km/s) required for an Earth–Mars–Venus–Earth (EMVE) free return, which is the minimum arrival V_∞ for the Earth–Venus–Mars–Earth (EVME) path. We note that a typical human mission to Mars does not necessarily employ the lowest energy transfer due to the long transfer time involved. For example, DRM's 180-day one-way TOF constraint requires a launch V_∞ of approximately 3.7 km/s, which is greater than the minimum launch V_∞ of 3.4 km/s for EMVE free returns.

Although an EMVE trajectory is feasible from an energy point of view, we have yet to confirm that the planets will be properly aligned, because the Tisserand graph does not provide phasing information. We use STOUR, which solves the phasing problem by patched-conic propagation, to search for EMVE trajectories for the 15-year span starting in 2010. The initial search uses 0 km as the flyby altitude constraint to obtain the broader spectrum of trajectories, but our finer analysis and optimization are performed with flyby altitudes of 300 km or above at both Mars and Venus. The initial Earth parking orbit is assumed to be 200 km. Some of the EMVE trajectories are shown in Fig. 6. To make Fig. 6 easy to read, we present this particular plot with a single launch V_∞ of 4.80 km/s, represented by the numeral 1.

We also found that trajectories with even lower launch energies exist, including the case in January 2014, which requires launch V_∞ comparable to the DRM. The minimum ΔV case is shown in Fig. 7. Departing from the Earth on 13 January 2014, the spacecraft spends 170 days on the outbound transit to Mars. This shorter (than 180 days) TOF results in a Mars arrival V_∞ of 6.97 km/s, which is slightly higher than that for 180-day transits, but which is still in the feasible design space. Typical trade studies of long-stay human missions to Mars consider a one-way TOF range of 150–200 days. In the year 2014, this translates into a Mars arrival V_∞ range of approximately 9.0–5.5 km/s, respectively. The size of the orbit is reduced using gravity assist from Venus, and the spacecraft returns to the Earth after one complete revolution about the sun, after the

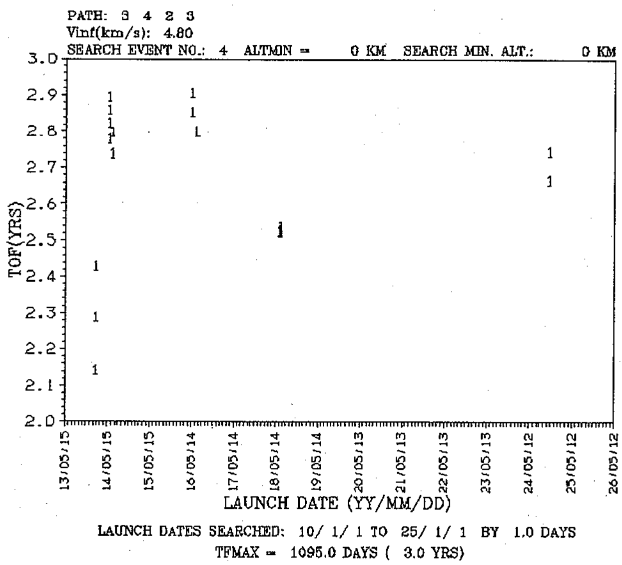

Fig. 6 EMVE free returns (Earth arrival).

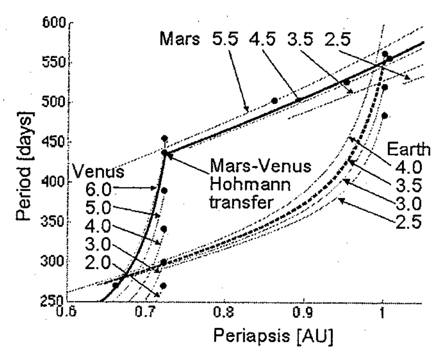

Fig. 5 P–r_P Tisserand graph (with V_∞ contours in km/s).

