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CIRCUMLUNAR FREE-RETURN CYCLER ORBITS FOR A MANNED EARTH-MOON SPACE STATION

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Multiple free-return circumlunar cycler orbits were designed to allow regular travel between the Earth and Moon by a manned space station. The presented cycler orbits contain circumlunar free-return "figure-8" segments and yield lunar encounters every month. Smaller space "taxi" vehicles can rendezvous with (and depart from) the cycling Earth-Moon space station to enter lunar orbit (and/or land on the lunar surface), return to Earth, or reach destinations including Earth-Moon L1 and L2 halo orbits, near-Earth objects (NEOs), Venus, and Mars. To assess the practicality of the selected orbits, relevant cycler characteristics (including ΔV maintenance requirements) are presented and compared.

INTRODUCTION

Periodic orbits in the infamous restricted three body problem have been studied since before the 20th century. Notable contributors to this field include Poincaré[1] (1892-1899), Darwin[2, 3] (1897 and 1910) who presented the first results using numerical integration for a particular parameter (planet-to-planet mass ratio) $\mu = 10/11$, Moulton[4, 5] (1914) who considered $\mu = 0.2$ and 0.5, and Birkhoff[6] (1915). In 1934, Strömgrén[7] led astronomers of the Copenhagen observatory in creating the extensive "Copenhagen category" which catalogued periodic orbits for $0.1 < \mu < 0.5$.

Later in the 1950s, computer-aided numerical integration simulations yielded many interesting periodic orbits in the Earth-Moon system ($\mu = 0.01215$), with notable results by Egorov[8], Message[9], Newton[10], Thüring[11], and many others[12-21]. Earth-Moon periodic (i.e., cycler) orbits can serve as regular routes for a space station that shuttles crew and cargo[22] between the Earth and Moon on a regular basis. This cycling Earth-Moon space station will be large (e.g., > 1 km diameter[23]), radiation-shielded, and in constant rotation to provide artificial gravity (e.g., 1/6 g) for its human occupants; smaller "taxi" craft will re-fuel and re-supply the station, allowing crew and cargo swaps between the Earth and Moon[15-18, 22-28].

For human-safety purposes, it is preferable for a station's cycler orbit to contain "figure-8" (or "boomerang" [13]) circumlunar free-return segments. These "figure-8" orbits require ≈3.5 days of Earth-Moon one-way travel time and were used in the *Apollo* program to ensure an Earth-return in case of a propulsion (or other) system failure preceding the critical lunar orbit insertion (LOI) maneuver. In tracing the origins of this "figure-8" orbit, one is led to Egorov's dissertation work undertaken from 1953 to 1955 (later published in 1958) in which he revealed and classified many fundamental Earth-Moon orbits including a theoretical form of the "figure-8" orbit (Fig. 1).

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In 1957, Lisovskaya published a report[29] (referenced by Egorov) in which she presents the mentioned "figure-8" orbit for what appears to be the first time, and in a more practical form (Fig. 1). Lisovskaya was seemingly unaware of Egorov's work prior to 1957 thus they appear to have independently discovered the "figure-8" orbit within a couple of years of each other.

Lisovskaya's report directly followed Chebotarev's report[30] (also referenced by Egorov), the latter of which revealed the symmetric nature (with respect to the Earth-Moon line) of free-return circumlunar orbits. However, the perilune altitude computed by Chebotarev was 29,860 km and thus the orbit was not eight-shaped according to a re-creation using STK/Astrogator (Fig. 1). Hohmann assumed an even higher perilune altitude (his model only included Earth's gravity), which resulted in a 30-day total transfer time[31]. Another study by Lieske[32] of The RAND Corporation displayed a circumlunar "figure-8" orbit that purposely avoided an Earth reentry (Fig. 1), which is relevant to the form of the cycler orbits presented in this paper.

Of note is that in 1959, *Luna 3* became the first spacecraft to fly a circumlunar trajectory, although the orbit flew over the lunar poles[33] and was thus not shaped as the mentioned "figure-8". The USSR also had plans for a manned circumlunar mission using the *Soyuz 7K-L1 (Zond)* spacecraft, but its first manned flight (scheduled for a 1970 launch) was cancelled after the successful flight of *Apollo 8* which became the first manned flight launched on a circumlunar "figure-8" free-return trajectory on December 21, 1968.

The presented circumlunar free-return cycler orbits are also required to lie in the lunar orbit plane to minimize energy transfers to the Moon (this allows a wide range of launch site latitudes to directly connect a "taxi" to the cycling station), pass near (≈5,000 km altitude) both the Earth and Moon upon every close encounter, and yield lunar encounters at least once per month.

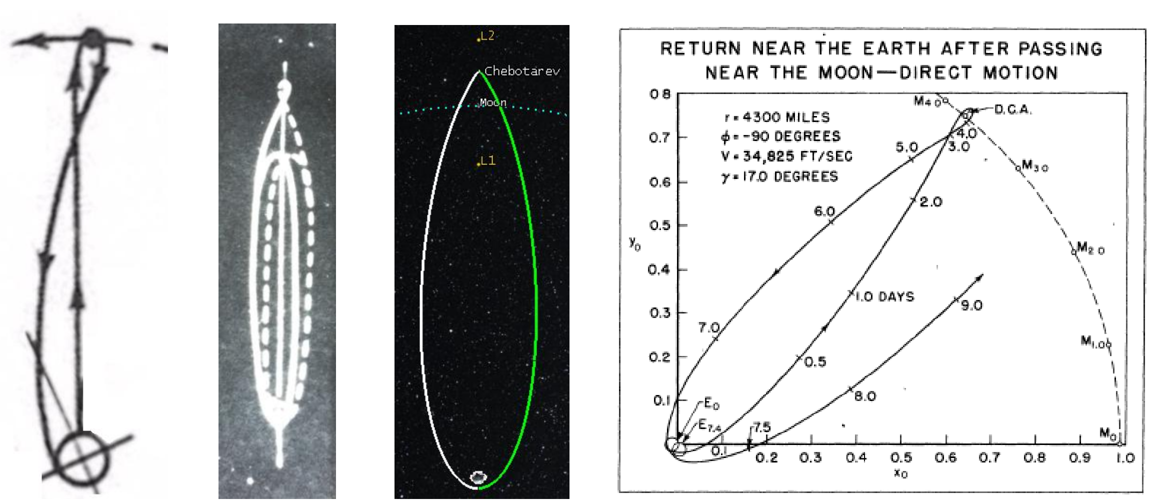

Figure 1. "Figure-8" Circumlunar Orbits by: Egorov[8] (far left), Lisovskaya[29] (6,100 km perilune; second from left), and Lieske[32] (far right). A distant circumlunar orbit (≈30,000 km perilune) by Chebotarev[30] is also shown, recreated using STK/Astrogator (third from left).

The presented trajectories were designed using AGI's System's Tool Kit (STK) Astrogator module, within a high-fidelity model that included gravity fields for the Earth (30X30), Moon (30X30), and Sun (4X0). The model also contained a Jacchia-Roberts atmospheric density model, solar radiation pressure, thermal radiation pressure, and the best-known ephemeris data for the

Earth, Moon, and Sun. The orbits were propagated using a Runge-Kutta $8^{th}/9^{th}$ order numerical integrator. The orbit analysis time period occurs between 2018 and 2022 unless otherwise noted.

Finally, transition trajectories connecting the Earth-Moon cyclers to each other and to multiple destinations/spacecraft are presented, including a lunar-orbiting space station, a halo-orbiting space station at Earth-Moon L2, and Mars. An example of a rendezvous with an Earth-launched space "taxi" and the cycler station is also shown. Other inner solar system destinations can be reached from the cycler station including Lissajous (and other halo) orbits, distant retrograde orbits (DROs), near-Earth objects (NEOs), and Venus.

TRAJECTORY DESIGN & ANALYSIS

"Mushroom" and "Shamrock" Earth-Moon Cycler Orbits

In 1985, Aldrin[27] theorized the existence of 2:1 and 3:1 resonance free-return Earth-Moon cyclers designated as *C-1-R* and *C-2-R* (Fig. 2, left). Uphoff also lists these resonances as the most practical for low-inclination Earth-transfer orbits that can transition to his cycler orbit's significantly inclined orbit plane[28]. However, in-plane cyclers with these resonances were not shown to exist in the restricted three-body problem: Arenstorf[18] presented a 3:1 resonance orbit but without the required close Earth passes (Fig. 2, center) and a 2:1 resonance orbit that contains higher than desirable perigee altitudes (discussed in a later section). For low perigee altitudes, Casoliva et al. presented a 3:1 lunar resonance orbit, but the spacecraft did not reach the Moon during each lunar encounter[34]. A similar trajectory was flown by the IBEX spacecraft (Fig. 2, right) in which Carrico et al.[35] note the stability of the 3:1 lunar resonance orbit (made to purposely avoid close lunar encounters), which had not been proposed for long-term use by a satellite.

