Strategies for Continuous Mars Habitation with a Limited Number of Cycler Vehicles

Damon Landau
James M. Longuski

October 2005

Prepared for

Dr. Buzz Aldrin
Starcraft Enterprises

By

Purdue University
School of Aeronautics and Astronautics
West Lafayette, IN 47907-2023

Introduction

The appeal of traveling to Mars in a safe, comfortable, and (consequently) massive interplanetary transfer vehicle has produced much interest in cycler and semi-cycler trajectories. These trajectories replace propulsive maneuvers at Earth, Mars, or both with gravity assists, thereby transferring the ΔV requirements of the transfer vehicle to a smaller taxi vehicle. Thus as the ratio of transfer vehicle to taxi mass increases, cyclers and semi-cyclers could become less expensive than traditional missions (i.e. architectures without gravity assists).

Assuming that the crew transits between Earth and Mars are short (at most one year) and that Mars is to be continuously inhabited, significant trades develop between the number of transfer vehicles, the duration the crew is away from Earth, and the trajectory ΔV requirements. While the trade space of cycler or semi-cycler missions has been examined in some detail,[1–12] the combination of cyclers with semi-cyclers (e.g. cycler out and semi-cycler in) has received comparatively little attention. To initiate a detailed analysis of cycler/semi-cycler architectures, three scenarios are presented: 1) one outbound cycler vehicle with one inbound cycler, 2) two outbound cyclers with one inbound cycler, and 3) a single semi-cycler vehicle.

Modeling Assumptions

All of the trajectories in this report are calculated in a circular coplanar model of the solar system. While cyclers and semi-cyclers have been propagated in a more accurate model,[9,11,12] a circular coplanar analysis provides average results. All gravity assists are modeled as instantaneous rotations of the $\mathbf{V}_\infty$ vector, and the minimum flyby altitude is 300 km above the planet's surface. Single-vehicle semi-cyclers are constrained to have a total time of flight (TOF) of less than one synodic period (780 days). The ΔV is minimized in all cases.

One outbound vehicle and one inbound vehicle

The outbound (Earth-Mars) transfer is achieved by the one-synodic period cycler shown in Fig. 1 (the Aldrin cycler).[4] Because this cycler repeats every synodic period, only one outbound vehicle is required. This cycler is based on a 2:1 Earth:spacecraft resonant transfer that is extended from 2 years to 2.14 years TOF. (This cycler orbit retains the two-year period of the 2:1 resonant trajectory.) A deep space maneuver (DSM) of 0.11 km/s near apoapsis is required each synodic period to maintain the Aldrin cycler trajectory. We note that increasing this DSM to 0.92 km/s would lower the Mars V_∞ to 6.9 km/s and lower the Earth V_∞ to 5.1 km/s.

