ASEN 6060 – Spring 2025

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

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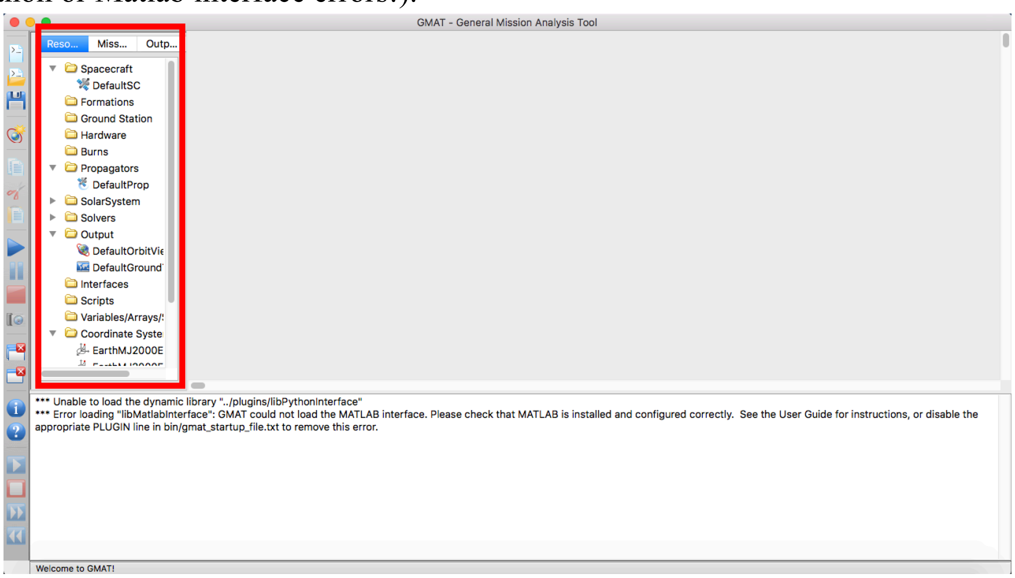
Objective: Using GMAT, create a scenario of a spacecraft in the Earth-Moon system and view the path in the Earth-Moon rotating frame. Then, correct the path to produce a trajectory that remains near a periodic orbit.

That there are two primary ways to interact with GMAT: via the graphical interface or via a scripting interface. We will focus on the graphical interface for this tutorial.

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 the Baseline Scenario

1. Open GMAT and resize the window to fit your screen. The window should resemble the following image. The left sidebar has panels for running and saving your mission scenario. The top left panel contains a graphical representation of all the components in your scenario, the mission sequence and output. The top right panel will feature any two-dimensional or three-dimensional plots. Then the bottom panel provide a summary of the run (don't worry about any Python or Matlab interface errors!).



Create a Moon-centered Inertial Coordinate System

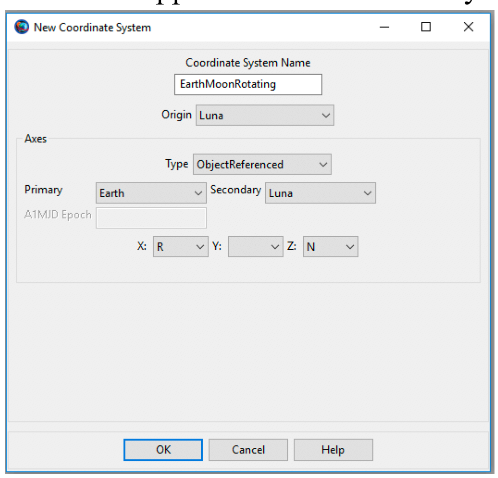
2. With the Resources tab highlighted in the panel within the red box, right click the "Coordinate Systems" folder and click "Add Coordinate System". Name the coordinate system "MoonInertial" with no spaces. Select the "Origin" as "Luna" from the drop-down list. Under "Type" select "BodyInertial". This BodyInertial option uses information about the Moon's orientation on the J2000 epoch to define the inertial axes. Click OK to save your new Moon-centered inertial coordinate system. We will use this system for visualization and

specification of state information when needed.

3. Now is a good time to save your scenario by clicking the floppy-disk "Save" icon in the left menubar. Choose a suitable name and location to save the scenario. **Save regularly!**

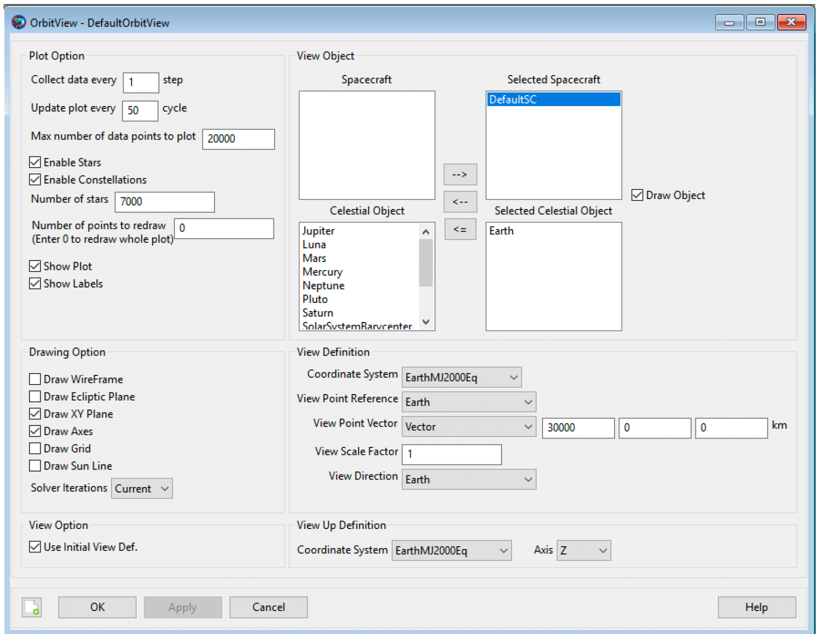
Create an Earth-Moon Rotating Coordinate System

