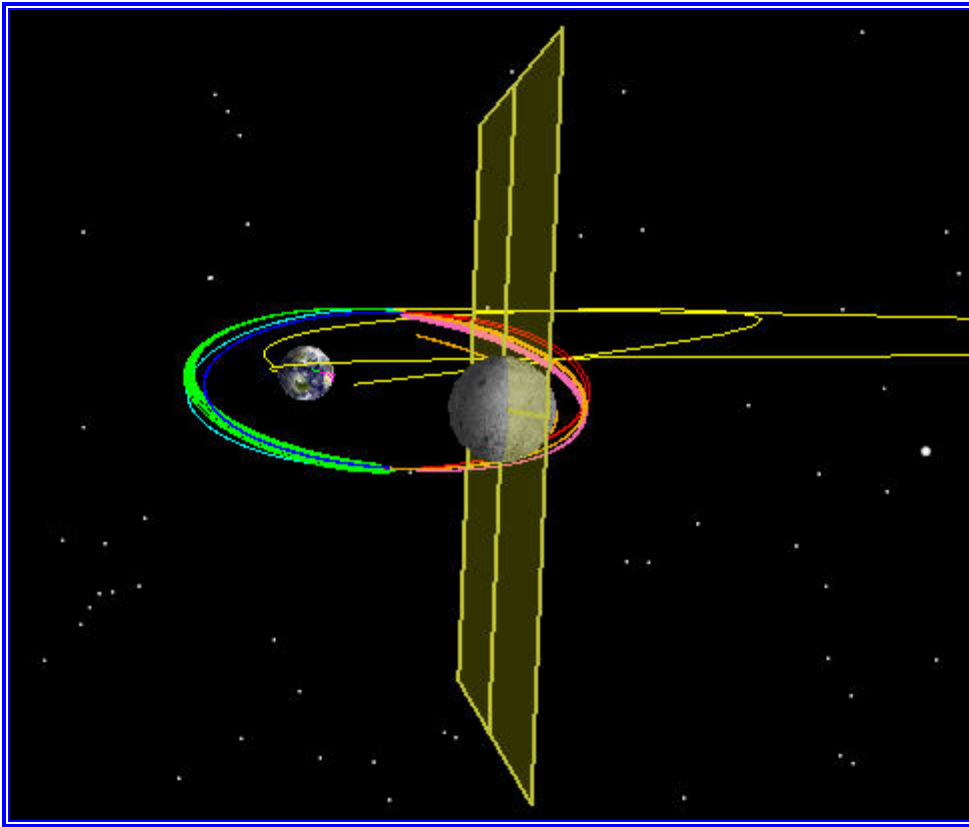


Trajectory Design with STK/Astrogator

Earth-Moon L1 Trajectory Tutorial



1.

Setting Up the Scenario

This next scenario involves creating a trajectory that goes from Earth Orbit to the Earth-Moon L1 libration point.

Setting up to Scenario and Animation Times

1. Open a new scenario in STK. By default, you should get a 3D Window and a 2D Map. We will configure these windows later for our Lunar mission.
2. Name the scenario 'L1_Orbiter'.
3. Specify the timeframe of the mission. This is important since the objects that don't fall within the interval of the scenario will not be displayed. The orbit epoch of this particular mission is July 1st, 2005. This is a good reference time for our scenario; therefore, we will use it as our start time.

Right click on the 'L1_Orbiter' scenario and select **Basic Properties**. On the **Time Period** verify that we have the follow parameters:

Time Period	
Element	Value
Start Time	1 Jul 2005 12:00:00.00
Stop Time	2 Jul 2005 12:00:00.00
Epoch	1 Jul 2005 12:00:00.00

Select the **Animation** page and introduce the following dates:

Animation	
Element	Value
Start Time	1 Jul 2005 12:00:00.00
Stop Time	2 Jul 2005 12:00:00.00

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Animation

Element	Value
Time Step	60 sec



You can access the Basic Properties of any object in STK by double-clicking on its object icon.

We are now ready to configure our 3D windows for our mission to L1. We will use the following settings to visualize the orbit on the XY plane as seen from the Sun Ecliptic North (Z Axis).

CREATING PLANETS

4. With the scenario selected, from the **Insert** menu, select **New** and then **Planet**.
5. From the **Basic Properties** of the new planet, on the **Definition** page, select '**Moon**' as the central body.
6. On the 3D Graphics/Attributes page, deselect **Inherit from Scenario** and leave the rest off.
7. Create another planet, this time the Earth.
8. On the 3D Graphics/Attributes page, deselect **Inherit from Scenario** and leave the rest off.

