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A CREWED MARS EXPLORATION ARCHITECTURE USING FLYBY AND RETURN TRAJECTORIES

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Sustainable human Mars exploration strategies are presented that use Mars flybys and return trajectories. Three mission models are considered that differ in the number of transit habitats and the type of flyby and return trajectories used. The strategies assume the existence and operation of the Space Launch System and the Orion spacecraft with no reliance or requirement for new technology development. The capability for hyperbolic rendezvous and complex orbital operations at Mars is needed. Advantages of the proposed strategies include, smaller transit habitats since they are only occupied for fractions of the overall mission time, lower propellant requirements since the interplanetary transit habitats need not be inserted into or taken out of Mars orbit, and some limited abort opportunities. The strategies can be used in a stair step approach that facilitates a logical sequence of flyby, orbital, Mars moons or surface missions. Representative solutions and selected mission performance data are presented for missions in the 2020-2050 time frame bracketing 15 complete Earth-Mars synodic cycles.

INTRODUCTION

Because crewed operations at the International Space Station (ISS) are expected to wind down in the mid to late 2020's, there is emerging debate about the future strategy for human space flight. Current U.S. space policy seeks to visit a near Earth asteroid redirected to near-lunar space. Many of the international partners in the ISS instead favor a return to the moon. But on one point there is common agreement, namely, that *the long-term and ultimate goal of human space flight in this first half century is to send humans to Mars.*

Unfortunately, despite a litany of trade studies there has not been any consensus reached regarding the strategy that should be used to transport humans to the Mars system, how long they should stay there, what propulsion should be used, etc. Proposals range from the huge armada of vessels in the original von Braun plan,[1] to the large nuclear propulsion systems of the current NASA baseline,[2] to the much leaner approach in the Mars Direct plan.[3,4] Following a White House directive in the late 1980's, NASA was tasked to develop plans to send humans to Mars. This led to the 90 Day Study and the Space Exploration Initiative (SEI).[5] But that was deemed unaffordable and the plans were quickly dropped.

Other approaches make use of very high efficiency propulsion systems, such as Solar Electric Propulsion (SEP).[6–8] Generally, the very long trip times for these low-thrust systems prevent their direct use for the crewed elements; however, they can be used to pre-deploy assets for crews for later use, such as consumables, propellant and propulsion stages. Additionally the large power provided by the SEP arrays may have other uses even after the propellant is depleted.[9]

Cycling vehicles between Earth and Mars has also been proposed for establishing a transportation infrastructure between Earth and Mars.[10–13] The concept certainly has merits if the goal is to establish a permanent transportation infrastructure, but it may be overly ambitious for the first human missions to Mars.

More recently, perhaps driven by the apparent stagnation in progress, other teams are proposing much less ambitious missions to get humans to the Mars system. For example, the Inspiration Mars Foundation,

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a privately sponsored initiative, sought a simple mission with a free return flyby of Mars in 2018.[14] There is considerable debate about its technical feasibility, and it is generally considered not programmatically viable as the current SLS vehicle development schedule cannot support it. In any case it is difficult to see the value of subjecting humans to the mission risks and long flight times to achieve just a few hours in the Mars system.

Zubrin[15] also considered the problem and described a habitat on a free-return, fly-by mission, that has two consecutive Mars flybys separated by about half a Mars year (~ 340 days). The time between these fly bys provides a co-orbiting and extended stay in the Mars vicinity that varies in distance up to about 20 million km from the planet.

Aside from the technical issues of sending humans to Mars, there is also the cost issue. It is clear that the US Congress and the governments of other countries are unwilling to spend enthusiastically on human space flight. Conventional wisdom has always suggested that Mars missions will require investments considerably larger than the ISS cost, itself the most costly construction and deployment project ever undertaken by humans. Such a cost for a Mars mission is likely unaffordable, even with extensive partnerships. However, a recent workshop[16] suggested that it is possible to develop affordable human Mars missions through changes in system engineering practices, use of lean development cycles, changes in government procurement practices, and importantly, by minimizing the use of new developments and the use of very advanced and sophisticated technologies.

The motivation of the present study is to explore possibilities within this paradigm shift by developing a lean Mars architecture using only systems expected to be available. That implies use of the SLS and the Orion crew vehicle since these are expected to be workhorse vehicles for the US space program for many years. Likewise, commercial interests are developing Earth orbit access systems that may also be useful within any architecture.

The discussion in this article begins with an examination of Earth-Mars fly-by and return trajectories which form the basis of the simplest type of mission (a single flyby mission). We then propose methods to exploit those trajectories to support orbital missions, Phobos-Deimos missions and surface missions with three distinct strategies:

1. The Dual Habitat (DH), consisting of an outbound transit habitat (OTH) occupied by the crew during the Earth-Mars transfer and a return transit habitat (RTH) occupied by the crew during the return.
2. The Loitering Habitat (LH), consisting of a single habitat that is on an Earth-Mars-Mars-Earth return trajectory.
3. The Hybrid Dual Loitering Habitat (HDLH) model which combines aspects of the first two by using two separate habitats each on closely spaced Earth-Mars-Mars-Earth return trajectories.

In all cases, the heavy transit habitats are not taken down into the Mars gravity well. Instead a Mars transfer vehicle (MTV) is used to depart from the arriving fly by hyperbola and capture into a Mars-centered orbit. At the end of the Mars stay, a hyperbolic rendezvous is required to transfer the crew to the habitat that flies by Mars for the return Mars-Earth leg.

These strategies offer key advantages to any transportation architecture. Firstly, the heavy transit habitats do not need to be inserted into and departed out of the Mars gravity well. Secondly, the transit habitats are only required to sustain human crews for a fraction of the total mission duration. This reduces the propulsive burden on the launch systems and we believe these types of missions are possible with existing, or soon to exist, launch system, and spacecraft. Finally, in some cases, there is a potential natural abort capability available and redundant return opportunities available which are desired attributes when human crews are considered.

The article closes with a discussion of candidate mission sequences leading to humans on the surface of Mars in the 2020-2050 time frame, and addresses the merits of a long stay versus a short stay in the Mars system.

EARTH-MARS FREE RETURN TRAJECTORIES

For travel between Earth and Mars, the shortest Earth-Mars (EM) trajectory, uses optimal planetary alignment and is often referred to as a conjunction class transit since the Earth and Mars are in conjunction at some point during the transit. There are also EM trajectories that allow transits that co-orbit beyond Mars until the heliocentric orbital paths again cross, with favorable resonances occurring periodically. Finally, there are families of trajectories that essentially take a short cut across the solar system and dip into the orbit of Venus, and may even take advantage of a Venus gravity assist (EVM). Of course there are return trajectories (ME, MVE) that mirror these outbound flights.

It should be noted that a single flyby of Mars that has a short outbound transit will, because of planetary miss-alignment for return, generally have a long duration return. And the converse is true, short inbound transits will require long outbound transits.

Any fly-by mission to Mars, with a free return to Earth, must use one of these trajectories, with the choice depending on the planetary alignment of the Earth departure epoch. To explore these, we use a broad trajectory search to form a comprehensive list of every low-ΔV transfer that departs Earth, encounters Mars, and returns to Earth within a reasonable flight time. This process can be summarized in three steps:

1. First, sets of Earth departure dates, Mars fly-by dates, and Earth arrival dates are established in discrete time intervals over the time frame of interest. This step also establishes the sets of Earth and Mars positions and velocities from their ephemerides.
2. Lambert fits are used to calculate every transfer (including 180-degree transfers, discretized by V_∞ magnitude) for each candidate Earth departure date for the outbound leg, and every transfer for the set of Mars fly-by dates to Earth arrival for the inbound leg. This step calculates the departure and arrival V_∞ at Earth and Mars, while transfers outside certain flight time constraints are filtered out.
3. Finally, the ΔV's to connect the incoming V_∞ to the outgoing V_∞ at Mars (assuming some minimum fly-by altitude) are computed for each fly-by date, and any ΔV larger than a maximum threshold are also filtered out.

The set of parameters and constraints that define the broad search are as follows:

Launch year:	2015–2052	Maximum Launch V_∞:	7 km/s
Maximum flight time:	1200 days	Maximum Arrival V_∞:	8 km/s
Time step for encounter dates:	3 days	Minimum Mars fly-by altitude: 300km	
V_∞ step for 180° transfers:	50 m/s	Maximum ΔV at fly by:	20 m/s
Heliocentric revolutions between encounters: 0 or 1		Number of gravity assists: 1 or 2	

The result from this process is a set of trajectories that depart Earth, fly by Mars, and return to Earth for low ΔV. The resulting set of trajectories then provide ideal initial guesses for a high-fidelity interplanetary trajectory optimizer to drive the ΔV to zero, thus computing a true ballistic free-return.

