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Low Energy Interplanetary Transfers Using Halo Orbit Hopping Method with STK/Astrogator *

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Abstract

The principal objective of this investigation is to find numerically low-energy interplanetary transfers from Earth to distant planets. This is accomplished by the methods of Halo orbit insertion at Sun-Planet L2 Lagrangian point. The proposed method present the advantages of keeping continuous direct communications with Earth and, simultaneously, to perform extensive exploration of the planet. This method has been found to be 35% more fuel efficient than the conventional gravity assisted trajectory method but approximately 5 times slower. The proposed procedures, which have been conceived in STK/Astrogator, take advantage from the powerful SVD differential corrector.

Introduction

Slingshoting or gravity assisted trajectory method is one of the most preferred methods while designing an interplanetary trajectory to the distant and outer planets of the Solar Systems, namely, Jupiter, Saturn and beyond. The gravity assisted approach implies an upper limit to how fast a spacecraft can get, because the higher the difference in velocity between the planet and the craft, the closer the craft must come to the planet's center of gravity. If the spacecraft were too fast, a collision would occur. Put in short, the slingshot effect is at much higher speeds, and is limited in use.

There is another approach of designing interplanetary trajectories that involves much lower speeds. Martin Lo and Shane Ross, discuss the idea of Low-energy interplanetary transfers using Lagrangian Points [1]. Figure 1 shows the Lagrangian Points for Sun-Earth system with anti-Sun line and corresponding reference system.

The invariant manifolds associated with the outer planets are extremely large objects in phase space. They are trajectories in the ecliptic which intersect one another [2]. This enables a low energy single impulse transfer between the planets which requires several orbital periods. The manifolds of the planets intersect. In other words, a great portion of the entire Solar System is dynamically linked by these manifolds. This offers a transport mechanism whereby objects can move in and out of Solar System along this pathway of L1 and L2 manifolds.

We are investigating a method of low energy interplanetary transfers from one planet to another through desktop computer simulation using full-force models and interplanetary propagation/targeting techniques of the STK/Astrogator module. Essentially, we wished to see how past studies and data compared to our full-force model targeting and propagation, and to generate new scenarios and data for future missions. In particular we are designing interplanetary transfers using Halo orbits hopping. Others have designed the low energy interplanetary transfers using special tools like LTOOL and other dedicated softwares written for these

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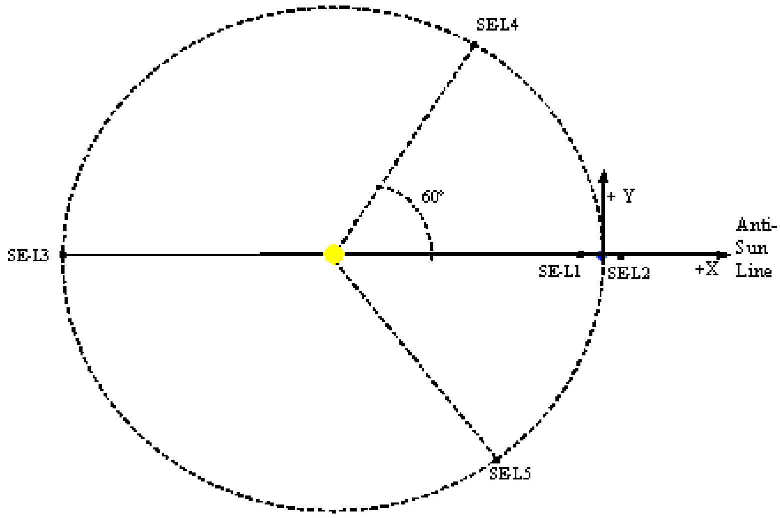

Figure 1: Lagrangian points for Sun-Earth System, Anti-Sun line and reference system for current mission.

kinds of trajectories [3]. We believe that we have identified similar low energy transfer trajectories of Shane Ross, et al, using our procedure. The basic idea to Halo hopping is to hop from one Halo orbit to another as a part of interplanetary exploration. We are interested in Halo orbit about L2 because while in a Halo orbit, the spacecraft can map the planet extensively and maintain seamless radio contact with Earth. Once the spacecraft is inserted in a Halo orbit, the station-keeping operations require a relatively small Δv budget.

1 Halo Orbit Insertion and Halo Orbit Hopping method

Martin Lo, et al talk and use the concept of Interplanetary Superhighways in their approach of finding low-energy interplanetary transfer trajectories [3]. The main problem that we had in Astrogator is that we could not specify these Inter-Planetary Superhighways (IPS) that are based on mathematical concepts called invariant manifolds. We would need to be able to define a 3-Dimensional Area Target in Astrogator but, unfortunately, Astrogator doesn't have that capability yet. Solution to this was that, typically, for a mission to SE-L2, one would want to perform a burn at the anti-Sun line that will take the spacecraft to the vicinity of L2. Then, one must to adjust the size of the burn in such a way that the spacecraft crosses the SE-L2 Z-X plane with a SE-L2 $V_x = 0$. After several SE-L2 Z-X plane crossings, there is a need to perform station keeping. The mission starts from an initial Earth circular parking orbit followed by a Halo orbit insertion at SE-L2 Lagrangian point. After this stage, the spacecraft gets off this Halo orbit and is propagated towards SM-L2 Lagrangian point on a low energy interplanetary transfer orbit. The spacecraft is inserted in a Halo orbit at this point. Thus, there is Halo orbit hopping from SE-L2 (SE-L2) to SM-L2 (SM-L2) Lagrangian point. In a similar way Halo orbit hopping can be achieved from SM-L2 (SM-L2) to SJ-L2 (SJ-L2) and Sun-Saturn L2 (SS-L2), and so on.

