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A FREE-RETURN EARTH-MOON CYCLER ORBIT FOR AN INTERPLANETARY CRUISE SHIP

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A periodic circumlunar orbit is presented that can be used by an interplanetary cruise ship for regular travel between Earth and the Moon. This Earth-Moon cycler orbit was revealed by introducing solar gravity and modest phasing maneuvers (average of 39 m/s per month) which yields close-Earth encounters every 7 or 10 days. Lunar encounters occur every 26 days and offer the chance for a smaller craft to depart the cycler and enter lunar orbit, or head for a Lagrange point (e.g., EM-L2 halo orbit), distant retrograde orbit (DRO), or interplanetary destination such as a near-Earth object (NEO) or Mars. Additionally, return-to-Earth abort options are available from many points along the cycling trajectory.

INTRODUCTION

Periodic orbits in the infamous restricted three body problem have been studied by many great minds over many centuries, with Darwin[1, 2] in 1897 (and 1910) being the first to use numerical integration to find periodic orbits for a particular parameter (planet-to-planet mass ratio) μ = 10/11, while Moulton[3, 4] considered μ = 0.2 and 0.5 values later in 1914. In 1934, Strömgrén[5] led astronomers of the Copenhagen observatory in creating the “Copenhagen category” which catalogued periodic orbits for $0.1 < \mu < 0.5$. Later in the 1950s, the computer epoch of experimental celestial mechanics yielded many interesting periodic orbits in the Earth-Moon system (μ = 0.01215), with the first results by Egorov[6] in 1957, and later by Message[7], Newton[8], Strömgrén[9], and many others[10-17].

Of practical interest are two Earth-Moon cycler orbits discovered by Arenstorf in 1963, who assumes the use of Earth free-return trajectory segments in the cycler, the same “figure-8” or so called “Arenstorf” orbit he discovered in 1963 and later used in the Apollo program. Of note is that in 1957 Egorov[6] presented a more theoretical version of such an orbit as seen in Fig. 1, bottom-left; while Kondratyuk[18] in 1916-1917 (unpublished works) may have assumed the use of a free-return trajectory for his leading edge lunar encounter as part of his lunar orbit rendezvous (LOR) concept (however, the leading edge could have been chosen for purposes of minimizing the lunar orbit insertion (LOI) ΔV requirement). Arenstorf’s first free-return Earth-Moon cycler[13] encounters the Moon every other month and is seen as a “5-petal” solution in the Earth-Moon rotating frame (Fig. 1, top-left). The second Arenstorf cycler[14] utilizes an element from one of Egorov’s periodic circumlunar orbits[6] (Fig. 1, bottom-right), which yields monthly lunar encounters; however the cycler must wait up to 22 days between Earth encounters (Fig. 1, top-right).

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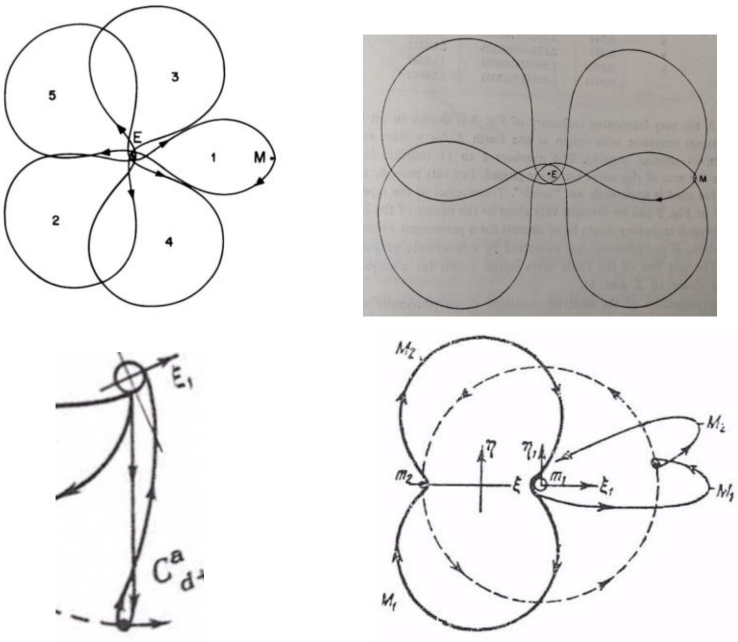

Figure 1. Examples of Periodic Circumlunar Orbits, clockwise from top-left: Arenstorf's 5-petal semi-monthly lunar cycler[13]; Arenstorf's 4-petal monthly lunar cycler[14]; Egorov's bi-monthly lunar cycler[6]; also shown is a "figure-8" lunar transfer by Egorov[6], similar to an "Arenstorf" orbit.

