ASEN 6060 – Spring 2025

Modeling a Spacecraft in the Earth-Moon System – STK Instructions

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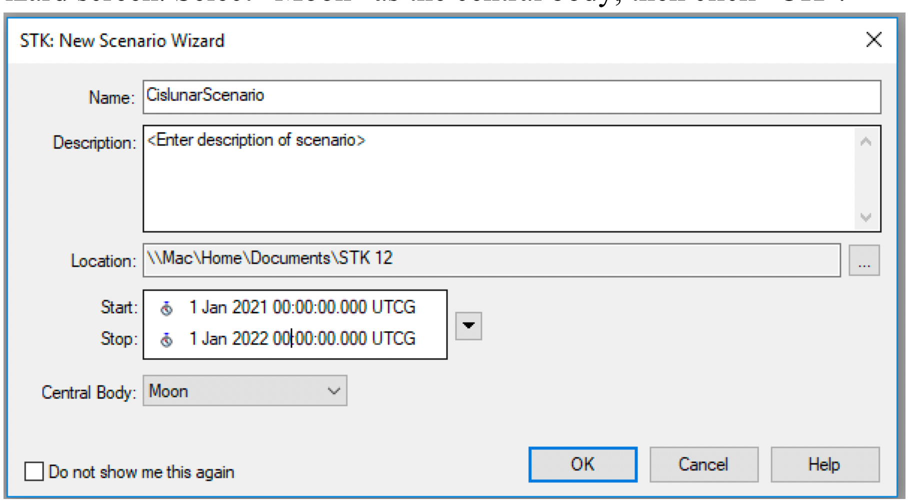
Objective: Using STK, create a scenario of a spacecraft in the Earth-Moon system and view the path in the Earth-Moon rotating frame. Then, correct the path to produce a trajectory that remains near a periodic orbit.

Note: there are multiple approaches to implementing this scenario, these instructions simply present one option. If you want to create a replica of the CR3BP in STK in your own time, follow these instructions: https://help.agi.com/stk/#training/Astro_CR3BP.htm

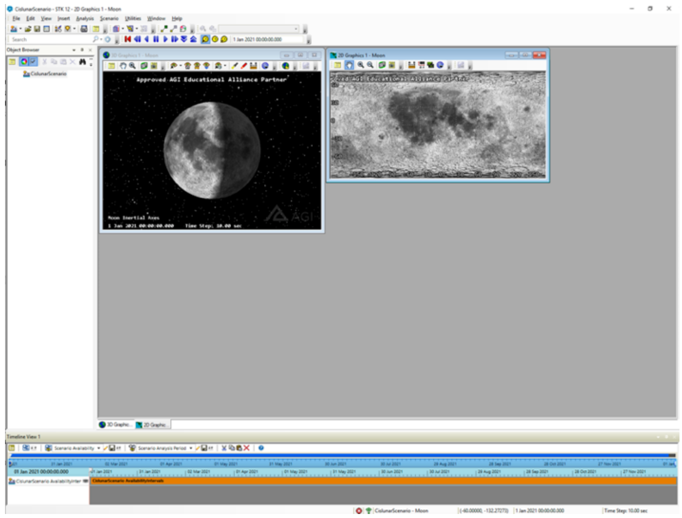
Note: For all input parameters, use the quantities in the text instructions. The quantities in the images may not match the text instructions as they have been updated since the images were taken.

Creating a Baseline Scenario

1. Open STK (select STK Enterprise). In the top menu bar, click "View" and then "Planetary Options".
2. Click "Create Scenario" in the welcome popup.
3. Create a scenario with the name "CislunarScenario" using a start time of 12 January, 2025 00:00:00.000 UTCG and stop time that is 1 year later by entering this information in the New Scenario Wizard screen. Select "Moon" as the central body, then click "OK".



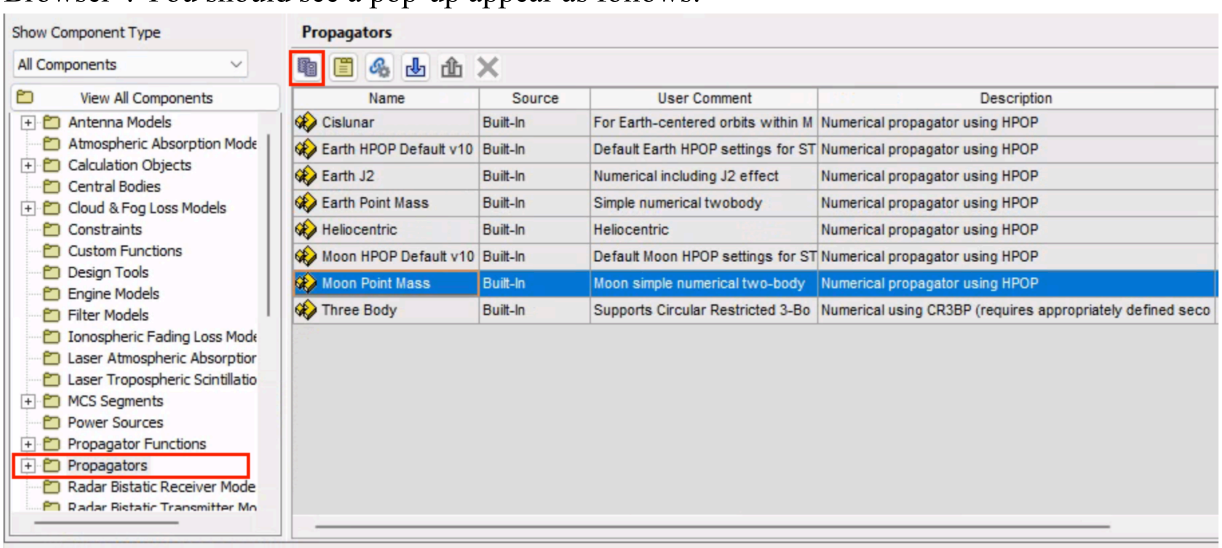
4. The STK window will then update to appear as follows (Be patient if it takes a while to load):



This window features both a 3D graphics window and a 2D ground track view (a projection of the satellite's location on a body's surface), with a panel on the left indicating the objects available within the STK scenario. Be sure to save this scenario by clicking the "Save" button or using the "File"→"Save" options within the menu. **Be sure to press the save button regularly!!!**

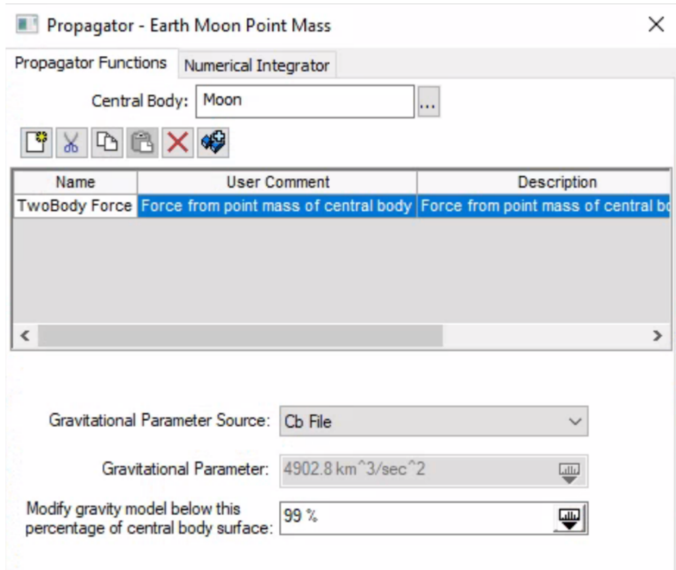
<u>Creating Dynamical Models for Propagation</u>

5. We will create a point mass ephemeris model to govern the motion of a spacecraft in cislunar space, with the state of the spacecraft defined relative to the Moon. To define this dynamical model, click "Utilities" in the top menu bar of the STK window and click "Component Browser". You should see a pop-up appear as follows:

