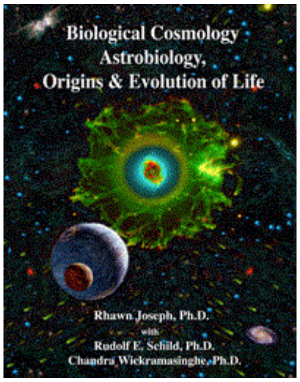


Journal of Cosmology, 2010, Vol 12, 3588-3600.
JournalofCosmology.com, October-November, 2010

Interplanetary Trajectory Analysis and Logistical Considerations of Human Mars Exploration

Takuto Ishimatsu[1], Paul Grogan[2], and Olivier de Weck, Ph.D.[3],

[1]Department of Aeronautics & Astronautics, Massachusetts Institute of Technology, Cambridge, MA
[2]Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA
[3]Department of Aeronautics & Astronautics, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA

Abstract

NASA's new direction for human spaceflight reaffirms that Mars is the ultimate goal of human exploration of the inner solar system. Eventually we envision colonies of humans and robots jointly exploring the Red Planet in a collaborative fashion. This paper addresses the challenge of long-term exploration and colonization of Mars from a logistical perspective. Adding to the technical challenges of Martian exploration, Mars transfer trajectories and logistical concerns should be considered in advance. An interplanetary trajectory analysis using a ΔV map and flight opportunity bat chart in addition to a traditional trajectory data table shows Venus flyby flight opportunities can be competitive with direct flights having smaller ΔV (velocity change) and shorter flight times because flyby opportunities open up additional launch windows. Therefore, direct flights should be planned in the early phase of a human Mars exploration campaign and Venus flyby flight opportunities may serve as urgent cargo resupply missions that cannot wait until next direct flight opportunities. Cargo flights for pre-positioning should minimize ΔV while crewed flights should reduce flight time at the cost of higher ΔV to minimize crew exposure to reduced gravity and space radiation during in-space transports. SpaceNet analysis from a logistics perspective reveals that the Mars exploration architecture as described by NASA's Mars DRA 5.0 is propulsively feasible but logistically infeasible without modifications to increase supply capacity during crewed transport and exploration periods. The most constrained transportation legs include the surface habitat (SHAB) and Mars descent/ascent vehicle (MDAV) descents to the Martian surface and the crewed MTV transit to Mars.

Key Words: Human Mars Exploration, Space Logistics, Launch Window, Mars DRA 5.0, Pre-Positioning, ISRU.

---

1. Introduction

The Red Planet has been a long-held goal of human spaceflight ever since NASA's two Viking probes landed there in 1976. Announced in 2004, the Vision for Space Exploration was to seek to implement a sustained and affordable human and robotic program to extend human presence across the solar system, starting with a human return to the Moon in preparation for human exploration of one of the ultimate destinations, Mars (Bush 2004; NASA 2004). This vision encouraged engineers to define and refine the top-level requirements and configurations for crew and cargo launch systems and to develop an exploration architecture concept to support sustained human and robotic Mars exploration programs (NASA 2005). The final report of the Review of U.S. Human Spaceflight Plans Committee, released in October 2009, also states that "a human landing followed by an extended human presence on Mars stands prominently above all other opportunities for exploration. Mars is unquestionably the most scientifically interesting destination in the inner solar system, with a planetary history much like Earth's" (Review of U.S. Human Spaceflight Plans Committee 2009). Although the Constellation Program is facing cancellation, NASA's new plan for space exploration reaffirms that Mars is the ultimate goal of human exploration of the inner solar system (Bolden 2010, Obama 2010). In response to this background, it can be expected to see an increasing number of robotic explorations of Mars over the next several decades, eventually followed by human missions. Eventually we envision colonies of humans and robots jointly exploring the Red Planet in a collaborative fashion. This paper addresses the challenge of long-term exploration and colonization of Mars from a logistical perspective.

NASA has undertaken substantial effort to develop a design reference architecture (DRA) for conceptual missions to Mars. DRA represents the current "best" strategy for human missions and architectures and should be constantly updated as we learn. It also serves as a benchmark against which alternative architectures can be measured. The most recent publication is Mars DRA 5.0 (Drake 2009, 2010). This design reference describes the spacecraft and missions which could be used for the first three excursions to the surface of Mars. The Mars exploration architecture is heavily based on lunar concepts from the Constellation Program, including the Ares V heavy lift launch vehicle, but also includes advanced technology concepts such as nuclear thermal rockets (NTR) for interplanetary propulsion, zero-loss cryogenic coolers for propellant transportation, aerocapture as the Mars arrival capture method, in-situ resource utilization (ISRU) for Mars ascent propellant production, and nuclear fission reactors for surface power.

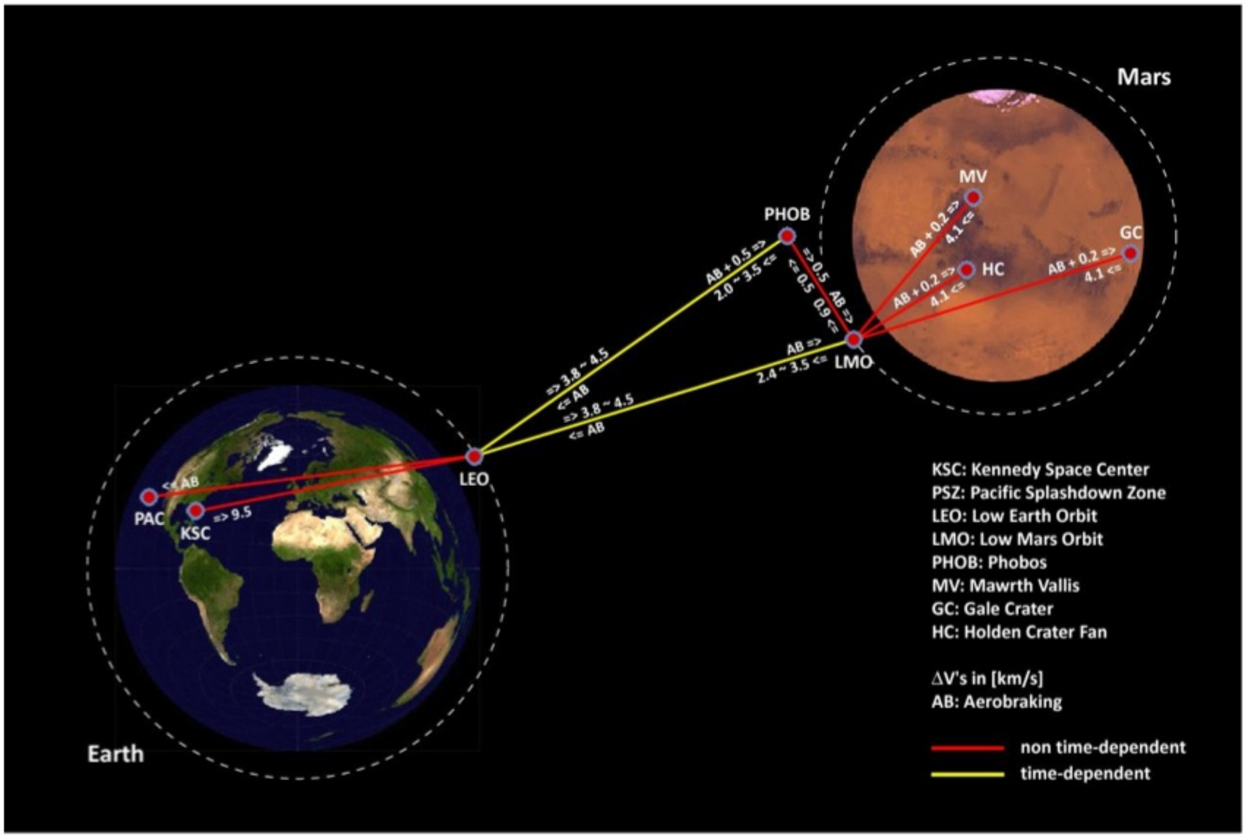


Figure 1: Earth-Mars logistical network with ΔV [km/s] shown along each transportation link.

