Genetic algorithms used to determine WSB trajectories for the LunarSat mission

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Abstract

This paper presents a novel way of constructing so-called Weak Stability Boundary (WSB) trajectories from GTO to the Moon, using genetic algorithms (GA). The work is part of the LunarSat project. LunarSat is an educational satellite sponsored by the new office for Education Outreach Activities and will function as the focus for a variety of related education activities. LunarSat (Lunar Academic and Research Satellite) is a 100 kg micro satellite, designed by young engineers and scientists and students from across Europe. It will be launched by Ariane 5 (auxiliary payload) into a GTO orbit around the millennium change. Once inserted into a 4hr Lunar polar orbit of perilune 100km above the south pole, it will observe the suitability of this area for locating the first extraterrestrial human outpost, i.e. measuring the solar illumination (peak of eternal light?) and the water ice distribution. Next to the cost, the main driver is mass. To maintain the 6-9 kg payload it is crucial to find the most economic trajectories from GTO to the Lunar polar orbit insertion. Being the auxiliary payload the launch date cannot be chosen. In general such trajectories make use of fly-by 's of the Moon and Earth as well gravity assists at the Weak Stability Boundaries of the Sun-Earth and Earth-Moon system. No systematic method is published for constructing weak stability trajectories from GTO to the Moon, although an ITT has been recently submitted by the Agency.

While the recognition of a suitable trajectory is easy, i.e. observing the total delta V, the elements for obtaining such a trajectory are very difficult to find. This type of problem, where the optimum is easy recognisable, but where its relationship with the various parameters is extremely complex and perhaps chaotic, has been solved in nature by the 'survival of the fittest' evolutionary process (Darwin). The use of genetic algorithm, mimicking such evolution, is presented here, demonstrating that this is a powerful tool for finding creative solutions for trajectories with very low delta V's.

For this specific application of GA bonuses were applied to favour orbits close to the WSB .
A range of launch dates and times were investigated, where the leading parameter seems to be the angle between GTO apsidal axes and the Sun direction. This angel ranges from +6 deg to +20 deg for the standard Ariane 5 launch window. It is shown that the GA is capable of finding optimum trajectories for the range of -20 to +20 deg, with a delta V's of 1185 to 1250 m/s, thereby providing savings of 200-260 m/s with respect to a bi-elliptical trajectory. Next to these savings, the sun's gravity provided also the necessary out-off plane manoeuvre to reach the Moon, of which the orbit is inclined at 23 degrees at the end of the year 2000. The resulting trajectories have been confirmed using standard trajectory propagators (USOC, ESOC and GEODYN, Delft University of Technology).

Background

This work was part of the LunarSat study, of which phase A & B were sponsored by ESA's new office for Educational Project Outreach Activities. LunarSat's technical objectives are:

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- Reach Lunar orbit from GTO via advanced, propellant saving transfer methods
- Orbit around the Moon for 6 months
- Investigate the Moon and particular the South polar region for its suitability for a first Lunar outpost

The space-craft data is:

- Mass: 100kg
- Dry mass: 59.74kg
- Payload mass: minimal 6kg
- Launcher: Ariane 5 ASAP → GTO orbit

Figure 1 shows the LunarSat satellite.

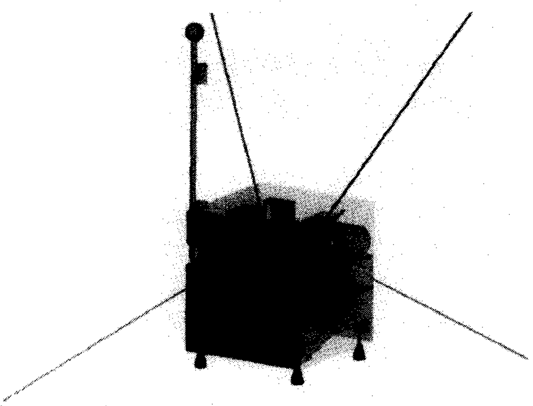

Figure 1: LunarSat

Problem definition

40% of space-craft total mass is fuel. Therefore, the total ΔV available is:

$$\Delta V = 2835 \cdot \ln\left(\frac{1}{1-0.4}\right) = 1460 \mathrm{m/s}$$

of which 10m/s is reserved for attitude & orbit control. Studies have proved that Lunar orbits exist requiring no orbit maintenance and therefore, the baseline ΔV available for the transfer orbit is 1450m/s. However, for contingency reasons, 100m/s is preferred for orbit maintenance. Therefore, the ΔV **wanted for orbit transfer is 1350m/s.**

Three Lunar transfer trajectory types exist:

1. Hohmann transfer (see figure 2).

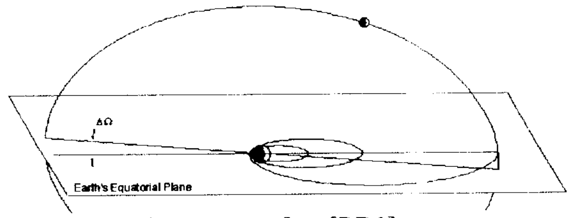

Figure 2: Hohmann transfer [RD1]

ΔV ranges from 1270 to 1770m/s. However, a Hohmann orbit is only possible when the GTO & Moon node are close together; a possibility which occurs only twice a year.

