Motivation And Optimization Considerations For Off-Earth Exploration Via Low-Latency Telepresence (LLT) With Humans In Orbit

Introduction

This topic contains an implied assumption worthy of immediate elaboration. The assumption here is humans explore an off-Earth destination from proximal orbiting habitats rather than from *in situ* habitats located on or below that destination's surface. In adopting this assumption, it should be understood neither exploration mode inherently excludes LLT techniques. Similar cost, schedule, exploration productivity, and safety benefits arise from LLT regardless of whether humans explore from orbit or *in situ* with respect to a specified off-Earth destination. Consequently, LLT systems and techniques developed for orbiting humans have nearly complete applicability to *in situ* LLT. At a particular destination, the only fundamental changes between orbital and *in situ* LLT modes are habitats and low-latency communication links between human explorers and their robotic surrogates.

Programmatic cost and risk considerations will tend to support LLT with orbiting humans well in advance of any *in situ* LLT at a given off-Earth exploration destination.[1] This precept of space exploration has been recognized for decades [1], [2]. Cost/risk reduction with orbiting humans vice *in situ* humans is particularly significant for a destination having a major gravity field, but it also arises to a lesser degree for small bodies such as asteroids or the moons of Mars. Landing and launching humans at a destination with a major gravity field typically requires specialized systems or dedicated staged vehicles. This specialization is costly, while high accelerations, vibrations, and destination environmental factors (such as atmospheric flight, unstable terrain, or toxic/abrasive dust) greatly reduce lander/launcher service life and reusability, further contributing to human transport cost and risk.

Quantifying Cost Advantages For Orbiting LLT

A reasonably objective cost metric, free from programmatic or currency inflation influences, is initial mass in low Earth orbit (LEO). This metric assumes all material required to transport humans off-Earth must first be launched to LEO, but assuming another "departure gateway" transport node in the Earth-Moon system would produce similar cost data among exploration destinations of interest. In this application, the "rocket equation" [3, p. 157] computes the ratio of mass in LEO divided by mass transported to the destination m_{LEO} / m_D. This computation utilizes the specified change-in-velocity magnitude Δv required for transport, together with transport propulsive efficiency termed "specific impulse" or I_{SP}.

Figure 1 plots the m_{LEO} / m_D ratio as a function of Δv for several I_{SP} values. Note Figure 1 Δv values between LEO and specific annotated destinations are one-way for the sake of simplicity. Associated m_{LEO} / m_D ratios would approximate roundtrip human architectures whose return consumable mass is pre-positioned near the destination. Architectures departing LEO with all consumable masses required for a roundtrip will have a considerably greater m_{LEO} / m_D ratio to a

[1] Another consideration tending to favor orbiting LLT before *in situ* LLT is planetary protection. If life exists at an exploration destination, protecting it from human contamination and protecting Earth from back-contamination by that extraterrestrial life can be better assured by confining explorers and their life support systems to orbit.

particular destination than that appearing in Figure 1 because the associated Δv is effectively doubled for those architectures.