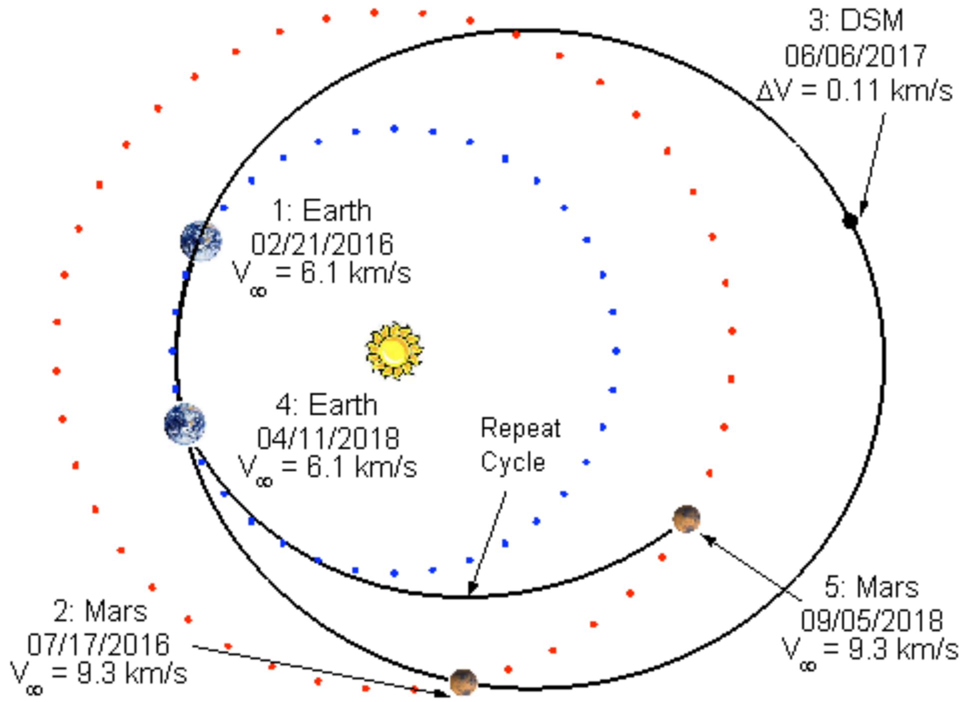

Fig. 1 Outbound Aldrin cycler with transit TOF of 147 days.

There is an inbound version of the Aldrin cycler, but the departure V_∞ at Mars is relatively large (i.e. 9.3 km/s in Fig. 1), which leads to prohibitive taxi masses. One solution (to reduce taxi mass) is to replace the inbound cycler with a Mars-Earth semi-cycler, which departs Mars, flies by Earth, then returns to Mars. There is potential for the V_∞ to decrease significantly because the Mars encounters are no longer constrained to be flybys and the TOF is no longer constrained to one synodic period. In order to minimize the number of vehicles, the semi-cycler TOF should be less than 780 days (26 months) so the same inbound vehicle can be used every opportunity. (We note that semi-cyclers with TOF longer than 780 days exist, but require more vehicles and less ΔV.)

A trajectory that has the same period as Mars (687 days) and a periapsis equal to Earth's orbit provides a good initial guess for a Mars-Earth semi-cycler. Because the spacecraft and Mars share the same orbital period, the spacecraft will encounter Mars after one revolution as long as Earth does not perturb the orbit. However, judicious use of Earth's gravity will lower the ΔV required from the spacecraft. The total ΔV for this trajectory comprises the departure maneuver from Mars orbit, any DSMs, and the arrival maneuver into a parking orbit for reuse. The optimized trajectory is presented in Fig. 2, where the Earth flyby altitude is 300 km and the total TOF is 780 days. We note that if aerocapture is available, the DSM can be removed with an increase in arrival V_∞ to 7.9 km/s.

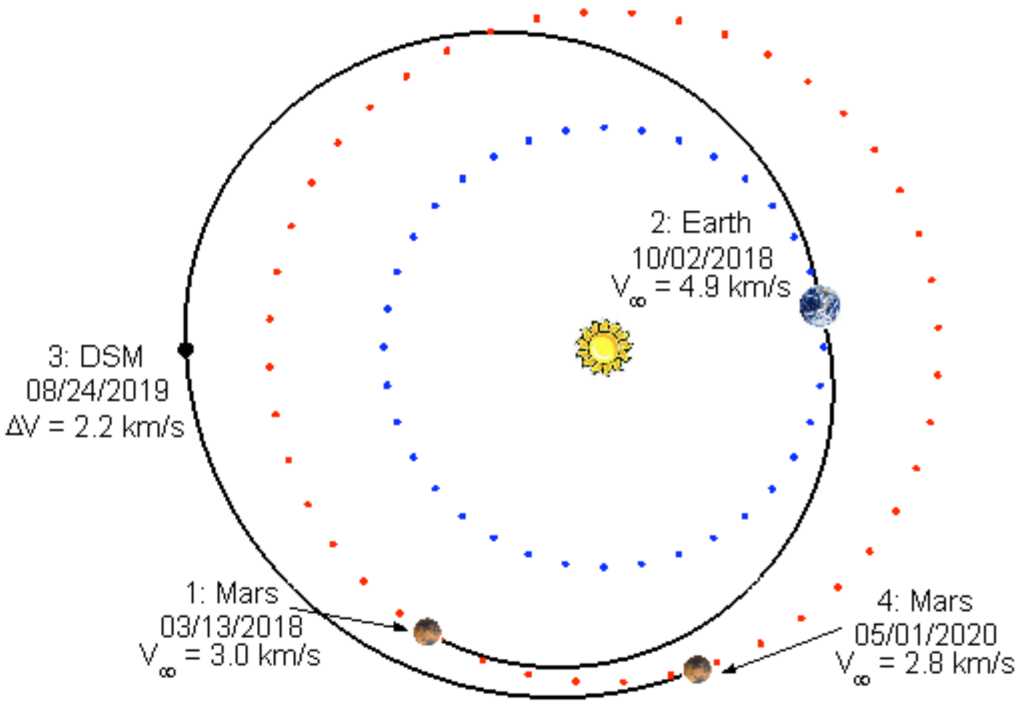

Fig. 2 Inbound Mars-Earth semi-cycler with transit TOF of 203 days.

