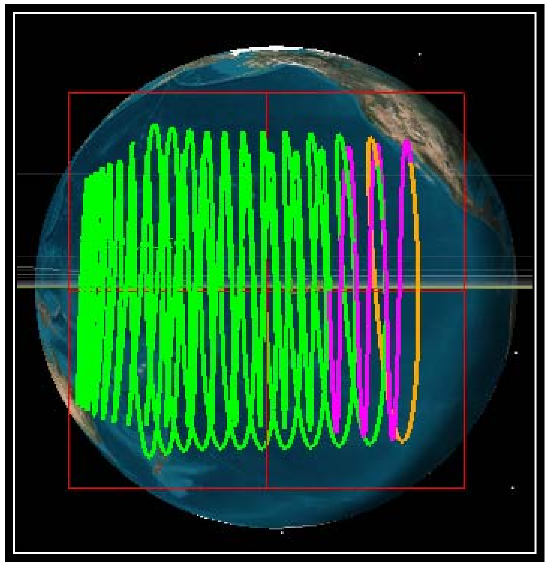
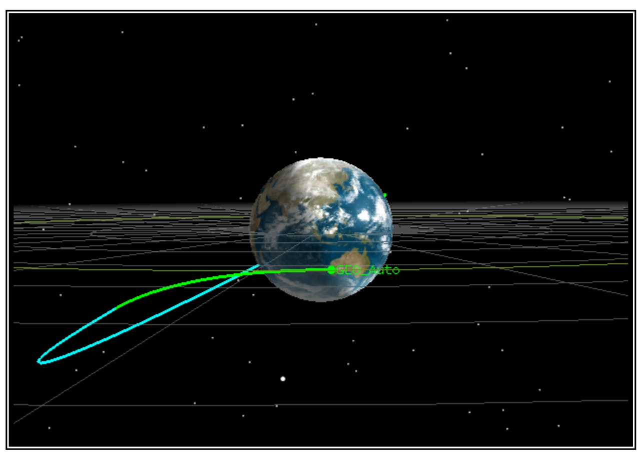
STK/Astrogator Tutorial: GEO Orbit Maintenance





Objectives

At the conclusion of this class, you will have:

- Planned a phase period in orbit in order to move closer to a target satellite.
- Performed a Hohmann transfer from one circular orbit to another.
- Used nested targeters to achieve a mission objective.
- Created and used a satellite proximity box in order to visualize an orbital 'Slot'
- Created a trajectory that achieves a targeted GEO slot from a GTO.
- Used 'backoff event location' to find an integration stopping point –before- a different condition is met.
- Targeted maneuvers to create a desired turn-around point in a control box.
- Created a polar graph to help for maneuver planning.
- Used the 'difference' mathematical calc object to prevent specific parameters from changing in a targeter profile
- Planned maneuvers to maintain a satellite in position in Geosynchronous Orbit both in inclination and longitude.
- Planned one year of station-keeping maneuvers using autosequences.
- Planned one year of station-keeping maneuvers using single segment propagation from Microsoft Excel and VBA.

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Exercise 1: GEO Orbit Insertion

In this exercise, we will use Astrogator to plan maneuvers that will place our satellite from its original Geosynchronous phasing orbit to the final GEO slot at 150W Longitude.

Scenario Setup

1. Open the “GTO” scenario in the “GTO to GEO” folder provided with this tutorial. This scenario is created in another separate tutorial and provides us with a nominal Geosynchronous Transfer Orbit that inserts our spacecraft in an orbit that is slightly lower than Geostationary altitude, with a 3 degrees/day drift rate.
2. Open the properties of the “3_deg_day” satellite and inspect the summary report of the ‘BABS’ segment, and find the Longitude at the end of the burn. (~ 107 deg.). Given that we targeted a drift rate of 3 deg/day, and that we wish to target a GEO slot of 150W, or 210 deg, we can estimate that we’ll have to phase in this orbit for 34 days.

Phase into Position

3. Create a new target sequence, and call it ‘Phase to 150W’. This targeter will be used to vary our time in our parking orbit so that we can get to the orbital slot we desire.
    a. Inside the targeter, add a new propagate segment, named ‘Phase’.
        i. Use the default stopping condition of duration
        ii. Set the Trip value to 34 days
        iii. Select the Trip value as a control
        iv. Change the propagator to ‘Earth Full VOP’
    b. After the ‘Phase’ Segment, add a Target Sequence, named ‘Hohmann Transfer’. This targeter will raise us from our parking orbit to our final GEO altitude.
        i. Inside this targeter, add an impulsive maneuver segment named ‘Apo Raise’
            1. Set the attitude control to ‘Thrust Vector’
            2. Set the X component to 0.01 km/sec
            3. Select the X component as a control
        ii. After ‘Apo Raise’ add a propagate segment named ‘Prop to Apogee’

NOTES

1. Change the stopping condition to Apogee
2. Change the propagator to 'Earth Full VOP'
3. Add a result of 'R Mag' (in the calc objects/spherical elems folder)

iii. Create a Targeting profile for 'Hohmann Transfer' called 'Target Rmag'

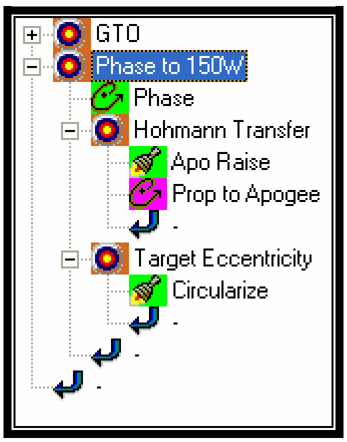
1. Set the 'Apo Raise' X component as a control
    a. Perturbation = **0.0001 km/sec**
    b. Max Step = **0.001 km/sec**
2. Set the 'Rmag' result as a constraint
    a. Desired = **42165 km**
    b. Tolerance = **0.01 km**

iv. Set the Targeter Action for 'Hohmann Transfer' to 'Run Active Profiles'

c. After 'Hohmann Transfer', inside of the 'Phase to 150 W' targeter, add another target sequence named 'Target Eccentricity'. This targeter will circularize our orbit at our desired altitude.

i. Add an impulsive maneuver segment to this targeter named 'Circularize'

1. Set the attitude control to 'Thrust Vector'
2. Select the X component as a control
3. Add a result of 'Eccentricity' to the 'Circularize' segment



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        ii. Create a Targeting profile for 'Target Eccentricity' called 'ECC = 0'

            1. Set the 'Circularize' X component as a control

                a. Perturbation = **0.0001 km/sec**

                b. Max Step = **0.001 km/sec**

            2. Set the 'Eccentricity' result as a constraint

                a. Desired = **0.0**

                b. Tolerance = **0.0001**

            3. Set the Targeter Action to 'Run Active Profiles'

        iii. Add 2 results to the 'Target Eccentricity' targeter itself:

            1. Longitude

            2. Longitude Drift Rate

        iv. Set the Action for the 'Target Eccentricity' targeter to 'Run Active Profiles'

    d. Create a Differential Corrector profile for 'Phase to 150W' targeter named 'Target Slot'. This profile will vary our duration in the parking orbit to achieve the desired longitude slot after the Hohmann transfer and circularization targeters have been run.