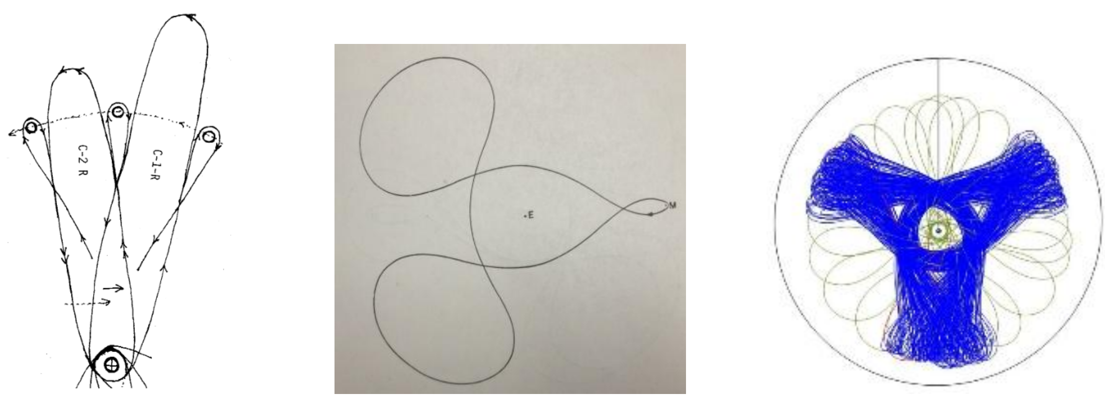

Figure 2. 3:1 Lunar Resonance Trajectories. C-2-R and C-1-R Earth-Moon Cycler Orbits theorized by Aldrin[27] in 1985 (left). Arenstorf[18] shows no close-Earth approaches are possible for a 3:1 resonance cycler orbit in the restricted three body problem (center). Also shown IBEX's 3:1 resonance eccentric orbit purposely designed to avoid the Moon[35].

However, the addition of modest ΔV maneuvers causes Aldrin's C-2-R theorized cycler orbit's apogee to drop temporarily below lunar distance which enables lunar phasing. The resulting cycler orbit (shown in Fig. 3) makes periodic close-approaches of the Earth every $\approx$7 or $\approx$9.5 days, with lunar encounters every $\approx$26 days.

These monthly lunar encounters were targeted to a 3,000 km perilune altitude on the lunar farside, with the cycling station flying in a circumlunar free-return, “figure-8” orbit with a targeted 3,000 km perigee altitude (this “figure-8” shape is seen in the inertial view of Fig. 3). The cycling station’s orbit is in 3:1 resonance with the Moon and resembles a three-leaf clover, or shamrock, as viewed in the Earth-Moon rotating frame (Fig. 3, right). Since the cycler’s inclination is in the lunar orbit plane, energy costs to transfer human crew (and cargo) between the Moon and the cycling station are relatively low.

There are three maneuvers performed per cycle to maintain the shamrock cycler orbit. The first maneuver is performed at perigee in the opposite direction of the orbit’s velocity (Fig. 3, C) which reduces the orbit energy to enable phasing with the Moon. The second maneuver is performed at the apogee preceding the “figure-8” segment, in the direction normal to the orbit’s velocity to maintain a cycler orbit inclination in the lunar orbit plane. After completing two sub-lunar Earth holding orbits (9.5 day period in each orbit), the third maneuver is performed in the velocity direction of the orbit at perigee (Fig. 3, E) to place the perilune altitude at 3,000 km on the lunar farside during the “figure-8” segment. Although apogee is increased to reach the lunar farside during a flyby (Fig. 3, H), the time between close Earth encounters decreases from ≈9.5 to ≈7 days given the final maneuver and Moon’s gravitational pull on the spacecraft during the “figure-8” trajectory segment of the cycler.

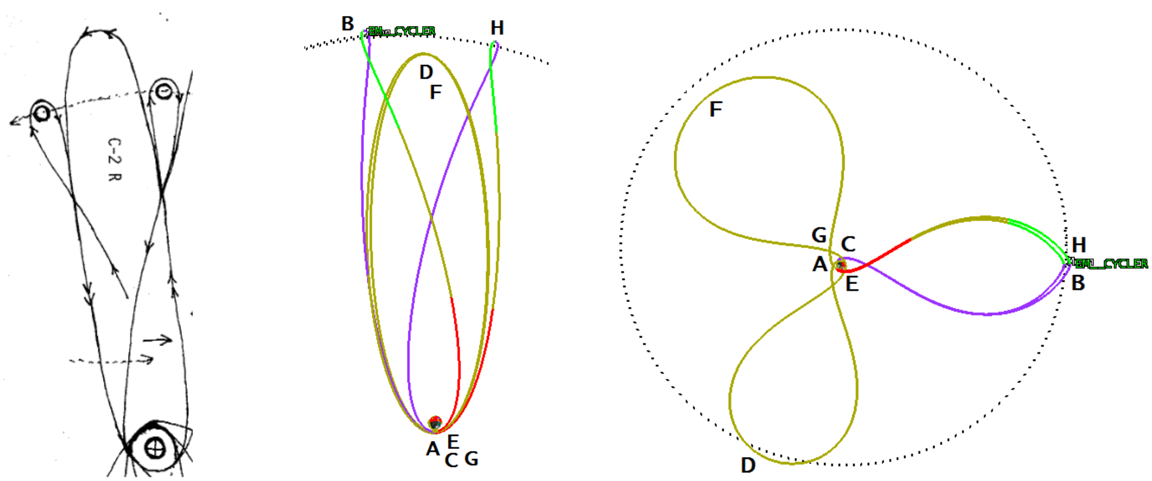

Figure 3. Shamrock Earth-Moon Cycler Orbit shown in Earth inertial (left & center) and Earth-Moon rotating (right) frames. One complete cycle is shown, with two complete sub-lunar phasing orbits connecting consecutive free-return “figure-8” orbits. Aldrin’s theorized cycler (C-2-R) is shown[27] for a side-to-side comparison (left).

By reversing the in-plane maneuvers just described, Aldrin’s theorized C-1-R cycler orbit is realized (Figs. 5 and 6). That is, the first maneuver increases the orbit energy to enable lunar phasing while the third maneuver decreases the orbit energy to set up the required circumlunar “figure-8” segment. The second maneuver is performed at the apogee preceding this “figure-8” segment to maintain the cycler orbit’s inclination in the lunar orbit plane.

The Moon’s varying Earth-range (due to the eccentricity of the lunar orbit) was observed as the primary cause of variance in the ΔV requirements to maintain either cycler orbit. These requirements are plotted together according to the cycler’s lunar encounter number (Fig. 7). The shamrock cycler requires 19 to 60 m/s per cycle (26.3 days) while the mushroom cycler orbit requires 29 to 70 m/s per cycle (25.7 days). The analysis period was 553 days, i.e., the time needed for the shamrock cycler to repeat itself in an inertial frame (Fig. 4, left).

The argument of perigee rotation rates are comparable between cyclers, thus one can still draw a meaningful conclusion from the complementary nature of the ΔV curves in Fig. 7. The lowest ΔV requirements are yielded near Moon's perigee for the shamrock cycler and near Moon's apogee for the mushroom cycler. Therefore, the cycling station can transition between cycler orbits depending on how far the Moon is from Earth to reduce the overall ΔV requirements. It is simply of matter of increasing or decreasing the orbital energy at perigee directly following the circumlunar "figure-8" segment common to both cyclers. And if the goal is in fact to reduce ΔV requirements, there would not be a direct ΔV cost to transition to the desired cycler orbit which would require less ΔV to enter when compared to the ΔV needed to remain in the initial cycler orbit. The shamrock/mushroom hybrid cycler is shown in Fig. 8, with the corresponding ΔV requirements plotted in Fig. 9. The maximum ΔV required per cycle is reduced to 45 m/s from the 60 or 70 m/s maximum observed for the shamrock and mushroom cycler orbits, respectively.

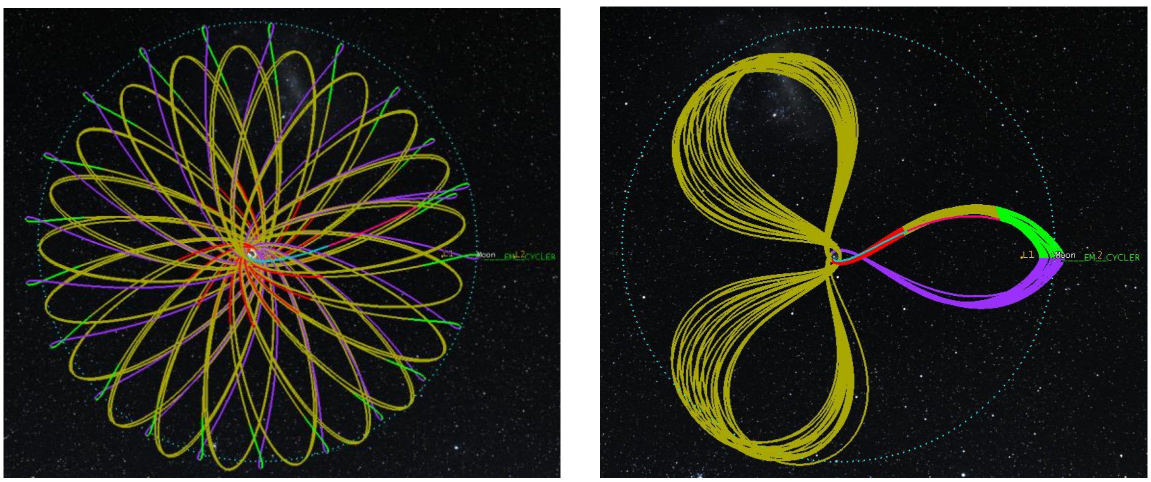

Figure 4. Shamrock Earth-Moon Cycler Orbit shown in Earth inertial (left) and Earth-Moon rotating (right) frames after many cycles so as to complete a full revolution in the inertial frame.