Because the TOF is one synodic period and the Mars-arrival and departure V_∞ are similar in Fig. 2, this semi-cycler can be molded into a cycler trajectory. The resulting cycler is presented in Fig. 3, where the ΔV includes the cycler DSM and the taxi departure maneuver at Mars. This one-synodic-period cycler is fundamentally different than the Aldrin cycler as it is based on a 1:1 resonance with Mars while the Aldrin cycler is based on a 2:1 resonance with Earth. In fact, the local minimum of the DSM ΔV for the cycler in Fig. 3 is 1.5 km/s while the local minimum for the Aldrin cycler is 0.11 km/s. Because the taxi V_∞ in Fig. 3 is acceptable and the ΔV for the cycler is less than that of the semi-cycler, we suggest using this new cycler for the inbound crew transfers.

The mission timeline is provided with the radial distance plot in Fig. 4. The crew departs Earth on February 21, 2016 and arrives at Mars 147 days later. Because Mars is to be continuously inhabited, the crew skips the return opportunity on April 19, 2018 and stays on Mars an extra 780 days until June 7, 2020, when they board the inbound cycler for a 173 day trip to Earth. The total mission duration (for the crew) is 4.8 years (58 months) with 3.9 years (47 months) on Mars.

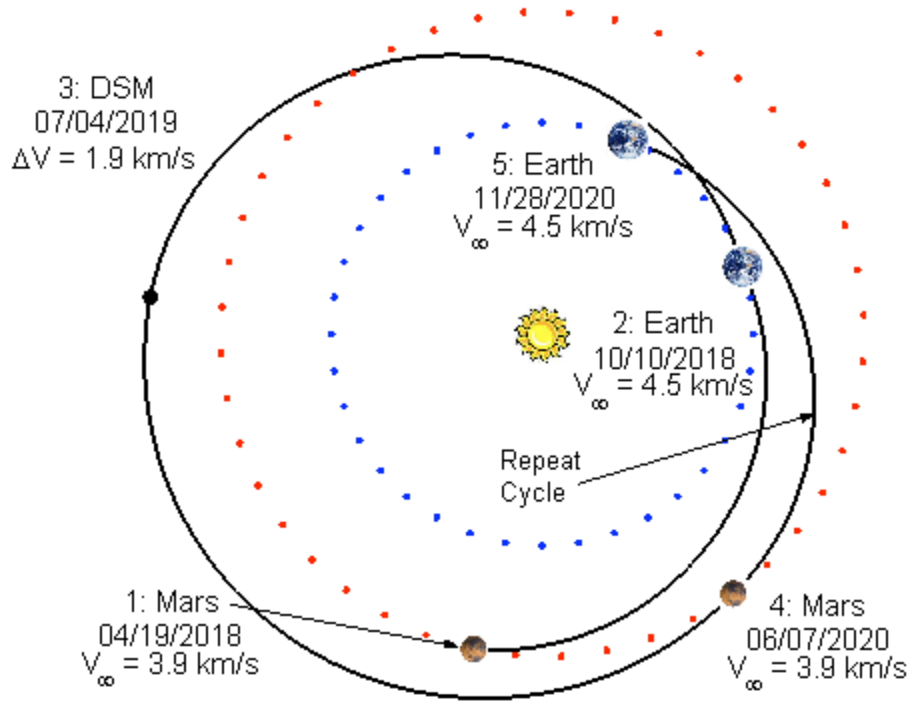

Fig. 3 New inbound cycler trajectory with transit TOF of 173 days and one-synodic period repeat time.