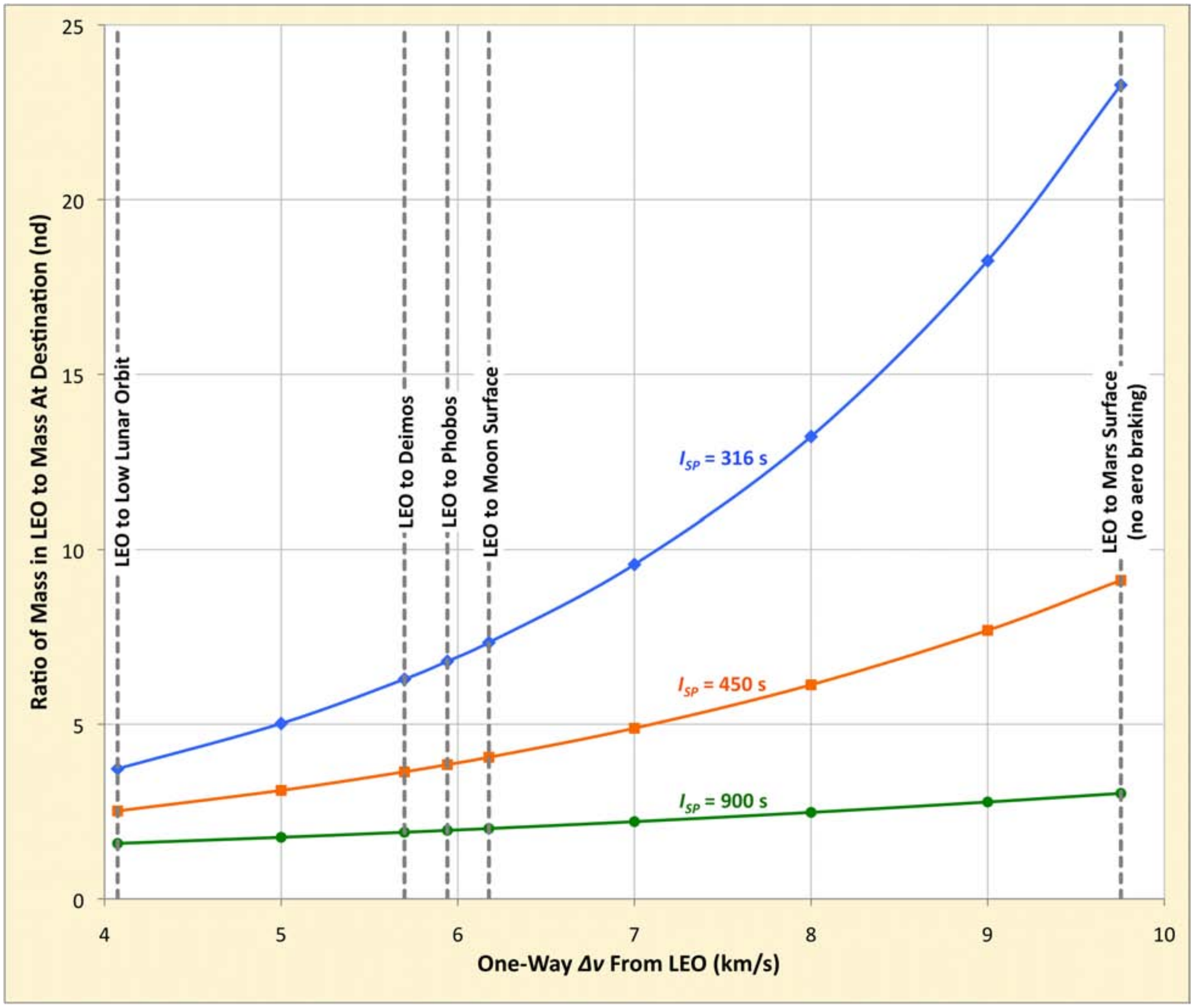

Figure 1. The ratio of enabling mass in LEO to mass thereby delivered to an off-Earth destination is plotted as a function of Δv associated with this mass transport. Because the mass ratio is also a function of transport propulsive efficiency I_{SP}, three color-coded plots are provided. The blue I_{SP} = 316 s plot corresponds to chemical propulsion systems consuming hypergolic liquids storable at room temperature (such as hydrazine and nitrogen tetroxide). The orange I_{SP} = 450 s plot corresponds to chemical propulsion systems consuming cryogenic liquids (such as liquid hydrogen and liquid oxygen). The green I_{SP} = 900 s plot corresponds to nuclear thermal propulsion systems consuming low-mass molecules (such as H_2).

When assessing the consequences of Figure 1, it should be noted that off-Earth human transport requires orders of magnitude more mass at the destination than does exclusively robotic exploration. Adding consumables pre-emplaced near the destination in support of returning humans to Earth, total mass required at a destination such as the Moon or Mars can easily fall into or exceed the 40,000 kg to 400,000 kg range (the latter being close to International Space Station mass) [4, Table 4-1 and Table 4-2], [5, Table 4].

As a Figure 1 assessment example, consider the orange I_{SP} = 450 s plot and compare the LEO mass ratio for one-way transport to the outer martian moon Deimos (3.637) with that for one-way transport to the surface of Mars (9.118). Even though the two destinations are proximal to each other, the cost metric for transport to the martian surface is 2.5 times greater than for transport to Deimos. Thus, it can be asserted that two human missions in Mars orbit can be conducted for a cost comparable with a single *in situ* human mission to the martian surface. Even at the current state of the art in robotics and astronautics, it is a dubious claim that the single *in situ* mission could explore as much of Mars as could two orbiting missions with LLT facilitated by robotic surrogates on the martian surface.

