EARTH DEPARTURE OPTIONS FOR HUMAN MISSIONS TO MARS
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Introduction: A round-trip mission to Mars would require multiple launches, even using the Space Launch System [1]. Components of the deep-space vehicle (habitat, consumables, propulsion stages, destination systems) would first be assembled at the chosen staging location, then the crew would launch to the assembled vehicle for rendezvous a few days prior to the Mars departure opportunity [2]. The choice of staging node therefore strongly affects the vehicle designs, crew contingency options, and mission backup opportunities. A comparison of Earth departures from Earth-Moon L_2, lunar orbit, high-Earth orbit, and low-Earth orbit is presented to inform decisions on how to initiate human exploration of Mars.

Departure Scenarios: Two Mars trajectory opportunities provide a range of potential mission characteristics. The 2033 launch opportunity has a relatively low launch energy but strains out-of-plane requirements with a launch declination that is -55 deg from the equator and -36 deg from the lunar plane. The 2035 opportunity requires higher launch energy, but has departures near the equatorial and lunar planes.

Earth-Moon L_2. The escape sequence from L_2 requires three critical maneuvers, as depicted in Figure 1. The ΔV provided covers only the trajectory portion from L_2 to Mars escape. An additional ΔV of 3.1 km/s and 3–4 months flight time (or 6.6 km/s and 1–2 years with high-efficiency electric propulsion) would be required to send vehicle components to L_2. The crew would travel to L_2 in the Orion Multi-Purpose Crew Vehicle using 3.5 km/s ΔV in about eight days.

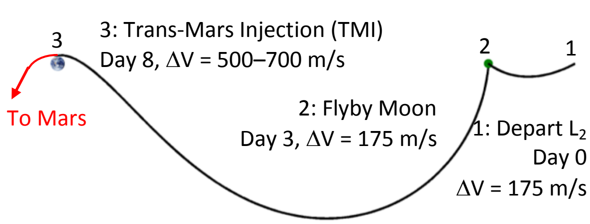

Figure 1 Three-burn escape sequence from L_2.

Opportunities exist to launch cargo and crew on any day before departure, however departure from L_2 is constrained by the escape direction required to reach Mars. As shown in Figure 2, there is a continuous window of only a few days when L_2 (and the Moon) is in the right orientation for Mars departure. The lunar flyby could provide out-of plane departures (e.g. 2033) for little additional ΔV. A contingency return from L_2 requires 350 m/s ΔV and 8 days to reach Earth.

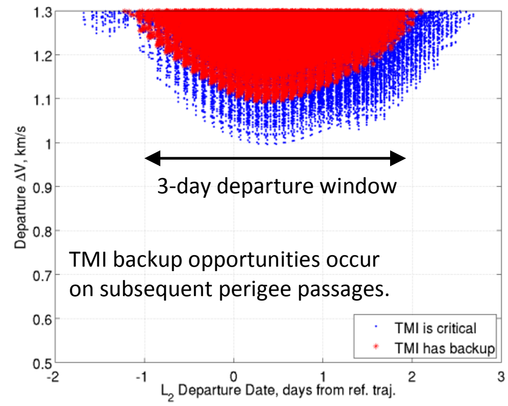

Figure 2 Range of departure time and ΔV from L_2.

Lunar Orbit. A high elliptical retrograde orbit at the Moon provides similar mission characteristics as the L_2 staging node. Cargo and crew (launched separately) could reach this staging location with 3.25 km/s ΔV and 4 days flight time. Station keeping requirements are similar in lunar orbit as in L_2, however lunar orbit would be an inherently more stable location for uncontrolled (passive) vehicles. Departure from lunar orbit would require less ΔV and has a slightly shorter departure window than L_2 as shown in Figure 3. A contingency return from a high elliptical lunar orbit requires 250 m/s ΔV and 4 days to reach Earth.

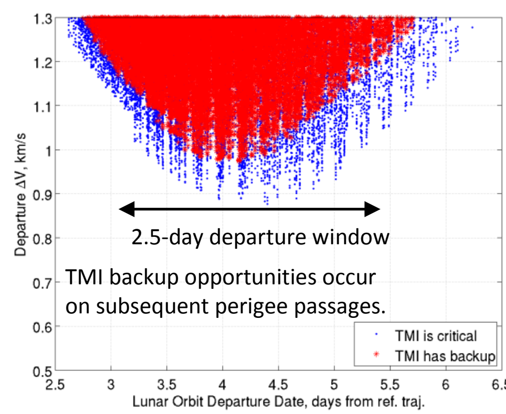

Figure 3 Lunar orbit departures are similar to L_2.

High-Earth Orbit. An elliptical orbit at Earth with a 10 day period would also provide multiple characteristics desired for human mission to Mars. The deep space vehicle could be assembled above the van Allen belts where lunar flybys or propulsive maneuvers could raise or lower perigee. Both cargo and crew could reach HEO in less than a day with 3.1 km/s ΔV.