2. Bi-elliptic transfer (see figure 3)

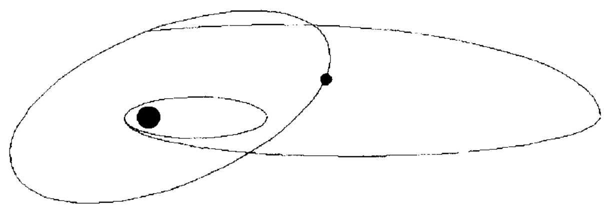

Figure 3: Bi-elliptic transfer [RD1]

ΔV ranges from 1380 to 1490m/s. With the available ΔV for LunarSat (1450m/s), the bi-elliptic orbit was chosen as the baseline for LunarSat:1450m/s (no orbit maintenance.)

3. WSB transfer (see figure 4)

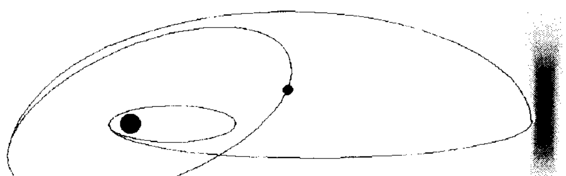

Figure 4: WSB transfer [RD1]

ΔV ranges from 1160 to 1300m/s and therefore, the WSB transfer increases payload mass by at least 4.5 kg compared to baseline bi-elliptic

This paper introduces a method to construct WSB transfers using genetic algorithms.

Genetic algorithms

A Genetic algorithm is an optimisation technique based on the mechanics of natural selection and genetics. GA's require the parameter set of the optimisation problem to be coded as a finit-length string containing elements (such as 0, 1). A population of individuals is created which goes through a process of evolution made up of the principles of combination (cross-overs, mutation and selection

Genetic Algorithms (GA's) are powerful when the optimum is easy recognisable but its relationship with the various parameters is complex. In this case: the optimum is the lowest total ΔV trajectory, which is indeed easy to 'detect'. However, the relationship with parameters (Sun & Moon positions, time, orbit parameters of transfer orbit) is very complex

Some GA techniques are described:

- Chromosome = string of bits
- Every chromosome represents a combination of parameters used to calculate the 'fitness' function (function of merit)
- population = set of 200 chromosomes
- Initial population is created randomly (every bit of every chromosome is randomly set to 0 or 1)
- Create new population / 'generation' using:
  - Selection (pairs of chromosomes ('parents') are selected according to their 'fitness': a higher value of the fitness function assures a higher chance for selection)
  - Cross-over (chucks of bits are swapped between two parents with probability 0.6)
  - Mutation (a bit is randomly changed ($1 \rightarrow 0$) or ($0 \rightarrow 1$). Probability depends on similarity)
- This process is repeated until the fitness is sufficient (typically 500 generations).

Optimisation method

The optimisation method used can be described as follows (see figure 5):

For a given launch date/hour:

- Wait 'Tphase' days in phasing orbit
- Give ΔV1 in perigee to increase the apogee to reach WSB region
- In the WSB region, give a very small ΔV2 to change the inclination and perigee
- Upon arrival at the Moon, calculate how much ΔV3 is required to be captured into 4hr polar orbit.
- Minimise the total ΔV = ΔV1 + ΔV2 +ΔV3

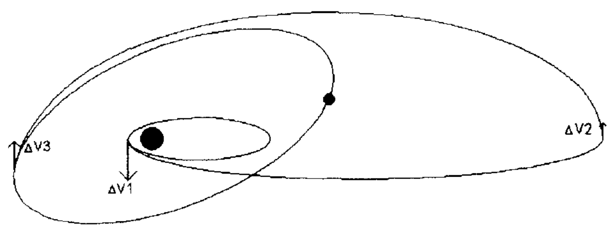

Figure 5: Overview of ΔV's given

If the space-craft doesn't arrive at the Moon after 150 days, stop the integration.