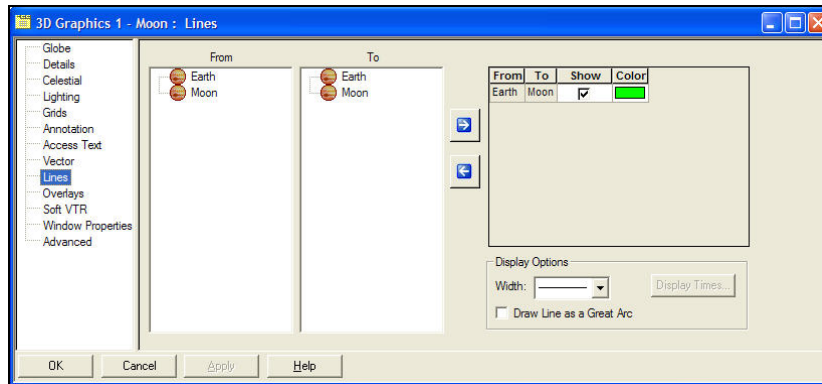
WINDOW SETTINGS

9. Delete the default 2D window, create a 2nd 3D window and:
 - a. Name it (via the 'Window Properties' tab) 'Rotating view'.
 - b. On the **Advanced** Page, change the Visible Distance to 1e+009 km.
 - c. On the 'Lines' page, create a line from the Earth to the Moon and set it to 'show'.

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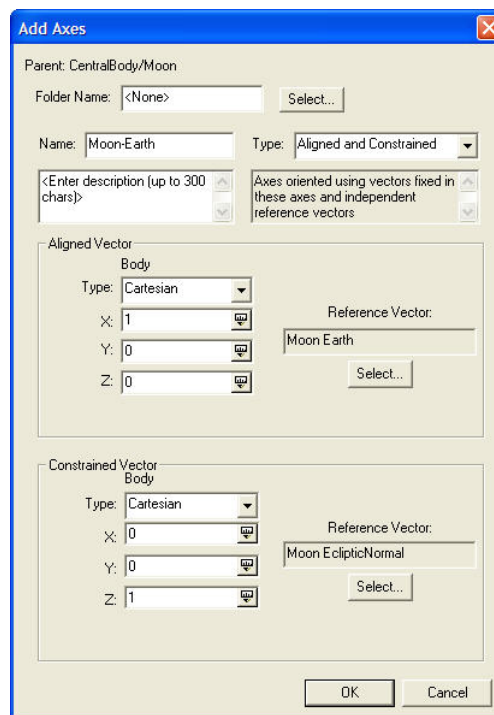
NOTES



- d. From the STK Tools toolbar, open the Vector Geometry Tool.



Create a new set of axes under the Moon object (use the blue globe Moon) called 'Moon-Earth Rotating' defined as follows:



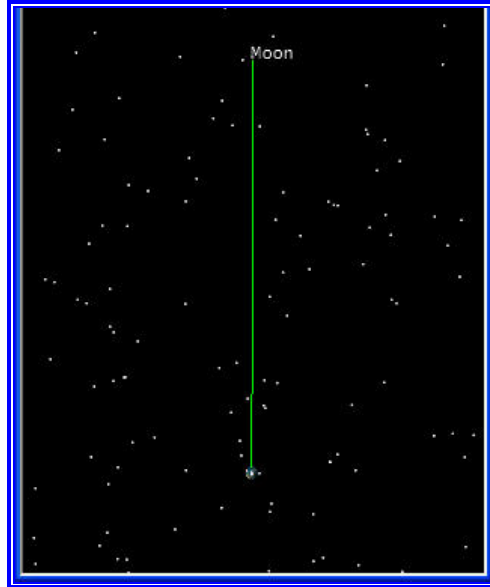
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This will give us a set of axes for our 3D window to follow.

- e. Select the 'Rotating View' 3D window, and then the 'View from/to' button.
- f. Using the 'Add' button, find and select the Moon-Earth Rotating' axes you just created.
- g. Using your mouse and the 'Shift' key, move your viewpoint around until you have a view that looks roughly like this:



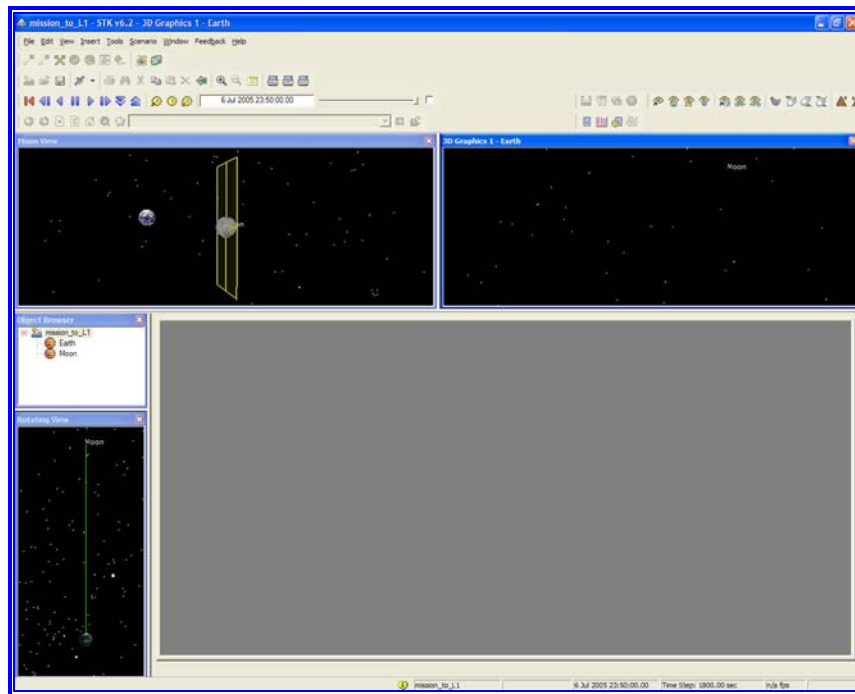
10. Dock this 3D windows to the left of your application and the other to the top (Select the window, and right click on the upper blue bar of the window for these options). We'd like the windows to be visible during targeting so it's best not to leave them Integrated, or Floating.
11. Create a 3rd 3D window and name it 'Moon View'
12. Select the 'Moon View' window, and click on the **Properties** button.
 - a. On the **Globe** page, change the Central Body to Moon.
 - b. On the **Advanced** Page, change the Visible Distance to 1e+009 km.
 - c. On the Celestial Page, turn on the Earth ('Other Bodies') and turn off its label.
 - d. With the 'Moon View' window selected, use the View To/From button to set the reference frame to 'Moon-Earth Rotating Axes'.

