FAST MARS TRANSFERS THROUGH ON-ORBIT STAGING.

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Introduction: The concept of On-Orbit Staging (OOS) combined with the implementation of a network of pre-positioned fuel supplies would increase payload mass and reduce overall cost, schedule, and risk [1]. OOS enables fast transits to/from Mars, resulting in total round-trip times of less than 245 days. The OOS concept extends the implementation of ideas originally put forth by Tsiolkovsky, Oberth, Von Braun and others to address the total mission design [2]. Future Mars exploration objectives are difficult to meet using current propulsion architectures and fuel-optimal trajectories. Applying the basic OOS concept to all major propulsive (in-space) events and utilizing proposed technological advances in propulsion efficiency allows us to demonstrate that exploration and science goals can be leveraged in a way never before possible enabling both sets of strategic goals to be met more quickly, effectively and efficiently.

OOS begins with a set of launch vehicles that place an assembly spacecraft, propulsive elements and bulk supplies into LEO in advance of mission hardware or crew. Once in LEO, the assembly spacecraft (launched first) assembles these propulsive elements into several larger collective elements that permit optimal staging and a significant increase in the ratio of payload mass to initial wet mass. This staging can be thought of as similar to that used for any launch vehicle, although the elements may not be vertically stacked like traditional Earth-to-orbit vehicles. While no single design has been put forward, the general idea is to have multiple stages that have a cluster of propulsive elements, either liquid or solid.

This abstract answers Challenge Area 2: Analyses of interplanetary trajectories from the vicinity of Earth to the Mars system and return that provide significant efficiencies in transportation systems, including delta-V, transit time, cost, etc. This includes a variety of Mars orbits and possible rendezvous with or landing on Phobos/Deimos.

Advantages of On-Orbit Staging: The utility of this concept was evaluated with both analytical methods and high-fidelity numerical analysis to demonstrate feasibility and validate assumptions. Through OOS, a significant increase in payload mass is achieved utilizing existing propulsion technologies. Performance gains can be realized by enhancing the OOS concept with pre-positioned fuel in orbit about the destination body and at other strategic locations. We previously demonstrated multiple cases of a fast (< 245-day) round-trip to Mars that, using OOS combined with pre-positioned propulsive elements and supplies sent via fuel-optimal trajectories, can reduce the propulsive mass required for the journey by an order-of-magnitude.

OOS can be applied with any class of launch vehicle, with the only measurable difference being the number of launches required to deliver the necessary assets to LEO for a particular mission.

Justification and Description: The realization of completing a round-trip Mars mission in under an Earth year is the primary justification. An associated mission driver is the cost of manufacturing space flight hardware and the launch costs for inexpensive cargo. Relaxed mass constraints through the use of OOS and pre-positioned propulsion elements can act as a catalyst to reduce the cost of manufacturing space flight hardware, and we evaluate the relative effect on the total mission cost. We also recommend the evaluation of the relative cost savings of developing an economical launch capability for inexpensive, acceleration-insensitive payloads – e.g. propulsive elements which make up the vast majority of the total mass for a round-trip Mars mission.

Figure 1 depicts the effects that staging has on the achievable payload mass ratio or ΔV for a representative case. Assuming an I_{sp} = 465 sec and structural mass fraction (ε) = 0.075, the plot indicates that for a single-stage vehicle initial to final mass (M_L/M_0) ≈ 0.02, and for a 4-stage vehicle, $M_L/M_0 \approx 0.071$. Assuming that M_0 is the same for both vehicles, this reveals that a 4-stage vehicle can impart a ΔV of 10.8 km/sec to a payload mass that is 355% greater than that of a single-stage vehicle. Alternatively, holding the payload mass constant, that mass can be accelerated to a higher ΔV of 15.66 km/sec, or the total mass (M0) required to accelerate the same mass to a ΔV of 10.8 km/sec can be reduced by ~70% by using a 4-stage vehicle.

Mars Fast Transfer: A fast transfer to Mars can be achieved by launching into a heliocentric orbit that arrives at Mars at Earth-Mars conjunction. Figure 2 shows an example of a fast transfer of 120 days from Earth to Mars, a 14-day stay and a 75-day return.