In this context we address the questions of "Why go there?", "How to go there?", and "How to remain there?". Namely, we address utility and usefulness, transfer and injection, and station keeping. The entire mission can be thought of as a series of targets that need to be hit at: First a Halo orbit at SE-L2 is targeted, followed by a SM-L2 Halo orbit, and so on.

Targeting: The Target Sequence segment gives Astrogator the powerful capability of analyzing and solving complex space flight problems quickly and accurately by defining maneuvers and propagations in terms of the goals they are intended to achieve. The Target Sequence segment has associated with it one or more nested Mission Control Sequence (MCS) segments, such as maneuvers and propagate segments, for which independent and dependent variables are defined. Setting up the Targeter involves making certain selections within these nested segments and in the Target Sequence segment itself. Any segment can be nested in a target sequence, and it is not uncommon to have the entire MCS nested in a target sequence. A brief summary of the MCS, maneuver and propagate segments is as follows:

1. *Mission Control Sequence*: The Mission Control Sequence (MCS) is the core of any space mission scenario. By adding, removing, rearranging and editing MCS Segments, one can define a mission of any desired level of complexity. The MCS is represented schematically by a tree structure and the MCS tree mirrors the timeline of events constituting a space mission.

2. *Maneuver segment*: Astrogator provides two basic types of maneuvers – impulsive and finite – for use in constructing a space mission scenario. Both types of segments are available for building up a Mission Control Sequence (MCS). The current paper uses only Impulsive Maneuver segments. The term "thrust vector" is used to describe the direction of acceleration applied to the satellite. This direction is opposite to the exhaust of an engine. The Impulsive Maneuver segment models a maneuver as if it takes place instantaneously and without any change in the position of the spacecraft. This is the classical Δv.

3. *Propagate Segment*: Propagation of an orbit is handled by the Propagate segment, the central feature of which is a mechanism for defining one or more conditions for stopping the propagation or initiating a follow-up sequence. Astrogator makes a variety of stopping conditions (e.g. *Z-X* plane crossing, Periapsis, Apoapsis, etc) available for use in defining Propagate segments. Another important option of Propagate Segment is the Propagation time (Minimum and Maximum). This feature can be used to set effectively with stopping conditions. For instance, with Minimum propagation time, no stopping conditions are checked until the specified amount of time has elapsed. Similarly, with Maximum Propagation time, a constraint can be imposed on the stopping condition that the stopping condition has to be met within specified maximum propagation time.

The basic targeting problem can be summarized as follows. Given a specified set of orbital goals, how can the initial conditions and intermediate variables be perturbed to meet those goals? A robust mechanism used by Astrogator for solving this problem is the differential corrector with Singular Value Decomposition (SVD) algorithm. The entire mission can be divided into a sequence: defining Lagrangian points, inserting new central bodies (as for instance a planet's moon), defining reference frames, etc. The Lagrangian or Libration point is defined by specifying: a) The primary central body, b) Number of secondary bodies (min: 1 and max: 2) c) Libration point definition: (L1, L2, L3, L4 or L5).

For starters, the definition of the SE-L2 Lagrangian point can be followed as:

Primary Central body :	Sun
Number of secondary bodies :	2
Secondary Central body 1 :	Earth
Secondary Central body 2 :	Moon
Libration point :	L2

Similarly, we can continue defining SM-L2, SJ-L2 and Sun-Saturn L2 Lagrangian points. The next step is defining different types of axes and vectors and Co-ordinate Systems. The Astrogator Component Browser provides a number of axes for use in constructing coordinate systems, including several editable ones with which one can create new axes. This mission requires using "Multi-body" type of axes. This type of axes is used frequently for Libration points and for Body-body rotating axes and can be defined the following types of axes.

First, we define the Multi-bodies and the Coordinates systems as defined in Table 1.

Then, we define the spacecraft physical properties. STK default values are given hereafter.

Table 1: Co-ordinate Systems Definitions

Name	Origin	Multi-body
Sun Earth-Moon L2	Sun Earth-Moon L2	Sun Earth-Moon L2 Libration Point Axes
Sun Mars L2	Sun Mars L2	Sun Mars L2 Libration Point Axes
Sun Jupiter L2	Sun Jupiter L2	Sun Jupiter L2 Libration Point Axes
Sun Saturn L2	Sun Saturn L2	Sun Saturn L2 Libration Point Axes
Saturn Titan L2	Saturn Titan L2	Saturn Titan L2 Libration Point Axes

Tank Pressure :	5,000 Pa
Tank Volume:	Default value
Tank Temperature :	Default value
Fuel Density :	Default value
Fuel Mass :	2,500 Kg
Dry Mass :	2,500 Kg
Drag Area :	10^{-6} Km^2
Solar Radiation Pressure area :	10^{-6} Km^2
Coefficient of Drag :	2.0
Coefficient of Reflectivity :	2.0

Some of the spacecraft properties, such as Drag area, fuel mass and Solar radiation pressure area, are "Set to new value", i.e., they are constantly updated. Having defined the background information in sufficient details, we can proceed on developing a model for Halo orbit insertion and Halo orbit hopping operations. We demonstrate here the typical procedure in STK/Astrogator that is used to design Halo orbit insertion and Halo orbit hopping method [4]. Figure 2 explains the step-by-step model for Halo orbit insertion and station keeping operations.

