ASEN 3200 Orbit Mechanics and Attitude Dynamics - Spring 2021

LABORATORY O-3

Assigned: Week of February 15, 2021

Due: March 11 or 12, 2021 at start of lab

PART I: Sun-Synchronous Orbits

Using STK 12/Astrogator, you will create a scenario with a satellite orbiting the Earth, designing the orbit to be sun-synchronous. Follow the outlined procedure and answer the questions presented throughout.

1) A sun-synchronous orbit leverages the effect of the Earth's oblateness on the secular evolution of the RAAN to achieve an orbit whereby the orbital plane maintains a constant angle with the radial direction to the Sun. Such satellites may be useful for remote sensing applications. Recall that the effect of oblateness on the RAAN and argument of perigee are expressed as follows:

$$\dot{\Omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu}J_2R^2}{(1-e^2)^2a^{7/2}}\right]\cos i$$

$$\dot{\omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu}J_2R^2}{(1-e^2)^2a^{7/2}}\right]\left(\frac{5}{2}sin^2 i - 2\right)$$

where $J_2 = 1.08263 \times 10^{-3}$ for the Earth, and $R = 6378$ km is the radius of the Earth. The rotation rate of the Earth is 15.04 degrees/hour.
2) Create a scenario with the Earth as the central body. Select the initial epoch for the scenario as February 21, 2020 19:00:00.000 UTCG, and a final scenario time of February 28, 2020 19:00:00.000 UTCG.
3) Add a satellite to the scenario and select Astrogator as the propagator.

Question 1: Using the rates of change for the RAAN and argument of periapsis, design a *sun-synchronous* orbit that also satisfies all of the following criteria, by selecting the orbital elements for the initial state at an epoch on February 21, 2020:

- Req. #1: An orbital period of 1.62 hours;
- Req. #2: A perigee altitude between 500 km and 600 km;
- Req. #3: A perigee that regresses over time; and
- Req. #4: After one orbital period, the ascending node should possess a longitude of zero to within a tolerance of 0.1 degrees (i.e. its location on the ground track should lie on the Greenwich meridian).
- Req. #5: An initial argument of perigee equal to 0 degrees.

Note that there may not be a unique solution to this problem, and some parameters may not even be constrained. You should justify your choice of any relevant orbital elements in your lab report, showing your working.

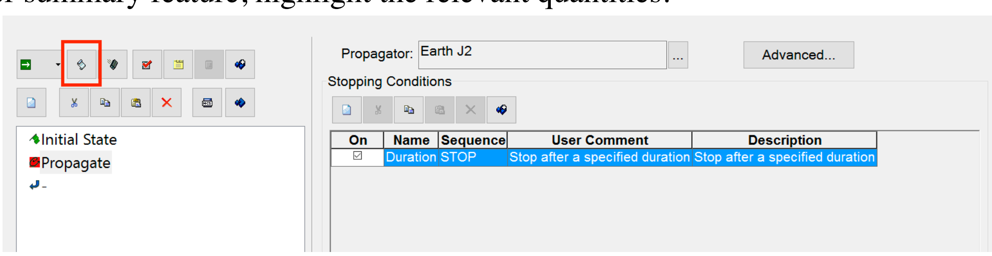
4) Set the initial state for your satellite using the Keplerian orbital elements you calculated in Question 1. Propagate the satellite for one orbital period using the built-in "Earth J2" propagator. Be sure to set the trip time for the duration stopping condition, ensuring that this value is equal to one orbital period. Customize the orbit and groundtrack color and linewidth to ensure that the figure is clear.

Question 2: Include a screenshot of the "Initial State" segment properties (displaying the orbital elements and initial epoch) in your lab report. Add the Earth North Pole vector to the 3D graphics window and take a screenshot that displays a useful and clear perspective of the three-dimensional orbit.

5) Navigate to the 2D graphics window properties page and remove both the day and night shading through the "Lighting" panel.
6) Ensure that the color and line width of the ground track for the satellite provide a clear view on the 2D graphics window. Alter these properties if necessary.

Question 3: Include a screenshot of the groundtrack of the satellite for one orbital period.