A significant metric to the viability of any fly-by trajectory is the TMI velocity impulse needed to place the spacecraft on one of these trajectories from an Earth orbit. The results from the analyses are shown in Figure 1 assuming departure from a 240 x 240 km altitude orbit without a Venus fly by (EME)and for the cases with Venus fly bys (i.e. EVME or EMVE, depending on whether the Venus fly by is on the outbound or inbound leg). The 26 month synodic period is evident and impulsive velocities between 4 and 5 kilometers per second from LEO are required. But this is an incomplete story as the flight times must also be considered. Also, the data must be further filtered as some of the trajectories give rise unrealistic Earth entry velocities. This was an issue with the 2018 opportunity chosen by Inspiration Mars.[14] So we have chosen to limit the data set by applying the following constraints:

Earth departure ΔV from a 240 x 200K km HEO	≤ 4.5 km/s (corresponds to C3 ~30 km2/s2)
Earth entry velocity at a 125 km entry interface	≤ 12.5 km/s (corresponds to arrival V_∞ < 5.8 km/s)
Mars fly-by periapsis altitude	300 ≤ hp ≤ 10K km
Mars fly-by periapsis velocity	≤ 8 km/s

Figure 2 shows these reduced data set, now presented as the round trip flight times. From Figure 2(a), with a Venus flyby (EVME or EMVE) the mission durations are 900 or more days. (By comparison, the 2021 opportunity proposed as an alternate to the 2018 for Inspiration Mars does have a much more favorable mission duration of 580 days but has an Earth entry velocity of 12.8 km/s and has therefore been filtered out in the figure).

The data without the Venus fly by (EME) in Figure 2(b) essentially fall into two groups, one with mission durations between 700 and 800 days (based on a 2:1 resonance with Earth), and another larger set with 1000 to 1200 days (based on a 3:2 resonance with Earth). The latter arise from flying an additional heliocentric orbit and are generally discarded for human missions due to the very long flight times. This is un-

fortunate as they clearly have lower departure energies. As we will show later, there may be ways that these can in fact be used to support human missions without the trip time penalty for the crew.

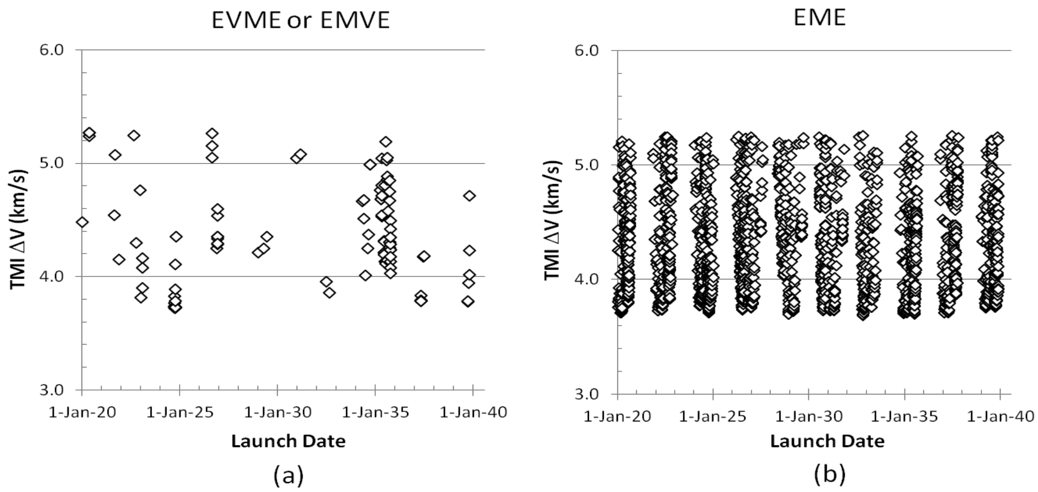

Figure 1. Earth departure ΔV needed from a 240 x 240 km altitude LEO for a Mars free-return fly by: (a) with Venus gravity assist, and (b) without Venus gravity assist

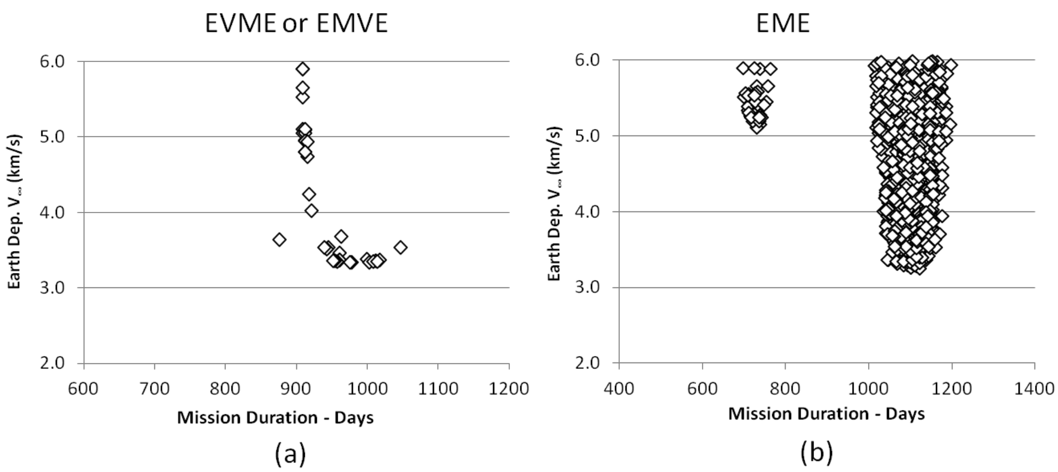

Figure 2. The Earth departure V_∞ needed for Mars free-return flyby with Venus gravity assist (a), and without Venus gravity assist (b). Cases with Earth entry velocities greater than 12.5 km/s at a 125 km altitude entry interface have been eliminated.

LAUNCH AND SPACE VEHICLE CAPABILITIES AND ENGINEERING A FLYBY MISSION

While this paper examines the planetary physics and energetics required to achieve a fly by mission to the Mars system, the bigger study also addressed the ability of SLS and Orion to support such missions. The results of that effort will be presented elsewhere, but some summary comments are worthwhile to provide engineering reality.

The SLS vehicle is presently proposed in three versions, that can deliver 70 t, 105 t, and 130 t to low Earth orbit respectively.[17,18] The Orion crew vehicle consists of a crew module and a service module with a total fueled mass of about 20 t.[19] To perform a fly by mission based on these variants of SLS and Orion, many vehicle configurations and mission designs are possible. In one of the simplest, one can envision a transit habitat aggregated with the Orion vehicle in some Earth orbit, and the resulting stack pushed through TMI by some propulsive stage. Possible aggregation sites are LEO, high Earth elliptical Orbits (HEO), lunar distant retrograde orbits (DRO), or halo orbits around the lunar Lagrange points (HLO).[20] Initial estimates can be made of required transit habit mass using current design practice,[21] then, using the energetics of Figure 1 and Figure 2, the required launch vehicle delivery can be estimated. While the details are beyond the scope of this paper, initial estimates suggest it will be possible to aggregate a viable transit habitat

in LEO and push the stack through TMI if two launches of the 105 SLS variant are used. Other options that make use of commercial providers may allow more efficient use of the SLS delivery system. The point is that the fly by mission is within the capabilities of the vehicles that are available or expected to become available.

Other approaches are naturally possible. For example, there is the tacit assumption in this suggested approach that the Earth re-entry vehicle, the Orion, travels all the way to Mars and back. We recognize that this need not be the case, and that the same mass could be used to carry propellant for a near-Earth capture maneuver at end of mission. But that does pose a host of alternative operational issues and given the typical arrival velocities at Earth, this may not be energetically beneficial.

Aside from the engineering viability of a fly by mission, there is the question of the utility of such a mission and whether such a mission is justifiable. We believe that a purely fly-by mission cannot be justified given the risks and the low scientific and operational return from such a short stay time at Mars. Much of the risk associated with the transit system can instead be mitigated safely with human flights in near-lunar space given that has an abort capability that is not provided with the extended duration fly-by flight.

But if the fly-by mission itself cannot be justified then we must ask the question: can such a fly-by trajectory, despite its short presence at Mars, ever be a useful component of a campaign to bring humans to the Mars system for extended stays, and ultimately to the surface? We believe the answer is in the affirmative and three possible approaches will be explored in the following sections.

THE DUAL HABITAT TRAJECTORY MODEL

Any mission into the Mars system, be it to the moons of Mars, or to the surface of Mars, will require first entering a Mars orbit, which a vehicle on a fly by does not do. An alternative strategy, as depicted in Figure 3, exploits beneficial properties of fly-by and return trajectories. In this concept, a dedicated Outbound Transit Habitat (OTH) is used for an outbound transit to Mars. As in the previous concept, the crew departs Earth in this habitat accompanied by an MTV. As they reach the Mars system, they depart the transit habitat and enter the Mars system in the MTV. The transit habitat is nominally assumed to be discarded even though it can be on a free-return path to Earth. The crew then completes mission operations at Mars, and leaves months later by rendezvousing with a second transit habitat, the Return Transit Habitat (RTH), that is also flying by on a free-return trajectory to Earth. The RTH is launched separately with an Orion entry vehicle, but without crew. Since the RTH is the crew's ride home, good mission design would suggest that it should leave Earth well ahead of the crew, and as we will show, this is indeed possible by using an Earth-Mars-Earth free return trajectory that allows the Earth to orbit the Sun three times while the RTH orbits the Sun twice (a 3:2 resonant trajectory of the RTH with respect to the Earth).