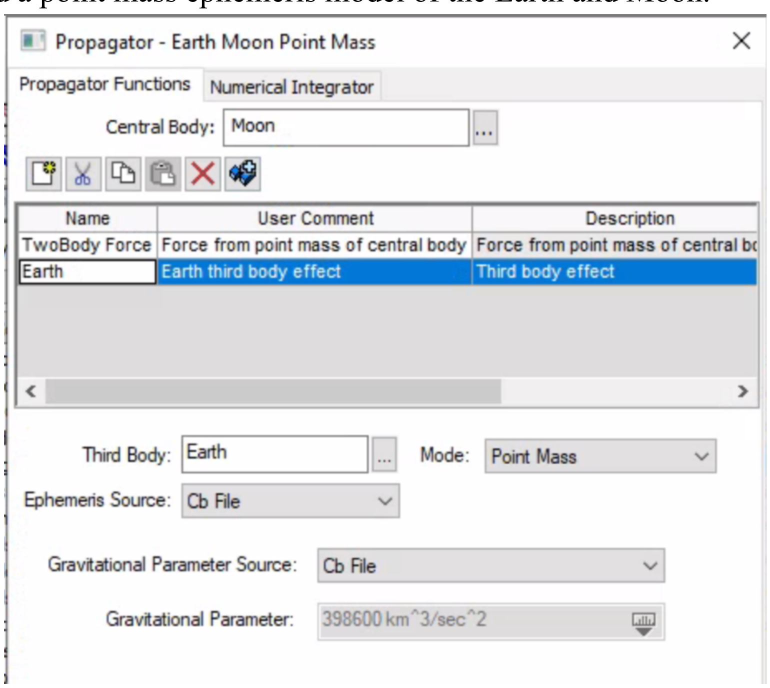


6. On the lefthand panel of the Component Browser, click Propagators, highlighted in red above. Then select "Moon Point Mass" and click the "Duplicate" button also highlighted in red above. (Note: do not use the default Cislunar propagator, it is a higher fidelity model of the cislunar environment that is not customizable) Name this propagator "Earth-Moon Point Mass Model"

and click “OK”. Double click the propagator you just created. A window should appear as follows:

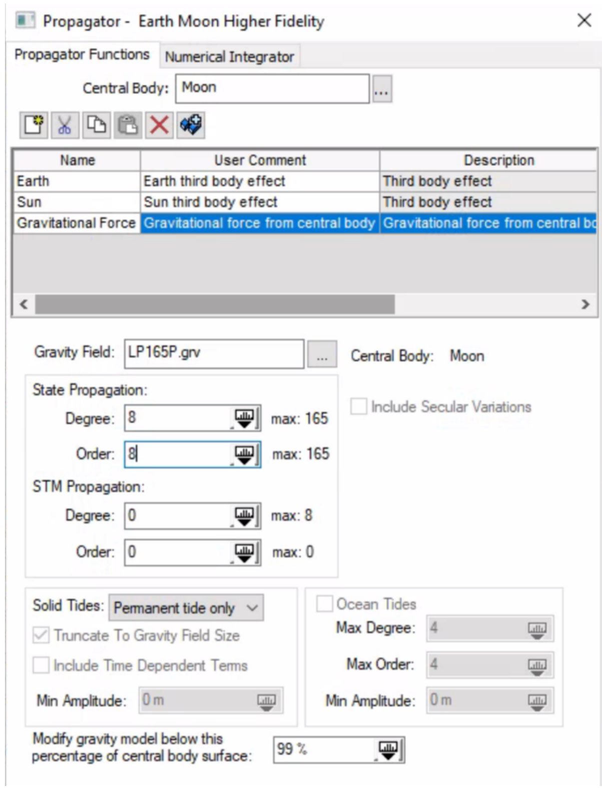


7. This model already incorporates the point mass gravitational influence of the Moon denoted as a “TwoBody Force”.
8. To add the point mass gravitational interaction of the Earth, use the blank page icon above the list to add a new force: “Earth” under the “Third Bodies” folder. Click OK. The propagator window should then appear as follows. Click to OK to save your changes. You have now created a point mass ephemeris model of the Earth and Moon.



9. Create another dynamical model by duplicating the Earth Moon Point Mass model. Label this new dynamical model “Earth Moon Higher Fidelity Model”. Once you open it, add a new Force that is another “ThirdBody” and select “Sun”; this option adds the Sun’s gravity. In

addition, let's add a higher-fidelity model of the Moon's gravity. Remove the Moon's "Two Body Force" by highlighting that item in the force list and clicking the red "X" button. Then add another force and under the "Gravity Models" folder, select "Gravitational Force". Click OK and return to the dynamical model properties window. Here, change the Gravity Field option by clicking the "…" button and selecting the "LP165.grv". Then, set the degree and order to 8 under "State Propagation". The properties should be configured as follows:



10. Click OK after creating this propagator and then close the component browser.

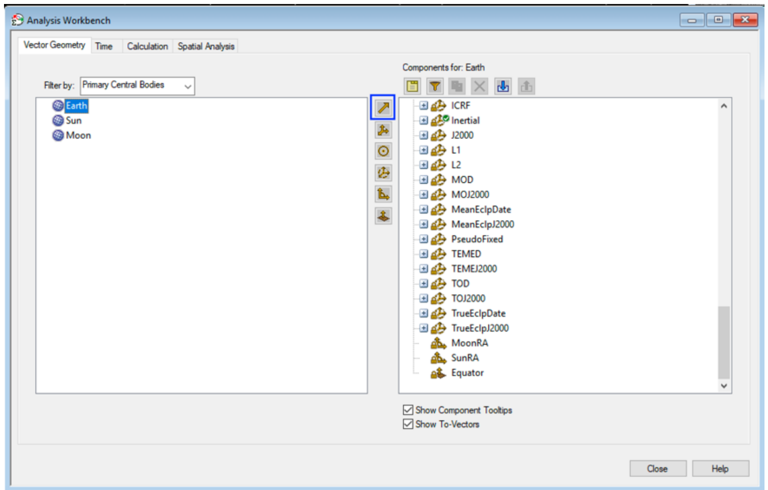
<u>Configure the 3D View</u>

11. Navigate to the 3D graphics window; here, you can view an orbit in three dimensions. You may need to zoom in/out to view the entire orbit later – this can be achieved by holding the right click button on your mouse while dragging the mouse towards or away from you. To rotate the view, click the left button on your mouse on a region in the 3D graphics window and drag. To remove the Moon shadow from the 3D graphics window, navigate to the 3D graphics properties window (the yellow page icon at the left of the toolbar in your 3D graphics window) and select the "Lighting" page. Then, uncheck the "Enable Lighting" property. Click "Apply" **Have you saved recently?**

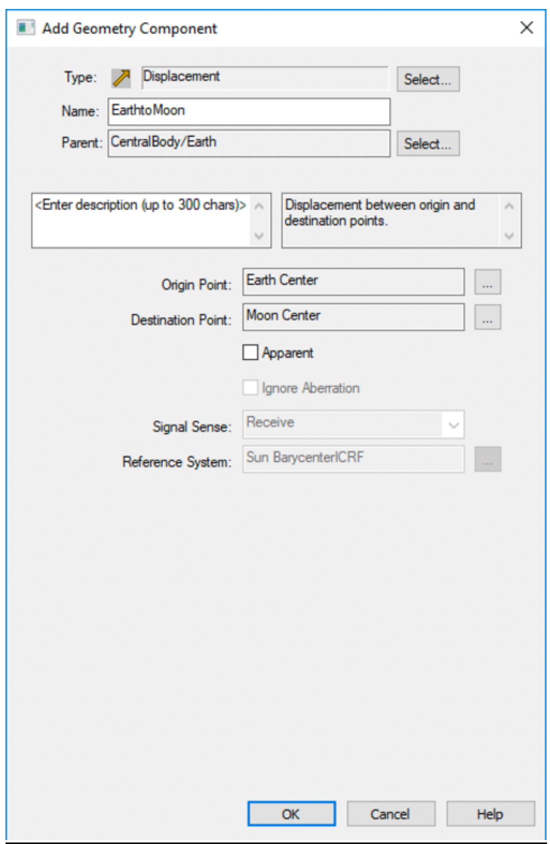
<u>Create an Earth-Moon rotating frame and associated Moon-centered coordinate system</u>

12. To create a rotating frame, we will first create a vector directed from the Earth to the Moon. To create this vector navigate to "Analysis" in the main STK window toolbar and click "Analysis Workbench". Select the "Vector Geometry" tab. Then, on the lefthand panel of the Analysis Workbench panel, select "Primary Central Bodies" from the "Filter by:" dropdown.