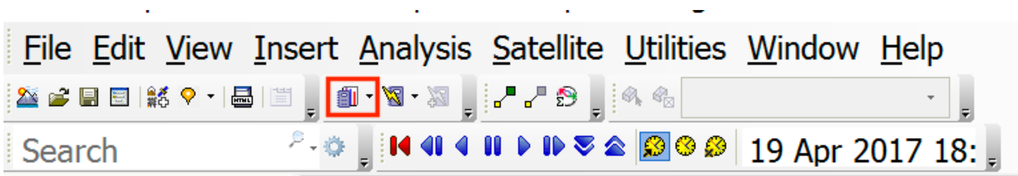
Question 4: Recall from previous labs that the Astrogator summary feature summarizes orbital and state characteristics at the end of a selected segment. To access this feature, highlight the segment of interest and then click the scroll icon as displayed below. Be sure to confirm that the information is displayed in the desired coordinate system, indicated at the beginning of the summary page as "State Vector in Coordinate System: ….". The coordinate system in which the summary information is displayed can be modified by double-clicking the segment of interest and selecting the desired system from the "Coord. System" option. Use the 2D graphics window (zoom-in if necessary) and/or the Astrogator summary feature to prove that the orbit you designed satisfies Req. #1, #2 and #4. In your lab report, reference any screenshots of this information to discuss whether your orbit satisfies the mission requirements. If using the Astrogator summary feature, highlight the relevant quantities.



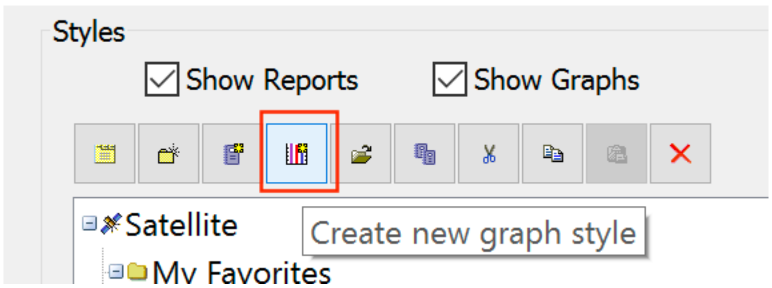
7) Modify the propagate segment in Astrogator to propagate the motion of the satellite for 100 orbital periods, via the duration stopping condition trip time. Run the MCS again.

Question 5: Include a screenshot of the 3D graphics window, visualizing the path of the satellite for 100 orbits of the satellite. In which coordinate system is this trajectory displayed?

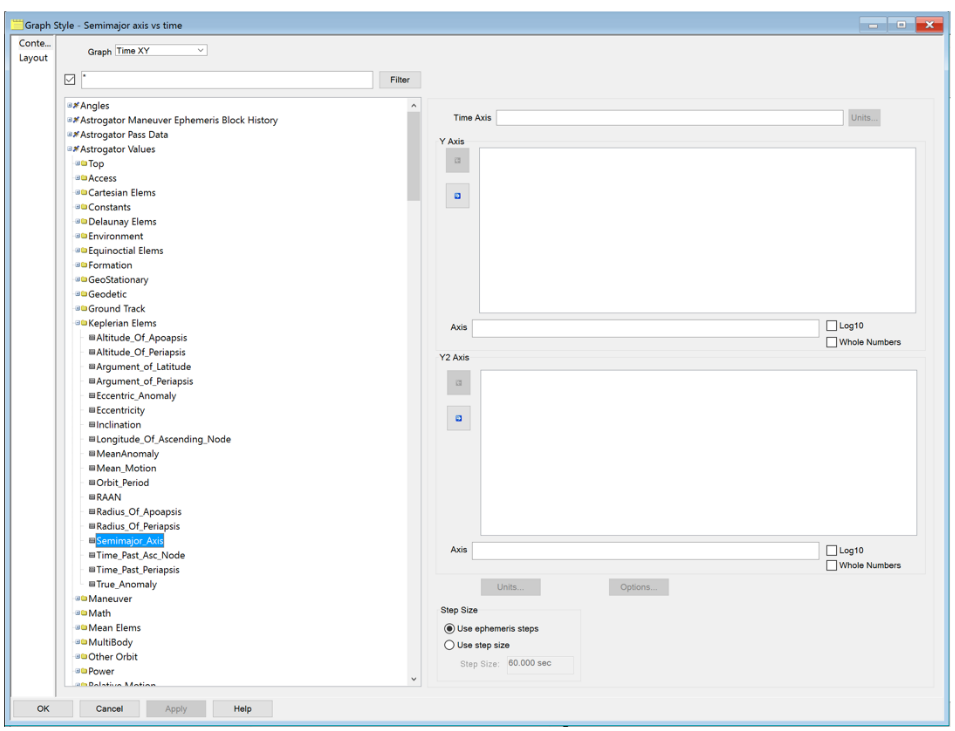
8) To explore the evolution of the orbital elements over time due to the effect of J2, we will leverage the Reports and Graphs feature of STK. To access this feature navigate to "Analysis"→"Report and Graph Manager" or click the following icon in the toolbar:



9) This graphing feature will allow us to observe the effect of J2 on each of the orbital elements. To explore this effect, you will create new graphs. First, let's create a graph displaying the evolution of the semi-major axis over 100 revolutions of the orbit. To create a new graph, ensure that your satellite is highlighted on the lefthand panel and then click the "Create new graph style" icon highlighted below and located above the righthand panel of the "Report and Graph Manager" page.



10) Name your new graph "Semimajor axis vs time". Once you have named the graph, press the "Enter" button and the graph style properties page will appear. You can also access this page by right-clicking the new graph selecting "Properties". The properties page should appear as below:



11) Ensure that in the "Graph" dropdown menu at the top of the properties page, "Time XY" is selected. Use the lefthand panel to select the semi-major axis as the quantity of interest to

plot on the vertical axis of the graph. Time is automatically selected as the parameter to plot on the horizontal axis of this graph. The semi-major axis is located in "Astrogator Values"→"Keplerian Elems"→"Semimajor_Axis". Highlight this quantity and then click the blue righthand arrow icon in the top right "Y Axis" panel. Click "Apply" and "OK" to save this information. You will then return to the "Report and Graph Manager" page.

12) Before generating the report, we must select the time steps used to calculate this semi-major axis over 100 orbital periods. Select a time step size that provides at least 50 data points per orbital period. Selecting the time step as too small a value can significantly increase the computational time (and sometimes crash the program!). Specify the desired time step in the bottom left panel of the "Report and Graph Manager" page as displayed below. Click the "Specify Time Properties" radio button and ensure that the Start and Stop times reflect 100 revolutions of your orbit. Then, click the "Use step size/time bound" radio button. Modify the step size by entering your desired value in the "Step Size" textbox.
13) Highlight the graph you created to visualize the evolution of the semi-major axis as a function of time subject to the J2 perturbation. Then, below the list of available graphs, ensure that the "Generate As" option that is selected is "Report/Graph". Click the "Generate…" button to generate the graph of semi-major axis as a function of time for the orbit you designed. Right click the graph and select "Font Size"→"Large"

Question 6: Use the "Copy to Clipboard" icon on the graph window to copy and paste this graph into your lab report. Use the procedure above to create additional graphs that display the evolution of the following orbital elements: Ω, ω. Discuss the time evolution of each of these orbital elements over 100 revolutions of the orbit you designed. Are your observations consistent with what you learned in class and in the textbook about the effect of J2 on the evolution of the orbital elements (which are otherwise constant in the two-body problem)?

PART II: Bound for Mars

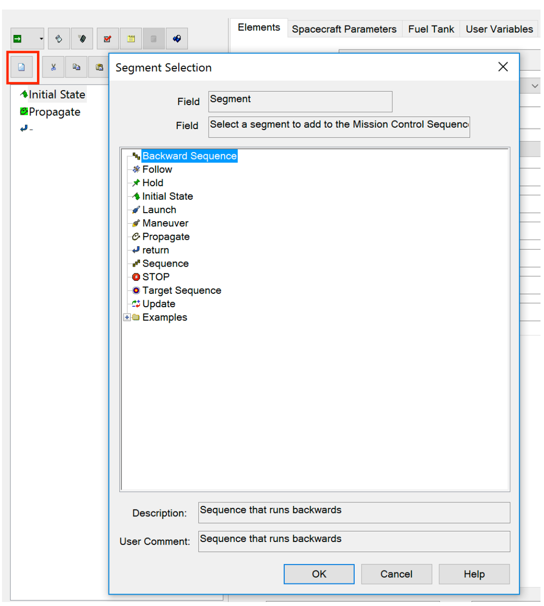
Using STK 11/Astrogator, you will create a scenario with a satellite in a heliocentric orbit, transferring from the Earth to Mars. Follow the outlined procedure and answer the questions presented throughout.

