ABSTRACT

A Search for Low ΔV Earth-to-Moon Trajectories

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Prepared for the
AIAA/AAS Astrodynamics Conference
Scottsdale, Arizona
August 1-3, 1994

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Introduction

Most spacecraft on Earth-to-Moon trajectories are limited in their mass by the propulsive requirements to propel such vehicles to the Moon. Of course, any reductions in the propulsive requirements arc beneficial since more mass (e.g., scientific instruments or humans) can be delivered to the final destination. This problem has been studied extensively since, and even before, space travel began. Such research has produced a number of useful trajectory designs and trajectory analysis tools. In recent work by Sweetser,[1] the minimum AV required to reach the Moon from Earth (as a lower bound) was quantified. This research, however, did not produce the actual trajectory that uses the minimum AV amount, assuming that one even exits. The results (applicable to the circular restricted three-body problem) do reveal some conditions on the trajectory that would use the minimum AV, however. This study has focused on trajectories computed using some of the conditions given in [1] that are required by the minimum AV trajectory. These conditions do not completely specify the number of maneuvers, their locations, magnitudes, and directions,' and thus determining the strategy to define each maneuver is one of the more important aspects of this work. While a trajectory has not yet been found that uses the minimum AV, some relatively low AV cases have been obtained and will be the subject of this paper.

Current Study

In seeking fuel-efficient trajectories to the Moon, it is useful to first identify the minimum required AV to leave the Earth and insert into lunar orbit. If this minimum AV can be quantified, efforts will not be wasted in attempting to compute a trajectory using less than this amount which cannot exist. This minimum AV has already been found by Sweetser for the circular restricted three-body problem.'*' This approach models the lunar orbit as circular about the Earth. Using Jacobi's constant, a quantity derived from a concept analogous to the conservation of energy in the circular restricted three-body problem, a lower bound on required AV was determined. The current effort, then, given the **minimum** AV amount, is to find a trajectory that uses that minimum (or at least is "close" to it). In cases where the time-of-flight is prohibitively long for practical applications, a transfer trajectory can be sought that is near the minimum but that has a shorter travel time.

Searching for these trajectories has been attempted primarily through numerical means, i.e., propagation by numerical integration. In accordance with the conditions from Sweetser's work, trajectories have been found originating from low Earth orbit that pass through the Earth-Moon L_1 libration point with almost no velocity (with respect to the rotating frame) and that inject into orbit about the Moon. Each trajectory consists of two "parts": first, from low Earth orbit (circular orbit of 167 km altitude) to the L_1 point, and second, from the L_1 point to lunar orbit (polar circular of 100 km altitude). Discrete AVS are applied at perigee/perilune locations to control the orbit periods so that the perturbing gravitational force from the "third" body (Moon or Earth) can be used advantageously. The software used to analyze this problem has been structured to allow convenient trial-and-error inputs of AVS and their locations. Analytical and graphical methods are also used for AV placement and selection.

Preliminary Results

The table on the following page summarizes AV amounts for various trajectories to the Moon. The first entry shows the theoretical minimum amount required as calculated in [1] using the circular restricted three-body problem. The second entry shows the best result obtained to date in this study. Refinements to this figure and the corresponding trajectory are continuing. The third case reflects work begun in the 1980s by Edward Belbruno and James Miller on a ncw type of Earth-to-Moon trajectory that uscs the gravitational influence of the Sun to produce an efficient trajectory. [2] The feasibility of their basic idea was confirmed by the Japanese Hiten spacecraft, which recently used the Beltmtno-Miller concept to achieve lunar capture at the end of its mission. The last entry in the table shows the cost for a Hohmann transfer computed using a patched-conic analysis.

Table: Earth-to-Moon Trajectories

Type	Model	Total AV (km/s)
Minimum	Circular Restricted Three-Body	3.721
This Study	Circular Restricted Three-Flody	3.833
Belbruno/Miller	Real-World	3.838
Hohmann	Two-Body	3.959

It should be noted that the AV costs listed for this study and for the Belbruno/Miller trajectory have the potential for further reduction. In fact, the Rlbruno/Miller type trajectories have a theoretical lower limit of approximately 3.776 km/s. The figure cited for "This Study" will be further reduced, perhaps below the theoretical limit of the Belbruno/Miller type trajectories. Two figures are included that show the low Earth orbit to 1.$_1$ portion of the trajectory corresponding to "This Study". Two figures are used to show the complicated trajectory more clearly. The trajectory is shown in the rotating frame and is entirely within the plane of the Earth-Moon orbit. The L_1 to Moon portion of the trajectory has a similar pattern and is omitted here' for the sake of brevity.