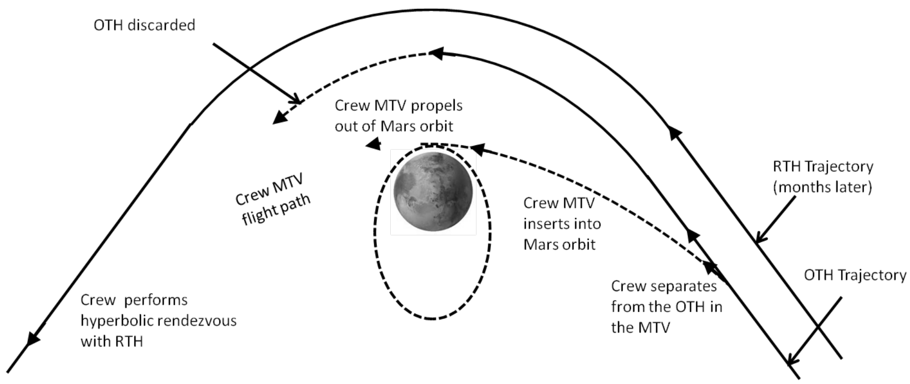

Figure 3. The Dual Habitat Trajectory Model

This concept is referred to as the Dual Habitat model. It has some operational similarities to the cycler concepts,[10–12] but is a simpler implementation. The question is whether the various trajectories summarized in Figure 1 and Figure 2 can support this kind of mission concept.

To explore that question, Figure 4 shows the same mission duration data that were presented previously in Figure 1(b) for the case without a Venus fly by (i.e. only EME), but now the data are parsed into the EM outbound transit duration and it's corresponding ME inbound transit duration. They are presented as a function of the date of the EM arrival at Mars. Since these are fly-by trajectories, this is also the date of the ME departure from Mars. Every EM outbound transit point is associated with a ME inbound transit point

that is vertically above or below it. The data fall into two horizontal bands showing that for every short outbound transit there is a long return, or conversely for every long outbound transit, there is a short return. As a result we can see that total mission durations for a single transit habitat on a fly-by return to Earth must have a mission duration of 200 to 400 days for one leg, and 700 to 1000 days for the other. That arises from the basic physics and that cannot be avoided. It is what leads to the total mission durations shown previously in Figure 2

But the unique feature of the Dual Habitat model is that it breaks this constraint. For any outbound transit in Figure 4, the mission designer can now pick a return transit by instead going horizontally in the graphic and picking a return flight Mars departure date that supports some desired stay time in the Mars system. And with proper choice, a short, conjunction class crewed outbound transit can be coupled to a short, crewed conjunction class inbound transit. The habitats themselves may spend quite long times in transit in their uncrewed outbound or inbound legs of the mission to support the missions, but the crewed legs are the much shorter transits.

This Dual Habitat model is a special case of a conjunction class mission, but differs from the conventional, single habitat, conjunction class mission because it avoids the penalty of parking a heavy transit habitat down in the Mars gravity well. Further, it means that the favorable energetics data set on the right of Figure 2(b), that are normally discarded due to prohibitively long round trip transit times (1000 to 1200 days) can in fact be used to support human missions. It is true that the transit habitat does fly for that duration, but the crew is only present for a short part of that time. This means the demands on the consumables and the life support system that the habitat must provide are substantially reduced, thereby relieving the habitat launch mass, and relieving the engineering challenge of providing life support for a very long mission duration, as would be needed for round trip flight with a single habitat.

The data in Figure 4 are the raw trajectory data but engineering reality must also be brought in to the discussion. We therefore filter the data set to a subset in the same way we derived the data of Figure 2 from the data of Figure 1 except that the Earth entry condition is applied only to the return transit habitats, as the outbound habitat is assumed to never return (although we will present some thoughts of what this might offer in terms of aborts if it does). Similarly the Mars periapsis conditions are only applied to the return habitats since the crew has to rendezvous with these incoming habitats. High periapsis altitudes or velocities would make that very challenging.

If these filters are applied to the full data set of Figure 4, then the reduced data set of Figure 5 is obtained. Certainly the options for matching a convenient return flight to any outbound flight are reduced, but a reasonable selection of choices still exists. For example, several arrival opportunities exist in mid-2032, following about a one year transit, and which match to departure about 6 months later with about a six month return flight. And there are some very favorable opportunities, such as arrival in early 2026, and others that offer a choice of short or longer stay times with reasonable transit times both ways.

These data only tell part of the story, however, as the actual arrival and departure conditions at Mars also need to be better understood. The fly-by trajectory data were therefore modeled using the Copernicus trajectory design and optimization system[21,22] using a high fidelity force model primarily to understand the characteristics of the solutions in the vicinity of Mars. This force model models the RTH fly by and the OTH Mars arrival as Mars centered hyperbolas. With this model, it is possible to estimate the capture maneuvers required by the MTV vehicle that detaches from the OTH vehicle at Mars arrival; and the MTV maneuver(s) required for the hyperbolic rendezvous with the RTH, several months later (see later).

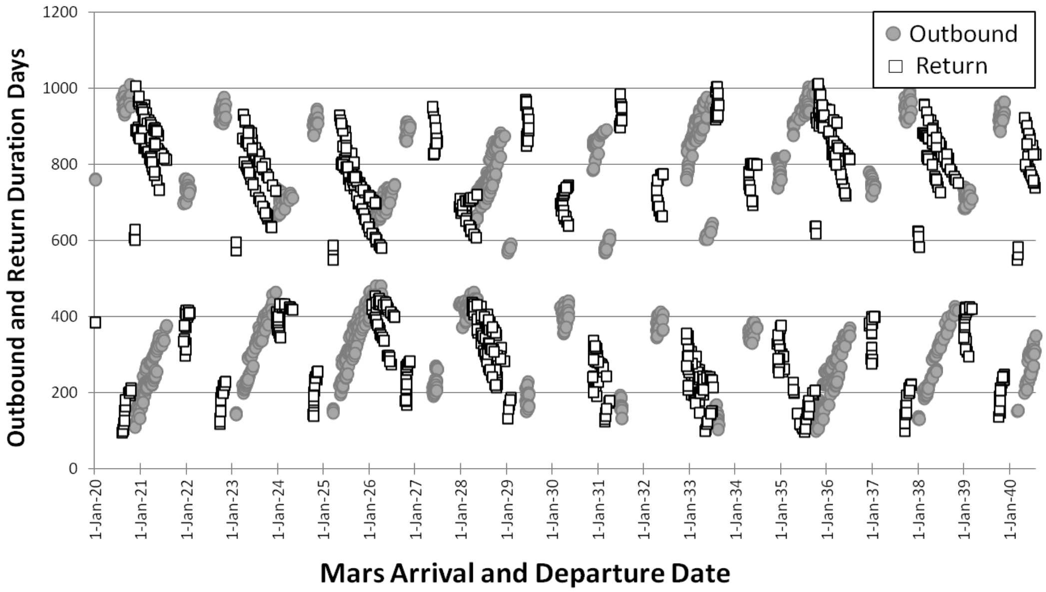

Figure 4. Break down of the EME fly by trajectories into Earth-Mars (Outbound) and Mars-Earth (Return) legs. No Venus fly by.

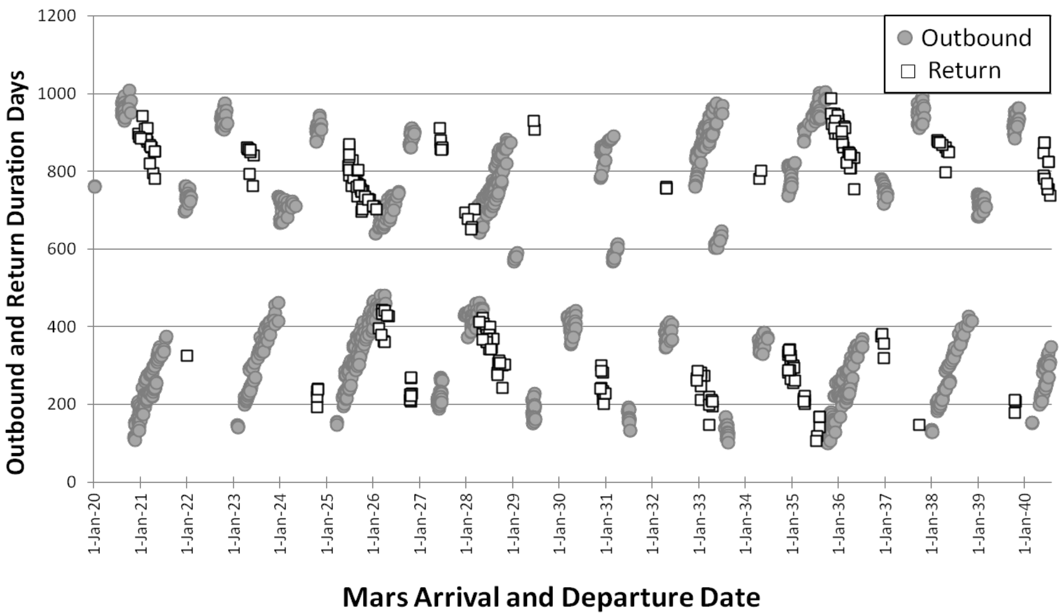

Figure 5. A subset of the breakdown of the EME fly by trajectories into their EM, and ME legs. Filters have been used to pick the data that meet engineering constraints (see text).

