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Lunar Cycler Orbits with Alternating Semi-Monthly Transfer Windows

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This paper is a presentation of a new type of cislunar transfer orbit that has encounters with the Moon twice per month every other month. The use of this technique is suggested for Earth-to-Moon Cycler spacecraft that contain the heavy and expensive life support equipment for human transfer from low Earth orbit to the Moon and for logistical supply of lunar bases. The basis for the technique is a 180° near-circular Moon-to-Moon transfer orbit that is inclined to the Earth-Moon plane by an angle that is compatible with a low-inclination, near-minimal energy Earth-to-Moon transfer orbit. Also included are preliminary discussions of Cycler spacecraft logistics for extensive manned operations on the Moon. Numerical studies are included to verify the usefulness of the technique in a realistic cislunar dynamic environment and estimates of navigation propellant requirements are given.

Introduction

In 1985, Aldrin [1]suggested the use of Cycler orbits (periodic trajectories that repeat the round-trip transfer from home planet to destination planet) for the life support equipment and logistical supplies necessary for extensive manned exploration of the Moon and Mars. He also presented his thoughts on the benefits of using Cycler spacecraft at the Space 88 Symposium in Albuquerque during a panel discussion on "Approaching the Construction Problems in Space." These trajectories must have the characteristic that they can be easily targeted for either launch or destination planet and that the times between encounters yield a reasonable stay time on the destination and provide for both routine and emergency return on a fairly regular basis.

In 1989, Uphoff [2] showed how the strength of the lunar gravity field can be used to yield a high-inclination (~45°) near circular Moon-to-Moon transfer trajectory that is compatible (has the same Jacobian constant) with a low-energy, low-inclination transfer from LEO to the Moon. This transfer orbit was dubbed "the BackFlip" in Reference 2 and was suggested there as a means of reversing the phase of Double Lunar Swingby [3] trajectories. In this paper we recommend the use of the same technique for semi-permanent logistic Cycler spacecraft which contain the life support equipment for the astronauts in transit to and from the Moon as well as storage facilities which provide a round-trip propellant depot capability.

This paper contains a description of the BackFlip concept, a 180° Moon-to-Moon transfer that permits two lunar encounters in about 14 days. Also discussed are unsuccessful attempts to find sequences that permit the immediate repeat of the BackFlip so as to maintain continuous encounters every 14 days. It turns out that such trajectories are possible but require a retrograde orbit ($i > 130°$) that is incompatible with low-energy Earth-to-Moon trajectories. Our solution to this problem is to insert a one-month lunar return holding orbit into the sequence of Earth-Moon-Moon-Earth transfers. In this way, it is possible to achieve semi-monthly Moon-Earth transfer windows using only two Cycler spacecraft. This technique has the added advantage that the two Cycler spacecraft can easily be joined together in case of emergency or to build onto an existing Cycler structure. These Cyclers require no nominal ΔV to remain on station and require targeting maneuvers of the order of a few meters per second per month to transfer between the constituent orbits even during extensive operations.

This methodology is sometimes perceived as a curiosity because, at first sight, it appears not to save any substantial ΔV. Moon-bound travelers must take a taxi from LEO to the Cycler and then another taxi from the Cycler to lunar orbit or lunar surface. The real savings come from the ability of the Cycler to provide propellant depot capability, safe-haven for astronauts during solar storms, and the fact that the heavy life-support equipment must be lifted from LEO only once. These and other advantages are discussed below.

Cislunar Transfer Basics

Most of the calculations required to study the trajectories presented here can be accomplished using the zero-sphere-of-influence (or point-to-point) patched-conic technique described in [2] and [4]. Of great conceptual assistance is the Jacobian integral [5] in the circular restricted three-body problem. It can be shown that the zero-patched conic method satisfies the Jacobian integral in the circular restricted problem to within terms of the order of the mass ratio of the two primaries and the normalized Moon-passage distance. After the fundamental quantities are established using these approximations, one can verify the usefulness of the trajectories using full-model numerical integration to include the effects of solar gravitational perturbations and other disturbances not included in the preliminary model. It is important, however, to use the vector methods described below (and in [2]) so as to include the effects of the ellipticity of the Moon's orbit.

The Dynamics of Moon-Passage

Figure 1 is a velocity diagram of the relevant quantities in a typical lunar swingby showing the velocities in an Earth- relative frame and their analogs in a Moon-centered coordinate system. If $\mathbf{V}_{IN}$ is the Earth-relative velocity vector on the transfer at lunar encounter (before the swingby), then $V_{\infty\, IN} = \mathbf{V}_{IN} - \mathbf{V}_M$, is the incoming hyperbolic excess velocity of the Moon passage hyperbola and $\mathbf{V}_M$ is the Moon's velocity vector (not necessarily perpendicular to the Earth-Moon vector). The transformation back to Earth-relative velocities after the swingby is given by, $\mathbf{V}_{OUT} = \mathbf{V}_M + \mathbf{V}_{\infty OUT}$.

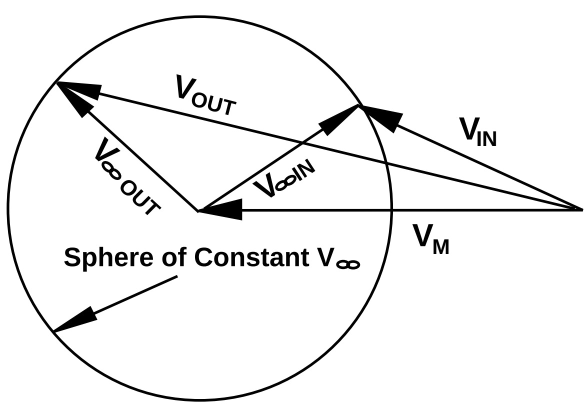

Fig. 1 Zero-Patched Conic Velocity Diagram

The key to the zero-patched conic method is to require

$$|V_{\infty OUT}| = |V_{\infty IN}|$$

and then to treat the swingby as a two-body problem during Moon passage. This technique is nearly identical to the one used by Rutherford in his famous analysis of the scattering of alpha particles in the early days of nuclear Physics.

The required angle, α, between the incoming and outgoing excess vectors can be obtained from the vector relationships above. The eccentricity of the hyperbola is then found from $\arcsin(1/e) = \alpha/2$, and the radius of perilune passage is obtained as $r_p = \mu(e-1)/v_\infty^2$. These methods have been applied to the lunar swingby problem for many years and usually provide starting conditions that are sufficiently accurate to begin a full-model simulation or targeting procedure.