Another Earth-Moon cycler of note can be constructed from the double-lunar swingby (DLS) trajectory solution to a geomagnetic tail problem presented by Farquhar and Dunham[19] in 1980. The DLS cycler would also alternate between trailing and leading edge lunar flybys (but now on both outbound and inbound legs) with apogee significantly beyond lunar distance. In 1991, Uphoff[20] presented a circumlunar periodic orbit with lunar encounters every other month; however, the "back-flip" technique used places the cycler significantly out of the lunar orbit plane, relatively unfavorable for energy transfer to and from lunar orbit from the cycler.

This paper presents details of a previously undiscovered free-return Earth-Moon cycler that is in 3:1 lunar resonance (3-petals as viewed in a rotating frame), with relatively frequent Earth and Moon close-encounters thus providing a route for an interplanetary cruise ship ferrying passengers and supplies between the Earth and Moon on a periodic basis, as envisioned by Aldrin[21] in 2013. Maneuvers are required to maintain the presented cycler, but it is shown that other cyclers (as seen in Fig. 1) require station-keeping maneuvers as well.

The trajectories were designed using AGI's System's Tool Kit (STK) Astrogator module, with a high-fidelity force model including gravity fields for the Earth (50X50), Moon (50X50), and Sun (4X0). The orbit was propagated using a Runge-Kutta 8th/9th order numerical integrator. Station-keeping ΔV requirements are analyzed for the 3-petal cycler over a full apsidal rotation around the Sun.

Also shown are transition trajectories connecting the cycler to multiple destinations/spacecraft, including a lunar-orbiting space station, a halo-orbiting space station at Earth-Moon L2, and a crewed craft launched from the Earth. More destinations, such as distant retrograde orbits (DROs), near-Earth asteroids (NEAs), and Mars will be explored in the full paper, if accepted.

3-Petal Earth-Moon Cycler

Although in 1985 Aldrin[22] theorized the existence of a 3:1 resonance free-return Earth-Moon cycler designated as C-2-R (Fig. 2, left), such a cycler was not shown to exist in the restricted three-body problem: Arenstorf[14] shows a 3:1 resonance orbit but without the required close Earth passes (Fig. 2, center). For low perigee altitudes, Casoliva et al[23] show a 3:1 lunar resonance orbit, but the spacecraft does not reach the Moon during each lunar encounter (Fig. 2, right). A similar trajectory was flown by the IBEX spacecraft in which Carrico et al note the stability of the 3:1 lunar resonance orbit, which had not been proposed for long-term use by a satellite[24].

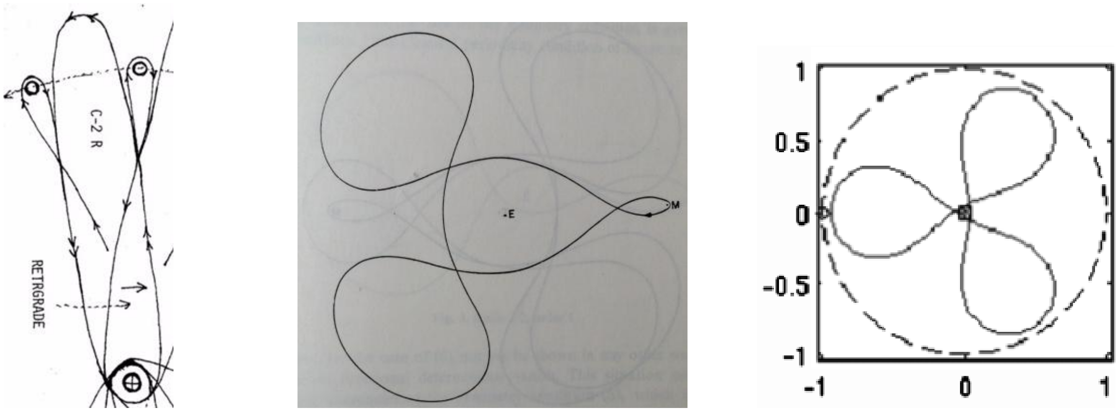

Figure 2. 3:1 Lunar Resonance Trajectories. C-2-R Earth-Moon Cycler theorized by Aldrin[22] in 1985 (left). Arenstorf[14] shows no close-Earth approaches are possible in the restricted three body problem (center). Casoliva et al[23] show close-Earth approaches by the spacecraft for a 3:1 lunar resonance solution, but the spacecraft does not reach the Moon (right).

However, the addition of solar gravity to the astrodynamics model and a modest ΔV maneuver causes Aldrin's C-2-R theorized cycler's apogee to drop temporarily below lunar distance which enables lunar phasing. The resulting 3-petal cycler (shown in Fig. 3) makes periodic close-approaches of the Earth every 7 or 10 days, with lunar encounters every 26 days (Fig. 4).