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NOTES

13. Open the Vector Geometry tool and create the L1 ZX Plane. We'll use this later to visualize how our targeter is working.
 - a. Under the Moon (Blue Globe) create a coordinate system (Type = Assembled) named 'Earth-Moon L1' that uses the Moon/L1 Object for the center and the Moon/L1 Axes.
 - b. Under the Earth, create a plane of type 'Quadrant', named 'L1 XZ Plane' and use the ZX Quadrant and the Earth, Earth-Moon_L1 coordinate system.
 - c. Select the properties of the 'Moon View' window and under the Vector page, add this plane. Make the plane transparent, and of size 5. Turn the label off.
14. Dock the 'Moon View' window to the top, and try to position things so that you can see them.



15. Select the 'Moon View' window and then Shift-Cntl-C. This will change the central body for the scenario to the Moon. Thus, all satellites we create after this point will be Moon centered.

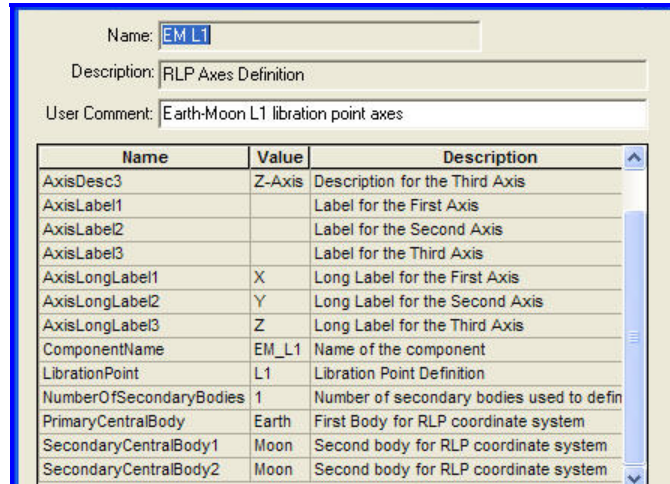
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Configuring Axes and Coordinate Systems

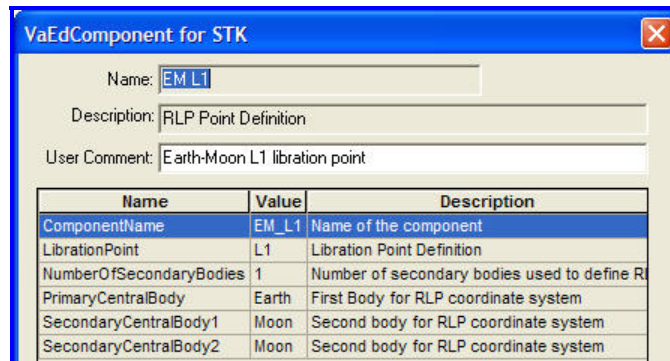
16. Open the Astrogator component browser and then the Axes/Multibody folder
17. Copy the 'SEM L1' Axes set (Sun-Earth-Moon L1) and rename it 'EM L1'. Configure it as follows:



Name	Value	Description
AxisDesc3	Z-Axis	Description for the Third Axis
AxisLabel1		Label for the First Axis
AxisLabel2		Label for the Second Axis
AxisLabel3		Label for the Third Axis
AxisLongLabel1	X	Long Label for the First Axis
AxisLongLabel2	Y	Long Label for the Second Axis
AxisLongLabel3	Z	Long Label for the Third Axis
ComponentName	EM_L1	Name of the component
LibrationPoint	L1	Libration Point Definition
NumberOfSecondaryBodies	1	Number of secondary bodies used to define
PrimaryCentralBody	Earth	First Body for RLP coordinate system
SecondaryCentralBody1	Moon	Second body for RLP coordinate system
SecondaryCentralBody2	Moon	Second body for RLP coordinate system

This sets up a set of libration point axes at L1 with the Earth as the primary body, and the Moon as the secondary. We can then use this to setup a coordinate system that uses this, but first we must set up a center point for the coordinate system to use.