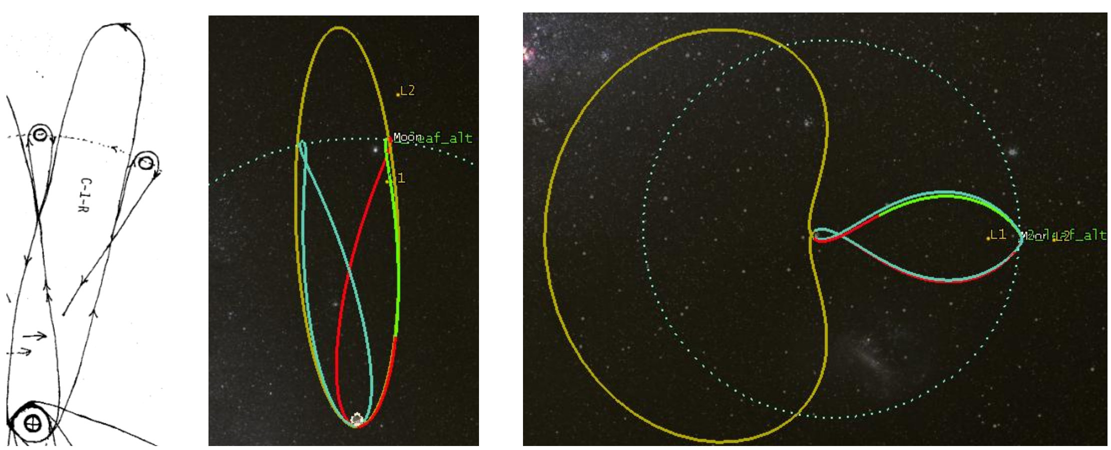

Figure 5. Mushroom Earth-Moon Cycler Orbit shown in Earth inertial (center) and Earth-Moon rotating (left) frames. Aldrin's C-1-R cycler orbit[27] displayed for side-by-side comparison (left).

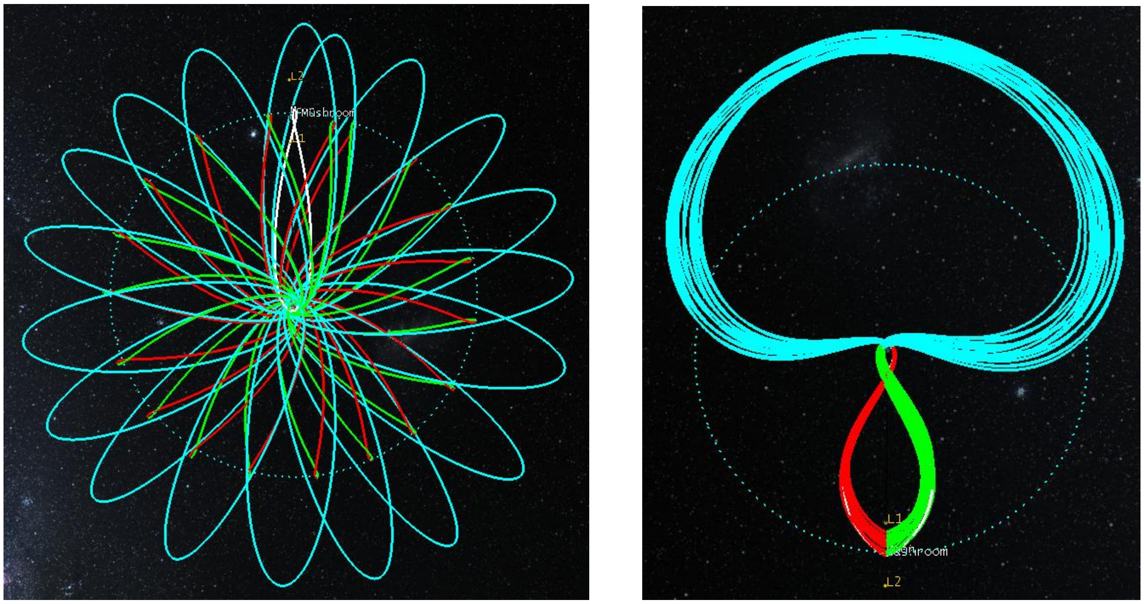

Figure 6. Mushroom Earth-Moon Cycler Orbit shown in Earth inertial (left) and Earth-Moon rotating (right) frames after many cycles so as to complete a full revolution in the inertial frame.

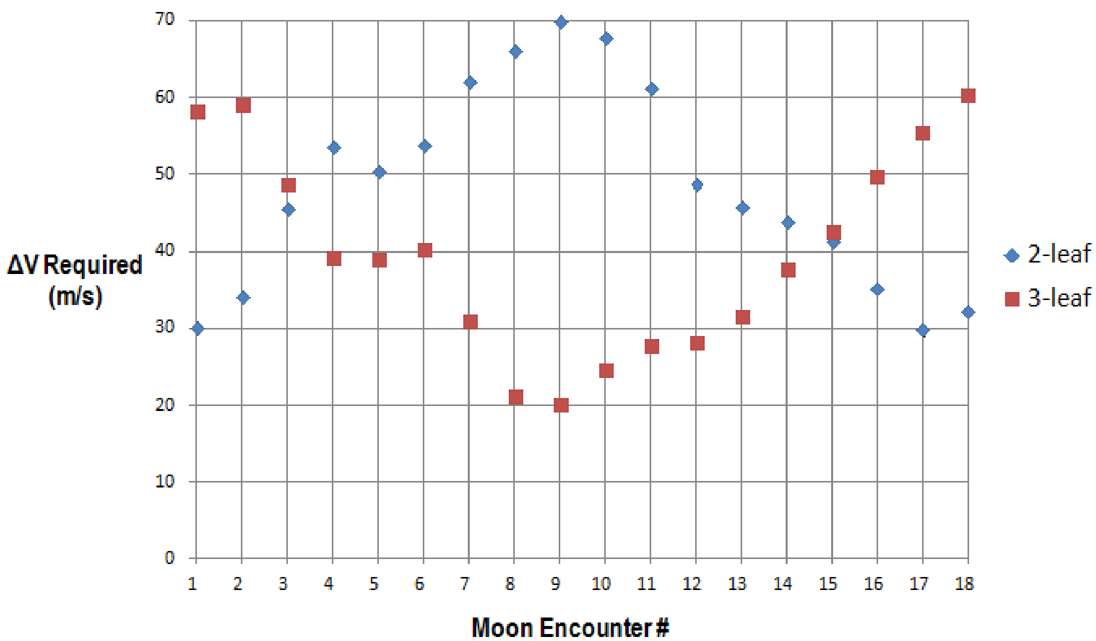

Figure 7. ΔV requirements per lunar encounter to maintain Shamrock and Mushroom Cycler Orbits.

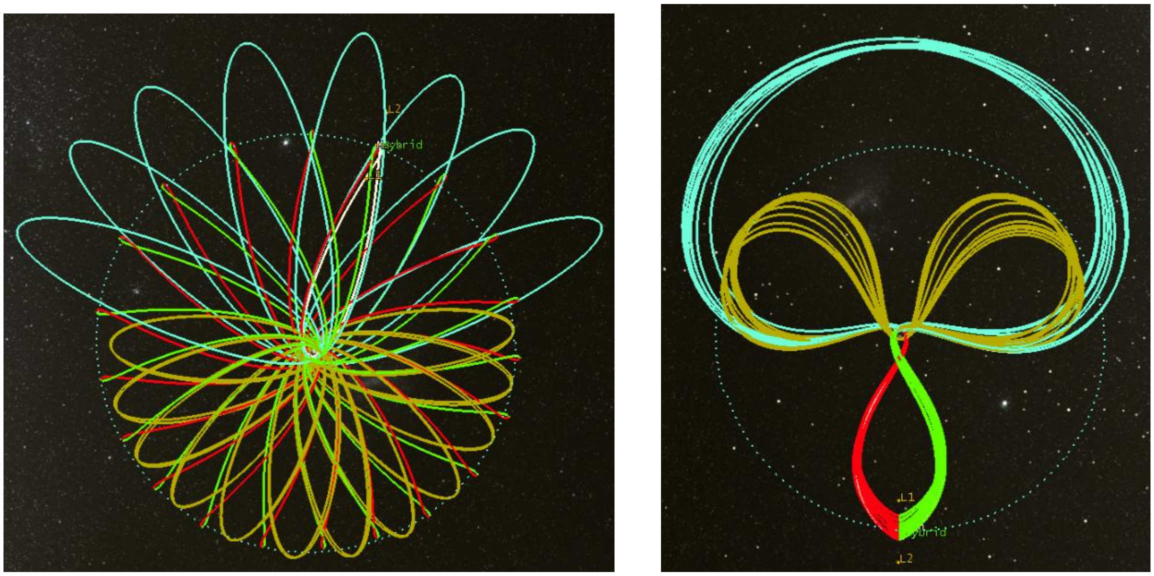

Figure 8. Hybrid Earth-Moon Cycler (cross between Shamrock and Mushroom cycler orbits) solved in the Earth inertial (left) and Earth-Moon rotating (right) frames.