        i. Set the 'Phase' Duration (StoppingConditions.Duration.Tripvalue) as a control

            1. Perturbation = **1 day**

            2. Max Step = **10 days**

        ii. Set the 'Longitude' result as a constraint

            1. Desired = **-150 deg**

            2. Tolerance = **0.001 deg**

    e. Create a 2nd Differential Corrector profile for 'Phase to 150W' targeter named 'Target Rate'. This targeter will insure that we have no drift rate with respect to the Earth once we are inserted into our final GEO slot.

        i. Set the 'Phase' Duration as a control

            1. Perturbation = **1 day**

            2. Max Step = **10 days**

NOTES

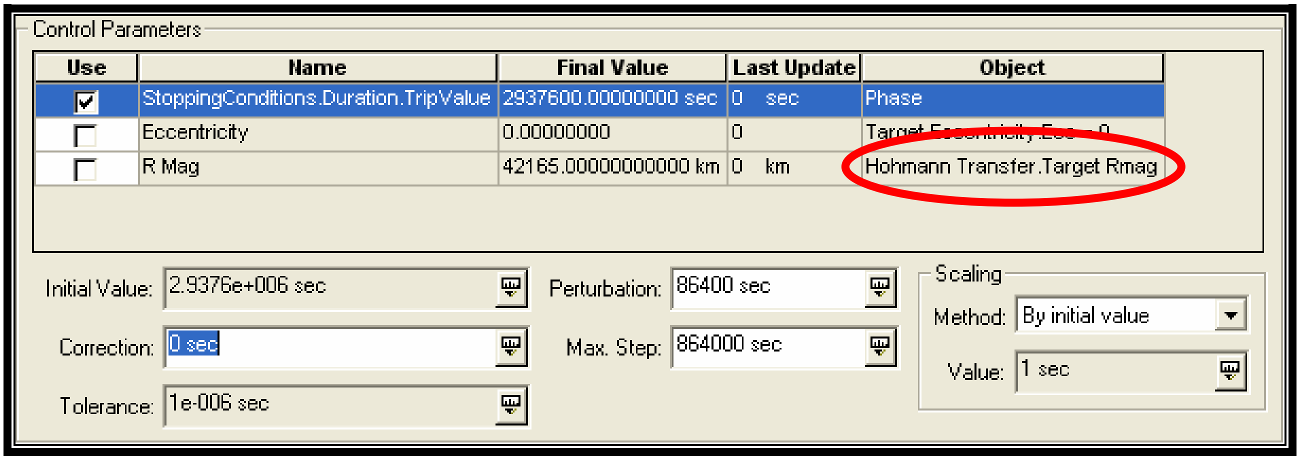

Note

When using the constraint of an inner targeter as a control of the outer targeter, it is important to note that the tolerance set on the inner targeter constraints (R Mag, in this case) must be less than the perturbations of the outer targeter. Otherwise, the inner targeter may not re-run at each perturbation.

ii. Set the R Mag constraint, from the inner 'Hohmann Transfer' Targeter, 'Target R Mag' Profile, as a control

1. Perturbation = **0.1 km**

2. Max Step = **1 km**



iii. Set the 'Longitude' result as a constraint

1. Desired = **-150 deg**

2. Tolerance = **0.001 deg**

iv. Set the 'Longitude Drift Rate' result from the 'Circularize' Targeter as a constraint

1. Desired = **0 deg/sec**

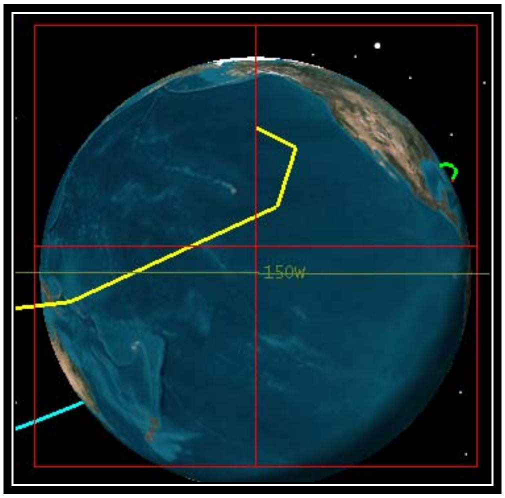
2. Tolerance = **1e-8 deg/sec**

f. Set the Targeter Action for 'Phase to 150W' to 'Run Active Profiles'


NOTES

Visualize the Slot

4. Create a new satellite named "150W":
   a. Using the orbit wizard,
      i. Create a Geostationary satellite centered at the -150W GEO slot.
      ii. Give it an ephemeris that spans 1 year starting at the scenario start time (Use "+365 days" for the Stop Time)
      iii. Use a Time Step of 20 Min
      iv. Open the properties of the satellite and set the Coord System to be 'TrueOfDate' and then set the Inclination to be 0.0
      v. Apply Changes
   b. Using the 2D Graphics, Attributes, and 'Custom Intervals' setting, turn off the label.
   c. Using the 3D Graphics, Proximity, 'Geostationary Box' setting, create a Geostationary box at -150 deg, a NS of 0.2 deg, and an EW of 0.2 Deg.
   d. In an Earth Fixed window, center on the Proximity box by centering on the 150W Satellite. Use the View From/To button, and select the 150W satellite to 'View From', and the Earth to 'View to'.
   e. In the 3D Graphics/Model page, turn off the model.
5. Run the targeter



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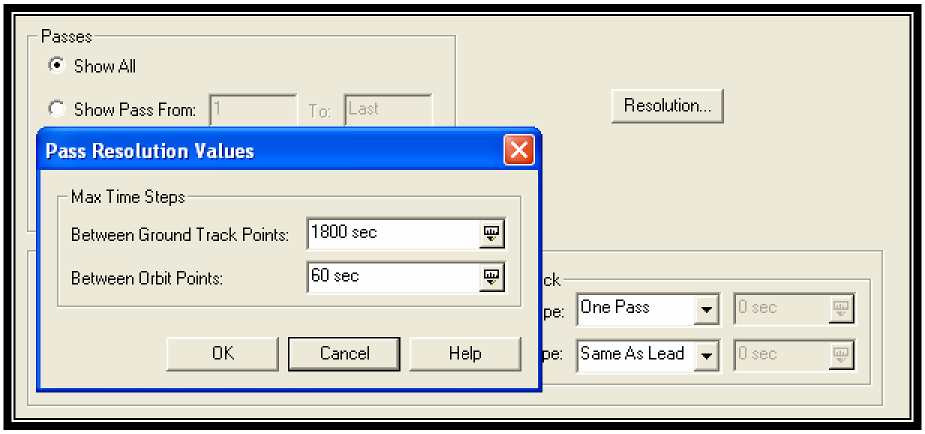
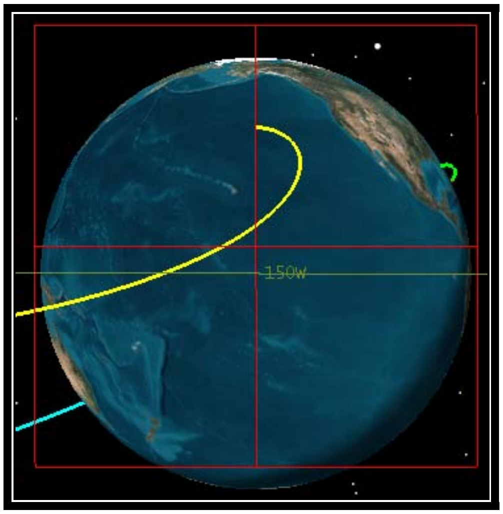
6. Note that the trajectory looks blocky, or unsmooth. This is a function of the VOP integrator, which takes large steps between integration points, and the 3D interpolation of that trajectory in the 3D window. By default the resolution in the 3D window is set to draw points at every 43200 seconds, or every integration point, whichever is smaller. In our case the VOP integration points are smaller, but that doesn't look good in our window. We can change that by changing the default drawing interval, or the interpolator resolution between orbit points. On the 2D Graphics/Pass page, select the 'Resolution' button and change the 'Between Orbit Points' to 60 seconds.





