

# AN EXAMINATION OF COMMON PITFALLS USING STK'S TARGET SEQUENCE

Kyle Kochel \*

August 2017

## Abstract

The Target Sequence (aka the Targeter) in Systems Tool Kit's (STK) Astrogator add-on module is a very powerful tool but requires some know-how by the user. The Targeter can be utilized to solve many complex orbital problems. Using iterative methods, the Targeter modifies the values of selected independent variables in order to obtain a desired solution for a number of dependent variables. The setup of these variables may not always be obvious to the user. Several of the most common pitfalls when trying to achieve a convergent solution will be examined. These cases are as follows: targeting zero eccentricity, targeting zero inclination, targeting zero eccentricity and zero inclination together, and how to properly convert an impulsive burn solution into a finite burn solution. The problem in each of these cases will be established along with brief instructions as to how the problem is set up in STK. After demonstrating the issue, the solution will be examined and a walk-through of the solution provided. The goal of this research was to provide an introductory guide to STK users who may experience issues when using the Targeter. There are many more cases that could be explored, however, they were outside the scope of this research.

---

\*Systems Engineering Intern, Analytical Graphics, Inc.

# Contents

<b>1 Introduction</b>	<b>2</b>
<b>2 Targeting Eccentricity</b>	<b>2</b>
2.1 Targeting Zero Eccentricity with an Impulsive Burn . . . . .	2
2.1.1 Problem and Setup of Orbit . . . . .	2
2.1.2 Solution . . . . .	5
<b>3 Targeting Inclination</b>	<b>6</b>
3.1 Targeting Zero Inclination with an Impulsive Burn . . . . .	6
3.1.1 Problem and Setup of Orbit . . . . .	6
3.1.2 Solution . . . . .	10
3.2 Targeting a Different Inclination with an Impulsive Burn . . . . .	10
3.2.1 Problem and Setup of Orbit . . . . .	10
3.2.2 Solution . . . . .	13
<b>4 Targeting Eccentricity and Inclination Together</b>	<b>14</b>
4.1 Targeting Zero Eccentricity and Zero Inclination with an Impulsive Burn . . . . .	14
4.1.1 Problem and Setup of Orbit . . . . .	14
4.1.2 Solution . . . . .	17
4.2 Targeting Zero Eccentricity and Zero Inclination with a Finite Burn . . . . .	17
4.2.1 Problem and Setup of Orbit . . . . .	17
4.2.2 Solution . . . . .	19
<b>5 Conclusion</b>	<b>21</b>

# 1 Introduction

To an inexperienced user, the Target Sequence (aka the Targeter) within the Astrogator add-on module to Systems Tool Kit (STK) can be tough to understand. The Targeter is a parent segment that allows other segments to be nested inside of it such as maneuvers and propagations. Several profiles can be created to drive the Targeter with the differential corrector being the most common. The differential corrector targets specific values on the nested segments - independent variables - and then iterates these values in order to achieve some specified goal defined by dependent variables with a given tolerance. Currently, the Targeter makes use of the Secant method when iterating these targeted variables in order to find a solution. The Newton Raphson method is also available and in some cases is used as the default when iterating. The Targeter can be a very powerful tool but it requires a proper initial setup by the user. This paper seeks to examine a few of the most common pitfalls that users experience when trying to use the Targeter to obtain a solution.

## 2 Targeting Eccentricity

### 2.1 Targeting Zero Eccentricity with an Impulsive Burn

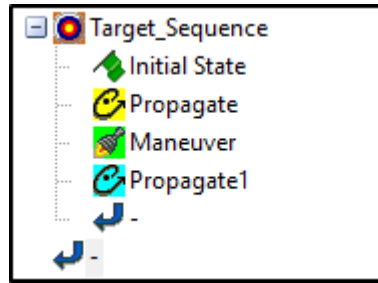
#### 2.1.1 Problem and Setup of Orbit

Achieving zero eccentricity for a satellite orbit is quite a common task, especially when targeting a geostationary orbit. Since eccentricity is not a smooth function users may run into issues converging on a desired solution when they target zero eccentricity alone. Eccentricity is not a smooth function because of the way it approaches zero (or the x-axis) from only the positive side. This is because it is not possible to have negative values of eccentricity. This makes it difficult for the differential corrector inside a Target Sequence to successfully converge on a solution. Currently, the differential corrector makes use of the Secant method. This method works best when the desired solution of a function can be approached from both sides. What often happens in the case of targeting zero eccentricity is that the Targeter jumps back and forth around a number that never quite meets the tolerance criteria specified for the eccentricity.

A common subproblem is that a user may try to circularize their orbit while doing only an in-track burn at a location that does not have a zero flight path angle. This is impossible as there is no way to adjust the direction of the velocity vector if the burn is limited to the direction the velocity vector is already pointed in. The simple solution to this is to make sure that in-track burn maneuvers occur at a location where the flight-path angle is equal to zero such as at periapsis or apoapsis. Another solution would be to burn in any direction rather than just the direction of the velocity vector.

To begin setup of the orbit a default satellite was inserted into STK and its propagator was changed to Astrogator. The default Initial State and Propagate segments were kept in the Mission Control Sequence (MCS). A Target Sequence was inserted at the top of the MCS and the current Initial State and Propagate segments were embedded inside this sequence. Additionally, a Maneuver and another Propagate segment were inserted after the first Propagate segment also within the Target Sequence. Figure 1 below shows the MCS setup. The Initial State's coordinate type was

changed to Keplerian and the following values seen in Table 1 below were inserted for the elements.