4. With the Resources tab highlighted in the panel within the red box, again right click the "Coordinate Systems" folder and click "Add Coordinate System". Name the coordinate system "EarthMoonRotating" with no spaces. Select the "Origin" as "Luna" from the drop-down list. Under "Type" ensure that "ObjectReferenced" is selected. Then, set the "Primary" as "Earth" and the "Secondary" as "Luna". Keep the default options where X is defined as "R", the position vector from the Earth to the Moon and "Z" is defined as "N", the orbit normal of the primary system. We will use this coordinate system to visualize the spacecraft path and specify state information as needed. Note that this differs from a regular EM rotating frame that we have used in this class because the origin is not the EM barycenter but, rather, the Moon. The window should appear as follows before you click "OK":



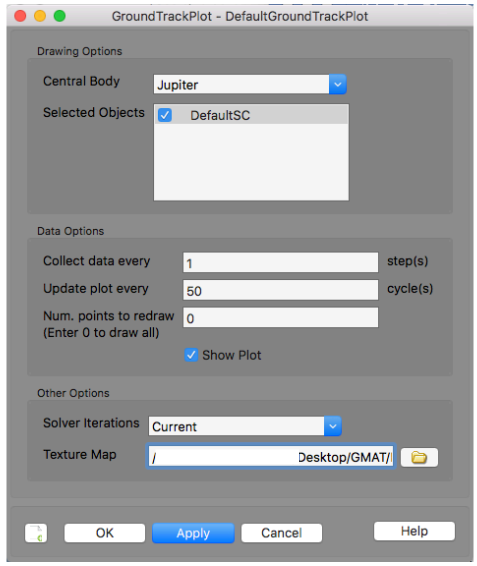
Configure the Graphics Windows

5. Next, you will create a 3D and 2D plot for visualizing the motion of the spacecraft.
6. With the Resources tab highlighted, ensure that the "Output" folder is open. If it not open, simply click the down arrow or the plus sign.
7. To customize the 3D view, double-click the "DefaultOrbitView" and a window resembling the following should appear:

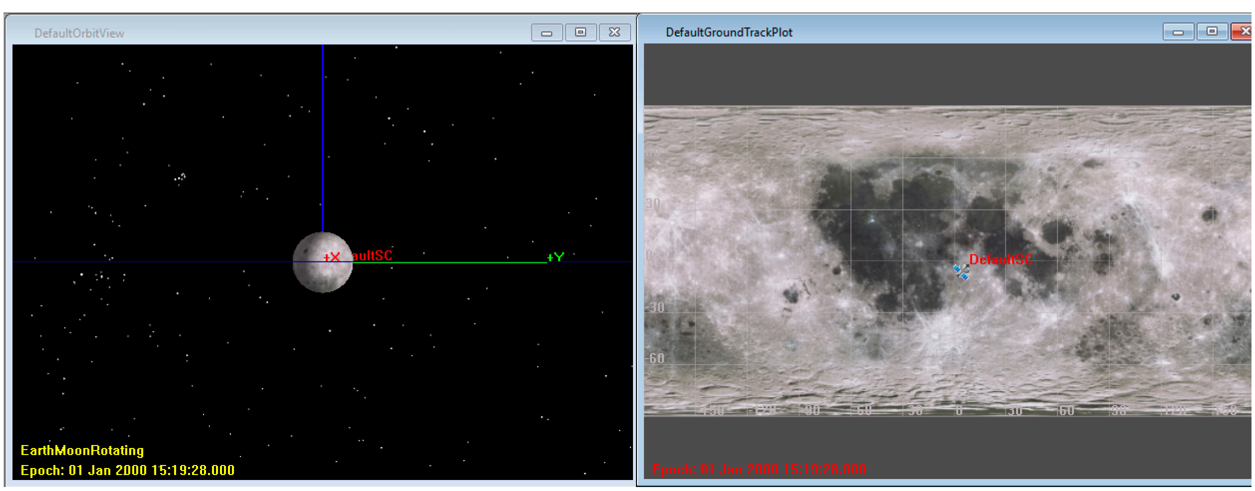


8. In the "ViewObject" panel, the Earth appears in a list labeled "Selected Celestial Object", which indicates which bodies are plotted in a 3D view. Highlight the Earth label and click the button with a "<=" arrow to remove it. Then, in the list labeled "Celestial Object", highlight "Luna" and click the "-->" arrow. This option displays the Moon.
9. Ensure that in the list labeled "Selected Spacecraft", the item "DefaultSC" appears. This a spacecraft that we will later configure.
10. Lower down on the window, in a panel labeled "View Definition", we will specify the coordinate system and view direction. For "Coordinate System" select "EarthMoonRotating" from the dropdown menu, "View Point Reference" as "Luna", "View Direction" as "Luna". Leave all other items at the default value. Next to "View Point Vector", in the first textbox, change the number in the field to "100000". This quantity gives the location for the camera for viewing the 3D plot. You can adjust this value later as needed.
11. Further down on the window, in the "View Up Definition" panel, set coordinate system as "EarthMoonRotating" and leave the "Axis" as "Z". This setting will orient the view so that the +Z direction is pointed upwards.
12. In the top left "Plot Option" panel of this window, uncheck "Enable Constellations". This removes extraneous information from your visualization. Click OK to save your changes and close.
13. Next, we will configure the 2D graphics window, by double-clicking the "DefaultGroundTrackPlot" object under the "Output" folder on the leftmost panel of the main screen.

