# *Aquarius*, A Reusable Water-Based Interplanetary Human Spaceflight Transport

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Attributes of a reusable interplanetary human spaceflight transport are proposed and applied to example transits between the Earth/Moon system and Deimos, the outer moon of Mars. Because the transport is 54% water by mass at an interplanetary departure, it is christened *Aquarius*. In addition to supporting crew hydration/hygiene, water aboard *Aquarius* serves as propellant and as enhanced crew habitat radiation shielding during interplanetary transit. Key infrastructure and technology supporting *Aquarius* operations include pre-emplaced consumables and subsurface habitat at Deimos with crew radiation shielding equivalent to sea level on Earth, resupply in a selenocentric distant retrograde orbit, and nuclear thermal propulsion.

#### Nomenclature

- $c_{DAC}$  = docking/airlock/centrifuge module mass-to-volume ratio  $m_{DAC} / V_{DAC}$
- $c_H$  = crew habitat module mass-to-volume ratio  $m_H / V_H$
- $c_{RCS} = \max \operatorname{ratio} m_{RCS} / (m_P + m_S)$
- $c_T = \max \operatorname{ratio} m_T / (m_P + m_S)$
- g = Earth surface gravity acceleration = 0.00980665 km/s<sup>2</sup>
- $m_A$  = miscellaneous stowage mass in pressurized volumes accessible to the crew, including the crew itself
- $m_B =$  budgeted propellant mass
- $m_C =$  centrifuge mass
- $m_{DAC}$  = docking/airlock/centrifuge module mass, excluding  $m_A$  and  $m_C$

 $m_H$  = crew habitat module mass, excluding  $m_A$  and  $m_{LS}$ 

- $m_J$  = mass of water jacketing the crew habitat module sufficient to provide marginally adequate crew radiation shielding (composed of  $m_S$  and typically a portion of  $m_P$ )
- $m_{LS}$  = mass associated with crew environmental control and life support systems consumables
- $m_{LS}' = m_{LS}$  loaded at a transit departure when T = 0

 $m_{NTP}$  = nuclear thermal propulsion system mass, excluding  $m_P$  and  $m_T$ 

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- $m_P$  = nominally usable water propellant mass
- $m_{RCS}$  = attitude control propellant mass
- $m_S$  = mass of water dedicated to crew habitat radiation shielding and usable as propellant only to address contingencies
- $m_T$  = structural mass of water tank holding  $m_P$  and  $m_S$
- $m_{TOT} =$  total *Aquarius* mass
- $m_Z$  = total of static Aquarius mass components for use in the rocket equation
- $r_0$  = a stable selenocentric orbit's mean radius over time
- $v_X =$  exhaust speed
- $v_{\infty}$  = asymptotic speed
- A = ratio of fully loaded *Aquarius* mass before to mass after 1.05  $\Delta v'$  is expended by nuclear thermal propulsion
- B = ratio of fully loaded *Aquarius* mass before to mass after 1.05  $\Delta v_D'$  is expended by nuclear thermal propulsion
- F = propulsive thrust
- $I_{SP}$  = specific impulse
- T = elapsed time since transit departure
- $V_{DAC}$  = total docking/airlock/centrifuge module volume
- $V_H =$  total crew habitat module volume
- $V_{H^+}$  = volume containing crew habitat module and a surrounding jacket of radiation shielding water
- $\rho_A =$  area density used to quantify radiation shielding mass about a specified volume's external surface area
- $\Delta t$  = interplanetary transit time from departure to arrival
- $\Delta t' =$  maximum  $\Delta t$  among interplanetary transits documented in Section III
- $\Delta v =$  change-in-velocity magnitude
- $\Delta v_C =$  second interplanetary transit abort  $\Delta v$  achieving capture at the departure planet
- $\Delta v_D =$  tally of  $\Delta v$  values for a transit's departure burns only
- $\Delta v_D' =$  maximum  $\Delta v_D$  among interplanetary transits documented in Section III
- $\Delta v_R =$  first interplanetary transit abort  $\Delta v$  commencing return to the departure planet
- $\Delta v' =$  maximum total  $\Delta v$  among interplanetary transits documented in Section III

# I. Introduction

Consider evolution of in-space nuclear thermal propulsion (NTP) technology to the point where fission reactor core temperatures exceeding  $3000^{\circ}$  C can be achieved during major translational maneuvers (burns). Under these conditions, water molecules pumped into the core will disassociate into hydrogen and oxygen atoms, and specific impulse  $I_{SP}$  near 1000 s could be achieved<sup>‡</sup>. This level of efficiency, twice that attainable with chemical propulsion, dramatically reduces total mass for an interplanetary transport of specified payload mass.

When high propulsive efficiency is achieved with water as propellant, the practicality of interplanetary human spaceflight is enhanced in multiple respects. First, liquid water is easily stored for months or years without exotic thermal conditioning burdens imposed by cryogens or toxicity hazards associated with hypergols. Second, liquid water stored about the crew habitat to

<sup>&</sup>lt;sup>‡</sup> Personal communication with Dr. James A. Dewar, U.S. Department of Energy, Retired, on 29 September 2010.

support arrival propulsion requirements at an interplanetary destination also serves as an effective radiation shield during interplanetary transit. Third, water is arguably the most common volatile to be found on small bodies such as asteroids and minor moons throughout our solar system, leading to the promise of in-situ resource utilization (ISRU). With ISRU producing water for propulsion, radiation shielding, and hydration/hygiene near an interplanetary destination, mass to be transported there from Earth in support of crew return is virtually eliminated.

A synergistic consequence of interplanetary arrival propellant doubling as a crew habitat radiation shield is transport reusability. In an Earth return transit from interplanetary space, discarding the transport while its crew undergoes direct atmospheric entry and landing becomes absurd if radiation shielding can instead be expended as propellant to deliver the crew to safe haven at an orbital destination where the transport is resupplied. With reuse, over 100 metric tons (t) of transport structure mass are thereby recycled before the next interplanetary departure. This mass includes costly systems that need not be fabricated, launched, and assembled in space for but a single mission. Specialized crew systems required to withstand Earth atmospheric entry and landing are superfluous in the context of an indirect crew return mission profile. These systems have a mass exceeding 10 t and need not be hauled out to an interplanetary destination before Earth return months or years later when their critical functions are at long last required.

An indirect Earth return from interplanetary space may be the only option for crew survival. Atmospheric accelerations following Earth entry speeds of at least 11 km/s after an interplanetary transit have proved to be survivable for humans only in the context of Apollo Program missions whose crews were de-conditioned by microgravity for at most two weeks beforehand (Ref. 1). In a typical Earth return interplanetary transit, the crew is subjected to microgravity for at least several months.

With these primary motivations in mind, a reusable NTP-powered interplanetary transport utilizing water as propellant and as radiation shielding for its crew is proposed and documented. Additional water for open-loop crew hydration and hygiene brings this transport's gross mass to slightly more than half water immediately prior to an interplanetary departure. She is therefore christened *Aquarius* in deference to the Zodiacal Water-Bearer of that name<sup>§</sup>.

To demonstrate *Aquarius* performance and supporting infrastructure functions, her first three interplanetary transits are documented. Transit 1 begins in the elliptical Earth parking orbit (EEPO) where *Aquarius* has undergone assembly and ends at rendezvous with the outer martian moon Deimos, arguably the optimal location for human tele-robotic exploration of Mars (Ref. 2). The crew conducts this exploration from a sub-surface Deimos habitat while *Aquarius* is resupplied for Transit 2 using pre-emplaced consumables cached there (via Deimos ISRU or robotically transported cargo) before Transit 1 began. Transit 2 departs Deimos and ends in a stable selenocentric distant retrograde orbit (SDRO) with mean radius  $r_0 = 12,500$  km, as would all future transits from Deimos until *Aquarius* is decommissioned. At this point, *Aquarius* has docked with SDRO-resident infrastructure for Transit 3 resupply while her first crew is replaced. Transit 3 begins in the SDRO and ends at Deimos, as would all future transits to Deimos until *Aquarius* is decommissioned. An SDRO appears to be the closest stable orbit to Earth in which a reusable spacecraft can be serviced between interplanetary transits without expending excessive

<sup>&</sup>lt;sup>§</sup> A male gender is usually associated with The Water-Bearer in mythology and astrology. But precedent refers to transports with feminine pronouns even in gender-neutral cases such as *Enterprise* or *Endeavour*. This feminine attribute will therefore be applied to *Aquarius* as well.

change-in-velocity  $\Delta v$  (Ref. 3 and Ref. 4, Section 2.2). As a further example, *Aquarius* return to Earth abort capability is estimated after Transit 3 enters interplanetary space.

By demonstrating practical roundtrips to Deimos, *Aquarius* capability delivering human explorers to more than 1100 near-Earth asteroids (NEAs) is inferred (Ref. 5). Although NEA destinations are generally more accessible than Deimos because of reduced total  $\Delta v$  and transit time  $\Delta t$ , practical human spaceflight roundtrip opportunities to a particular NEA are generally less frequent than those to Deimos. Even if *Aquarius* never visits an NEA, supporting ISRU capability is offered by water-rich NEA material (raw or pre-processed in-situ) robotically transported to infrastructure near *Aquarius* transit termini (Ref. 6).

## **II.** Interplanetary Transit Assumptions

Each of the following paragraphs documents an assumption and rationale relating to capabilities of *Aquarius* or her supporting infrastructure. Together, these enable interplanetary transits between EEPO/SDRO and Deimos. A unique 3-character code with format **Axx** or **Bxx**, where **xx** is a sequential 2-digit integer, initiates each paragraph to aid concise referencing. An **Axx** code relates primarily to *Aquarius*, and a **Bxx** code relates primarily to supporting infrastructure.