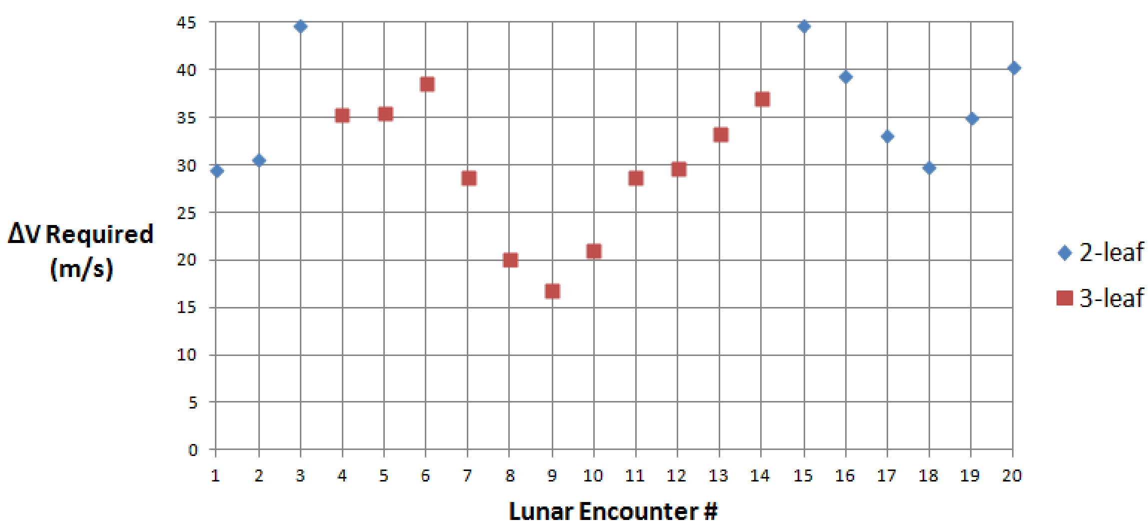

Figure 9. ΔV required per lunar encounter to maintain the Hybrid (Shamrock & Mushroom) Cycler Orbit.

Four-Leaf Clover Earth-Moon Cycler Orbit

In 1963, Arenstorf[18] presented a cycler orbit that resembles a four-leaf clover in the Earth-Moon rotating frame (Fig. 10). It is of note that in 1958, Egorov published a periodic circumlunar orbit that contains the reverse "figure-8" circumlunar segment[8] (Fig. 11) utilized by Arenstorf in the four-leaf clover cycler orbit design. This reverse "figure-8" segment approaches the Moon on its front side (counterclockwise rotation as viewed from north of the lunar equatorial plane; Fig. 10, F) before heading back out to apogee (Fig. 10, G) and eventually passing close to the Earth (Fig. 10, H). This reverse "figure-8" segment yields 22 days of wait time between Earth encounters. Otherwise, the wait time between perigee passes in the Earth phasing/holding orbits is 13 days. Lunar encounters occur every ≈27.5 days (close to a lunar sidereal month which equals ≈27.32 Earth days) due to the cycler's low apsidal rotation rate given its alternating circumlunar "figure-8" segment pattern. This cycler orbit repeats itself every 55 days, measured as the time between perilune encounters during the required "figure-8" orbits.

Although this cycler orbit was discovered without deterministic ΔV required for maintenance, when the Moon is near perigee the required ΔV can increase to as much as 55 m/s per lunar sidereal month. Thus, the same transition strategy assumed to create the previous hybrid cycler orbit is implemented to create a new hybrid cycler orbit. Specifically, the shamrock cycler orbit is crossed with this four-leaf clover cycler orbit to reduce the total ΔV requirements near lunar perigee. Secondary advantages of transitioning to the shamrock cycler orbit include the increase in frequency of close Earth encounters and required "figure-8" orbits. The resulting hybrid cycler orbit is shown in Fig. 12, in both the Earth-Moon rotating and Earth inertial frames. The maximum ΔV requirement per month is reduced to ≈37 m/s (Fig. 13), with an average ΔV requirement of ≈18 m/s per lunar sidereal month.

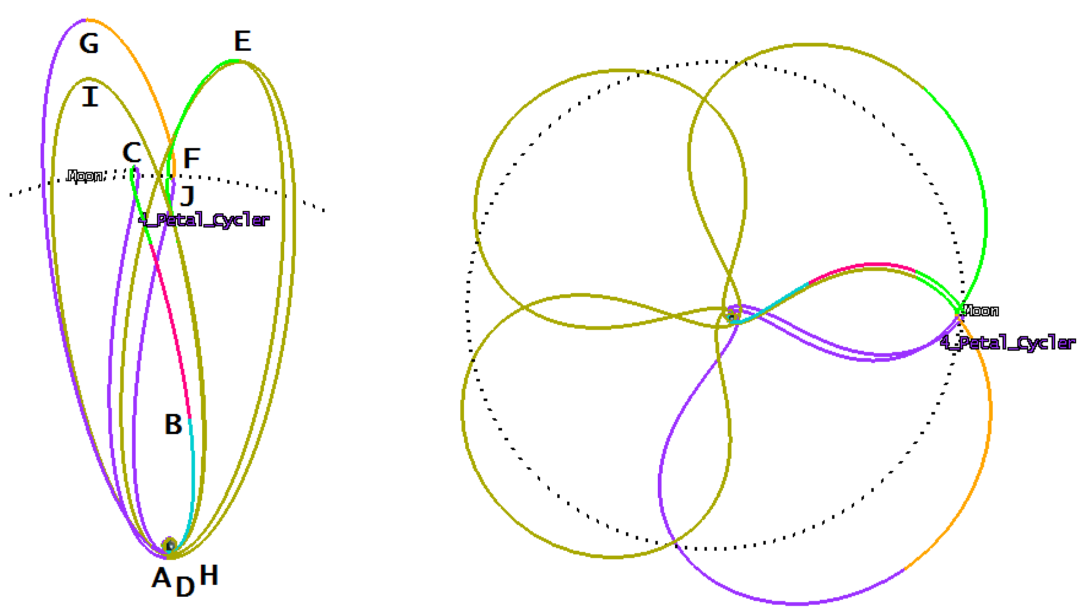

Figure 10. Four-Leaf Clover Cycler Orbit, shown in the Earth inertial (left) and Earth-Moon rotating (right) frames. Originally presented by Arenstorf[18] in 1963.

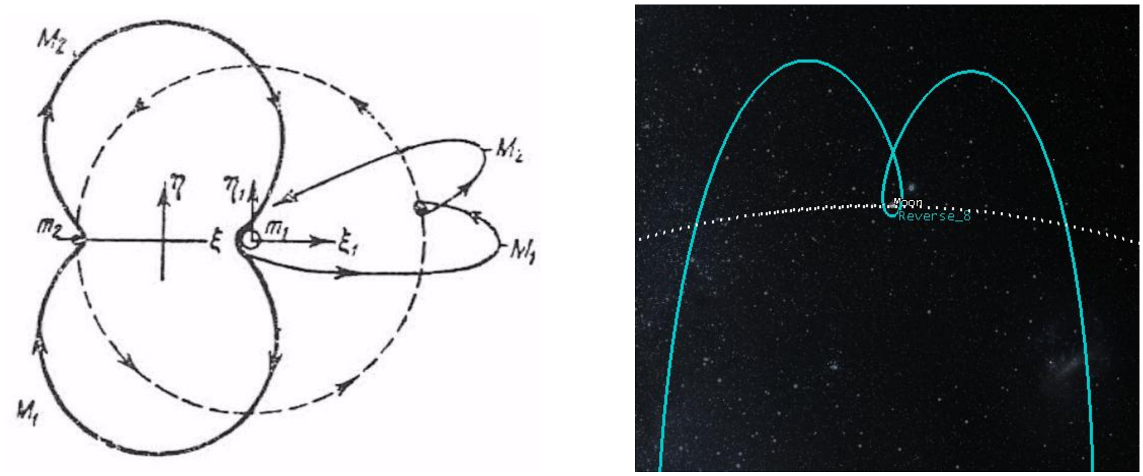

Figure 11. Egorov's periodic circumlunar orbit[8] with reverse "figure-8" segment, shown in Earth-Moon rotating and Earth inertial frames on the same plot (left). Reverse "Figure-8" motion theorized by Aldrin and independently verified using STK/Astrogator (right).

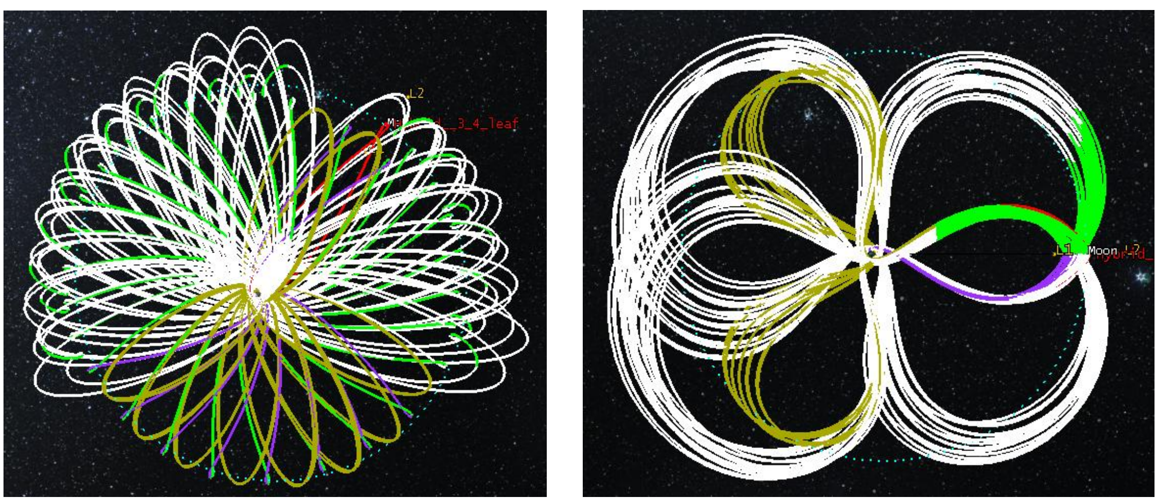

Figure 12. Hybrid Cycler Orbit (cross between Four-Leaf Clover and Shamrock Cycler Orbits), shown in the Earth inertial (left) and Earth-Moon rotating (right) frames.