Then, select the Earth. Then, click the vector button between the left and right panel, as indicated by the blue box below:

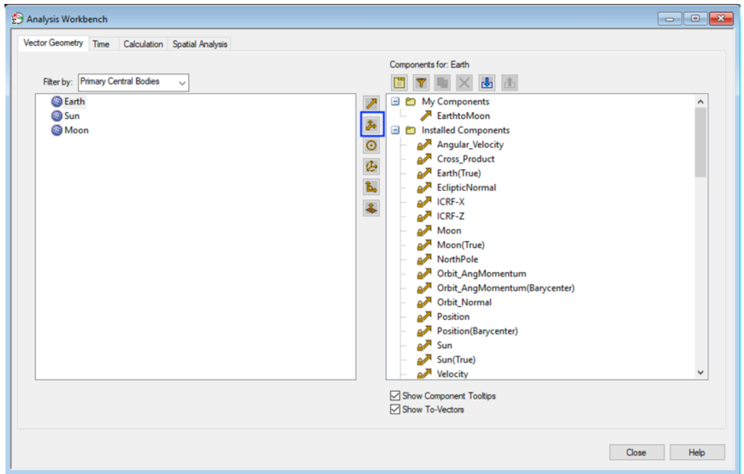


13. To create a vector from the Earth to the Moon, update the panel to appear as follows and then click “OK”:

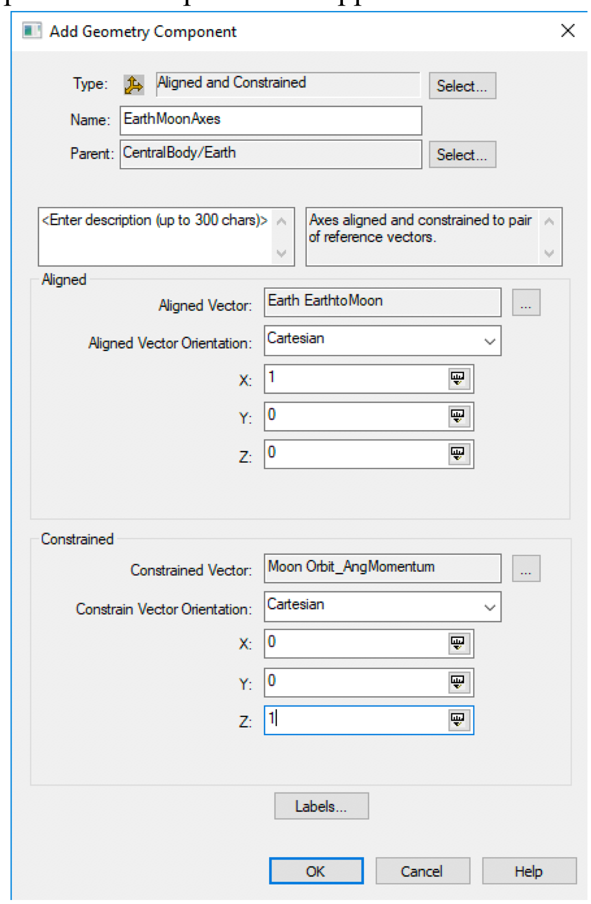


Note that to change the “Destination Point” to the center of the Moon, simply click the “…” button and select “Moon” from the lefthand panel and “Center” from the righthand panel of the “Select Reference Point” window.

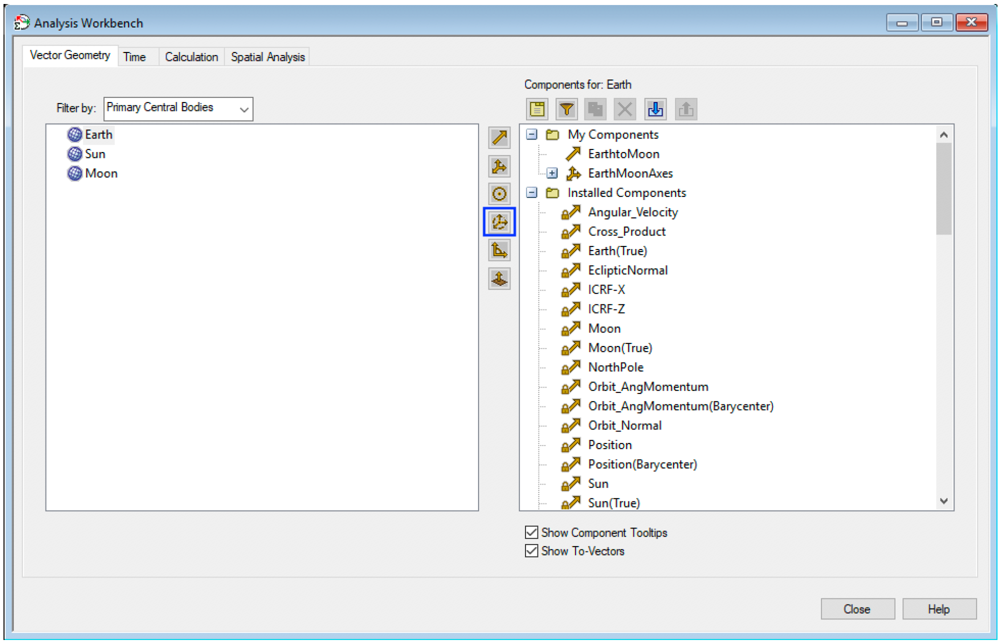
14. Then, we will create the three axes of the Earth-Moon rotating frame. To create the axes, select the button indicated by the blue box below:



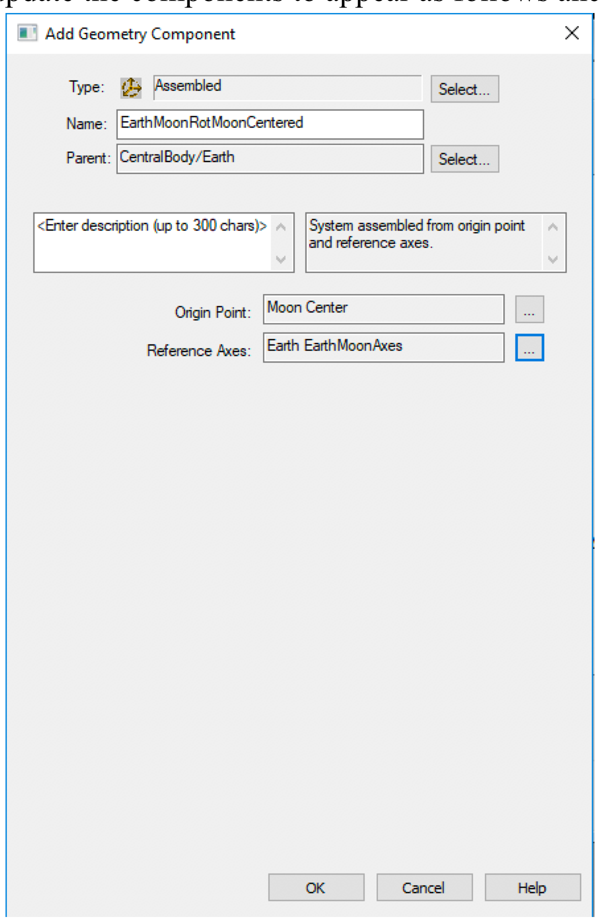
15. In the popup window, update the components to appear as follows and then click "OK":



16. Next, we will create a Moon-centered coordinate system that uses the Earth-Moon rotating axes. To create the system, select the button indicated by the blue box below:



17. In the popup window, update the components to appear as follows and then click "OK":

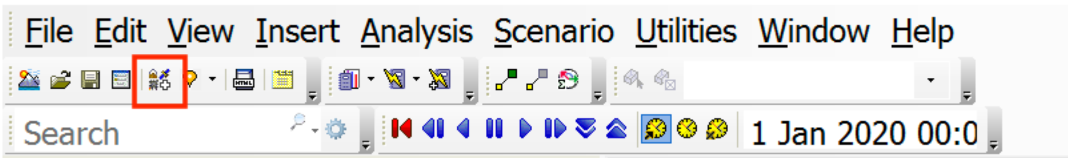


18. Then close the Analysis Workbench.

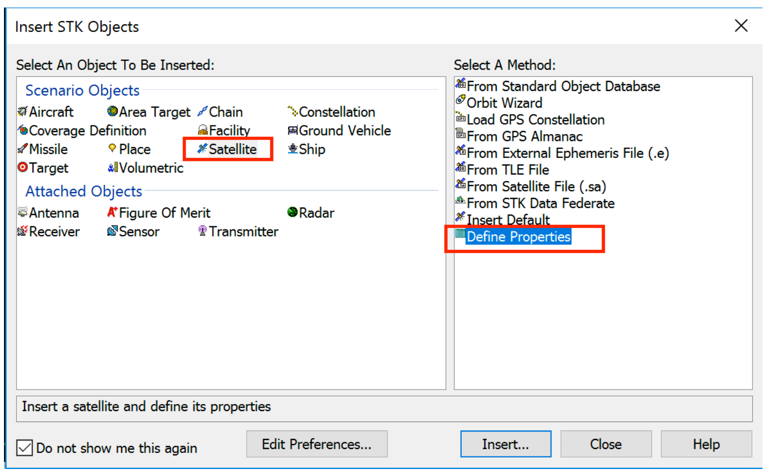
Have you saved recently?