**A01**: *Aquarius* will fly roundtrips to Deimos in accord with a conjunction mission profile. This entails spending about 500 days at Deimos while Earth phases through a solar superior conjunction observed from Mars before an Earth return transit can begin. With protracted time at Deimos, significant tele-robotic Mars exploration can be conducted by the crew to justify risks in sending them so far from Earth. The Deimos loiter interval is also of sufficient duration to ensure *Aquarius* resupply from pre-emplaced resources, whether they originate on Demos through ISRU or on Earth through robotic transport.

**A02**: *Aquarius* will fly short-way (Type 1) transits to reduce time spent in interplanetary space with respect to alternative long-way (Type 2) transits. A short-way transit requires about 200 to 240 days to complete. Reducing transit duration by excluding long-way trajectories also reduces undesirable crew exposure to radiation and micro-gravity.

A03: radiation shielding to an area density  $\rho_A > 51.5 \text{ g/cm}^2$  will be provided throughout the crew habitat module (Hab) aboard *Aquarius* except during intervals less than 100 hours required to reach crew safe haven during arrival at an interplanetary destination. At 51.5 g/cm<sup>2</sup>, Hab shielding is 5% of the 1030 g/cm<sup>2</sup> provided by Earth's atmosphere at sea level and is called "radiation protection 5" (RP5) shielding. This shielding "jacket" has two components. Hab structure is assumed to provide 14.5 g/cm<sup>2</sup>, and water surrounding this structure is assumed to provide the remaining 37.0 g/cm<sup>2</sup>. The RP5 specification is assumed sufficient to satisfy radiation exposure standards during short-way transits from Earth to Deimos and back (per A01 and A02) for any adult astronaut (Ref. 7). Exposure rates no greater than on Earth's surface (RP100) are further assumed during Deimos loiter between transits (per B01).

**A04**: to effect safe rendezvous as an interplanetary destination is approached, *Aquarius* must consume water propellant to the point Hab shielding is less than RP5 (per A03). Under these conditions, extra water propellant will be expended in the interest of expediting crew arrival at safe haven from radiation exposure beneath the surface of Deimos (per B01) or at SDRO-resident infrastructure (per B02). Near the end of a transit, this overriding interest will generally result in propellant expenditure that is <u>not</u> minimal.

A05: the NTP system aboard *Aquarius* has  $I_{SP} = 900$  s, exhaust speed  $v_X = g I_{SP} = 8.826$  km/s, and develops a total thrust F = 333,617 Nt from three engines (Ref. 8, p. 25). Fission reactors

Daniel R. Adamo & James S. Logan

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powering these engines are also capable of powering all electrical loads aboard *Aquarius* during cruise periods (called "bi-modal" reactor operation in Ref. 4, Section 3.1). During NTP burns, a partial power-down of nonessential electrical loads may be necessary. Mass of NTP systems (excluding usable water propellant mass  $m_P$  and water tank structural mass  $m_T$ )  $m_{NTP} = 41,700$  kg (Ref. 8, p. 27).

A06: the mass ratio of Aquarius attitude control propellant to NTP propellant plus dedicated Hab radiation shielding water  $c_{RCS} = m_{RCS} / (m_P + m_S) = 4.9 / 59.7 = 0.0820770$  (Ref. 8, p. 27). Because an attitude timeline during Aquarius transits is beyond the scope of this study,  $m_{RCS}$  is not depleted from its initial interplanetary departure value as a conservative assumption when Aquarius transits are assessed in Section IV.

A07: the mass ratio of water tank structure to NTP propellant plus dedicated Hab radiation shielding water  $c_T = m_T / (m_P + m_S) = 14.0 / 73.1 = 0.191518$  (Ref. 8, p. 27).

**A08**: the Hab mass-to-volume ratio is that of the ISS *Destiny* lab module  $c_H = m_H / V_H = 24,023 / (\pi * 2.15^2 * 9.2) = 179.809 \text{ kg/m}^3$  (Ref. 9).

A09: Aquarius will transport a crew of 3.

A10: the Hab is a cylinder 2.3 m in radius and 12.2 m in length with a total volume  $V_H = \pi * 2.3^2 * 12.2 = 202.752 \text{ m}^3$ . Although pressurized Hab volume will be somewhat less than  $V_H$ , the total volume for each crewperson is  $202.752 / 3 = 67.584 \text{ m}^3$  (per A09). This is 3.38 times the 20 m<sup>3</sup> NASA standard for "Optimal" per capita habitable volume at  $\Delta t = 6$  months or more (Ref. 10, Figure 8.6.2.1-1).

A11: the Hab has mass  $m_H = 179.809 * 202.752 = 36,457$  kg (per A08 and A10). If  $m_H$  is distributed uniformly within the Hab, it contributes  $\rho_A = 36,457 / (2 * \pi * 2.3^2 + 2 * \pi * 2.3 * 12.2) = 173.982$  kg/m<sup>2</sup> = 17.4 g/cm<sup>2</sup> to Hab radiation shielding (per A10), indicating the assumed Hab structure shielding component of 14.5 g/cm<sup>2</sup> is adequate (per A03). Note that a component of  $m_T$  also serves to shield crew in the Hab from radiation, but this contribution is ignored as an additional conservative (and simplifying) assumption.

A12: water mass jacketing the Hab exterior must provide an area density of 37 g/cm<sup>2</sup> (per A03). A cylinder exceeding Hab length by 74 cm and Hab radius by 37 cm has a volume  $V_{H+} = \pi * 2.67^2 * 12.94 = 289.806 \text{ m}^3$  (per A10). Thus, the volume  $V_{H+} - V_H = 289.806 - 202.752 = 87.053 \text{ m}^3$  jackets the Hab with liquid water sufficient to shield the crew (per A03). Liquid water has a density of 1000 kg/m<sup>3</sup>. Therefore, the Hab's shielding water jacket has mass  $m_J = 1000 * 87.053 = 87,053 \text{ kg}$ . Until NTP burns commence near an interplanetary transit's destination,  $m_S + m_P > m_J$  (per A03).

A13: environmental control and life support systems (ECLSS) consumables are dumped/vented overboard *Aquarius* in open-loop fashion for simplicity and reliability. Crew per capita ECLSS consumables mass depletion rates are 29.26 kg/day of water (stowed in a dedicated reservoir distinct from that holding  $m_P$  and  $m_S$ ), 0.82 kg/day oxygen, 0.72 kg/day dehydrated food, 0.69 kg/day miscellaneous supplies, 0.69 kg/day atmospheric losses, and 0.69 kg/day ECLSS maintenance. These allocations are relatively liberal with respect to others considered state-of-the-art (Ref. 11). The entire crew therefore consumes a total ECLSS mass of 98.61 kg/day (per A09). Total ECLSS mass to be loaded for a transit has a 5% margin such that  $m_{LS}' = 1.05 * \Delta t' * 98.61$  kg initially, where the maximum transit time  $\Delta t'$  among transits documented in Section III is measured in days. If T is measured in days, ECLSS consumables mass at any time during transit is  $m_{LS} = m_{LS}' - T * 98.61$ .

5

A14: miscellaneous mass stowed aboard *Aquarius* in pressurized volumes accessible to the crew includes (Ref. 8, p. 34) crew accommodations (4210 kg), extravehicular activity systems (870 kg), spare equipment (4180 kg), and the crew itself (560 kg). These total to  $m_A = 9820$  kg.

A15: the docking/airlock/centrifuge module (DAC) mass-to-volume ratio is that of the ISS *Quest* airlock module  $c_{DAC} = m_{DAC} / V_{DAC} = 9923 / (\pi * 2^2 * 3) = 263.216 \text{ kg/m}^3 (\text{Ref. 12})^{**}$ .

A16: the DAC is a cylinder 4 m in radius and 2 m in length accommodating a 3 m short-arm centrifuge with a total volume  $V_{DAC} = \pi * 4^2 * 2 = 100.531 \text{ m}^3$ . Although pressurized for crew access, crew time spent inside the DAC will be limited in duration because its habitable volume is shielded from radiation only by DAC structure.

A17: the DAC has mass  $m_{DAC} = 263.216 * 100.531 = 26,461 \text{ kg}$  (per A15 and A16).

A18: the 3 m short-arm centrifuge has mass  $m_C = 1700 \text{ kg.}^{\dagger\dagger}$ 

A19: the minimum safe perigee height for targeting Oberth burns at Earth is +400 km.

A20: the minimum safe periapsis height for targeting Oberth burns at Mars is +384.1 km.

A21: the minimum safe pericynthion height for targeting Oberth burns at the Moon is +100 km.

A22: capacity of Aquarius to stow component masses is sized to the most demanding transit documented in Section III for each. Thus, maximum  $m_{RCS}$  (per A06) and  $m_P$  capacity are computed based on a transit with the maximum tally of change-in-velocity magnitudes  $\Delta v'$ . This case may differ from the transit associated with  $\Delta t'$  on which maximum  $m_{LS}$  capacity is based (per A13). The  $m_S$  allocation is based on  $\Delta v_D'$ , the maximum tally of change-in-velocity magnitudes during departure among all transits documented in Section III (per A03). Each of these stowage capacity allocations is computed by applying a 1.05 inflation factor to the pertinent transit parameter.

A23: regardless of transit-specific  $\Delta v$  and  $\Delta t$ , Aquarius will always be loaded to capacity stowage (per A22) before an interplanetary departure. This strategy will typically provide the crew with additional radiation shielding and with positive consumables margins in the event of unexpected contingencies.

**B01**: Aquarius crew habitat beneath the surface of Deimos provides at least RP100 shielding mass such that crew radiation exposure rates are no greater than on Earth's surface. This habitat will also provide the crew with pre-emplaced power, communications, and ECLSS systems/consumables. Crew exploration of Deimos, the inner martian moon Phobos, and Mars through pre-emplaced tele-robotics is enabled from the Deimos habitat. Ideally, the entire habitat is part of a rotating centrifuge capable of generating sensed acceleration up to 1 g for the crew with subliminal Coriolis effects. This ideal habitat may evolve after Transit 1, but a shortarm centrifuge similar to that in the DAC is assumed to be the minimal crew conditioning capability in the Deimos habitat.