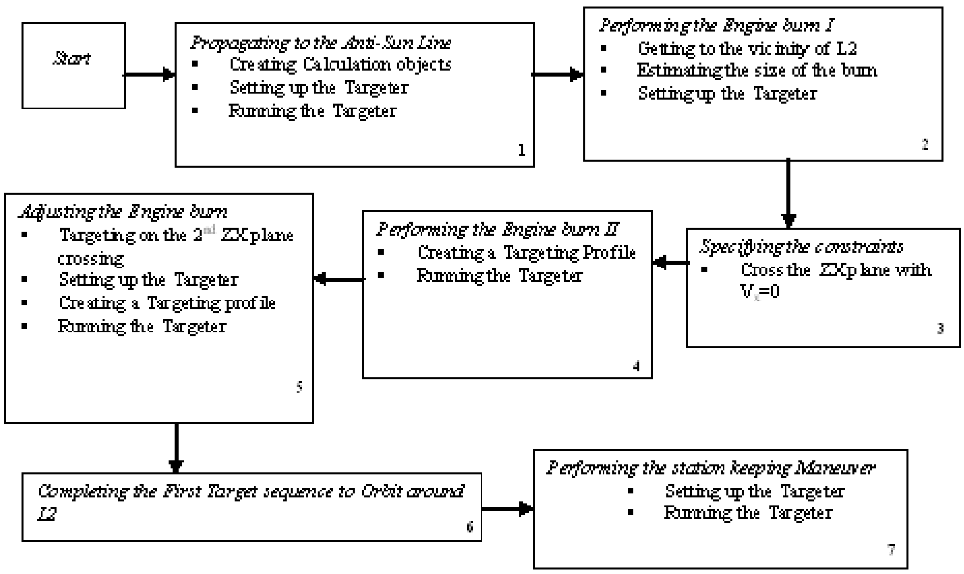

Figure 2: Sequences in Halo orbit insertion and station keeping operations.

Let us have a brief look at the stages indicated in above process:

1. **Propagating to the Anti-Sun Line**

- *Creating Calculation Objects*: a) Right Ascension of the SE-L2 centered at the Earth, b) Z Cartesian component of the position in the SE-L2 reference frame.
- *Setting up the Targeter*: a) To control the Right Ascension of the Ascending Node and the Argument of Perigee so our spacecraft will be propagated to the Anti-Sun line b) Specifying the Control variables: Right Ascension of the Ascending Node and the Argument of Perigee c) Specifying the Constraints: SE-L2 Z and SE-L2 Right Ascension are both zeroes.
- *Running the Targeter*: a) Running the Targeter for first time. b) Change the Action of Targeter to Run Corrected Control Values. c) Click on GO button. d) Change the Action of Targeter to Calculate New Control Values. e) Click on GO button. f) Apply All Corrections button. g) Change the Action of Targeter to Run Nominal Control Values h) When the Targeter converges, the Pop up panel shows that Targeter has converged after 'x' number of iterations as shown in Figure 3.

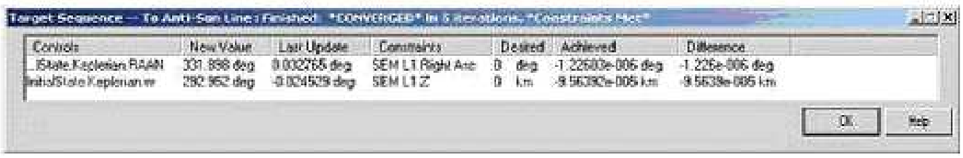

Figure 3: Pop up Panel showing convergence of Targeter.

2. **Performing the Engine burn I**
   - *Getting to the vicinity of L2*: a) Add an impulsive maneuver segment. b) Change the Attitude control of the Maneuver direction to Thrust vector and use the VNC (Velocity-Normal-CoNormal) Thrust Axes for the impulsive maneuver. c) Propagate the spacecraft to the intersection of the Z-X plane of the SE-L2 Co-ordinate system. d) Adjust the Minimum and Maximum Propagation Time
   - *Estimating the size of the burn*: a) Change the size of the burn and iterate b) Propagate to see if the spacecraft has enough energy to reach the vicinity of SE-L2.
   - *Setting up the Targeter*: a) Use the Cartesian SE-L2 V_x as the constraint b) Measure X in SE-L2 Co-ordinate system c) Condition that V_x be nearly zero at the Rotating Lagrangian point (RLP) Z-X plane crossing been chosen to ensure that the spacecraft remains near L2.
3. **Specifying the constraints**
   - $V_x = 0$ at the Z-X plane crossing.
4. **Performing the Engine Burn II**
   - *Creating a Targeting Profile*: a) Use Add/Modify Profile list to add a new profile " to 1st Z-X plane crossing". b) Make above profile Active. c) Select control variables and constraints for this profile d) Turn OFF RAAN and Argument of Perigee and Turn ON Cartesian X velocity. e) Adjust the perturbation size for above control variable
   - *Running the Targeter*: a) Change the Action of Targeter to Run Targeter (Calc. New Control Values). b) Run the Targeter. c) Apply All Corrections. d) When done, change the Action of the Targeter to Run Nominal Control Values. When the Targeter converges, the Pop up panel shows that Targeter has converged after 'x' number of iterations as shown in figure 2.
5. **Adjusting the Engine Burn**

- *Targeting the 2nd Z-X plane Crossing*: a) Propagate the spacecraft to 2nd *Z-X* plane crossing maintaining Vx perpendicular to the plane ($V_x = 0$ Km/s) b) Change the stopping condition for propagate segment as " Stop when crossing *Z-X* plane". c) Adjust the Minimum and Maximum Propagation time.
- *Setting up the Targeter*: a) Repeat the procedure of 1st *Z-X* plane crossing
- *Creating a Targeting profile*: a) Create a new Targeting profile and name it, "To L2 DeltaV 2nd crossing". b) Make this profile active and the same control variables and constraints. c) Adjust the perturbation size for the Cartesian *X* velocity component.
- *Running the Targeter*: a) Change the Action of Targeter to Run Targeter (Calc. New Control Values). b) Run the Targeter. c) Apply All Corrections. d) When done, change the Action of the Targeter to Run Nominal Control Values.