14. A new screen will appear and resemble the following:



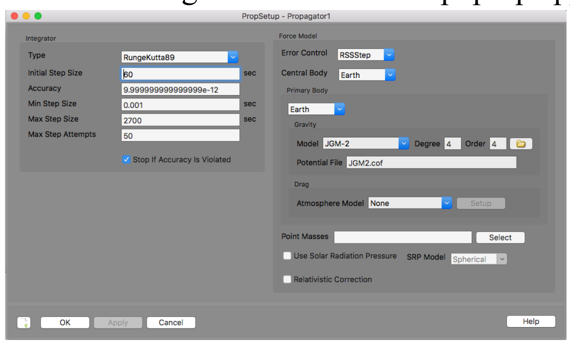
15. Change the “Central Body” to “Luna”. Under “Texture Map”, click the open folder icon to find a new surface image if it has not already been updated. Within the GMAT folder, navigate to /data/graphics/texture/ Moon_HermesCelestiaMotherlode.jpg and select this file.
16. Click OK to save your changes to the 2D graphics window.
17. To preview the appearance of your 2D and 3D graphics windows before we construct a simulation, press the blue “Play” icon at the top/left of the main control window depending on your operating system. Your views should resemble the figures shown below. To zoom in and out, hold the “Control” button down and use the left click of your mouse to drag in and out. To change the orientation of the view vector simply use the left click of your mouse to drag the view around. You will see on the view the X,Y,Z unit vectors of your Earth-Moon rotating frame, and a blue radial grid in the XY plane.



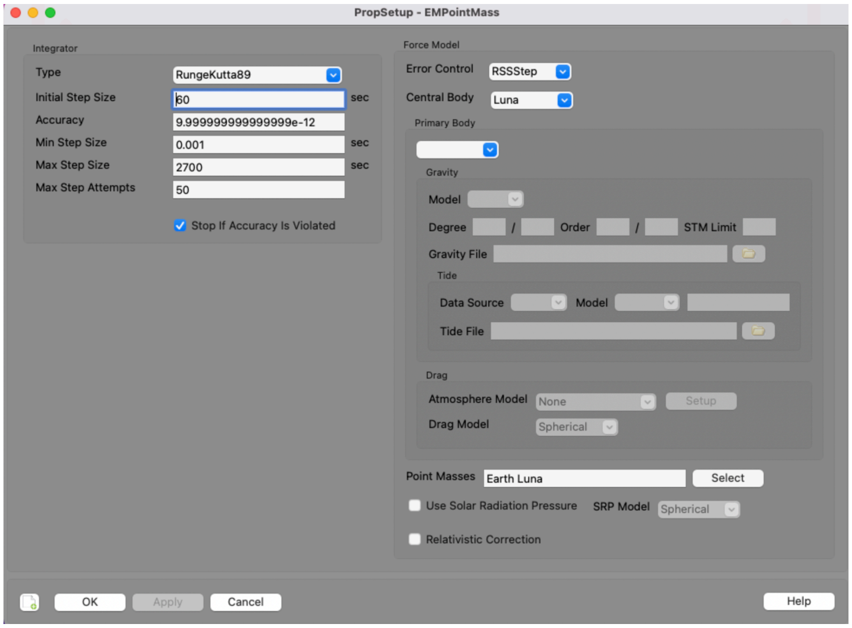
Have you saved your scenario recently?

Creating Dynamical Models for Propagation

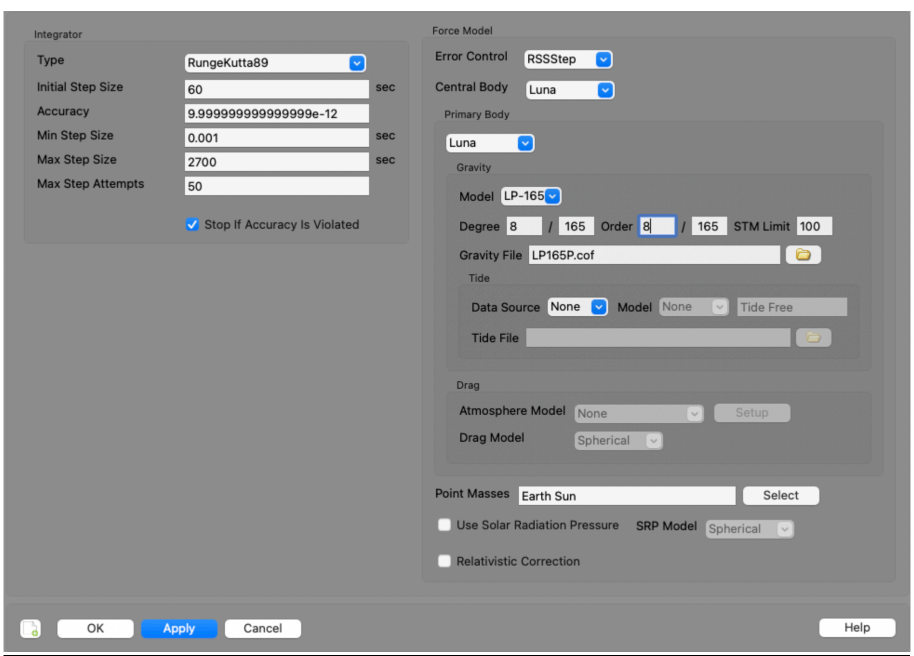
18. Let's create a dynamical model to govern the motion of a spacecraft near the Moon under the point mass gravitational interactions with the Earth and Moon (note: this is not the CR3BP as the two objects are following their true paths, not circular orbits). To define this dynamical model, right-click the "Propagators" folder in the left panel of the main control window. Then, right click and select "Add Propagator". A new propagator will be added called "Propagator1". Depending on your GMAT version/OS, you may be able to right click the propagator and rename it. If so, rename it to "EMPointMass". If you cannot rename it, just keep track of the name that GMAT assigned as default.
19. Open the propagator by double-clicking. You should see a pop-up appear as follows:



20. You can leave the numerical integration parameters in the left panel of this window as the default. On the right panel, you will configure the force model. Change the "Central Body" to "Luna". This tells the propagator that quantities are measured relative to the Moon. Under "Primary Body" change the selected item to "None" since we are only going to model the point mass gravitational interactions of the Earth and Moon with the spacecraft. The only bodies that should be listed under "Primary Body" are those with gravitational fields that differ from that of a point mass. Next to the "Point Mass" list, click "Select". Highlight "Earth" in the list on the left of the new popup window and then click the "->" button to add it to the list of point masses incorporated in your dynamical model. After adding Earth to the list of point masses, the propagator will incorporate the gravitational influence of Earth, modeled as a point mass. Do the same to the add the Moon as "Luna". Click OK to return the propagator properties window. Then click OK to save your propagator. Your window should be configured as follows:



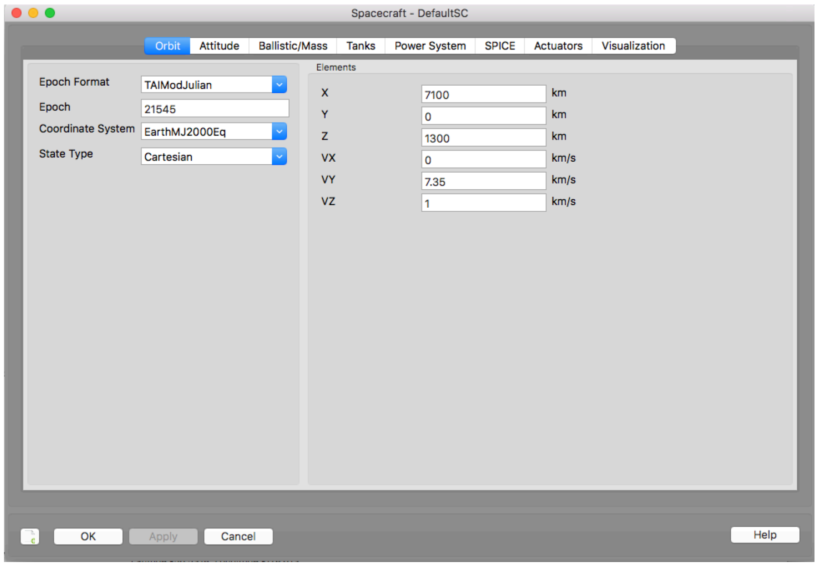
21. Next, create a second propagator which will use a more complex dynamical model. To define this dynamical model, right-click the “Propagators” folder in the left panel of the main control window. Then, right click and select “Add Propagator”. A new propagator will be added called “Propagator1”. Depending on your GMAT version/OS, you may be able to right click the propagator and rename it. If so, rename it to “HigherFidelityModel”. If you cannot rename it, just keep track of the name that GMAT assigned as default.
22. Open “HigherFidelityModel” and follow the steps used in the previous propagator. Then, dd the Sun as a point mass. Also, remove the Moon from the “point masses” list and add it as a “Primary Body”. Then, create an 8x8 gravity model of the Moon using the LP165.cof data file by configuring the propagator as shown below:



23. Click Apply and OK to exit.

Create and Configure a Spacecraft

24. A satellite is added to the scenario already by default. Rename it, if you are able by right-clicking the satellite object. In the main control window, double click the satellite object. A new properties window appears as follows:



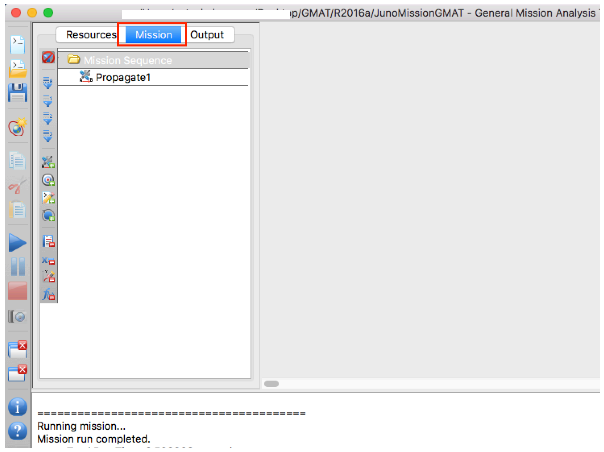
25. From this window, you can configure the initial state and epoch. In the "Orbit" tab of the popup window, select "Epoch Format" as "UTCGregorian" and enter the "Epoch" as "12 Jan 2025 00:00:00.000".
26. Next, let's calculate an initial guess for an initial state vector. We will implement the most foundational methods; more complex approaches are beyond the scope of this course. Consider an L1 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 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] km

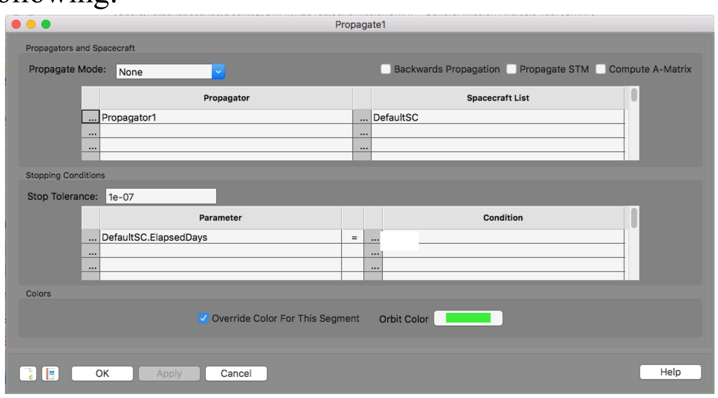
    c) Dimensionalize the state vector components using the computed instantaneous values of $l*$ and $t*$.
27. Select the "Coordinate system" as "EarthMoonRotating" and state type as "Cartesian". Then, enter the dimensional state variables in the Earth-Moon rotating frame that you calculated in the last step in the right panel labeled "Elements". Note that if you copy-paste information to the textboxes, it may not save. You may need to enter at least one character manually in the keyboard in order for it to recognize the values before pressing "Apply". Also set the y-

component to +1e-10 to ensure it does not trip an event later on.