**B02**: Aquarius crew habitat at SDRO-resident infrastructure will provide at least RP5 radiation shielding using structure and water masses similar to that for the Hab during Aquarius transits. This habitat will also provide ECLSS systems/consumables and conditioning equipment

<sup>&</sup>lt;sup>\*\*</sup> In order to compute *Quest* volume as a single cylinder, Ref. 12 length is reduced from 5.5 m to 3 m. This is because Ref. 12's 4.0 m width only applies to *Quest*'s Equipment Lock. *Quest* is actually two cylinders with its Crew Lock having a much smaller width than 4.0 m.

<sup>&</sup>lt;sup>††</sup> Personal communication with Jim Kukla, VP, Wyle Technology, Science and Engineering Group on 29 January 2014. This value is for an Earth-based centrifuge, and a similar 3 m unit aboard *Aquarius* would be less massive.

enabling the crew to attain readiness for Earth return at an atmospheric entry speed of at least 11.0 km/s within 30 days of arrival at SDRO infrastructure.

**B03**: during *Aquarius* assembly in EEPO, perigee height is maintained near +7700 km, reducing human and electronics exposure to particle radiation trapped in the geomagnetic field (Ref. 13). Apogee height is maintained near +113,300 km such that rendezvous phase repetition recurs each orbit, every two days. With nearly constant rendezvous phase at each EEPO launch opportunity, logistics supporting *Aquarius* assembly (per B04) are standardized.

**B04**: logistics supporting *Aquarius* assembly are conducted with multiple launches, each delivering a total mass of 130 t into a circular orbit at +185 km height at 45.6° inclination to Earth's equator<sup>‡‡</sup>. The propellant mass fraction of this initial mass to low Earth orbit (IMLEO) is 51.4% or 66,854 kg, and that propellant delivers  $I_{SP} = 450$  s when burned to achieve rendezvous with the nascent *Aquarius* in EEPO (per B03). Immediately after rendezvous, the remaining 720 kg of this propellant mass is burned to deorbit and dispose of upper stage propulsive systems, structure, and avionics not supporting *Aquarius* assembly as payload mass<sup>§§</sup>. In this manner, each launch delivers a payload mass of 50,360 kg, including proximity operations consumables mass in addition to that ultimately placed aboard *Aquarius*. In practice, each launch is therefore assumed to deliver 50,000 kg to *Aquarius* as she is assembled and supplied in EEPO.

**B05**: infrastructure supporting *Aquarius* servicing/resupply at Deimos is in proximity to the B01 habitat. Resupply water would presumably come from Earth or as an ISRU product (from Deimos or from asteroid material redirected to the vicinity of Deimos infrastructure). With an orbit period of 1.263 days, Deimos ensures periapsis at Mars flyby can be properly placed to arrive from or return to Earth on virtually any day (per A02).

**B06**: infrastructure supporting *Aquarius* servicing/resupply orbits the Moon with the B02 habitat in a stable, near circular SDRO whose mean radius  $r_0$  is near 12,500 km. Resupply water would presumably come from Earth or as an ISRU product (from the Moon and asteroids redirected to SDRO). With  $r_0 >> 3000$  km, infrastructure trajectory perturbations from local variations in lunar gravity need not be periodically corrected to avoid impact on the Moon. With  $r_0 << 70,000$  km, gravity perturbations from the Earth and Sun leading to orbit instability are also avoided. At  $r_0 = 12,500$  km, selenographic period (equivalent to the interval cycling through all phase angles with respect to the Earth/Moon line) is a moderate 1.38 days. Consequently, optimal phase for arriving at or departing from SDRO infrastructure can be achieved in a few lunar orbits with semi-major axis differing from 12,500 km (and pericynthion height above +100 km, per A21) or by varying transit time between the Earth and Moon. At 27.3 days, the Moon's geocentric orbit period is just short enough to ensure perigee at Earth flyby can be properly placed to depart for or return from Deimos during the interval *Aquarius* capabilities support an interplanetary transit (per A02).

## **III.** The First Three Interplanetary Transits By Aquarius

The first three subsections to follow document each of the first three transits to be made by *Aquarius* after her assembly in EEPO (per B03 and B04). A fourth subsection contains notes on unique or comparative aspects of these transits' trajectory designs. Transit 1, the maiden voyage

<sup>&</sup>lt;sup>‡‡</sup> This is near the minimum possible inclination for Earth departure to Mars in Transit 1. Significantly lower inclinations would be possible for another *Aquarius* maiden interplanetary transit.

<sup>&</sup>lt;sup>§§</sup> It should be noted that all 66,854 kg of IMLEO propellant for rendezvous and deorbit is consumed within about a day following launch. Consistent with  $I_{SP} = 450$  s, this propellant is therefore assumed to be cryogenic with minimal concern for significant thermal losses, thanks to its prompt consumption.

of Aquarius, departs EEPO in late 2022 such that Mars is near aphelion when Aquarius arrives for Deimos rendezvous. This transit is near the start of a sequence of high  $\Delta v$  Mars mission opportunities from Earth (Ref. 2, p. 5) and is timed with the intent of stressing Aquarius capabilities to the degree they cover any conjunction class mission opportunity to Deimos (per A01 and A02). Although proving this to be the case universally is beyond the scope of this paper, Aquarius  $\Delta v$  capability will cover the challenging transits documented here to margins of approximately +5% or more (per A22).

Trajectory designs for Transits 1-3 are manually optimized for minimal  $\Delta v$  tallies among all burns within the arrival constraints of A04. An automated optimizer would undoubtedly improve on these designs, perhaps to a significant degree. But the objective here is to demonstrate *Aquarius* can fly practical trajectories, even when interplanetary geometry is uncooperative. To that end, fully optimizing transit cases documented in this section could suggest *Aquarius* capabilities insufficient to cover worse cases not yet studied.

Although some trajectory design parameters such as  $v_{\infty}$  inherently reflect a patched conic pedigree, data presented in this section represent preliminary segmented transits as evolved into continuous precision trajectories. The only discontinuities remaining following this evolution are velocity increments associated with impulsively approximated NTP burns. Precision trajectories are numerically integrated (Ref. 14) and simulate gravity accelerations from the Sun, Earth, Mars, and Moon along with excess equatorial mass within the oblate figures of Earth and Mars. Ephemerides for the Earth, Mars, and Moon as documented in Ref. 15, Appendix II are utilized throughout this section. Mars-centered Deimos positions are from the Jet Propulsion Laboratory's *Horizons* computation service (Ref. 16).

A trajectory design feature common to all transit termini, whether departing EEPO, departing/arriving Deimos, or departing/arriving SDRO, is the Oberth maneuver. At each terminus, distance from the Earth/Mars/Moon is sufficiently great, along with departure/arrival  $v_{\infty}$ , to warrant this technique. Under these conditions, minimal  $\Delta v$  required to depart/arrive a terminus is obtained when the required prograde/retrograde burn is performed as close to the Earth/Mars/Moon as safety permits. This precept holds in Transits 1-3 even though a second retrograde/prograde burn at each terminus must be paired with the opposing prograde/retrograde burn close to the Earth/Mars/Moon.

As an example, consider departure from or arrival at Deimos. The Direct strategy for departure/arrival entails a single prograde/retrograde burn to/from a Mars-centered hyperbola whose periapsis height is exactly that of Deimos (+20,073.3 km in this example). In contrast, the Oberth strategy utilizes two burns. For departure, a retrograde burn at Deimos initiates a Hohmann transfer to Mars periapsis height +384.1 km (per A20), where a prograde burn imparts escape from Mars. For arrival, Mars capture from the approach hyperbola is achieved with a retrograde burn at the +384.1 km periapsis height, initiating Hohmann transfer to Deimos, where a prograde burn achieves rendezvous at Mars apoapsis.

Total  $\Delta v$  values<sup>\*\*\*</sup> for the Direct and Oberth strategies are plotted as functions of Mars depart/arrive  $v_{\infty}$  in Figure 1. These plots indicate Deimos arrival/departure with  $v_{\infty} > 2.0$  km/s requires less  $\Delta v$  using the two-burn Oberth strategy than would a single Direct strategy burn. Such is clearly the case for all transits documented here. The Transit 1 Deimos arrival has  $v_{\infty} =$ 

<sup>&</sup>lt;sup>\*\*\*</sup> In the interest of simplicity, these values assume the Mars depart/approach asymptote lies in the Deimos orbit plane such that out-of-plane burn components are absent. Transits 1-3 do possess these burn components, but the associated plane changes would challenge both the Direct and Oberth strategies equally.



3.658 km/s, Transit 2 Deimos departure has  $v_{\infty}$  = 3.471 km/s, and Transit 3 Deimos arrival has  $v_{\infty}$  = 4.215 km/s.

Figure 1. Total  $\Delta v$  required to depart from or arrive at the Deimos terminus of an interplanetary transit (assuming a depart/arrive asymptote in the Mars-centered Deimos orbit plane) is plotted as a function of the associated Mars asymptotic speed  $v_{\infty}$  for two trajectory design strategies. When  $v_{\infty} > 2.0$  km/s, the 2-burn Oberth strategy (red squares) requires less total  $\Delta v$  than does the 1-burn Direct strategy (blue diamonds). All three Deimos departures/arrivals documented in this section have  $v_{\infty} > 3$  km/s and therefore utilize the Oberth strategy in their trajectory designs.

# A. Transit 1: EEPO To Deimos

The maiden interplanetary transit of *Aquarius* begins by utilizing the Oberth strategy to depart her assembly EEPO and escape Earth on an interplanetary trajectory intercepting Mars. A similar strategy is employed at the transit's arrival terminus to achieve Mars capture and rendezvous with Deimos. The transit's burns are summarized in Table 1.