6. **Completing the First Target Sequence to Orbit around L2**
7. **Performing the Station-keeping maneuver**
   - *Setting up the Targeter*: a) Repeat the procedure of 2nd *Z-X* plane crossing
   - *Running the Targeter*: a) Change the Action of Targeter to Run Corrected Control Values. b) Run the Targeter. c) When done, change the Action of the Targeter to Run Nominal Control Values.

The summaries for Halo orbit Insertion, for Station-keeping, and for Halo Hopping procedures are given in the following:

- *Halo orbit insertion procedure*: The spacecraft, after initial Earth-orbit is propagated till it intersects the anti-Sun line. An impulsive maneuver is applied at this stage that takes the spacecraft towards SE-L2 Lagrangian point. The end condition for this propagate segment is that spacecraft should cross the SE-L2 *Z-X* plane with SE-L2 $V_x = 0$ and that SE-L2 $Z = Y = 0$. These conditions ensure that spacecraft gets inserted in a Halo orbit at SE-L2 Halo orbit. A similar approach is followed for Halo orbit insertion at point SM-L2, SJ-L2, and SS-L2, respectively, albeit with different values of Δv.
- *Station Keeping procedure*: For station keeping, basically, the period of orbit has been controlled. In literature, it is called Period or Frequency Control and the resulting periodic orbit is called a Halo orbit. So, the calculate the period, the propagation time (of the propagate segment) was calculated in the following manner. The spacecraft was given a stopping condition as "stop when crossing *Z-X* plane" with constraint SE-L2 $V_x = 0$. An initial guess value for minimum and maximum propagation segment was set and the number of plane crossings was changed from 1 to 2. This was done to check the sample trajectory for each impulsive maneuver. When the Targeter was run, different trajectories were produced. After every run, every trajectory was viewed in *Z-X* plane, *X-Y* plane and *Y-Z* plane for their symmetrical nature (approximately). After many runs, Targeter converged to give a trajectory that was symmetrical (somewhat) in each of these planes. That value of propagation time is the period of the Halo orbit. For the SE-L2 Lagrangian point, the propagation time for each of the propagate segment (4 in all) was approximately 1.0274 years. i.e. roughly 93.75 days. This means that there was a *Z-X* plane crossing after every 93.75 days at SE-L2 Lagrangian point. Having obtained this period, the number of *Z-X* plane crossings can be changed from 2 to 3 or 4 keeping the same constraints on spacecraft.
- *Halo Hopping procedure*: Assuming that the spacecraft is still in Halo orbit at SE-L2 Lagrangian point and it is piercing *Z-X* plane after periodic intervals of time. To get off this Halo orbit the spacecraft will apply an impulsive maneuver on next *Z-X* plane crossing. This means that the spacecraft will get off the Halo orbit on some *Z-X* plane crossing. A small Δv can also help spacecraft exit the Halo orbit but the propagation time will be too big. A big enough Δv will take the spacecraft off the Halo orbit and towards the subsequent Lagrangian point i.e. SM-L2 but the propagation time will be too small. Now, this Δv has to be found out optimally since the spacecraft should also not burn too much fuel

and should also not take too much time to reach SM-L2. Now, how is this Δv found out? The end condition is that the spacecraft has to pierce the *Z-X* plane of SM-L2 Lagrangian point with SM-L2 Vx = 0. An initial (guess) Δv value is given and the maximum propagation time for the Propagate segment is turned OFF at this stage. An initial value (10 days) for minimum propagation time is also given. Astrogator calculates the maximum propagation time based on above inputs, stopping conditions and constraints. A lot of Δv values and corresponding values of maximum propagation time were found out and a plot of their variation was made as shown in Figure 4. It can be seen that a