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Exercise 2: GEO Orbit Maintenance

The noncircular shape of the earth's equator causes satellites to be slowly drawn to one of two stable equilibrium points at 105.3 Deg W and 75.1 Deg E. Because we're at 150 deg W (210 E) longitude, we'll tend to drift east towards 105.3 Deg W, the closest stable point. We can use this to our advantage, and bias our satellite with a small amount of velocity in the westerly direction. If the velocity is small, eventually the acceleration to the east will win over, causing a turn-around point. We can target this turn-around point to occur where we desire, which will be the edge of our defined GEO box.

In this exercise, we will first build a sequence that keeps us within an East-West 'box'. Then, we will build a similar North-South sequence, which maintains our satellite within the Northern and Southern boundaries of the box. We will define our 'box' to be 0.2 degrees north and south of the equator, and 0.2 degrees east and west of the 150 Deg W reference point.

East-West Station-Keeping

Since we know that our satellite will drift to the east, we will first create a 'Sequence' MCS segment that contains a targeter that causes the satellite's drift to reverse direction (i.e. go from a western drift to an eastern drift) at the edge of our box.

1. Insert a Sequence segment after the last targeter, and name it 'EW Station Keeping'
    a. Inside the sequence, add a propagate segment named 'Stop on Apogee before Limit'. This segment will propagate to the last Apogee that occurs before our satellite's longitude has drifted out of our 'box' on the eastern side.
        i. Change the stopping condition to Apogee
        ii. Change the propagator to 'Earth Full VOP'
        iii. Configure the 'Before' condition to use -149.8 Longitude as a stopping condition, 1e-006 deg tolerance.

Note

This demonstrates the 'Backoff Event Location' feature. Activating the 'Before' field will cause the segment to propagate to the Apogee right before our trajectory crosses -149.8 degrees in longitude. The user can configure a stopping condition that occurs before another. The numerical integrator actually propagates forward to the longitude crossing first, and then searches back through the ephemeris to find the previous apogee.

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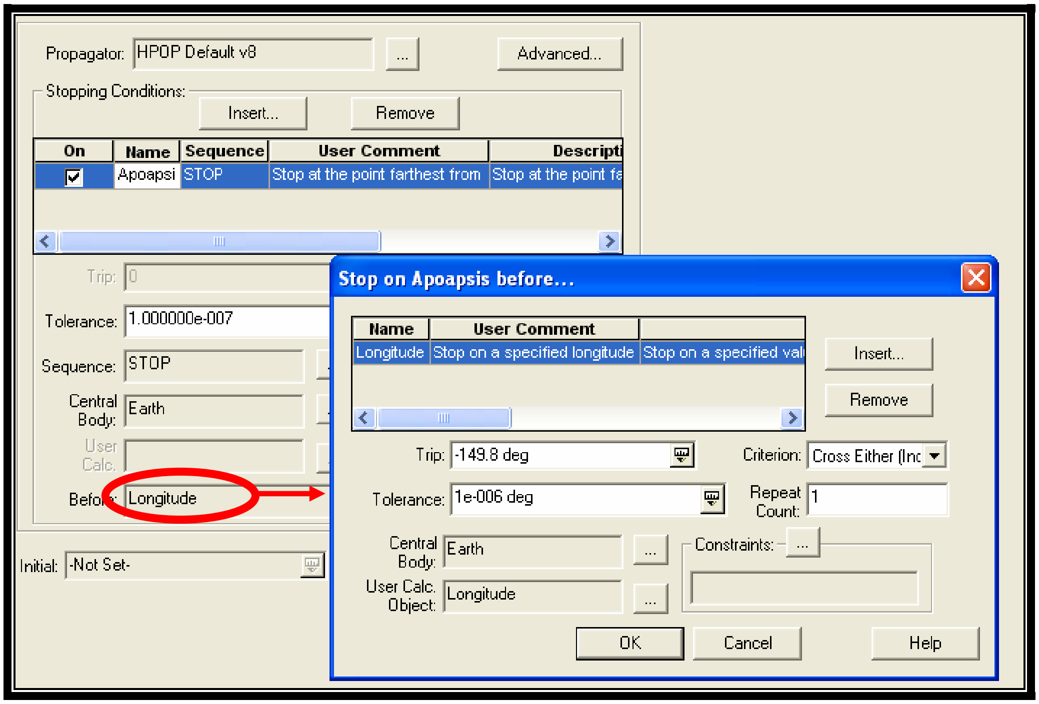
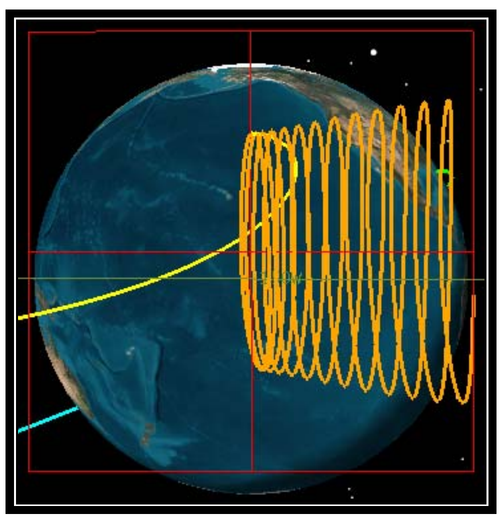


b. Apply the profiles in the previous targeters, set the action on the targeters to 'Run Nominal Sequence' and run the MCS.



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c. Make sure your MCS 'Run' button is set to 'Run Only Changed Segments'.