Table 1. Transit 1 burns are summarized as *Aquarius* departs EEPO and arrives at Deimos. The leftmost column provides the date and universal time (UT) of each event in the rightmost column. Values in the  $\Delta v$  column are positive for prograde burns and negative for retrograde burns. A total  $\Delta v = 3.695$  km/s is expended over  $\Delta t = 204$  days during Transit 1 with  $\Delta v_D = 1.358$  km/s.

Date @ UT	$\Delta v  (\text{km/s})$	Event
2022 Sep 08 @ 02:01	-0.242	Lower perigee height from +7725 km to +400 km
2022 Sep 09 @ 00:00	+1.116	Trans-Mars injection (TMI)
2023 Mar 30 @ 20:00	-1.586	Mars orbit insertion (MOI)
2023 Mar 31 @ 02:00	+0.751	Deimos rendezvous

Figure 2 plots inertial geocentric motion of *Aquarius* from her final EEPO through perigee lowering and TMI burns. Note perigee lowering also serves as an NTP systems test before committing *Aquarius* to interplanetary space post-TMI. Figure 3 plots heliocentric motion of Earth, Mars, and *Aquarius* during Transit 1, while Figure 4 plots Mars-centered Deimos and *Aquarius* motion as Transit 1 concludes.



Km Units View From Y=270.0°, P= 0.0°, R= 9.0° Earth-Centered J2KE Coordinate System

Figure 2. Geocentric inertial *Aquarius* motion is plotted from her last EEPO through perigee lowering and TMI burns as she departs Earth for Mars and Deimos rendezvous. The plot plane nearly coincides with the plane of *Aquarius* motion. Time tick labels are 2022 September 6-9 UT in day-of-year (DOY)/hh:mm format. Dotted lines are projections onto the ecliptic plane, and the shaded area is Earth's nightside.



Sun-Centered J2KE Coordinate System

Figure 3. *Aquarius* heliocentric motion during her maiden short-way Transit 1 is plotted (blue) along with that of Earth (green) and Mars (red) during this interval. The plot plane coincides with the ecliptic, Earth's heliocentric orbit plane. Time ticks at 30-day intervals are annotated with the date in yyyy-mm-dd format.



 Km Units
 View From Y= 90.0°, P= 0.0°, R= 0.0°
 Sun Illumination

 Mars-Centered EPM Coordinate System @ 2023y
 B9d (3-30) 20: 0: 0 UTC

Figure 4. Mars-centered inertial *Aquarius* motion (blue) is plotted during her first rendezvous with Deimos (red). The plot plane coincides with that of the martian equator. Time tick labels are 2023 March 30-31 UT in DOY/hh:mm format. The shaded area is the nightside of Mars. This shading indicates *Aquarius* approaches Deimos with at least half of the moon's lit surface visible.

Upon arrival at Deimos, *Aquarius* crew transfer to the pre-emplaced RP100 subsurface habitat is expedited to minimize radiation exposure (per A04 and B01). Ideally, this transfer would be facilitated by a pressurized docking interface. Such an interface would also simplify transfer of pre-emplaced water and other consumables from Deimos infrastructure to *Aquarius* in preparation for Transit 2 (per B05). In addition to Transit 2 preparations, the 496-day Deimos loiter interval following Transit 1 would be filled with Deimos and Mars exploration activities in which the *Aquarius* crew operates pre-emplaced tele-robotic systems from its subsurface habitat (per B01).

# **B. Transit 2: Deimos To SDRO**

The second interplanetary transit of *Aquarius* begins by utilizing the Oberth strategy to depart Deimos and escape Mars on an interplanetary trajectory intercepting Earth. This strategy is employed twice upon Earth arrival. The first instance achieves Earth capture and initiates lunar intercept when *Aquarius* performs her first trans-lunar injection (TLI) burn, and the second achieves lunar capture followed by rendezvous with SDRO-resident infrastructure. Transit 2's burns are summarized in Table 2.

Table 2. Transit 2 burns are summarized as *Aquarius* departs Deimos and arrives at Earth and SDRO-resident infrastructure. The leftmost column provides the date and universal time (UT) of each event in the rightmost column. Values in the  $\Delta v$  column are positive for prograde burns and negative for retrograde burns. A total  $\Delta v = 3.827$  km/s is expended over  $\Delta t = 240$  days during Transit 2 with  $\Delta v_D = 2.205$  km/s.

Date @ UT	∆v (km/s)	Event
2024 Aug 08 @ 17:30	-0.652	Depart Deimos for Mars flyby
2024 Aug 09 @ 00:00	+1.553	Trans-Earth injection (TEI)
2025 Apr 03 @ 00:00	-0.935	Trans-lunar injection (TLI)
2025 Apr 05 @ 21:44	-0.378	Lunar orbit insertion (LOI)
2025 Apr 06 @ 05:19	+0.309	SDRO-resident infrastructure rendezvous

Figure 5 plots inertial Mars-centered motion of *Aquarius* and Deimos from Deimos separation through the TEI burn. Figure 6 plots heliocentric motion of Earth, Mars, and *Aquarius* during Transit 2, while Figure 7 plots geocentric Moon and *Aquarius* motion as Transit 2 concludes. Figure 8 plots selenocentric motion as *Aquarius* reaches the Moon and achieves rendezvous with SDRO-resident infrastructure at  $r_0 = 12,500$  km.



Mars-Centered EPM Coordinate System @ 2024y 222d ( 8- 9) O: O UTC

Figure 5. Mars-centered inertial *Aquarius* motion (blue) is plotted during her first departure from Deimos (red). The plot plane coincides with that of the martian equator. Time tick labels are 2024 August 8-9 UT in DOY/hh:mm format. The shaded area is the nightside of Mars. This shading indicates *Aquarius* departs Deimos with at least half of the moon's lit surface visible.



Sun-Centered J2KE Coordinate System

Figure 6. *Aquarius* heliocentric motion during her short-way Transit 2 is plotted (blue) along with that of Earth (green) and Mars (red) during this interval. The plot plane coincides with the ecliptic, Earth's heliocentric orbit plane. Time ticks at 30-day intervals are annotated with the date in yyyy-mm-dd format.



Earth-Centered J2KE Coordinate System

Figure 7. Geocentric inertial motion of Aquarius (blue) and the Moon (red) are plotted as the spacecraft returns to her SDRO "garage" for the first time. The plot plane nearly coincides with the plane of Aquarius motion. Time tick labels are 2025 April 2-8 UT in day-of-year (DOY)/hh:mm format. Dotted lines are projections onto the ecliptic plane, and the shaded area is Earth's nightside. From this shading, note how the Moon must be slightly past first quarter phase at LOI to minimize TLI  $\Delta v$ .



Km Units View From Y= 0.0°, P= 0.0°, R= 30.0° Sun Illuminatio Moon-Centered EPM Coordinate System @ 2025y 95d (4-5) 21:44: O UTC

Figure 8. Selenocentric inertial motion of Aquarius is plotted as she achieves capture in the lunar gravity field and conducts rendezvous with SDRO-resident infrastructure at  $r_0 = 12,500$  km. The plot plane nearly coincides with the plane of Aquarius motion. Time tick labels are 2025 April 5-7 UT in day-of-year (DOY)/hh:mm format. Dotted lines are projections onto the lunar equatorial plane, and the shaded area is the Moon's nightside.

Upon docking with SDRO-resident infrastructure, *Aquarius* crew transfer to RP5 habitat is expedited to minimize radiation exposure (per A04 and B02). Ideally, this transfer would be facilitated by a pressurized docking interface. Such an interface would also simplify transfer of pre-emplaced water and other consumables from the SDRO infrastructure to *Aquarius* in preparation for Transit 3 (per B06).

#### C. Transit 3: SDRO To Deimos

As illustrated by Figure 8, the initial rendezvous performed by *Aquarius* with SDRO-resident infrastructure at the conclusion of Transit 2 assumes that infrastructure has cooperatively phased to the optimal SDRO position just as *Aquarius* reaches her first post-LOI apocynthion nearby. Absent such cooperative phasing, *Aquarius* would under-burn the Transit 2 LOI to enter a more eccentric intermediate phasing orbit (with apocynthion exceeding the SDRO's  $r_0 = 12,500$  km) before completing the Transit 2 LOI and achieving rendezvous. Although *Aquarius* active phasing with SDRO infrastructure would have little impact on Transit 2 total  $\Delta v$ , her crew would be exposed to additional radiation in the Hab with RP < 5 during time spent in the phasing orbit. This tends to conflict with A03.

Such a conflict does not develop when departing SDRO infrastructure to initiate Transit 3. With a full consumables load, *Aquarius* provides considerably more than RP5 Hab shielding at this time. Initial conditions for Transit 3 therefore assume the Figure 8 SDRO is coasted 574 days (398 orbits, as reckoned by tallying ascending node crossings on the lunar equator) into the next Earth departure season for Mars. To depart the SDRO and lunar orbit for Earth and TMI at the beginning of Transit 3 then requires *Aquarius* perform TEI in three parts. A retrograde TEIa burn enters a phasing orbit with pericynthion height near +4936 km, a retrograde TEIb burn lowers pericynthion height to +100 km two orbits after TEIa, and a prograde TEIc burn departs the Moon for Earth. Thanks to the TEIa and TEIb burns, TEIc can be performed at the selenocentric position and time required for a near-Earth TMI in fulfillment of Transit 3 Oberth departure strategy. These initial burns and those required to achieve Transit 3 Deimos rendezvous appear in Table 3.

Table 3. Transit 3 burns are summarized as *Aquarius* departs SDRO and arrives at Deimos. The leftmost column provides the date and universal time (UT) of each event in the rightmost column. Values in the  $\Delta v$  column are positive for prograde burns and negative for retrograde burns. A total  $\Delta v = 4.437$  km/s is expended over  $\Delta t = 241$  days during Transit 3 with  $\Delta v_D = 1.696$  km/s.