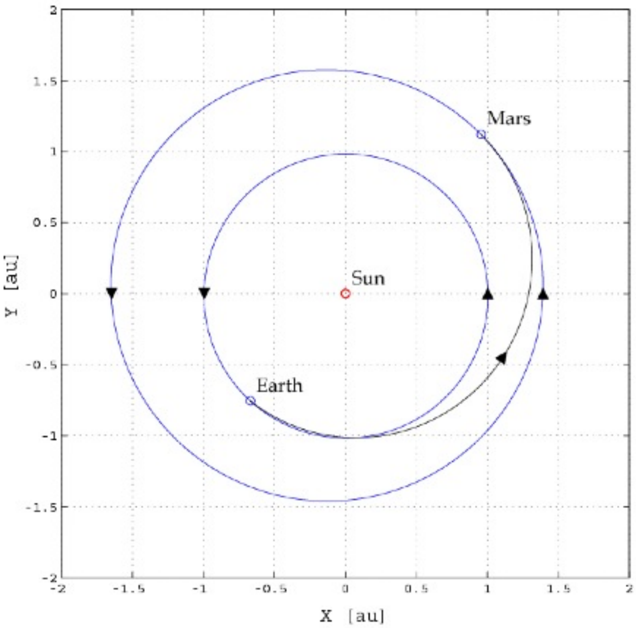
Adding to the technical challenges of Martian exploration, logistical concerns should be considered far in advance. Far away from home, depending on complex equipment, and with limited capability to manufacture the basic resources to sustain life, astronauts are constantly at risk of logistical lapses. A well-planned logistics strategy is essential to balance risks, ensure robustness, and achieve maximum exploration capability. Although a vast body of research exists for terrestrial supply chain logistics in business and military applications, space exploration introduces several fundamental differences. First, unlike transports on Earth, space resupply missions are possible only at discrete intervals corresponding to favorable positions of planetary bodies and accommodating lead times required for spacecraft manufacturing, assembly, and ground operations. Second, transports in space can last significantly longer (weeks and months) compared to terrestrial transport options which tend to unfold in hours and days with the exception of ocean freight. Finally, the fraction of usable cargo in space vehicles is an order of magnitude smaller than that of terrestrial transports. While a semi-trailer gross weight may be nearly 50% cargo and a passenger aircraft about 10%, usable cargo mass fractions for launch vehicles to low-5 Earth orbit including to the International Space Station range between 0.5% to 1.5% and the Apollo lunar landings contribute a mere 0.05%.

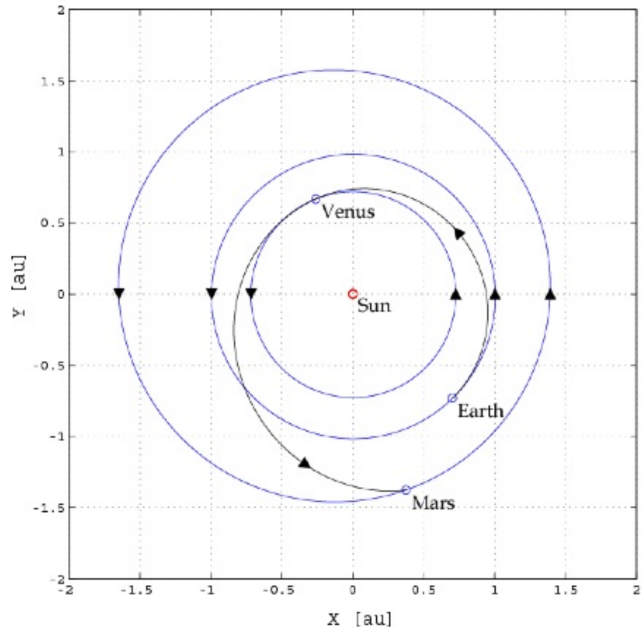
The challenges of space logistics – infrequent launch windows, long transport durations, and minimal cargo capacity – emphasize the importance of Mars transfer trajectories design and analysis. Planning future missions requires advance trajectory data such as departure and arrival dates (times of flight), C3 (energy required for departure), and ΔV for departure, arrival, and flyby maneuvers. The past studies of interplanetary trajectories have been mainly focused on showing trajectory data in the form of tables that tabulate only one typical choice of launch and arrival dates for each launch window, which is selected based on a minimum C3 over each launch window (Matousek and Sergeyevsky 1998). Considering interplanetary missions from the perspective of not individual missions but a long-term spaceflight campaign, however, future mission designers should have more exhaustive in-hand trajectory data by which they can perform a trade-off analysis between C3 and time of flight (i.e., duration) within each launch window or even between neighboring launch windows.

In summary, to safely explore distant locations in space logistics must respond to a wide range of unexpected events far enough in advance to accommodate launch window opportunities and the long-duration transports while working with severely limited mass capacities. These opposing constraints may require advanced strategies such as completely closed-loop environmental control and life support systems, ISRU and manufacturing or repair capabilities, highly efficient packing and container design, significant part commonality between systems, and orbital supply depots. Additionally it is desirable that one mission build on the next and so concepts like pre-positioning and reuse becoming major enablers.

2. Earth-Mars Mission Launch Catalog

2.1. Interplanetary Trajectories to and from Mars There are two main types of interplanetary trajectories from Earth to Mars: Earth-Mars direct trajectories (Fig. 2) and Earth-Venus-Mars flyby trajectories (Fig. 3). One of the important characteristics representing a trajectory is the energy required for departure, referred to as C3. A lower C3 is desired since it indicates a smaller velocity change, ΔV, for transfer injection, consuming less fuel. A lower ΔV at arrival also results in less fuel for braking or imposes a less stringent requirement for insulating against heating generated through aerocapture.





Figures 2 & 3: (left) Earth-Mars direct trajectory. (right) Earth-Venus-Mars flyby trajectory.

Against the aforementioned background of interplanetary trajectory data, Ishimatsu et al. developed a tool capable of creating not only a trajectory data table but also an exhaustive ΔV map for both direct and flyby trajectories in a single chart (Ishimatsu 2008; Ishimatsu et al. 2009, 2010). The contours of ΔV for a range of departure dates (x-axis) and times of flight (y-axis) serve as a "visual calendar" of launch windows useful for the creation of a long-term transportation schedule for mission planning purposes.

2.2. Mission Launch Windows Figure 4 shows an exhaustive ΔV map (upper) and a "flight opportunity bat chart" (lower) for the 2030-2040 time frame during which manned missions to Mars seem most likely to happen while Table 1 is a traditional tabular form of interplanetary trajectory data. As the criteria for mission feasibility to filter this ΔV map, the following four constraints were defined: 1) a departure C3 must be less than 30 [km2/s2] due to launch feasibility, 2) an arrival C3 must be less than 40 [km^2/s^2] for Mars arrival and 45 [km^2/s^2] for Earth arrival, respectively, due to aerocapture tolerance, 3) a minimum passing altitude at Venus flyby must be greater than 100 km above the surface, and 4) a ΔV for powered flyby maneuver should be less than 0.3 [km/s]. A circular parking orbit with an altitude of 300 km was assumed in the conversion from C3 to ΔV. Note that ΔV_{tot} is the sum of a departure ΔV and a powered flyby maneuver 7 ΔV, if any (an arrival ΔV is ignored assuming aerocapture). Filtered by the above four constraints, the "craters" in the figure represent "mission feasible" regions, ΔV_{tot}ranging from 3.6 to 4.8 [km/s].