**Figure 1:** Setup of MCS

**Table 1:** Keplerian Elements

Periapsis Radius	6678.14 km
Apoapsis Radius	42164 km
Inclination	0 deg
RAAN	0 deg
Arg. of Periapsis	0 deg
True Anomaly	0 deg

The first propagate segment was given a stopping condition of apoapsis and the second propagate segment was given a stopping condition of periapsis. Each of these segments was given a repeat count of 1. The Maneuver segment was setup for a burn along the thrust vector and the satellite's Cartesian X and Z directions were selected to be used as control parameters in the Targeter.

Additionally, the apoapsis radius in the Initial State segment was also set to be used as a control parameter so that the desired conditions would be met once the first orbit propagated to apoapsis. Simply leaving the apoapsis radius set to 42,164 km in the Initial State while not targeting it results in a lower apoapsis radius once the satellite actually reaches apoapsis. This is due to the gravitational effects that the satellite experiences as it propagates out toward apoapsis. The goal is to circularize into an orbit with a radius of 42,164 km so the satellite must be at this value when it reaches apoapsis.

Next, the equality constraints for the Targeter were set. The two constraints used were radius of apoapsis on the first propagate segment and eccentricity on the last propagate segment. The differential corrector was then setup to use the three control parameters mentioned above as well as the two equality constraints. The desired values for the radius of apoapsis and eccentricity equality constraints were set to 42,164 km and 0, respectively. The tolerance on the eccentricity constraint was changed to 1e-05. Figure 2 on the following page shows the differential corrector window.

**Differential Corrector**

Variables | Convergence | Advanced | Log | Graphs | Scripting

☐ Hide Inactive

**Control Parameters**

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	InitialState.Keplerian.ApoapsisRadShape	42164 km	0 km	Initial_State	<input type="checkbox"/>	km
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.XSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.ZSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec

Initial Value: 42164 km Perturbation: 1 km  
Correction: 0 km Max. Step: 1000 km

Scaling  
Method: By initial value  
Value: 0.001 km

**Equality Constraints (Results)**

☐ Hide Inactive

Use	Name	Desired Value	Current Value	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	Radius_Of_Apoapsis	42164 km	-Not Set-	Propagate	<input type="checkbox"/>	km
<input checked="" type="checkbox"/>	Eccentricity	0	-Not Set-	Propagate1	<input type="checkbox"/>	

Difference: 0  
Tolerance: 1e-05

Scaling  
Method: By desired value  
Value: 1 Weight: 1

OK Help

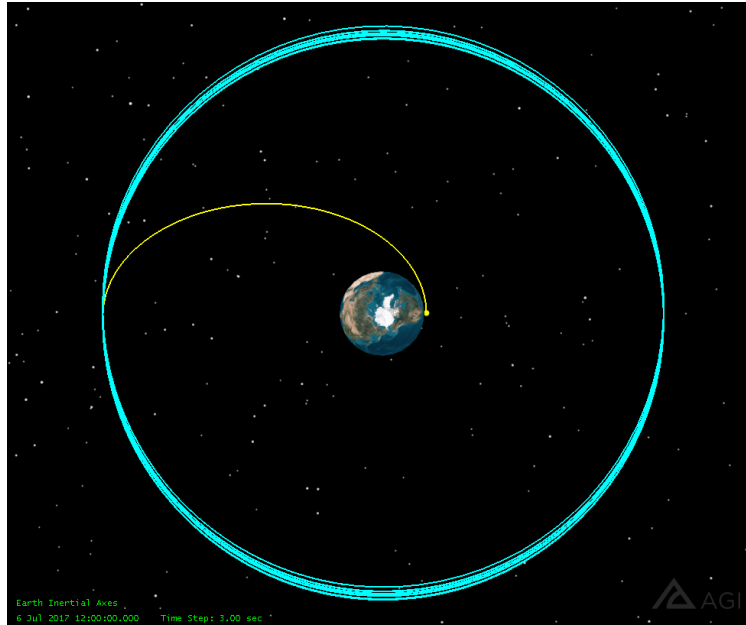
**Figure 2: Differential Corrector Setup**

The MCS was then run and visualized in STK but the Targeter failed to converge. Figure 3 below shows the Targeter's failure to converge on the desired solution. Figure 4 on the following page shows the various attempts at achieving the zero eccentricity GEO orbit.

Target Sequence.Differential Corrector: Finished: \*DID NOT CONVERGE\* in 50 iterations.

Control	New Value	Last Update	Constraint	Desired	Achieved	Difference	Tolerance
Initial_State : InitialState.Keplerian.ApoapsisRadShape	42344.8 km	-2.4097e-11	PropToApo : Radius Of Apoapsis	42164 km	42164 km	-2.9802e-11	0.1 km
Maneuver : ImpulsiveMnvr.Cartesian.XSDU	1474.34 m/sec	5.9543 m/sec	PropToYZ : Eccentricity	0	0.0051912	0.0051913	1e-05
Maneuver : ImpulsiveMnvr.Cartesian.ZSDU	-0.608341 m/sec	2.4174 m/sec					

**Figure 3: Non-converging Target Sequence for Zero Eccentricity**



**Figure 4:** Non-convergent Zero Eccentricity GEO Orbit

Note from the Targeter window in Figure 3 that the best value achieved for eccentricity was 0.0132941 which is well above the tolerance of 0.0001 that was specified. This particular value of eccentricity leaves the orbit with a difference between radius of apoapsis and radius of periapsis of roughly 1,100 km.