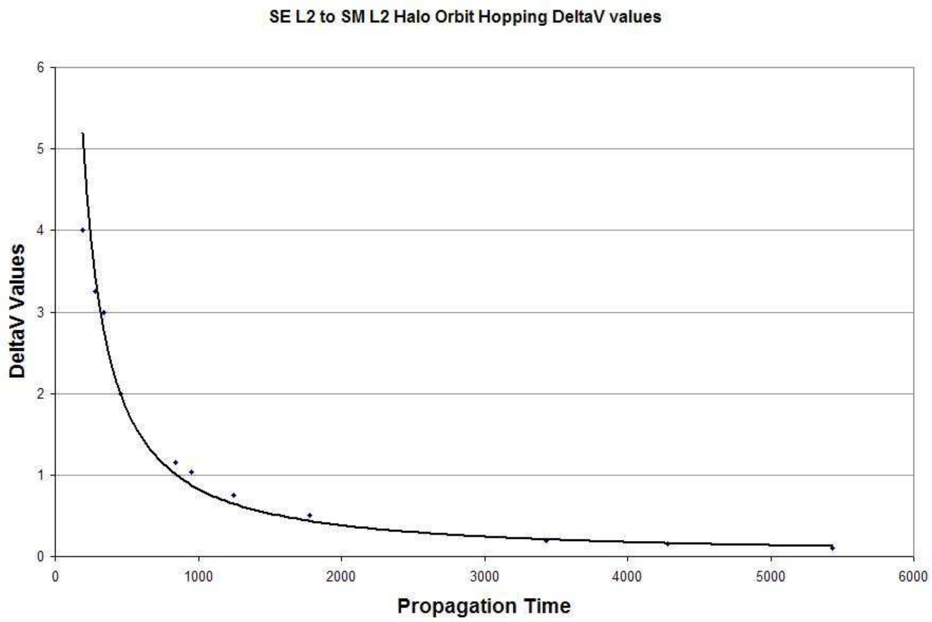

Figure 4: SE-L2 to SM-L2 Halo Orbit Hopping Δv values

small enough Δv will take the spacecraft to SM-L2 but it will take long time to reach. A big enough Δv will propagate the spacecraft fast enough to SM-L2. An optimum value of Δv is chosen keeping in mind the propagation time involved and a small enoughΔv. Similarly, other Δv values for other segments, i.e. halo hopping from SM-L2 to SJ-L2 and SJ-L2 to SS-L2 are found out. As compared to the a Cassini-like Mission(involving gravity assist at Jupiter) Halo orbit Hopping method is slower and hence involves low energy. Another advantage of this method over gravity assist method is that for sending spacecraft to outer planets(e.g. Saturn and beyond) a flyby at Jupiter (a bigger Planet) is imperative. So there is a constraint on spacecraft to have a flyby at such a planet. That is why, a mission to Saturn or Pluto is heavily dependent on planetary positions and therefore such a mission is conceived once in two or three decades. Additionally, flyby involves higher speed and there is a high energy involving method. Halo Hopping method does not need any such alignment of planets. Thus a low energy interplanetary trajectory from SE-L2 to SM-L2 is found out. A similar approach was applied to found out subsequent low energy interplanetary trajectories from SM-L2 to SJ-L2 and from SJ-L2 to SS-L2.

2 Example of Investigation for Halo Orbit Hopping method

An example of our investigation was designing a mission to Titan using the above Halo hopping method. Titan is analogous to the primitive Earth in some respects and therefore, may be the focus of robotic exploration in the next decade. NASA/JPL has plans for another Orbiter/Lander for Titan in 2012. We constructed a scenario of the Halo-hopping method from SE-L2 to SM-L2 to SJ-L2 to SS-L2 and finally to Saturn-Titan L2, to investigate the Δv budget and time frame of the mission. Another scenario of using gravity assisted trajectory from Earth to Saturn (with a flyby at Jupiter) was constructed to compare and contrast the Δv and the duration of the mission for both the methods. While the duration of the mission was only of "academic interest" for Halo hopping method (five times more time than that for the gravity assisted trajectory method), it was the saving in terms of fuel that was more important. Typically for this scenario of Halo hopping, the saving in of fuel was 35.68127% (up to Saturn only) as compared to the gravity assisted trajectory scenario (Cassini). This is a significant figure. Note that, due to the longer duration of the mission, this method could be ideal for cargo ships but not for human missions.

2.1 Sequence of events and vital statistics

The sequence of events and the preliminary results (approximately) are as follows:

Table 2: Earth Departure: 2007/8/1

What	Duration (days)	Δv (Km/sec)
Halo Orbit Insertion at SE-L2	14.5	3.1708
Transfer from SE-L2 to SM-L2	955.0	1.0318
Halo Orbit Insertion at SM-L2	321.0	-0.2797
Station-keeping at SM-L2	378.0	0.1974
Transfer from SM-L2 to SJ-L2	2,595.0	2.0893
Halo Orbit Insertion at SJ-L2	411.0	-0.4230
Station-keeping at SJ-L2	1,642.5	0.4063
Transfer from SJ-L2 to SS-L2	4,881.0	1.3077
Station-keeping at SS-L2	2,244.0	0.8798

More details about the cost of station-keeping at SE-L2, SM-L2, SJ-L2 and SS-L2 are given in Table 2.1.

Table 3: Cost Details for Station-keeping at SE-L2, SM-L2, SJ-L2, and SS-L2

What	Δv (Km/s/Yr)	Duration (Yr)	Z-X plane crossings
Station-keeping at SE-L2	0.024827	1.0274	4
Station-keeping at SM-L2	0.190630	1.0356	3
Station-keeping at SJ-L2	0.090286	4.5000	3
Station-keeping at SS-L2	0.143111	6.1480	3

2.2 STK Screenshots

The trajectory of the spacecraft can be seen as below in different STK screenshots.

Future Work

There is still a wide scope to further investigate using our approach. The flexibility of bringing together the power and versatility of STK/Astrogator with the dynamics of low energy transfer orbits is a powerful combination. The simplicity of our Halo Orbit hopping approach is the logical execution of the events/stages in trajectory targeting and designing. The trajectory targeting has been done in a series of steps and phases,