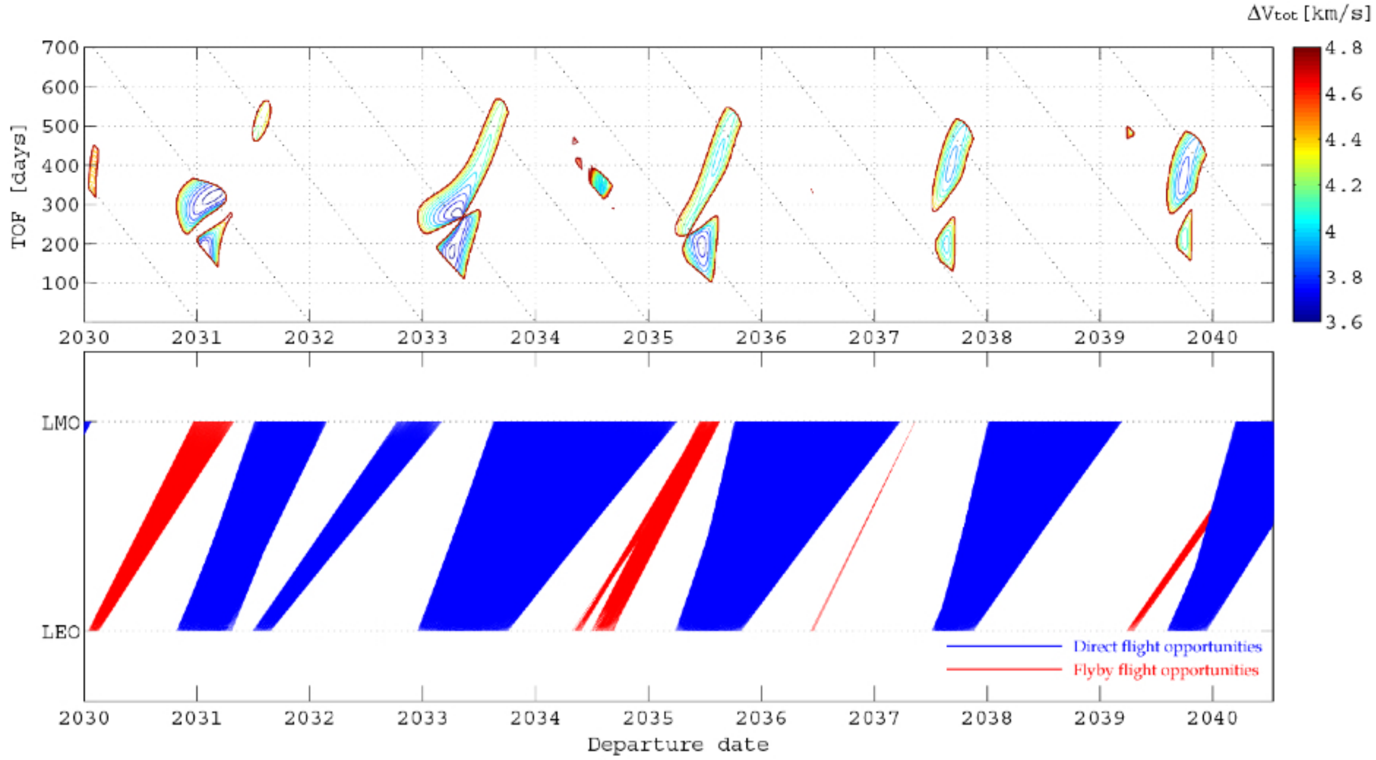


Figure 4: 2030-2040 Earth-Mars ΔV_{tot} [km/s] map (upper) and flight opportunity bat chart (lower).

Table 1: 2030-2040 Earth-Mars trajectory data.

#	Trajectory	Departure	Flyby	Arrival	TOF [days]	departure C3d [km²/s²]	dep. (+ flyby) ΔVtot [km/s]	arrival C3a [km²/s²]	Competitiveness
1	2030 Earth-Venus-Mars	01/24/30	07/09/30	12/22/30	332 (166 + 166)	24.72	4.279	39.40	competitive
2	2031 Earth-Mars	01/27/31	-	08/05/31	190	9.00	3.604	30.70	competitive
3	2031 Earth-Mars	02/22/31	-	01/08/32	320	8.24	3.571	30.60	dominated
4	2031 Earth-Mars	07/04/31	-	10/10/32	464	21.66	4.150	39.97	competitive
5	2033 Earth-Mars	04/04/33	-	09/29/33	178	8.41	3.579	15.96	competitive
6	2033 Earth-Mars	04/28/33	-	01/27/34	274	7.78	3.551	19.16	dominated
7	2034 Earth-Venus-Mars	07/22/34	12/07/34	06/29/35	342 (138 + 204)	13.92	3.835	33.31	competitive
8	2035 Earth-Mars	05/08/35	-	12/20/35	226	18.01	3.996	8.02	dominated
9	2035 Earth-Mars	06/23/35	-	01/05/36	196	10.20	3.658	7.20	competitive
10	2035 Earth-Mars	08/14/35	-	10/03/36	416	17.52	3.975	16.76	dominated
11	2036 Earth-Venus-Mars	06/11/36	11/22/36	05/13/37	336 (164 + 172)	24.39	4.410	39.91	competitive
12	2037 Earth-Mars	08/21/37	-	03/07/38	198	17.07	3.955	11.19	competitive
13	2037 Earth-Mars	09/06/37	-	10/07/38	396	14.85	3.860	11.26	dominated
14	2039 Earth-Venus-Mars	04/19/39	08/25/39	08/15/40	484 (128 + 356)	19.83	4.088	39.87	dominated
15	2039 Earth-Mars	09/26/39	-	09/20/40	360	12.18	3.744	7.23	dominated
16	2039 Earth-Mars	09/30/39	-	05/01/40	214	18.65	4.023	15.92	competitive

***Flyby missions are shaded.**

A mission scenario is often represented by a "bat chart." In a bat chart, a mission scenario is indicated by edges in a graph where the x-axis represents dates and the y-axis represents nodes. However, flight opportunities of interplanetary missions are highly time-dependent in terms of ΔV so that possible edges in a bat chart are limited to some extent. Thus, a bat chart with all possible edges drawn is defined as a "flight opportunity bat chart," each bunch of edges corresponding to a launch window. In Fig. 4, Earth-Mars direct flight and Earth-Venus-Mars flyby flight opportunities are represented by blue and red lines, respectively. This chart, along with a ΔV map, can be used to see the flexibility of the transportation schedule and to perform a trade-off analysis between departure and arrival dates, time of flight, and ΔV required for each maneuver on a mission-by-mission basis.

Additionally, the "competitiveness" of each launch opportunity is defined by the following criteria and shown in the rightmost column of Table 1.

· · If two neighbor opportunities have an overlapping departure date (an overlapping arrival date), and one has an earlier arrival date (a later departure date) than the other, the other is regarded as "dominated" since a shorter time of flight would be desirable from the perspective of exposure to both reduced gravity and space radiation.

· If an opportunity does not have neighbors with overlapping departure or arrival dates, the opportunity is non-dominated and thus regarded as "competitive" since it would add a new launch window even if it requires a relatively high ΔV.

Between 2030 and 2040 three out of four flyby windows are competitive because they open up new additional opportunities that cannot be replaced by direct flight opportunities. Having more launch windows available gives us flexibility of mission planning. However, those flyby windows tend to have a relatively high ΔV_{tot} and a long time of flight.