The departure ΔV is more sensitive to Mars escape declination than the L_2 or lunar options, where additional ΔV is required when the crew would launch to an inclination that is less than the departure declination. From Figure 4, difference between launching to a 28.5 degree inclination (optimal from FL) and a higher inclination (e.g. the space station orbit) could be around 200 m/s ΔV. Departures from HEO (trans-Mars injection) occur at instantaneous opportunities near perigee. Backup opportunities exist in increments of the HEO period, where three TMI opportunities could be distributed over a 21-day interval. In the event of a contingency, the crew could return to Earth in 4–10 days (HEO orbit period) with less than 25 m/s ΔV.

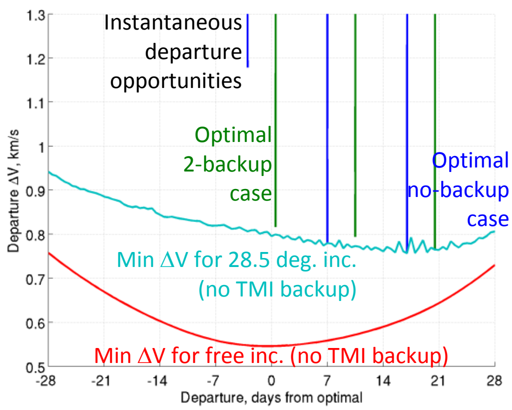

Figure 4 2033 departure characteristics from HEO.

Low-Earth Orbit. Assembly of the deep space vehicle could also occur in LEO. With LEO departures there is no intermediate staging node at a high energy with respect to Earth (as with the other options), so low-thrust transfers with high-efficiency electric propulsion could not be used to lower propellant mass at this location. As with HEO staging, the ΔV depends on the departure declination, where large declinations benefit from an intermediate HEO to reorient the orbit. This results in a 3-burn sequence where the vehicle would depart LEO into an elliptical HEO, reorient the high-Earth orbit into the departure plane, then perform TMI for escape. Departure windows from LEO typically exist from one to several days depending on the difference between launch inclination and departure declination. Crew contingency return from LEO would require 100 m/s ΔV and take less than one day.

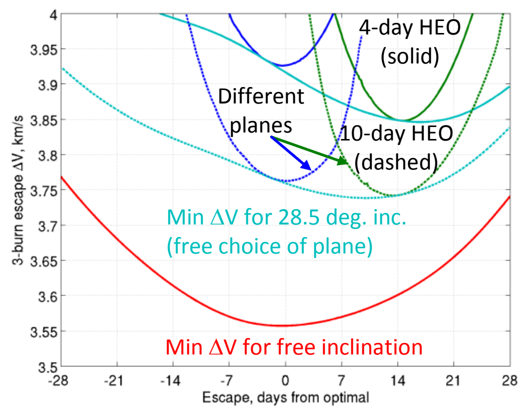

Figure 5 2033 departure characteristics from LEO.

Comparative Analysis: A comparison of the costs and benefits of the staging options are summarized in Table 1.

References: [1] Landau D. F. and Longuski J. M. (2009) *Acta Astro.*, 65, 893–911. [2] Merrill R. G. at al. (2012) "An Initial Comparison of Selected Earth Departure Options for Solar Electric Propulsion Missions" *IEEE/AIAA Aero. Conf.*

Table 1 Departure Scenario Considerations for Human Missions to Mars

Aggregation Location	L_2 Halo	10-d HEO	Lunar Orbit	Low Earth Orbit
Cargo Delta-v (from LEO)	3150 m/s, 3 mo.	3100 m/s, 1 d	3230 m/s, 4 d	0 m/s, 0 d
Crew to rend. location (from LEO)	3500 m/s, 8 d	3100 m/s, 1 d	3230 m/s, 4 d	0 m/s, 0 d
Departure 2033 (51.6 deg LEO)	1040-1200 m/s	600-650 m/s	910-1200 m/s	3600
Departure 2035 (28.5 deg LEO)	1100-1300 m/s	700-750 m/s	975-1300 m/s	3650-3950
Total Delta-V (cargo leg from LEO) through TMI	4190-4450 m/s	3700-3850	4140-4530	3600-3950
Trans-Mars Departure Window Length # TMI Opportunities	 3-4 days 1-2 opportunities	 20 days 1-3 opportunities	 2.5-3.5 days 1-2 opportunities	5-14,[a] 28–56[b] days 100-200 ,[a] 1–3[b] opp. [a]For Dec=Inc. (e.g. 2033) [b]For Dec<Inc. (e.g. 2035)
Crew Critical maneuvers	Depart LEO Lunar Flyby Out/In L_2 Halo Arr./Dep. TMI	Depart LEO HEO Arrival TMI	Depart LEO Lunar orbit arrival Lunar orbit depart TMI	LEO Arrival TMI
Crew Contingency return	350 m/s, 8 d	<25 m/s, 5 d	250 m/s, 4 d	100 m/s, 0 d