Implementation into GA

Five parameters were chosen to be optimised:

1. Tphase: time spent in GTO or phasing orbit
2. ΔV1: amount of ΔV given at GTO perigee
3. ΔV2: amount of ΔV given at WSB region
4. α: azimuth of ΔV2
5. δ: declination of ΔV2

One chromosome represents all parameters in concatenated order:

Bit:	1	13	36	61	70 77
	Tphase	ΔV1	ΔV2	α	δ

The fitness function is defined as:

$$f \cong -\Delta V total \quad [km/s]$$

A 'bonus' is added when the WSB region is reached (maximum distance Earth-satellite is between 1.32 and 2 million km).

Results

The GA was able to find WSB transfers for each day in a year. Figure 6 shows a typical resulting WSB transfer.

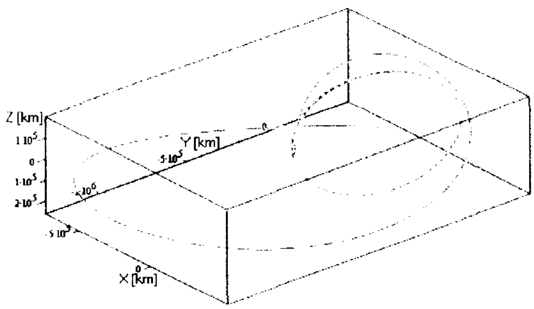

Figure 6: Typical result of GA

The ΔVtotal is always below 1232 m/s for standard Ariane 5 launch window (compare to 1450m/s base-line), see figure 7.

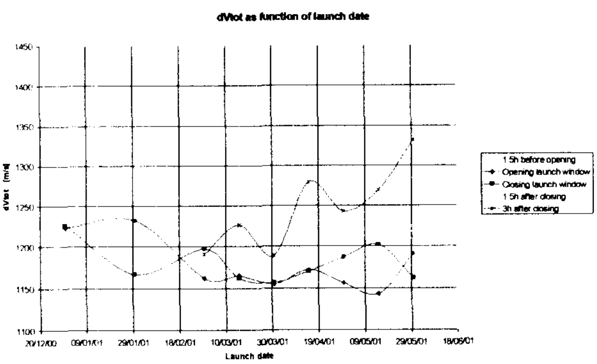

Figure 7: ΔV for all cases treated.

Cases treated outside standard launch window below 1331m/s, see figure 8.

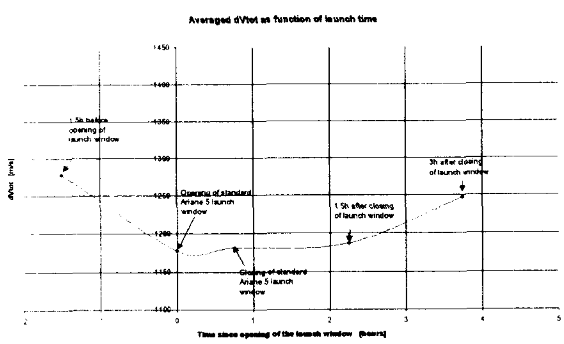

Figure 8: Average ΔV per launch hour

Conclusions

The genetic algorithm was able to find WSB transfers compatible to the constraints given, for all cases treated.
Some creative solutions were found using swing-by's, see figure 9:

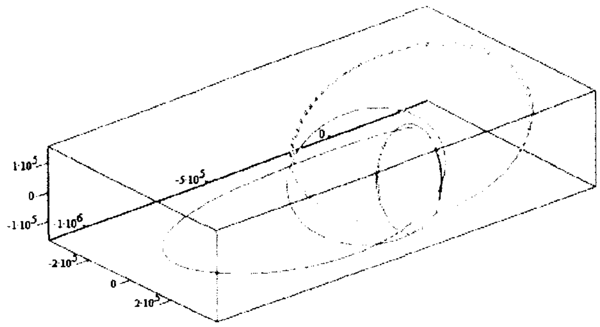

Figure 9: Solution with swing-by's

Savings in ΔV range from 218 to 265m/s corresponding to 4.7 to 5.8kg increase in payload mass over 6kg baseline as seen in figure 10.

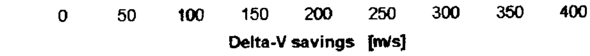

Figure 10: Payload mass increase

A detailed report on this work can be found in [RD2].

References

[RD1] *Lunar Mission From GTO*, W. Seefelder, RT-DA 98/05 Muenchen.

[RD2] *Study on Lunar Trajectories from GTO by Using Weak Stability Boundary Transfers and Swing-by's*, R. Biesbroek, EWP 2014, ESTEC, Noordwijk.