18. Open the 'Points/Multibody' folder and make a copy of the 'SEM L1' object called 'EM L1'
19. Configure it as follows:



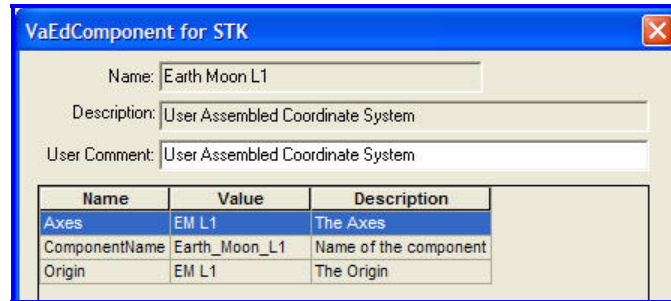
Name	Value	Description
ComponentName	EM_L1	Name of the component
LibrationPoint	L1	Libration Point Definition
NumberOfSecondaryBodies	1	Number of secondary bodies used to define R
PrimaryCentralBody	Earth	First Body for RLP coordinate system
SecondaryCentralBody1	Moon	Second body for RLP coordinate system
SecondaryCentralBody2	Moon	Second body for RLP coordinate system

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20. Now we need to use both the point and the axes to create a coordinate system. Open the “Coordinate Systems” folder and copy the ‘User defined’ object and call it ‘Earth-Moon L1’. Configure it as follows:



Name	Value	Description
Axes	EM L1	The Axes
ComponentName	Earth_Moon_L1	Name of the component
Origin	EM L1	The Origin

21. Now that we have a proper coordinate system for the Earth-Moon L1, we will define some Cartesian coordinates that use it.
- Open (inside the Astrogator Component Browser still) the ‘Cartesian Elements’ folder.
 - Make a copy of each of the existing elements (X, Y, Z, X, Vx, Vy, Vz) and rename them. (i.e. L1 X, L1 Y, L1 Z, etc...). Configure each of these individually to use the EM L1 Coordinate system that we created above.

Now we will begin to build the Mission Control Sequence. Our first task is to get from Earth orbit to L1. Once there, we will insert ourselves into an ‘orbit’ around the L1 point and then maintain that orbit to stay there. As with our other scenarios, we’ll start using a Launch and Coast segment.


CREATING THE SPACECRAFT

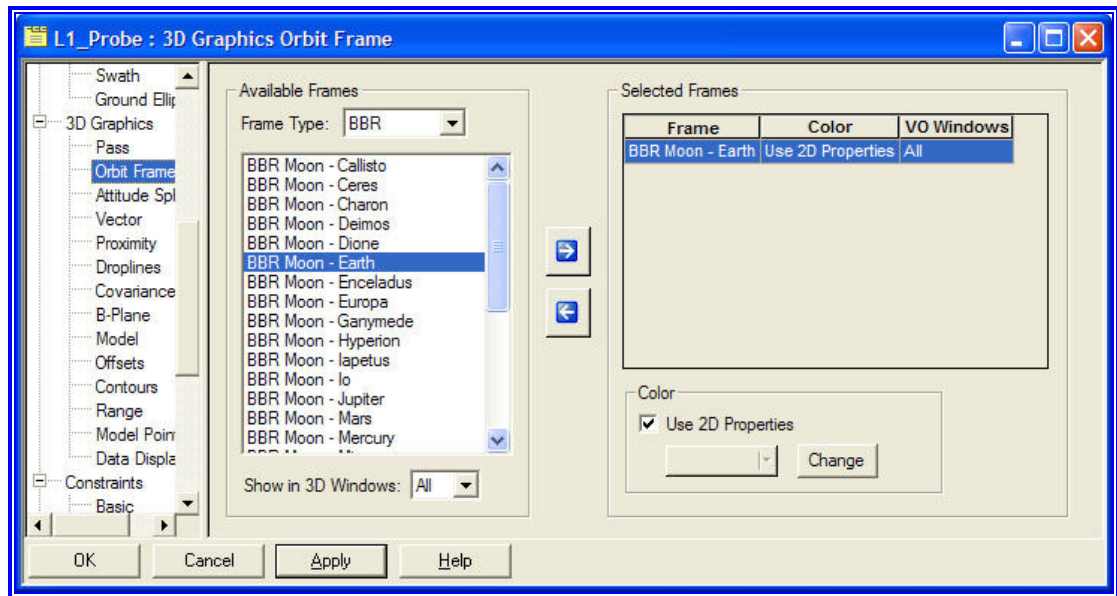
- With the scenario selected, from the Insert menu, select New and then Satellite. Dismiss the orbit wizard.
- Name the satellite ‘L1_Probe’.
- Select the Basic Properties of the satellite.
- From the Orbit page, change the propagator to ASTROGATOR.

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26. Remove all the segments in the Mission Control Sequence (MCS) using the Delete Segment button .
27. On the **3-D graphics page/Pass** page turn the **Orbit Track/Lead Type** to **All**.
28. From the **3-D graphics/Model** page, for the Detail Thresholds, slide the Marker label and the Marker bars to the maximum.
29. On the **3D Graphics/Orbit Frame** page, set the selected frame to 'BBR/BBR-Moon-Earth' for windows 2 and 3, and Inertial by Window for window 1.