Now we've got ourselves stopped on the eastern boundary of our GEO box.

d. After the 'Stop on Node before Limit', and inside the EW Station Keeping sequence, add a Targeter named 'Target Turn Around'. This targeter will target a maneuver that will place our 'turnaround point' right at the western edge of our 'box'.

   i. Inside the Targeter, add an impulsive maneuver segment named 'Drift Control'

      1. Set the attitude control to 'Thrust Vector'

      2. Set the X component to **0.00012 km/sec**

      3. Select the X component as a control

   ii. After 'Drift Control', add a propagate segment called 'Prop to First Node'

      1. Change the stopping condition to Ascending Node, and change the Coord. System to Earth True of Date (Earth TOD).

      2. Change the propagator to 'Earth Full VOP'

      This first propagate segment insures that the first data point used in the 'Greater than minimum' constraint is measured at an ascending node. Without this, the first data point would come from wherever the 'Prop to Asc Node' propagation started, which in this case would be from the 'Drift Control' Maneuver, which took place at apogee.

   iii. After 'Prop to First Node', add a propagate segment called 'Prop to Asc Node'

      1. Change the stopping condition to Ascending Node, again using the Earth TOD coordinate system.

      2. Add a constraint to the Ascending Node stopping condition that requires a "Greater than Minimum" condition to have been reached on Longitude, with a tolerance of **0.001 deg**.

      This will cause our propagation to stop when we've reached the ascending node AND our longitude at the node is greater than the minimum longitude we've seen so far in this propagation.

      3. Change the propagator to 'Earth Full VOP'

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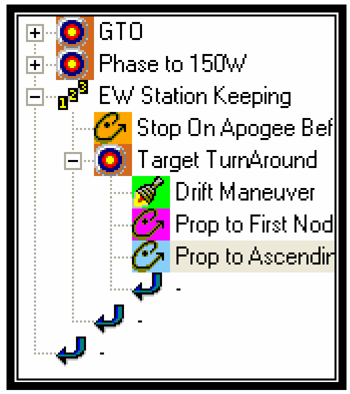
4. Add a result to this segment of Minimum Longitude (create this in the Astrogator browser, by using a copy of the 'Minimum' calc object in the 'Math' folder, and then selecting the Longitude calc object)

The way the current propagation is set up, it stops AFTER it has detected a turnaround, i.e. it's greater longitude is greater than the minimum. However, this minimum may still be outside of our box. So we'll measure the actual minimum, and ta rget that to be at the box's edge.



iv. Create a Differential Corrector profile in the 'Target Turn Around' targeter called 'Target Western Edge'

1. Select the impulsive maneuver X as a control

   a. Perturbation **= 1.e-6 km/sec**

   b. Max Step Size **= 1.e-4 km/sec**

2. Select the Min Longitude as a constraint

   a. Desired = **-150.2 deg**

   b. Tolerance = **0.0001 deg.**

v. Set the targeter to 'Run Active Profiles'

2. Run the MCS.

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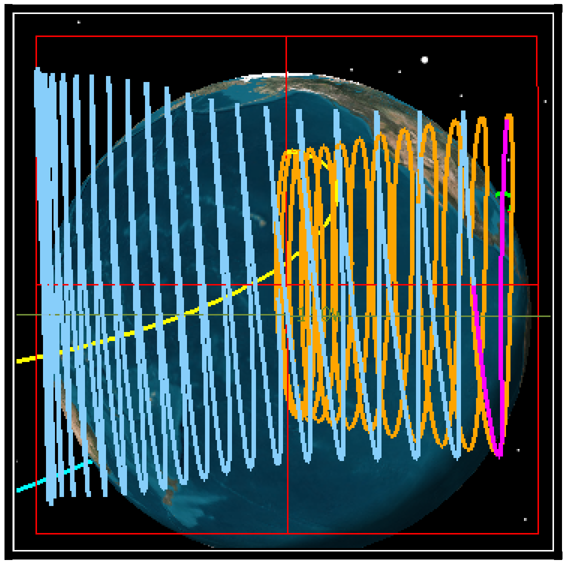
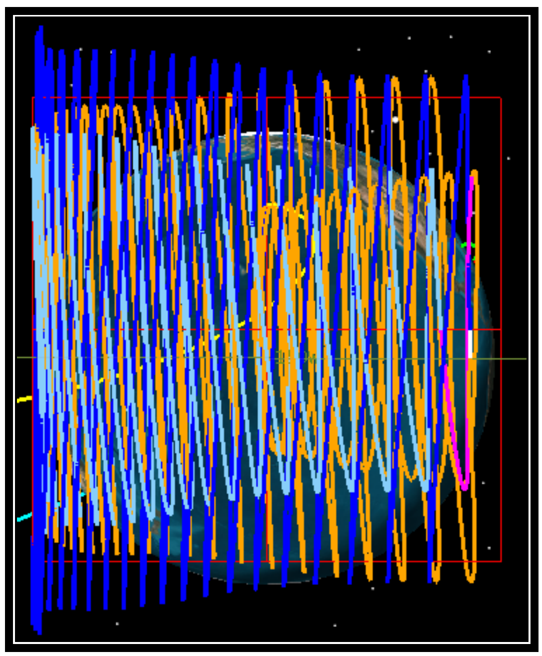


3. Copy 'EW Station Keeping', and paste it after the first copy. Reset the Profiles in the copy's targeter.
4. Re-run the MCS.



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North-South Station-Keeping

Now that we have targeted our east-west turnaround to take place at the western boundary of our 'box', we need to do something about our inclination, which we can see is taking us outside of our box to the North and to the South.

Out of plane perturbations on GEO spacecraft come from the gravitational effects of the Moon and the Sun. The Sun lies roughly 23 degrees out of the equatorial plane in the ecliptic, and the Moon is 5 degrees out of ecliptic. When the sun is at its most northern point (mid-summer) and its most southern (mid-winter) it produces its maximum torque on the orbit, which causes the orbital inclination vector to precess. This causes a semi-annual effect. The Moon's perturbations are similar, but vary on a semi-monthly basis. The total effect on the inclination is the sum of these two effects, plus some smaller effects cause by the Earth's gravity field.

The satellite's inclination will evolve over time, and the direction of the evolution (i.e. if the inclination is increasing, or decreasing) will depend on where the RAAN is with respect to the Sun and Moon. The orientation of the orbital inclination vector (i.e. the angular momentum vector of the orbit) with respect to the Sun and Moon will determine how this vector precesses.

In this example, we will use the STK graph tool to determine how our inclination will change over time, and then we will choose a different RAAN to change this trend to a direction that is more desirable. First, we will create the graph, and then we'll create a North-South (inclination) station-keeping sequence similar to our East-West station keeping segment.

