Several Ways to Leave for Luna[†]

An Abstract for Consideration for the 1995 AAS/AIAA Astrodynamics Conference
by
Theodore H. Sweetser, Ph. D.*

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

As the poet could have said:

There are half a dozen ways
A lunar course to lay
And every single one is good for something.

These half-dozen or so classes of lunar transfer trajectories vary in their propellant requirements, flight. time, and arrival geometry. All of them can be combined with a phasing orbit at the beginning if it is desired to extend the launch period, and all of them allow various options at arrival: direct descent, descent from orbit, or insertion into lunar orbit.

Direct

Ironically, this class which includes the Hohmann transfer is the most expensive in terms of propellant requirements. It is also the simplest and fastest — just inject from low earth orbit into an ellipse which extends past the Moon's orbit and time it so that the Moon is there at the same time as the spacecraft. Typically flight time varies from a few days up to a week, depending on the energy of the transfer ellipse and whether you encounter the Moon on the way out or on the way in. Either way the approach to the Moon tends to be toward the leading side. See Figure 1, taken from (Ridenoure et al., 1991).

Reverse Interior AV Lunar Gravity Assist (RIDL)

This takes the direct transfer a step beyond. Instead of staying at the Moon when it is encountered, the spacecraft flies by in a gravity assist which raises its perigee and apogee slightly. Then a small perigee maneuver lowers the apogee to tangency with the Moon's orbit, resulting in a lower arrival velocity at the Moon and a small overall propellant saving. For example, in the case described by Sweetser (1 993a) there is a total AV reduction of 23 m/s (including a 13 m/s perigee maneuver) compared to the Hohmann transfer. The flight time is either one or two months, depending on the period of the ellipse after the flyby. The arrival geometry at the Moon is similar to that of the direct transfer. See Figure 2, taken from (Sweetser, 1993a).

Backflip

This is an adaptation of the lunar cycler trajectory described by Uphoff and Crouch (1 993). This transfer also does a lunar flyby at first encounter, but this time the spacecraft flies by in a gravity

[†] The research described in this abstract was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

* Mathematician, Member AAS, AIAA

assist, which raises its geocentric inclination and energy so that it reencounters the Moon 14 days later after traveling back across the Moon's orbit over or under the plane of the Earth–Moon system. This increases the flight time, of course, but it means that the approach to the Moon for the final encounter is from out of the Moon's equatorial plane. See Figure 3, taken from (Uphoff and Crouch, 1993).

Fig 3

Bielliptic/biparabolic

Since the Moon's orbit is more than 9 times larger than low Earth orbit, the Hohmann is not the minimal transfer between these orbits. Instead it requires less propellant to inject into a large ellipse (ideally a parabola), raise perigee to the Moon's orbit radius with a maneuver at apogee (infinitesimally small at infinity), and time everything to encounter the Moon at perigee. Flight time ranges around months (infinite in the biparabolic case). In this class of transfer the approach to the Moon tends to be toward the trailing side, opposite the direct approach. Theoretically, this would reduce the ΔV needed for the transfer by only 13 m/s at best, but by combining it with an initial lunar gravity assist, an additional 45 m/s or so could be saved at injection. In the real world, however, if the apogee is large enough to offer any advantage over the Hohmann transfer, then solar perturbations become significant, leading to . . .

Weak Stability Boundary (WSB)

The prototype of the WSB transfer is the Belbruno–Miller transfer (Miller and Belbruno, 1991). It is like the bielliptic transfer but differs in two ways: firstly, the apogee "maneuver" is effected by solar perturbations — since it has no propellant cost it is done at a lower apogee than would otherwise be optimal so that the lunar arrival velocity is further reduced; secondly, the lunar arrival takes advantage of the Moon's gravity so that the spacecraft is "captured" ballistically, i.e., its osculating eccentricity at periselene is less than one. Belbruno calls this being near the Earth-Moon Weak Stability Boundary. Yamakawa (1992, 1993), has done the most extensive analysis in categorizing WSB transfers, which differ according to how long is spent in the intermediate "ellipse", whether one or two revolutions are done in that "ellipse", and where the apogee is relative to the Sun-Earth line. Flight time ranges from 2½ up to many months, but substantial ΔV savings are possible, typically around 180 m/s compared to the Hohmann transfer. The approach to the Moon tends to be toward the far side. See Figure 4, taken from (Miller and Belbruno, 1991).