<u>**Create and Configure a Spacecraft**</u>

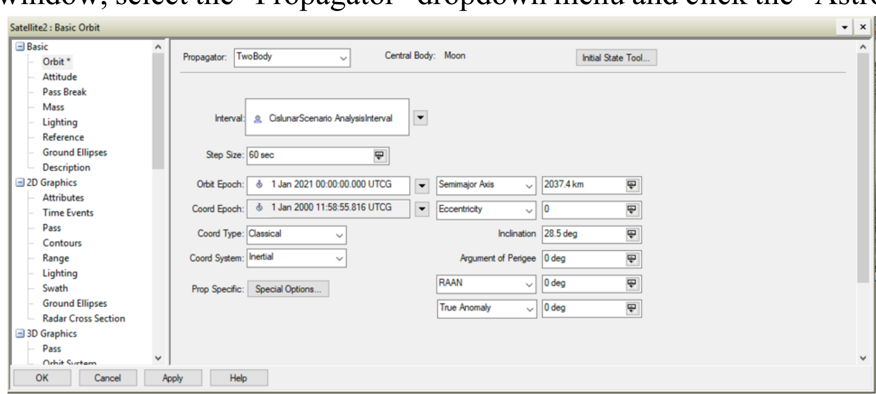
19. Insert a satellite in cislunar space either by clicking the button highlighted by a red square in the figure below, located within the toolbar at the top of the window or accessing the "Insert"→"New…" option in the menu bar.



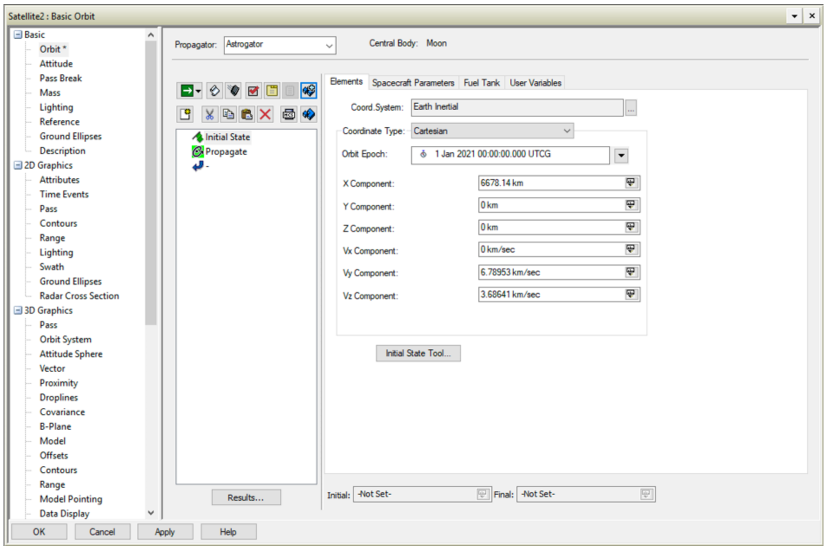
20. An "Insert STK Objects" popup should appear. Select the "Satellite" object on the left panel of this window and click the "Define Properties" method for inserting the object. These options are highlighted in the picture below. Once the desired object and insertion method have been selected, click "Insert…".



21. The satellite's properties window then appears as displayed below. On the "Basic"→ "Orbit" page of this window, select the "Propagator" dropdown menu and click the "Astrogator" label.



The new Astrogator window that appears should resemble:



Astrogator is a powerful feature of STK that enables the construction of a Mission Control Sequence (MCS). An MCS is essentially a sequence to define the various phases of a trajectory: initial conditions, propagation over some time interval or until an event is reached, application of maneuvers, etc. When propagating a satellite in Astrogator, we can define various force models, add vectors of interest, perform propagations near a variety of bodies, generate reports describing the satellite state at various locations along the trajectory, and even target transfers.

22. Configure the MCS (which appears on the lefthand side of the Astrogator panel). By default, STK has already added two components of the MCS: an initial state, and a propagate segment. Keep these two segments.
23. Click on the "Initial State" segment in the MCS. Here, we will set the initial conditions on the selected epoch of 12 Jan 2025 00:00:00.000 UTCG. Next, let's calculate an initial guess for an initial state vector. We will implement the most foundational methods; more complex approaches are beyond the scope of this course. Consider an L_1 northern halo orbit with an approximately 12-day period. In the CR3BP, a nondimensional state that lies along the leftmost xz-plane crossing of this periodic orbit is truncated as:
    $\bar{x} = [8.35071 \times 10^{-1}, 0, 1.40622 \times 10^{-1}, 0, 2.51487 \times 10^{-1}, 0]$, T = 2.76312 nondim
    a) Translate this state vector from using the Earth-Moon barycenter to using the Moon center as the origin by subtracting 1-mu from the x-coordinate
    b) Calculate the instantaneous l^* and t^* characteristic quantities from the following truncated position vector of the Moon relative to the Earth at the specified epoch and expressed in the GCRF:

    $$\bar{r} = [1.890395e{+}04;\ 3.292575e{+}05;\ 1.785784e{+}05]\ \text{km}$$

    c) Dimensionalize the state vector components using the computed instantaneous values of l^* and t^*.
24. Use the following parameters to define the satellite's orbit in the "Elements" tab in the panel on the righthand side:
    a. *Coord. System: EarthMoonRotMoonCentered (After clicking the "…" button next to*

Coord. System, click Earth as the body on the left panel of the popup window and on the right panel select the coordinate system that we created earlier.)

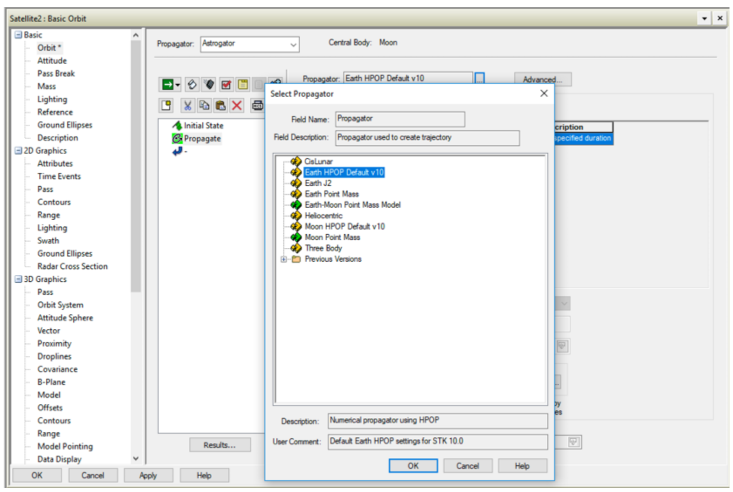
b. *Coordinate Type: Cartesian*

c. *Orbit Epoch:* 12 Jan 2025 00:00:00.000 *UTCG*

d. For the Cartesian components, input the dimensional state vector components you calculated earlier.

Once these values have been entered to define the initial state of the spacecraft, click the “Apply” button to save your changes.