The BackFlip or 180° Moon-to-Moon Transfer

In [2], a powerful technique for cislunar orbit shaping was presented; it was suggested there as a means for quickly reversing the phase of Double Lunar Swingby trajectories. This technique, called "the BackFlip", can be used for many cislunar applications and forms the dynamical heart of the repeating Cycler orbits presented here.

The velocity vector diagram shown in Fig. 2 is an example of a very useful devise due to P.H. Roberts [4] that shows the loci of achievable post-swingby trajectories for situations where the spacecraft is constrained to maintain certain energy values. In Fig. 2, the conditions for achieving a near-180° Moon-to-Moon transfer are shown. The figure shows two fundamental spheres representing the loci of trajectories that have equal Earth-relative energies after the swingby (Equal Energy Sphere centered on the tail of the Moon's velocity vector) and the loci of trajectories having equal Moon-relative excess speed (Equal V_∞ Sphere centered on the head of the Moon's velocity vector). Of course, the zero-patched conic method (and the constancy of the Jacobian integral) demand that all outgoing trajectories have the same value of V_∞ as the incoming trajectory.

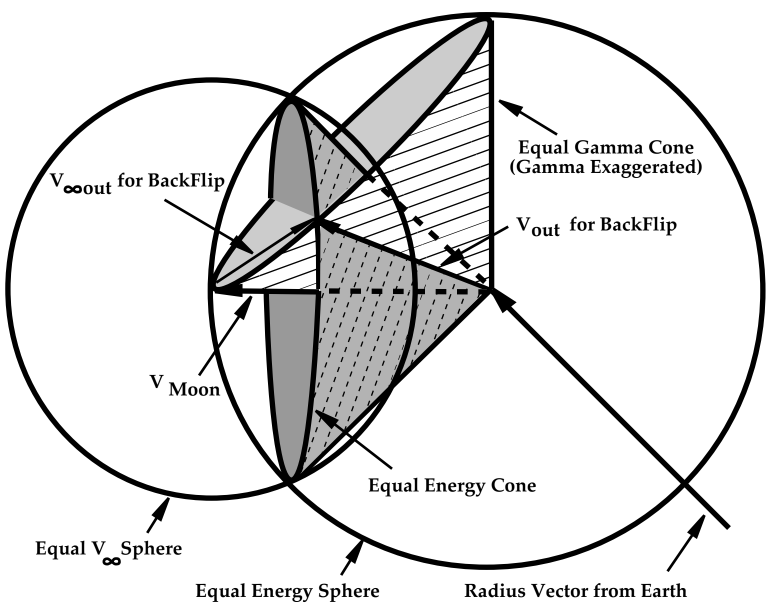

Fig. 2 Velocity Vector Diagram for BackFlip

The objective of the BackFlip is to transfer from Moon to Moon in approximately half a lunar month (about 14 days). A little reflection on Lambert's theorem will show that this is possible (for transfer angles less than 360°) only if the transfer orbit has the same orbital energy as the Moon's orbit with respect to the Earth. Thus, the BackFlip must have the same Earth-relative speed as the Moon immediately after the swingby ($|\mathbf{V}_{OUT}| = |\mathbf{V}_{M}|$) and the outgoing Earth-relative velocity vector must lie on the Equal Energy Cone shown in Fig. 2. This cone has its apex at the Moon's center and is truncated by the circle representing the intersection of the Equal V_∞ Sphere and the Equal Energy Sphere.

Not only must the BackFlip orbit have the same orbital energy as the Moon, it must have the same ellipticity ($e \approx 0.055$) if it is to go from where the Moon is at the time of the first encounter to where the Moon will be half a revolution later. The conditions for the BackFlip therefore require that the outgoing Earth-relative velocity vector have the same path angle as the Moon at the first encounter. This condition is represented by the (much exaggerated) Equal Gamma Cone in Fig. 2. Thus, for a given incoming $|\mathbf{V}_{\infty IN}|$, there are only two outgoing Earth-relative velocity vectors that will yield the half-month Moon-to-Moon transfer, those represented by the intersections of the Equal Energy and the Equal Gamma Cones in the figure. The two options correspond physically to 180° transfers above and below the Earth-Moon plane respectively. In the figure, only one of the vectors is shown.

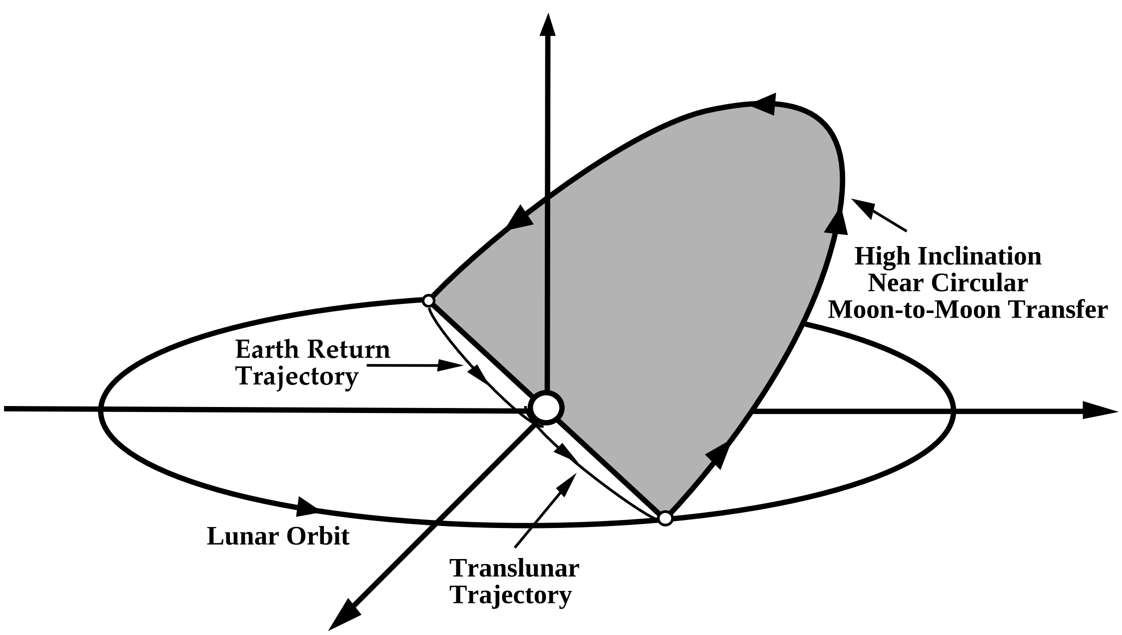

Fig. 3 The BackFlip -- 180° Moon-to-Moon Transfer

Figure 3 shows a physical view of the BackFlip as it was presented in [2] where the technique was suggested as a means of reversing the phase of Double Lunar Swingby [3] trajectories or, indeed, of most cislunar trajectories, in a minimum of time without the need for on-board propulsion. The figure shows the near-minimal-energy Earth-to-Moon transfer trajectory, the Moon-to-Moon transfer, and an Earth-return trajectory. The entire sequence shown can be accomplished without the need for propulsion beyond that required to insert into the initial trans-lunar trajectory and small navigational impulses required to ensure the proper aim-points for the lunar encounters. The lunar passage distances for these encounters are of the order of 4000 to 8000 km, well above the lunar surface. Errors in aim-point at the first encounter can be corrected by the application of a few meters per second of ΔV, applied in the early portion of the BackFlip trajectory, to ensure the second lunar encounter.