Table 1. Dual Habitat Trajectories: Outbound Transit Habitat 2024-2050

Mission #	OTH Departure (date)	OTH Mars Transit (days)	OTH Earth Departure V_∞ (km/s)	OTH Mars Arrival V_∞ (km/s)	Crew Mars Stay (days)	Crew Total Mission (days)
1	7/23/20	345	4.338	3.141	468	1014
2	8/31/22	350	3.849	2.616	432	1017
3	10/2/24	333	3.349	2.436	408	1007
4	10/31/26	310	3.044	2.551	366	985
5	11/23/28	301	3.016	2.955	425	1027
6	12/28/30	285	3.219	3.507	501	1040
7	4/28/33	274	2.776	4.374	439	932
8	6/27/35	201	3.219	2.616	347	867
9	9/1/37	222	4.395	2.595	275	846
10	10/13/39	252	4.772	2.574	486	943
11	10/20/41	318	3.124	2.465	390	997
12	11/14/43	305	3.005	2.776	340	996
13	12/13/45	292	3.112	3.280	494	1048
14	1/29/48	273	3.448	3.863	508	1006
15	5/25/50	206	2.828	2.777	365	906

Table 2. Dual Habitat Trajectories: Return Transit Habitat 2024-2050

Mission #	RTH Departure (date)	RTH Mars Outbound (days)	RTH Earth Inbound (days)	RTH Earth Departure V_∞ (km/s)	RTH Mars Flyby V_∞ (km/s)	RTH Mars Flyby Periapsis Radius (km)	RTH Earth Arrival V_∞ (km/s)
1	3/21/20	937	202	3.364	7.614	10000	5.082
2	5/2/22	902	236	3.461	6.315	1185	5.338
3	5/29/24	867	266	3.816	4.653	391	4.939
4	6/5/26	824	310	4.447	3.140	250	4.245
5	7/21/28	851	301	5.410	2.477	3158	5.293
6	9/26/30	879	254	3.459	2.430	10000	4.997
7	10/25/32	898	219	3.253	3.070	1001	3.083
8	12/7/34	750	319	3.308	6.023	10000	4.378
9	1/28/37	714	348	3.430	7.683	10000	4.472
10	6/4/39	870	204	4.320	5.403	10000	3.734
11	6/6/41	844	289	4.153	3.682	256	4.586
12	6/11/43	801	352	5.552	2.570	3846	3.917
13	9/11/45	878	262	3.775	2.464	7155	5.708
14	10/14/47	888	225	3.254	2.598	10000	3.055

15	10/18/49	791	334	4.679	5.189	2284	3.461

The results for Dual Habitat Trajectory cases are presented as a set of trajectories in the 2020-2050 time period in Table 1 and Table 2. The set consists of pairing an RTH free return trajectory with an OTH one way trajectory. The RTH trajectory is on a 3:2 resonant solar orbit with respect to the Earth (i.e. the RTH orbits the sun twice while the Earth orbits three times) and the RTH Earth departure date and OTH departure dates are tabulated. In all cases the crew can be assured their return ride is on its way before they ever leave Earth. The Crew Mission Total Time is the sum of the time on the Earth-Mars transit leg on the OTH, the Mars Stay time, and the time on the Mars-Earth transit leg on the RTH. Also tabulated are the RTH Earth departure, Mars fly by, and Earth arrival V_∞ values. Likewise for the OTH, the Earth departure V_∞ and Mars Arrival V_∞ are listed. For the RTH, its single Mars fly-by periapsis altitude was constrained to be between 250 and 10,000 km. There are no en-route maneuvers for any of the trajectories described in Table 1 or Table 2. Based on this analysis there are several distinct local optimal solutions that exist for any given opportunity.

Several observations can be made. All solutions have RTH Earth arrival V_∞ values well below the 5.8 km/s limit which correspond to the imposed limit of Earth entry interface velocity of 12.5 km/s at 125 km altitude. Unfavorable are the high RTH Earth departure V_∞ values required for the July 2028 and June 2043 opportunities and the excessively high V_∞ values required for the MTV hyperbolic rendezvous for the December 2034, February 2037, and June 2039 opportunities. These three opportunities also yield the highest value of the cost function. These years are unfavorable, but not impossible, for the Dual Habitat model. It is worth mentioning that the departure V_∞ and the Mars fly-by V_∞ can probably be lowered by the use of en-route maneuvers for the RTH, thereby reducing the performance demanded of the launch system, but at the expense of carrying en-route propellant. The October 2032 opportunity yields the best overall result from the point of view of crew mission duration and composite cost function. The actual trajectories for that case are shown in Figure 6 including a mission timeline.

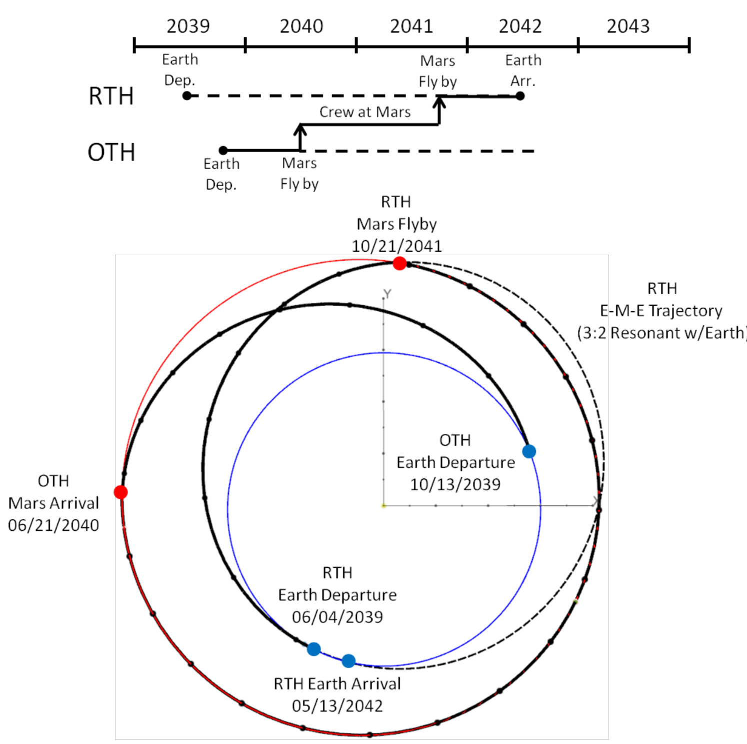

Figure 6. Dual Habitat Trajectory for the June 2039 (RTH Departure) Mission Opportunity. Markers shown every 30 days (the dash curve represents the uncrewed portion of the transit)

Contingencies and Abort Scenarios with the Dual Habitat Model

The use of dual habitats on free return trajectories is a unique approach to allow crews to access the Mars system. With careful mission design it may be possible to protect for some contingencies. We have

already seen that the crew does not need to leave Earth until the RTH has been successfully sent on its way to Mars. They can be assured that their ride home is on its way before leaving. At first sight it also seems that the strategy might support certain other contingency situations. For example, one can also imagine scenarios in which telemetry suggests the RTH has failed catastrophically in some way while the crew is still on their outbound transit in the OTH. In that case they can abort the mission and return to Earth in the OTH if it truly is on a free return trajectory. But adequate consumables would need to be carried to protect for this contingency and the crew mission duration in deep space would be quite long, defeating some of the mass advantage of the concept. But more importantly, this would require an Earth entry vehicle be carried with them attached to the OTH. This would represent a significant mass penalty to the OTH and trades would be needed to assess that penalty.

Another scenario can be imagined in which the OTH itself fails, say due to a massive depressurization event and it can no longer support the crew. In principle the crew might abandon the Mars mission and use the attached Orion as a life boat to catch up with the RTH already in flight and ride it home. A cursory examination does show that the trajectories allow for this possibility. The issue is that the flight times to reach the RTH can be quite long, some hundreds of days. Orion does not have the capacity to support a crew for that length of time. Nonetheless, the question of supporting aborts is one that is worth further examination.

THE LOITERING HABITAT MODEL

The Dual Habitat model is an approach that circumvents the difficulties that arise when a single habitat on a fly-by mission is used to support an extended stay in the Mars environment. As already suggested, the idea of a single loitering habitat would seem to fail to offer adequate residence time in the Mars environment. However, we know there are infrequent occasions when free return fly-by trajectories exist wherein a transit vehicle can inhabit the Mars system for extended periods. These free returns have two consecutive Mars fly bys (i.e. EMME) and require the transit habitat to rise out of the ecliptic and co-orbit Mars for a half Mars orbit period in a 1:1 resonant orbit. One example of this is shown in Figure 7. Unfortunately, there are prolonged periods when pure ballistic EMME free returns like this are not possible. That would offer little hope as a basis for a sustainable architecture. But those comments apply to unpowered, free return trajectories. If some modest propulsive capability is provided then a very different story emerges.