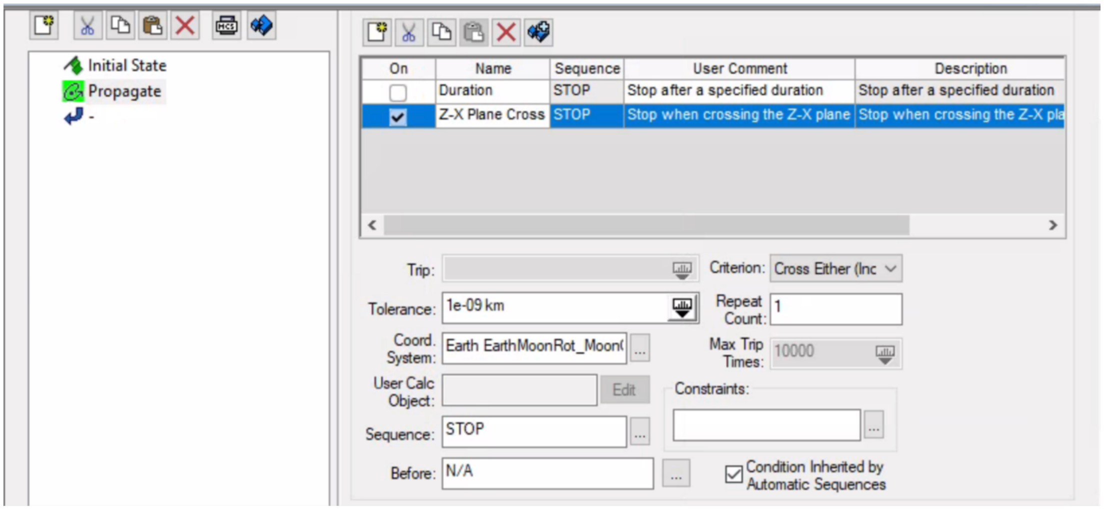
25. Next, configure the “Propagate” segment by clicking its label in the MCS. A new panel should appear on the righthand side of the Astrogator page. Click the “…” button next to the Propagator selection box at the top of this window. We will change the integration and dynamical model properties via this option. A new popup window should appear as follows:



Select the “Earth-Moon Point Mass Model” you created from the list and then click “Ok”. This propagator only includes the point mass model of the Earth and Moon’s gravity, allowing us to integrate the motion of the satellite in a three-body problem (but not the CR3BP because the Earth and Moon are not following circular orbits but, rather, their actual paths). Once you have returned to the “Propagate” configuration panel and the “Propagator” textbox has updated, click “Apply”.

26. This panel also enables configuration of the time interval, or other condition, over which the spacecraft is integrated. For this example, let’s define the “Propagate” segment to integrate until reaching the xz-plane in the Earth-Moon rotating frame (when y=0). First, uncheck the box next to the “Duration” stopping condition list to ensure this is not used to influence the numerical integration. Then, add a new stopping condition to the “Stopping Conditions” list by clicking the blank page icon. Then, select “Z-X Plane Cross”. Click OK to return to the Stopping Conditions list. Keep the tolerance and the Criterion which stops numerical integration when the trajectory passes through this plane in either direction. However, we need to select the coordinate system used to define this XZ plane. In the “Coord. Sys.” option, select the Earth-Moon rotating frame (with the Moon as the origin)

that you created earlier. Your configuration of this stopping condition should look as follows:

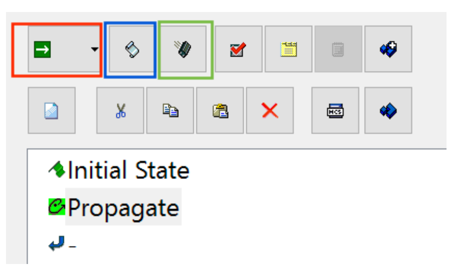


Once you have configured these properties, click the “Apply” button.

27. Change the color of the satellite orbit by double-clicking on the “Propagate” segment in the MCS to reveal an “Edit Segment” popup. Change the color in the “Color” dropdown menu.

Run the MCS

28. Return back to the “Basic”→”Orbit” page. Run the MCS and integrate the motion of the spacecraft until its first crossing of the xz-plane crossing in the Earth-Moon rotating frame by clicking the “Run Entire Mission Control Sequence” button highlighted in the leftmost red box below. To clear the graphics from the 3D graphics window at any time, simply click the “Clear Graphics” button highlighted by the rightmost green box below. The summary button highlighted by the middle blue box below will allow us to generate reports providing information about the satellite’s trajectory.



Have you saved recently?

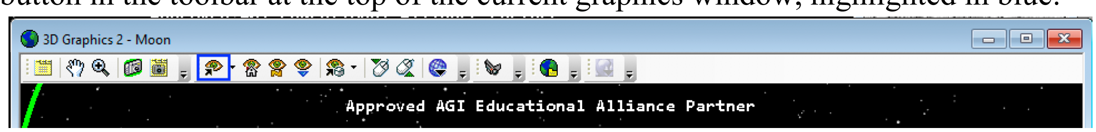
29. The line representing the orbit may be thin – let’s increase the thickness. Navigate back to the satellite properties window (you can double click the satellite in the object panel on the very left in the STK window), and under the “2D graphics”→”Attributes” window, click the “More” next to the second item in the list (with a start date matching the initial epoch). Under “Graphics

Attributes”, increase the line width to the maximum thickness using the drop down menu. Click OK to save your changes, then “Apply” in the “2D graphics attributes” window. Run the MCS again and navigate back to the 3D graphics window to view the orbit. (Sometimes you may have to come back to this step and reselect this option)

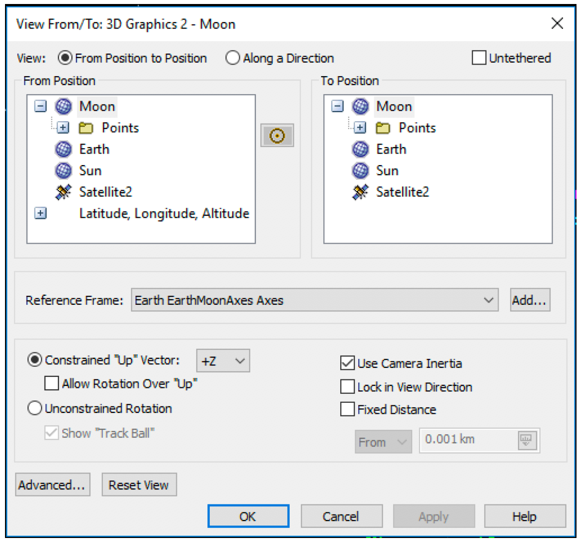
30. Then, select the “3D Graphics”→ “Model” page. In the “Details Threshold” panel, increase the value for all options to the maximum by dragging all the blue icons all the way to the right, or entering the value “1e+012 km” in the textboxes. This will allow you to see the spacecraft within its orbit, even when zoomed out in the 3D Graphics window.
31. To view the spacecraft with a marker that resembles a spacecraft: under “Model”, increase the value in the Log scale textbox to around 6.50 or so, but adjust based on your preference. You may adjust the Log scale textbox value iteratively. The Model file should list “satellite.mdl” which will allow us to see a model satellite in the graphics windows. Then click “Apply”.
32. Then, return to the 3D graphics window, change the view perspective if necessary by rotating/zooming, reset the scenario time via the red reset button in the animation toolbar. Then, click play and watch the satellite/s, planet/s, and vector/s evolve through the scenario window. You can increase the time step to speed up the animation by using the “Increase Time Step” button within the animation toolbar.
33. The current 3D graphics window is displaying the path in the Moon inertial frame. However, sometimes we may want to view the path in other frames.