In Lab O2, you modeled the motion of an orbiter in a low altitude Mars orbiter which flew directly over a space-based habitat, located near the 1997 Pathfinder landing site. Now, let's consider how the spacecraft will rendezvous with Mars from the Earth. We will simplify this problem and consider a spacecraft leaving from Earth's orbit via an impulsive maneuver. The spacecraft will then be placed on a heliocentric transfer orbit that, with the assistance of additional impulsive maneuver/s, will reach the orbit of Mars, assuming that the Earth and Mars each travel along circular coplanar orbits.

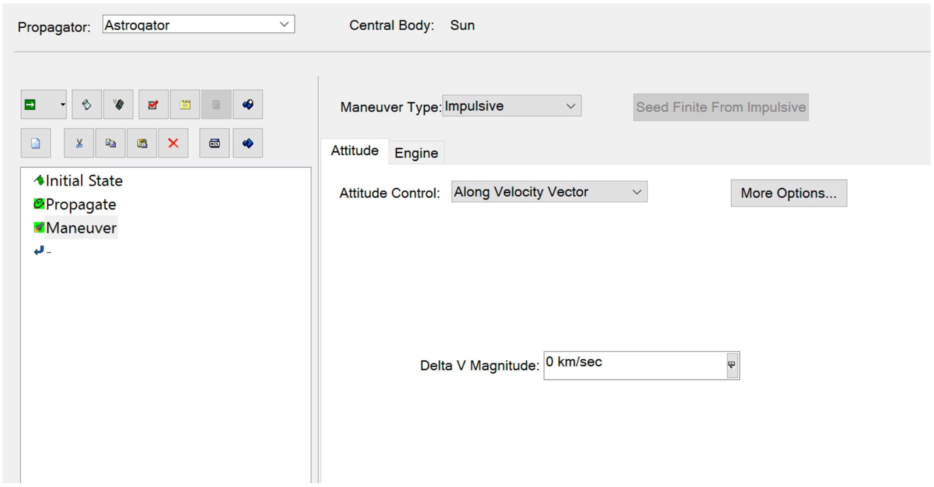
1) Create a scenario with the Sun as the central body. Select the initial epoch for the scenario as February 21, 2020 19:00:00.000 UTCG, and a final scenario time of February 21, 2023 19:00:00.000 UTCG. You can set the Sun as the central body by activating the "Planetary Options" feature prior to creating a new scenario.
2) In the 3D graphics window, confirm that the central body is the Sun. We will not use the 2D graphics window in this example, so you may close it.
3) If needed, create a new Sun point mass gravity propagator using the same method as the previous labs: open the component browser from the utilities option in the menu. Navigate to the "Propagators" item in the lefthand panel and single click on the "Earth Point Mass" model in the righthand panel. Then, click the "Duplicate" button. Change the name to "Sun Point Mass" in the popup window. Double click the "Sun Point Mass" entry and a new popup window will appear. Change the central body to "Sun" and click ok. (Note that there is a heliocentric propagator preset in STK. However, this is not a Sun point mass model)
4) Recall that you will need to ensure that the trajectory of a satellite is visible by navigating to the 3D graphics window properties page. Then, on the "Advanced" page, change the "Visible"→"Max Visible" value to 1e+012km.

Question 7: Use a Hohmann transfer to design a heliocentric trajectory for the spacecraft to reach Mars' orbit from the Earth. First, calculate the TOF and required Δv's, and total Δv. Do each of the maneuvers "speed up" or "slow down" the spacecraft? Assume that each planetary body travels along a circular orbit with a radius equal to the semi-major axis listed in the textbook ($a_{\text{Mars}} = 1.5234 AU$). Show your working in your lab report, and draw a diagram of the heliocentric transfer, including the initial and final circular orbits. Also add arrows indicating the impulsive maneuvers and their direction of application (i.e., along the velocity or anti-velocity vector). Note that the spacecraft must be launched from the Earth, and eventually rendezvous with Mars. In designing this Hohmann transfer, what are the assumptions and limitations of the trajectory design process and, therefore, your estimate of the required Δv? Is the total required Δv for this transfer large? Justify your response.