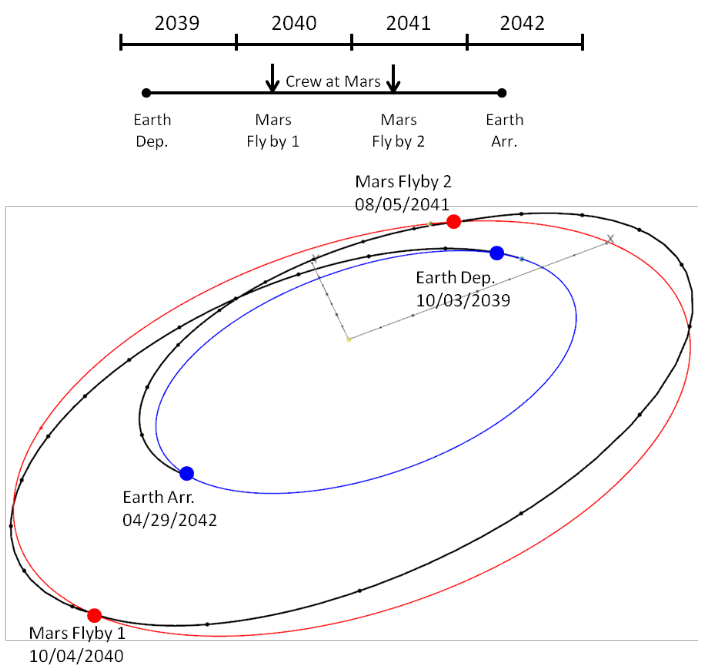

Figure 7. Loitering Habitat Scenario using the October 2039 Earth-Mars-Mars-Earth Free Return Trajectory. Markers shown every 30 days.

To examine this possibility, trajectory solutions have been generated for the EMME return trajectories between 2024 and 2050. These are based on an approximate force model consisting of the Sun as a point mass, and Mars as a point mass for the hyperbolic fly bys and the Mars-Mars leg. The departure and arrival at Earth used a zero-sphere-of-influence (patched conic) model for the Earth. The minimum fly-by altitude at Mars was set to 250 km. En-route maneuvers were allowed along the Earth-Mars, Mars-Mars, and Mars-Earth legs of the trajectory but were not allowed 5 days before and after the periapsis point of the two

Mars fly-bys.. For each synodic period departure opportunity, an attempt was first made to seek a pure ballistic EMME free return. If it existed, then the sum of the Earth departure and arrival V_∞ magnitudes was minimized and the en-route maneuvers were constrained to be zero. If a pure ballistic EMME free return did not exist, then the Earth departure and Earth arrival V_∞ magnitudes were removed from the cost function, and the sum of the en-route maneuver magnitudes was minimized. For this case, the Earth departure and arrival V_∞ magnitudes were allowed to be free and unconstrained. With these conditions, a consistent set of trajectories was generated which can be used to generate other results such as specific LEO/HEO departure maneuver costs, Earth entry interface conditions, and maneuvering requirements for Mars centered orbit operations. These trajectories can also serve as starting points for further refinement once better launch system and habitat mass and propulsion characteristics are known. For now, they serve as a reasonable data model as far as this study is concerned. The results are shown in Table 3, where each trajectory is constrained to have an Earth departure $V\infty$ of 4 km/s or less.

A generalized result from this analysis is that the 2033, 2035, 2048, and 2050 solutions are unfavorable in terms of en-route maneuver requirement. However, the 2024, 2026, 2029, 2037, 2039, and 2041 opportunities are ideal opportunities for the loiter habitat model in terms of propulsive requirement.

Table 3. EMME Trajectory Characteristics: Case for Earth Departure $V_\infty \leq 4.0$ km/s

Departure (date)	Earth Mars Transit (days)	Mars Mars Transit (days)	Mars Earth Transit (days)	Total Mission Duration (days)	Earth Departure V_∞ (km/s)	Mars Fly-by1 V_∞ (km/s)	Mars Fly-by2 V_∞ (km/s)	Earth Arrival V_∞ (km/s)	Deep-Space ΔV (km/s)
8/6/20	399	325	303	1028	3.794	2.550	3.018	4.714	1.676
9/8/22	380	311	320	1010	3.673	2.573	2.887	3.787	0.621
10/5/24	348	305	325	976	3.335	2.555	2.721	3.018	0.000
11/27/26	280	303	358	941	4.000	2.942	2.989	3.546	0.126
12/29/28	252	305	366	923	4.000	3.746	3.505	4.609	0.205
2/13/31	223	321	379	924	4.000	3.804	3.251	4.317	0.515
3/31/33	218	358	346	922	4.000	3.703	3.108	4.410	1.100
7/22/35	364	346	213	923	4.000	3.100	3.737	3.884	0.856
9/10/37	370	317	234	921	4.000	3.178	3.669	4.118	0.195
10/3/39	367	305	267	939	3.530	2.852	3.041	4.045	0.000
10/21/41	341	302	338	981	3.159	2.635	2.647	3.268	0.000
10/15/43	331	303	381	1016	4.000	2.782	2.666	3.630	0.495
1/22/46	244	315	375	934	4.000	3.762	3.289	4.227	0.477
3/13/48	219	343	360	923	4.000	3.877	3.214	4.453	0.775
7/7/50	347	361	209	917	4.000	3.046	3.606	3.721	1.068

THE HYBRID DUAL LOITERING HABITAT MODEL

The third strategy proposed for using fly-by and return trajectories to access the Mars system is a hybrid of the Dual Habitat and Loitering Habitat strategies. Two habitats are placed on distinct EMME trajectories

which are offset in time thus offering, among other things, more than one return opportunity. Because there are two habitats and each one has two distinct Mars fly by dates, there are six possible mission scenarios. The timelines for these six scenarios are captured in Figure 8. The first four, M1-M4 correspond to the crew leaving Earth on Habitat-1, and the last two, M5 and M6, correspond to departing on Habitat-2. Admittedly, some of these are probably not realistic. For example, M4 waits to use the very last return opportunity, throwing away the redundancy offered by the architecture. M1 would seem to be favored since it offers two additional return opportunities if the first one is missed for some reason. However, M5 is probably preferable since it allows the crew to depart Earth secure in the knowledge that their ride home has safely left, while still offering a backup return opportunity. This flexibility and added redundancy is a unique benefit and advantage of this trajectory model.

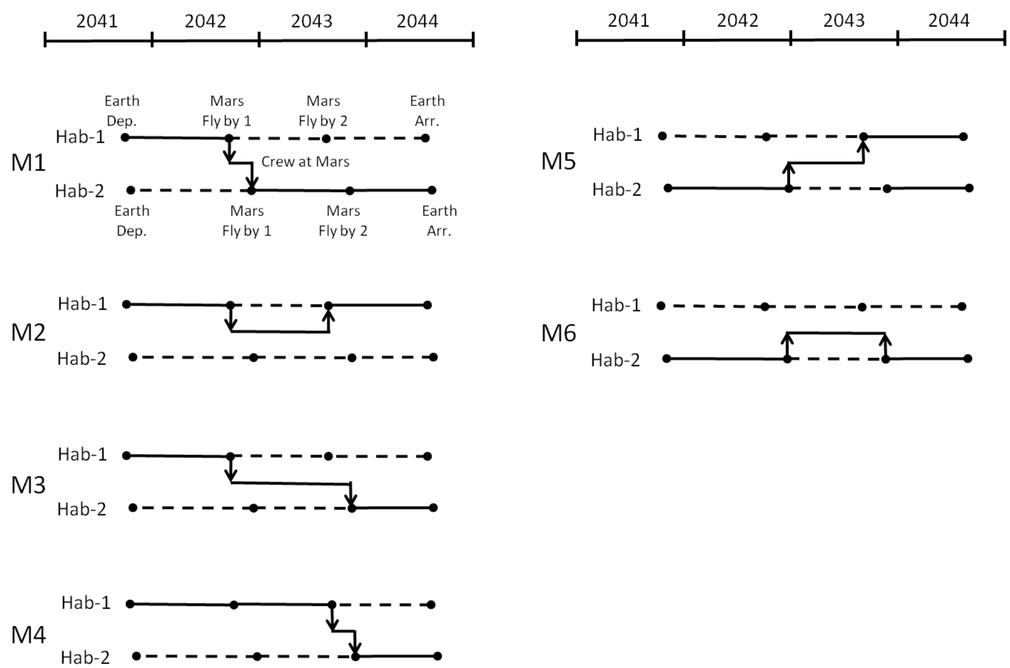

Figure 8. The six E-M-M-E mission possibilities for the Hybrid Dual-Loitering habitat strategy. The dash lines represent the flight of the transit habitats without crew.

To allow a paired trajectory analysis to be developed for this hybrid strategy, a specific EMME trajectory opportunity (October, 2041) has been chosen from the available solutions listed in Table 3**.** The base solution is defined to be the trajectory for the first habitat, Habitat-1, and as a restriction its trajectory is constrained as close as possible to its original solution with some of its defining parameters being allowed to vary in an overall optimization process. The second habitat, Habitat-2, follows a similar trajectory but the time of its Mars fly by, relative to the first, is specified and serves as the independent and scanning parameter. This parameter is varied from 10 to 90 days in increments of 10 days and because of this forced offset constraint, all of the defining parameters of the resulting EMME trajectory will change, and en-route maneuvers may be needed. Optimization variables include all departure, fly by, and arrival dates for both habitats and as before, both have their Earth departure V_∞ values constrained to be no more than 4.0 km/s and their Earth arrival V_∞ values to be no more than 5.8 km/s. Since Habitat 1 does not have en-route maneuvers originally (as shown in Table 3), it is constrained not to have any when used in this hybrid model. The en-route maneuvers for Habitat-2 are allowed only on the Earth-Mars and Mars-Earth transit legs and are constrained to be no more than 1 km/s each, and they must occur outside of a 20 day exclusion time zone relative to Earth departure, Earth arrival, and Mars fly by times. The optimization problem minimizes the total en-route maneuvering requirement for the 2nd habitat consistent with all the assumptions and constraints given.