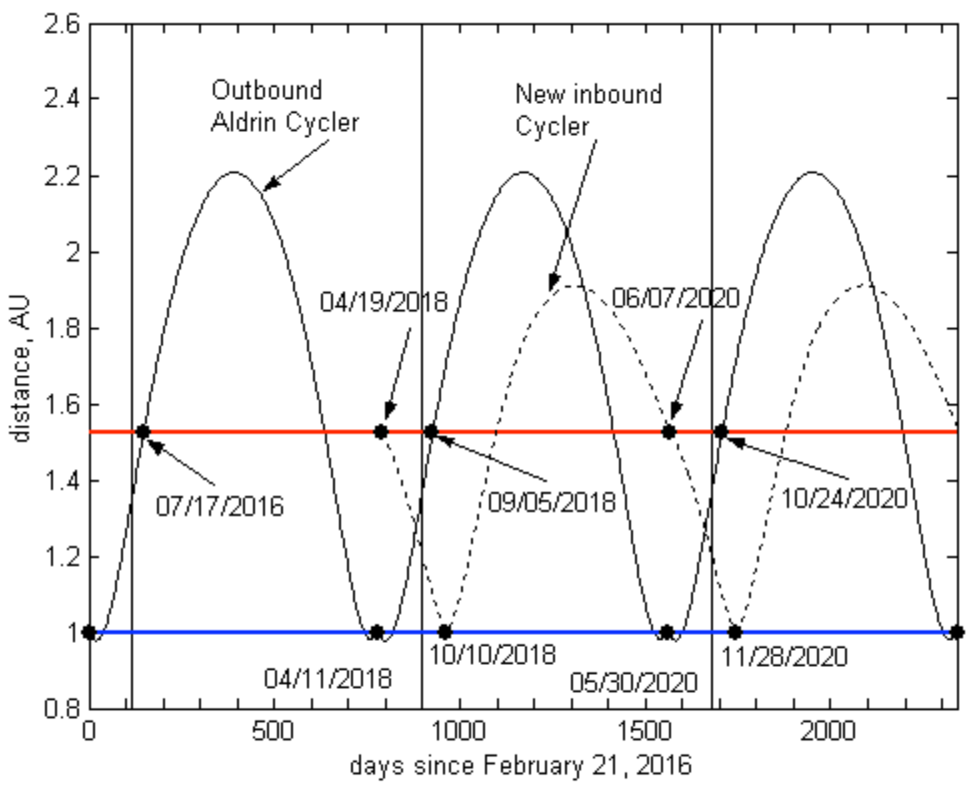

Fig. 4 Radial distances of outbound and inbound cyclers. Closed circles denote planetary encounters and the vertical lines denote dates of opposition.

Two outbound vehicles and one inbound vehicle

The scenario with two outbound cyclers is similar to the single cycler case, except the repeat time on the cycler trajectory is two synodic periods, requiring an extra transfer vehicle to complete an Earth-Mars transfer during every opportunity. This two-synodic period cycler is based on a 3:2 Earth:spacecraft resonant trajectory (1.5 year period) followed by a near 1.5 year Earth-Earth transfer (as in Fig. 5). The trajectory shifts between the 3:2 and 1.5:1.5 resonances via Earth gravity assists. This sequence requires zero deterministic ΔV (even in the more accurate elliptical-inclined solar system as shown in Ref. 9) and is thus a ballistic cycler. (We note that a ballistic inbound version of this cycler exists, but the Mars departure V_∞ reach approximately 8 km/s every 15 years.)

The return (Mars-Earth) crew transfer is achieved by the single inbound cycler vehicle (Fig. 3). The mission sequence is therefore 150 days to Mars, 1,366 days (45 months) on Mars, then 173 days back to Earth. The total trip time is 4.6 years with 3.7 years on Mars. This sequence is provided in more detail in Fig. 6.