5) Add a satellite to the scenario and select Astrogator as the propagator.
6) Now, let's construct the mission timeline for a Hohmann transfer to reach the orbit of Mars from the Earth in Astrogator. To achieve this goal, we will construct the MCS using the following segments in the specified order, with instructions in the next step:
    a. **Initial state** corresponding to a satellite in a circular approximation to the Earth's orbit.
    b. **Propagate** for one entire period of the Earth's orbit around the Sun using a Sun point mass model. (Will represent a circular approximation to the Earth's orbit)
    c. **Impulsive maneuver**, representing $\Delta\bar{v}_1$ and applied in either the velocity or anti-velocity direction with a magnitude equal to the value you found in Question 7.
    d. **Propagate** for the TOF you calculated in Question 7 in a Sun point mass model.
    e. **Impulsive maneuver**, representing $\Delta\bar{v}_2$ and applied in either the velocity or anti-velocity direction with a magnitude equal to the value you found in Question 7.
    f. **Propagate** for one entire period of Mars' orbit around the Sun using a Sun point mass model. (Will represent a circular approximation to Mars' orbit)
7) To implement this timeline in the MCS, you will need to add each of the segments chronologically to the MCS. By default, Astrogator has already added the "Initial State" and "Propagate" segments. Configure the initial state using the "Sun MeanEclipJ2000" coordinate system, and input a set of Keplerian orbital elements that reflect a circular orbit with a radius equal to the semi-major axis of the Earth's heliocentric orbit. Set the remaining orbital elements equal to zero. Configure the first propagate segment to integrate this initial state forward in time for one period of the Earth's heliocentric orbit.
8) To add additional segments to the end of this MCS, first highlight the segment at the end of the MCS (i.e. the "Propagate" segment) and then click the blank page icon above the MCS, highlighted in the image below. A "Segment Selection" popup window will appear, with a series of sample segments.

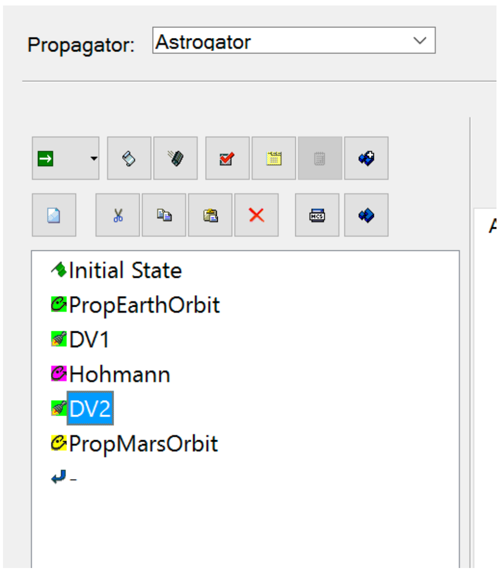


9) To add an impulsive maneuver segment, click the "Maneuver" option and then click ok. This will add the maneuver to the end of the MCS. The Maneuver configuration page will appear as displayed below. Ensure that the "Maneuver Type" is listed as impulsive. Then, you can modify the "Delta V Magnitude" to reflect the maneuver size you calculated in Question 7. To apply this maneuver in the velocity direction and "speed up" the spacecraft, select "Along Velocity Vector" for the "Attitude Control". To apply the maneuver in the anti-velocity direction and "slow down" the spacecraft, select "AntiVelocity Vector" for the "Attitude Control". After you have entered the desired maneuver magnitude and direction, click "Apply".



10) To add additional propagate and maneuver segments, highlight the segment at the end of the MCS and then click the "Blank Page" icon, repeating the procedure to add new segments. For visualization purposes, ensure that each propagate segment is displayed using a different and clearly-visible color.

11) Once each segment has been added and configured (including the maneuver magnitude and direction, as well as propagate segment durations), your MCS should resemble the image below.