Completing a round-trip mission, Mars-Earth return trajectories are shown in Fig. 5 and Table 2. Since Mars gravity is less than Earth's, trans-Earth injection (TEI) requires a relatively small energy, ΔV_{tot} ranging from 2 to 4 [km/s]. As no good timing of the Mars-Venus-Earth relative configurations exists under the above four constraints, there are no flyby opportunities available during this time period.

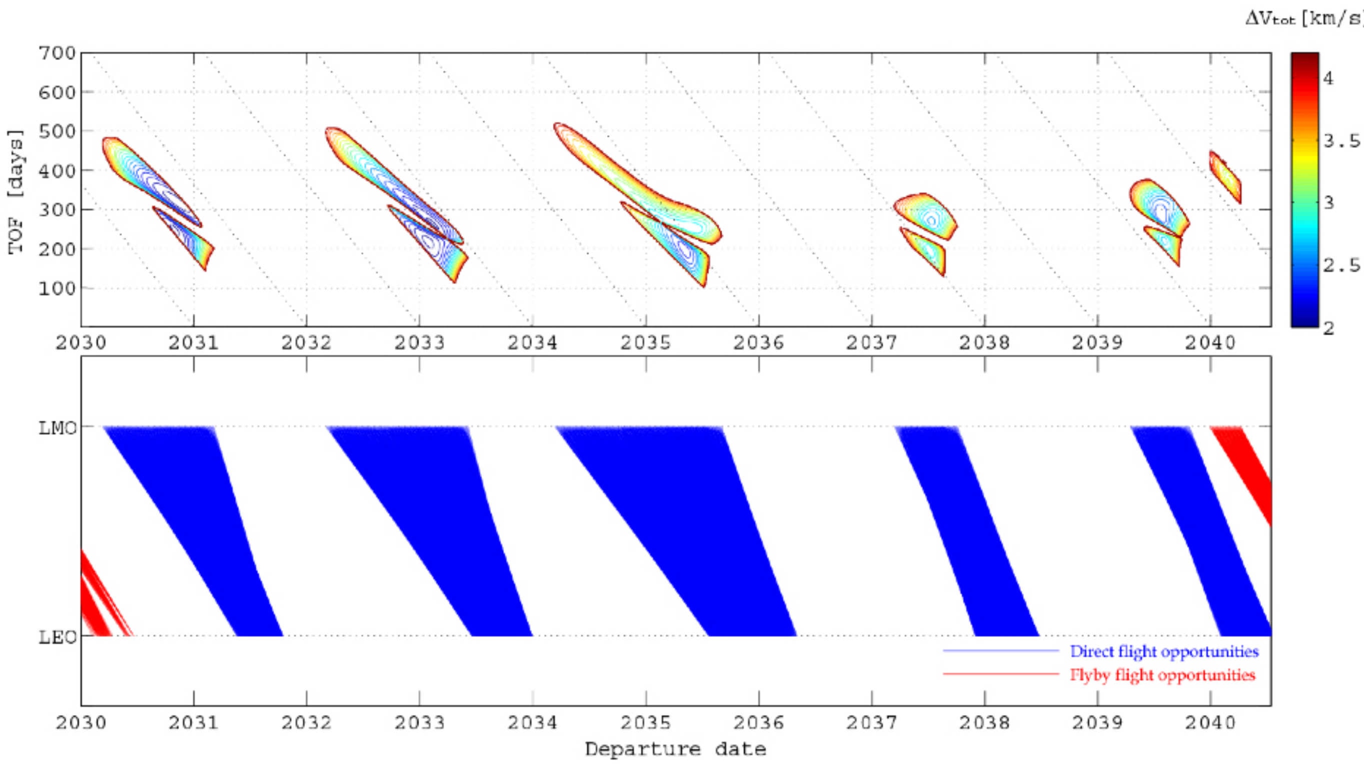


Figure 5: 2030-2040 Mars-Earth ΔV_{tot} [km/s] map (upper) and flight opportunity bat chart (lower).

Table 2: 2030-2040 Mars-Earth return trajectory data.

#	Trajectory	Departure	Arrival	TOF [days]	departure C3d [km²/s²]	departure ΔVtot [km/s]	arrival C3a [km²/s²]	Competitiveness
1	2030 Mars-Earth	10/31/30	07/06/31	248	5.79	1.978	31.86	competitive
2	2030 Mars-Earth	11/08/30	09/22/31	318	5.43	1.945	29.57	dominated
3	2033 Mars-Earth	01/26/33	09/01/33	218	5.72	1.971	16.69	competitive
4	2033 Mars-Earth	02/11/33	11/02/33	264	5.81	1.980	24.38	dominated
5	2035 Mars-Earth	02/15/35	11/12/35	270	13.07	2.616	9.57	dominated
6	2035 Mars-Earth	05/08/35	11/22/35	198	8.77	2.248	9.16	competitive
7	2037 Mars-Earth	07/08/37	01/18/38	194	14.31	2.719	15.49	competitive
8	2037 Mars-Earth	07/12/37	04/08/38	270	12.55	2.573	12.62	dominated
9	2039 Mars-Earth	07/22/39	05/03/40	286	9.59	2.320	8.14	dominated
10	2039 Mars-Earth	08/03/39	03/10/40	220	13.60	2.660	20.06	competitive

It can be observed from the above results that flyby flights can be competitive because they open up additional launch windows in between but in general, direct flights are preferable to flyby flights in terms of both ΔV and time of flight. Therefore, direct flights should be taken in the early phase of human Mars exploration campaign while flyby flights may serve as urgent cargo resupply missions that cannot wait until next direct flight opportunities. Flyby flights could be more important if a permanent presence is established on Mars.

Cargo flights for pre-positioning should minimize ΔV since a long transport duration does not have much impact. For crewed flights, on the other hand, a shorter time of flight would be desirable even at the cost of somewhat higher ΔV from the perspective of crew exposure to both reduced gravity and space radiation during in-space transports.

3. Mars Campaign Analysis

3.1. Space Exploration Strategic Analysis Space exploration campaigns are characterized by highly-coupled missions and elements functioning within a spatially-distributed network over a long duration. An integrative approach to campaign analysis is beneficial to accommodate the many levels of system decomposition and mixed levels of fidelity required to analyze futuristic exploration. A space exploration campaign may be broken down into small components for which detailed models can be created and the resultant product aggregated back to the system level. The process of system decomposition and integration to uncover lifecycle system properties of space exploration has been referred to as strategic analysis (Cirillo et al. 2008).

In coordination with NASA's Constellation Program lunar architectural studies in 2004-2005, MIT founded its Space Logistics Project to build a research base supporting interplanetary supply chain management and logistical analysis necessary for extended exploration campaigns. The project initially studied several terrestrial analogs to space exploration, including operations in remote terrestrial environments such as the Arctic and Antarctic, commercial supply chains, and military logistics operations, culminating in the development of a space logistics framework (de Weck and Simchi-Levi 2006, Shull et al. 2006, Taylor et al. 2007).

SpaceNet implements the established space logistics framework within a discrete event simulation environment to support campaign analyses and trade studies (de Weck et al. 2007, Lee et al. 2008, Armar and de Weck 2009). From a logistics perspective, SpaceNet evaluates the movement of resources in attempt to satisfy demands during an exploration campaign. Demands originate from crew members requiring food, water, gases, and hygiene items, infrastructure elements requiring spares or replacement parts, and vehicles requiring propellant required to complete transports. For feasible campaigns (those in which all demands can be satisfied), sensitivity and trade studies evaluate system responses to changes and inform design decisions.