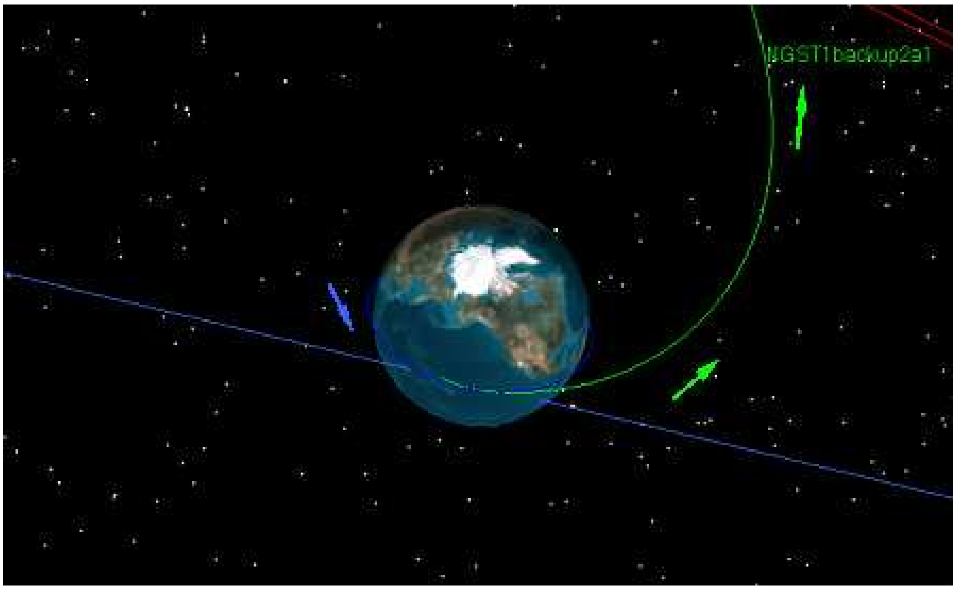

Figure 5: Halo orbit insertion at SE-L2 Lagrangian point as seen in STK VO view.

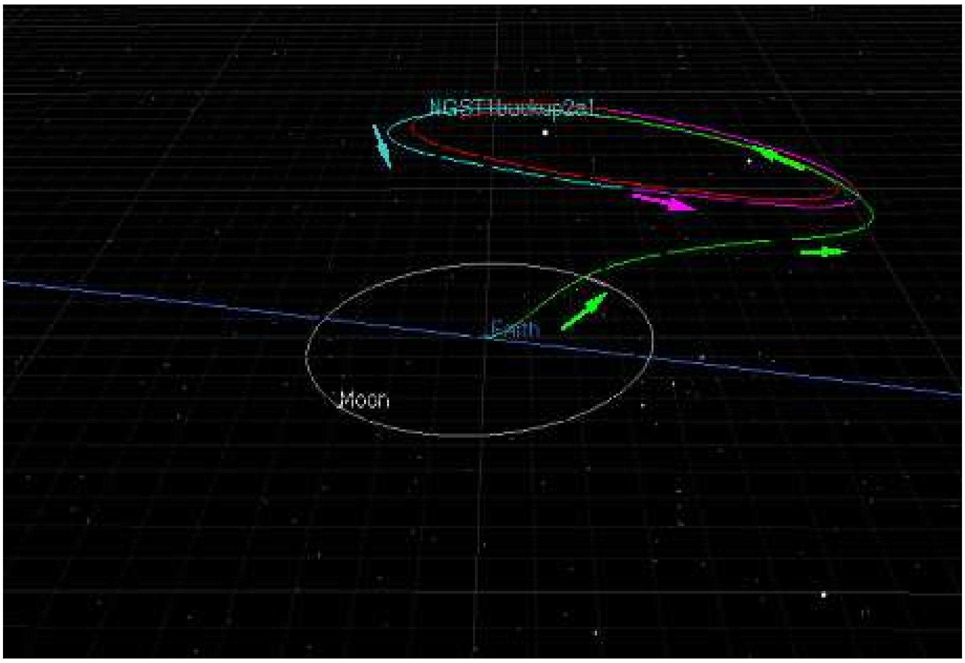

Figure 6: Halo Orbit at SE-L2 Lagrangian point as seen in VO view

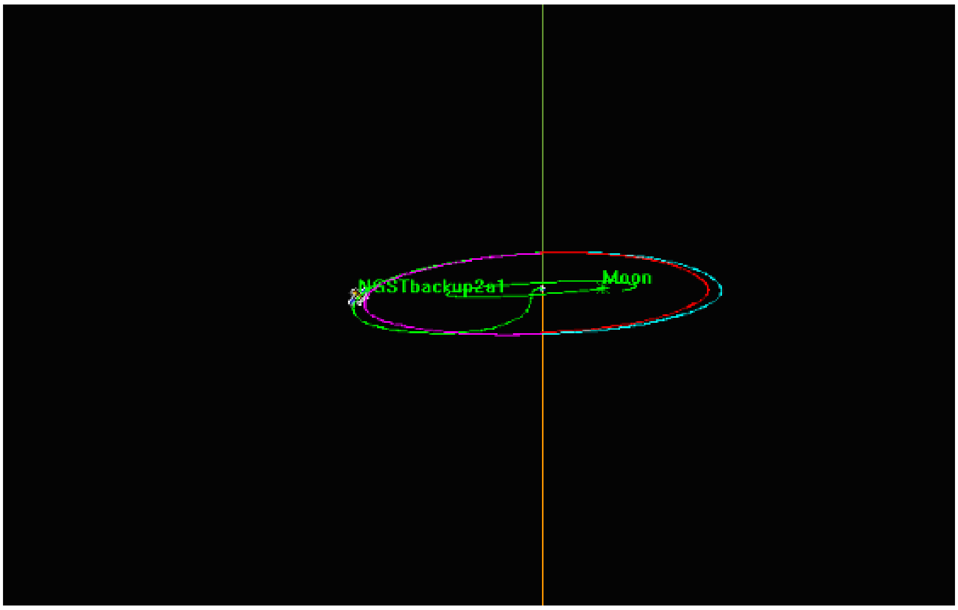

Figure 7: Halo Orbit at SE-L2 Lagrangian point as seen in Y-Z plane (Map view)