12) Use a sample image of a satellite to locate the spacecraft along the trajectory. To add a spacecraft image as a location marker, use the spacecraft properties window. Navigate to the "3D Graphics"→"Model" page. In the top left panel, drag the slider next to "Log Scale" all the way to the right until the value in the textbox is equal to 10 (or another reasonable value). Ensure that in the bottom panel of this page labeled "Details Thresholds" all the sliders are dragged to the right. Click "Apply" and then run the MCS to generate the entire mission trajectory.

Question 8: Take a screenshot of your heliocentric transfer looking down the angular momentum vector of your elliptical transfer orbit.

Question 9: Use the Astrogator summary feature to verify the orbital elements of the spacecraft at the end of the final propagate segment. Do the orbital elements reported by STK match the desired orbital elements for an assumed circular orbit? Is the assumption of circular and coplanar orbits for the Earth and Mars a reasonable assumption?

Question 10: Use a bi-elliptic transfer to design a heliocentric trajectory for the spacecraft to reach Mars' orbit from the Earth, assuming the planets each follow circular and coplanar orbits. Use a value for the intermediate radius of the bi-elliptic transfer (i.e. apoapsis radius of the two transfer arcs) that is equal to 2.7 AU. Calculate the TOF and required $\Delta\bar{v}$'s, as well as the total $\Delta\bar{v}$. Do each of the maneuvers "speed up" or "slow down" the spacecraft?

Question 11: Implement this transfer sequence in STK by adding additional maneuver and propagate segments. Then, reconfigure each segment to reflect the transfer itinerary and maneuver information you calculated in Question 10. Include a screenshot of your heliocentric transfer looking down the vector normal to the plane in which your transfer is contained.

Question 12: Use the Astrogator summary feature to verify the orbital elements of the spacecraft at the end of the final propagate segment. Do the orbital elements reported by STK match the desired orbital elements for an assumed circular orbit? When the spacecraft is traveling from the Earth to Mars along the bi-elliptic transfer you constructed, could it potentially encounter any celestial bodies other than the Earth and Mars?

Question 13: Compare the TOF and total $\Delta\bar{v}$ required by each of these two transfers. Discuss whether your observations are consistent with our discussion in class about the relative cost of the Hohmann and bi-elliptic transfers and justify your answer.

Question 14: Discuss five different considerations in the mission design process (e.g. spacecraft subsystems, operations, etc) that may impact the range of acceptable transfer times, total $\Delta\bar{v}$ and/or transfer geometry for a mission from the Earth to Mars.

ASEN 3200 Lab O-3 Spring 2021 Rubric

Title Page (1 pt.) – Lab, Course Number, Group Members, Date
Abstract (5pts) – short summary of objectives, experiment, results, and analysis
Introduction (5pts) – brief introduction to this lab, what you plan to investigate, etc

Within the writeup in the below sections, using subheadings such as "Question X" to clearly identify your answer to each question.

PART I: Sun Synchronous Orbits (35 pts)

- Description of scenario setup and initial parameters
- Theory – explain, with equations, how you calculate the orbital elements for your orbit.
- Results and Analysis – show all plots and summarize output generated from STK, describe results. Ensure that any plots are clear and 3D graphics views provide a useful perspective of the orbit. Justify your responses to any questions.

PART II: Bound for Mars (35 pts)

- Description of scenario setup and initial parameters
- Theory – explain, with equations, how you calculated the TOF and maneuvers required for each of the Hohmann and bielliptic transfers.
- Results and Analysis - for each question, show all plots and summarize output generated from STK and describe results. Ensure that any plots are clear and 3D graphics views provide a useful perspective of the orbit. Justify your responses to any questions.

Conclusions and Recommendations (4 pts)

- What did you learn from this lab?
- What would you be interested in exploring beyond the given objectives or STK features?

Acknowledgements (1 pt.)
List who did what in the group and any outside assistance you received

References (1pt, must cite all external sources, including images)

Style & Clarity (13 pts)
Organization (3) – clear flow, follows required outline, numbered pages
Figures (2.5) – clear figures, appropriate axes, informative titles, clearly labeled units
Tables (2.5) – clear tables, significant figures, headings, informative titles, clearly labeled units
Spelling & Grammar (5)