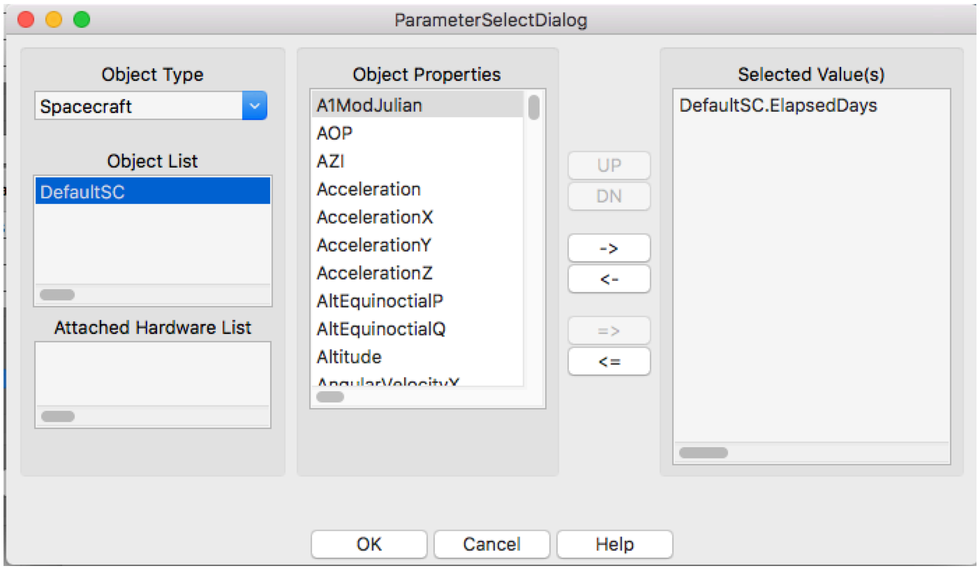
28. After you have entered these values defining the initial state, click the “Apply” button and then the “OK” button.
29. Next, we will configure the mission scenario which is contained with the “Mission” tab on the left panel of the main control window as displayed below:



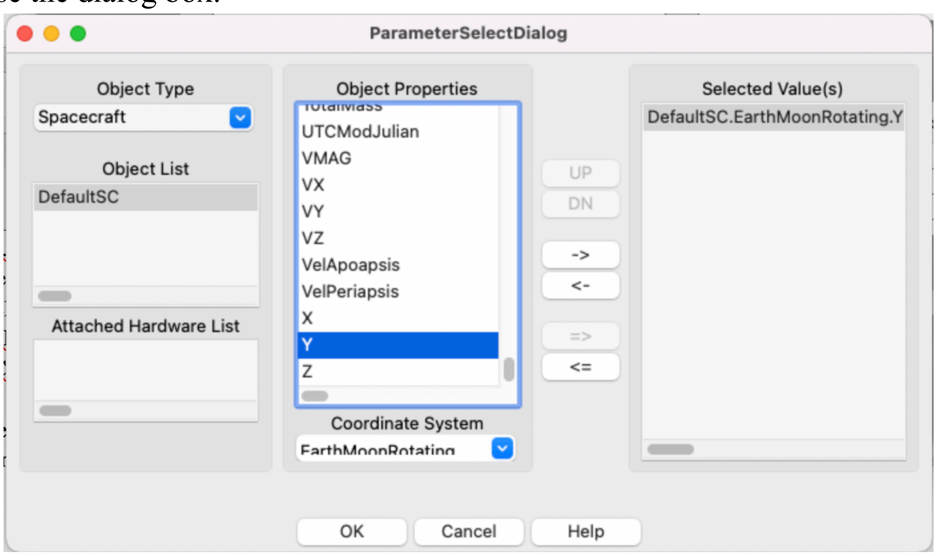
30. The only item contained in the mission sequence is a propagate segment, meaning that GMAT will propagate the initial condition defined earlier until some stopping condition – we will set that stopping condition now.
31. Double click the “Propagate” segment in the Mission Sequence, and a new window will appear and resemble the following:



32. In the top table, we will set the “Propagator” to “EMPointMass” or the default name for your Earth and Moon point mass gravitational model and integration scheme. You can set the propagator by clicking the “…” button to the left of the existing Propagator name. Ensure that on the righthand side of this table, “DefaultSC” appears, meaning that GMAT will propagate the spacecraft you defined within the selected dynamical environment.
33. Now we need to define the stopping condition for the propagation, and we will use the crossing of the xz-plane in the Earth-Moon rotating frame. Under the “Stopping Conditions” table, next to the default condition of DefaultSC.ElapsedSecs, click the “…” button. A parameter selection dialog box will appear similar to the following:



34. Highlight the "DefaultSC.ElapsedSecs" in the "Selected Values" list, and click the "<-" button. Then, in the Object Properties, locate and click "Y". Ensure that in the leftmost "Object List" you have "DefaultSC" selected. Also ensure that below the Object Properties box, you have selected the "EarthMoonRotating" frame as the "Coordinate System" Then, click the "->" button to see "DefaultSC.EarthMoonRotating.Y" appear in the "Selected Values" list. Click OK to close the dialog box.

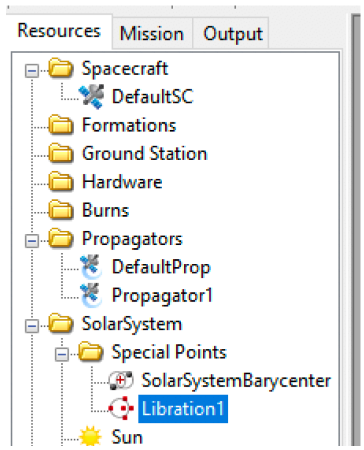


35. Set the "Condition" value in the "Stopping Conditions" table to 0 by double clicking the existing number and typing the number of days to have elapsed before the propagator will stop. This stopping condition will ensure that propagation stops when the y-coordinate equals 0.
36. Finally, check the "Override color for this segment" checkbox and select a bright "Orbit Color" that will appear clearly on a dark background. Click "Apply", "OK" to save your changes to the propagation segment.

Have you saved your scenario recently??