Building the MCS

30. Add a new satellite to the scenario. Make it an Astrogator satellite and delete the default segments. Name it 'L1_Sat'.
31. Insert a target sequence and name it 'Target L1'.
32. Inside the target sequence, insert a Launch segment (use the default Launch segment). Select the Launch **Epoch** as a control. Set the **Burnout Azimuth** to **80** deg, and the **Downrange Distance** to **3000** km.

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33. After A1 Launch, insert a propagate segment. Name it 'Coast', change it's color, and set the trip duration to 3000 seconds. Select the **Trip Duration** as a control.
34. After 'Coast', insert a maneuver segment name 'TLI' (Trans-Lunar Injection). Set the Attitude Control to 'Thrust Vector', set the X(Velocity) component to **3.05** km/sec and select the **X(Velocity)** as a control.
35. After 'TLI', insert a propagate segment named 'Prop to Plane Crossing'. Change the propagator to 'Cislunar', and change the stopping condition to 'Apoapsis'.
36. Rename the default Differential Corrector profile in 'Target L1' to 'Target Apogee'.

First Guess Profile

37. Add 2 results to the 'Prop to Plane Crossing' segment (from the 'Multibody' calc objects folder):
 - a. **Delta RA** (keep all default values)
 - b. **Delta Dec** (keep all default values)

We will use these for our first guess, which will be to target our Apogee to line up with the Earth-Moon line. We've guessed a TLI magnitude that won't quite get to the Moon, and if we force our apoapsis to line up with the Moon, we will be close to L1.

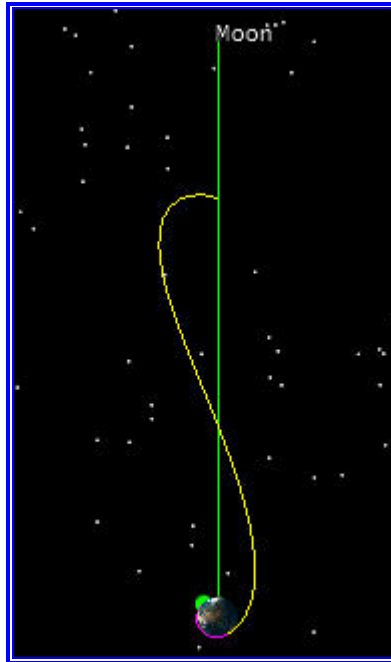
38. Configure this profile as follows:
 - a. Controls:
 - i. **Launch Epoch**. Perturbation **1000** sec. Max Step size **10,000** sec.
 - ii. **Coast duration**. Perturbation **100** sec, Max Step size **1000** sec.
 - b. Constraints
 - i. **Delta RA** (from 'Prop to plane crossing') default tolerance.
 - ii. **Delta Dec** (from 'Prop to Plane crossing') default tolerance.
39. Under the MCS options, set the trajectory to 'Draw Trajectory in 3D as it is calculated'.
40. Turn off 'Draw Trajectory in 2D as it is calculated'.
41. Set the Targeter Action to 'Run Active Profiles'

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42. Run the MCS.



Our first guess was to line up with the Moon at apoapsis. Now that we've done that, we are no longer interested in stopping on Apoapsis, but we'd actually like to stop on the X-Z plane crossing in our L1 libration point coordinate system. Once we've stopped there, we will target ourselves to a particular point on that plane in order to achieve the L1 orbital conditions we desire.

We'd like our scenario to be able to target all the way to L1 from any starting epoch (without any user configuring) we give it, so we need our first profile to be able to give us our first guess (Apoapsis with a matching RA Dec) without any subsequent segments running. We can do this by placing a return segment within the targeter. When a return segment is active, no segments after the return will execute.

43. Add a Return after the 'Prop to Plane Crossing' segment and rename it 'Return for RA Dec'.

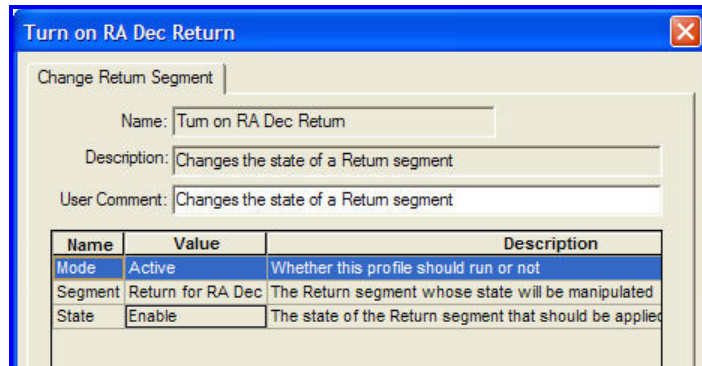
This segment will prevent any subsequent segments from running until after the first profile converges. In order to properly use this segment, we need to first turn it on, and then after the profile converges, turn it off.