Fig 4

Charmed WSB

The standard WSB transfer seems strange enough, but one step beyond strangeness is charm; in the charmed transfer the arrival at the Moon occurs the third time the Moon is encountered. This transfer is initially the same as before, but at the second lunar encounter instead of coming close to the Moon and achieving a ballistic capture, the spacecraft dots a more distant flyby, which results in the spacecraft orbit lying entirely inside the Moon's orbit. This interior orbit can be timed so that half a month, one month, or two months later the spacecraft again encounters the Moon in a Weak Stability way and gets captured ballistically. The flight time is somewhat more than that of the standard WSB transfer, but now the approach to the Moon at arrival is toward the near side, See Figure 5.

Fig 5

Minimizing

Is there any end to this? In the ΔV sense there is, at least in the circular restricted three-body model. An analysis based on Jacobi's constant (Sweetser, 1991) has shown that the total ΔV absolutely required to go from low Earth orbit to low lunar orbit is about 230 m/s less than for the Hohmann transfer. Using approaches suggested by this analysis, Pernicka et al. (1994) have found transfers which involve a transition from geocentric ellipses to selenocentric ellipses near the intermediate

Earth-Moon Lagrange point and which require about 135 m/s less than Hohmann transfers. These transfers have flight times of many months but do not seem to be restricted in their approach direction at the Moon. See Figure 6, taken from (Pernicka et al., 1994).

Table 1 summarizes characteristics of the transfers described above. The post-injection AV given is for stopping at the surface of the Moon and includes 100 m/s for midcourse corrections for all except the minimizing transfers; since minimizing transfers included multiple revolutions around the Earth after injection they are not sensitive to injection errors so they are allocated 50 m/s for midcourse corrections. Similarly, the use of phasing orbits after injection might reduce the propellant needed for correcting injection error; such phasing orbits are required in the cases of the WSB and Charmed transfers if launch periods of more than a few days are needed each month. Table 1 does not include any steering or gravity loss at the lunar arrival, The C3 and AV required for a transfer depend on the launch and arrival times since the Moon's orbit is significantly non-circular; the numbers given in Table 1 are for typical cases with comparable arrival dates.

Table 1. Trajectory Characteristics of Assorted Types of Lunar Transfer

Type of Transfer	Injection C_3 (km^2/s^2)	Post-Inj. ΔV (m/s)	Longitude of Approach (deg)	Sun-Moon-Probe Angle (deg)	Transfer Time (days)	Max. Earth Distance (km)
Direct	>-2.0	>2604	--270	arbitrary	~5	400000
RIDL	-1.7	2581	-270	arbitrary	-30	400000
Backflip	-1.7	2604	--270	arbitrary	-20	400000
Biparabolic	-1.4	2511	-90	arbitrary	∞	∞
WSB	-1.4	2441	~180	-45 or -225	>75	1500000
Charmed	-1.4	2441	-o	~45 or -225	>100	1500000
Minimizing	-2,9	2475	arb.	arbitrary	>150	450000
Best minimizing	-2.9	2372	arb.	arbitrary	>150	450000

The paper to be presented will extend this analysis further to calculate the landed mass possible for selected types of transfer for the Taurus/STAR 37xfp and the Med-lite launch vehicles. The transfer types analyzed will be the worst, best, and an intermediate type of interest from Table 1.

References

[Miller and Belbruno, 1991] James K. Miller and Edward A. Belbruno, "A Method for the Construction of a Lunar Transfer Trajectory Using Ballistic Capture", A AS Paper91 -100, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Houston, Texas, 11-13 February 1991.

[Pernicka et al., 1994] H. J. Pernicka, D. P. Scarberry, S. M. Marsh, and T. H. Sweetser, "A Search for Low AV Earth–to–Moon Trajectories", AIAA Paper 94-3772, presented at the AIAA/AAS Astrodynamics Specialist Conference, Scottsdale, Arizona, 1–3 August 1994.