5. Create a TOD Inc Calc Object, by copying the Inclination Calc object and using the Earth TOD coordinate system. TOD stands for True of Date, and represents the inertial coordinate system of the specific date in question, rather than a mean coordinate system like the J2000 system. (See the STK help system for 'Coordinate Systems')

6. Create a TOD RAAN Calc object

7. Create a Polar Graph of TOD Inc and TOD RAAN:

    a. Polar Graph

        i. R = TOD Inclination

        ii. Theta = TOD RAAN

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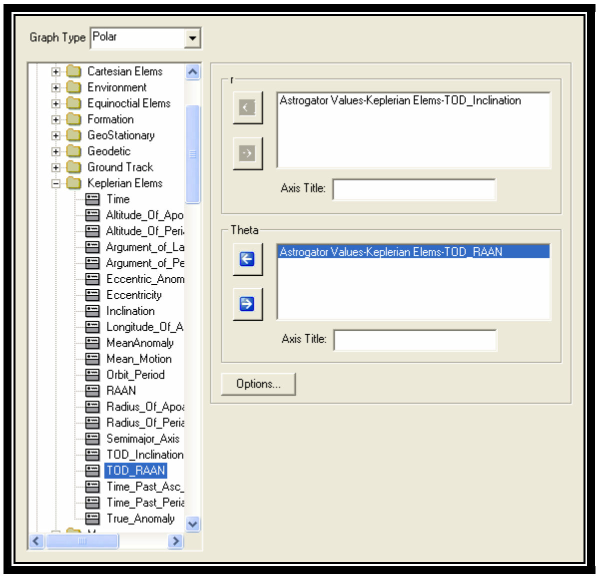
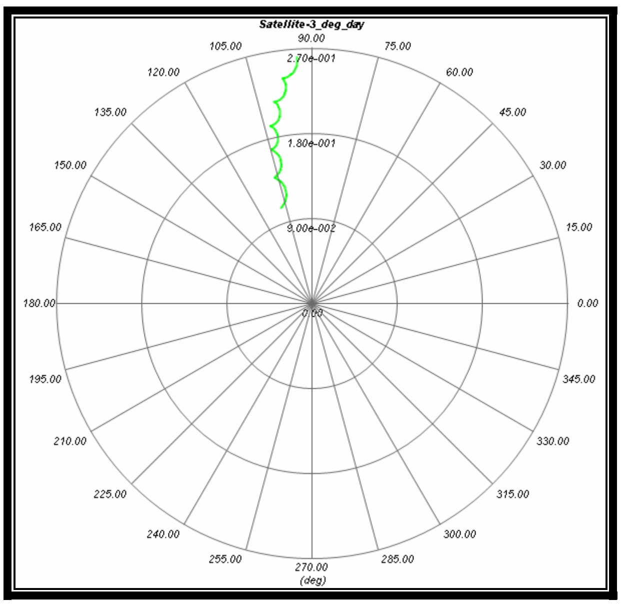


b. Using the 'Time Period' button on the graph dialogue, set the start time to equal that of the final epoch of the 'Phase to 150W'targeter.



NOTES

This graph shows us the trend of the RAAN-Inclination pair at this GEO location, which is up and to the left on this graph. Note that the outer ring on the graph is at 0.27 degrees, which is outside of our 0.2 deg box. Rather than simply targeting our inclination to zero at one of the nodes, we can change our RAAN to a spot on this graph where it will tend back towards zero thus and give us the longest possible time between inclination maneuvers. In order to do this, we will create an new North-South station-keeping targeter that will allow us to target a change in RAAN. We will start with a guess of a 260 degrees, as our trend appears (from the graph) to be linear.

8. Create new Targeter between the two EW station-keeping sequences, named 'NS Station Keeping' to target new RAAN.
    a. Inside the targeter, add a Propagate segment named 'Prop to Ignition'
        i. Set the propagator to 'Earth Full VOP'
        ii. Leave the stopping condition as 'duration'
        iii. Set the trip value to 1 day
        iv. Select the Trip value as control
    b. After the 'Prop to Ignition' Segment, insert Impulsive Maneuver segment named 'RAAN Adjust'
        i. Set Attitude control to 'Thrust Vector'
        ii. Set X component as control, with a value of 0.0 km/sec
        iii. Set Y component as control, with a value of -0.2 km/sec

        We now want to set up a targeter to vary the X and Y components of our maneuver in order to change the RAAN. We'll want to keep our SMA and Inclination constant (to minimize delta-v) and target a specific desired RAAN of 285 deg.

        iv. Add 3 results
            1. SMA diff (copy of 'Difference' calc object, from math, using the Semi Major Axis calc object)
            2. TOD Inc Diff (copy of 'Difference' calc object, from math, using the TOD Inclination calc object)

NOTES

3. TOD RAAN

c. Create a 'Target RAAN' Differential Corrector Profile on the NS StationKeeping Targeter

i. Select 'Prop To Ignition' duration as control

1. Perturbation = **1000 sec**

2. Max Step Size = **10000 sec**

ii. Select X component of 'RAAN Adjust' as control

1. Perturbation = **0.001 km/sec**

2. Max Step Size = **0.01 km/sec**

iii. Select Y component of 'RAAN Adjust' as control

1. Perturbation = **0.001 km/sec**

2. Max Step Size = **0.01 km/sec**

iv. Select SMA Diff as constraint

1. Desired = **0.0 km**

2. Tolerance = **0.01 km**

v. Select TOD Inc Diff as constraint

1. Desired = **0.0 deg**

2. Tolerance = **0.01 deg**

vi. Select TOD RAAN as a constraint

1. Desired = **260 deg**

2. Tolerance = **0.1 deg**

d. Set the targeter to 'Run Active Profiles'

9. Copy and Paste 2 copies of the EW station Keeping after at the end of the MCS

10. Run the MCS

11. Re-plot the Graph of RAAN vs Inclination, and alter your targeted RAAN value if necessary.

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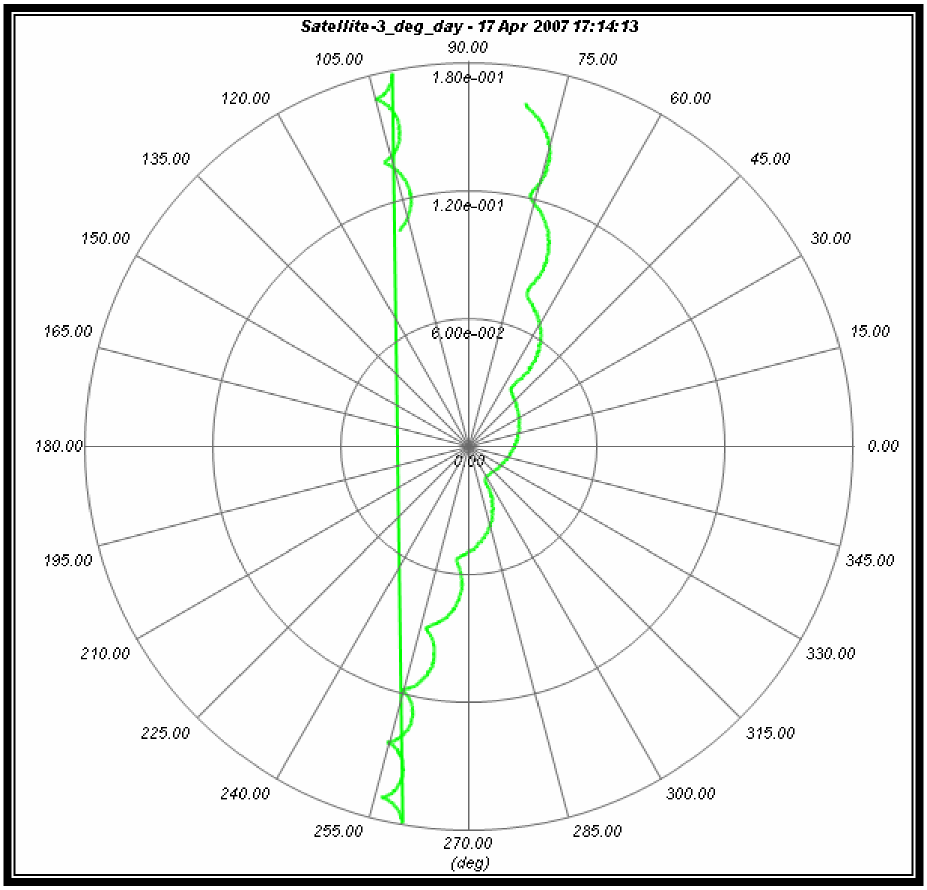