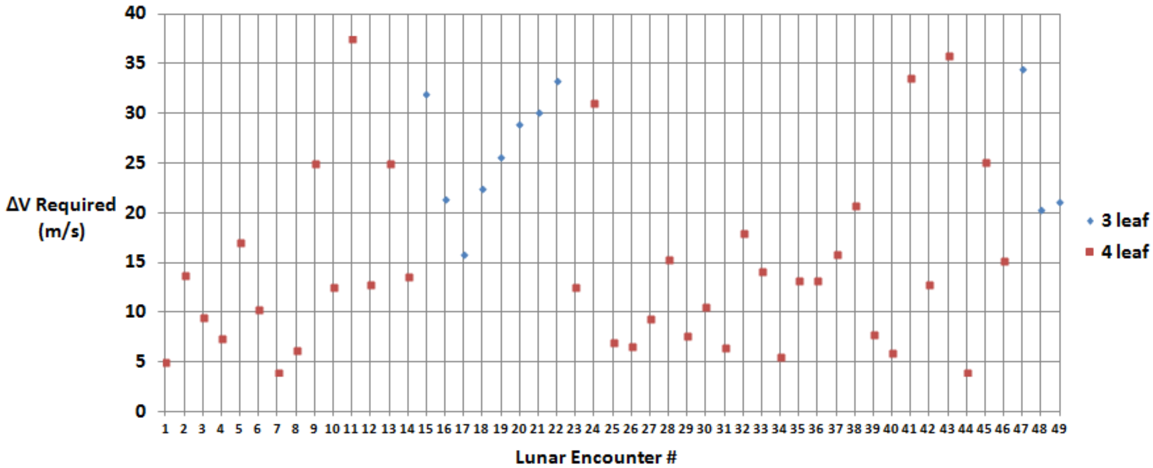

Figure 13. ΔV Requirements per lunar encounter for Hybrid Cycler Orbit (cross between Four-Leaf Clover and Shamrock {i.e., Three-Leaf clover} Cycler Orbits).

Earth-Launched Crew "Taxi" Rendezvous with Earth-Moon Cycling Station

The previously discussed mushroom cycler was designed as an alternative to Arenstorf's cycler orbit, both of which contain one phasing orbit separated by monthly "figure-8" circumlunar segments; however, the latter cycler orbit contains an unfavorably high perigee altitude of ≈40,000 km (Fig. 14)[15-17]. By crossing Arenstorf's monthly cycler orbit with, for example, the shamrock cycler, the resultant hybrid contains "figure-8" segments every month with alternating high (≈40,000 km) and low (≈3,000 km) perigee altitudes (Fig. 14). Although a slightly lower C3 is needed to reach Arenstorf's high-perigee cycler orbit (≈ -2.3 km^2/s^2 vs. ≈ -1.75 km^2/s^2 for a low-perigee cycler orbit), a full investigation of any cycler containing high-perigee cycler segments was not performed because of the relatively high "taxi" ΔV rendezvous requirements yielded. This is demonstrated by analyzing "taxi" transfers to either cycler orbit, coplanar to the cycling station's orbit plane from 6 to 48 hours after launch/injection (Figs. 15 and 16).

However, not all launch sites can attain launches directly into the lunar orbit (and thus cycling station's) plane. Therefore, the inclination of the orbit transfer plane of the "taxi" was varied from 0 to 90 degrees to determine the total ΔV cost for a rendezvous with the cycling station. The amount of time spent in the relatively small "taxi" by the crew was assumed to be one day, which is the approximate duration of the longest direct commercial airline flight at the time of this writing. Both cycler orbits were solved with a "figure-8" lunar encounter occurring in March of 2034, which is when the lunar orbit plane is near its minimum inclination; the inclination varies between ≈18 and ≈28.5 degrees with respect to the Earth's equatorial plane over an 18.6 year period, seen in Figure 17. The resulting "taxi" to cycling station rendezvous ΔV requirements are plotted in Figure 18; as can be seen, the inclination of the transfer orbit is at least ≈18 degrees for this solution, with every inclination greater in value yielding two solutions that travel either below (south) or above (north) the cycling station's orbit plane. In general, these ΔV requirements increase as the orbit inclination increases above that of the lunar orbit plane. If the lunar inclination is at its maximum of ≈28.5 degrees, then the minimum launch site latitude for a direct "taxi" connection is also ≈28.5 degrees. For a "taxi" launched by a conventional rocket at latitudes much higher than 28.5 degrees, rendezvous may be better suited following a lunar encounter, so as to use a lunar swingby to match the taxi's orbital plane with that of the cycling station.

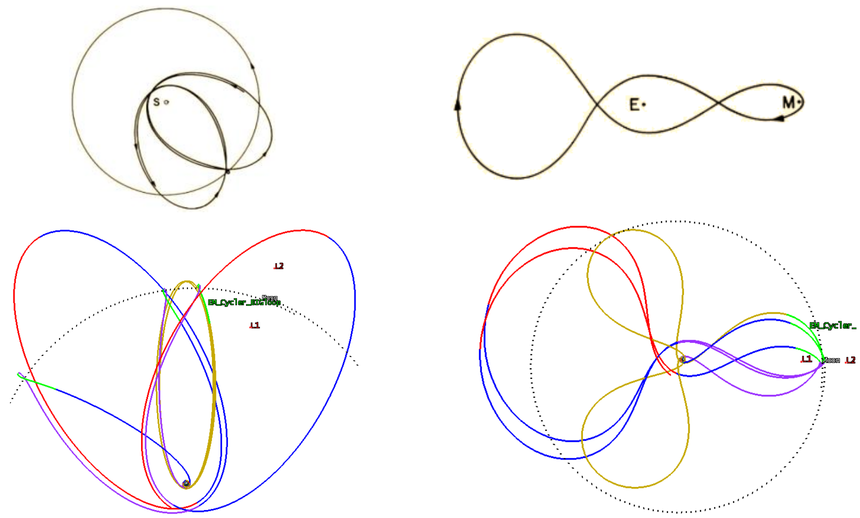

Figure 14. Arenstorf's monthly Earth-Moon cycler[15-17] (top-left and top-right) crossed with Shamrock cycler orbit to produce hybrid cycler (bottom-left and bottom-right).

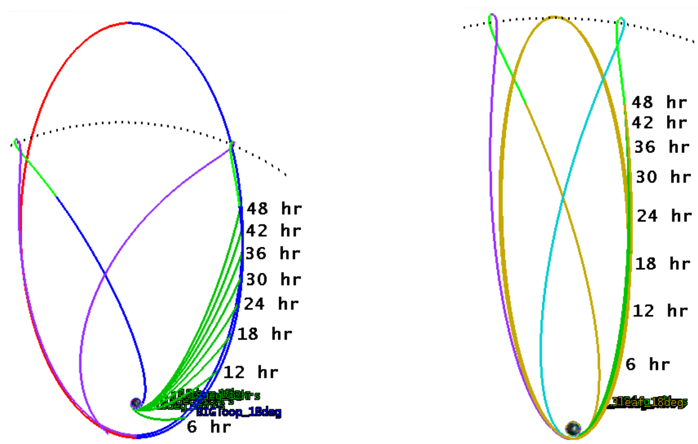

Figure 15. Rendezvous with Cycling Station by Earth-Launched "Taxi", 12 to 48 hours after launch into the cycler's orbit plane (Arenstorf's monthly cycler on left; Shamrock cycler on right).

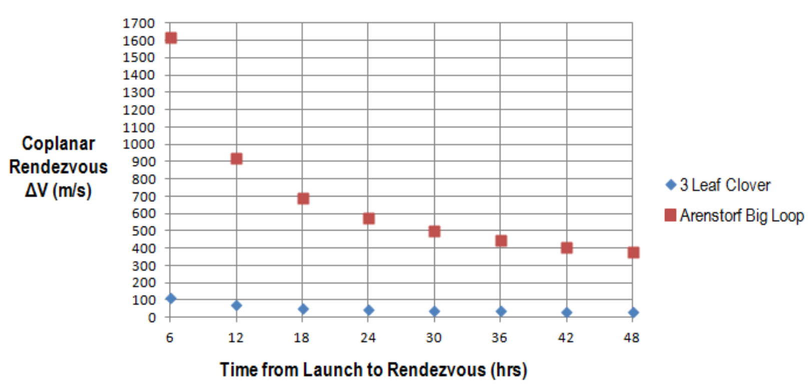

Figure 16. ΔV Requirements for Earth-Launched (coplanar with cycling station) "Taxi" Rendezvous with Three-leaf clover and Arenstorf's "Big Loop" cycler orbits, from 6 to 48 hours after launch.

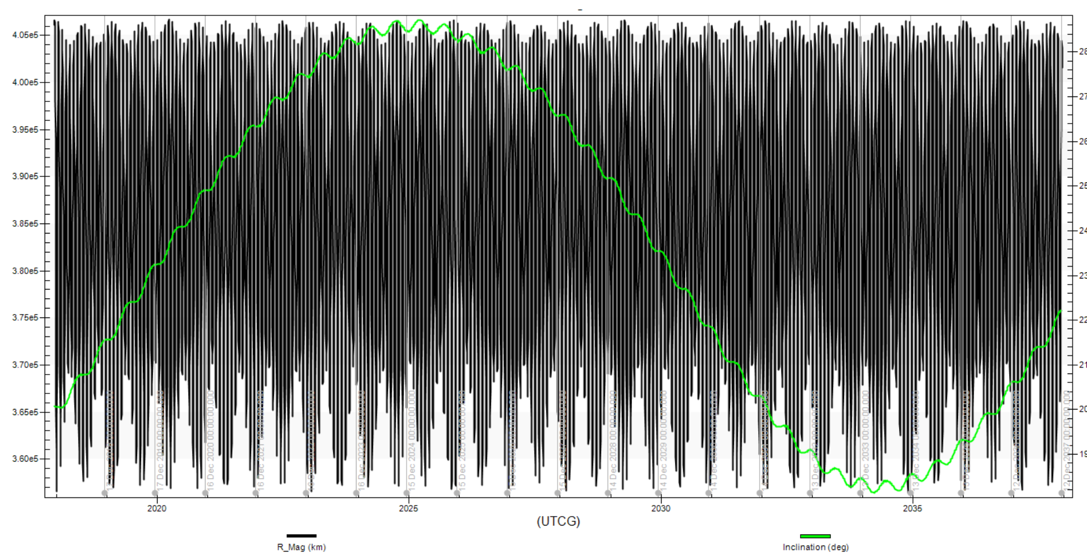

Figure 17. Moon Inclination (Y-axis on right) and Moon-Earth range (Y-axis on left) variance over 18.6 year period (shown for 20 years, from December 17, 2017 to December 17, 2037).