[Ridenoure et al., 1991] Rex W. Ridenoure, ed., *Lunar Observer: A Comprehensive Orbital Survey of the Moon,* JPL Document D–8607, 15 April 1991.

[Surveyor, 1969] *Surveyor Project Final Report: Project Description and Performance.* JPL Tech. Rep, 32-1265, Part 1. July 1, 1969.

[Sweetser, 1991] Theodore H. Sweetser, " An Estimate of the Global Minimum AV Needed for Earth–Moon Transfer", A AS Paper91 -101, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Houston, Texas, 11-13 February 1991.

[Sweetser, 1993a] Theodore H. Sweetser, "Jacobi's Integral and ΔV-Earth-Gravity-Assist (ΔV-EGA) Trajectories", AAS Paper 93-635, presented at the AAS/AIAA Astrodynamics Specialist Conference, Victoria, Canada, 16-19 August 1993.

[Sweetser, 1993b] Theodore H. Sweetser, "Jacobi's Integral: a New Perspective on Trajectories in the Sun-Earth-Moon System", Advances in Non-linear Astrodynamics Conference, Minneapolis, MN, 8-10 November 1993.

[Sweetser, 1993c] Theodore H. Sweetser, "Initial Trajectory Analysis for the Small Lunar Interferometer Mission", JPL IOM 312/93.2–1 894, 17 March 1993.

[Sweetser, 1993d] Theodore H. Sweetser, "The Reverse Interior AV–1 .GA Lunar Transfer Trajectory", JPL IOM3 12/93.2–1 900, 8 April 1993.

[Uphoff, 1989] Chauncey Uphoff, "The Art and Science of Lunar Gravity Assist", AAS Paper 89-170, presented at the AAS/GSFC International Symposium on Orbital Mechanics and Mission Design, April 1989.

[Uphoff and Crouch, 1993] C, Uphoff and M. A. Crouch, "Lunar Cycler Orbits with Alternating Semi-Monthly Transfer Windows", *J. Astronautical Sci. 41:2*, pp. 189-05, April–une 1993.

[Yamakawa and Kawaguchi, 1992] Hiroshi Yamakawa and Jun'ichiro Kawaguchi, "A Numerical Study of Gravitational Capture Orbit in the Earth-Moon System", A AS Paper 92-186, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Colorado Springs, Colorado, 24-26 February 1992.

[Yamakawa et al., 1993] Hiroshi Yamakawa, Jun'ichiro Kawaguchi, Nobuaki Ishii, and Hiroki Matsuo, "On Earth-Moon Transfer Trajectory with Gravitational Capture", A AS Paper 93-633, presented at the AAS/AIAA Astrodynamics Specialist Conference, Victoria, Canada, 16-19 August 1993.

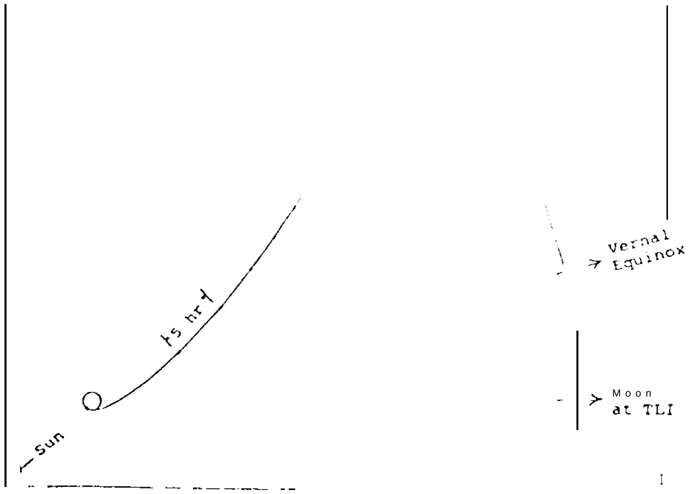

Figure 1. A Direct Transfer shown in inertial coordinates (Ridenoure et al., 1991).