The nearly monthly lunar encounters are targeted to 3,000 km perilune on the lunar farside, with the cycler essentially flying a free-return, figure-8 "Arenstorf orbit" bringing the cycler back to a 3,000 km perigee altitude for each Earth encounter (this "figure-8" is best seen in the inertial view of Fig. 3, right). Since the cycler's inclination is in the lunar orbit plane, energy costs to enter the Moon's gravity field are relatively low which is desirable for human (and cargo) transfer to/from lunar orbit (or a nearby Earth-Moon L2 halo orbit for example). The cycler is in 3:1 resonance with the Moon, as best seen in the Earth-Moon rotating frame (Fig. 3, left).

There are three maneuvers performed per cycle to maintain the cycler's trajectory: the first maneuver (13 m/s of ΔV) is performed at perigee (Fig. 3, C) which enables phasing with the Moon and yields close-Earth encounters every 9.5 days in a sub-lunar Earth holding orbit, completing two such orbits before performing the second maneuver (14 m/s of ΔV) at perigee (Fig. 3, E) to increase apogee back to true lunar distance. The third maneuver (8 m/s of ΔV) is performed 0.5 days later to correct for drift out of the lunar plane, likely due to solar perturbations. Although apogee is increased to reach the lunar farside during a flyby (Fig. 3, H), the time between Earth close 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 (Fig. 4).

Solar gravity perturbations cause variance in the ΔV requirements, from 20 to 62 m/s per cycle (not including the near-zero ΔV needed on the initial injection leg), or 26 days, needed to maintain the presented Earth-Moon cycler. The analysis period was 553 days, i.e., the time needed for the cycler to repeat itself in an inertial frame with the line of apsides rotating a full 360 degrees (Fig. 5, right), which is also the approximate period of ΔV requirements (Fig. 6).

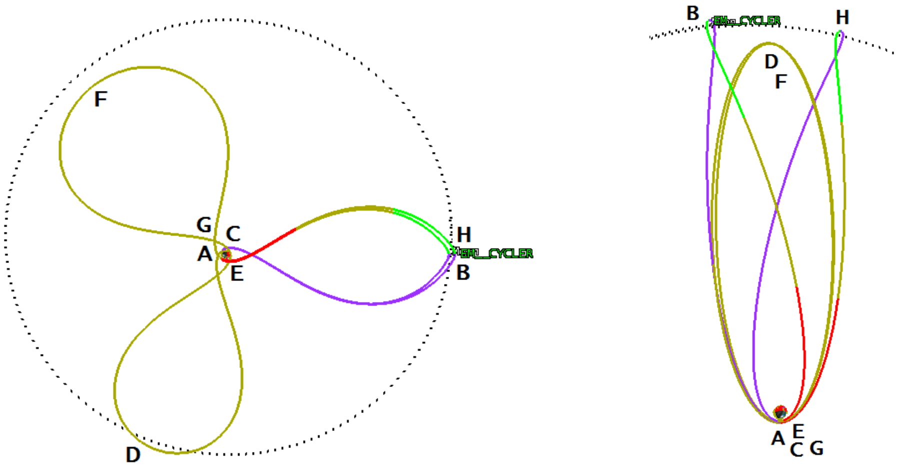

Figure 3. 3 Petal Earth-Moon Cycler shown in Earth-Moon rotating (left) and Earth inertial frames. One complete cycle is shown, with a two complete sub-lunar phasing orbits connecting consecutive free-return (to 3,000 km perigee altitude) legs of the cycler.

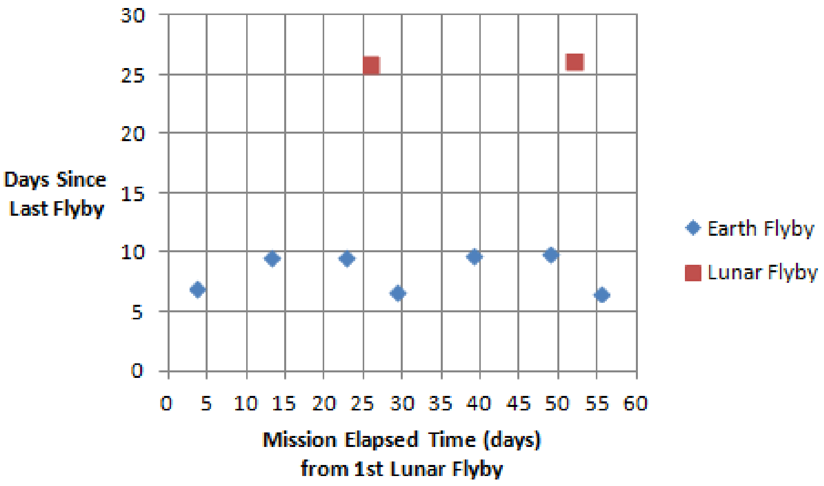

Figure 4. Time spent between Earth and Moon close-encounters, starting from the first lunar flyby on July 15, 2019. As seen, the cycler spends about 7 days between Earth encounters on legs including the lunar flyby, the latter of which occurs every 26 days. In the holding orbits, just under 10 days is spent between Earth encounters.