Considerations For Optimal Orbiting LLT

Arguably the most essential orbit attribute with respect to LLT is sufficient proximity to the destination under exploration. Sufficient proximity is a necessary condition for low-latency enabling productive LLT, but it may not be sufficient.[2] Acceptable latency for telepresence depends to some degree on the exploration task being conducted. Consensus among this study's participants finds 200 ms latency is sufficiently low to facilitate any envisioned exploration task. Assuming no appreciable latency contributions other than roundtrip light-time at 300,000 km/s, orbiting humans more proximal than 30,000 km to their robotic surrogates will enjoy light-time latencies of 200 ms or less. The moons Phobos (at a mean orbit radius of 9400 km) and Deimos (at a mean orbit radius of 23,500 km) lie well within the proximity constraint for Mars exploration, assuming line-of-sight communications links without "bent pipe" relays.[3] In a lunar exploration context, the cislunar and translunar libration points (EML1 and EML2, respectively) lie about 60,000 km from the Moon. The most latency-critical exploration tasks would be difficult from the vicinity of EML1/L2, but less demanding operations could be practical.

Particularly during high-dexterity or otherwise critical LLT operations, uninterrupted communications between orbiting humans and their robotic surrogates is essential. An orbiting communications relay constellation is typically unable to avoid interruptions because an individual satellite element is unable to maintain simultaneous lines-of-sight with humans and their surrogates indefinitely. These interruptions occur for about a minute when one constellation element hands over to another. The best strategy for minimal LLT communications interruptions may be maintaining the longest possible intervals with human/surrogate line-of-sight. Orbits implementing this strategy would therefore have nearly synchronous periods. In a

[2] Latency is dependent on many attributes of a communication interface between humans and robotic surrogates. In addition to the distance spanned by this interface, communications infrastructure scheduling may greatly affect latency. This scheduling might be required to resolve conflicts with other users or to cope with line-of-sight disruptions arising from orbit motion and destination rotation dynamics.

[3] Both moons of Mars orbit in planes near its equator. Consequently, a habitat near the orbit of Deimos is able to establish line-of-sight communications with surrogates nearer the poles of Mars than could a habitat orbiting near Phobos at a much lower altitude.

Mars exploration context, an orbit near that of Deimos would offer nearly synchronous motion. At the Moon, periodic orbits proximal to EML1/L2 are nearly synchronous.

Maintaining uninterrupted lines-of-sight to the Sun (for power) and Earth (for communications) may be of critical importance to humans conducting LLT from orbit, regardless of the exploration destination. Except at times near the martian equinox, orbits near that of Deimos have continuous lines-of-sight to both the Sun and Earth. In contrast, an observer in orbit near Phobos will see the Sun and Earth occulted by Mars every 7.7 hours. Solar occultations by the Earth and Moon can occur during eclipse seasons arising every 6 months for humans near EML1/L2. Occultations of Earth by the Moon near EML2 can be minimized in "halo" periodic orbits, but these communications interruptions are eliminated in periodic orbits about EML1. As at Mars, frequency and duration of Sun/Earth occultations tend to increase as orbit distance from the Moon decreases.

Owing to its high accessibility, the Moon stands apart from other off-Earth exploration destinations. High accessibility can translate to lowered risk for orbiting humans conducting LLT on the Moon if the proper orbit is selected. These low-risk orbits lie in planes near that of the Moon's equator, and they have selenographic periods less than about 2 days[4]. Risk to humans is minimized in such orbits because logistics to and from Earth enjoy maximum flexibility. Following LEO departure on any specified day, nearly constant Δv will deliver a payload to a low-risk orbit habitat three to five days later. Likewise, departure from a low-risk orbit habitat on any specified day will result in Earth return three to five days later after expending nearly constant Δv.

Another consideration in the context of humans proximal to EML1/L2 is orbit stability. Periodic orbits about these libration points are inherently unstable, and Δv-efficient stationkeeping requires small impulses typically be imparted on a weekly basis [6]. This activity may conflict with productive LLT operations. Frequent stationkeeping maneuvers may also prove impractical for massive cislunar habitats, particularly when they are unoccupied. In contrast, lunar distant retrograde orbits are inherently stable and are also low-risk orbits at lunar inclinations near 180° and radii from 3000 km to 16,000 km [7].

References

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[4] A circular lunar orbit with radius near 16,000 km has a selenographic period of 2 days. For reference, periodic orbits proximal to EML1/L2 have selenographic periods near 7 days.

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