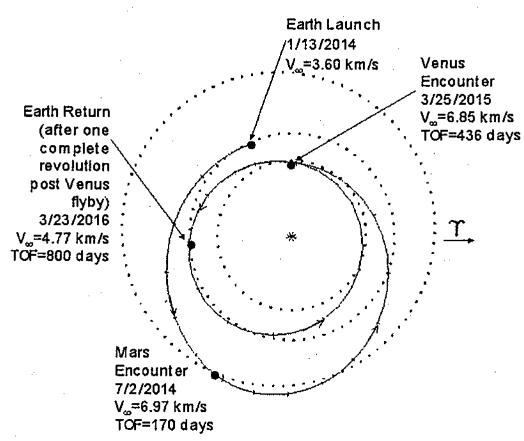

Fig. 7 EMVE abort option. (Tick marks denote 30-day increments.)

Table 1 Nominal and abort missions available in Jan. 2014 (launch ΔV optimized in all cases)

Trajectory	Launch date	Earth launch V_∞, km/s	Transit to Mars, days	Mars arrival V_∞, km/s	Earth arrival V_∞, km/s	Free-return total TOF, years
DRM-class mission[a]	4 Jan. 2014	3.32	180	6.78	7.34	N/A
EME ($P = 1.5$ years)	29 Dec. 2013	3.30	184	6.90	3.30	3.00[b]
EME ($P = 2.0$ years)	11 Jan. 2014	5.01[b]	135	11.22[b]	5.02	1.99
EME ($P = 3.0$ years)	18 Jan. 2014	6.84[b]	111	14.63[b]	6.85	3.00[b]
EMVE[c]	13 Jan. 2014	3.60	170	6.97	4.77	2.19

[a]Consistent with 180-day one-way TOFs for both outbound and inbound legs.
[b]Values exceed constraint guidelines.
[c]Total TOF is fixed at 800 days.

Venus flyby. The required Earth approach speed of 4.77 km/s is much less than that of the nominal mission (about 6.5–7.5 km/s for this year). Our abort case in January 2014 (coincidentally the planned DRM mission date) meets all of the mission constraints regarding launch energy, Mars approach speed, trip time to Mars, total TOF to Earth, and Earth approach speed. The details of this mission scenario are summarized in Table 1.

The main concern of the EMVE abort option is the expected increase in radiation dosage. The sources of radiation are galactic cosmic radiation (GCR) and solar particle events (SPE). Although the constant flux of GCR is very difficult to protect against, the GCR dose is expected to result in only a small increased risk of cancer over the nominally planned mission. A greater hazard may occur during an SPE, when the crew will seek protection within the storm shelter of the DRM vehicle. Thus, the long TOF and low perihelion of EMVE will expose the crew to higher radiation levels than the nominally planned mission. We note, however, that the proposed EMVE is the very last resort and is considered only after all of the other options, including the abort to surface, are determined to be infeasible.

Earth, Mars, and Venus have a composite periodicity of about 6.4 years, but the characteristics of EMVE do not exhibit a similar periodicity, as the phasing of the three planets becomes sensitive to the eccentricity of Mars.[2] To find launch opportunities of such an EMVE, we expanded our STOUR search to a 100-year period starting in 1950. An EMVE similar to the case in January 2014 is found available in January 1950, January 1982, and January 2046, making a 32-year cycle (exactly five times the composite period of 6.4 years). During the 32-year period, Venus and Mars revolve about the sun almost exactly 52 times and 17 times, that is, 52.0168 and 17.0139 revolutions, respectively. The inertial geometry of the three planets thus repeats every 32 years.

Aerogravity Assists

Some design improvement is possible, when we consider a case where the vehicle flies through the Martian atmosphere during the gravity assist. The DRM version 3.0 entry vehicle for Mars aerocapture has the lifting capability to meet all aerocapture and descent-to-surface requirements.[12] The study team shows that the aerocapture at Mars does not exceed the 5-g maximum deceleration limit, a limit necessary for crew safety and performance during the aerobraking maneuver. The DRM proposes a triconic aerobrake shape with a lift-to-drag (L/D) ratio of 0.6 for a trim angle of attack of 47 deg. This is consistent with the study done by Lyne et al.,[15] in which both C_D and C_L are maximized at around $\alpha = 47$ deg, whereas maximum $L/D = 1.0$ is found around $\alpha = 22$ deg (Fig. 8).