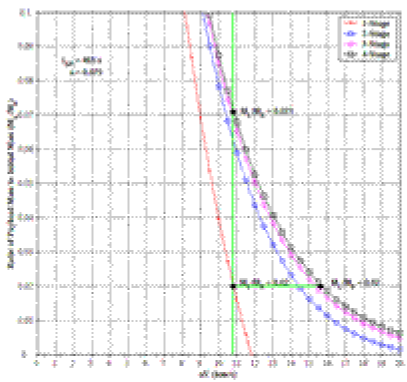

Figure 1: Ratio of Payload Mass to Initial Mass as a Function of ΔV for 1 to 4-Stages with I_{sp} = 465 sec

The trajectory shown in the figure requires much higher ΔVs than a slow conjunction or opposition trajectory. While slow (Hohmann) transfers require ΔVs in the range of 3-4 km/sec, the fast-transfer ΔVs can be several times as large and are driven by the relative geometry between Earth and Mars at the beginning and end of the transfer period. Trajectory design parameters are the incoming trajectory asymptote with regard to the required B-plane (the B-plane of Mars is targeted for the optimal incoming trajectory to minimize the insertion ΔV), the final orbit semi-major axis and eccentricity, and the surface stay time.

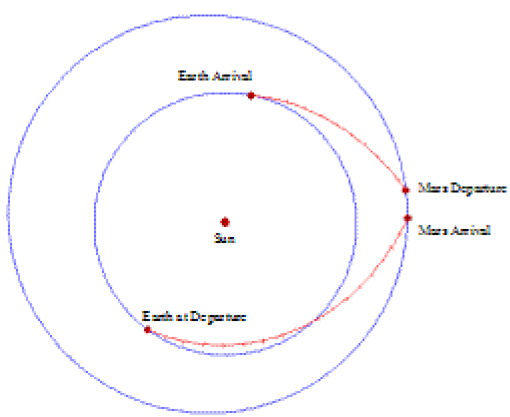

Figure 2. Mars Fast Transfer Trajectory

ΔVs can range from approximately a few km/sec to upwards of 15 km/sec for each Mars insertion or departure maneuver. The total ΔV for all legs remains fairly constant, implying that a trade must be performed between the insertion and departure legs at Mars in order to optimize the amount of usable payload mass in the OOS equations. Figure 3 presents a contour plot of sample Mars insertion and departure ΔVs for various surface stay times and launch dates. Transfer time must be traded to minimize the impact of the high arrival and departure ΔVs at Mars, which are the dominant drivers.

Next Steps: The combination of On-Orbit Staging with aggregated propellant enables fast transfers of humans or robotic missions to/from Mars with robust amounts of hardware. OOS alone results in a substantial increase in payload mass over current methods as verified by simulations using operational software. OOS enables missions that are not feasible by current launch methods, increases the ratio of payload mass to launch mass, and can be applied to any class of launch vehicle or mission design. Adding pre-positioned fuel permits an order-of-magnitude reduction in required resources in the high ΔV fast-transfer cases we have analyzed. OOS and aggregated propellant enable fast-transfer trajectories, payload masses measured in metric tons rather than tens or hundreds of kilograms, and robotic Mars sample returns on the order of hundreds of kilograms rather than grams. Trades still need to be performed on ΔV allocations, staging design, trip durations, architecture impacts, and propulsion system parameters, in order to yield the most efficient fast-transfer scenarios.

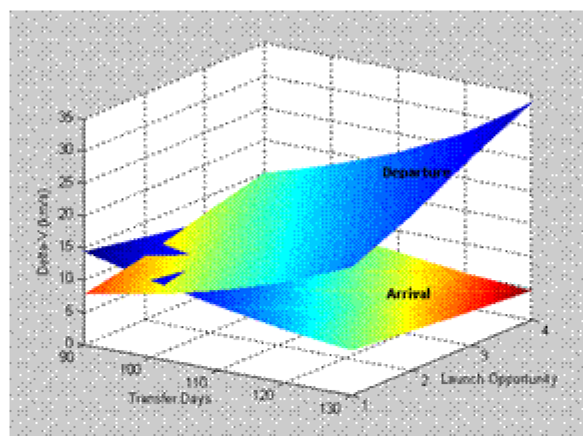

Figure 3. Example Mars Arrival and Departure DV

References:

[1]Folta D. et al, (2005), "Enabling Exploration Missions Now: Applications of On-Orbit Staging", AAS/AIAA Astrodynamics Specialists Conference, Paper no. 05-273

[2]Hepburn, C.D., (1991) "Interplanetary Roundtrip Trajectory Optimization: Round Trip Delta-V (RTDV) Plots", AAS/AIAA Astrodynamics Specialist Conference, Paper no. 91-526.