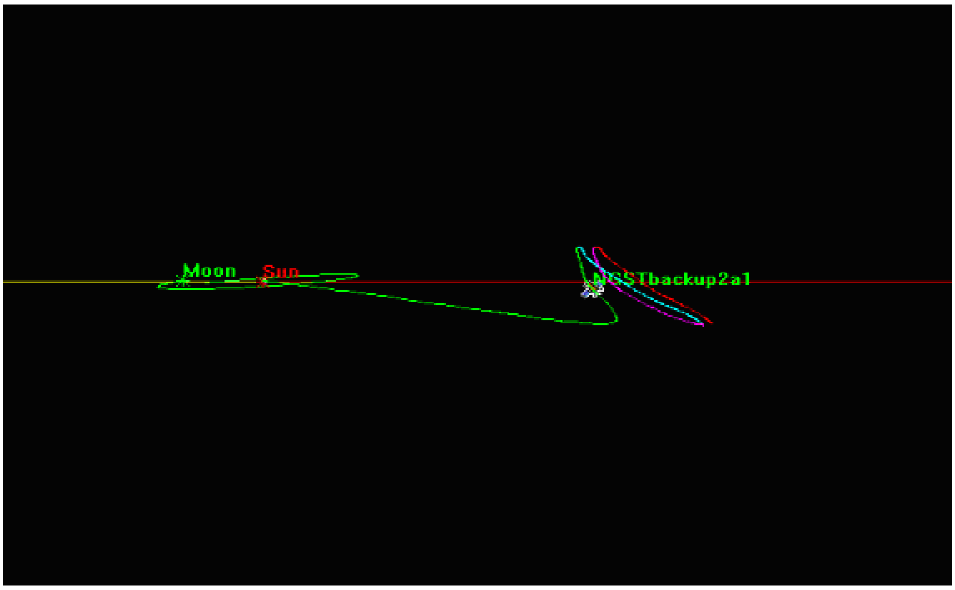

Figure 8: Halo Orbit at SE-L2 Lagrangian point as seen in X-Z plane (Map View)

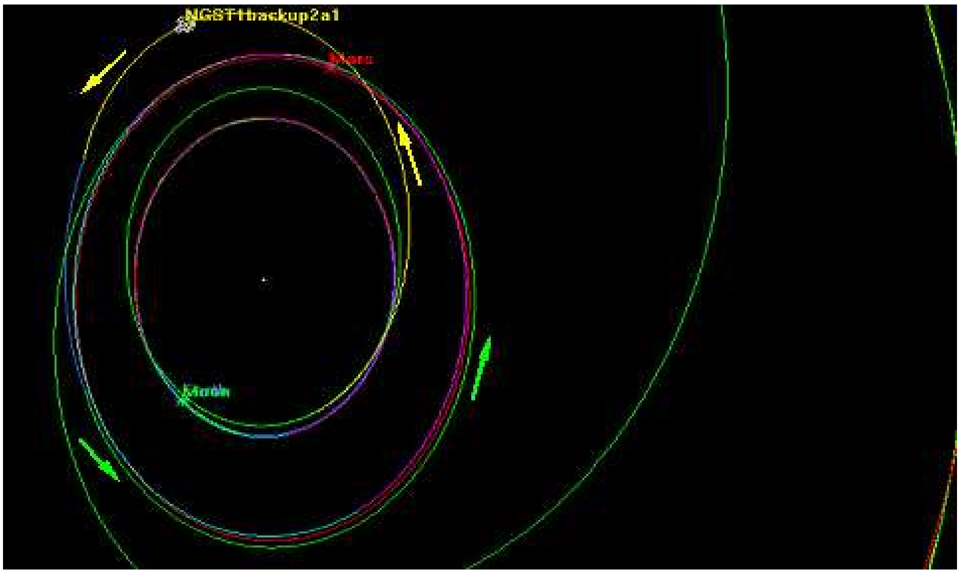

Figure 9: Low energy interplanetary transfer orbit from SE-L2 to SM-L2 Lagrangian point (Map view)

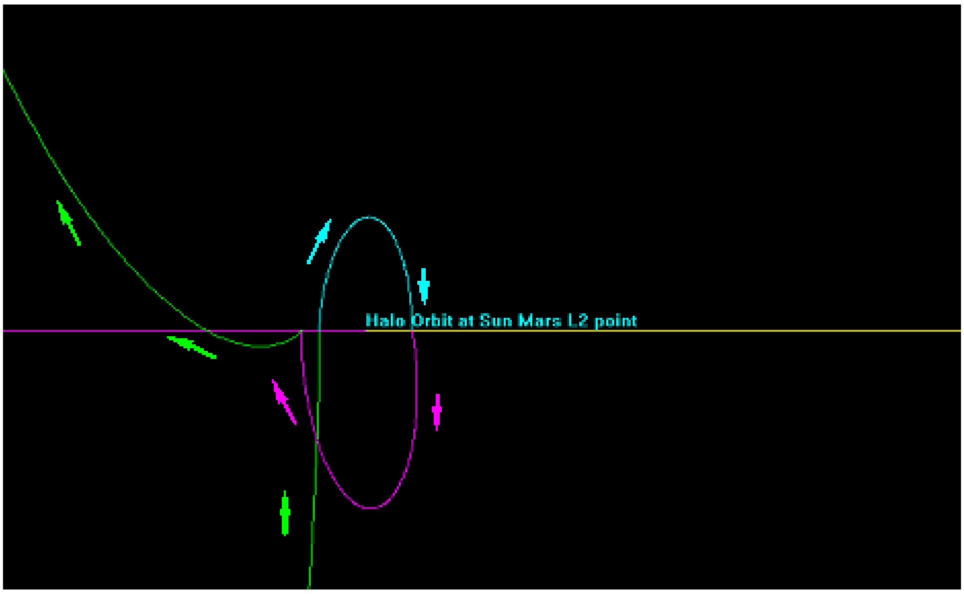

Figure 10: Halo orbit insertion and getting off the Halo orbit at SM-L2 Lagrangian point as seen in Sun-Mars rotating frame of reference (X-Y plane: Map view)