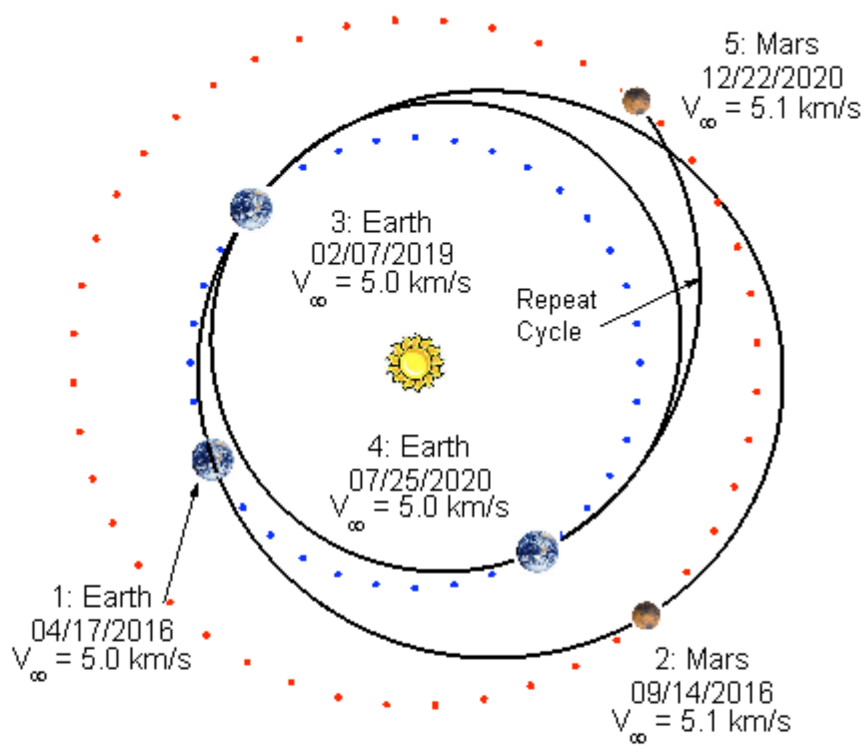

Fig. 5 Outbound cycler trajectory with two-synodic period repeat time.

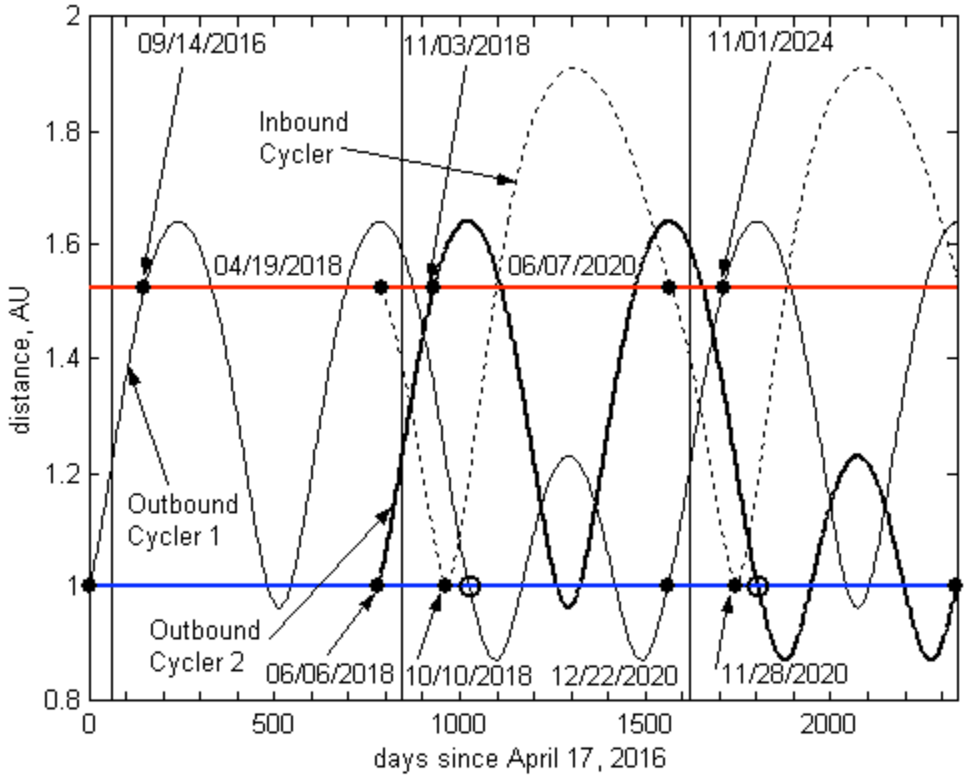

Fig. 6 Radial distances for two outbound cyclers and one inbound cycler. Closed circles denote arrival or departure flybys, open circles denote gravity assists, and vertical lines denote dates of opposition.