Date @ UT	$\Delta v  (\text{km/s})$	Event				
2026 Nov 01 @ 11:41	-0.109	TEIa lowers SDRO pericynthion height to +4936 km				
2026 Nov 03 @ 09:26	-0.208	TEIb lowers pericynthion height to +100 km				
2026 Nov 03 @ 16:52	+0.488	TEIc departs Moon for Earth				
2026 Nov 06 @ 23:49	+0.891	TMI				
2027 Jun 29 @ 15:30	-1.940	MOI				
2027 Jun 29 @ 22:00	+0.801	Deimos rendezvous				

Figure 9 plots selenocentric *Aquarius* motion as she departs SDRO-resident infrastructure and leaves the Moon for Earth while performing the TEIa, TEIb, and TEIc burns. Effects from this burn sequence, together with TMI, are plotted geocentrically for *Aquarius* accompanied by the Moon's motion in Figure 10. Heliocentric motion of Earth, Mars, and *Aquarius* during Transit 3 are plotted in Figure 11. Finally, Mars-centered motion of Deimos and *Aquarius* are plotted in Figure 12 as Transit 3 is completed.



Km Units View From Y= 0.0", P= 0.0", R= 0.0" Sun Illumination Moon-Centered EPM Coordinate System @ 2026y 305d (11- 1) 11:41: 0 UTC

Figure 9. Selenocentric inertial motion of *Aquarius* is plotted as she departs SDRO for Earth and TMI. The plot plane coincides with the Moon's equator and very nearly coincides with that of *Aquarius* motion. Time tick labels are 2026 November 1-3 UT in day-of-year (DOY)/hh:mm format, and the shaded area is the Moon's nightside.



Earth-Centered J2KE Coordinate System

Figure 10. Geocentric inertial motion of the Moon (red) and Aquarius (blue) are plotted as SDRO and Earth are departed for Mars. The plot plane coincides with the ecliptic plane and very nearly that of Aquarius motion. Time tick labels are 2026 November 1-7 UT in day-of-year (DOY)/hh:mm format, and the shaded area is Earth's nightside. From this shading, note how the Moon must be slightly past last quarter phase at TEIc to minimize TMI  $\Delta v$ .



Sun-Centered J2KE Coordinate System

Figure 11. Aquarius heliocentric motion during her short-way Transit 3 is plotted (blue) along with that of Earth (green) and Mars (red) during this interval. The plot plane coincides with the ecliptic, Earth's heliocentric orbit plane. Time ticks at 30-day intervals are annotated with the date in yyyy-mm-dd format.



Mars-Centered EPM Coordinate System @ 2027y 180d (6-29) 15: 9:22 UTC

Figure 12. Mars-centered inertial *Aquarius* motion (blue) is plotted during her second rendezvous with Deimos (red). The plot plane coincides with that of the martian equator. Time tick labels are 2027 June 29 UT in DOY/hh:mm format. The shaded area is the nightside of Mars. This shading indicates *Aquarius* approaches Deimos with at least half of the moon's lit surface visible.

# **D.** Trajectory Design Notes

Among conceivable Aquarius transit departures or arrivals, initial EEPO departure is unique because no previous constraint conflicts with precise alignment between the EEPO plane and that of the associated Earth departure hyperbola. Other transports might manage planar misalignment between the terminus orbit and the departure/approach hyperbola by adding a dedicated plane change burn to the Oberth strategy. Such a burn is best performed at the lowest possible speed and typically imposes an increase in  $\Delta t$  while a large distance from the Earth/Mars/Moon is achieved before escape in a departure or after capture in an arrival. The increased  $\Delta t$  associated with this "detour" is generally undesirable for human spaceflight, and it conflicts with A04 in an arrival. Consequently, Oberth burns performed by Aquarius contain

Daniel R. Adamo & James S. Logan

21 March 2014

appreciable out-of-plane  $\Delta v$  components, the only exception being departure from her assembly EEPO to begin Transit 1.

As noted in B05, the short orbit period of Deimos helps facilitate Oberth departures and arrivals at Mars on virtually any day. Per B06, the Moon's much longer orbit period could pose challenging constraints to Oberth departures and arrivals at Earth. These challenges are managed with tolerable  $\Delta v$  increases in Transits 2 and 3. In an Earth departure transit, it might be acceptable to depart SDRO and the Moon a few weeks before TMI to achieve the proper perigee geometry for TMI, assuming the increased  $\Delta t$  did not violate A13. At the end of an Earth return transit, however, a post-TLI loiter of several weeks to encounter the Moon would likely violate A03 even if compliant with A13.

Short-way heliocentric transits between Earth and Mars (per A02) are in a plane inclined to the ecliptic by at most a few degrees. The Moon's equator and geocentric orbit plane are closely aligned with the ecliptic, and this alignment facilitates departures and arrivals at SDRO, the Moon, and Earth. Although the orbit of Deimos about Mars is nearly in the martian equatorial plane, that plane is inclined to the ecliptic by 26.7°. It is therefore no surprise that Transit 3 approaches Mars in a trajectory plane inclined 30.0° to the martian equator and requires considerably more  $\Delta v$  at MOI and at Deimos rendezvous than does Transit 1, whose arrival inclination is 23.3° to the martian equator (see Tables 1 and 3 to compare  $\Delta v$  values in Transits 1 and 3, respectively).

## **IV.** Aquarius Transit Departure Mass Baseline and Assessments

At any point in time during a transit, *Aquarius* total mass is obtained from the following summation.

$$m_{TOT} = m_A + m_C + m_{DAC} + m_H + m_{LS} + m_{NTP} + m_P + m_{RCS} + m_S + m_T$$
(1)

Of these component masses, only  $m_{LS}$  and  $m_P$  are to be modeled as dynamic quantities during a transit ( $m_{RCS}$  would be dynamic in real world transits but is conservatively held at its transit departure value in lieu of an attitude timeline per A06). This section first develops a transit departure baseline for *Aquarius* total mass under A22 assumptions. Per A23, this baseline will apply to departure on any interplanetary transit. The baseline is then assessed against each of the transits documented in Section III to verify adequate NTP propellant, radiation shielding, and ECLSS consumables margins. Note that mass values reported in this section are rounded to the nearest kg from extended precision computations.

Buildup of the *Aquarius* departure mass baseline begins by computing  $m_{LS}'$ . Per A13, this quantity depends on  $\Delta t'$ , and a survey of captions for Tables 1-3 shows  $\Delta t' = 241$  days during Transit 3. Thus,  $m_{LS}' = 1.05 * 241 * 98.61 = 24,953$  kg.

Although the  $m_{LS'}$  value will be decremented with transit time *T* during an assessment, it will be held constant as a simplifying and conservative approximation when used in the rocket equation to obtain  $m_P$  and  $m_S$  at departure. This approximation leads to the definition of static *Aquarius* mass for use in the rocket equation.

$$m_Z = m_A + m_C + m_{DAC} + m_H + m_{LS}' + m_{NTP}$$
(2)

Therefore,  $m_Z = 9820$  (per A14) + 1700 (per A18) + 26,461 (per A17) + 36,457 (per A11) + 24,953 (per A13) + 41,700 (per A05) = 141,091 kg.

Another survey of captions for Tables 1-3 shows  $\Delta v' = 4.437$  km/s during Transit 3 and  $\Delta v_D' = 2.205$  km/s during Transit 2. The rocket equation for all of Transit 3 is then expressed as

Daniel R. Adamo & James S. Logan

21 March 2014

follows, substituting  $m_{RCS} = c_{RCS} (m_P + m_S)$  per A06 and  $m_T = c_T (m_P + m_S)$  per A07. In the natural exponent (exp) argument, note  $\Delta v'$  has been amplified by 5% per A22.

$$m_{Z} + m_{P} + c_{RCS} (m_{P} + m_{S}) + m_{S} + c_{T} (m_{P} + m_{S}) = [m_{Z} + c_{RCS} (m_{P} + m_{S}) + m_{S} + c_{T} (m_{P} + m_{S})] \exp\{1.05 \Delta v' / v_{X}\}$$
(3)

The rocket equation for Transit 2's Deimos/Mars departure is expressed in a manner similar to that for Transit 3, where the  $m_J$  constraint is valued per A12.

$$m_Z + m_P + c_{RCS} (m_P + m_S) + m_S + c_T (m_P + m_S) = [m_Z + c_{RCS} (m_P + m_S) + m_J + c_T (m_P + m_S)] \exp\{1.05 \Delta v_D' / v_X\}$$
(4)

Exponential factors in Equations 3 and 4 are abbreviated as  $A = \exp\{1.05 \Delta v' / v_X\}$  and  $B = \exp\{1.05 \Delta v_D' / v_X\}$ , respectively. This notation is used in the following expressions for  $m_P$  and  $m_S$  resulting from simultaneous solution of Equations 3 and 4.

$$m_{P} = \frac{(1 - A) B (m_{Z} + m_{J} \{c_{RCS} + c_{T} + 1\})}{A (\{c_{RCS} + c_{T}\} \{B - 1\} - 1)}$$
(5)

$$m_{S} = \frac{A\left(m_{Z} + m_{J}\left\{c_{RCS} + c_{T}\right\}B\right) - B\left(m_{Z} + m_{J}\left\{c_{RCS} + c_{T} + 1\right\}\right)}{A\left(\left\{c_{RCS} + c_{T}\right\}\left\{B - 1\right\} - 1\right)}$$
(6)

With this simultaneous solution, the transit departure baseline for *Aquarius* total mass can be computed per A22. Table 4 provides the mass for each Equation 1 component of this baseline.

Table 4. The Aquarius departure mass baseline is summarized with values for each component of Equation 1, ending with the components' sum,  $m_{TOT}$ .