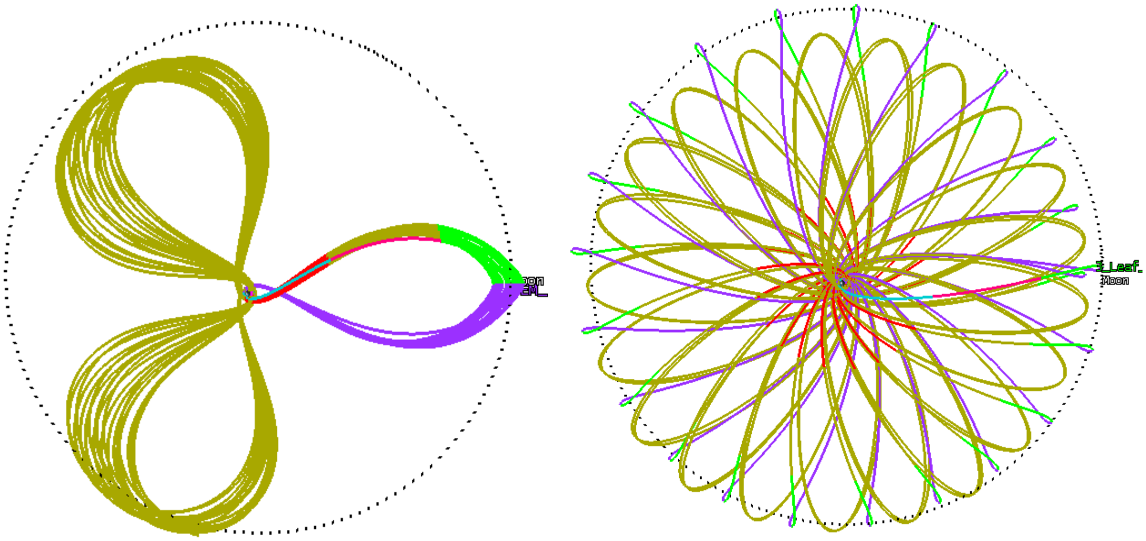

Figure 5. 3 Petal Earth-Moon Cycler shown in Earth-Moon rotating (left) and Earth inertial frames. 21 complete cycles (i.e., 22 lunar flybys) are shown, so as to complete a full revolution in the inertial frame. Trans-lunar injection (TLI) of the cycler assumed on July 12, 2019 with the last perigee (following the 22nd lunar flyby) on Jan. 15, 2021, or 553 days.

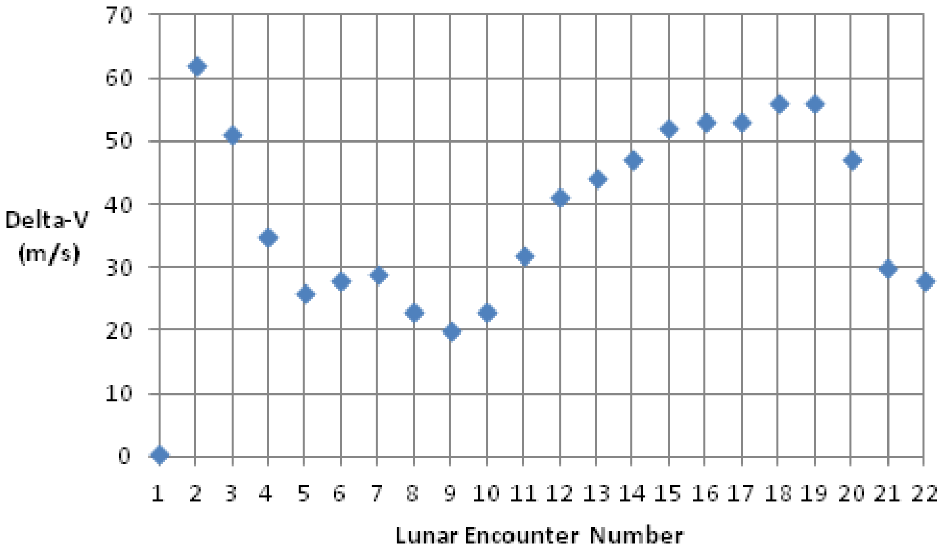

Figure 6. Delta-V requirement to maintain the 3-Petal Earth-Moon Cycler. The near-zero ΔV cost for the first lunar swingby is due to the initial assumption of an injection from a typical parking orbit from a KSC launch.