One outbound and inbound vehicle

We note that in Fig. 4 and Fig. 6, the outbound vehicle arrives at Mars a few months after opposition, while the inbound vehicle departs Mars a few months before opposition. As a result, the population on Mars is lower for several months each synodic period between the times that one crew departs and another one arrives. A possible solution is to “squeeze” the Mars departure and arrival dates together so that the new crew arrives shortly before the previous crew departs. In this scenario, only one vehicle is required because the outbound and inbound transits may be performed by the same vehicle. Moreover, if the Mars arrival and departure occur on the same day, there is a possibility to replace the parking orbit at Mars with a gravity assist that sends the transfer vehicle back to Earth. Such trajectories that depart Earth, flyby Mars, then arrive back at Earth are called Earth-Mars semi-cyclers, as opposed to Mars-Earth semi-cyclers, which have a Mars-Earth-Mars sequence.

The trajectory in Fig. 7 and Fig. 8 begins at Earth (say in a parking orbit) takes 356 days to reach Mars, then returns to Earth 356 days after a Mars flyby. Because the total TOF is less than one synodic period, a single transfer vehicle may be reused to provide trips to Mars every synodic opportunity. From Fig. 7 we see that this trajectory is reminiscent of a bi-elliptic transfer, where the vehicle follows a Hohmann transfer to a perihelion of about 0.8 AU, then a DSM pushes the aphelion to just above the orbit of Mars. A Mars gravity-assist rotates the line of apsides of this second ellipse, and the transfer vehicle again drops to a perihelion of 0.8 AU before a second DSM lowers aphelion back to 1 AU. This trajectory was optimized to minimize the sum of the departure maneuver at Earth, any DSMs, and the injection maneuver into a parking orbit. The Mars flyby occurs at an altitude of 1,040 km.

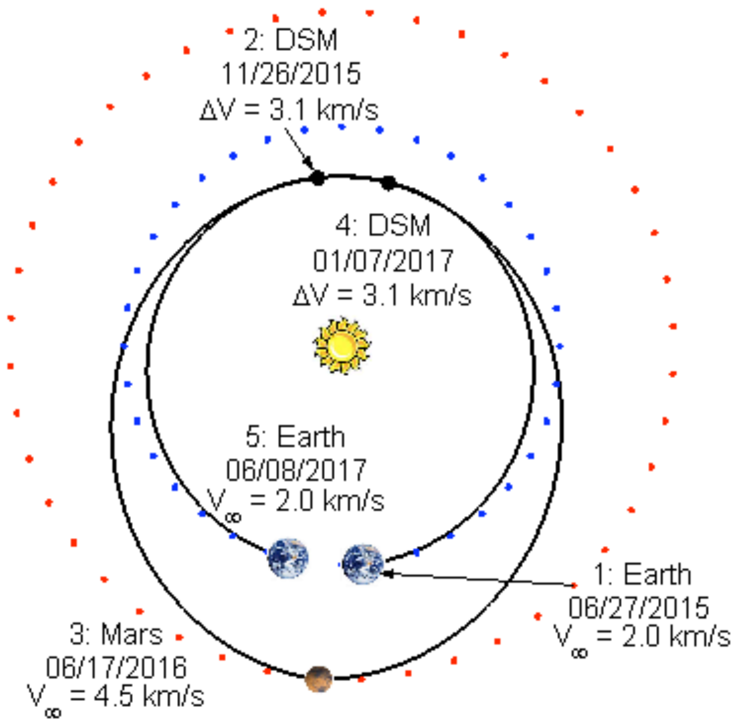

Fig. 7 Earth-Mars semi-cycler trajectory with one-synodic-period repeat time and 356-day transits between Earth and Mars.

From Fig. 8 we note the Mars arrival and departure date occurs at opposition. The crew sequence begins on June 27, 2016 with a 356-day transfer to Mars. The crew remains on Mars for 780 days from June 7, 2016 until August 6, 2018. Then the crew departs Mars for another 356-day transfer to arrive at Earth on July 28, 2019. Here the total duration is 4.1 years with 2.1 years on Mars. We note that the transfer TOF can be reduced from 356 days to 300 days with an additional 0.3 km/s of ΔV, or reduced from 356 days to 265 days for an extra 1.5 km/s ΔV. This trade in transfer TOF reduces the total mission duration, but the Mars stay time remains constant at 2.1 years.

On the other hand, the transfer TOF could be extended to 390 days, which would place the trajectory flight time at 780 days, or one synodic period. If the Earth departure and arrival maneuvers are replaced with gravity assists, then the semi-cycler becomes a cycler with 390-day Earth-Mars transits. Though this transit TOF is relatively long, only one cycler vehicle is required. Comparatively, if only one vehicle travels along the trajectory in Fig. 1 or Fig. 3, then either the inbound or outbound TOF would exceed 600 days. We do not investigate this cycler further in this report because the transfer times exceed one year and the ΔV is much greater than the DSMs of the other cyclers.