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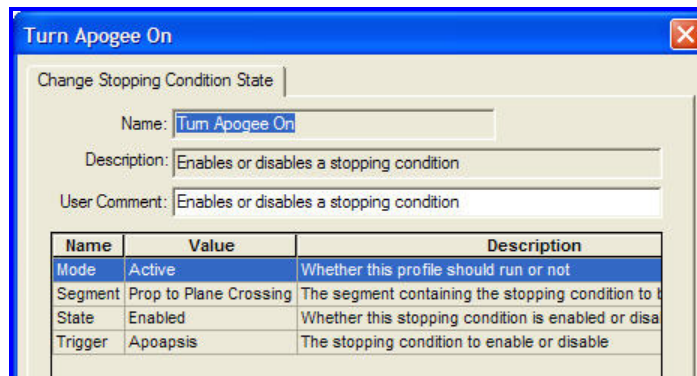
NOTES

44. Add a 'Change Return Segment' Profile to the Beginning of the profile list of 'Target L1' and name it 'Turn on RA Dec Return'. Set it to turn on the First return.



Name	Value	Description
Mode	Active	Whether this profile should run or not
Segment	Return for RA Dec	The Return segment whose state will be manipulated
State	Enable	The state of the Return segment that should be applied

45. Add a 'Z-X Plane Crossing' stopping condition to the 'Prop to Plane Crossing'. Configure it to use the 'EM L1' Coordinate system. Set the tolerance for the crossing to 0.001 km.
46. Create two 'Change Stopping Condition State' profiles after the 'Turn on RA Dec Return' profile.
- Rename the first 'Turn Apogee on' and configure it to turn on the Apoapsis stopping condition of the 'Prop to plane crossing' segment.



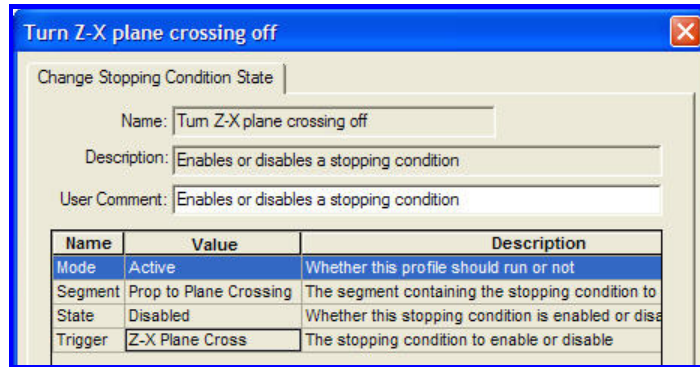
Name	Value	Description
Mode	Active	Whether this profile should run or not
Segment	Prop to Plane Crossing	The segment containing the stopping condition to be manipulated
State	Enabled	Whether this stopping condition is enabled or disabled
Trigger	Apoapsis	The stopping condition to enable or disable

- Rename the second 'Turn Plane Crossing off' and configure it to turn off the Z-X Plane Crossing stopping condition of the 'Prop to plane crossing' segment.

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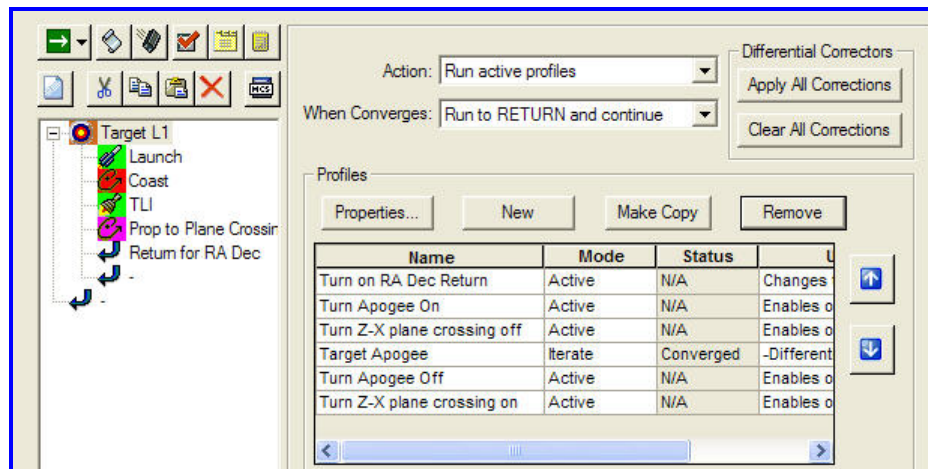
47. Clear corrections from the Targeter and re-run it to make sure it converges.

This configures our targeter so that it can always run the first profile without running any subsequent segments. This functionality is key, because when targeting our first guess (i.e. apogee on the Earth-Moon line) our other segments (which we haven't created yet) wouldn't work.

48. Add two profiles after the 'Target RA Dec' profile that do the opposite of 2 of our other profiles (Make copies of them and toggle the settings):

- Turn Apoapsis stopping condition off
- Turn ZX plane crossing stopping condition on.

49. Your MCS and profiles should look like this:



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NOTES

We now have a set of profiles that are configured to do the following:

- Turn on the return, preventing any segments after the return from executing
- Turn on the Apogee stopping condition
- Turn off the ZX plane crossing stopping condition
- Vary our launch and coast segments in order to align our apogee with the Moon.
- Turn off the Apogee stopping condition.
- Turn on the ZX plane crossing stopping condition.

Once the ZX stopping condition is on, and we are close to the L1 point, we can now target for our specific L1 Libration point insertion conditions. Next we need to set up a new profile to do this.