Assuming that the Mars vehicle can produce negative lift by pointing the nose down, an extrapolation of the plot in Fig. 8 implies that the L/D would be -0.6 for an angle of attack around -8 deg. The downward lift helps bend the velocity vector during the aerogravity-assist (AGA) flyby. The intention here is to show the potential of the DRM vehicle for an AGA. For our AGA study, an L/D value well within the design specification, for example, $L/D = -0.6$, which is 60% of the maximum lifting capability, is somewhat arbitrarily picked. We assume the L/D and altitude (61 km) are constants during Mars AGA flyby.[22]

Figure 9 presents the results of our search for AGA free-return trajectories near the DRM launch date for an L/D of -0.6. For comparison, we show pure gravity-assist trajectories in Fig. 10 for the same launch window. In both Figs. 9 and 10, the vertical axis represents the one-way TOF to Mars, instead of the total TOF for Earth return. The numerals 1–8 and the letters A–G in the plots represent gravity-assist and AGA missions, respectively, with launch $V_\infty = 3.4, 3.6, 3.8, 4.0, 4.2, 4.4, 4.6,$ and 4.8 km/s, respectively. The results show that AGA trajectories seamlessly fill the gaps in the launch window for the lowest-energy missions ($V_\infty = 3.4$ km/s, A for AGA, 1 for pure gravity assist), as can be seen by comparing Figs. 9 and 10. For example in Fig. 10 (for pure gravity assist at Mars), during a one-week period beginning around 25 December 2013, there are no launch opportunities for the abort option. However, in Fig. 9, which assumes AGA at Mars, we see that this particular week has launch opportunities and at the lowest possible launch energy. We also note that the AGA reduces the TOF. Figure 9 indicates that some of the Earth-to-Mars TOFs can be decreased by more than 10 days. For example, around 1 February 2014, the numeral 8, which represents pure gravity assist with launch V_∞ of 4.8 km/s, is above the letter H, represented by AGA with the same V_∞, by 0.03 year (or about 10 days). This reduced TOF is made available during the lowest TOF date for pure gravity assist.

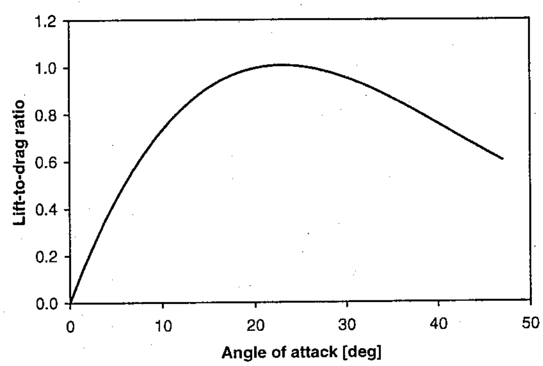

Fig. 8 Lift-to-drag ratio for the triconic aeroshell.[15]

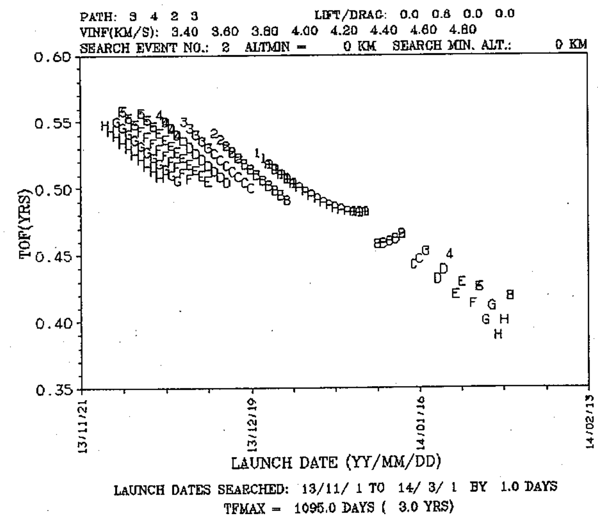

Fig. 9 AGA EMVE free returns (Mars encounter).