Component	Reference	Mass (kg)
$m_A$	A14	9820
$m_C$	A18	1700
$m_{DAC}$	A17	26,461
$m_H$	A11	36,457
$m_{LS}$	A13, Transit 3 $\Delta t' = 241$ days	24,953
$m_{NTP}$	A05	41,700
$m_P$	Equation 5, Transit 3 $\Delta v' = 4.437$ km/s	146,343
$m_{RCS}$	A06	13,903
$m_S$	Equation 6, Transit 2 $\Delta v_D' = 2.205$ km/s	23,042
$m_T$	A07	32,440
$m_{TOT}$	Equation 1	356,819

Per A13,  $m_{LS}$  is 3 \* 29.26 / 98.61 = 89.017% water by mass. Using Table 4 values, *Aquarius* is therefore (0.89017  $m_{LS} + m_P + m_S$ ) /  $m_{TOT} = 53.7\%$  water by mass at an interplanetary departure. She is truly The Water-Bearer.

Per B04 and Table 4's value for  $m_{TOT}$ , 356,819 / 50,000 = 7.14 launches are required to assemble *Aquarius* in EEPO and supply her there for a maiden transit to Deimos. Except for  $m_P$ , which will require nearly 3 launches for delivery, no single Table 4 *Aquarius* mass component exceeds the deliverable payload capacity of 50,000 kg per launch. A smaller crew ferry launch

Daniel R. Adamo & James S. Logan

vehicle with considerably less than 130 t IMLEO performance could supply the fractional payload mass requiring an eighth launch. In this manner, the crew, their gear, and sundry personal items would presumably be the final delivery to *Aquarius* in EEPO.

Tables 5-7 summarize depletion of the Table 4 departure baseline during Transits 1-3, respectively. These baseline assessments indicate margins per A03, A13, A22, and A23 are adequate during each of the transits documented in Section III.

Table 5. Depletion of the Table 4 departure baseline is assessed for Transit 1. Values in the rightmost three columns are masses immediately after the corresponding events in the leftmost column. Radiation shielding in the Hab is at least RP5 when the rightmost column is positive.

Event	T (days)	∆v (km/s)	m <sub>LS</sub> (kg)	$m_P$ (kg)	m <sub>TOT</sub> (kg)	$m_P + m_S$ - $m_J$ (kg)
Perigee Lowering	0	0.242	24,953	136,692	347,168	+72,680
TMI	1	1.116	24,855	95,468	305,846	+31,456
MOI	204	1.586	4837	48,456	238,816	-15,555
Deimos Rendz.	204	0.751	4837	28,976	219,336	-35,036

Table 6. Depletion of the Table 4 departure baseline is assessed for Transit 2. Values in the rightmost three columns are masses immediately after the corresponding events in the leftmost column. Radiation shielding in the Hab is at least RP5 when the rightmost column is positive.

Event	T (days)	<i>∆v</i> (km/s)	m <sub>LS</sub> (kg)	$m_P$ (kg)	m <sub>TOT</sub> (kg)	$m_P + m_S$ - $m_J$ (kg)
Deimos Sep.	0	0.652	24,953	120,934	331,410	+56,922
TEI	0	1.553	24,953	67,462	277,938	+3450
TLI	237	0.935	1583	41,873	228,978	-22,138
LOI	240	0.378	1287	32,286	219,095	-31,726
SDRO Rendz.	240	0.309	1287	24,748	211,558	-39,264

Table 7. Depletion of the Table 4 departure baseline is assessed for Transit 3. Values in the rightmost three columns are masses immediately after the corresponding events in the leftmost column. Radiation shielding in the Hab is at least RP5 when the rightmost column is positive.

Event	T (days)	∆v (km/s)	m <sub>LS</sub> (kg)	$m_P$ (kg)	m <sub>TOT</sub> (kg)	$m_P + m_S$ - $m_J$ (kg)
TEIa	0	0.109	24,953	141,963	352,439	+77,952
TEIb	2	0.208	24,756	133,759	344,038	+69,748
TEIc	3	0.488	24,657	115,258	325,439	+51,247
TMI	6	0.891	24,362	84,037	293,922	+20,026
MOI	241	1.940	1188	30,612	217,323	-33,400
Deimos Rendz.	241	0.801	1188	11,757	198,468	-52,254

Of all the NTP burns documented in Tables 5-7 during planetary departure, Transit 2's TEI has the largest  $\Delta v$ , consuming 120,934 - 67,462 = 53,472 kg according to the  $m_P$  column in Table 6. Because  $m_{TOT}$  is nearly at its fully loaded value immediately before TEI, this burn is near the greatest duration *Aquarius* is likely to encounter during nominal short-way transits between

Earth and Mars. Effective water flow rate during an NTP burn is  $F / v_X = 333,617 / 8826 = 37.8$  kg/s (per A05<sup>†††</sup>). The TEI burn is therefore 53,472 / 37.8 = 1415 s = 23.6 min in duration.

Table 7 shows the slimmest margin with respect to  $m_{LS}$  for Transits 1-3 to be +1188 kg, as expected. The consumption rate required to bring  $m_{LS}$  to zero at the end of Transit 3 would be  $m_{LS}' / \Delta t = 24,953 / 241 = 103.54$  kg/day. With respect to A13's assumed consumption rate, the zero margin rate is greater by a factor of 103.54 / 96.61 = 1.05 per A13.

Table 7 also shows the slimmest  $m_P$  margin for Transits 1-3 at arrival to be +11,757 kg, as expected. Total *Aquarius* propulsive capability at this point is obtained by solving Equation 7 for  $\Delta v$ .

$$m_{TOT} = (m_{TOT} - m_P) \exp(\Delta v / v_X) \tag{7}$$

Substituting  $m_{TOT} = 198,468$  kg, and  $m_P = 11,757$  kg from Table 7, together and  $v_X = 8.826$  km/s per A05, the desired Equation 7 solution is  $\Delta v = 0.539$  km/s. Normalizing this surplus to the  $\Delta v$  actually expended during Transit 3 produces a margin of +0.539 / 4.437 = +12.1%, well in excess of the 5% per A22. Excess  $m_P$  margin in the Transit 3 worst case arises from conservative assumptions used to solve Equations 3 and 4. If assessment of Transit 3 did not deplete  $m_{LS}$  in accord with Equations 3 and 4 assumptions, Table 7's final  $m_P$  value would be reduced to 5358 kg, Equation 7 would produce  $\Delta v = 0.222$  km/s, and the normalized  $m_P$  margin would be 5.0%.

As expected, Table 6 indicates Transit 2 has the slimmest margin with respect to RP5 radiation shielding for Transits 1-3 after  $\Delta v_D$  is expended. Post-TEI, the water mass shielding margin is but +3450 kg above  $m_J = 87,053$  kg. But the margin is +3450 / 87,053 = +4.0% in this worst case. Shielding to better than RP5 is therefore provided until Transit 2 arrives at Earth per A03.

# V. Aquarius Abort Capability Example

As an example of *Aquarius* contingency operations, suppose an abort targeting Earth return is necessary following Transit 3 TMI. Assuming full NTP functionality post-abort, Table 7 indicates  $m_P = 84,037$  kg of usable water propellant is available post-TMI in Transit 3. In a contingency, dedicated water shielding mass  $m_S = 23,042$  kg from Table 4 would presumably be added to produce an abort propellant mass budget  $m_B = m_P + m_S = 107,079$  kg. Ignoring depletion of  $m_{LS}$  after TMI as a simplifying and conservative assumption, the rocket equation governing abort follows.

$$m_{TOT} = (m_{TOT} - m_B) \exp(\Delta v / v_X)$$
(8)

With  $m_{TOT} = 293,922$  kg from Table 7, and  $v_X = 8.826$  km/s per A05, Equation 8 can be solved for  $\Delta v$  to produce a Transit 3 post-TMI *Aquarius* abort capability of 3.999 km/s.

The abort trajectory profile utilizes two NTP burns. The first burn has change-in-velocity magnitude  $\Delta v_R$  and reverses nominal motion away from Earth to initiate return. Per B03,  $\Delta v_R$  targets an Earth flyby with perigee height of +7700 km. When *Aquarius* reaches this perigee, a second purely retrograde burn with change-in-velocity magnitude  $\Delta v_C$  achieves Earth capture into an EEPO with apogee radius near 400,000 km. Assuming ECLSS systems and consumables have not been severely compromised, an orbit like this will permit the crew to remain aboard

<sup>&</sup>lt;sup>†††</sup> The flow rate computation must use exhaust speed units of m/s in order to be compatible with thrust units of Nt, equivalent to kg-m/s<sup>2</sup>.

*Aquarius* while they await rescue. This or a similar orbit should also support whatever *Aquarius* repair or salvage operations are possible following abort.

Figure 13 represents a matrix of Transit 3 patched conic abort trajectory solutions with the sum  $\Delta v_R + \Delta v_C$  for a particular solution tabulated in each matrix cell. Thus, Cell L33 represents an abort initiated from the nominal Transit 3 trajectory with  $\Delta v_R$  performed on 20 November 2026 and  $\Delta v_C$  performed 14 April 2027. The sum  $\Delta v_R + \Delta v_C$  for Cell L33 is a marginal 3.995 km/s. All Figure 13 cells with  $\Delta v_R + \Delta v_C \leq 3.999$  km/s are colored green, indicating the corresponding abort trajectories are within Aquarius capability post-TMI. Those cells not satisfying this condition are colored red.