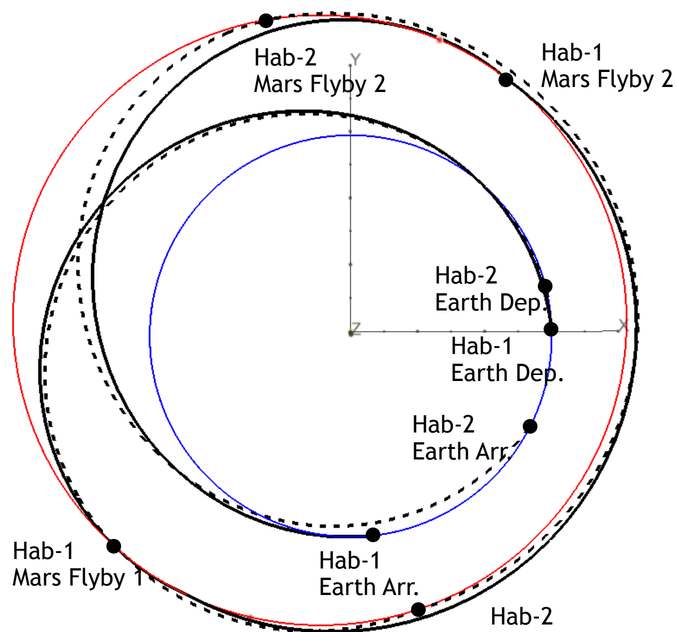

Figure 9. Hybrid Dual Loitering Habitat Strategy: Using the 21 Oct 2041 EMME Reference Solution for Habitat 1. 2nd Mars Flyby Separation Time is 90 Days.

Table 4. Dual Loitering Habitat Model: Maneuver Data and Performance

Hab-1, Hab-2 2nd Mars Fly By Diff. (days)	Hab1 Earth Depart V_∞ (km/s)	Hab1 Earth Arrive V_∞ (km/s)	Hab2 Earth Depart V_∞ (km/s)	Hab2 Earth Arrive V_∞ (km/s)	Hab2 Total Enroute Δv (km/s)
10	3.901	3.293	3.214	3.265	0.000
20	4.000	3.248	3.214	3.303	0.098
30	4.000	3.248	3.226	3.622	0.229
40	4.000	3.248	3.571	3.932	0.384
50	4.000	3.248	3.761	4.374	0.550
60	4.000	3.248	4.000	4.865	0.723
70	4.000	3.248	4.000	5.378	0.914
80	4.000	3.248	4.000	5.802	1.124
90	4.000	3.248	4.000	5.802	1.393

Table 4 tabulates the changes in the Earth departure and arrival V_∞ values, and the total of the needed enroute maneuver cost for Habitat-2. As expected, the sum of the two enroute maneuvers for Habitat-2 increases as the separation time increases, since its trajectory is being forced to move away from the naturally occurring EMME trajectory associated with that of Habitat-1. This cost varies from 0 km/s for a second Mars flyby separation of 10 days, to 1.393 km/s for a separation of 90 days. A the cost of this additional ΔV, the Hybrid Dual Loitering Habitat model trajectory model offers several notable features to the transportation architecture:

1. The crew stay time in the Mars system is no longer constrained to be half a Martian year as in the Loitering Habitat concept. It is true that each habitat co-orbits with Mars for that time, but the arrival and departure times can be phased to limit the crew stay time. This architecture is unique in that it allows control over stay time. That means the number and amount of consumables and assets that must be predeployed to support a human mission can be significantly reduced.

2. The crew now can have a back-up to their ride home. In the event they are unable to rendezvous with the first returning habitat, they can, in principle wait until the second returns and rendezvous with it. Redundancy in return opportunities is a unique benefit of the concept.

ACCESS INTO THE MARS SYSTEM: MTV CAPTURE AND DEPARTURE

The three architectural concepts that have been proposed each allow reaching the Mars system but a strategy is needed to allow access down into the Mars system. That basic strategy was depicted in Figure 3, and for simplicity we assume the arrival and departure maneuvers are performed by one vehicle, the Mars Transfer Vehicle (MTV) which carries the necessary arrival capability to allow rendezvous with pre-deployed orbital assets, and those in turn provide the capacity for the subsequent departure propulsion and the hyperbolic rendezvous. It is worth pointing out, that after the rendezvous, the MTV and the depleted propulsion unit can remain docked to the RTH for the entire return journey to Earth and augment the habitable living space and possibly provide additional power for that part of the journey.

For the architectures that have been described, the arrival and departure Mars fly-by hyperbolas are separated in time by the Mars stay time and as a result will lie in very different orbital planes. To properly size the MTV and understand its maneuver requirements it is necessary to understand the capture, stay, and departure geometry between these two hyperbolas. For this discussion, we assume the capture orbit has a 1-Sol orbit period and a periapsis altitude of at least 250 km. The other elements of the 1-Sol stay orbit depend on the results of a capture-departure optimization process. It is assumed that a Mars habitat with a departure propulsion unit has been pre-deployed on this orbit to sustain the crew during the stay period.

The combined optimization of the entire capture, orbit selection, and departure phases is a complicated orbital mechanics problem deserving of a separate and complete independent study. At first glance, it would seem that prohibitively large plane changes would be needed. However, it is possible to minimize the energy required to access the departure plane from the arrival plane using the same techniques developed for an any-time Lunar orbit to Earth abort trajectory.[23] The fundamental idea is to allow for multiple burns and generally the burns near the planet are used mostly for energy changes and those that occur far from the planet are used for plane changes.

The Copernicus tool has been used to construct and optimize this particular problem for all of the opportunities listed in Table 3. To provide realistic bounds, capture into a 1-Sol orbit is constrained to take no more than 10 days, and at most four maneuvers are allowed. The first maneuver is a slowdown capture maneuver that generates a definable ellipse. This is followed by a coast period to a point far from Mars where a second maneuver is applied and is considered mostly a plane change maneuver. This is followed by a coast period to a third maneuver that mirrors the second maneuver and is also mostly a plane change maneuver, but also brings the vehicle back to a point near Mars where the capture into a 1-Sol orbit is made. Following the stay period at Mars, at most two maneuvers are used to perform the rendezvous with the OTH arriving along the departure hyperbola. The hyperbolic rendezvous is constrained to be at most two days in duration. The first maneuver of this hyperbolic rendezvous sends the vehicle on an escape trajectory, and the second maneuver is used for the final rendezvous.

A simple capture model can be used that forces the 1-Sol orbit to be constrained to the same plane and have the same line of apsides and periapsis point as the arrival or the departure hyperbola. But a more complex model can be used that is less restrictive and offers a lower total ΔV cost. In this model, the 1-Sol orbit is not constrained in anyway except only to have a minimum periapsis altitude of 250 km. Essentially the optimal 1-Sol orbit is selected that best balances the capture and departure phases between the two very different hyperbolas. The result is that the orbit plane and orientation of the 1-Sol orbit lies in some intermediate plane. Since this 1-Sol orbit now no longer shares at least one intersection point with the departure hyperbola, the hyperbolic rendezvous must be made with two maneuvers. The capture phase is allowed to have at most four maneuvers, but interestingly, as the results will show, the capture phase naturally converges to a three burn capture phase. There are also a total of five or six maneuvers for this complex capture and departure transfer model; three or four to capture and two for the hyperbolic rendezvous. These results are shown in Table 5 for all of the opportunities tabulated in Table 3.

As can be seen, capture and departure model yields lower total ΔV costs that are surprisingly reasonable, particularly considering that the Loitering Habitat model leaves no option to choose the arrival and departure hyperbolas—they are fixed by the trajectories and lie in significantly different planes. This can be seen in Figure 10 which shows the Mars centered capture and departure phases for the October 2039 Loitering Habitat model opportunity. The optimal 1-Sol orbit stay orbit does not lie in the plane of the departure hyperbola, something that should not be an issue in an actual mission, provided the choice of the 1-Sol orbit allows access to the required surface locations.

The results in Table 5 can be used directly to develop rough estimates of the propulsion requirements of the MTV for this particular mission. To do that, an MTV dry mass and propulsion system dry must be known. For now those must be speculative, but we know for example that a 3 person crew can be accommodated for a few hours by a Soyuz descent capsule, with a mass of 3 t, but that is a very cramped vehicle. We also know from Apollo that a crew module of 6 t can support three crew members for several days. So for the present purposes we will assume a 5 t MTV dry mass. If we take the pre-deployed propulsion system dry mass also as 5 t, then we derive the total propellant mass for all these maneuvers as around 14 t, assuming LOX-Methane propulsion supporting a total ΔV of 3 km/sec. It is likely that further reductions in propulsive capability would be achieved by use of aerocapture to augment the arrival deceleration, but this does have a significant impact on the MTV design since must now be an entry vehicle with a heat shield.