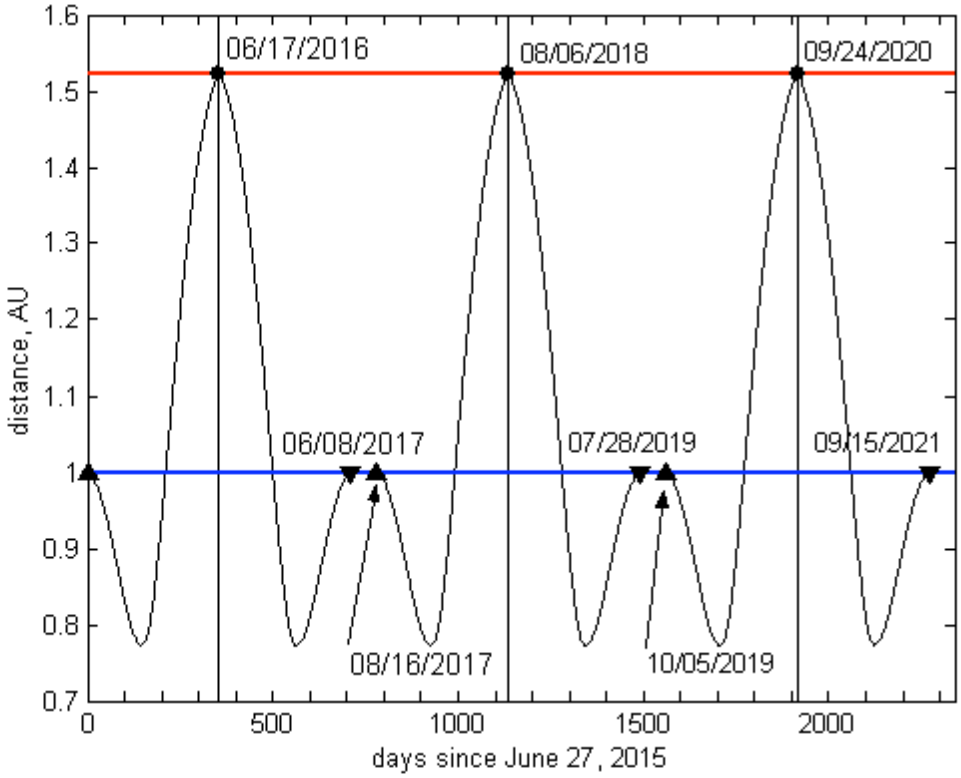

Fig. 8 Radial distance plot of the Earth-Mars semi-cycler in Fig. 7. ▲ denotes departure, ▼ denotes arrival, and ● denotes flyby. Vertical lines are dates of opposition.

Discussion

For a preliminary comparison of these three scenarios we examine the ΔV, flight time, and number of vehicles required by each. The one outbound vehicle with one inbound vehicle scenario only requires two transfer vehicles and is very similar to the Aldrin cycler. By starting with a different inbound "seed" trajectory, the undesirable launch V_∞ of 9.3 km/s with the inbound Aldrin cycler is reduced to 3.9 km/s with an extra 1.8 km/s of DSM ΔV required from the transfer vehicle each synodic period. While the DSM for the inbound cycler is relatively large, the ΔV is still less than that of Mars-Earth semi-cyclers. For the inbound cycler one complex (i.e. not "off the shelf") transfer vehicle and one complex propulsion system must be developed and maintained. (We postulate that building and maintaining the propulsion systems could be just as expensive as the transfer vehicles.) Because the outbound cycler requires periodic adjustments (DSMs) to maintain its orbit and perhaps to mollify the extreme taxi entry speeds, a complex propulsion system is required for the outbound transfer vehicle part of the time (perhaps three missions out of a seven mission cycle). Thus, the one outbound and one inbound vehicle scenario requires two reusable transfer vehicles and at least one, but probably two, reusable propulsion systems.