$\diamond$	Α	В	С	D	E	F	G	Н		J	K	L	М
1	Earth Return		Aquarius Abort Date										
2	Date	11/10/26	11/11/26	11/12/26	11/13/26	11/14/26	11/15/26	11/16/26	11/17/26	11/18/26	11/19/26	11/20/26	11/21/26
3	11/15/26	6.524	8.574	12.454	21.202	49.911							
4	11/20/26	5.072	5.681	6.506	7.649	9.294	11.783	15.809	22.992	38.141	85.157		
5	11/25/26	4.626	4.946	5.357	5.857	6.481	7.269	8.287	9.631	11.460	14.036	17.834	23.801
6	11/30/26	4.409	4.621	4.876	5.177	5.532	5.951	6.449	7.049	7.778	8.678	9.806	11.246
7	12/5/26	4.276	4.427	4.608	4.816	5.055	5.327	5.639	5.997	6.411	6.892	7.457	8.126
8	12/10/26	4.186	4.300	4.436	4.591	4.766	4.963	5.182	5.428	5.705	6.016	6.369	6.771
9	12/15/26	4.123	4.211	4.317	4.439	4.575	4.725	4.891	5.075	5.277	5.501	5.749	6.025
10	12/20/26	4.077	4.146	4.232	4.330	4.439	4.560	4.692	4.836	4.994	5.166	5.354	5.559
11	12/25/26	4.042	4.097	4.167	4.248	4.339	4.439	4.547	4.665	4.793	4.931	5.081	5.244
12	12/30/26	4.012	4.057	4.115	4.184	4.260	4.345	4.436	4.535	4.642	4.758	4.882	5.015
13	1/4/27	3.987	4.023	4.072	4.130	4.196	4.269	4.347	4.432	4.524	4.622	4.728	4.841
14	1/9/27	3.966	3.995	4.036	4.087	4.144	4.207	4.275	4.350	4.430	4.515	4.607	4.705
15	1/14/27	3.949	3.972	4.007	4.051	4.101	4.157	4.217	4.283	4.354	4.430	4.512	4.598
16	1/19/27	3.935	3.953	3.983	4.021	4.066	4.116	4.170	4.230	4.294	4.363	4.436	4.514
17	1/24/27	3.923	3.937	3.963	3.997	4.037	4.082	4.132	4.186	4.244	4.307	4.375	4.446
18	1/29/27	3.912	3.922	3.944	3.975	4.011	4.052	4.098	4.148	4.202	4.260	4.323	4.390
19	2/3/27	3.902	3.908	3.928	3.955	3.988	4.026	4.068	4.115	4.165	4.220	4.279	4.341
20	2/8/27	3.893	3.897	3.913	3.938	3.968	4.003	4.043	4.086	4.134	4.186	4.241	4.301
21	2/13/27	3.885	3.887	3.901	3.923	3.951	3.984	4.021	4.062	4.108	4.157	4.210	4.267
22	2/18/27	3.878	3.878	3.890	3.910	3.936	3.967	4.002	4.042	4.085	4.132	4.183	4.238
23	2/23/27	3.872	3.869	3.880	3.898	3.922	3.952	3.985	4.023	4.065	4.111	4.160	4.214
24	2/28/27	3.865	3.861	3.870	3.887	3.909	3.937	3.969	4.006	4.046	4.091	4.139	4.191
25	3/5/27	3.859	3.853	3.860	3.875	3.897	3.923	3.954	3.990	4.029	4.073	4.120	4.171
26	3/10/27	3.852	3.845	3.851	3.865	3.885	3.910	3.941	3.975	4.013	4.056	4.102	4.153
27	3/15/27	3.847	3.838	3.842	3.855	3.874	3.898	3.928	3.961	3.999	4.041	4.086	4.136
28	3/20/27	3.841	3.830	3.833	3.845	3.863	3.886	3.915	3.948	3.985	4.026	4.071	4.121
29	3/25/27	3.834	3.822	3.824	3.834	3.851	3.874	3.902	3.934	3.971	4.012	4.057	4.106
30	3/30/27	3.826	3.813	3.813	3.823	3.839	3.861	3.888	3.920	3.956	3.997	4.041	4.090
31	4/4/27	3.817	3.802	3.801	3.810	3.825	3.847	3.873	3.905	3.941	3.982	4.026	4.075
32	4/9/27	3.807	3.790	3.788	3.795	3.810	3.831	3.858	3.889	3.925	3.966	4.011	4.060
33	4/14/27	3.793	3.775	3.771	3.778	3.793	3.814	3.840	3.872	3.908	3.950	3.995	4.044
34	4/19/27	3.775	3.755	3.751	3.757	3.772	3.793	3.821	3.853	3.891	3.933	3.979	4.029
35	4/24/27	3.748	3.727	3.723	3.731	3.747	3.770	3.799	3.834	3.873	3.916	3.964	4.016
36	4/29/27	3.705	3.688	3.688	3.701	3.721	3.748	3.781	3.819	3.861	3.907	3.957	4.010
37	5/4/27	3.664	3.666	3.680	3.701	3.729	3.760	3.796	3.836	3.880	3.927	3.978	4.032
38	5/9/27	108.317	9.867	5.511	4.613	4.295	4.157	4.096	4.074	4.076	4.092	4.120	4.156
39	5/14/27	115.422	115.353	115.215	114.756	110.426	33.958	11.994	7.676	6.129	5.419	5.049	4.845

Figure 13. Total abort  $\Delta v$  in km/s required to depart the nominal Transit 3 post-TMI trajectory and return to an EEPO is tabulated according to depart date (columns) and return date (rows). Row 2 and Column A provide these dates in mm/dd/yy format. Cells colored red require more total abort  $\Delta v$  than is available aboard *Aquarius* after Transit 3 TMI, while green-colored cells are viable abort opportunities. In Figure 13 terminology, Transit 3 TMI occurs on 11/7/26.

Viable abort cases in Figure 13 typically expend less than 5% of the tabulated total  $\Delta v$  when achieving EEPO with  $\Delta v_c$ . The majority of abort  $\Delta v$  is required to reverse motion away from Earth with  $\Delta v_R$  in order to intercept Earth months later. This "slow return" attribute is compounded when the abort date is delayed. In Figure 13, note the earliest viable Earth return date (corresponding to the uppermost green cell in a given column) is typically delayed 10 days for every day the abort date is delayed.

Figure 13 indicates the Transit 3 point of no return is reached on 20 November 2026, about 13 days after TMI. Using Cell L33 as an example abort on this date with the earliest viable Earth

Daniel R. Adamo & James S. Logan

return, the patched conic solution is evolved to a precision trajectory with a pedigree matching those documented in Section III. Results of this evolution are summarized in Table 8.

Table 8. When evolved to a precision Earth return trajectory, the patched conic abort solution corresponding to Figure 13's Cell L33 is shown to be 2.7% pessimistic with respect to the  $\Delta v_R + \Delta v_C \leq 3.999$  km/s post-TMI viable abort capability criterion.

Trajectory	$\Delta v_R  (\mathrm{km/s})$	$\Delta v_C  (\text{km/s})$	$\Delta v_R + \Delta v_C  (\mathrm{km/s})$
Patched Conic	3.842	0.153	3.995
Precision	3.721	0.169	3.890

The precision trajectory's final approach to Earth and capture into an EEPO are plotted in Figure 14. This EEPO is not at all conducive to *Aquarius* reuse because its ecliptic inclination is 85.6°, making access to SDRO-resident infrastructure difficult without major propulsive effort. Inclination with respect to Earth's true equator in the Figure 14 EEPO is 64.6°, and near the minimum possible for this abort case in order to facilitate crew rescue. High inclinations challenging *Aquarius* reuse and her crew's rescue arise because geocentric  $v_{\infty}$  is only 0.6 km/s when *Aquarius* returns to Earth. Although this slow approach technique makes abort possible with available propellant as *Aquarius* nearly matches Earth's heliocentric orbit, it also tends to disproportionally magnify any deviations from this orbit during final Earth approach.

These potential difficulties must be considered before a specific abort case is addressed by returning *Aquarius* to the departure terminus of an interplanetary transit. It may be continuing onward to the destination terminus is a better course of action.

Using the water flow rate of 37.8 kg/s for NTP burns established at the end of Section IV,  $m_B = 107,079$  kg would require 47.2 min to burn in a Transit 3 maximum effort abort. Because the bulk of  $m_B$  is presumably consumed far from a transit terminus to achieve  $\Delta v_R$ , it could be split into multiple segments to remain within NTP duty cycle limits. But splitting the burn would not be an option during time-critical abort scenarios affecting NTP capability, such as a rapid water tank leak.



Earth-Centered J2KE Coordinate System

Figure 14. Geocentric inertial motion of *Aquarius* (blue) and the Moon (red) are plotted as the spacecraft returns to Earth from a Transit 3 abort. The plot plane nearly coincides with the plane of *Aquarius* motion. Time tick labels are in yyyy-mm-dd format at 00:00 UT, and the shaded area is Earth's nightside.

Daniel R. Adamo & James S. Logan

## VI. Additional Work Relating To The Aquarius Proposal

Many of the assumptions cited in Section II are based on educated guesses, extrapolation, or pure speculation. Knowledge gaps relating to more critical functions in the *Aquarius* proposal are briefly discussed in the following paragraphs.

The RP5 specification in A03 reflects a point of diminishing returns documented in Ref. 7 (see Figure 2-15 on p. 42), where proportionally greater  $\rho_A$  beyond 51.5 g/cm<sup>2</sup> is required to further shield a habitable volume. Ref. 7 data reflect a fixed 10 cm layer of water and a progressively thicker layer of aluminum. Diminishing  $\rho_A$  returns are largely due to incident radiation scattering (called spallation) by aluminum. How will spallation change if a 37 cm layer of water overlays Hab structure (presumably aluminum, per A12)? Will RP5 in the context of A01, A02, and B01 be an acceptable specification with respect to evolving interplanetary human spaceflight radiation dose standards?

Although NTP is the primary interplanetary human spaceflight propulsion system in NASA's Ref. 8 baseline, very little progress has been made since 1973 toward that end on technical, political, and diplomatic fronts (Ref. 4, Section 3.1). It should be noted the Ref. 8 NTP system uses liquid hydrogen as propellant to achieve  $I_{SP} = 875-950$  s (Ref. 8, p. 25). Is technical risk of the presumably higher 3000° C nuclear reactor core temperature necessary to "burn" water propellant and achieve this  $I_{SP}$  (per A05) a good trade against the potentially greater difficulties of refining, storing, and transporting liquid hydrogen, particularly in an ISRU context? How will spent fissile material aboard *Aquarius* be disposed of and replaced?