<u>Create new graphics window to view trajectory in Earth-Moon rotating frame</u>

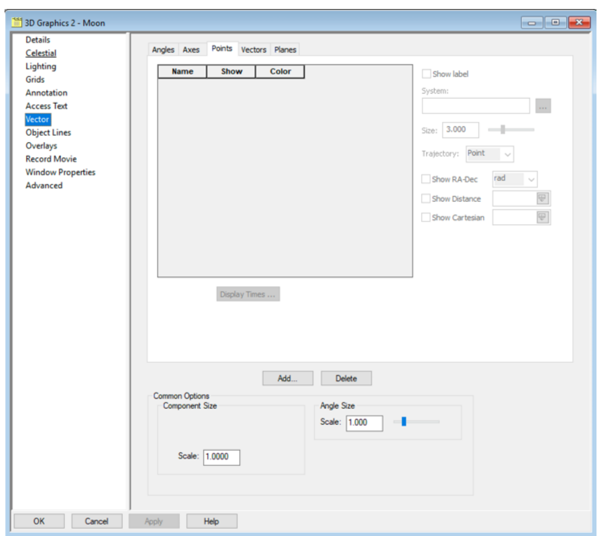
34. To create a new graphics window that displays the path of the spacecraft in the Earth-Moon rotating frame, navigate to the “View” option the main toolbar at the top of the STK window. Click “Duplicate 3D graphics window” and select “3D Graphics 1-Moon”. This new graphics window likely has a name similar to “3D Graphics 2 – Moon”.
35. To change the view to use the Earth-Moon rotating frame, select the View From/To button in the toolbar at the top of the current graphics window, highlighted in blue:



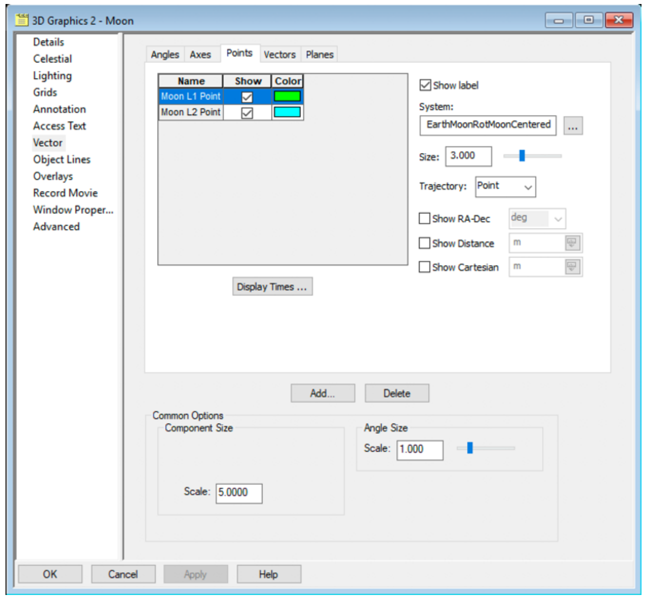
36. Then, configure the panel to appear as follows:



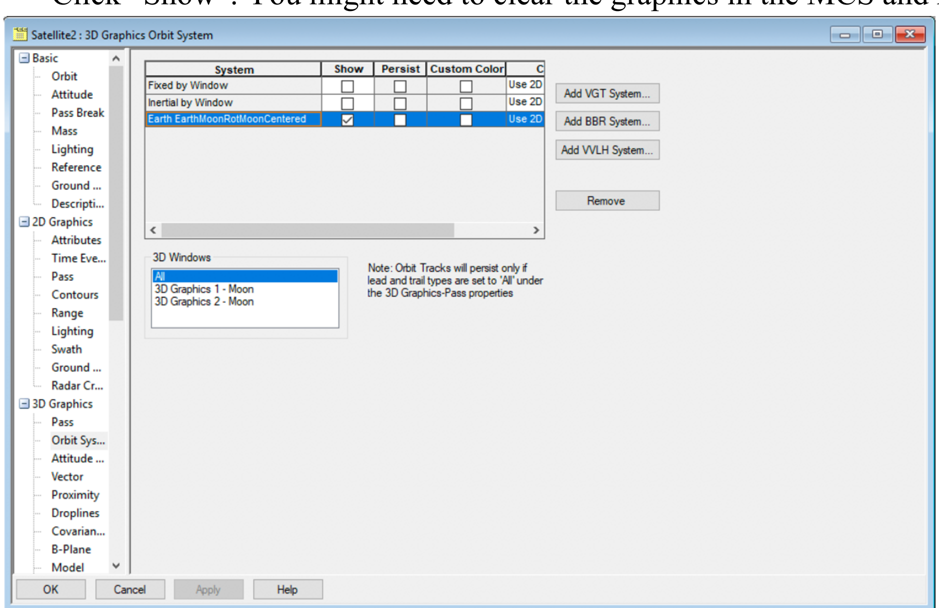
37. Next, we can add the locations of L1 and L2 in the Earth-Moon system. Open the properties tab of the new window by clicking the yellow page icon at the left of the toolbar in this 3D graphics window. In the leftmost panel, select the "Vector" option and then select "Points" from the tabs at the top of the panel as displayed below:



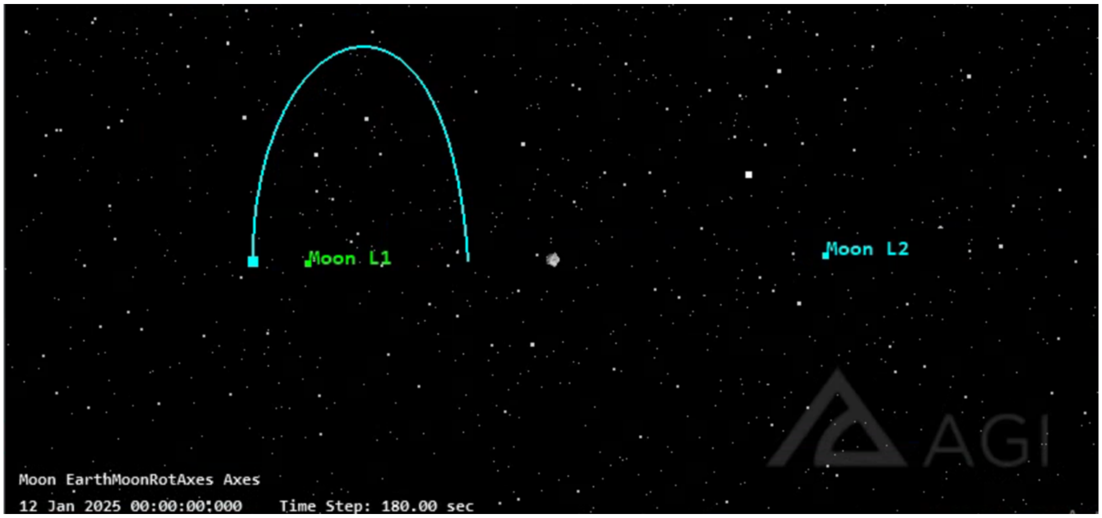
Then, click the "Add…" button. To add Earth-Moon L1, select "Moon" from the leftmost panel and then the "L1" point located near the bottom of the list in the rightmost panel (do not add the L1 axes towards the middle of the list!). Click "OK" to add the location of L1 to the current graphics window. On the righthand side of the "Vector"→"Points" page, select the system as the Moon-centered system you created using the axes of the Earth-Moon rotating frame, "EarthMoonRotMoonCentered". Your panel should resemble the following:



38. Follow this procedure to add Earth-Moon L2. You can follow a similar approach to add the axes of the Earth-Moon rotating frame by using the "Axes" tab at the top of this panel; if you do, consider a component size of at least 5.00 to ensure the axes are big enough to view. If you wish to turn off the text labels, just uncheck "Show label".
39. Next, we need to update the visualization properties of the satellite path to ensure that it is plotted in the same frame as the new 3D graphics window. In the satellite properties window, navigate in the lefthand panel to "3D graphics"→ "Orbit System". In the panel that appears, uncheck "Show" for "Inertial by Window". Then click the "Add VGT System …" button to the right. You may need to change the "Filter by" option to "Primary Central Bodies" and click the Earth. Select the Moon-centered coordinate system that you created using the axes of the Earth-Moon rotating frame, i.e., "EarthMoonRotMoonCentered". Click "Show". You might need to clear the graphics in the MCS and rerun the MCS.



40. Return to the graphics window and zoom out to view L_1 and L_2 in the expected locations in the Earth-Moon rotating frame, as follows:



Now, this looks more like half a revolution of a halo orbit.

<u>View the simulation of the spacecraft</u>

41. In the 3D graphics window, you can watch the spacecraft move within its orbit by using the animation toolbar at the top of the STK window:

42. The play button runs the animation, the up and down arrows change the time step, and the red reset button return the spacecraft to its original location at the beginning of the scenario. The epoch changes in the textbox in the righthand side of this toolbar.