In [2], the global conditions for the inclination of the BackFlip were given in the framework of the circular restricted three-body problem. Jacobi's integral of that problem can be approximated by the linear combination of energy and axial angular momentum in a non-rotating Earth-centered frame as $C = E - n' h_Z$ where E represents the Earth-relative orbital energy of the particle or spacecraft, n' is the orbital mean motion of the Moon, and h_Z is the component of spacecraft orbital angular momentum normal to the plane of motion of the two primary bodies. In terms of more familiar orbital elements, the approximated integral can be written

$$C = -\mu/2a - n' [\mu a(1-e^2)]^{1/2} \cos i.$$

This relationship is known to astronomers as Tisserand's criterion for the identification of comets that have made a close approach to a planet between apparitions. The equation refers to times when the spacecraft (or comet) is well away from the disturbing body because there are other terms in Jacobi's integral that are of the order of the mass ratio and the normalized passage distance. Szebehely's book [6] has excellent discussions of Jacobi's integral and its importance to research in the restricted three-body problem.

Above, μ is the gravitational constant of the central primary (Earth), a and e the semi-major axis and eccentricity of the orbit, and i is the inclination of the orbit with respect to the Earth-Moon plane. This relationship is particularly useful for design and study of lunar Cycler orbits because, in the circular restricted problem, the value of C must remain constant no matter how many times the spacecraft encounters the Moon. Furthermore, in any one swingby,

$$\Delta E = n' \Delta h_Z.$$

This simple relationship means that the change in Earth-relative energy caused by any lunar swingby will be accompanied by a change $\Delta E/n'$ in the component of angular momentum that is normal to the Earth-Moon plane.

An understanding of the relationship between energy and axial angular momentum allowed us to write down the inclination [2] of the BackFlip orbit in terms of the shape and inclination of the Earth-to-Moon transfer orbit, viz.

$$\cos I = \frac{\left[-\frac{\mu_E}{2a'} - C_T\right]}{n'\sqrt{\mu_E a' (1 - e'^2)}},$$

where the primes refer to the Moon's orbit, μ_E is the Earth's gravitational constant, and

$$C_T = -\mu_E/(2a_0) - n'[\mu_E\, a_0(1-e_0^2)]^{1/2} \cos i_0.$$

The subscript 0 refers to the initial Earth-to-Moon transfer orbit and the inclinations are with respect to the Earth-Moon plane. Note that [2] has a sign error on the energy term in the expression for cos I.

It is important to note that lunar gravitational perturbations act on the spacecraft in a cumulative way during the BackFlip transfer. Indeed, the spacecraft never gets farther from the Moon than $a'\{2(1-\cos\ I)\}^{1/2}$ or about 78% of the Earth-Moon distance during the BackFlip transfers used for the Earth-Moon-Moon-Earth Cycler trajectories. These perturbations were the subject of some concern during early attempts to define full-model simulations of the BackFlip. Because the lunar perturbations act nearly perpendicularly to the spacecraft's velocity vector, however, their effect on orbital energy is small and their net effect on the transfer is to move the orbital node on the Earth-Moon plane a few degrees in the retrograde direction. This results in transfers a few hours shorter than those predicted by the zero-patched conic approximations but, in no case did the perturbations interfere with the targeting procedure enough to obviate the desired Moon-to-Moon transfer.

The Reflected BackFlip - A Family of Periodic Orbits

During the search for viable lunar Cycler orbits, undertaken at the suggestion of Dr. Aldrin, we investigated the possibility of transferring directly from one BackFlip orbit to its reflection off the Earth-Moon plane. Such a scheme would be ideal for a single Cycler spacecraft as it would provide twice-monthly Earth return opportunities. Unfortunately, such trajectories that are compatible with realistic Earth-Moon transfer orbits ($V\infty > \sim 0.7$ km/s) require a lunar encounter with perilune substantially beneath the lunar surface. We include this section on the reflected BackFlip because it helps illuminate the process of discovery, because it helps explain the need for the alternating holding orbits described later, and because the trajectory is an example of a family of periodic orbits in the three-dimensional circular restricted three-body problem. Study of this family may lead to important academic insights and analytic continuation. There may also be practical applications for the retrograde ($I > \sim 135°$) reflected BackFlip which is compatible with launch conditions for some asteroid and comet missions.

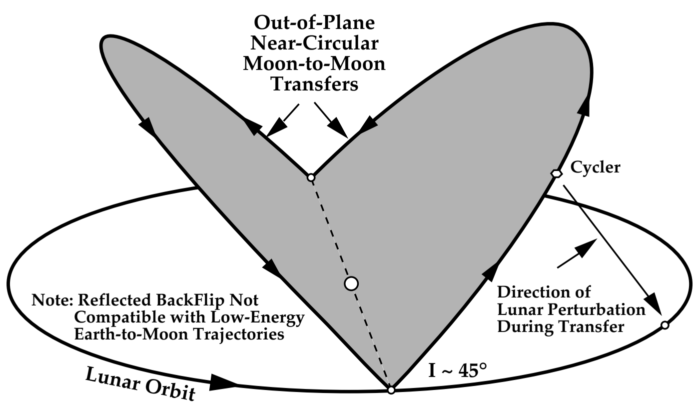

Fig. 4 Prograde Reflected BackFlip

Figure 4 is a diagram of the reflected BackFlip trajectory shown in the sidereal (non-rotating) coordinate system. These trajectories require sub-surface encounters with the Moon for inclinations less than about 130° in the idealized case where perturbations are not considered during transit. For low inclinations ($I < \sim 25°$), these trajectories become highly perturbed during transit and evolve into a class of orbits studied by Breakwell and others [7-10] as early as 1962 and suggested as a mechanism for launching out-of-ecliptic interplanetary probes that return to Earth more often than every six months. The early studies dealt with the interplanetary equivalents of the (relatively) unperturbed BackFlip transfers used in the Lunar Cycler mechanism described below. In our search for viable out-of-plane Moon-to-Moon transfers, we generated low-inclination, highly perturbed trajectories similar to those suggested by Breakwell and Gillespie [7]. These trajectories, although very interesting and potentially useful for other applications, required very low (< 0.4 km/s) values of V_∞ with respect to the Moon. They were abandoned for the Lunar Cycler application because they are not compatible with low-energy Earth-to-Moon trajectories.