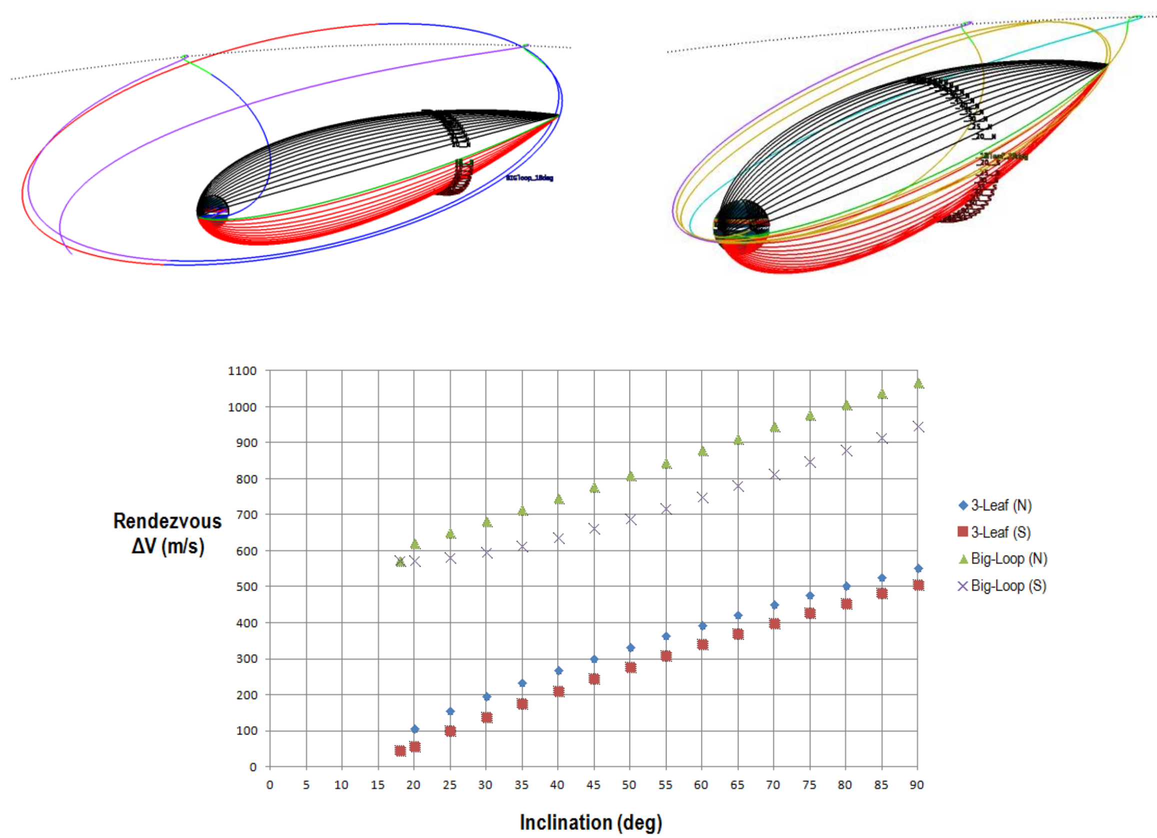

Figure 18. Earth-Launched "Taxi" Rendezvous with Arenstorf's "Big Loop" (top-left) and the Three-Leaf Clover (top-right) cycler orbits one day after launch, plotted against the inclination of the transfer orbit plane for launches north and south of the cycling station's orbit plane (bottom).

Crewed Rendezvous with Lunar Space Station from Earth-Moon Cycling Station

Both equatorial and polar low lunar orbits (LLOs) provide useful locations as exploration hubs for lunar development[23]. A station in the former LLO can provide a lunar lander/ascent vehicle access to the lunar surface near its equator, allowing passengers to ride on a magnetic levitation train to visit future lunar cities and historic landing sites[23] such as *Apollo 11*.

Since the presented Earth-Moon cycling stations' orbits lie in the lunar orbit plane, sending a cycling crew in a "taxi" to/from a station in equatorial LLO is relatively simple in terms of energy and time requirements. If the equatorial LLO is circular, both the right ascension of the ascending node (RAAN) and the argument of perilune are indeterminate thus further simplifying the "taxi" rendezvous targeting procedure. To illustrate this point, an initial altitude of 500 km was chosen for an equatorial LLO, given the orbit's stability over a five year period: without station-keeping maneuvers the geodetic altitude varied from ≈470 to ≈530 km (Fig. 19).

To rendezvous with the equatorial LLO station, the cycling crew departs in a "taxi" near perigee to target a 500 km (instead of 3,000 km) lunar altitude upon approach and set up a perilune braking maneuver (ΔV of 326 m/s) to enter a 12-hour period lunar orbit inclined 174 degrees to the lunar equatorial frame. This sequence is similar to the lunar orbit rendezvous (LOR) concept developed by Kondratyuk in 1916-1917 (unpublished works[36]) and flown during the Apollo program, albeit the "figure-8" orbit was separated by a circular lunar orbit entered without the elliptical staging orbit described here. When the spacecraft's orbit plane intersects the lunar equatorial plane in the 12-hour orbit (best seen in the far right image of Fig. 20), a maneuver (88 m/s of ΔV) is performed to change the inclination to the required 180 degrees. At the following perilune, the final braking maneuver (ΔV of 492 m/s) is performed to circularize the orbit and rendezvous with the equatorial LLO station. The ΔV needed for cycler-separation, lunar flyby targeting, and lunar phasing totaled 33 m/s, which yielded a total ΔV requirement of 939 m/s, or ≈90 m/s more than a typical ΔV requirement to achieve a circular lunar orbit from the required "figure-8" orbit.

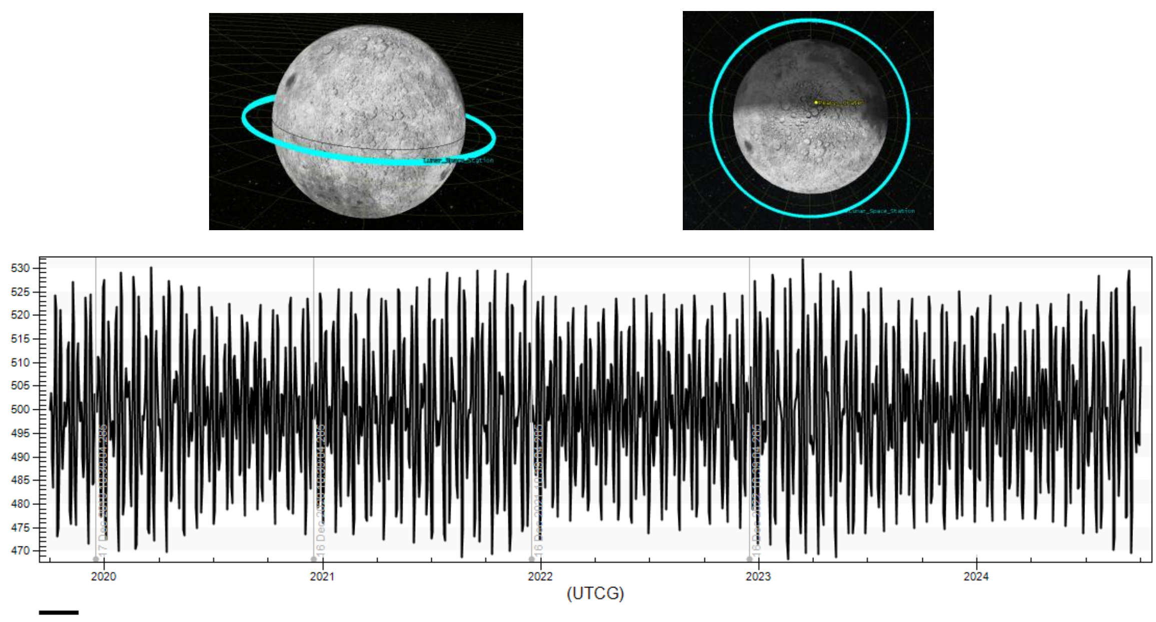

Figure 19. Five year variance in geodetic altitude for lunar-orbiting station (bottom). Inertial orbit views in the Moon inertial frame, angled (top left) and normal to (top right) the equatorial plane.

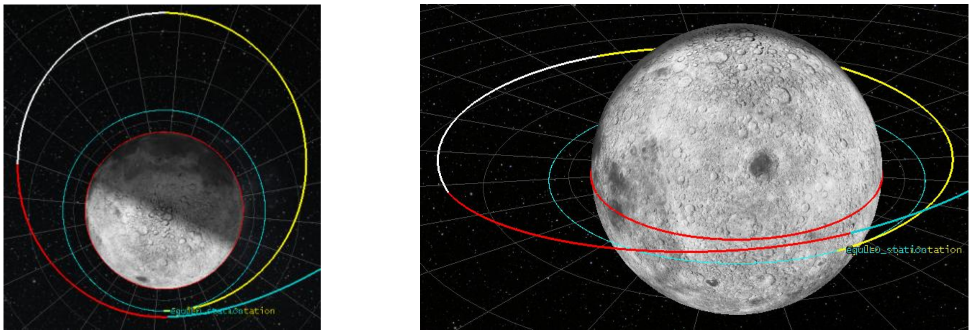

Figure 20. Crew Rendezvous w/ Lunar Space Station in 180 degree, 500 km circular orbit.