Profile to Hit L1

50. Add 3 new results to the 'Prop to Plane Crossing' segment

- a. L1_X (from Cartesian Folder)
- b. L1_Z (from Cartesian Folder)
- c. L1_Vx (from Cartesian Folder)

We'll use these to place ourselves 5000 km directly above the L1 point (x and y =0) and with a Vx =0, which will dictate that we are roughly at apogee and moving perpendicular to the Earth-Moon line.

51. Create a new 'differential corrector' profile, after the 'Turn Z-X Plane Crossing on' profile, named 'Target L1 Insertion Point'. Configure it as follows:

- a. Controls
 - i. **Launch Epoch.** Perturbation **100** sec. Max Step size **10,000** sec.
 - ii. **Coast duration.** Perturbation **10** sec, Max Step size **1000** sec.
 - iii. **TLI X-component.** Perturbation **0.001** Km/sec, Max Step size **0.01** km/sec.
- b. Constraints
 - i. L1_Vx. **Desired Value 0.0** km/sec, **Tolerance of 1.0e-5** km/sec
 - ii. L1_X. Desired Value **0.0** km, Tolerance **1** km.

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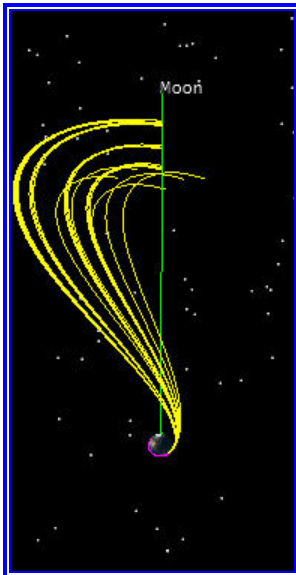


NOTES

iii. L1_Z. Desired Value **5000.0** km, Tolerance **1** km.

Using the Z-X plane crossing as a stopping condition forces our L1_Y to be zero without targeting.

52. On the 'Prop to Plane Crossing' segment, select the 'Advanced' button, and set the **Minimum Propagation Time** to **1** day. This will prevent us from stopping on the first crossing of the Z-X plane, which occurs while we are still close to the Earth.
53. Clear all corrections from your targeter and run the MCS.



At this point we've hit a spot 5000 km above the Earth-Moon L1 Libration point. Now we'd like to insert ourselves into an orbit here. The orbital parameters we pick here are appropriate for the 5000 km offset. Some orbit analysts have their own Circular Restricted Three-Body Problem (CRTBP) solvers that give them these sorts of parameters, we derived these from trial and error within STK/Astrogator

54. Before the 'Return for RA Dec' segment, insert a Maneuver segment named 'L1 Insertion'
55. Set the Attitude Control to 'Thrust Vector' and select all three components as controls.

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NOTES

Insertion Profile

56. Add three results to this segment:

- a. L1_Vx
- b. L1_Vy
- c. L1_Vz

57. Create a new Differential Corrector Profile in the 'Target L1' Targeter at the end of the Profile list. Name it 'Set Velocity' and set it up as follows:

- a. Controls
 - i. **L1 Insertion X-component** default Perturbation and Max Step size
 - ii. L1 Insertion **Y-component** default Perturbation and Max Step size
 - iii. L1 Insertion **Z-component** default Perturbation and Max Step size
- b. Constraints
 - i. L1 Vx **Desired Value** of **0.03** km/sec, Tolerance **0.0001** km/sec
Gives us a slight velocity towards the Earth along the Vx
 - ii. L1 Vy **Desired Value** of **-0.06** km/sec, Tolerance **0.0001** km/sec
Gives us a tangential velocity (to the Earth-Moon Line) so that we can be in an 'orbit' around L1.
 - iii. L1 Vz **Desired Value** of **0.0** km/sec, Tolerance **0.0001** km/sec
Give us a zero Z component.

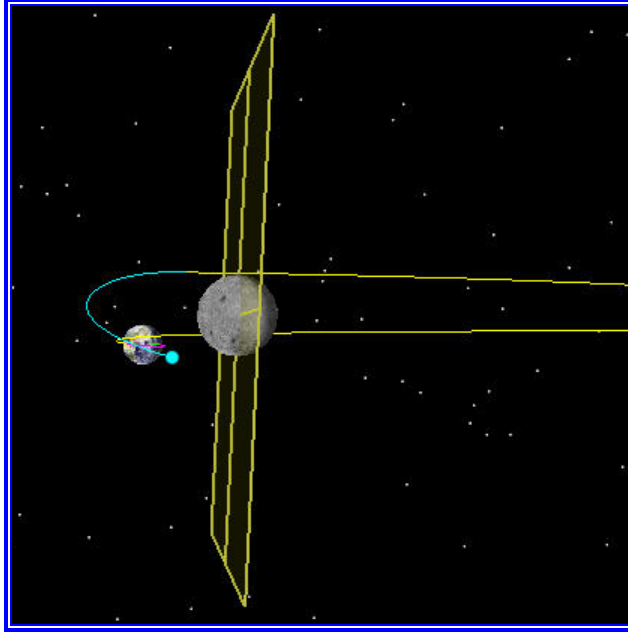
58. Insert a propagation segment outside of the 'Target L1' Target sequence and name it 'Prop to 2nd Plane Crossing'. Set it to stop on Z-X Plane Crossing, and set the coordinate system to EM_L1. Set the tolerance for the crossing to 0.001 km. Change the propagator to Cislunar.