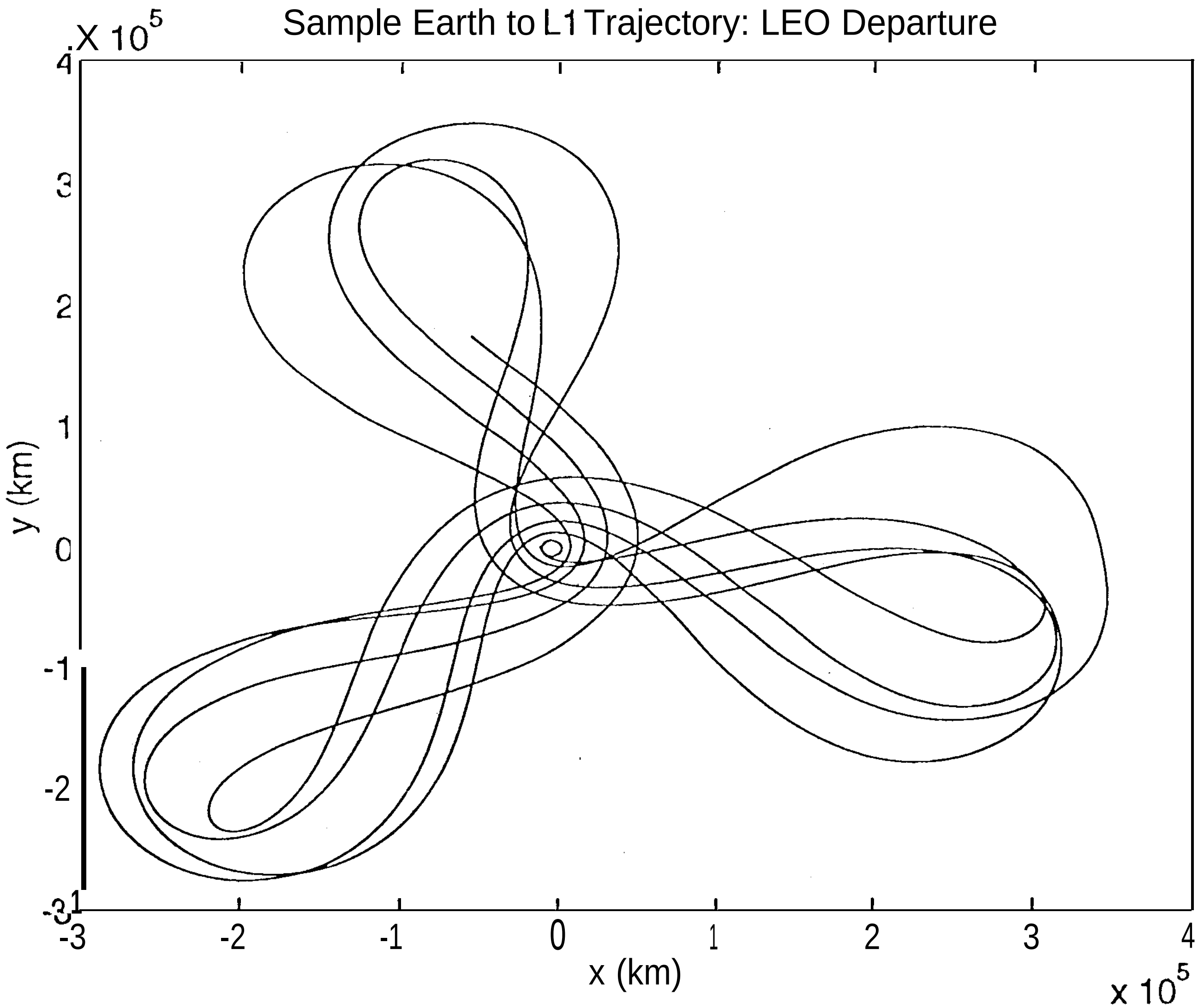
Summary

This study has produced low AV trajectories that compare well to some of the Earth-to-Moon transfers in use today. The time-of-flights are long (approximately one year) and efforts in the near future will seek more practical flight durations. The full paper will include the specific strategy used to find the transfers as well as plots of some of the various trajectories.