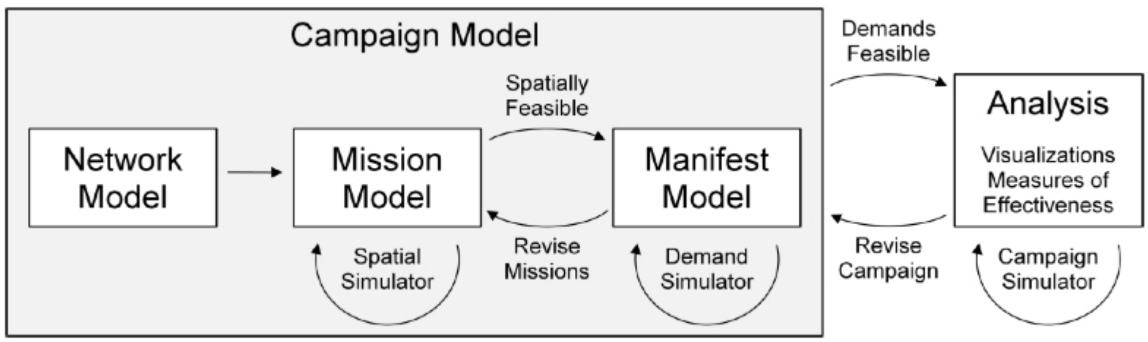


Figure 6: SpaceNet campaign modeling and analysis sequence (Grogan 2010).

Modeling and analyzing space exploration within SpaceNet is comprised of four steps, as illustrated in Fig. 6. First, a time-expanded network model is constructed which encompasses all of the surface and orbital locations (nodes) to be reached and the available paths between nodes (edges) over time. Physics-based network constraints including selected trajectories' ΔV requirements are included in the network model inputs. Second, a baseline mission sequence is defined. Each mission model is comprised of events such as element initialization, transportation segments, and exploration processes which drive a discrete event simulation. Propulsive feasibility, i.e., verifying sufficient fuel is available to complete all propulsive transportation burns, is established during the mission definition phase. Third, a demands analysis is performed to inspect the generation of demands by various elements throughout the simulation. The demanded resources are sequentially packed into logistics containers and manifested onto various transports for consumption. During manifesting, logistical feasibility is established if the defined transports have sufficient capacity for all demanded resources – revision of the baseline scenario may be required to close the logistics loop. Finally, the full campaign is simulated to quantify measures of effectiveness and build final visualizations.

The most recent release of SpaceNet is version 2.5, a Java executable program released in October 2009 under a GPL open-source license. SpaceNet 2.5 implements a revised and expanded model for flexible space exploration analysis (de Weck et al. 2009). The SpaceNet graphical user interface (GUI) was designed with user-centric methods and allows users to build, edit, and analyze exploration campaigns without detailed knowledge of the underlying models. SpaceNet also provides visualizations and feedback to simplify the campaign creation process and quickly identify and reduce the number of simulation errors. The SpaceNet project website (http://spacenet.mit.edu) includes additional information, downloads, and links to the user community to facilitate interaction between users and developers.

3.2. SpaceNet Analysis of NASA DRA 5.0

In parallel with the capabilities of SpaceNet, the following analysis is focused on establishing the in-space propulsive feasibility to deliver surface elements and identifying the driving factors to manage logistical feasibility for a crew of six. A single crew rotation is modeled as a campaign requiring multiple launches over a five-year span, though at least three crew rotations would likely be incorporated in a full Mars exploration. Surface operations are not modeled in detail, though future analysis could introduce surface excursions using pressurized rovers and micro-logistics between logistics depots. Also, several simplifying assumptions are used to drive demands that could be revised with refined designs and additional analysis.

Model Inputs The network model for Martian exploration contains nodes and edges in the Earth-Mars system. The nodes include Kennedy Space Center (KSC) for launches, a Pacific Ocean splashdown zone (PSZ) for crew return, a low-Earth parking orbit (LEO) for assembly of in-space vehicles, a reference Mars orbit (RMO) for stationary operations on orbit, and Mawrth Vallis (MV), the target surface exploration site on Mars. The edges connecting the nodes are a mix of propulsive burn sequences and abstracted flights. Launches of heavy-lift launch vehicles, in-space transfers to and from Mars orbit, and descent to the Martian surface are modeled as propulsive burn sequences requiring propellant amounts based on required ΔV and engine specific impulse. Ascent from the Martian surface is modeled as an abstracted flight without explicit propellant demands to simplify the modeling of ISRU production of its liquid oxygen propellant. The crew exploration vehicle (CEV) launch from KSC is also modeled without propellant utilization because its launch vehicle does not interact with the other components of the campaign.

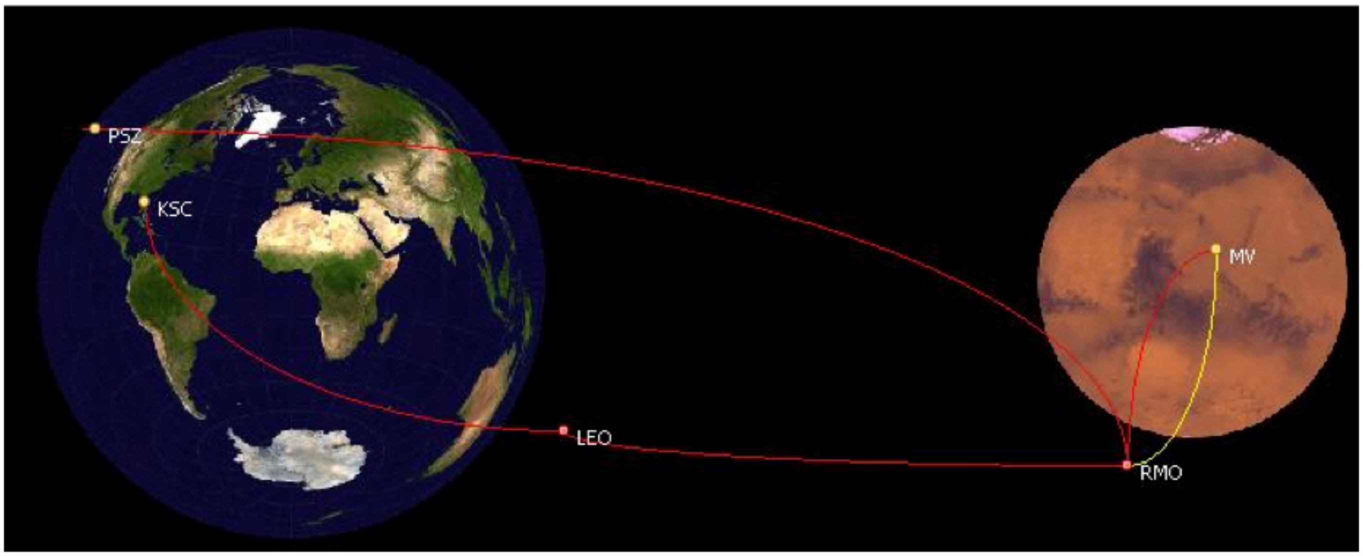


Figure 7: Mars exploration network modeled in SpaceNet.

The elements modeled include the heavy-lift launch vehicle (HLV), in-space vehicles and landers for Martian exploration, and human crew members. Several of the HLVs use a modified payload fairing which serves as a dual-use aeroshell for aerocapture and shielding for entry into the Martian atmosphere. In-space Mars transfer vehicles (MTVs) are assembled in low-Earth orbit from nuclear thermal rocket (NTR) stages, fuel tanks, and other components delivered in separate launches. Two un-crewed MTVs pre-position the cargo lander on the Martian surface and the habitat lander in Martian orbit. The crewed MTV carries the six crew members and the Mars transfer habitat (MTH) to rendezvous with the habitat lander before descent and surface operations. Since the mass of spares is included in element mass estimates in DRA 5.0, demands primarily originate from the crew using a linear demand model with two operational states. While in transit, the net crew demands total 3.375 kilograms per crew member per day. While on the surface, it is assumed ISRU production can reduce net demands to 2.375 kilograms per day.