59. Run the MCS. Your window should look roughly like this:

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NOTES



This shows us where our first plane crossing after insertion will take place. In order for us to get a 2nd plane crossing, we need to force this plane crossing to be perpendicular to the ZX plane. We'll do this by forcing V_x to be zero at the plane crossing.

Stay in orbit for 2 Revs

60. Cut the 'Prop to 2nd Plane Crossing' and paste it after the 'Return for RA Dec' segment.
61. In order to get this segment to execute, we'll need to deactivate the return segment. Copy the 'Turn RA Dec Return On' segment and leave it at the end of the profile list.
62. Rename it 'Turn RA Dec Return Off' and reconfigure it to disable the return.
63. Make a copy of the 'Prop to 2nd Plane Crossing' segment, paste it after the original, and rename it 'Prop to 3rd Plane Crossing'. Set the color different from the original.
64. Add the $L1_V_x$ result to both the 'Prop to 2nd Plane Crossing' and the 'Prop to 3rd Plane Crossing'.
65. Create a new Differential Corrector Profile in the 'Target L1' Targeter at the end of the Profile list. Name it '2nd Plane Crossing' and set it up as follows:
 - a. Controls

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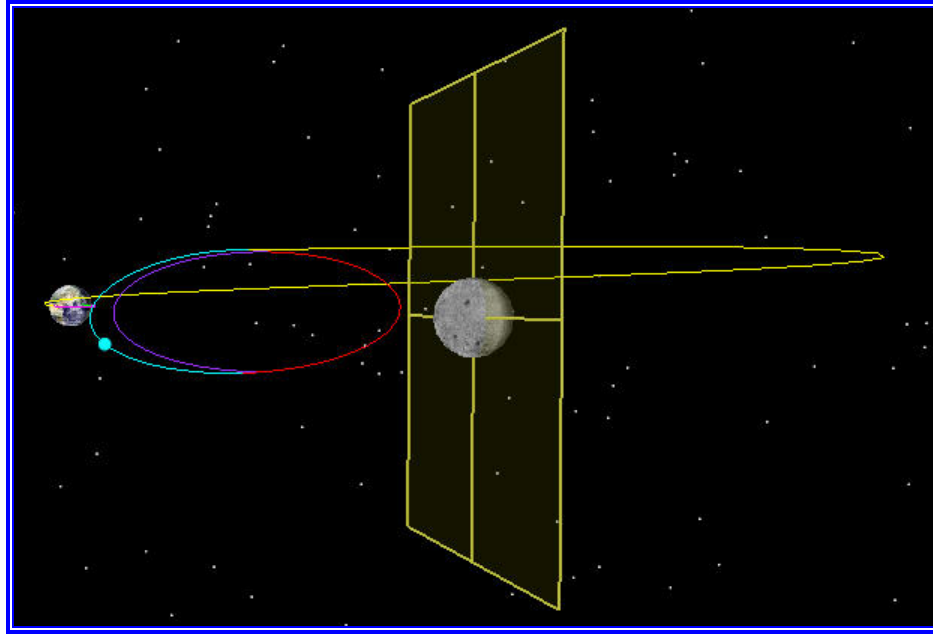
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- i. **L1 Insertion X-component** Perturbation **0.0001** km/sec, Max Step size **0.01** km/sec
 - ii. L1 Insertion **Y-component** Perturbation **0.0001** km/sec, Max Step size **0.01** km/sec
 - iii. L1 Insertion **Z-component** Perturbation **0.0001** km/sec, Max Step size **0.01** km/sec
 - b. Constraints
 - i. L1 Vx (Prop to 2nd Plane Crossing Segment) **Desired Value** of **0.00** km/sec, Tolerance **1e-5** km/sec
- 66. Create a new Differential Corrector Profile in the 'Target L1' Targeter at the end of the Profile list. Name it '3rd Plane Crossing' and set it up as follows:
 - a. Controls
 - i. **L1 Insertion X-component** Perturbation **0.00001** km/sec, Max Step size **0.0001** km/sec
 - ii. L1 Insertion **Y-component** Perturbation **0.00001** km/sec, Max Step size **0.0001** km/sec
 - iii. L1 Insertion **Z-component** Perturbation **0.00001** km/sec, Max Step size **0.0001** km/sec
 - b. Constraints
 - i. L1 Vx (Prop to 3rd Plane Crossing Segment)**Desired Value** of **0.0** km/sec, Tolerance **1e-5** km/sec
- 67. Make another copy of the 'Prop to 2nd Plane Crossing' Segment, and paste it outside of the 'Target L1' Targeter. Rename it '4th Crossing' and change the color.
- 68. Run the MCS. You should get a view that looks roughly like this:

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NOTES



69. Use the 'Insert' menu and add the 'Save_1Rev' satellite that is saved in the folder with this PDF file. It will contain a portion of an MCS that can be used to do orbit maintenance for 1 full rev.

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