Table 5. Total Maneuver Requirements for Capture and Departure to and from a 1-Sol Orbit for the Loitering Habitat Model Mission Opportunities.

Loiter Hab Departure (date)	Arrival ΔV_1 (km/s)	Arrival ΔV_2 (km/s)	Arrival ΔV_3 (km/s)	Arrival ΔV_4 (km/s)	Departure ΔV_1 (km/s)	Departure ΔV_2 (km/s)	Arrival Total ΔV (km/s)	Departure Total ΔV (km/s)	Total ΔV (km/s)
8/6/20	0.786	0.000	0.208	0.184	1.096	0.043	1.179	1.138	2.317
9/8/22	0.805	0.000	0.198	0.177	1.013	0.036	1.179	1.049	2.228
10/5/24	0.768	0.000	0.195	0.176	0.929	0.032	1.139	0.960	2.099
11/27/26	0.956	0.082	0.111	0.174	1.063	0.026	1.323	1.089	2.412
12/29/28	1.327	0.098	0.086	0.174	1.349	0.025	1.686	1.373	3.059
2/13/31	1.364	0.095	0.100	0.176	1.206	0.033	1.736	1.239	2.975
3/31/33	1.309	0.000	0.199	0.190	1.152	0.049	1.698	1.201	2.899
7/22/35	0.964	0.000	0.202	0.183	1.501	0.038	1.350	1.539	2.889
9/10/37	1.001	0.000	0.190	0.177	1.449	0.029	1.368	1.478	2.845
10/3/39	0.827	0.000	0.187	0.176	1.091	0.028	1.189	1.119	2.308
10/21/41	0.725	0.000	0.199	0.180	0.890	0.052	1.104	0.942	2.046
10/15/43	0.798	0.000	0.201	0.176	0.916	0.039	1.175	0.955	2.130
1/22/46	1.338	0.064	0.117	0.175	1.224	0.032	1.694	1.256	2.950
3/13/48	1.413	0.000	0.188	0.182	1.183	0.059	1.783	1.242	3.025
7/7/50	0.938	0.000	0.213	0.191	1.436	0.043	1.343	1.479	2.822

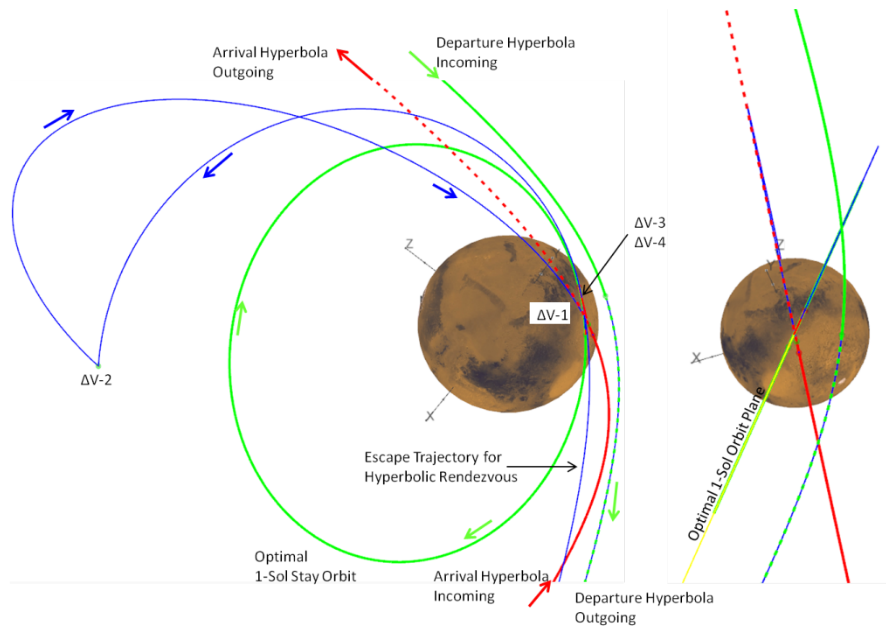

Figure 10. Capture, Stay, and Departure Transfer Sequence for the Oct 2039 Loitering Habitat Strategy Opportunity using the complex capture and departure transfer. The 1-Sol orbit is optimal and is not coplanar with either the arrival or the departure hyperbolas. There are a total of five required maneuvers (final rendezvous maneuver is not shown) for a total ΔV cost of 2.308 km/s.

Needless to say capturing a single large transit habitat and Orion into the same orbit and providing a similar propulsive capability for return would require significantly more propellant, certainly well over 100t. This is the advantage of the Dual Habitat and Loitering Habitat strategies.

For the Dual Habitat model, the Mars Transfer Vehicle must accompany the OTH and crew to Mars. Of course the RTH must still be configured to transit with an Orion and since the Orion provides the crew launch capability, the crew must also launch to the OTH in an Orion. After crew egress to the OTH, the Orion could then be autonomously docked to the waiting RTH and sent to Mars prior to crew departure to Mars. But more probably, a second Orion would be used to accompany the return transit habitat since in many instances it leaves Earth well ahead of the crew. For the Loitering Habitat model, the Orion and the MTV must accompany the transit habitat.

THE PURE ORBITAL MISSION

The concept of operations in Figure 3 brings the crew into the Mars orbit, and can, in principle, support any mission such as a purely orbital mission, a Phobos-Deimos mission or a surface mission. In each case additional vehicles would be deployed as required to support that particular mission.

However, as for the fly by, we also wrestle with the question of the merits of a purely orbital crewed mission. True, it would allow the transportation system to be flight qualified, but the need to have crew actually on board to do that is debatable. Another common argument is that an extended stay in Mars orbit would allow operation of surface assets, such as rovers, without the problems of the long communication delays back to Earth. It is true that the communication delays would be shorter, but actual line of sight communications to the surface assets from orbit would be periodically interrupted as the vehicle flies below the horizon. But even more importantly, the idea that the major source of delay in operating robotic assets is the communication delay is an all too common misconception. The real delay arises from the time specialists in the mission control center require to assess the situation, and do the back-room planning to define the next steps that should be commanded to the surface asset. Having a shorter communication delay will not really change this. There would be little true benefit to the operation of surface assets because of communication delay reductions resulting from having crews in Mars orbit.

THE PHOBOS-DEIMOS MISSION

On the other hand, a crewed mission to Phobos and Deimos certainly benefits from the crew presence, and remaining close to the surface of one of these bodies significantly reduces the crew exposure to cosmic radiation. But accessing the moons does pose a host of transportation challenges. Firstly, the orbits of the Mars moons are nearly equatorial, and the arrival planes of the incoming transit habitats and by association, that of the arriving MTV, will almost certainly be different. Further, those orbits are nearly circular so that circularization burns will be required.

Nonetheless, for a crew mission to Phobos and Deimos (Ph-D) using either the Loiter Hab or Dual Hab model, we can imagine some kind of Ph-D exploration vehicle to first be pre-deployed into an arrival Mars orbit and a sequence of propulsive maneuvers would be required of the MTV to dock with the Ph-D vehicle followed by access Phobos and Deimos. That would consist of burns for the periapsis raise, plane changes and circularization to match the orbit of the first moon being visited. Following a Hohmann transfer to the second moon, a reverse of the sequence would be used to bring the crew out of the Mars system to align with the arrival hyperbola of the incoming return habitat.

The points at which the vehicles meet up and dock, and later undock, can also be changed, so the suggested sequence is just one option, but it does enable the energetics to be understood. As in the discussion of the MTV capture and departure from Mars, a careful phasing of the series of maneuvers could be developed that minimize the propulsive penalty of this sequence, from which the Ph-D Exploration Vehicle could be sized. Rough estimates of the burn sequence that has been described suggest a ΔV capability as much as 5 km/sec would be required.

THE CADENCE OF MISSIONS: SHORT STAYS VERSUS LONG STAYS

Of course, the goal of any Mars program is to develop a sustainable approach to getting humans to the surface through flying a mission cadence that logically builds to that final goal using the transportation approaches such as those that have been proposed. We are of the opinion that a mission cadence need not include a fly by or a basic orbital mission for the reasons already given. However, a surface mission preceded by a Phobos-Deimos mission certainly is compelling. It makes sound engineering sense, and is reminiscent of the logical build up cadence employed in Apollo for what is now seen as a much less daunting task.

The data that have been presented in Figure 5 for the fly-by opportunities have therefore been explored to develop a cadence that begins with a Phobos-Deimos mission as a precursor to a surface mission. If the assumption is made that the first missions will be short duration within the Mars system, with the attendant long transits, at least on one leg of the journey, then the arrival dates of Figure 5 suggest one possible manifest as shown in Figure 11. This is based on the Dual Habitat model beginning with the late 2020's opportunity. The Loitering Habitat model of course cannot support this kind of short stay mission although the Hybrid model can.