12. Retarget your RAAN in the NS Targeter to get the maximum time within the tolerance.

13. Create a graph of 'Astrogator Pass Value' 'Eccentricity' to make sure ECC isn't diverging. The 'Astrogator Pass Value' data providers measure the value of a calc object at every 'pass'. By default, passes are measured at every ascending node. (See the Basic/Pass Break page in the satellite properties window)

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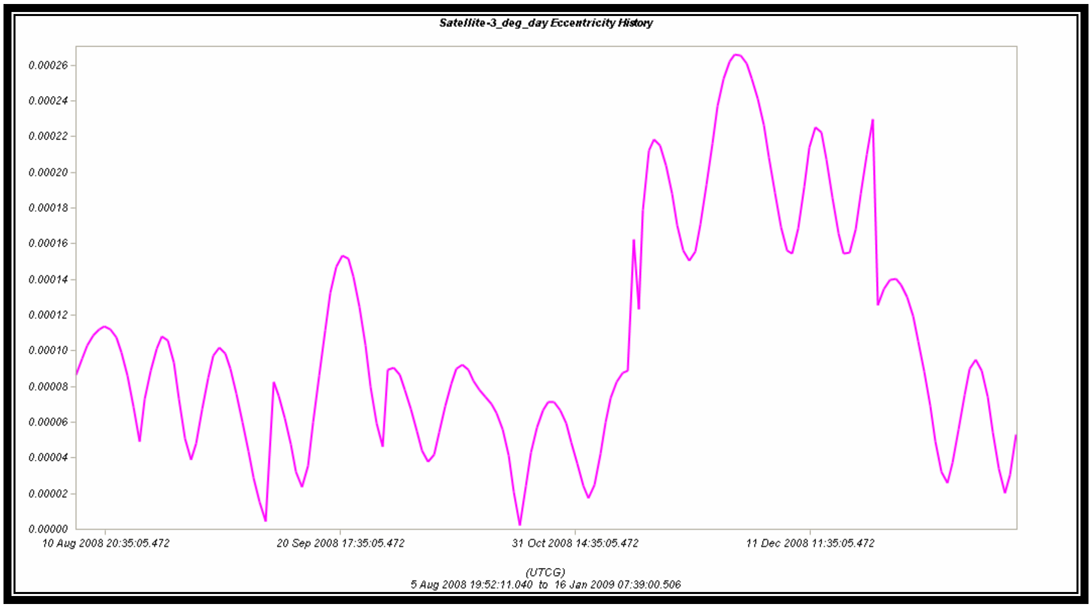
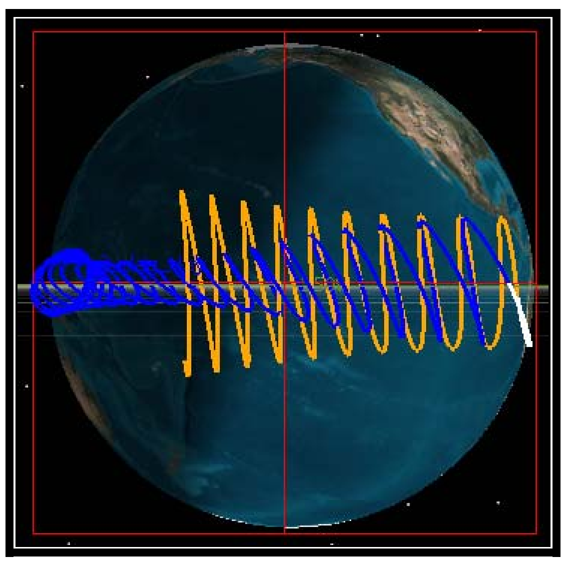


14. Set the 3d Graphics/Pass/Orbit Track settings to a Trail type of 30 days, Lead type none.
15. Animate the scenario starting at the end of the Phase to 150W segment to see how the inclination and longitude evolve over time.



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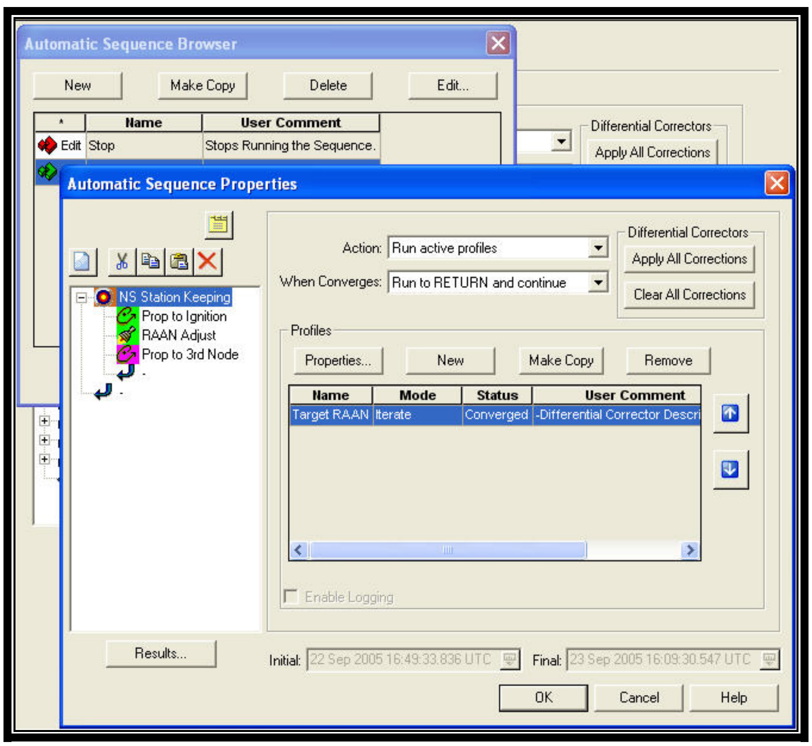
Automation of Station-Keeping: Autosequences

We've set up our North-South and East-West station-keeping sequences by hand and entered them sequentially in the MCS. Now we will automate this process, and execute these events in an event-loop that triggers the autosequences whenever the conditions for them are met.