### 2.1.2 Solution

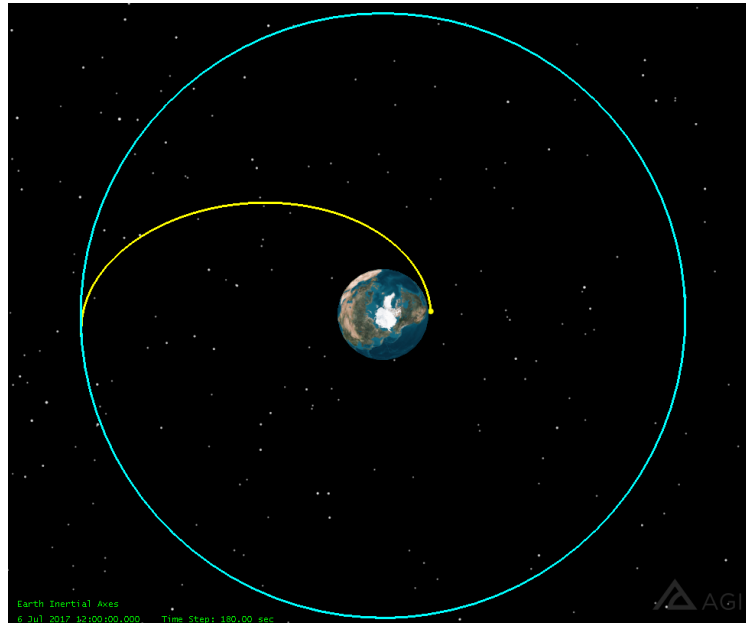
In order to achieve a smaller value for eccentricity within STK a zero flight path angle (FPA) must also be targeted in addition to eccentricity. Theoretically, if an orbit was perfectly circularized the FPA would be equal to zero at every point on the orbit.

Simply adding in zero FPA as an equality constraint in the differential corrector still does not fix the issue however. In its current setup, the Targeter is targeting conditions at periapsis. From orbital mechanics, the FPA is already equal to zero at both the periapse and apoapse of an orbit. Thus, the FPA condition is already achieved and it gives no help in achieving zero eccentricity. Additionally, once the orbit becomes very near circular there is often weird behavior where the periapsis and apoapsis may move around. This can also cause issues when targeting elements at periapsis or apoapsis.

The solution is to target a stopping condition other than periapsis or apoapsis and preferably one that won't move around. For example, true anomaly would not be a good choice because the periapsis vector will move around once the orbit is nearly circular. A much better option is choosing the Y-Z plane crossing. After using a Y-Z plane crossing for the stopping condition the Targeter finally converges on the desired solution as seen in Figure 5. Figure 6 below shows the final converged solution as seen in the 3D window.

Target Sequence.Differential Corrector: Finished: *CONVERGED* in 1 iteration. *Constraints Met*							
Control	New Value	Last Update	Constraint	Desired	Achieved	Difference	Tolerance
Initial_State : InitialState.Keplerian.ApoapsisRadShape	42344.8 km	-2.3265e-10	PropToApo : Radius Of Apoapsis	42164 km	42164 km	9.6858e-11	0.1 km
Maneuver : ImpulsiveMnvr.Cartesian.XSDU	1466.35 m/sec	-0.00015901	PropToYZ : Eccentricity	0	1.2162e-0	1.2162e-08	1e-05
Maneuver : ImpulsiveMnvr.Cartesian.ZSDU	0.222717 m/sec	0.84028 m/se	PropToYZ : Flight Path Angle	0 deg	5.79684e-	5.7968e-09	1e-05 deg

**Figure 5:** Converging Target Sequence for Zero Eccentricity and Zero FPA



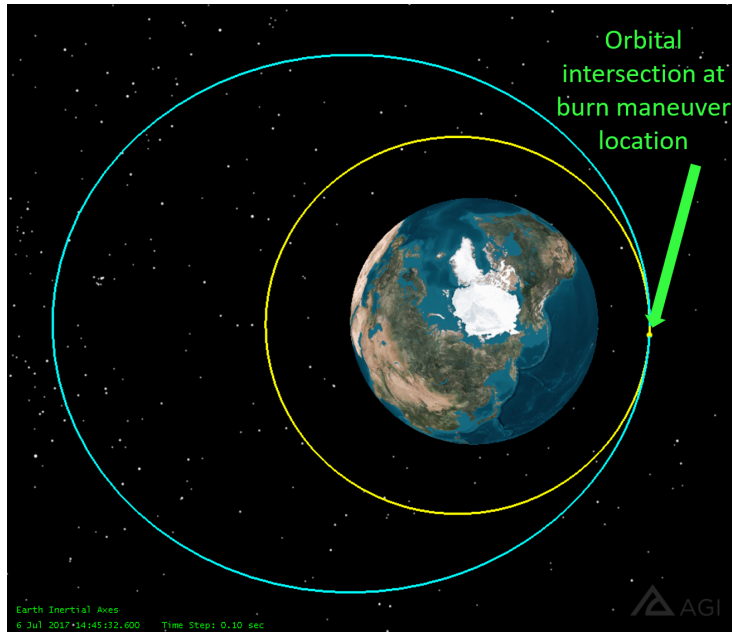
**Figure 6:** Convergent Zero Eccentricity GEO Orbit