The first mission brings crew for a two-week stay to explore Phobos and Deimos in the late 2020's. An exploration vehicle is pre-deployed to allow the crew to visit these sites, and also carry them back to the passing Return Transit Habitat as described previously in the discussion of Phobos-Deimos exploration. This mission provides a qualification of the in-space transportation system while also providing useful scientific return and is a compelling use of humans in the Mars orbital environment. The next planetary alignment opportunity is for the surface mission itself. Dual SLS launches are needed to bring the Lander to the Mars system, as described in the previous section, but only a short stay is supported.

Some observations immediately become apparent. Firstly, the launch manifest is extremely compressed with the required SLS launches taking place over a period of just a few weeks. This is not within expected SLS ground operations capability. Secondly, the crew spends upwards of 1200 days in transit, for only a week or two in the Mars system. This does not seem like an efficient approach to exploration. Alternative planetary alignment opportunities at other epochs can be used, but the conclusions that follow do not change significantly.

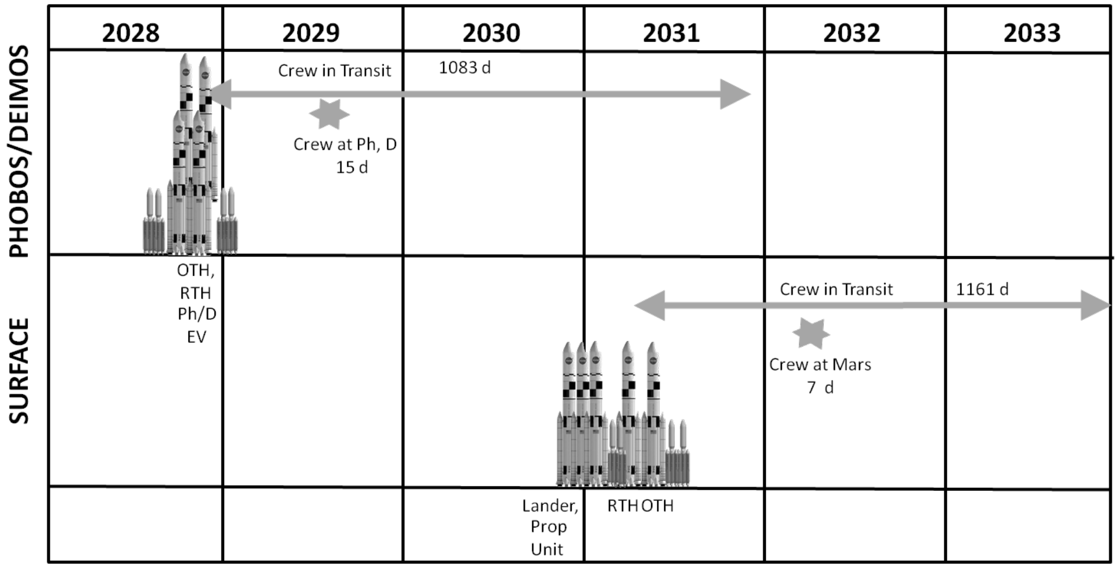

Figure 11. A mission campaign based on short stays within the Mars system using the Dual Habitat strategy

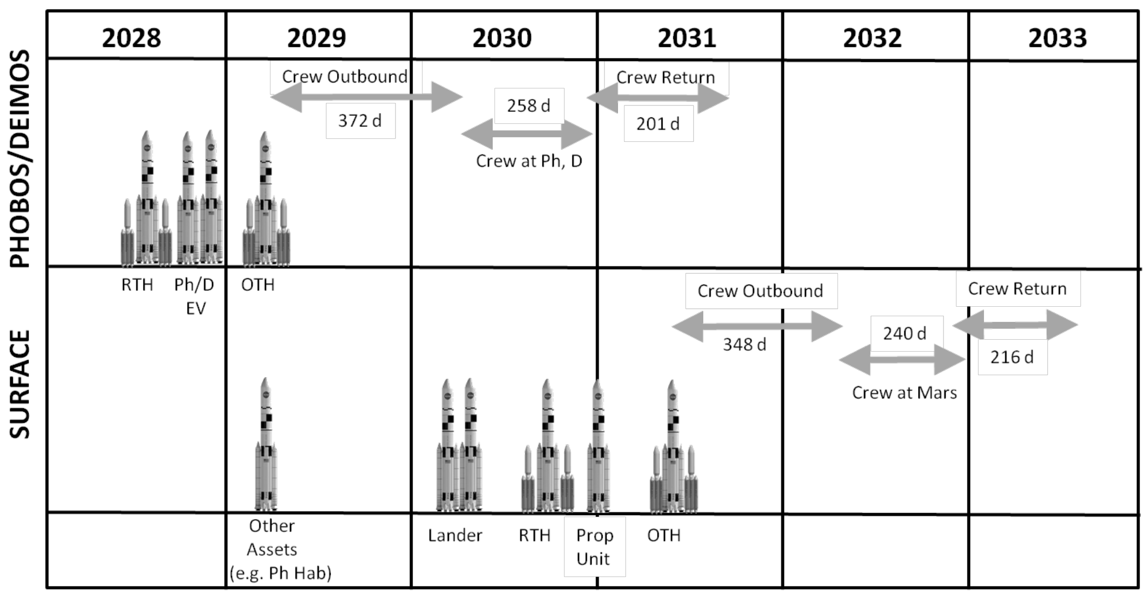

Figure 12. A mission campaign based on long stays within the Mars system using the Dual Habitat strategy.

An alternative approach is to assume long stays in the Mars system, with conjunction class transits both ways. An approach using the Dual Habitat model is shown in Figure 12 and was also derived by mining the data of Figure 5. As before, it is assumed the first crew to the Mars system evaluates the transportation elements possibly including the Lander systems, with exploration of Phobos and Deimos in the manner suggested previously. A suitable habitat is pre-deployed for them in the Phobos-Deimos system. The second crew arrives at the next opportunity to perform the surface mission. But a long stay in the Mars system does not necessarily imply a long surface stay, and in this scenario, the initial surface stay is quite short. It would be defined by how much surface infrastructure we choose to pre-deploy ahead of the crew and we assume initially that the crew lives out of the Lander in a style reminiscent of Apollo. Later missions would extend the surface stay time as flight experience and system reliability is established. At completion of the surface stay, the crew awaits Earth return in the Phobos-Deimos system in the same habitat left by the first crew.

In comparison to Figure 11, several features immediately become apparent. Firstly, the SLS launches are spread out over about a one year period. This is still very challenging programmatically, but is a much

more realistic goal. Secondly, in-space transit times are much reduced, a clear benefit of the approach. That of course comes with a price, namely long stay times in the Mars system. But even with those, the total mission durations are still less than those of the short stay mission in Figure 11 by some hundreds of days.

Finally, by having the crew awaiting return close to the surface of one of the Mars moons, the GCR is effectively halved for that part of the mission, compared to being in free space. Coupled with the shorter transit legs, this mission would expose the crew to about two thirds of the total exposure of the long-transit, short-stay mission. This is another benefit of the short-transit, long-stay mission scenario.

It is worth remarking that the number of launches for the surface mission is similar to that suggested in DRA 5.0, but that plan uses large, and presumably costly nuclear propulsion. Admittedly, the current proposal is much less ambitious having fewer surface assets, but it does not require substantial new developments by utilizing existing chemical propulsion technology and systems.

CONCLUSION

Innovative strategies for transporting humans to and from Mars that exploit the beneficial properties of fly by and return trajectories have been presented. These consists of three concept trajectory models that differ in the number of transit habitats needed, and the type of return and flyby trajectories used. These strategies all benefit from not having to transport massive transit elements into and out of the Mars gravity well. Initial estimates suggest that the strategies can be supported by SLS and Orion as currently envisioned.

The suggested Dual Habitat model offers the advantage that the OTH and RTH each only have to transport the crews for a fraction of the total mission duration; a number that varies depending on the opportunity, between 200 and 350 days. As a result of this split in transit habitation, individual system mass and propulsive requirements can be reduced. In all cases significant investments in new technologies is not required.

On the other hand, the Loiter Habitat model requires only one transit habitat but that need not be captured into Mars orbit, or carried back out. It must be designed to support the crew for about two thirds of the mission duration; a number that varies between 560 and 720 days.

The Hybrid Dual Loitering Habitat model benefits from the advantages of the Dual and Loitering Habitat models, and further provides redundant return opportunities. It offers unique a unique flexibility with its ability to use conjunction class transits but choose the crew Mars stay time and make it less than the half Mars year arising with most conjunction missions.

Furthermore, the multi-maneuver Mars centered orbital operations, although requiring significant plane change and rotations, to move an MTV in and out of an optimal 1-Sol orbit, still lie within a reasonable propellant budget.

Finally, a cadence of missions is examined to show how these ideas can be used to establish a human presence in the Mars system. It is suggested that there is little merit to putting crew on a fly by or even an orbital mission as the first flight. Instead it is proposed that the first crewed flight be to Phobos and Deimos followed by a second mission, also to Phobos and Deimos but with a short excursion to the surface of Mars. The launch rates and mission durations suggest long stays in the Mars system with the crew remaining under the protection of Phobos or Deimos are preferable to short stays. This can later be followed by more extended stays on Mars itself once confidence in the transportation system has been established.

ACKNOWLEDGMENTS

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