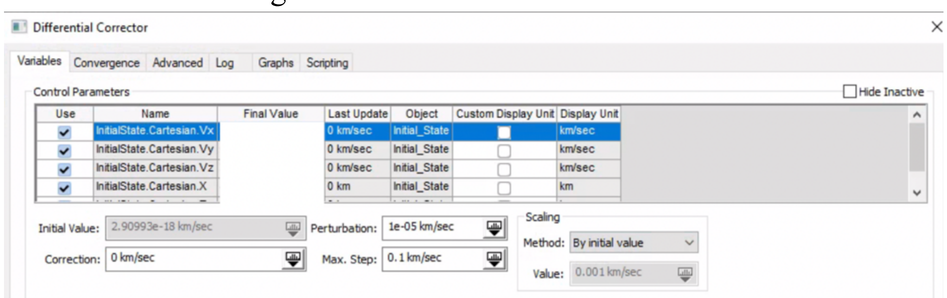
You have now created a scenario that allows you to visualize and analyze the path of a spacecraft in the Earth-Moon system!

<u>Construct a Targeter To Adjust the Initial Condition</u>

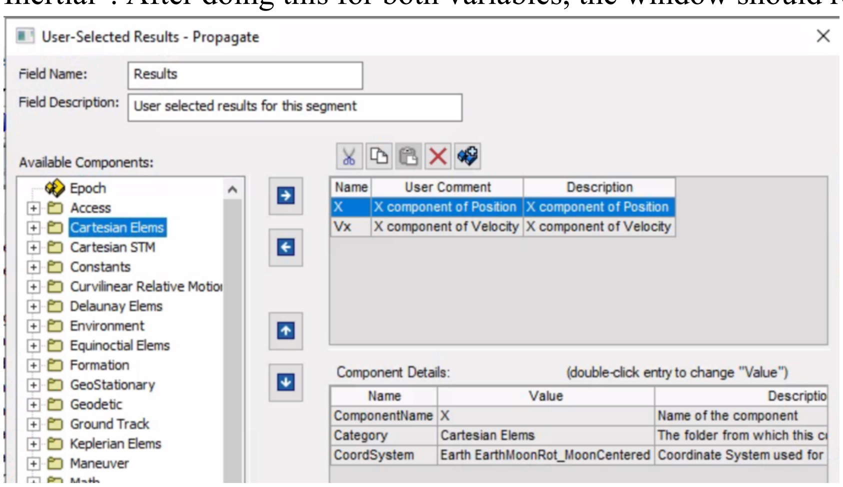
43. Return to the MCS in the satellite properties window so that you can construct a targeter to adjust the initial condition to produce that targets our orbit condition within half a revolution.
44. In the MCS, right-click the "Initial State" segment and "Insert Before.." a "Target Sequence". Drag the existing "Initial State" and "Propagate" segments to inside the Target Sequence. Then, single-click the "Target Sequence" segment header to view the properties and configure the targeter. At the top, change "Run the nominal sequence" to "Run active profiles"; this change essentially activates the targeter.
45. Scroll down in this panel to the Differential Corrector in the Profiles list. We are going to select the variables that this differential corrector will adjust to meet the target conditions. First, click the "Initial State" segment. You will now see a bullseye icon appear next to quantities. Selecting these quantities indicates that it can be adjusted by the differential

corrector. In this example, click the bullseye icon next to the following five state components in the Earth-Moon rotating frame: X, Z, VX, VY, VZ. We will not change the y-component of the initial state in the Earth-Moon rotating frame to ensure the initial state remains on the xz-plane. Once you have selected a target variable, you should see a checkmark appear over the bullseye.

46. Return to the Target Sequence and double-click the Differential Corrector item in the "Profiles" list. Here, you will see all five variables appear in the variable list. Check the box under the "Use" column next to each variable. Then, change the maximum allowable step in the position and velocity components as 100 km and 0.01 km/s, respectively. Change the perturbation used to calculate the corrections (this governs the numerical calculation of the DF matrix) to 0.001 km and 0.00001 km/s, respectively. Your list should resemble the following:



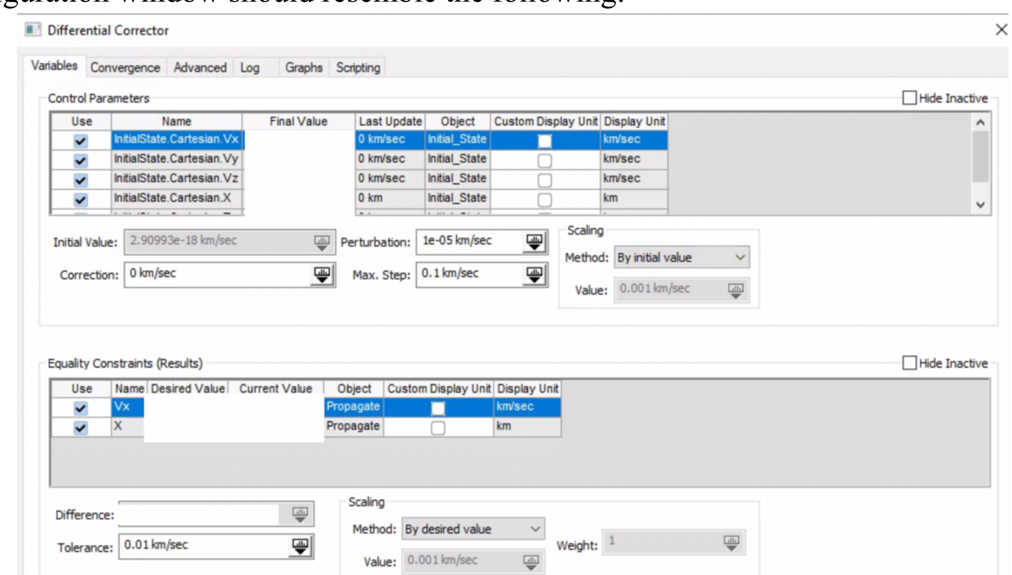
47. Next, we need to specify the target conditions. Return to the MCS and right-click the "Propagate" segment. Click "Results" to select quantities to extract at the end of the segment. Navigate to the "Cartesian Elems" folder and select "X" and "VX", adding them to the list of variables by clicking the button with the right-arrow. Highlight each variable once it has been added to the top table on the righthand side of this window. Then, in the bottom table, change the Coord. System Value to the Earth-Moon rotating system you created earlier – to make this change, simply double-click the default "Earth Inertial". After doing this for both variables, the window should resemble:



48. We will target the x and vx coordinates of the xz-plane crossing after ½ a revolution. Return to the Differential Corrector via the Target Sequence segment in the MCS. You

should see both variables, calculated at the end of the Propagate segment, appear in the Equality Constraints list. Check the box next to each item in the "Use" column. We will then specify the target values.

49. To define a target, calculate the following state vector which corresponds to the first crossing of the periodic orbit with the xz-plane of the Earth-Moon rotating frame in the CR3BP:
    A) Propagate the initial state vector derived from the Earth-Moon CR3BP forward for half a revolution. This is the state at the next xz-plane crossing.
    B) Translate this xz-plane crossing state from using the Earth-Moon barycenter to using the Moon center as the origin by subtracting 1-mu from the x-coordinate
    C) Calculate the instantaneous l^* and t^* characteristic quantities from the following truncated position vector of the Moon relative to the Earth at ½ a period after the specified initial epoch and expressed in the GCRF:
       $\bar{r}$ =[-3.33590e+05; 1.82242e+05; 9.83307e+04] km
    D) Dimensionalize the state vector components using the computed instantaneous values of l^* and t^*.
50. Set the value as the x-coordinate of the following state vector you calculated in the previous step by double-clicking the "Desired Value" and entering it in the textbox. Also set the tolerance as 100 km.
51. Repeat the above step to target the vx-coordinate of the xz-plane crossing in the Earth-Moon rotating frame to within 0.01 km/s of 0 km/s. Your differential corrector configuration window should resemble the following:



52. In the Convergence tab here, change the maximum number of iterations to 100.
53. Click OK to exit the differential corrector configuration window.
54. Run the MCS and watch the iterations of the corrector in the panel that updates both the targets and variables. If you return to the MCS and click on the Target Sequence segment, you can click the "Apply Changes" button to update the initial state with the