### 3 Targeting Inclination

#### 3.1 Targeting Zero Inclination with an Impulsive Burn

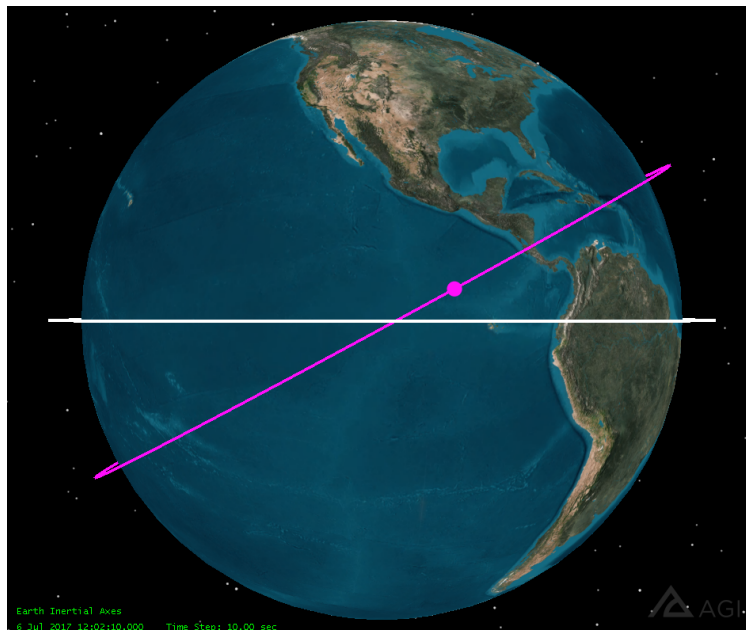
##### 3.1.1 Problem and Setup of Orbit

Like eccentricity, inclination can have its fair share of targeting issues when using it as an equality constraint. One of the most common issues is trying to target zero inclination with a burn maneuver that doesn't occur in the equatorial plane. When a single impulsive maneuver is used the initial and final orbits must intersect at (or very close to) the point that the maneuver was conducted. For a two body problem the final orbit will intersect this point exactly. For a different problem including other gravitational effects the final orbit will be slightly different but very close. This concept can be visualized in Figure 7.



**Figure 7: Orbital Intersection Point**

Thus, if the location of the satellite at the time of the burn maneuver is not within the equatorial plane then it is not possible for the satellite to change into an orbit that completely lies within the equatorial plane and thus have zero inclination. To visualize this take a look at Figure 8 below.



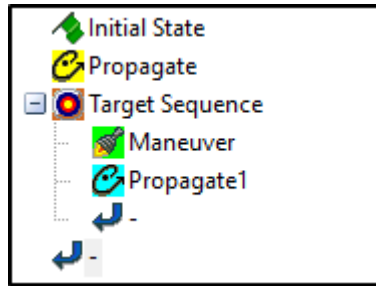
**Figure 8: No Possible Transfer Between Orbits at Highlighted Point**

If the satellite was to do a single burn at the position of the highlighted point on the magenta orbit then it would not be possible for the satellite to transfer to the white equatorial orbit since the white orbit does not pass through the highlighted point. This issue typically happens in Targeter



if the periapsis point of the orbit does not lie in the equatorial plane (e.g. the satellite is in a slightly eccentric orbit with an argument of perigee of 20 degrees) and the user initiates the burn maneuver at periapsis. Periapsis is probably the most well-known place to do a burn maneuver so making this mistake is not a far stretch.

To begin setup of the orbit a default satellite was inserted into STK and then its propagator was changed to Astrogator. The default Initial State and Propagate segments were kept in the MCS. A Target Sequence was inserted after the Propagate segment and then a Maneuver and another Propagate segment were inserted within the Target Sequence. Figure 13 below shows the MCS setup. The Initial State's coordinate type was changed to Keplerian and the following values seen in Table 3 below were inserted for the elements.



**Figure 9:** Setup of MCS

**Table 2:** Keplerian Elements

Semi-major axis	10000 km
Eccentricity	0.2
Inclination	28.5 deg
RAAN	0 deg
Arg. of Periapsis	20 deg
True Anomaly	0 deg

Both of the Propagate segments were setup to have stopping conditions at Periapsis. The first Propagate outside of the Targeter was given a repeat count of 1 while the Propagate1 inside the Targeter was given a repeat count of 2. The Maneuver segment was setup to target the X, Y, and Z directions of the burn.

Then, inclination and semimajor axis were added as equality constraints (Results) from the Propagate1 segment inside the Targeter. Finally, the differential corrector of the Target Sequence was setup to use the Maneuver's Cartesian X, Y, and Z directions as the control parameters and Propagate1's inclination and semimajor axis values as the equality constraints. The desired values for inclination and semimajor axis were inputted as 0 deg and 10000 km and were given tolerances of 0.001 deg and 0.1 km, respectively. The differential corrector setup can be seen in Figure 10 on the following page.