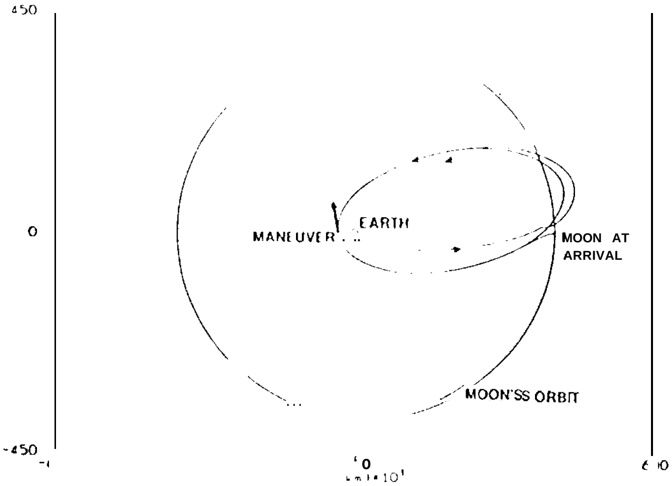

Figure 2. A RIDL Transfer shown in inertial coordinates (Sweetser, 1993a).

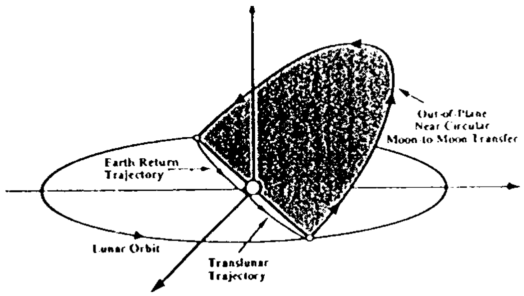

Figure 3 A Backflip Transfer shown in inertial coordinates (Uphoff and Crouch, 1993)

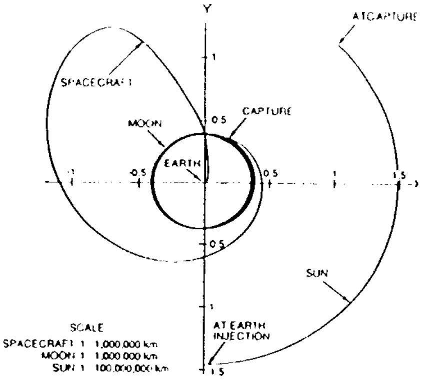

Figure 4. The Belbruno Miller Transfer (the prototypical Strange Transfer), shown in inertial coordinates (Miller and Belbruno, 1991)

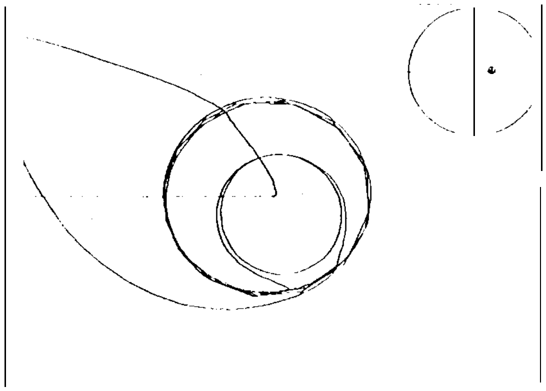

Figure 5. A Charmed Transfer, shown in rotating coordinates with the Earth-Sun line freed The B-plane diagram in the corner shows the aimpoint of the first lunar flyby

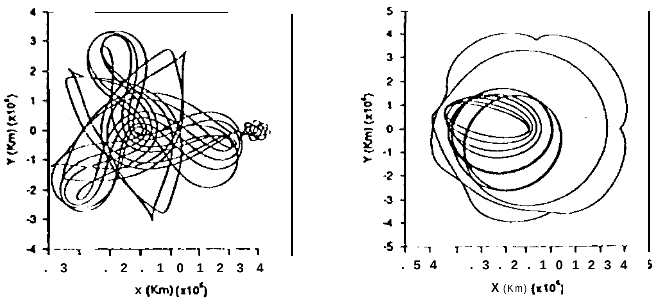

Figure 1. Earth-to-Moon Trajectory Shown in the Rotating Frame

Figure 2 Earth to Moon Trajectory Shown in the Inertial Frame

Figure 6. A Minimizing Transfer (Pernicka et al 1994)