Transition to a 4-Petal Earth-Moon Cycler

If the in-plane lunar phasing maneuver is missed, the interplanetary cruise ship's course can transition from a 3 to 4-petal cycler. In 1963, Arenstorf[14] (with the help of Davidson) discovered this 4-petal cycler, as mentioned briefly and shown in Fig. 1 (top-right). This cycler is solved with N-bodies and shown in both the Earth-Moon rotating and Earth inertial frames (Fig. 7); it does not require as much ΔV to implement compared to the 3-petal cycler, but the ΔV cost of 19 m/s per 2 months is significant enough to warrant the need for some means of propulsion (e.g., auxiliary engine with high-thrust, which would be well suited to perform emergency/avoidance maneuvers), so about ¼ of the average ΔV required for the 3-petal cycler. (More analysis is needed for this cycler to determine the full range of potential ΔV requirements).

The 4-petal cycler includes a reverse figure-8 flyby on the lunar frontside (counterclockwise rotation as viewed from north of the lunar equator; Fig. 7, F) before heading back out to apogee (Fig. 7, G) and eventually pass close to the Earth (Fig. 7, H). This leads to a longer wait time between Earth encounters, up to 22 days as seen in Fig. 8, with 13 days between perigee passes in the holding orbit that contains a super-lunar apogee altitude. Data from Fig. 8 reveals that lunar encounters occur every 27.5 days, very close to the 28-day lunar cycle since the apsidal rotation rate is nearly frozen in this alternating farside/frontside lunar cycler. The 4-petal cycler repeats itself approximately every other lunar cycle (seen in Fig. 8), with about 55 days elapsing between farside, figure-8 lunar flybys.

The 3-petal cycler can transition to this 4-petal cycler by targeting a trailing edge lunar flyby that pulls the apogee beyond lunar distance to set up the 4-petal frontside flyby one complete holding orbit later (Fig. 9). The total ΔV and time cost of the cycler transition is 68 m/s and 58 days (i.e., about two lunar cycles), respectively.

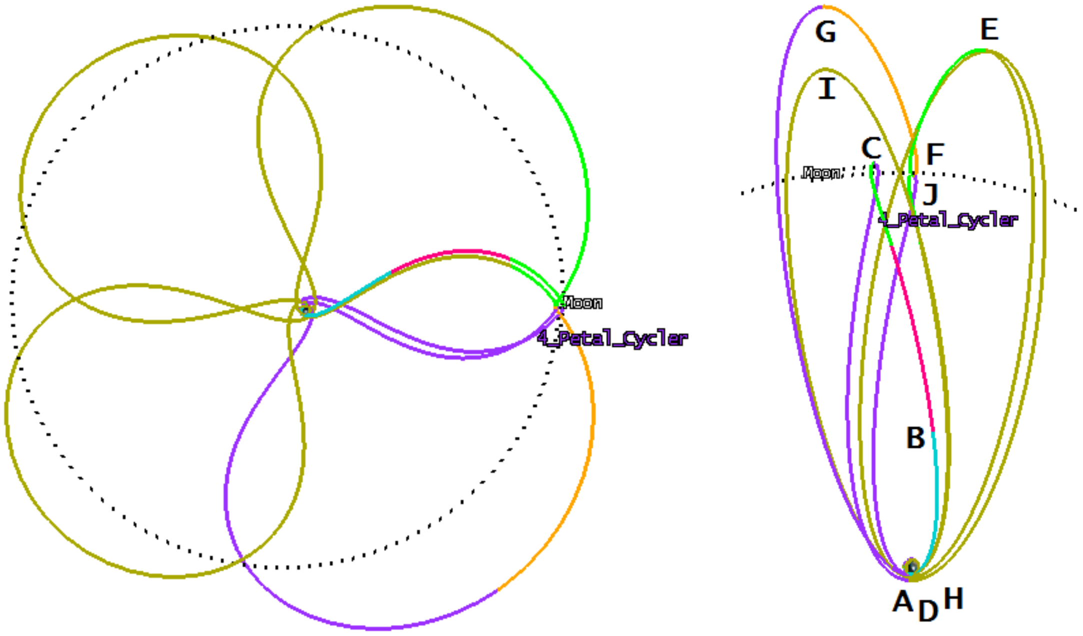

Figure 7. 4-Petal Cycler, shown in Earth-Moon rotating frame (left) and Earth inertial frame (right). Originally discovered by Arenstorf[14] in 1963.