Add the L1 and L2 points to the Scenario

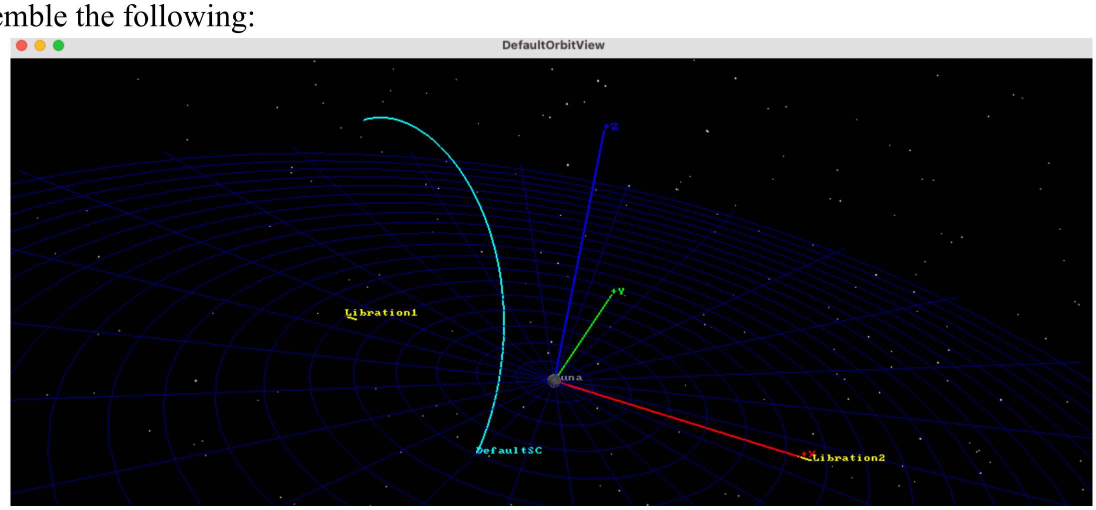
37. To add the location of L1 in the Earth-Moon system, navigate back to the main Resources panel on the lefthand side of the GMAT window. Expand the "Solar System" item and right-click the "Special Points" item and "Add"→ "Libration Point".



38. Double-click Libration1 and update the "Primary" to "Earth" and "Secondary" to "Moon". Then select L1 as the "Libration Point". Change the color of this object as desired and click "OK" to return to the main GMAT window. Follow this procedure to also add L2.
39. To add L1 and L2 to the 3D graphics window, navigate back to the Resources panel and double-click the graphics window you created earlier. Under the "View Object" panel, add the "Libration1" and "Libration2" objects to the view by highlighting them and clicking the "→" button. You should see these to objects under "Luna" in the Selected Celestial Object list. Click OK to exit this window.

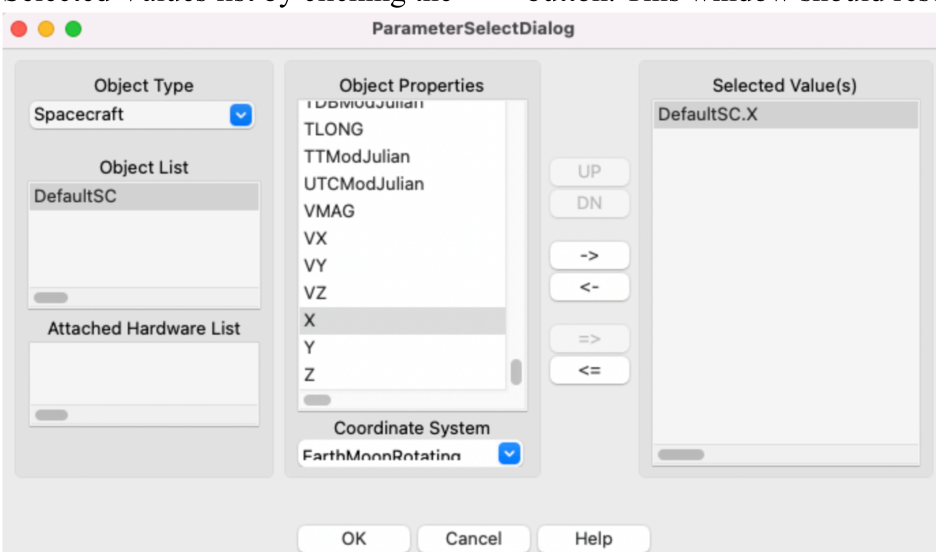
Run the Scenario

40. Run the scenario and integrate the motion of the spacecraft until it reaches the xz-plane in the Earth-Moon rotating frame while under the influence of Earth and Moon's point mass gravitational attraction by clicking the play button in the left menu bar of the main control window. View each of the 3D graphics window and 2D graphics window. Your view may resemble the following:



You have now created a scenario that allows you to visualize and analyze the path of a spacecraft in the Earth-Moon system! You can see that L1 and L2 shift along the x-axis in this non-pulsating Earth-Moon rotating frame.

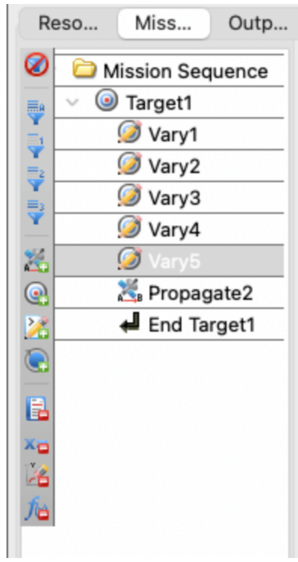
<u>Construct a Targeter To Adjust Initial Condition</u>