16. Create a copy of your satellite in the object browser. Call the new satellite GEO_AUTO
17. In the 2d Graphics/Attributes page of your original satellite, select the 'basic' button, and deselect the 'show' option. This will turn off our original satellite.
18. In your new satellite, create an autosequence named 'NS Station-Keeping' and paste the NS target sequence into it.
19. Add a propagate segment at the end of the NS Sequence (Inside the targeter) that stops on the third TOD ascending node. Use the Earth Full VOP propagator. This will prevent the autosequence from being triggered on successive nodes if the inclination adjustment takes a few orbits to reverse the inclination trend.



20. Create an autosequence named 'EW Station Keeping' and paste the EW sequence into it.

NOTES

21. On the 'Stop on Apogee Before Limit' segment, remove the 'After' parameter. Rename the segment 'Stop on Apogee' to reflect the change.

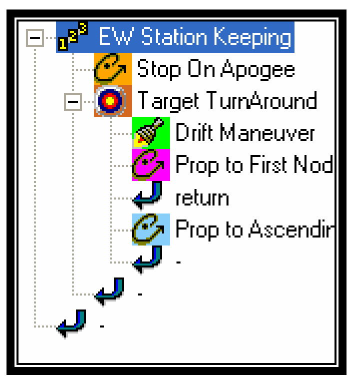
We'll deal with the eastern boundary a different way this time, using a limit in the external propagation.

22. Add a return after the 'Prop to first Node' segment, and set it to 'Enable (except profiles bypass)'

Note

> The setting 'Enable (except profiles bypass)' on a return sets the return segment to be ignored by targeting profiles (i.e. they will act as if it's not there) but the return will be active the last time the targeter is run, i.e. when it has converged. This allows us to target for parameters that won't necessarily be reached within this part of the MCS. In this case, we don't want the condition that triggers the NS autosequence to occur while we're waiting for the EW turn around inside of this targeter. So the targeter measures the turnaround here for targeting, but once the targeted goals have been achieved, it returns the state at the end of the 'Prop to first node' segment to the outside propagation.

23. Set the repeat count for the 'Prop to first node' segment to 3. This will insure that when we leave this autosequence, we won't immediately trigger it again. It will give us at least 3 nodal crossing that take place inside the autosequence.



24. Delete all the sequences and target sequences after the 'Phase to 150W' targeter.

25. Insert a propagate segment and name it Name it 'Prop 1 year'

    a. Change the propagator to 'Earth Full VOP'

NOTES

b. Change the max prop time to 2 years

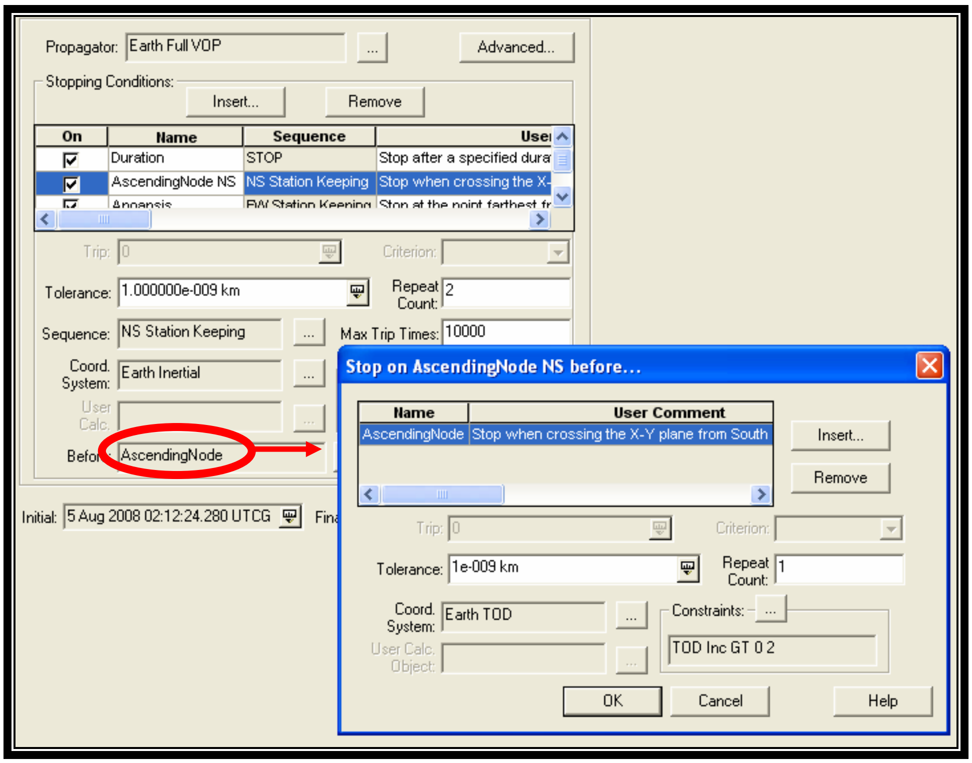
c. Add three stopping conditions

i. Duration (default), set to 1 year

Next we'll add a stopping condition that triggers our NS Station-Keeping auto sequence on the 2nd Ascending node **BEFORE** we get outside of 0.2 deg in inclination.

ii. Ascending Node NS (rename the Ascending Node Stopping Condition)

1. Give it a repeat count of 2
2. Add a **before** condition of Ascending Node, with a constraint of the TOD Inclination being greater than 0.2 deg, with a tolerance of 0.01 deg.
3. Change the activated sequence from 'Stop' to the NS Station-Keeping autosequence.



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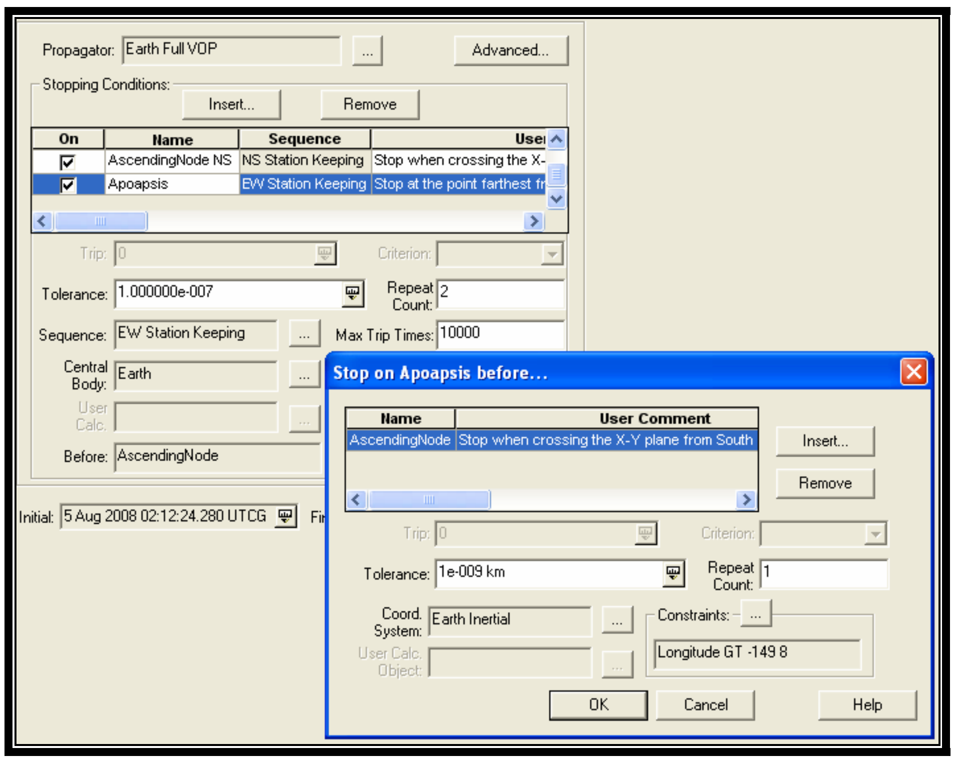
Recall that we have 3 nodal crossings that will take place inside the NS station keeping autosequence, so when we come back from the autosequence we will be below 0.18 deg.