Table 2 Short-stay missions with EVME free-return abort options[a]

Mars stopover, days	Mars launch V_∞, km/s	Mars to Earth TOF, days	Earth arrival V_∞, km/s	Earth arrival date	Total mission duration,[b] days
0[c]	5.98[d]	125	13.94	11 July 2018	475
30	4.12	125[e]	9.12	11 Aug. 2018	505
60	4.08	125[e]	5.52	10 Sept. 2018	535
90	5.49	125[e]	4.16	10 Oct. 2018	560
0	2.48	219[f]	3.19	14 Oct. 2018	564
30	2.61	197[f]	3.22	22 Oct. 2018	572
60	3.33	178[f]	3.56	2 Nov. 2018	584
90	4.48	171[f]	4.64	24 Nov. 2018	605

[a]For Earth launch V_∞ of 4.43 km/s on 24 March 2017 and Mars arrival V_∞ of 5.98 km/s on 9 March 2018.
[b]Duration from Earth launch to Earth return.
[c]Free return.
[d]Flyby V_∞.
[e]Fixed to 125 days.
[f]Longer TOF for lower ΔV trajectories.

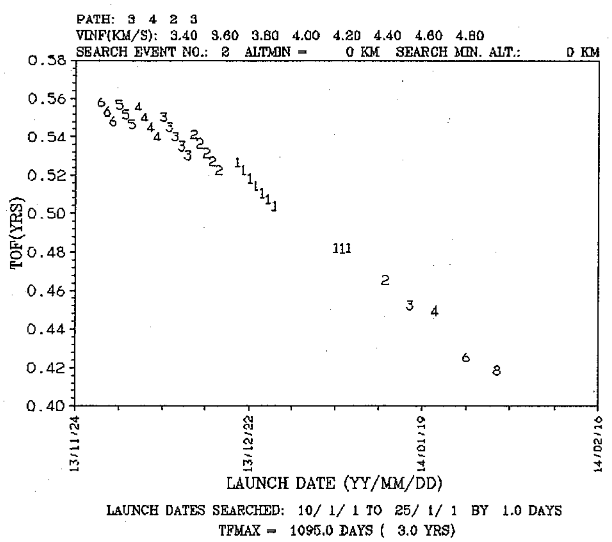

Fig. 10 Pure gravity-assist EMVE free returns (Mars encounter).

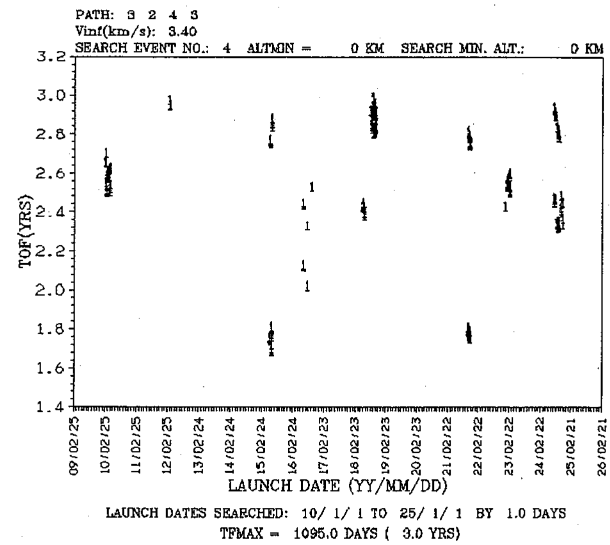

Fig. 11 EVME free returns (Earth arrival).

Considering the advantage that AGA provides to the EMVE trajectory, we searched for potential improvement in the EME and EVME trajectories. Unfortunately the EME and EVME options do not enjoy sufficient improvement from AGA to meet the DRM constraints. We also found that EMVE cannot be improved with AGA to open new launch year opportunities. Of course, with much larger L/D ratios (3–10), new trajectories become available as indicated in a preliminary study by Bonfiglio and Longuski,[22] but the DRM vehicle cannot provide such high values.