Differential Corrector

Variables
Convergence
Advanced
Log
Graphs
Scripting

☐ Hide Inactive

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.XSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.YSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.ZSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec

Initial Value: 0 m/sec
Perturbation: 0.1 m/sec

Correction: 0 m/sec
Max. Step: 100 m/sec

Scaling
Method: By initial value
Value: 1 m/sec

☐ Hide Inactive

Use	Name	Desired Value	Current Value	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	Inclination	0 deg	-Not Set-	Propagate1	<input type="checkbox"/>	deg
<input checked="" type="checkbox"/>	Semimajor_Axis	10000 km	-Not Set-	Propagate1	<input type="checkbox"/>	km

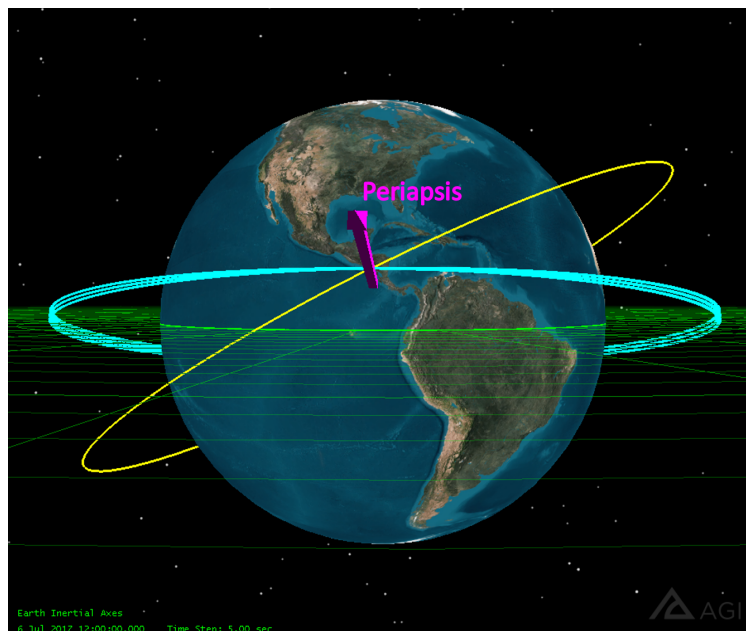
Difference: 0 deg
Tolerance: 0.1 deg

Scaling
Method: By desired value
Value: 1 deg
Weight: 1

OK
Help

**Figure 10: Differential Corrector Setup**

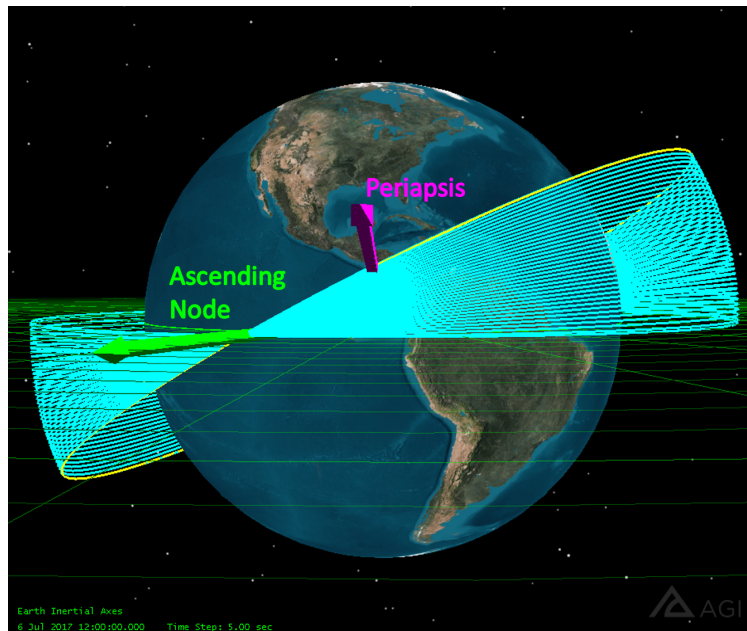
After setting everything up and running the MCS the Targeter did not converge as expected. Figure 11 below shows the attempted solution. Observation of the image shows that the maneuver burn occurs at the periapsis point which does not lie within the equatorial plane due to the satellite's argument of perigee of 20 degrees.



**Figure 11: Non-convergent Zero Inclination Change**

### 3.1.2 Solution

The solution to getting the Targeter to converge for this problem is to simply change the location of the burn maneuver. The reason the burn maneuver currently happens at the periapsis point of the orbit is because the Propagate segment before the Target Sequence was set to end on a stopping condition of periapsis. In order for the burn maneuver to occur in the equatorial plane the stopping condition was changed to ascending node. The ascending node of an orbit is the location where the orbit track passes through the equatorial plane while passing from the southern side of the equatorial plane to the northern side. Ending the Propagate segment at the ascending node will place the satellite very close to the equator. After making this adjustment and rerunning the Targeter the satellite is able to converge on the desired solution as seen in Figure 12 below.