41. Return to the “Mission” table in the leftmost panel of GMAT. Here, we will create a targeting scheme to adjust the initial condition to produce that targets our orbit condition within half a revolution.
42. Right-click the Propagate segment and “Insert Before” a “Target”. Then, delete the Propagate segment and recreate it to lie within the “Target” function. First, right-click “End Target1” and click “Insert Before…” to add a “Propagate” segment. Configure it using the Steps 32-36 implemented earlier.
43. Then, right-click the propagate segment and “Insert Before…” a “Vary” segment. This will allow us to define one of the variables to adjust when targeting a specific xz-plane crossing. Double click this Vary segment to produce a window where you can specify the variable, its minimum and maximum bounds, etc. We are going to set the first variable that can vary as the “X” component of the initial state. To set this variable, click the “Edit” button next to the “Variable” field. Select the Object Type as Spacecraft and ensure that “DefaultSC” is highlighted in the “Object List”. Next, select the “X” variable from the Object Properties list and define its Coordinate System to be “EarthMoonRotating”. Add this variable to the Selected Values list by clicking the “->” button. This window should resemble the following:


Then, click OK and return to Vary1 properties window. Set the initial condition as the value you calculated earlier. Select the upper and lower bound to be 100 km above/below the value you selected for the initial condition. Set the max step to 1 and leave all remaining fields at their default values. Click OK to save these changes.
44. Repeat the above steps by adding additional Vary segments for each of the following variables: “Z”, “VX”, VY”, “VZ”. Allow the position variables to vary by up to 100 km and the velocity variables to vary by up to 0.01 km/s. Select the max steps as 100 km and 0.01

km/s, respectively. Note that "Y" is not selected as a variable here to ensure that the initial state remains on the xz-plane of the rotating frame.

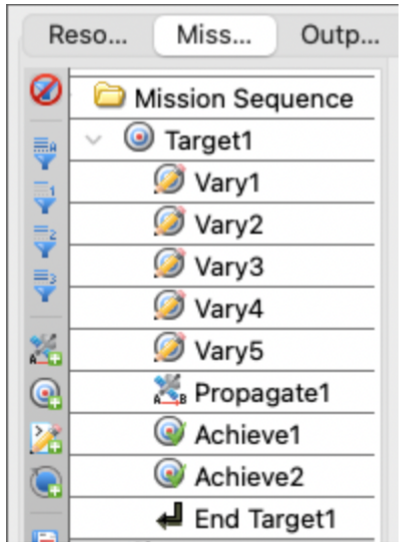
45. At this step, your Mission panel should resemble the following:



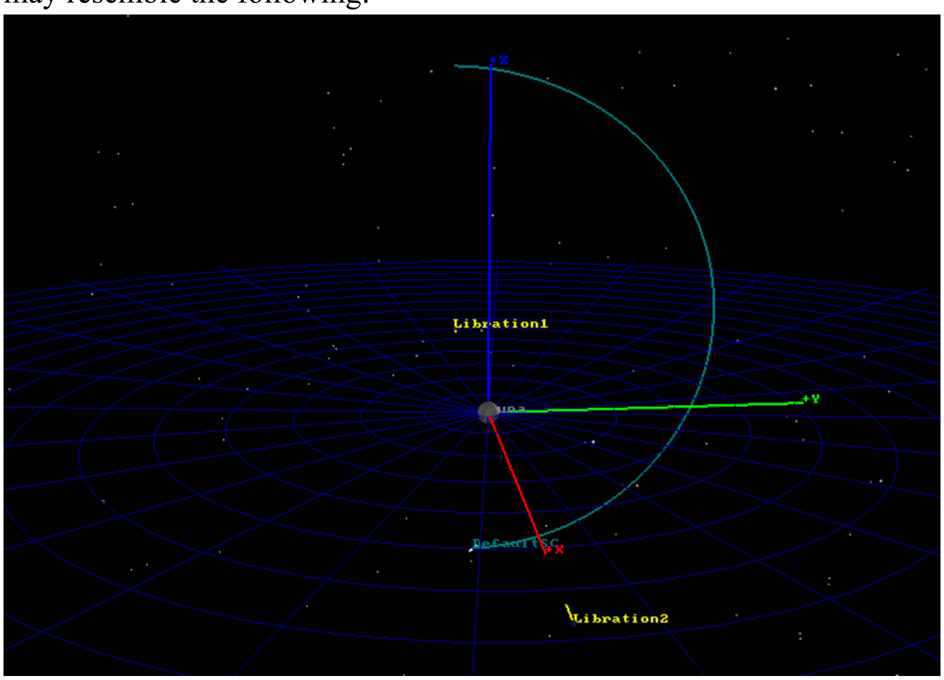
46. Next, let's add the target conditions. To do this, right-click the Propagate segment and "Insert After…" an "Achieve" segment. We will target the x and vx coordinates of the xz-plane crossing after ½ a revolution. Double-click the "Achieve" segment and then click the "Edit" button next to the "Goal" field to specify the x-coordinate in the Earth-Moon rotating frame using the same procedure as the Vary segments. Set the value as the x-coordinate of the following state vector you calculate and the tolerance as 100 km:
    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:

    $$\bar{r} = [\ -3.33590e{+}05;\ 1.82242e{+}05;\ 9.83307e{+}04]\ \text{km}$$

    d) Dimensionalize the state vector components using the computed instantaneous values of $l*$ and $t*$.
47. Repeat the above step to add another "Achieve" condition to target the vx-coordinate of the xz-plane crossing in the Earth-Moon rotating frame to within 0.01 km/s of 0.
48. Your mission panel should resemble the following:



49. Next, return to the Resources tab and under "Solvers"→"Boundary Value Solvers", select "DefaultDC" which is referring to a differential corrector. Double-click "DefaultDC" and select the max iterations to 100 so that the corrector has a sufficient number of maximum iterations to recover a solution.
50. Run the scenario and watch the iterations of the corrector in the panel that updates both the targets and variables. Once the corrector has converged on a solution, your 3D orbit view may resemble the following:



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

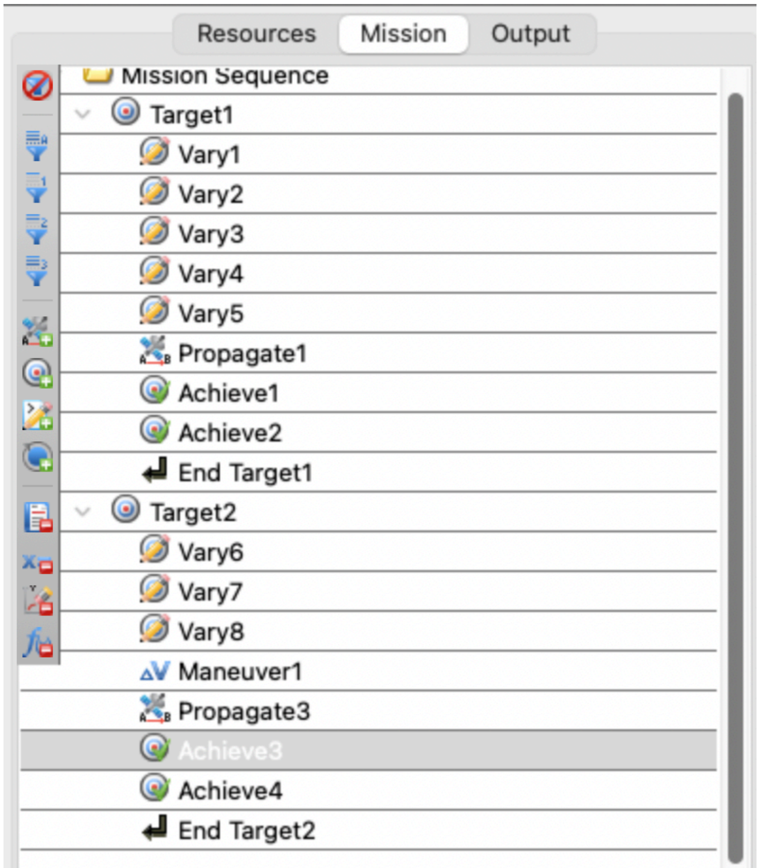
<u>Construct a Targeter To Compute a Maneuver to Target Next XZ-Plane Crossing</u>

51. Next, we will apply a maneuver and vary its components to target the next xz-plane crossing.
52. First, add a maneuver to the Resources tab by double-clicking the DefaultIB object under "Burns". In the panel that pops up, select the coordinate system as "EarthMoonRotating". Do not change any additional quantities.
53. Next, return to the Mission tab of the GMAT window. Add another target sequence after the one we already calculated. Within this sequence, Add the maneuver and then a Propagate segment that propagates to the next xz-plane crossing. If you double-click the maneuver segment, you will notice that it will apply the DefaultIB burn to the spacecraft, so it is not necessary to change these defaults in this case. Configure the propagate segment using the same approach as earlier.
54. To this target sequence and before the maneuver, add three Vary segments that modify each component of the maneuver. To do this, once you add a Vary segment, double-click it and in the configuration window click "Edit" next to the Variable name. Here, ensure that the Object Type is Impulsive Burn and the Object is the DefaultIB maneuver. Next, select "Element1" and place it in the Selected Values list. Repeat this process, adding "Element2" and "Element3" to two more vary segments. Set their initial values as 0.0001 and their min/max values to be -0.1 and 0.1 km/s with max steps of 0.01 km/s.
55. Next, we will target the x and vx coordinates of the xz-plane crossing after the next ½ a revolution. Double-click the "Achieve" segment and then click the "Edit" button next to the "Goal" field to specify the x-coordinate in the Earth-Moon rotating frame using the same procedure as the Vary segments. Set the value as 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:

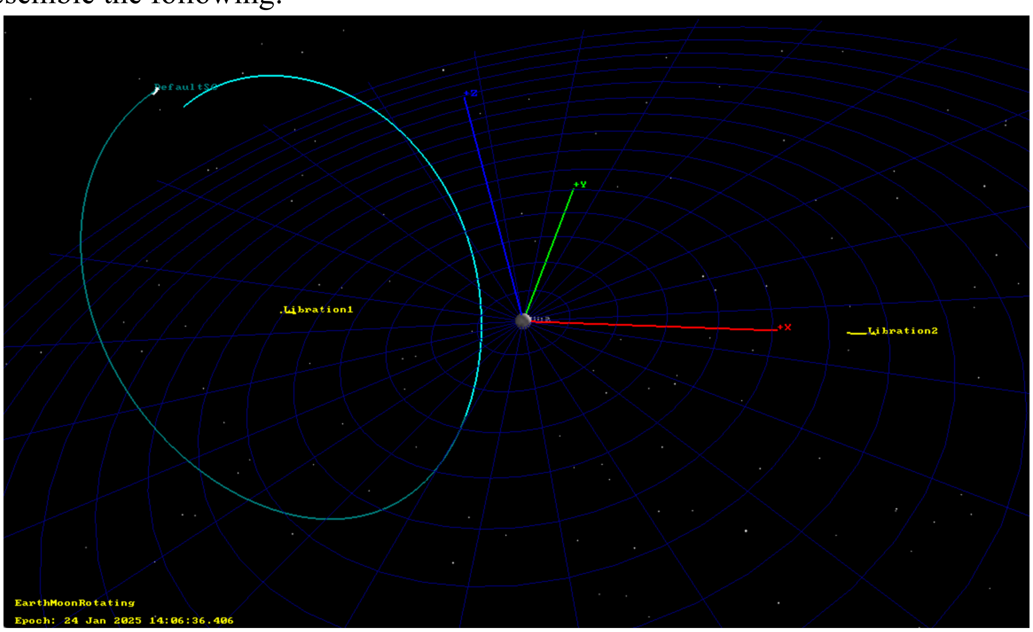
    $$\bar{r} = [\ -3.69926e{+}05;\ -1.42961e{+}05;\ -7.85727e{+}04]\ \text{km}$$

    c) Dimensionalize the state vector components using the computed instantaneous values of $l*$ and $t*$.
56. Repeat the above step to add another "Achieve" condition to target the vx-coordinate of the xz-plane crossing in the Earth-Moon rotating frame to within 0.01 km/s of 0.

57. Your mission panel should resemble the following:



58. Run the scenario and watch the iterations of the corrector in the panel that updates both the targets and variables. Once the corrector has converged on a solution, 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?