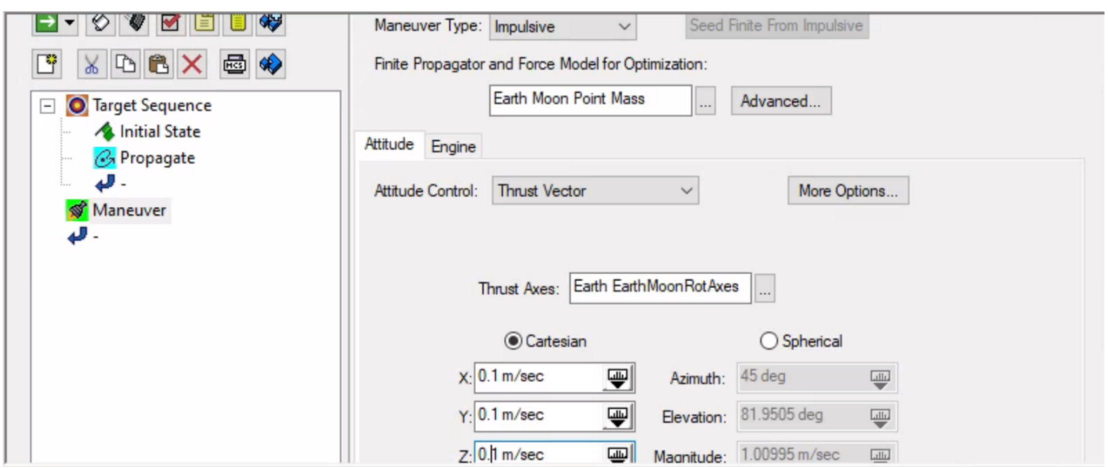
new vector calculated following corrections.

55. Once the corrector has converged on a solution, your 3D orbit view may resemble the following (you may need to clear the graphics and/or rerun the MCS to see only the last trajectory and not all the trajectories generated during corrections):

Question: how much did your state vector change to achieve the specified target condition? And how many iterations were required for the targeter to satisfy the constraints?

<u>Construct a Targeter To Compute a Maneuver to Target Next XZ-Plane Crossing</u>

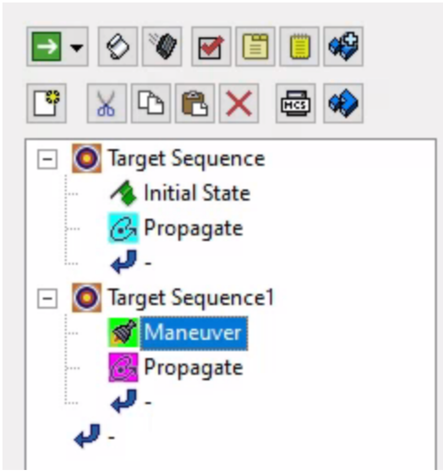
56. Next, we will apply a maneuver and vary its components to target the next xz-plane crossing.
57. Add an impulsive maneuver to the MCS after the targeter (not inside it) by right clicking the last arrow in the MCS and "Insert Before…" a "Maneuver". Here, you configure the maneuver to be Impulsive and change the propagator to the Earth Moon Point Mass propagator you created. Next to Attitude Control, select "Thrust Vector" so that you can describe the maneuver using three components. Select the Thrust axes to be the Earth Moon rotating axes that you created earlier. Enter components in each direction equal to 0.1 m/s; this is our initial guess for the maneuver. Your maneuver should be configured as follows:



58. Next, insert a propagate segment after the maneuver in the MCS and configure it using the exact same steps as the last propagate segment you constructed, i.e., to integrate the

path of the spacecraft until the next xz-plane crossing.

59. Next, create another target sequence and drag both the new Maneuver and Propagate segments you just made to inside the target sequence so that your MCS resembles the following:

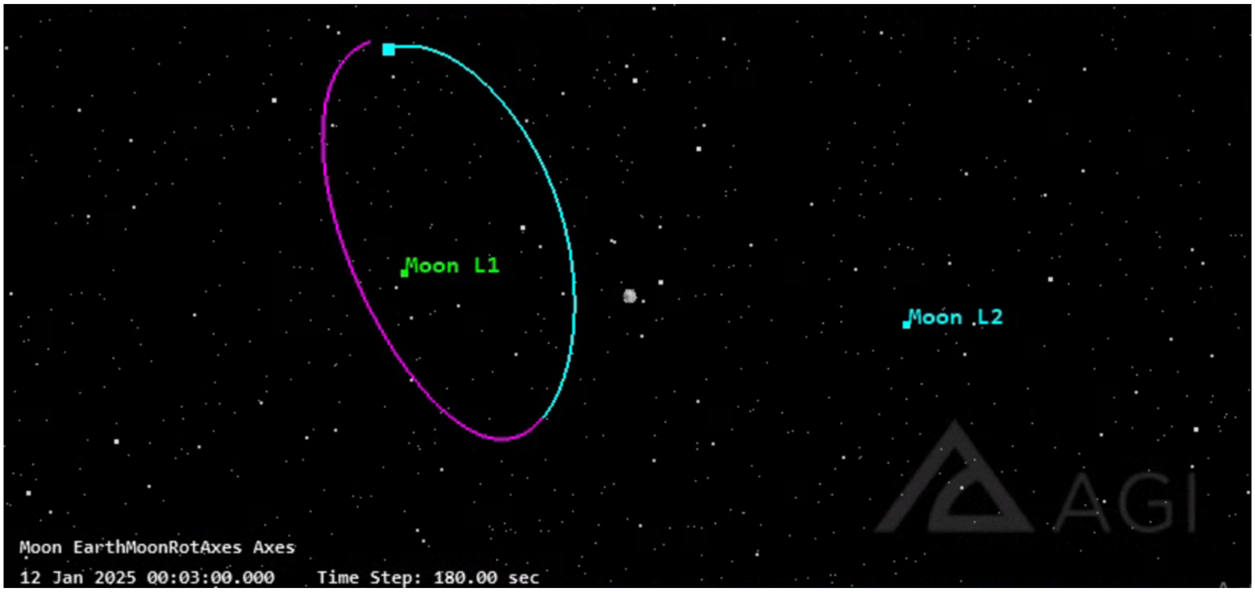


60. This target sequence will vary the maneuver components to target the next xz-plane crossing to complete a full revolution near the periodic orbit. Accordingly, click the Maneuver segment and click the bullseye icons next to each of the three X, Y, Z elements of the maneuver. Then, right-click the propagate segment and navigate to “Results” and add the X and VX components of the state at the end of the segment in the Earth-Moon rotating frame.
61. Click the “Target Sequence” segment and configure the differential corrector used to modify this maneuver using a similar process to the last target sequence. Set the desired value of the x-coordinate the xz plane crossing to the x-coordinate of the following state vector you calculate and the tolerance as 100 km:
    a) Translate the state vector used to define the initial condition from using the Earth-Moon barycenter to using the Moon center as the origin by subtracting 1-mu from the x-coordinate
    b) Calculate the instantaneous l^* and t^* characteristic quantities from the following truncated position vector of the Moon relative to the Earth at 1 period after the specified initial epoch and expressed in the GCRF:

$$\bar{r} = [\, -3.69926e{+}05;\ -1.42961e{+}05;\ -7.85727e{+}04] \text{ km}$$

    c) Dimensionalize the state vector components using the computed instantaneous values of l^* and t^*.
62. Also target the vx-coordinate of the xz-plane crossing in the Earth-Moon rotating frame to within 0.01 km/s of 0.
63. When configuring the components of the maneuver that will be varied by the corrector, set the max step as 10 m/s and the perturbation to 0.0001 m/s.
64. Ensure that you have selected “Run active profiles” at the top of target sequence properties page and have changes the max iterations in the Differential Corrector to 100.

65. Finally, run the scenario and watch the iterations of the corrector in the popup window. Once the corrector has converged on a solution, apply the changes in the differential corrector. Rerun the MCS and your 3D orbit view may resemble the following:



Question: how large a maneuver was calculated to meet the specified target conditions?

Question: examine and discuss with your peers the orbit in 3D and its groundtrack on the surface of the Moon.

Next steps: Try running the same targeters with your HigherFidelityModel (just replace the model in the propagate segments in the Mission tab). How do the results change with a higher-fidelity model? Do you have to change either the max number of iterations for the corrector or the tolerances on any of the target conditions for either half revolution along the trajectory in order to compute a solution?