**Figure 12:** Convergent Zero Inclination Change

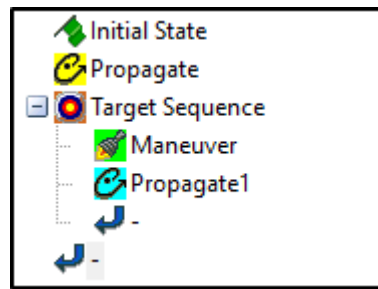
## 3.2 Targeting a Different Inclination with an Impulsive Burn

### 3.2.1 Problem and Setup of Orbit

Though not as common, a user may wish to do a burn maneuver at a location other than the equatorial plane to change their satellite's inclination. This is less common because it is the most fuel efficient to do an inclination change at the ascending node. A possible reason a user may want to avoid burning at the equatorial plane is if they are in a GEO orbit and need to avoid a piece of space debris; the satellite may need to do an emergency burn regardless of the inclination value that it is currently at. Following the same reasoning in the problem of targeting zero inclination (Section 3.1), an issue will occur if a user tries to target a different inclination than the current value while using an unsatisfactory burn location. As mentioned above in Section 3.1.1 the final orbit after a single maneuver must intersect the initial orbit at the location of the impulsive burn maneuver. Therefore, a user will get a non-convergent Target Sequence if they try to change

inclination at an incorrect burn location. It is impossible to change the satellite's inclination to be smaller than it's current latitude. In this example, the initial orbit is setup with some inclination value and some argument of perigee which moves the periapsis point away from the ascending node and thus locates it at a latitude greater than zero. If the burn maneuver is placed at the periapsis point then the satellite should not be able to target an inclination value less than the latitude at periapsis.

To begin setup of the orbit a default satellite was inserted into STK and then its propagator was changed to Astrogator. The default Initial State and Propagate segments were kept in the MCS. A Target Sequence was inserted after the Propagate segment and then a Maneuver and another Propagate segment were inserted within the Target Sequence. Figure 13 below shows the MCS setup. The Initial State's coordinate type was changed to Keplerian and the following values seen in Table 3 below were inserted for the elements.



**Figure 13:** Setup of MCS

**Table 3:** Keplerian Elements

Semi-major axis	10000 km
Eccentricity	0.2
Inclination	28.5 deg
RAAN	0 deg
Arg. of Periapsis	20 deg
True Anomaly	0 deg

Both of the Propagate segments were setup to have stopping conditions at Periapsis. The first Propagate outside of the Targeter was given a repeat count of 1 while the Propagate1 inside the Targeter was given a repeat count of 2. The Maneuver segment was setup to target the X, Y, and Z directions of the burn.

Then, inclination and semimajor axis were added as equality constraints (Results) from the Propagate1 segment inside the Targeter. Finally, the differential corrector of the Target Sequence was setup to use the Maneuver's Cartesian X, Y, and Z directions as the control parameters and Propagate1's inclination and semimajor axis values as the equality constraints. The desired values for inclination and semimajor axis were inputted as 5 deg and 10000 km and were given tolerances of 0.001 deg and 0.1 km, respectively. The differential corrector setup can be seen in Figure 14 on the following page.

The screenshot shows the 'Differential Corrector' window with two main sections: 'Control Parameters' and 'Equality Constraints (Results)'.

**Control Parameters:**

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.XSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.YSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.ZSDU	0 m/sec	0 m/sec	Maneuver	<input type="checkbox"/>	m/sec

Initial Value: 0 m/sec    Perturbation: 0.1 m/sec    Scaling Method: By initial value    Value: 1 m/sec

Correction: 0 m/sec    Max. Step: 100 m/sec

**Equality Constraints (Results):**

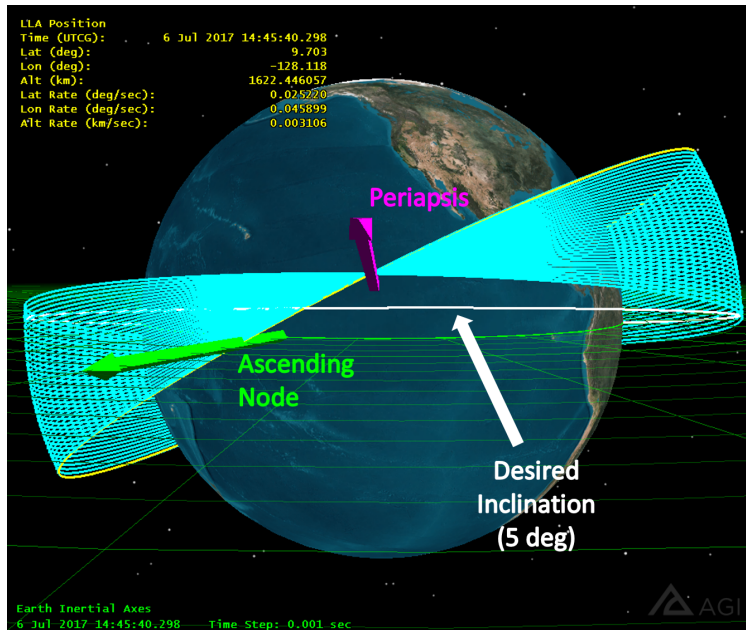
Use	Name	Desired Value	Current Value	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	Inclination	5 deg	-Not Set-	Propagate	<input type="checkbox"/>	deg
<input checked="" type="checkbox"/>	Semimajor_Axis	10000 km	-Not Set-	Propagate	<input type="checkbox"/>	km