Short-Stay Missions

A free-return trajectory can be considered as an extreme case of a short-stay mission with a Mars stopover of 0 days. Thus, in principle, we can always convert free returns into short-stay missions by increasing the Mars stay time.

For example, the Earth–Venus–Mars/Mars–Venus short-stay mission with a total mission duration of 1.6 years shown in Fig. 2 is obtained by first searching for EVME free returns with short TOF. (A similar trajectory is reported by Desai et al.[10]) Figure 11 shows EVME with launch V_∞ of 3.40 km/s, represented by the numeral 1 in the plot. We note that this launch energy achieves a total TOF of less than 1.7 years, a dramatic improvement over the EME, which requires a launch V_∞ of over 6 km/s (Fig. 3) to achieve comparable TOF. (For EME cases, a launch V_∞ of around 4 km/s achieves total TOFs of around 3 years.) When we perform the search with a slightly wider range of launch $V_\infty = 3.40$–4.80 km/s with an increment of 0.2 km/s, the shortest TOF of 1.3 years with launch V_∞ of 4.6 km/s is found in March–April of 2017. In our MIDAS optimization (Fig. 12), we fixed the TOF to exactly 1.3 years and minimized the launch ΔV by finding the optimal launch date. A slight reduction in total ΔV is possible by inserting a deep-space maneuver, but to facilitate comparisons between all free-return cases, we omit this maneuver. Finally, a short-stay mission with a Mars stopover of almost 3 months (Fig. 2) is designed from this EVME trajectory (Fig. 12).

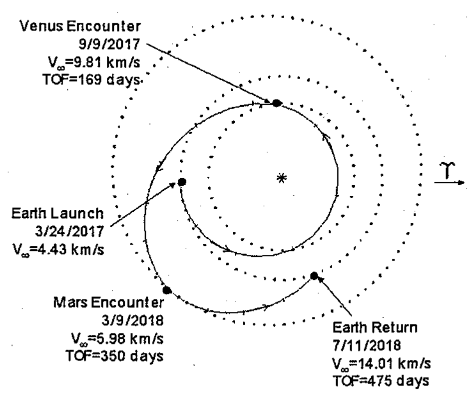

Fig. 12 Optimal EVME free return. (Tick marks denote 30-day increments.)

In Table 2 we present variations of this free return to demonstrate that a free return can be converted to a short-stay mission. We consider Mars stopovers of 0, 30, 60, and 90 days. By constraining the Mars to Earth TOF to 125 days (the time required in the free return), we find that optimal launch V_∞ at Mars ranges from 4.08 to 5.98 km/s. By allowing the TOF from Mars to Earth to be free, we find that the launch V_∞ at Mars drops considerably, ranging from 2.48 to 4.48 km/s, whereas the total mission duration ranges from 564 days (1.55 years) to 605 days (1.67 years).

The fact that all short-stay missions obtained from EMVE and EVME trajectories possess free-return abort capabilities, and that their TOF and energy requirements are less than EME free returns, may prove valuable in designing the first human mission to Mars. For typical long-stay missions, such as NASA's DRM, the EMVE free return is the only practical choice because a Venus flyby on the way to Mars (in the case of EVME) usually violates the one-way TOF constraint for long-stay missions.

Conclusions

We have revisited the problem of Mars free returns in the light of current plans for the first human mission. For the likely launch window, Mars alone does not provide an acceptable free return. However, when we consider Venus–Mars or Mars–Venus paths we find that the Mars–Venus free return is acceptable because it can achieve a short transit time to Mars.

Fortuitously, our Mars–Venus free-return trajectory fits neatly into the DRM for 2014. The free return satisfies all of the DRM constraints concerning launch energy, launch window, flight time to Mars, and total time to return. If the lifting body of the aerocapture vehicle is used for an AGA, the launch window for the free return opens wider, and in many cases the TOF decreases.

This free-return trajectory could easily be adopted in future DRM plans because it requires no significant changes in the mission constraints or vehicle specifications and it significantly improves crew safety by granting a practical abort option similar to that of Apollo 13. The trajectory is only available in 2014 in the near future, because it repeats in a 32-year cycle, making this launch year particularly important for the first human mission to Mars.

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