Another option is to replace the outbound transfer vehicle and propulsion system with two transfer vehicles and no (complex) propulsion systems. (An off-the-shelf system would perform small flyby targeting maneuvers.) The inbound transit is achieved by the inbound cycler in Fig. 3. In this scenario, three reusable transfer vehicles and one reusable propulsion system are required. The mission timeline is very close to that of the one outbound and one inbound vehicle scenario, so there is little difference in the time that the crew is away from Earth. The ΔV required from the transfer vehicles is less with two outbound cyclers than with only one, and the mass requirements of the taxis (e.g. upper stage and heatshield) are much less.

The single inbound and outbound vehicle concept is a stark shift from the other two cycling scenarios. The key benefit is that only one transfer vehicle and propulsion system must be built and maintained. Also, the total time a crew is away from Earth is only 3.6 to 4.1 years compared to 4.6 to 4.8 years with the cyclers. However, in this scenario the ΔV far exceeds that of the cycler trajectories. The reduction in number of vehicles and mission duration must be balanced against the additional ΔV (with larger propulsion systems and more propellant mass) necessary to transport a crew to Mars and back each synodic opportunity.

References

[1]Rall, C. S., and Hollister, W. M., "Free-Fall Periodic Orbits Connecting Earth and Mars," AIAA Paper 71-92, Jan. 1971.

[2]Aldrin, E. E., "Cyclic Trajectory Concepts," SAIC presentation to the Interplanetary Rapid Transit Study Meeting, Jet Propulsion Laboratory, Oct. 1985.

[3]Friedlander, A. L., Niehoff, J. C., Byrnes, D. V., and Longuski, J. M., "Circulating Transportation Orbits between Earth and Mars," AIAA Paper 86-2009, Aug. 1986.

[4]Byrnes, D. V, Longuski J. M, and Aldrin B., "Cycler Orbit Between Earth and Mars," *Journal of Spacecraft and Rockets*, Vol. 30. No. 3, May–June 1993, pp. 334–336.

[5]Bishop, R. H., Byrnes, D. V., Newman, D. J., Carr, C. E., and Aldrin, B., "Earth-Mars Transportation Opportunities: Promising Options for Interplanetary Transportation," The Richard H. Battin Astrodynamics Conference, AAS Paper 00-255, College Station, TX, March 20–21, 2000.

[6]Aldrin, B., Byrnes, D. V., Jones, R., and Davis, H., "Evolutionary Space Transportation Plan for Mars Cycling Concepts," AIAA Space 2001 Conference and Exhibition, AIAA Paper 2001-4677, Albuquerque, NM, Aug. 28–30, 2001.

[7]Chen, K. J., McConaghy, T. T., Okutsu, M., and Longuski, J. M., "A Low-Thrust Version of the Aldrin Cycler," AIAA/AAS Astrodynamics Specialist Conference, AIAA Paper 2002-4421, Monterey, CA, Aug. 5–8, 2002.

[8]Chen, K. J., Landau, D. F., McConaghy, T. T., Okutsu, M., Longuski, J. M., and Aldrin, B., "Preliminary Analysis and Design of Powered Earth-Mars Cycling Trajectories," AIAA/AAS Astrodynamics Specialist Conference, AIAA Paper 2002-4422, Monterey, CA, Aug. 5–8, 2002.

[9]McConaghy, T. T., Yam, C. H., Landau, D. F., and Longuski, J. M., "Two-Synodic-Period Earth-Mars Cyclers with Intermediate Earth Encounter," AAS Paper 03-509, AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, August 4–7, 2003. To appear in the *Journal of Spacecraft and Rockets.*

[10]Russell, R. P., and Ocampo, C. A., "A Geometric Analysis of Half and Full-Revolution Return Trajectories via Planetary Flybys," AAS/AIAA Astrodynamics

Specialist Conference, AAS Paper 03-508, Big Sky, MT, Aug. 3–7, 2003. To appear in the *Journal of Spacecraft and Rockets*.

[11]Landau, D. F. and Longuski, J. M., “A Reassessment of Trajectory Options for Human Missions to Mars,” AIAA Paper 2004-5095, AIAA/AAS Astrodynamics Specialist Conference, Providence, RI, August 16–19, 2004.

[12]Chen, K. J., McConaghy, T. T., Landau, D. F., and Longuski, J. M., and Aldrin, B., “Powered Earth-Mars Cycler with Three Synodic-Period Repeat Time,” *Journal of Spacecraft and Rockets*, Vol. 42, No. 5, September–October 2005.