Difference: -5 deg    Tolerance: 0.1 deg    Scaling Method: By desired value    Value: 1 deg    Weight: 1

Buttons: OK, Help

**Figure 14: Differential Corrector Setup**

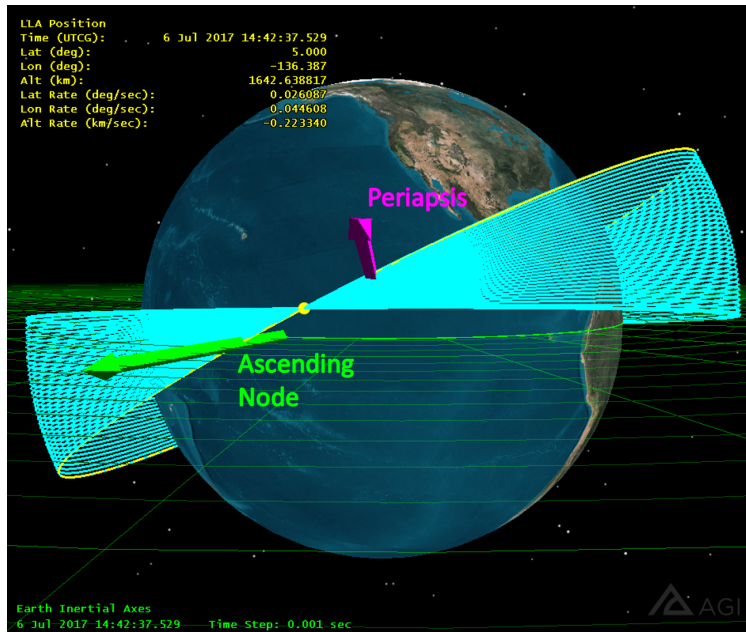
After setup was complete the MCS was run in order to show that the Targeter would not converge on the desired solution of achieving a 5 degree inclination. Figure 15 on the following page shows the Targeter's attempted solution. The yellow shows the initial orbit, the light blue shows the Targeter's iterated orbits, and the white shows the desired orbit. Observation of the image shows that the periapsis point does not lie within the white orbit and thus it is impossible to do a burn maneuver at the periapsis point to achieve the white orbit. Looking closely at the Lat value in the upper left corner shows that the latitude of the periapsis point is 9.703 deg. We can also tell that this orbit is unachievable since this value of latitude is higher than our desired inclination value.



**Figure 15: Non-convergent Inclination Change**

### 3.2.2 Solution

The solution to this problem, like the other inclination problem, is to simply modify where the burn maneuver occurs. Again, this example seeks to demonstrate doing an inclination change while burning somewhere else other than at the ascending node. A potential solution is to complete the burn maneuver at the exact latitude of the desired inclination though any latitude value between zero degrees and the final inclination value could be set as the stopping condition. This solution was setup by adding and setting a User Select stopping condition to the Propagate segment outside of the Target Sequence. The User Select option allows you to stop on a specified calculation object which in this case was chosen to be latitude. The Trip value was set to 5 deg and the Criterion was set to Cross Increasing to ensure that the satellite burned at the desired latitude while heading northward. The Targeter was then rerun and a converged solution was found. This solution can be seen in Figure 16 on the following page. Notice that at the time just before the maneuver the satellite was located at a latitude of 5 deg as listed in the data display in the upper left corner.



**Figure 16:** Convergent Inclination Change

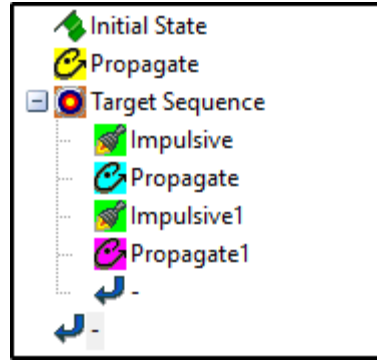
## 4 Targeting Eccentricity and Inclination Together

### 4.1 Targeting Zero Eccentricity and Zero Inclination with an Impulsive Burn

#### 4.1.1 Problem and Setup of Orbit

The topics of targeting zero eccentricity and zero inclination have been visited above in sections 2 and 3, respectively. Applying a combination of both of those solutions however still does not provide a convergent Target Sequence when targeting both eccentricity and inclination at the same time. Again, both eccentricity and inclination are not smooth functions which makes it difficult for the differential corrector to find the desired solution.

The example MCS that will be used to demonstrate this issue will first set up a parking orbit, then do an impulsive burn to reach a Geostationary radius (42,165 km is used), and then finally do another impulsive burn in order to both circularize the orbit and change its inclination to zero degrees once it hits the equatorial plane. Figure 17 on the following page shows the setup of the MCS for this particular example and Table 4 lists the Keplerian elements for the initial parking orbit.