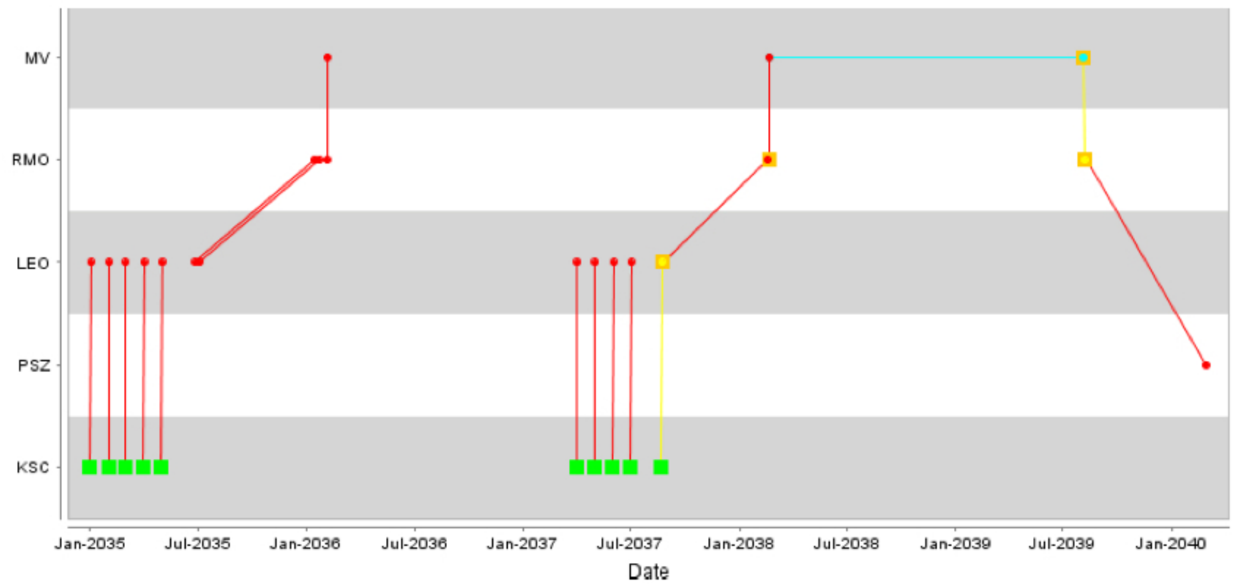


Figure 8: Mars exploration bat chart illustrating campaign events and transports.

A single Mars exploration mission is divided across two transit windows approximately 26 months apart, illustrated in Fig. 8 in a time-expanded bat chart showing the movement of elements between nodes. In the figure, green squares represent instantiation of elements before launch, orange squares represent movement of elements between carriers, red lines represent propulsive transports along edges, the blue line represents surface exploration, and yellow lines represent abstracted flights. The first five HLV launches provide the elements to assemble the two cargo MTVs in low-Earth orbit. The first cargo MTV contains the cargo lander and the second the habitat lander. Once both vehicles are constructed, they depart for Mars using a trans-Mars injection (TMI) burn and are aerocaptured 200 days later. The cargo 13 lander subsequently descends to the Martian surface to commence oxygen production while the habitat lander remains in orbit for the arrival of the crew.

The next four HLV launches provide the elements to assemble the crewed MTV in low-Earth orbit. Once constructed, the crew of six is delivered and the MTV departs for Mars, jettisoning an empty drop tank after the TMI burn and arriving with a Mars orbit insertion (MOI) burn 170 days later. Once in Mars orbit, the crewed MTV docks with the habitat lander and the crew descend to the Martian surface to perform surface operations for 530 days while the crewed MTV remains in Mars orbit.

After the exploration, the crew and surface samples use the fueled ascent vehicle to return to Mars orbit and dock with the crewed MTV. The contingency food canister (CFC) is jettisoned prior to the Earth orbit injection (EOI) burn and the crew returns to Earth using a CEV for the final re-entry and splashdown into the Pacific Ocean.

4. Analysis and Discussion

The first phase of analysis focuses on determining the propulsive feasibility of the campaign. As a simplified manifesting model, notional resource containers are used to hold the maximum cargo capacity for each of the carrier elements. For example, a mass-less resource container packed with 4,500 kilograms of consumables is created inside the Mars descent/ascent vehicle (MDAV). All space transports in the Martian exploration are found to be propulsively feasible with baseline element properties. The propellant margins for descent, however, are especially tight. The MDAV has a propellant margin of 627 kilograms (5.9%) and the surface habitat (SHAB) a margin of 435 kilograms (4.1%).

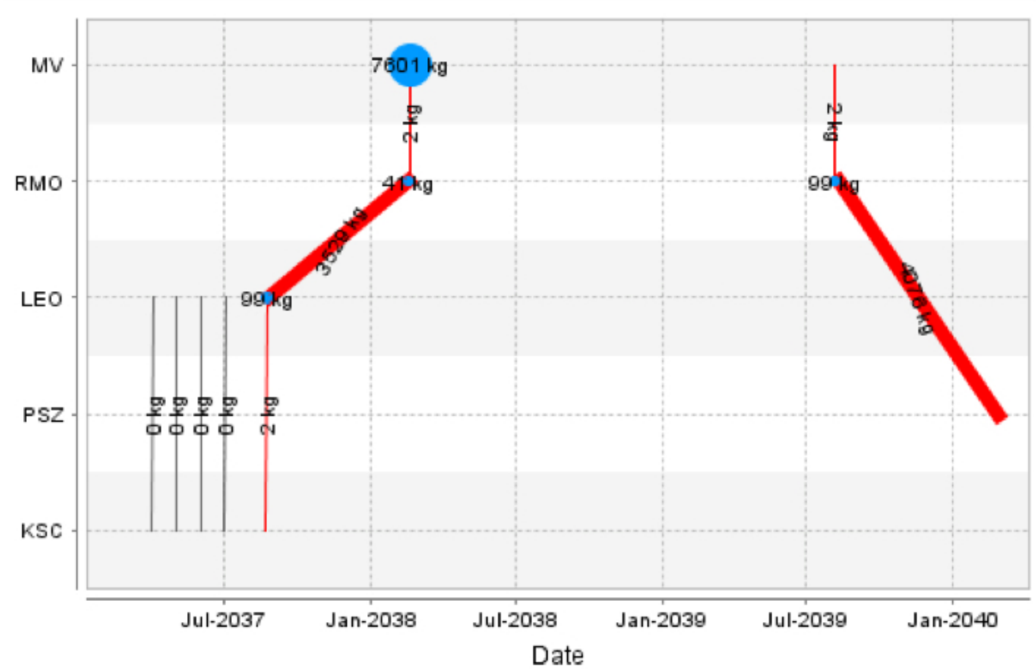


Figure 9: Mars exploration aggregated crew demands [kg].

Though propulsively feasible, the consumables capacities in DRA 5.0 cannot supply the required demands either during transport or during surface operations, even without taking into account the tare mass of any resource containers that would be needed. Figure 9 shows the mass of demands required during transport (red lines) and exploration (blue circles), totaling 3.6 tons during transport to Mars, 7.6 tons during surface operations, and 4.1 tons during the transport to Earth. DRA 5.0 allocates 5.5 tons aboard the MDAV and 1.5 tons aboard the SHAB (totaling 7.0 tons for surface operations), and 5.3 tons aboard the MTH (2.65 tons per transport). To close the logistics loop for consumables, design changes are suggested to the MTH for transport and the SHAB and MDAV for surface demands.

Although the delivery of the MTH and its components to LEO is not closely-constrained with the Ares V launch vehicle, the crewed MTV is a bottleneck of the in-space transports. As the crewed MTV cannot support additional resources for consumption during the infeasible transport, a "creative" solution using existing element designs is sought using excess capacity on the cargo MTVs.