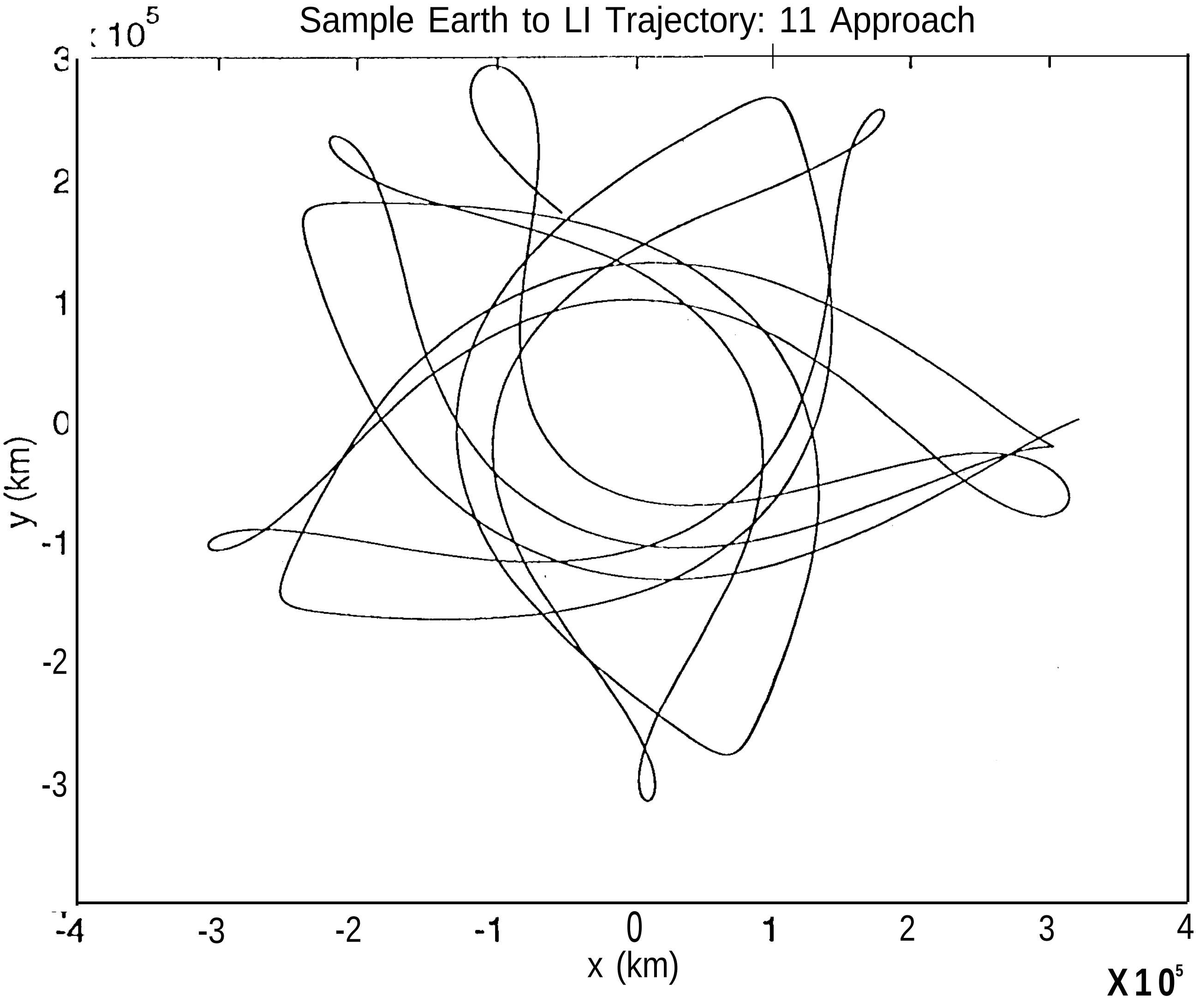
References

1. T.H. Sweet.scr, "An Estimate of the Global Minimum DV Needed for Earth-Moon Transfer," in J.K. Soldner, A.K. Misra, 1...1.. Sackett, and R. Holdaway (eds.), *Spaceflight Mechanics* 1991, Volume 75, Part I of *Advances in the Astronautical Sciences*, pp. 111-120, Univelt, San Diego, 1991.

2. J.K. Miller and E.A. Belbruno, "A Method for the Construction of a Lunar Transfer Trajectory Using Ballistic Capture," presented at the AAS/AIAA Spaceflight Mechanics Meeting, Houston, Texas, February 11-13, 1991.



Sample Earth to L1 Trajectory: LEO Departure
X 10^5
4
3
2
1
0
-1
-2
-3
y (km)
-3
-2
-1
0
1
2
3
4
x (km)
x 10^5



Sample Earth to LI Trajectory: 11 Approach
x 10^5
3
2
1
0
-1
-2
-3
y (km)
-4
-3
-2
-1
0
1
2
3
4
x (km)
X10^5