The statements above require some clarification. It is not impossible for minimal energy Earth-to-moon transfer trajectories to arrive at the moon with the low excess speeds required for the prograde reflected backflip - but it is impossible in the context of the circular restricted *three-body* problem. When the gravitational influence of the Sun is considered, as in Belbruno's [11] transfers through what he calls the weak stability boundary in the Sun-Earth-moon-spacecraft *four-body* problem, then the solar gravitational perturbations can change the orbital angular momentum without greatly affecting the orbital energy. This, in turn, can disrupt the linear relationship, given above, between the change in energy and the change in axial angular momentum. That is to say that the solar gravity can be used to change the value of the Jacobian constant in the Earth-moon-spacecraft system and, therefore, change the moon-relative energy of the spacecraft during close lunar encounter. But such transfers require a trip to the region near the sphere of influence of the Sun-Earth system. As these transfers require from 4 to 6 months, they are not practical for the short (days to weeks) lunar cycler transfers we seek for regular transport of humans and perishable life-support supplies. Without benefit of solar gravity, spacecraft leaving the moon with excess speeds of less than 300 m/s cannot have subsequent perigee distances less than about 120,000 km no matter how many lunar swingbys are used.

The process of reflection may, however, offer some academic insight into the circular restricted three-body problem. Because the reflected BackFlip is invariant under a reversal of time, and, because the particle returns twice per month to the same position in the rotating frame, the orbit is periodic with respect to that frame. If the regression of the node on the Earth-Moon plane is commensurable with the lunar motion, the orbit is also periodic in the sidereal or non-rotating system although the period may be very long. These orbits seem to correspond to the "collision" cases of the families of almost rectilinear halo orbit families between the two colinear libration points studied by Breakwell and Brown [8] and by Howell [10]. The reflected BackFlip is almost certainly unstable although we have not studied the linear variational equations or even regularized the equations, hoping to return to this very interesting problem in the near future.

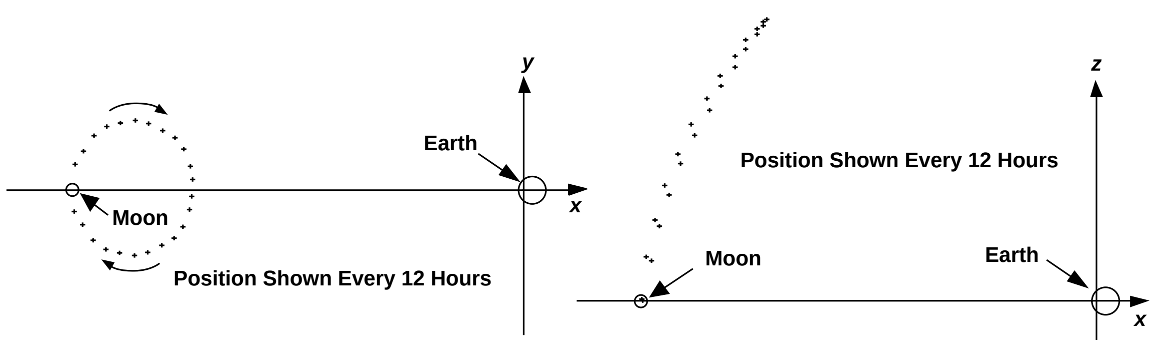

Fig 5 Trajectory of the Reflected BackFlip in the Synodic Frame

Figure 5 shows the motion of the BackFlip orbit in a rotating frame whose x axis points from Moon to Earth, whose z axis is normal to the Earth-Moon plane, and whose y axis completes a right-handed system. The slight asymmetries shown are due to the facts that the orbit was not targeted exactly for reflection and that the numerical integration from which the graphs were made included the ellipticity of the lunar orbit, the solar gravitational perturbations, and the physical libration of the Moon. Nevertheless, the symmetry of the problem and the nature of the curves show the periodicity of the reflection process. Note that the orbit is not symmetrical with respect to the xy plane and that the particle appears to "bounce" off the Earth-Moon plane at the encounters. It is also of some interest to note that another whole family of orbits exists out of the plane by the use of odd $n\pi$ transfers with $n = 3,5,...$ A. Kogan [12] has devised a method of deep-sky survey using a combination of a planar arc and a 540° out-of-plane Moon-to-Moon transfer. The arcs are joined by a practical lunar swingby. Kogan showed that the sequence is periodic in the synodic system and, therefore, repeatable for continuous practical application.

During the review process for this paper, one of the referees suggested that the exact conditions for the reflected BackFlip be published so that others may reproduce the results without undue difficulty. Since the publication of the preprint, we have performed a few numerical studies in the circular restricted problem with $\mu = 0.0121516$, the mass ratio in the moon-Earth problem. These studies revealed that the following particular solution (see Table 1.) is periodic to the order of the (direct) hunting procedure and the accuracy of the numerical integrations.

$x_0 = -0.9879360$,	$y_0 = 0.0$	$z_0 = -0.0019897$
$dx/dt_0 = 0.0$	$dy/dt_0 = 3.508312$	$dz/dt_0 = 0.0$
At time, $t = 2.54439$ normalized units:		
$x = -0.9879335$,	$y = 8.0 \times 10^{-7}$	$z = -0.0019912$
$dx/dt = -0.0267222$	$dy/dt = 3.5069625$	$dz/dt = 0.0008999$

Table 1. Initial and Final Conditions for Periodic Orbit

In Table 1, the usual conventions are used with the Earth-Moon distance = 1.0, the origin is at the barycenter, the mass of the system is 1.0, the mean motion of the primaries is 1.0, and the period of motion of the primaries about each other is 2π. The maximum z aquired is about 0.4 and the unnormalized passage distance is about 766 km, well below the surface of the moon.