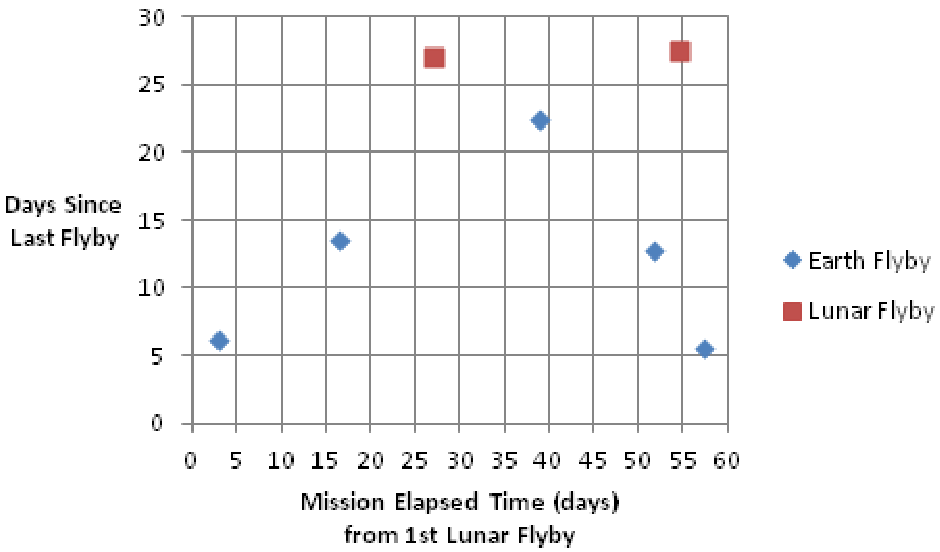

Figure 8. Time spent between Earth and Moon close-encounters, starting from the first lunar flyby. As seen, the cycler spends about 7 days between Earth encounters on legs including the lunar flyby, the latter of which occurs every 27.5 days. In the holding orbits, about 13 days is spent between Earth encounters (these holding orbits have super-lunar apogee altitudes).

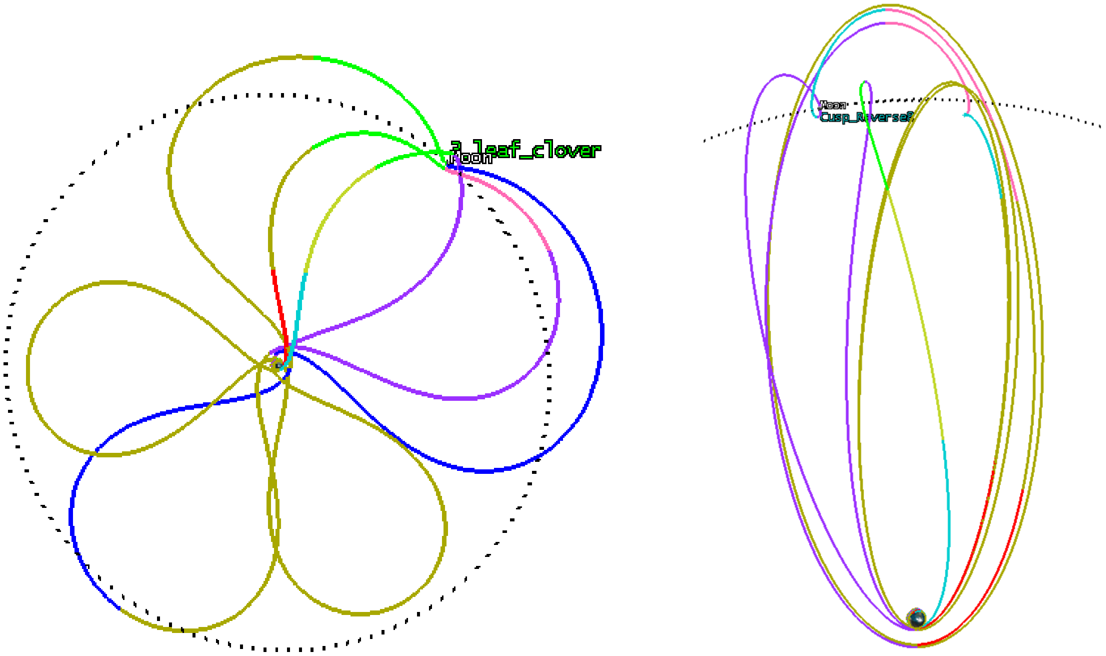

Figure 9. Transition from 3-Petal to 4-Petal Earth-Moon Cycler via trailing edge lunar flyby. Shown in Earth-Moon rotating (top-left and bottom) and Earth inertial (top-right) frames.