Current designs of the MTH use the CFC and its 7.9-ton capacity to supply sufficient consumables to sustain the crew until the TEI launch window opens if all or part of the Martian surface operations were aborted. If a secondary CFC (or equivalent resources) were carried aboard either of the cargo MTV transports for use in the case of an emergency in Mars orbit, the first could be used to satisfy in-space transport demands. This solution assumes that consumables could safely be stored in a CFC for up to five years, a secondary CFC could be manifested on a cargo MTV launch, the primary CFC would be accessible during transit to Mars, and the secondary CFC could be accessible in Mars orbit.

A sample implementation of this solution includes a secondary CFC for the cargo MTV launch 3, currently the least mass-constrained. The secondary CFC is coupled with the habitat lander MTV for transport and docked with the crewed MTV in orbit in advance of the surface exploration. As before, all required resources are transferred to the MTH and both CFCs are jettisoned before the TEI transport.

To support the additional demands during surface exploration, either the MDAV or the SHAB must have an increased capacity. If the MDAV resource capacity is increased from 5,500 to 6,500 kilograms, the cargo lander propellant margin is reduced to 465 kilograms (4.4%). If the SHAB consumables capacity is increased from 1,500 to 2,000 kilograms, the habitat lander propellant margin is reduced to 340 kilograms (3.2%). Since the descent stages have narrow propellant margins for both landers, the additional capacity may very well come at the cost of scientific and exploration equipment.

5. Summary and Conclusions

The Mars exploration ΔV map and flight opportunity bat chart show that Venus flyby flight opportunities can be competitive with direct flights because they open up additional launch windows. Though direct flights are preferable in the early phase of human Mars exploration in terms of both ΔV and time of flight, flyby flight opportunities enable urgent cargo resupply missions and could provide more flexibility for resupply in longer-term exploration campaigns. Cargo flights for pre-positioning should stick to a minimal ΔV while crewed flights should trade between ΔV and time of flight. It is found from SpaceNet analysis that the Mars exploration architecture as described by DRA 5.0 is propulsively feasible as specified and logistically feasible with modifications to increase supply capacity during crewed transport and exploration periods. The most constrained transportation legs include the SHAB and MDAV descents to the Martian surface and the crewed MTV transit to Mars.

The next step of analysis could model the surface operations in much more detail. Currently, the cargo lander and habitat lander are modeled as single elements; however they are actually comprised of many components including pressurized, unpressurized, and robotic rovers, science equipment, stationary power systems, and ISRU plants. Modeling these elements separately could provide much more detailed information for surface logistics, including the accumulation of ISRU resources and the option of analyzing spare parts demands on a per-element basis.

Acknowledgments The research described in this paper was carried out at the Massachusetts Institute of Technology and was supported by the Jet Propulsion Laboratory. The authors wish to acknowledge the support of Prof. Richard Battin, Dr. Wilfried Hofstetter, and Shinya Umeno at MIT and Gene Lee, Elizabeth Jordan, and Dr. Robert Shishko at JPL. Financial support was provided under NASA Strategic University Research Partnership (SURP) contract number 1344341.

REFERENCES

Armar, N. and de Weck, O., (2009). "Cargo Revenue Management for Space Logistics," AIAA-2009-6723, AIAA Space 2009 Conference & Exposition, Pasadena, CA, September 2009.

Bolden, C., (2010). "Statement by Charlie Bolden," NASA Budget Press Conference, February 2010.

Bush, G. W., (2004). "A Renewed Spirit of Discovery – The President’s Vision for U.S. Space Exploration," The White House, Washington, D.C., January 2004.

Cirillo, W., Earle, K., Goodliff, K., Reeves, J.D., Stromgren, C., Andraschko, M., Merrill, R.G., (2008). "Strategic Analysis Overview," AIAA-2008-7778, AIAA Space 2008 Conference & Exposition, San Diego, CA, September 2008.

de Weck, O., Grogan, P., Jordan, E., and Lee, G., (2009). "SpaceNet 2.5 User’s Guide," September 2009.

de Weck, O., Jordan, E., Lee, G., Grogan, P., Ishimatsu, T., and Siddiqi, A., (2009). "SpaceNet 2.5 Quick Start Tutorial," September 2009.

de Weck, O., and Simchi-Levi, D., (2006). "Haughton-Mars Project Expedition 2005," Final Report, NASA/TP-2006-214196, January 2006.

de Weck, O., Simchi-Levi, D., Shishko, R., Ahn, J., Gralla, E., Klabjan, D., Mellein, J., Shull, S., Siddiqi, A., Bairstow, B., and Lee, G., (2007). "SpaceNet v1.3 User’s Guide," NASA/TP-2007-214725, January 2007.

Drake, B. G., editor, (2009). "Human Exploration of Mars Design Reference Architecture 5.0," NASA, NASA-SP-2009-566, July 2009.

Drake, B. G. (2010). Human Exploration of Mars: Challenges and Design Reference Architecture 5.0, Journal of Cosmology, 12, 3578-3587.

Grogan, P., (2010). "A Flexible, Modular Approach to Integrated Space Exploration Campaign Logistics Modeling, Simulation, and Analysis, " Master’s thesis, Massachusetts Institute of Technology, Cambridge, MA, September 2010.

Ishimatsu, T., (2008). "Interplanetary Trajectory Analysis for 2020-2040 Mars Missions including Venus Flyby Opportunities," Master’s thesis, Massachusetts Institute of Technology, Cambridge, MA, May 2008.

Ishimatsu, T., Hoffman, J., and de Weck, O., (2009). "Interplanetary Trajectory Analysis for 2020-2040 Mars Missions including Venus Flyby Opportunities," AIAA-2009-6470, AIAA SPACE 2009 Conference & Exposition, Pasadena, CA, September 2009.

Ishimatsu, T., Hoffman, J., and de Weck, O., (2010). "Method for Rapid Interplanetary Trajectory Analysis using ΔV Maps," submitted to Journal of Spacecraft and Rockets.

Lee, G., de Weck, O., Armar, N., Jordan, E., Shishko, R., Siddiqi, A., and Whiting, J., (2008). "SpaceNet: Modeling and Simulating Space Logistics," AIAA-2008-7747, AIAA Space 2008 Conference & Exposition, San Diego, CA, September 2008.

Matousek, S. and Sergeyevsky, A., (1998). "To Mars and Back: 2002-2020 Ballistic Trajectory Data for the Mission Architect," AIAA-98-4396, AIAA/AAS Astrodynamics Specialist Conference, AIAA, Boston, MA, August 1998.

NASA (2004). "The Vision for Space Exploration," NASA-NP-2004-01-334-HQ, NASA, Washington, D.C., February 2004.

NASA (2005). "Exploration Systems Architecture Study – Final Report," NASA-TM-2005-214062, NASA, Washington, D.C., November 2005.

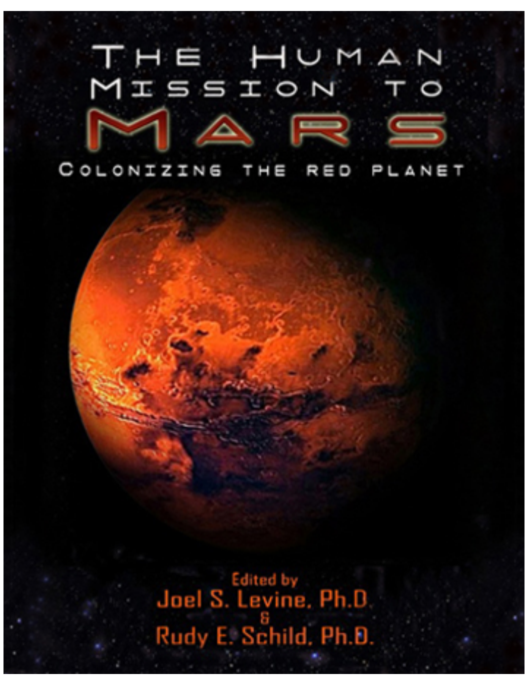
Obama, B., (2010). "Remarks by the President on Space Exploration in the 21st Century," April 2010.