Crewed Rendezvous with Earth-Moon Cycling Station from Equatorial & Polar LLO Stations

If a circular equatorial LLO is instead assumed as the starting location for a departing crewed "taxi" to the Earth-Moon cycling station, the former's outgoing declination must connect to the latter in the lunar orbit plane. To accomplish this, a 7 degree plane-change maneuver (ΔV of 51 m/s) is performed at the lunar orbit node farthest from perilune in a notional 6-hour orbit. Note that the line of apsides of the 6-hour holding orbit is made to align with the required departure asymptote via proper timing of the apolune-raise maneuver (ΔV of 281 m/s) in the (2.9-hr period) circular orbit of the LLO station. The Moon-escape maneuver (ΔV of 533 m/s) occurs at the following perilune to set up a rendezvous (ΔV of 46 m/s) with the cycling station one day later. The total transfer duration of this trajectory is 30 hours, with a total ΔV requirement of 860 m/s.

A complementary space station in a polar LLO can serve the entire lunar globe, including the permanently-shadowed water-ice craters on the poles[37-39]. A circular polar LLO can directly connect to the Earth-Moon cycling station in the lunar orbit plane if the former's RAAN is properly aligned with the required departure asymptote. This geometry is not favorable for a single LLO station. However, a single "taxi" launched from a lunar pole can vary its launch azimuth to achieve the required RAAN to rendezvous with the cycling station; an example of this transfer required a rendezvous ΔV of 100 m/s with the cycling station one day after a Moon-escape maneuver (ΔV of 801 m/s). The total ΔV requirement was calculated as 901 m/s for this transfer.

Both equatorial and polar transfers to the cycling station are shown in Fig. 21 for comparison.

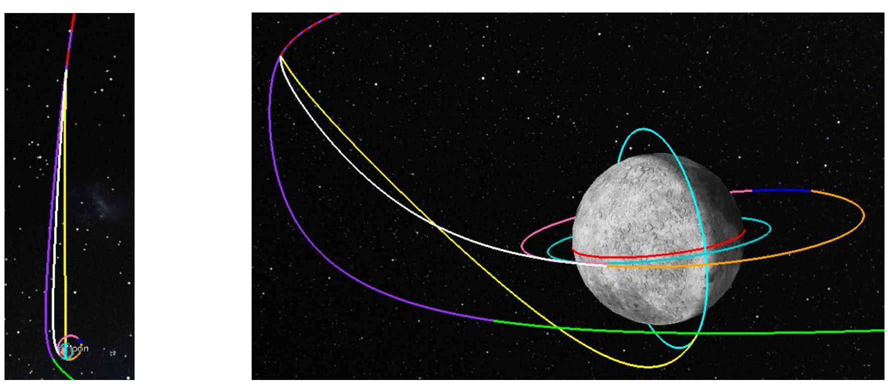

Figure 21. Crew Rendezvous with Earth-Moon Cycling Station from Polar and Equatorial Lunar circular orbits. Both orbits assume a 1-day transfer from the Moon-escape perilune maneuver to the Cycler station rendezvous.

For the case in which the RAAN of a polar circular LLO is not aligned with the required departure asymptote to reach the cycling station, Earth-Moon weak stability boundary (WSB) gravity effects can be used to enable a rendezvous. A spacecraft flying a highly elliptical WSB transfer can perform a relatively small plane-change maneuver at apolune to change its orbit plane from polar to equatorial (or vice-versa), among other things such as the orbit motion (direct to/from retrograde) and the orbit RAAN. Although more acceptable RAAN values emerge from their connections to valid Earth-Moon WSB transfers, a requirement on RAAN is rather restrictive.

To eliminate this restrictive RAAN requirement, an Earth-Moon WSB transfer can be used to connect a departing "taxi" from a polar LLO station to a circular LLO/station before transitioning to the required departure asymptote for cycling station rendezvous. Thus, significant flexibility is attained for an added cost in the energy needed to change between circular orbits inclined 90 degrees to each other.

The transfer used to demonstrate this point (Fig. 22) required 6 days between the initial maneuver performed at perilune (573 m/s of ΔV to raise the apolune altitude) and the Moon-escape maneuver (342 m/s) performed at the following perilune to rendezvous with an Earth-Moon cycling station. The plane-change maneuver performed at apolune near the Earth-Moon weak stability boundary (WSB) required 87 m/s of ΔV, yielding a total transition ΔV cost of 2,120 m/s.

The effects of the apolune altitude location (with respect to the Earth-Moon WSB) on the ΔV and transfer time requirements are subjects for future work.

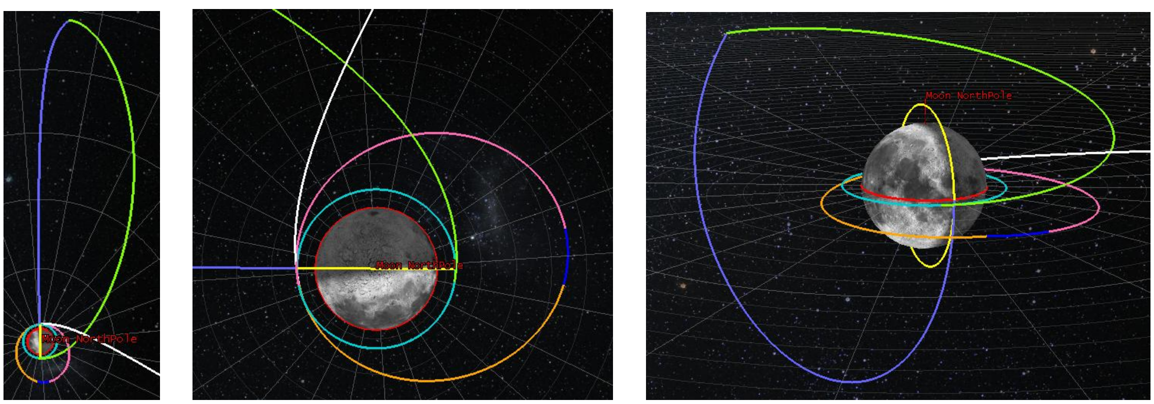

Figure 22. Transfer from polar circular LLO to circular equatorial LLO. Trajectory shown in Moon inertial frame.

Crewed Rendezvous with Earth-Moon L2 Halo Orbit Station from Earth-Moon Cycling Station

An Earth-Moon L2 halo orbit provides another interesting location for a space station (e.g., as a propellant depot)[40-46]. A relatively small "taxi" can depart the Earth-Moon cycling station (e.g., from the shamrock cycler orbit) to rendezvous with this L2 station, by imparting 11 m/s of ΔV at perigee on June 17, 2018 (Fig. 23). This sends the "taxi" toward the Moon for a trailing edge powered flyby (ΔV of 184 m/s) at 1,000 km perilune altitude on June 22, 2018. The craft reaches the point of halo orbit insertion (ΔV of 54 m/s) near Earth-Moon L2 on July 4, 2018, 17 days after departing the Earth-Moon Cycler. A 10 day segment corresponding to time spent in the halo orbit is shown as the final segment in white (Fig. 23). The total ΔV requirement for this L2 station rendezvous was calculated as 249 m/s. Shorter transfer durations are possible at the expense of increasing the ΔV requirement.

The authors thank Dr. David W. Dunham for providing the state vector for the Earth-Moon halo orbit used in this example. This orbit is considered a northern Class I quasi-periodic halo orbit[46] with Z amplitude of $\approx$7,000 km and a Y amplitude of $\approx$33,000 km.

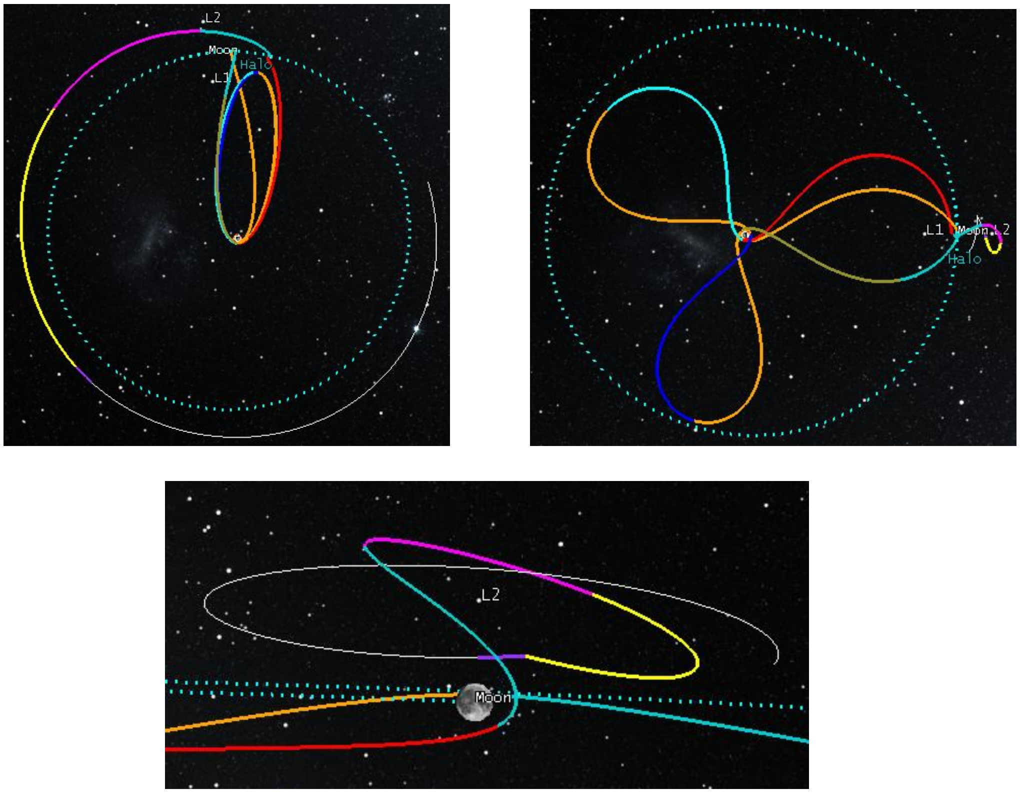

Figure 23. Crew Rendezvous w/ Earth-Moon L2 Halo Orbit after departing the Earth-Moon Cycler.