Launched Crew Rendezvous with 3-Petal Earth-Moon Cycler

The trajectory shown in Fig. 10, shown in an Earth inertial frame, begins with a launch (Fig. 10, A) from KSC (C3 = -2 km^2/s^2) on an Earth-return free-return trajectory (similar to that flown in the *Apollo* program). One half day after launch (Fig. 10, B), an out-of-plane maneuver (84 m/s of ΔV) is performed to match the cycler's inclination in the lunar orbit plane to allow rendezvous with the cycler 300,000 km from Earth (Fig. 10, C), before the apogee of the first holding orbit following a lunar swingby. It takes about 2 days to rendezvous with the cycler, with 43 m/s of ΔV required for the associated final rendezvous maneuver (performed at C in Fig. 10).

More analysis is needed to understand the ΔV requirement trade space, which will include varying the time of maneuvers and time of rendezvous with the cycler craft. For launch latitudes much higher than the 24 degrees contained in the cycler, rendezvous may be better suited following a lunar flyby, so as to use the flyby to change the orbital plane without the use of propellant.

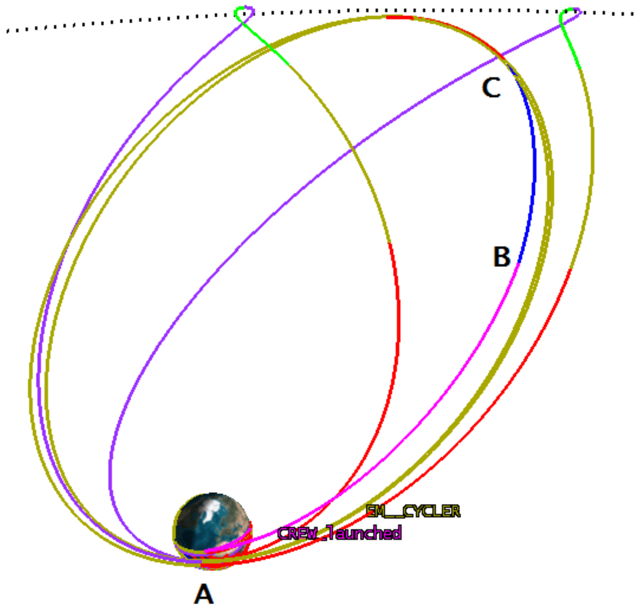

Figure 10. Crew Rendezvous with Earth-Moon Cycler from launch at Kennedy Space Center (KSC). 84 m/s out of plane maneuver performed 0.5 days after launch (pink to blue transition). Rendezvous (ΔV = 43 m/s) w/ cycler occurs 300,000 km from Earth in the first gold phasing orbit.

Crewed Rendezvous with Lunar Space Station from 3-Petal Earth-Moon Cycler

Since the cycler's inclination is about 174 degrees in the Moon true-of-date (TOD) frame, an ideal orbit for a lunar space station is circular and inclined at 180 degrees, since the right ascension of the ascending node (RAAN) is indeterminate in the equatorial plane and the argument of perilune is indeterminate in a circular orbit, thus highly simplifying the rendezvous procedure. An initial altitude of 500 km was chosen for the lunar space station, given its stability over a 5 year period with no station-keeping maneuvers (Fig. 11). The 500 km is low enough to significantly benefit from the Oberth effect with regard to lunar orbit insertion (LOI) and lunar escape ΔV costs (to be shown).

To rendezvous with the lunar space station, the crew departs the cycler at perigee to target a 500 km (instead of 3,000 km) altitude upon lunar approach and perform a perilune (Fig. 12, A) braking maneuver (ΔV of 325 m/s) to enter a 12-hour period lunar orbit inclined at 174 degrees in the lunar equatorial frame. When the spacecraft's orbit plane intersects the lunar equatorial plane (Fig. 12, B), a maneuver (88 m/s of ΔV) is performed to change the inclination to the required 180 degrees. At the following perilune (Fig. 12, C), the final braking maneuver (ΔV of 492 m/s) is performed to circularize the orbit and rendezvous with the lunar space station. An additional 32 m/s was needed for cycler-separation, lunar flyby targeting, and lunar phasing bringing the total ΔV requirement to 947 m/s, within 100 m/s of a typical LOI ΔV requirement from a free-return trajectory.