Review of U.S. Human Spaceflight Plans Committee (2009). "Summary Report of the Review of U.S. Human Spaceflight Plans Committee," September 2009.

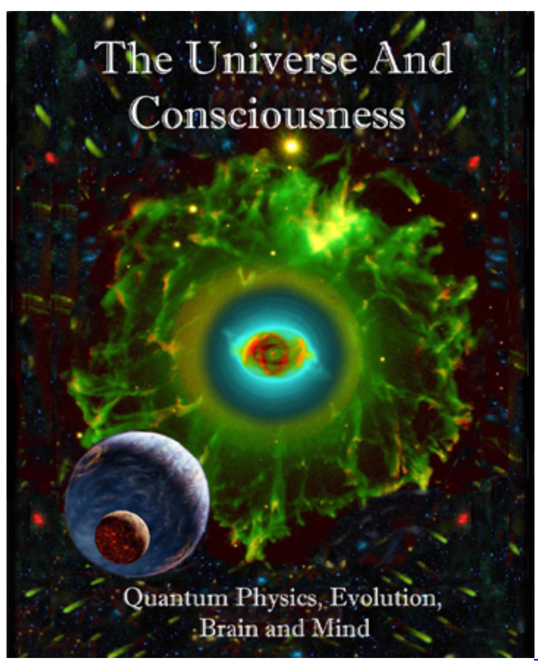
Review of U.S. Human Spaceflight Plans Committee (2009). "Seeking A Human Spaceflight Program Worthy of A Great Nation," October 2009.

Shull, S., Gralla, E., and de Weck, O., (2006). "A Modeling Framework for Interplanetary Supply Chains," AIAA-2006-7229, AIAA Space 2006 Conference & Exposition, San Jose, CA, September 2006.

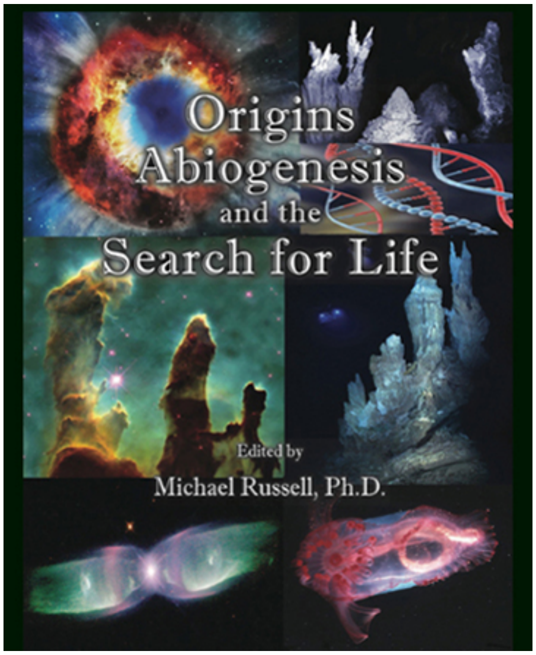
Taylor, C., Song, M., Klabjan, D., de Weck, O., and Simchi-Levi, D., (2007). "A Mathematical Model for Interplanetary Logistics," Logistics Spectrum, Vol. 41, No. 1, 2007, pp. 23-33.



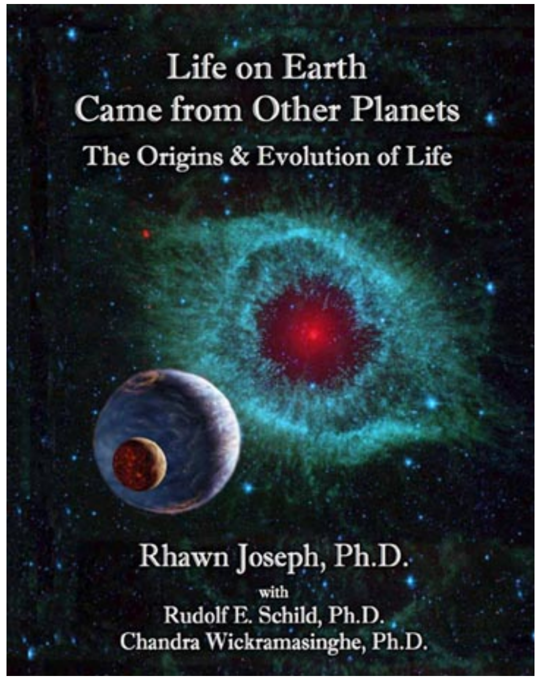
The Human Mission to Mars.
Colonizing the Red Planet
ISBN: 9780982955239



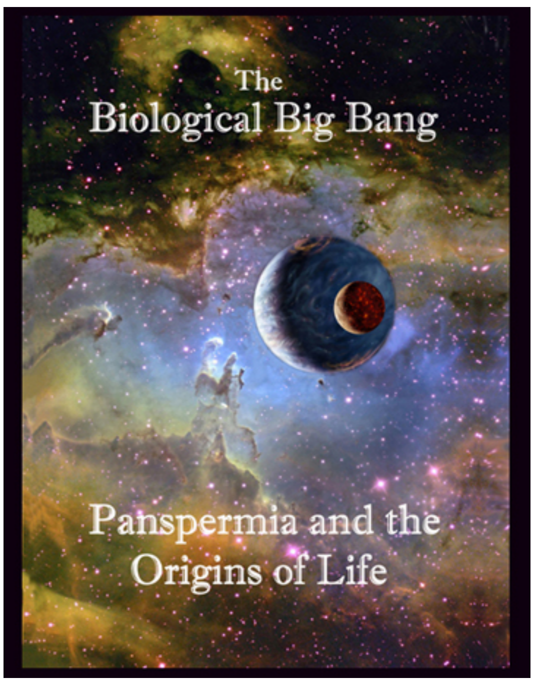
Edited by
Sir Roger Penrose & Stuart Hameroff
ISBN: 9780982955208



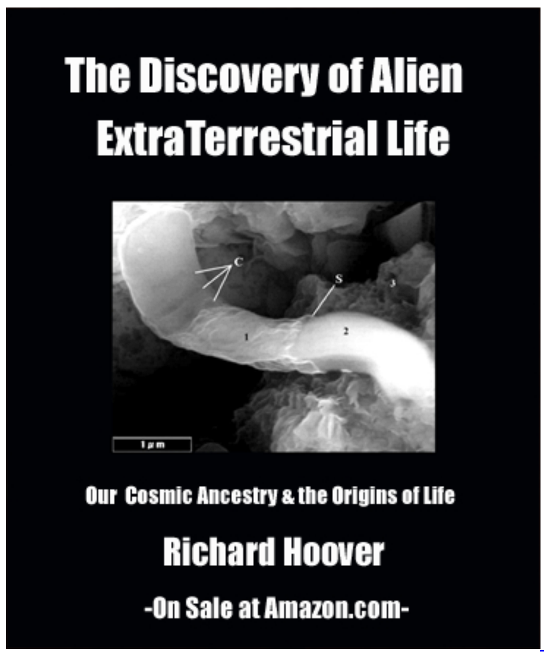
Abiogenesis
The Origins of LIfe
ISBN: 9780982955215



Life on Earth
Came From Other Planets
ISBN: 9780974975597



Biological Big Bang
Panspermia, Life
ISBN: 9780982955222



20 Scientific Articles
Explaining the Origins of Life
ISBN 9780982955291