Next we'll add a stopping condition that triggers our EW Station-Keeping autosequence on the 2nd Apoapsis **BEFORE** we get to an ascending node that has a longitude greater than -149.8. In other words, we look for the first ascending node that would be outside the box to the east, and run out autosequence on the 2nd apogee before that.

iii. Apoapsis

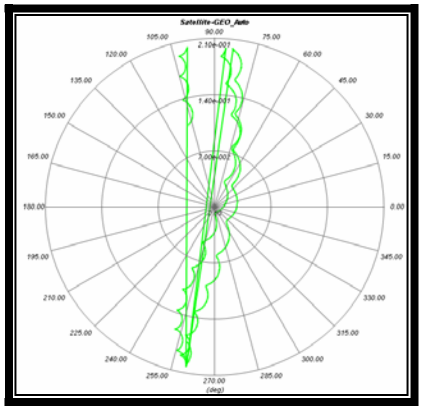
1. Give it a repeat count of 2
2. Add a **before** condition of Ascending Node with a constraint of Longitude greater than -149.84 deg, tolerance of 0.01 deg.
3. Change the activated sequence from 'Stop' to the EW station-Keeping autosequence.



NOTES

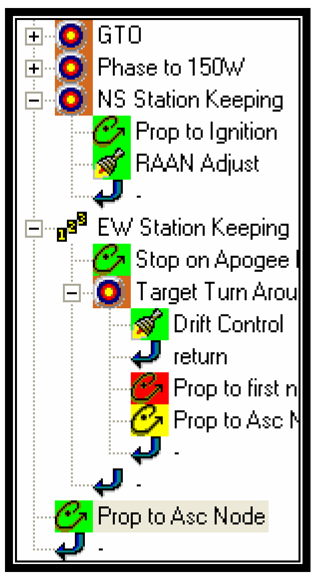
26. Run the MCS

27. Plot the RAAN vs. Inc plot again, and compare it to the previous satellite.



28. Create a 'Maneuver History' report (use a start time equal to the end of the 'Phase to 150W' segment).

29. A similar scenario called 'GEO Script' is included with the material for this tutorial. Open this scenario and inspect the properties of the 'Script' satellite



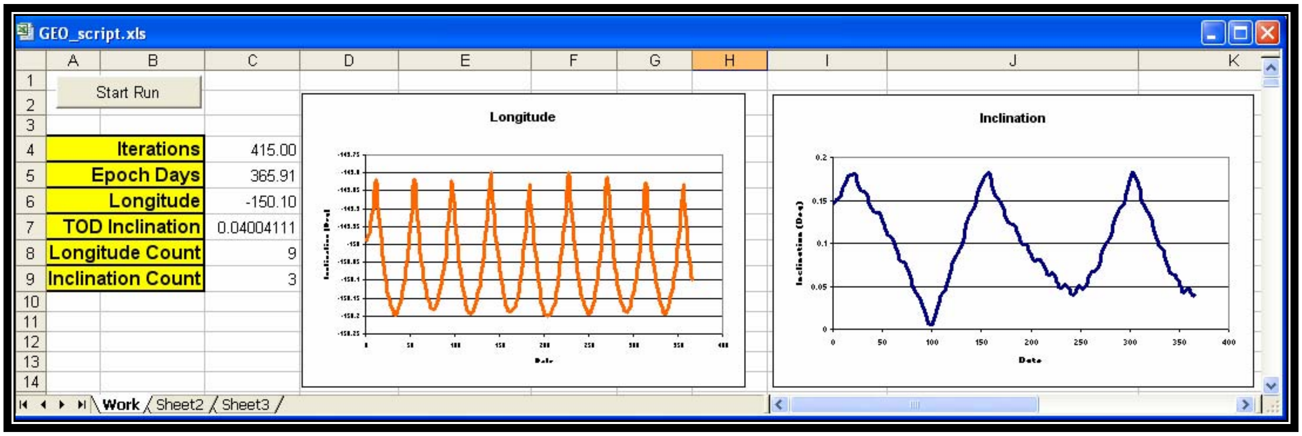
NOTES

30. Note the ‘STOP’ segment at the beginning, a sign that this MCS won’t be run the usual way.

In this case we will run the MCS in ‘single segment’ mode, i.e. each segment will be triggered individually by an external script. Rather than running these segments sequentially in the MCS, we have provided an Excel spreadsheet that executes each of the segments (in this case, sequences and target sequences) and tests at the end of the sequence inside the script, to see if another sequence should be run.

Note that the EW Station Keeping sequence now has both propagate segments after the return. Also note the ‘Prop to Asc Node’ segment. This segment stops on the ascending node. In this case, our script will call that segment repeatedly, each time checking if the EW or NS conditions have been met that require the execution of those scripts.

31. Open the Excel file called ‘GEO Script’



This script uses Visual Basic for Applications (VBA) to run the segments. Using single segment propagation, a script can call and recall any sequence in the MCS to build the ephemeris.

32. Under the Excel tools/macro menu, open the Visual Basic Editor to see the VBA code. You’ll find a loop that calls a propagate segment repeatedly, and then executes other segments based on the logic of the code.

33. With Excel and STK visible, hit the ‘Start Run’ button. You should see the iterations, Epoch days etc.. progressing, and the graphs being updated as the maneuvers are calculated for a year. The ‘Longitude Count’ signifies how many times the EW station keeping has been called, and the ‘Inclination Count’ signifies the amount of times the Inclination adjustment has been necessary.

34. Plot out the polar graph from before, and see that the graphs match.

NOTES

35. Create the Maneuver History report (again using the end time of the 'Phase to 150w' segment) and check it against the GEO_Auto satellite.

You should see slight differences between the two methods, due to the slightly different logic implemented in the single segment script. Ultimately the single segment method is more flexible, as it gives the user the full functionality of the VBA programming language and full if-then-else logic. However, an equally valid answer can be achieved completely within the STK/Astrogator GUI using autosequences.

The scenario we built in this tutorial is included in a folder named 'Final GEO Station Keeping'.

Now that you can stay in GEO, are you ready for induction into the Astrogator's Guild? Maybe.....

Find out more at: www.astrogatorsguild.com

Finally, if you need more help: www.see.com for all of your advanced Astrogator requirements.

NOTES