Transition from Earth-Moon Cycling Station to Mars

To transition from an Earth-Moon cycling station (shamrock cycler chosen in this example) to a Mars hyperbolic departure asymptote, the latter was first optimized outside of STK/Astrogator in a two-body Lambert solver (with an injection performed on August 3, 2020, i.e. the beginning of an optimal 20-day launch window). This departure asymptote was then fine-tuned in STK/Astrogator using the aforementioned high-fidelity four-body model. The trajectory was then solved backwards in STK/Astrogator to connect the asymptote to the shamrock cycler orbit (Fig. 24). The apogee altitude of the solution shown is $\approx$665,000 km which required a plane-chance maneuver (265 m/s of ΔV) performed at said apogee altitude; otherwise, a longer-duration weak-stability boundary transfer trajectory could have been used to lower the overall ΔV requirement for the Mars transfer. The injection maneuver was performed at perigee and required 736 m/s of ΔV (compared to $\approx$4,100 m/s if the injection were performed from a low-Earth orbit). This trajectory could be helpful in the event supplies are needed at Mars, since it may take longer to send an Earth-launched supply ship compared to the 28-day transfer duration computed for this solution. However, the Earth-Moon cycler must contain the proper argument of perigee value to align with this Mars asymptote. Thus it may be desirable to transition from the shamrock cycler to

Arenstorf's 2:1 resonance cycler (Fig. 14) to take advantage of the latter cycler's relatively high argument of perigee rotation rate. This direction of this rotation can be reversed via a transition to a trailing edge outbound lunar flyby trajectory (e.g., Fig. 24, bottom-right), similar to the first half of a double-lunar swingby (DLS) orbit[47].

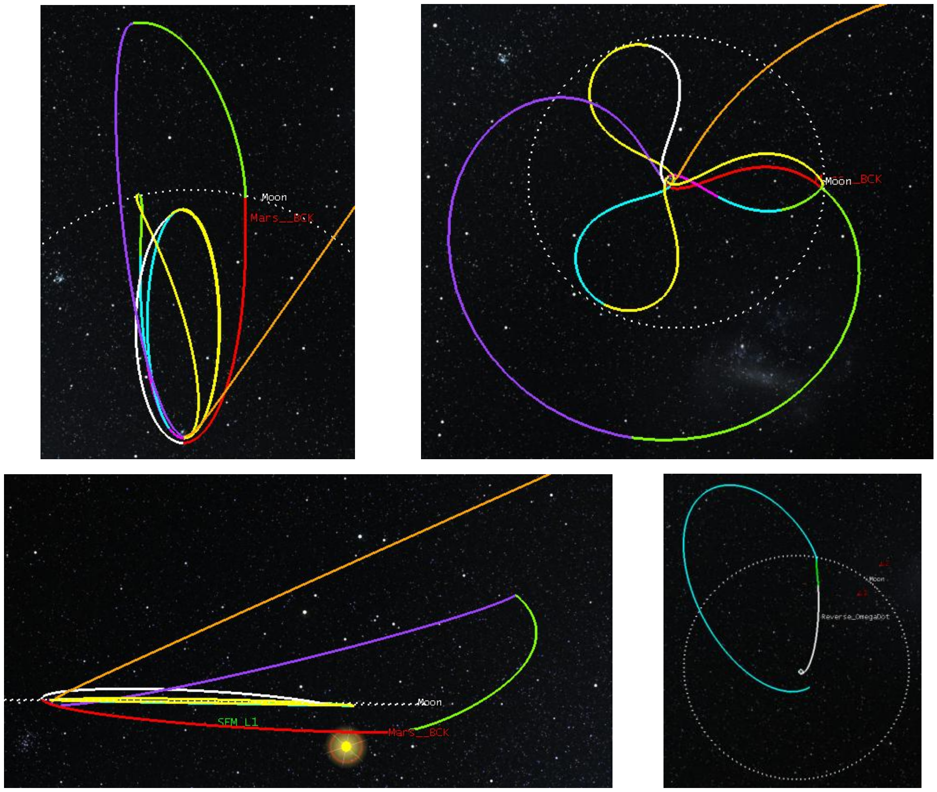

Figure 24. Trajectory transfer from Earth-Moon cycler to Mars departure asymptote. Solution shown in Earth inertial (top-left) and Earth-Moon rotating frames (top-right), also viewed edge-on the lunar orbit plane in an inertial frame (bottom). Lunar swingby trajectory with reversed argument of perigee rotation (bottom-right).

CONCLUSIONS

Multiple cycler orbits have been presented for the purpose of providing routes for a space station that ferries passengers and supplies between the Earth and Moon on a periodic basis, as envisioned by Aldrin and others[15-18, 22-28]. Important mission characteristics among the presented monthly circumlunar cycler orbits are summarized in Table 1. The shamrock cycler orbit is the only monthly cycler orbit to yield its minimum ΔV requirement near Moon's perigee. Thus the shamrock cycler orbit was crossed with the other two presented cyclers to create hybrid orbits that require less ΔV. The first hybrid cycler orbit (cross between the shamrock {i.e., three-leaf clover} and mushroom cyclers) requires the least amount of ΔV (maximum of 47 m/s and average of 31.5 m/s per lunar sidereal month) among cyclers with monthly "figure-8" segments. The second hybrid cycler orbit (cross between the three and four-leaf clover cyclers) requires the least amount of ΔV (maximum of 37 m/s and average of 18 m/s per lunar sidereal month) among cyclers with monthly circumlunar segments (which alternate between the required “figure-8” and a reverse “figure-8”). The shamrock cycler orbit is also of note since it yields the most frequent close-Earth encounters, with a maximum of ≈9.5 days between perigee passes. The maximum time between perigee passes observed among any cycler was 22 days, yielded by the reverse “figure-8” segment contained in the four-leaf clover cycler orbit.

The perigee altitudes directly following the “figure-8” segments were targeted to 3,000 km for the shamrock cycler orbit (and 5,000 km for the other cyclers) to avoid perigee maintenance maneuvers. For purposes of minimizing the rendezvous ΔV by an Earth-launched “taxi”, the perigee altitude preceding the “figure-8” segment should be targeted to as low as practicable. It may also be desired to reduce the targeted 3,000 km perilune altitude (e.g., to 100 km). By varying these targeted perigee and perilune altitudes, the ΔV requirements to maintain the presented cycler orbits can be altered thus providing a method for energy optimization.

Although the maneuvers performed in this analysis were assumed to be instantaneous, the presented trajectories can be converted to constant thrust solutions by centering the thrust arcs at perigee (or apogee). A feasibility analysis will depend on many factors including the station’s mass, thrust, specific impulse, etc., which is out of this paper’s scope.

Future work will focus on contingency trajectories in the event of a missed maneuver during a cycling station’s orbit sequence. Furthermore, the orbit types presented are quite sensitive to errors in velocity[8, 48] but this sensitivity has not been quantified in this paper.

It is of note that multiple cycling stations may be desired to provide more frequent “taxi” rendezvous opportunities (i.e., to exchange crew and/or cargo) and to cover a wide spread in geocentric argument of perigee values to minimize the time needed for a cycler to “clock” around the Moon’s orbit to align with a desired interplanetary departure asymptote.

Advantages of the cycler station include the capability of providing the crew with a safe, spacious, comfortable, and efficient to and from the Moon[23]. It has been shown that the presented Earth-Moon cycler orbits can connect to each other and with nearby targets of interest when desired, forming an ever-changing bridge to our sister “planet” and the inner solar system.

Table 1. *Monthly Earth-Moon Cycler Orbit Summary Table*

CYCLER NAME	**Cycler Period (Lunar Sidereal Months)**	**Max. Time between Perigee Passes (Earth Days)**	**Time between Lunar Encounters (Lunar Sidereal Months*)**	**Time between Required “Figure-8” Segments (Lunar Sidereal Months*)**	**Min. ΔV Observed per Lunar Sidereal Month***	**Max. ΔV Observed per Lunar Sidereal Month***
Mushroom	≈1	18.5	≈1	≈1	≈32 m/s	≈74 m/s
Shamrock (i.e., 3-Leaf Clover)	≈1	9.7	≈1	≈1	≈20 m/s	≈62 m/s
4-Leaf Clover	≈2	22	≈1	≈2	≈4 m/s	≈55 m/s
Hybrid: (Mushroom & Shamrock)	≈1	18.5	≈1	≈1	≈18 m/s	≈47 m/s
Hybrid: (3 & 4-Leaf Clovers)	≈1 or ≈2	22	≈1	≈1 or ≈2	≈4 m/s	≈37 m/s

**** One lunar sidereal month ≈ 27.32 Earth days***

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