It is interesting to note that this trajectory is within the region considered strongly perturbed by the moon during transit and that attempts to continue this solution by numerical means into the region of the solutions represented by Fig. 5 have been unsuccessful. Indeed, the local minima of the performance parameter reach a barrier in the function space of z_0 and dy/dt_0 which is suggestive of bifurcation of the phase space.

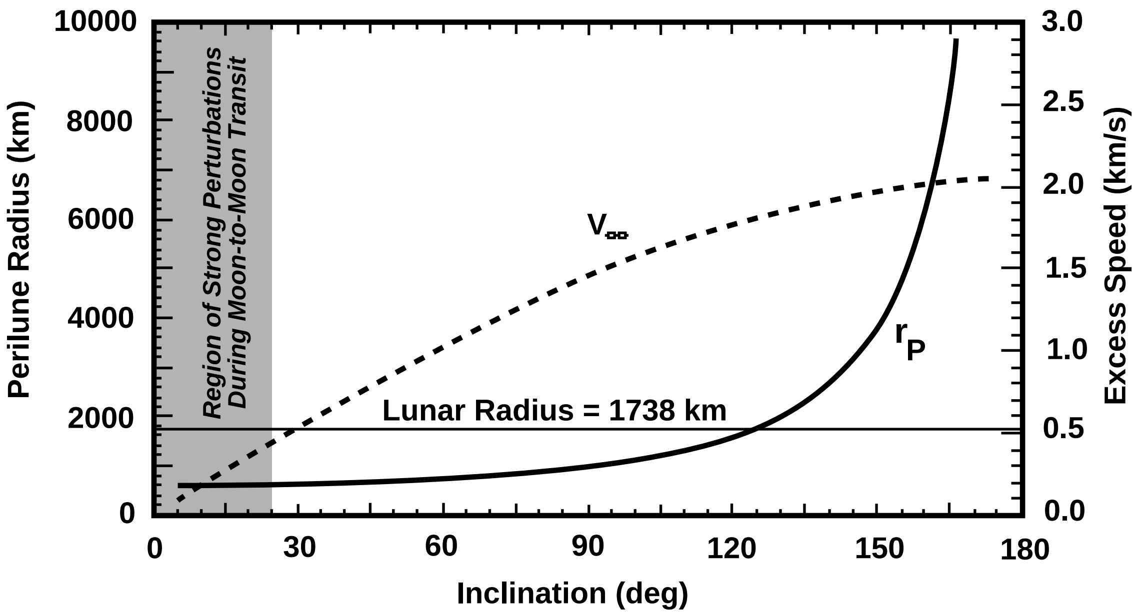

Fig. 6 Requirements for Idealized Reflected Lunar BackFlip

Figure 6 shows the conditions for the reflected BackFlip in the idealized circular restricted three-body problem where the term idealized refers to the assumed absence of perturbations in transit from Moon to Moon. The figure shows the required passage distance and Moon-relative excess speed for the reflection as a function of idealized inclination of the Moon-to-Moon transfer. The value of V_∞ is given by $\{2V_M^2\,(1 - \cos I)\}^{1/2}$ and the perilune distance during the reflecting encounter follows from $\sin(\alpha/2) = V_M \sin I / V_\infty$.

The idealized requirements are not valid for inclinations less than about 25° ; indeed, for inclinations less than about 9°, the spacecraft never even leaves the Moon's ~60000 km sphere of influence and the perturbations are quite strong throughout the transfer. For retrograde Moon-to-Moon transfers, even though the trajectories are practicable, the required excess speed is far too high to be compatible with low-energy Earth-to-Moon transfers. Thus, in spite of the interesting and possibly useful nature of the reflected BackFlip, we were forced to abandon its use to ensure return to the Moon twice per month for a single Cycler. We hope to return to the retrograde reflection in future studies as a potential holding and propellant-depot orbit for spacecraft preparing for departure to Mars or to a near-Earth asteroid or short-period comet.

The Holding Orbit

The failure of our attempts to provide twice-monthly Earth return windows using a reflected BackFlip maneuver, and the impracticality, in the Earth-Moon system, of "standoff" encounters† that do not affect the trajectory led us to insert an elliptic, one-month return orbit

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† In the Jupiter satellite tour problem[4], because of the small mass ratio, it was possible to target away from the encounter without substantially affecting the phasing of the orbit so that the spacecraft could return to the same satellite after one or more revolutions of the spacecraft in its orbit. These encounters were dubbed "standoff" encounters. In the Earth-Moon system, this technique is not viable because of the large mass ratio.

into the sequence for the Lunar Cycler. The sequence is shown in Fig. 7 where, as before, the Earth-to-Moon transfer is shown followed by a BackFlip transfer. At this second lunar encounter, we wish to have the option to target for either an Earth return or a lunar return transfer. If the Earth-return option is not desired (e.g. if there is no one at lunar base or lunar orbit who wishes to come home), the Cycler is targeted for an elliptic holding orbit that returns to the Moon after one revolution in its one month orbit.

This holding orbit will normally occur after a BackFlip transfer and will therefore require an inclination change to accompany the change in eccentricity as the energy of the orbit must remain constant before and after the second lunar encounter. An important characteristic of the holding orbit is that it be capable of being targeted for either an Earth-return or another BackFlip when it returns to the Moon after its one revolution transfer. This pattern will provide three Earth-return opportunities every two months using a single Cycler and without disrupting the pattern of viable Moon-to-Moon transfers during times when it is desired not to select an Earth-return transfer. Thus, the Cycler, once placed in its out-of-plane, one-month period orbit, can simply continue to switch from a BackFlip orbit to a holding orbit for as long as required until an Earth-return trip is desired. Then, a few meters per second applied a few days before the previous encounter will be sufficient to retarget the Cycler for an Earth-return trajectory that has a period of 1/2 month (or 1/3 month is some cases) in order to ensure return to the Moon after 2 (or 3) revolutions of the Cycler in its Earth-return orbit.