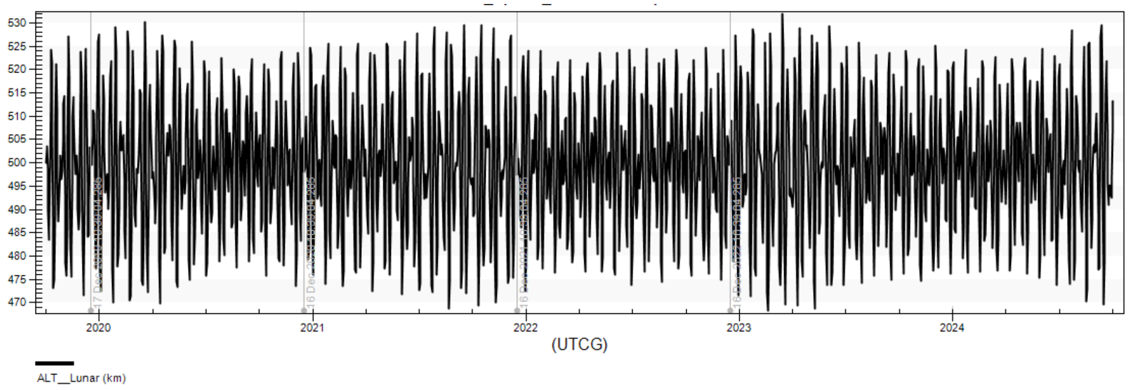

Figure 11. Long-term propagation of 500 km circular orbit at 180 degrees for Lunar Space Station. High-Fidelity model, Moon gravity: 100X100, Earth: 40X40, Sun 4X0, SRP, TRP. Altitude is relatively stable (no station-keeping) over 5 year propagation (range about 470 to 530 km).

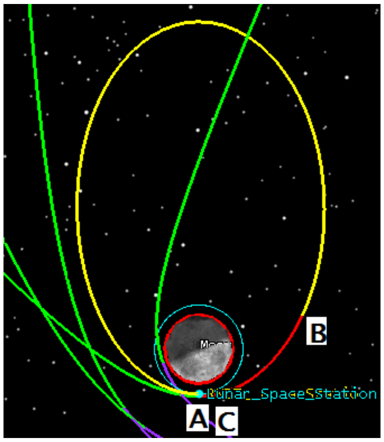

Figure 12. Crew Rendezvous w/ Lunar Space Station in 180 degree, 500 km circular orbit. Orbit plane change performed at farthest (from perigee) crossing of spacecraft's orbit plane with the lunar equatorial plane; 82 m/s needed above to change inclination about 7 degrees.

Crewed Rendezvous with Earth-Moon L2 Halo Orbit Space Station from Cycler

Departing the 3-petal Earth-Moon Cycling interplanetary cruise ship, a smaller craft imparts 11 m/s of ΔV at perigee on June 17, 2018 (Fig. 13, A). This sends the craft toward the Moon for a trailing edge powered flyby (ΔV of 184 m/s) at 1,000 km perilune altitude on June 22, 2018 (Fig. 13, B). The craft reaches the point of halo orbit insertion (ΔV of 54 m/s) near Earth-Moon L2 on July 4, 2018 (Fig. 13, C), about 17 days after departing the Earth-Moon Cycler. The total ΔV requirement is 249 m/s.

More analysis is needed to understand the ΔV requirement trade space, which will include varying the time of maneuvers and time of halo orbit insertion.

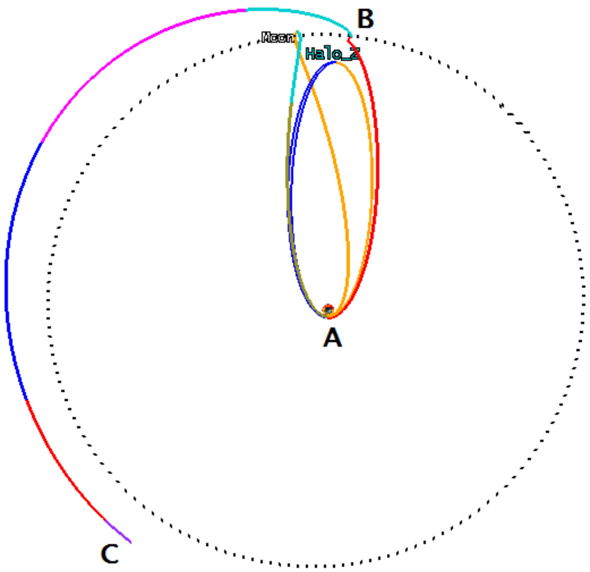

Figure 13. Crew Rendezvous w/ Earth-Moon L2 Halo Orbit after departing the Earth-Moon Cycler. Powered lunar flyby (184 m/s ΔV) performed for this 17-day transfer solution.

Crewed Rendezvous with Other Interplanetary Destinations from Cycler

Time and ΔV requirements to reach other interplanetary destinations, including a distant retrograde orbit (DRO), near-Earth object (NEO), and Mars will be analyzed.

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