What "gravity prescription" will be used with the DAC's centrifuge per A16 (Ref. 4, Section 12.8)? Will crew time in the centrifuge required by that prescription in turn require radiation shielding from DAC structure be supplemented with a water jacket? Will DAC centrifuge crew conditioning during a return transit to SDRO infrastructure be sufficient to enable an Earth atmospheric entry at 11.0 km/s within 30 days (per B02), or will additional conditioning and loiter time in SDRO be necessary? A plan to develop the gravity prescription for crew readiness to withstand atmospheric entry from cislunar space after ~240 days in microgravity should be a major focus of centrifuge research with subjects confined to bed rest on Earth and aboard the International Space Station after it is equipped with a short-arm centrifuge.

Pre-positioned consumables and habitat in SDRO and at Deimos require masses in excess of 100 t be robotically transported over lunar and interplanetary distances (per B05 and B06). Robotic assembly in both locations and robotic excavation at Deimos will be necessary. Depending on whether or not ISRU is practical at or near these locations, mass transported from the Earth can be replaced by mass transported from the Moon or NEAs. Efforts to survey the Moon and a few NEAs for ISRU-pertinent materials are underway, but these need to be supplemented by surveys of Deimos and Phobos for ISRU material (Ref. 4, Table 13-6, p. 502 advocates such an ISRU survey of Phobos and Deimos as a high priority). Capability to robotically transport ~500 t of NEA material to SDRO is advocated in Ref. 6 via solar electric propulsion. This capability should also be applied to pre-positioning masses required to enable the *Aquarius* proposal.

## VII. Conclusions

From its inception in 1927, trans-Atlantic air transport has been a one-way proposition. Viable roundtrips are possible only because pre-emplaced return consumables are available for transport resupply at the destination. The *Aquarius* interplanetary transport proposed here has the same dependency. Return consumables robotically pre-emplaced on Deimos, or cached on over a *thousand* occasionally more accessible NEAs, drastically reduce *Aquarius* total mass.

Because water is transported and stored over long time intervals in space with relative ease, its role as the primary *Aquarius* consumable poses no special obstacles to pre-emplacement logistics. The abundance of water on the Moon, Deimos, Phobos, and NEAs may virtually eliminate logistics from Earth through a combination of robotic ISRU and NEA material transport.

To serve as propellant at high efficiencies, water must be heated to its 3000° C atomic disassociation temperature, and the system to accomplish this aboard *Aquarius* is assumed to be a nuclear reactor. This efficiency, together with return consumables pre-emplacement, reduces fully resupplied total *Aquarius* mass before an interplanetary departure to 357 t, about 90% of the assembled International Space Station's mass in March 2014.

*Aquarius* uses dedicated water mass and propellant residuals following interplanetary departure to shield much of her onboard habitable volume from radiation. Until interplanetary arrival propellant consumption begins, she provides her crew radiation shielding protection equivalent to at least 5% of that offered by Earth's atmosphere at sea level.

Because a large quantity of water mass must accompany *Aquarius* to shield her crew until an interplanetary arrival, burning that mass upon Earth return to permit her reuse is a logical consequence. Utilizing lunar orbit to garage and resupply *Aquarius* between roundtrips to Deimos has been demonstrated as a viable reuse strategy. Furthermore, flight profiles akin to those documented by this paper may be mandatory for crew survival if direct atmospheric entry poses unacceptable stress risks following an interplanetary roundtrip.

*Aquarius* is assembled in an elliptical Earth orbit with 2-day period and perigee above the inner Van Allen radiation belt. This orbit permits payload delivery about a day after launch and is thus able to capture the total energy deliverable by a cryogenic upper stage with great efficiency because long-term cryogenic storage is avoided. Assuming 130 t IMLEO per launch, *Aquarius* can be assembled and readied for her maiden interplanetary transit with an estimated 7.14 launches. Thanks to her reusability, even complete resupply of propellant and crew consumables amounts to 185 t, 52% of *Aquarius* fully loaded total mass.

An abundance of water aboard *Aquarius* opens up potentially useful abort options. Even following an interplanetary departure with relatively large propellant consumption, a viable return to the departure planet is demonstrated for an abort initiated nearly two weeks after departure.

In 1954, the U.S.S. *Nautilus* was christened as the world's first nuclear-powered submarine. This paper's findings indicate a similar effort is necessary to achieve viable and sustainable interplanetary human transport. Admiral Hyman G. Rickover, who planned and personally supervised *Nautilus* construction, had appropriate advice for development of *Aquarius*. "The Devil is in the details, but so is salvation."

## References

- [1] Orloff, R. W. and Harland, D. M., *Apollo: The Definitive Sourcebook*, Springer-Praxis, Chichester, UK, 2006.
- [2] Hopkins, J. B., "Deimos and Phobos as Destinations for Human Exploration", Lockheed-Martin Corporation, 2013.<sup>‡‡‡</sup>
- [3] Adamo, D. R., "Trajectory Challenges Faced By Reusable Infrastructure In Earth Orbit Supporting Multiple Departures For Mars", *The Space Show Classroom*, 2013.<sup>§§§</sup>
- [4] Drake, B. G. and Watts, K. D. (ed.), *Human Exploration of Mars Design Reference Architecture 5.0*, NASA/SP-2009-566-ADD2, 2014.\*\*\*\*
- [5] Barbee, B. W., "Accessible Near-Earth Asteroids (NEAs)", NASA, 2014.<sup>††††</sup>
- [6] Brophy, J., Culick, F., Friedman, L. (et al), *Asteroid Retrieval Feasibility Study*, Keck Institute for Space Studies, 2012.<sup>‡‡‡‡</sup>
- [7] National Research Council Committee on the Evaluation of Radiation Shielding for Space Exploration, *Managing Space Radiation Risk in the New Era of Space Exploration*, The National Academies Press, 2008.<sup>§§§§§</sup>
- [8] Drake, B. G. (ed.), Human Exploration of Mars Design Reference Architecture 5.0, NASA/SP-2009-566, 2009.\*\*\*\*
- [9] NASA/Boeing, "U.S. Laboratory Module (Destiny)", *International Space Station (ISS) Interactive Reference Guide*, Release 2.4, NASA, 2010.<sup>†††††</sup>
- [10] NASA, Volume I Man-Systems Integration Standards, Revision B, NASA-STD-3000, NASA, 1995.<sup>‡‡‡‡‡</sup>
- [11] Akin, D. L., "Introduction to Space Life Support", University of Maryland, 2011. \$\$\$
- [12] NASA/Boeing, "U.S./Joint Airlock (Quest)", International Space Station (ISS) Interactive Reference Guide, Release 2.4, NASA, 2010.\*\*\*\*\*
- [13] British Antarctic Survey, "Mind The Gap: Space Scientists Uncover Causes Of Gap In Van Allen Belts", *Science Daily*, 2006.<sup>††††††</sup>

tttp://www.lpi.usra.edu/sbag/science/NHATS\_Accessible\_NEAs\_Summary.png (accessed 23 February 2014).

<sup>\*\*\*\*‡</sup> This document may be downloaded from http://kiss.caltech.edu/study/asteroid/asteroid\_final\_report.pdf (accessed 20 March 2014).

\$\$\$\$\$Thisdocumentmaybedownloadedfromhttp://spacecraft.ssl.umd.edu/academics/697S11/697S11L12.lifesupport.pdf.

<sup>&</sup>lt;sup>‡‡‡</sup> This document may be downloaded from http://www.csc.caltech.edu/talks/hopkins.pdf (accessed 23 February 2014).

 <sup>\*\*\*\*</sup> This
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 may
 be
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 from

 http://spaceshowclassroom.files.wordpress.com/2013/11/multiplemarsdeparturesr1.pdf (accessed 23 February 2014).
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 This document may be downloaded from http://www.nasa.gov/sites/default/files/files/NASA-SP-2009-566-ADD2.pdf (accessed 22 March 2014).

<sup>&</sup>lt;sup>§§§§§</sup> This document may be downloaded from http://www.nap.edu/catalog.php?record\_id=12045 (accessed 24 February 2014).

<sup>\*\*\*\*\*</sup> This document may be downloaded from http://www.nasa.gov/exploration/library/esmd\_documents.html (accessed 25 February 2014).

<sup>&</sup>lt;sup>†††††</sup> This document may be downloaded from http://www.nasa.gov/externalflash/ISSRG/pdfs/destiny.pdf (accessed 25 February 2014).

<sup>&</sup>lt;sup>11111</sup> This document may be downloaded from http://msis.jsc.nasa.gov/ (accessed 26 February 2014).

This document may be downloaded from http://www.nasa.gov/externalflash/ISSRG/pdfs/quest.pdf (accessed 27 February 2014).

<sup>&</sup>lt;sup>††††††</sup> This document may be downloaded from http://www.sciencedaily.com/releases/2006/09/060926171157.htm (accessed 27 February 2014).

- [14] Adamo, D. R., "A Precision Orbit Predictor Optimized for Complex Trajectory Operations", AAS 03-665, *Volume 116 of the Advances in the Astronautical Sciences*, Univelt, San Diego, pp. 2567-2586, 2003.
- [15] Meeus, J., Astronomical Algorithms, Willman-Bell, Inc., 1991
- [16] Giorgini, J. D., Yeomans, D. K., Chamberlin, A. B., Chodas, P. W., Jacobson, R. A., Keesey, M. S., Lieske, J. H., Ostro, S. J., Standish, E. M., Wimberly, R. N., "JPL's On-Line Solar System Data Service", *Bulletin of the American Astronomical Society*, Vol. 28, No. 3, p. 1158, 1996.<sup>######</sup>

<sup>&</sup>lt;sup>‡‡‡‡‡‡</sup> This service is available at http://ssd.jpl.nasa.gov/?horizons (accessed 10 March 2014).