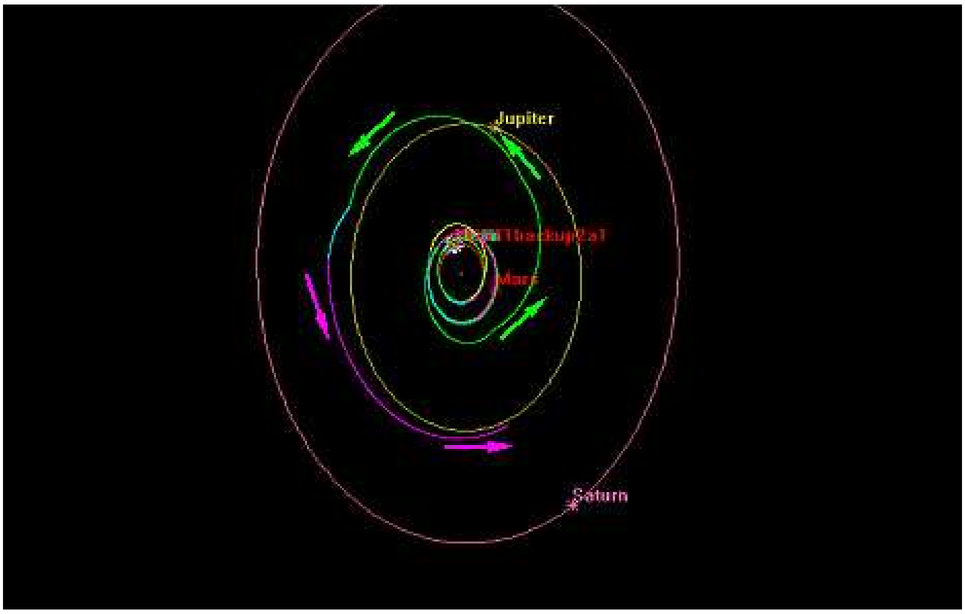

Figure 11: Trajectory of spacecraft in a Halo orbit at SJ-L2 Lagrangian point as seen in Sun-centered inertial frame of reference (Map view)

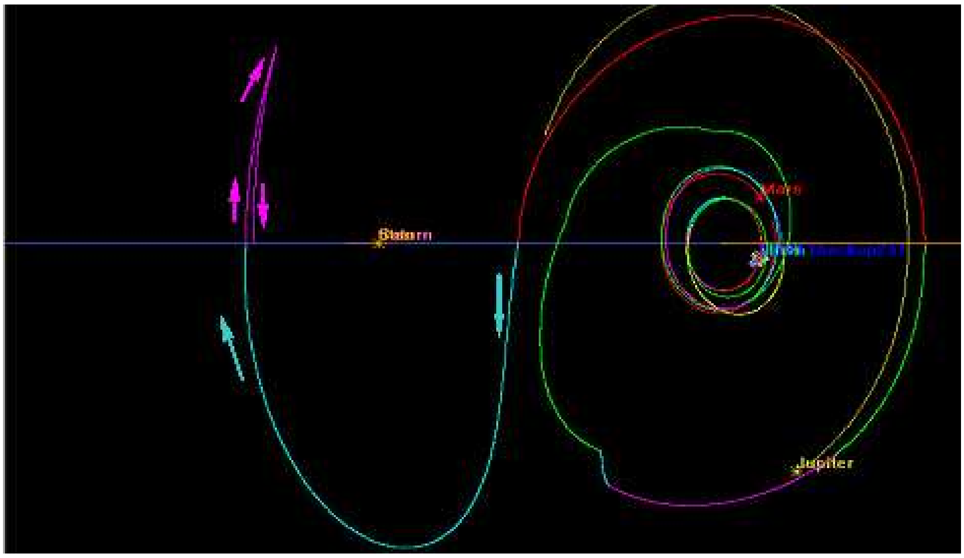

Figure 12: Halo orbit insertion at Sun-Saturn L2 Lagrangian point as seen in Sun-Saturn rotating frame of reference (X-Y plane: Map view)

depending upon the complexity and goals. A lot of optimization can be done by varying the initial orbit state and maneuver execution errors. Instead of Halo orbits, Lissajous orbits around L1 and L2 or the transit orbits from L1 to L2 Lagrangian points can also be investigated further.

This Halo orbit hopping method can be tested in the design of a multi-moon orbiter spacecraft visiting Jovian moons [5]. One more application of the above research is in tune with the recent Presidential Moon-Mars exploration announcement. The existing research has identified potential utility and data for satellites orbiting the L1 and L2 points serving as Earth-Moon [6] and Earth-Mars communication relays [7].

Conclusion

The method based on Halo Orbit hopping is quite different and much lower speeds are involved. So trade off is that spacecraft can travel along the trajectories indefinitely, and it is essentially coasting anywhere it wants to go (theoretically). The only fuel needed would be for minor corrections, and to actually get on/off the trajectory at the beginning and end of the mission. For example, the typical mission to Saturn, for example, the Cassini mission, the total time to reach Saturn is close to 7-8 years. By using above Halo-hopping method the time taken is more than 35-40 years (roughly 5 times more). The time of flight for this preliminary trajectory can be minimized by finding a compromise between fuel and time optimization during the different phases of the mission.

Acknowledgements

The authors want to dedicate this paper to the memory of Chauncey Uphoff, one of the main authors of STK/Astrogator, who recently passed away. We thank John E. Hurtado, for the time and the discussions he dedicated to this work.

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