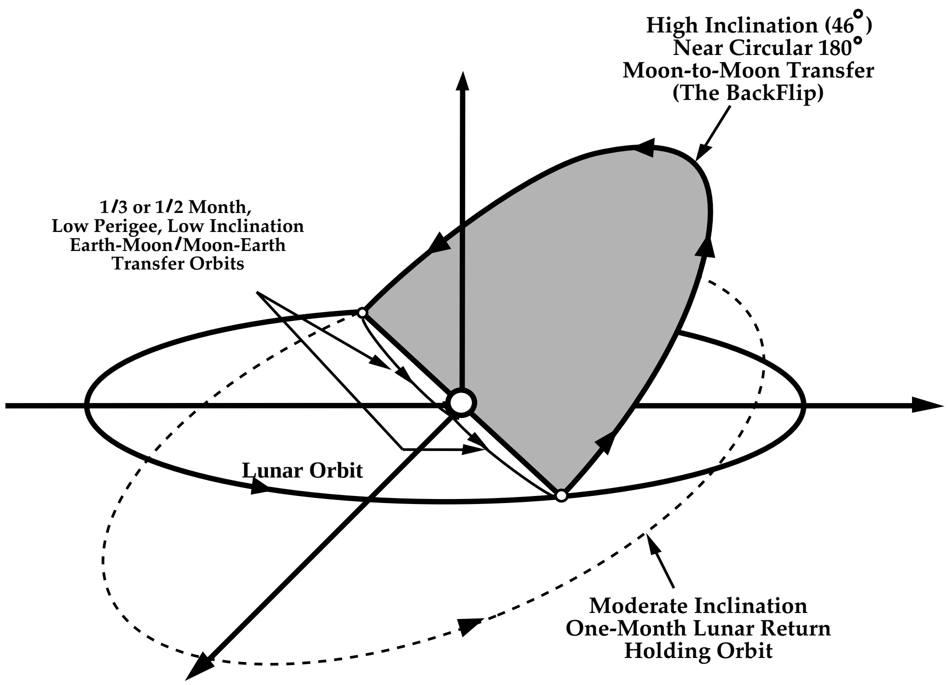

Fig. 7 Encounter Geometry for Cycler with BackFlip and Holding Orbit

It should be kept in mind that the entire sequence must be capable of repeating in any case. No transfer should take place that requires substantial ΔV to re-establish the pattern. The major advantage of the Cycler is that it can be large and massive so that the entire program can benefit from the life-support systems, radiation shielding, and propellant depot capabilities of the Cycler. This heavy equipment must be lifted to translunar orbit only once. If the repeating

Earth-Moon...Moon-Earth pattern is disrupted, proportionately large amounts of propellant or time will be required to restore the sequence.

The Earth-return transfers must, therefore, be resonant with the lunar motion. The most practical Earth-return transfers have periods of 1/2 month and 1/3 month. The 1/3 month transfers are not always available because the apogees of these orbits do not reach the lunar apogee. In some cases, it may be efficacious to use an Earth-return orbit that is 2/5 resonant with the lunar motion although, in these cases, the Cycler will not return to the Moon for 2 months. The inclination of these orbits with respect to the Earth-Moon plane will be slightly different in each case. The differences are slight because, for these highly elliptic orbits, the Jacobian constant is dominated by the energy term. For most applications involving the return of astronauts to low Earth orbit, the selection of the particular resonance will not affect the propellant requirements for the transfer vehicles because most of the maneuvers will be accomplished using aerobraking. For resupply and Cycler expansion missions, however, there will be an advantage to scheduling these missions for a time when the (near minimal energy) 1/3 month Earth-Moon-Earth transfer can be used.

Adding More Cyclers

The encounter sequence recommended above is compatible with the addition of other Cycler spacecraft that can increase the frequency of Earth-return opportunities and can provide for rendezvous and/or joining of two Cyclers. If the sequence above is followed, two Cyclers can provide semi-monthly Earth-return opportunities for as long as required. Once every 1 and 1/2 months, the two Cyclers can rendezvous with each other to trade supplies or to remain together as a larger station while a third Cycler takes the now-empty place of one of the first two.

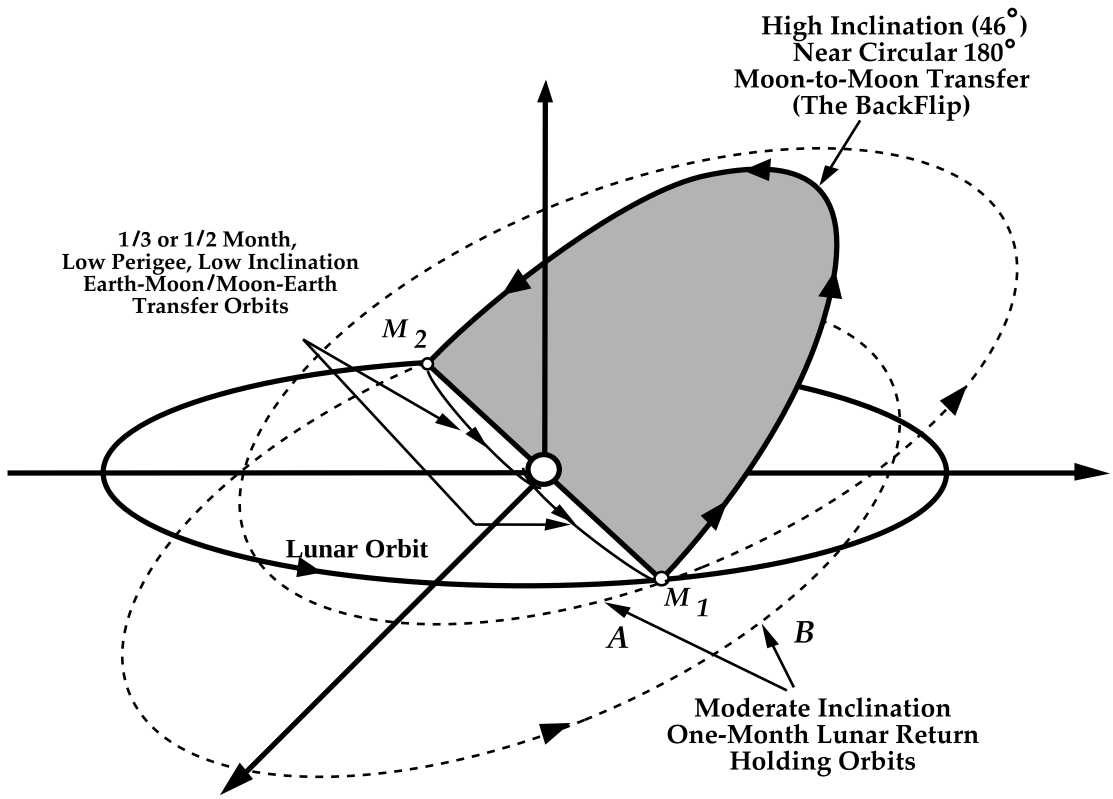

Fig. 8 Encounter Geometry Using Two Cyclers

Clearly, the phasing of the two Cyclers must be selected carefully if these advantages are to be had. Further, there appears to be only one way to provide twice-monthly Earth-return windows using only two Cyclers. The "trick" is to ensure that both Cyclers encounter the Moon at essentially the same time somewhere in the sequence.

Figure 8 is a diagram of the Cycler system showing two holding orbits. Only one BackFlip orbit is shown to avoid obscuring the figure. The reader is asked to imagine the BackFlip to be movable in the figure. Because the BackFlip orbit can be entered from any of the other orbits (except another BackFlip), it can be mentally inserted whenever necessary. The sequence is as follows. Suppose one Cycler encounters the Moon at M_1 and enters the BackFlip orbit shown in the figure while a second Cycler (also at M_1) enters holding orbit A. The first Cycler will return to the Moon 1/2 month later at M_2 where it enters holding orbit B. At this time, the second Cycler has completed 1/2 of its lunar return transfer on holding orbit A. When the Moon returns to M_1, so does the second Cycler which now enters the BackFlip orbit shown on the figure. At this time, the first Cycler is halfway around holding orbit B. When the second Cycler completes its BackFlip at M_2, the first completes its holding orbit B and both Cyclers encounter the Moon simultaneously at M_2. The first Cycler now enters a BackFlip from M_2 to M_1 (not shown) while the second Cycler (just completing a BackFlip) enters holding orbit B. The entire sequence repeats with the roles of the Cyclers and the points M_1 and M_2 reversed. After three months, the sequence repeats exactly. Notice that the two-Cycler sequence provides Earth-return opportunities twice per month whereas the single Cycler scenario yields 3 return windows in 2 months.

Now consider the situation when one of the Cyclers is targeted for an Earth-return transfer. If the Earth-return orbit is entered from a BackFlip orbit, the phasing will remain the same as if the homeward-bound Cycler had entered a holding orbit; the Cycler will return to the Moon in one month and can enter its scheduled BackFlip. If the Earth-return orbit is entered from a holding orbit, however, the phasing relationship of the two Cyclers will be disrupted because the Earth-return orbit will not return to the Moon for a full month rather than the 1/2 month return it would have made if it had entered a BackFlip orbit instead of the Earth-return orbit. The solution is simple; do the same thing with the other Cycler the next time it is scheduled to enter a BackFlip -- take it to Earth instead. Then the phase of that Cycler is reversed and the two-Cycler sequence is re-established. There are other solutions such as using a 540° Moon-to-Moon transfer (see Ref. 11) instead of a holding orbit somewhere in the sequence. The most frugal solution is to do nothing and let the Cyclers remain out of phase until another Earth return is required and then initiate that transfer from a holding orbit. If the Cyclers are out of phase in this way, there will be a gap in the Earth-return opportunities even though each Cycler independently provides three windows every two months. It is therefore to be preferred, whenever possible, that Earth-return transfers be initiated from BackFlip transfers rather than from holding orbits.

Finally, consider how the two Cyclers can rendezvous for supply and personnel transfer or for joining together to form a larger station. Because the sequence provides for simultaneous Moon-passage once every month and a half, there is an opportunity, at such times, to target both Cyclers for Earth-return *on the same trajectory*. During the one-month period of the Earth-return transfer, the two spacecraft can transfer supplies and equipment needed by one or the other as well as take on equipment and personnel sent up from LEO. Crew members or travellers can return to Earth near any of the multiple perigee passes made by the two Cyclers on the (Moon-resonant) Earth-return trajectory. When the two Cyclers return to the Moon with fresh supplies and/or crew, they may separate prior to Moon passage. One can be targeted for a BackFlip while the other can enter a holding orbit and the two-Cycler encounter sequence is reacquired. It was Dr. Aldrin who first noticed that the recommended sequence provides for rendezvous of the two Cyclers. We are grateful to him for pointing out this major advantage of the pattern that also provides twice-monthly Earth-return opportunities.

Navigation and Targeting Requirements

The advantages of a relatively massive station travelling permanently from Earth to Moon and back do not come entirely for free. The Cyclers must be actively controlled in order to maintain the pattern and the requirements for retargeting the transfers for Earth-return or Cycler rendezvous will be somewhat greater than those for normal maintenance of the BackFlip/holding orbit sequence. Nevertheless, these requirements are quite small if the maneuvers are scheduled early enough in the sequence. Our experience shows that the aim point at the second encounter of a BackFlip can be moved more than 10,000 km by the application of about 10 m/s of ΔV 10 to 15 hours before the previous encounter. No attempt was made to optimize the timing of the maneuvers nor to use multiple impulse transfers. Normal maintenance ΔV for the sequence will be much less than the value quoted above. After the Cycler is "on station", the only requirements will be to correct for small errors in the previous maneuver, magnified, perhaps by one or two intervening encounters. Small trim maneuvers of a few tenths of a meter per second will probably be required after each encounter to correct for orbit determination and modeling errors. These normal maintenance maneuvers are probably best performed over an optimally scheduled period of time using ion thrusters.

A full-time Cycler servicing extensive traffic between Earth and Moon will almost certainly have an emergency maneuver capability drawing on its stores of cryogenic propellant normally used for the transfer vehicles. Or it may prove advantageous to have emergency "tugs" that can leave the Cycler and rendezvous with disabled transfer vehicles and bring the vehicle or the passengers back to the Cycler. These emergency capabilities could be used to perform Cycler maneuvers that may not have been planned far enough in advance. Retargeting a BackFlip transfer, for example, becomes very costly of ΔV after the Cycler has reached its maximum latitude and starts back down to the Earth-Moon plane. Retargeting only a few days before encounter can require several tens or even hundreds of meters per second. Thus, emergency maneuvers, while costly, are still within the realm of possibility, even for a large Cycler.

Perhaps our best experience with the sensitivity of these trajectories comes from our efforts to target through the two encounters of a BackFlip transfer to yield an Earth-return transfer after the second encounter. ΔV was added impulsively in the three Cartesian directions at 72 hours into the Earth-Moon transfer (approximately 16 hours before the first Lunar swingby) and the effects of these changes observed through both lunar swingbys and the return to Earth. Elements were compared well before and after lunar encounters to remove any "noise" due to the swingby. With this scheme the task became, in effect, to target through two unpowered lunar swingbys to obtain the proper final geocentric trajectory. This method allowed the targeting to take place at the 72 hour mark. The impulsive velocity changes required had a vector sum of about 10.2 m/sec. So it did prove possible to effect the desired trajectory from the 72 hour mark, well before the first Lunar swingby.

The success with targeting at the 72 hour mark indicates that it should be much cheaper of ΔV to target from a point earlier in the Earth-Moon transfer. The proper selection of the Earth-Moon midcourse correction time should allow transfer into the BackFlip orbit with impulses of almost negligible magnitude. It was found that the second swingby parameters, miss distance and location, and the final elements, were sensitive to very small changes in the impulsive velocity increments. The radius of closest approach on the return to the Earth's vicinity was sensitive to changes of the order of 0.01 m/sec near perigee of the original Earth-Moon trajectory. It proved quite easy to escape the Earth-Moon system after the second swingby if insufficient care was used in targeting. Of course, for other mission scenarios, hyperbolic escape will be of great value and not a hindrance.

Numerical Verification

The targeting studies and general curiosity led us to attempt to target full-model numerical simulations of these trajectories from a low Earth orbit (with a 28.5° equatorial inclination) through a BackFlip transfer, into a 1/2 month Earth-return orbit, and back to the Moon. The only control variables used were the time of launch and the position of the perigee of the Earth-moon transfer (which can also be controlled by selecting the time of translunar injection.) The trajectories were propagated using Cowell's method and a 7th-Order, 10-cycle Runga-Kutta integration scheme although for some of the near-collision transfers, a variation of parameters method was selected, with mean anomaly as the fast variable, for use during lunar encounter. The gravitational effects of the Sun and the lunar ellipticity were included along with the (less important) gravitational asymmetries of the Earth and the Moon. These simulations were targeted "by hand" simply by keeping track of the partial derivatives of the post-encounter Earth orbital elements with respect to the position of the initial nodal position and argument of perigee.

After relatively painless monitoring of several sets of minor trajectories to get the sensitivities, we managed to target through both BackFlip encounters, then through a two-revolution Earth-return trajectory, and back to within 35,000 km of the Moon without the use of any control other than the time of translunar injection. The lunar encounter distances were 4808 km., 6340 km., and 32,448 km at 144 , 443, and 1110 hours past launch respectively. Of course, we started with a trajectory that had already been targeted for the Moon with approximately the correct Jacobian constant for a 45° BackFlip. The final set of minor trajectories showed sensitivity of the third lunar encounter position to be several tens of thousands of kilometers per hundredth of a degree in initial node and perigee position. Naturally we would not expect to launch this accurately from low Earth orbit. The point is that it is possible to design real-world nominal transfers that achieve the objectives of the Cycler encounter sequence. And the exercise convinced us beyond any reasonable doubt that the ΔV requirements for a carefully planned Cycler encounter sequence will not exceed 10 m/s per month, even with a lot of traffic.

Conclusions

A method has been presented for continuous orbital transfer between Earth and Moon that requires no nominal impulses. Retargeting impulses are required which, if carefully planned, do not exceed 10 m/s per selected Earth-return window. The principal mechanism of the method is the use of the BackFlip or 180° Moon-to-Moon transfer. A description of some unsuccessful trial sequences was included to show the evolution of the Cycler concept as finally presented. One of these ideas was the reflected BackFlip maneuver which turned out to require sub-lunar encounters for prograde trajectories compatible with low energy Earth-to-Moon transfers. It was suggested that these reflected transfers are periodic orbits in the restricted three-body problem and may be of theoretical interest. They may also have some practical value for retrograde transfer in the Earth-Moon system. A phasing mechanism was devised for the recommended sequence that permits the addition of more Cyclers to the system and it was shown that a two-Cycler program provides twice-monthly Earth-return windows. A single Cycler provides 3 Earth-return opportunities every 2 months. It is our opinion that this is the maximum continuous Earth-return frequency possible for a single prograde Cycler without application of impulse. A brief description of numerical verifications and rudimentary targeting techniques was given and it was found possible to target through three lunar encounters of the sequence using only the time of launch from low Earth orbit as a control. It was pointed out that the Cycler concept will gain great advantage over direct round-trip transfer from Earth-to-Moon because of the ability of the Cycler to be made very large, in affordable increments, and thereby provide radiation protection for astronauts in transit, propellant depot capability (ultimately cryogenics), and reusable life-support facilities. It was pointed out that the two-Cycler system recommended here is particularly amenable to incremental growth and efficiency because of the ability of the two Cyclers to rendezvous with each other and join, if desired, into a larger station while a third Cycler takes the now empty place of one of the first two. Other advantages were pointed out which include the role of the Cycler as a logistical and technological prototype for deep-space Cyclers to planets and other solar system destinations.

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References:

[1] Aldrin, B., "Cyclic Trajectory Concepts", SAIC Presentation to the Interplanetary Rapid Transit meeting. Jet Propulsion Laboratory, October 1985.

[2] Uphoff, C., "The Art and Science of Lunar Gravity Assist",Paper No. AAS 89-170, Presented to the AAS/GSFC International Symposium, April 1989.

[3] Farquhar, R. and Dunham, D., "A New Trajectory Concept for Exploring the Earth's Geomagnetic Tail," *Journal of Guidance and Control*, Vol. 4 , No. 2, March-April 1981.

[4] Uphoff, C., Roberts, P.H., and Friedman, L.D., "Orbit Design Concepts for Jupiter Orbiter Missions" *Journal of Spacecraft and Rockets*, Vol. 13, June 1976, pp. 348-355.

[5] Brouwer, D. and Clemence, G.M., *Methods of Celestial Mechanics*, Academic Press, 1961.

[6] Szebehely, V., *Theory of Orbits*, Academic Press, 1967.

[7] Breakwell, J. and Gillespie, R., "Missions Normal to the Ecliptic", *Astronautics*, Sept 1962.

[8] Breakwell,J. and Brown,J., 'The "Halo" Family of 3-Dimensional Periodic Orbits in the Earth-Moon Restricted 3-Body Problem', *Celes. Mech.*, **20**, 1979.

[9] Howell,K., and Breakwell,J., "Almost Rectilinear Halo Orbits", *Celes. Mech.* **32**, 1984.

[10] Howell,K., 'Three-Dimensional Periodic "Halo" Orbits', *Celes. Mech.*, **32**, 1984.

[11] Miller, J., K., and Belbruno, E. A., "A Method for Construction of Lunar Transfer Trajectories, Using Ballistic Capture," AAS 91-100, AAS/AIAA Meeting, Feb. 1991.

[12] Kogan, A., "Orbits with Periodic Flights Around the Moon and their Use in Very Long Baseline Interferometry", *Cosm. Res.* ,**24**, No. 1, 1986, pp. 43-48 (English).