**Figure 17:** Setup of MCS

**Table 4:** Keplerian Elements

Semi-major Axis	6600 km
Eccentricity	0
Inclination	10 deg
RAAN	0 deg
Arg. of Periapsis	0 deg
True Anomaly	0 deg

The first propagate segment before the Target Sequence was given a stopping condition of the descending node crossing. This makes sure that the first impulsive burn lies within the equatorial plane. The first propagate segment inside the Target Sequence was given a stopping condition of the ascending node crossing. This makes sure that the second impulsive burn also occurs in the equatorial plane since we know we must burn there to achieve a zero inclination (See Section 3.1). The second propagate segment within the Targeter was given a stopping condition of the Y-Z plane cross with a repeat count of 1. This will help visualize the solutions to the iterated orbits when the Targeter is run.

Two differential correctors were used for this scenario. The first corrector, given the name 'Target R Mag', used the X direction of the first impulsive burn as a control in order to target an R Mag of 42,165 km as the equality constraint. All of the defaults were kept for this corrector. The second corrector, given the name 'Zero Ecc and Inc', used the X, Y, and Z directions as controls in order to target zero eccentricity and zero inclination as a constraint. Eccentricity was given a tolerance of 1e-05 and inclination was given a tolerance of 0.001 deg. The setup of this differential corrector can be seen in Figure 18 on the following page.



Zero Ecc and Inc

Variables Convergence Advanced Log Graphs Scripting

Control Parameters ☐ Hide Inactive

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	ImpulsiveMnvr.Cartesian.XSDU	0 m/sec	0 m/sec	Impulsive	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.XSDU	0 m/sec	0 m/sec	Impulsive1	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.YSDU	0 m/sec	0 m/sec	Impulsive1	<input type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.ZSDU	0 m/sec	0 m/sec	Impulsive1	<input type="checkbox"/>	m/sec

Initial Value: 0 m/sec Perturbation: 0.1 m/sec  
Correction: 0 m/sec Max. Step: 100 m/sec

Scaling  
Method: By initial value  
Value: 1 m/sec

Equality Constraints (Results) ☐ Hide Inactive

Use	Name	Desired Value	Current Value	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	R_Mag	0 km	42165 km	Propagate	<input type="checkbox"/>	km
<input checked="" type="checkbox"/>	Eccentricity	0	0.0196027	Impulsive1	<input type="checkbox"/>	
<input checked="" type="checkbox"/>	Inclination	0 deg	2.29517e-05 deg	Impulsive1	<input type="checkbox"/>	deg

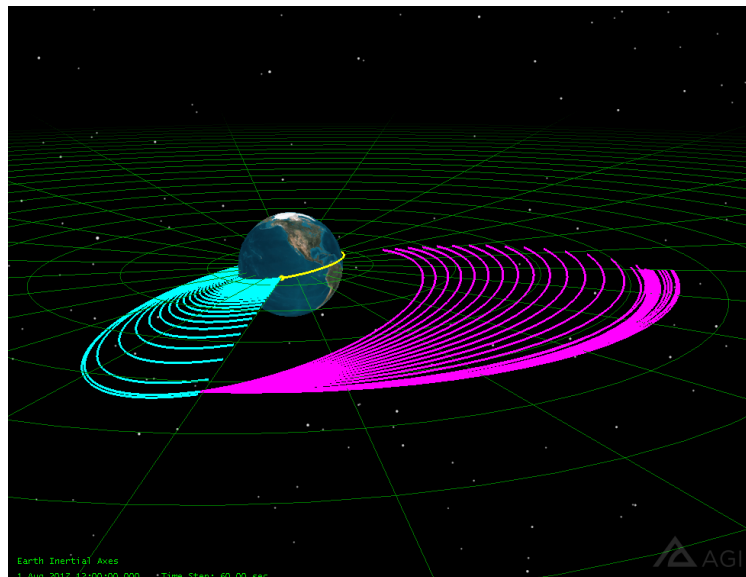
Difference: 0.0196027  
Tolerance: 1e-05

Scaling  
Method: By desired value  
Value: 1 Weight: 1

OK Help

**Figure 18: Differential Corrector Setup**

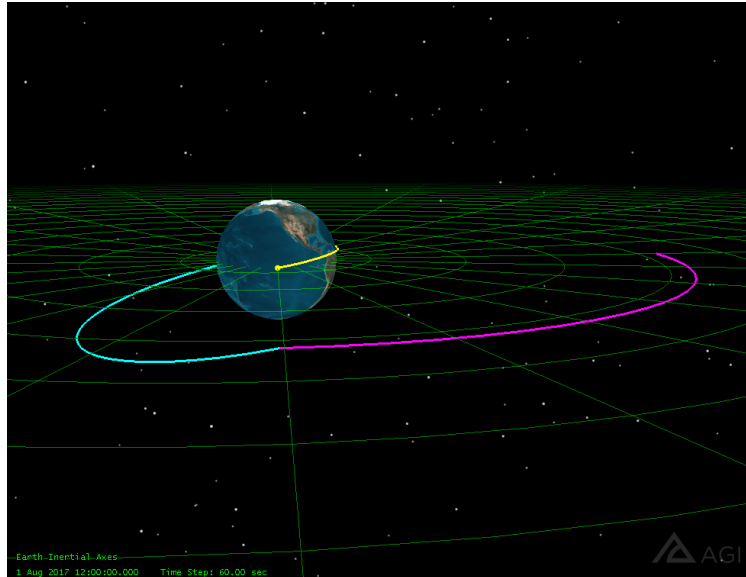
The MCS was then run but the Targeter failed to converge as expected. Figure 19 below shows the attempted solution as seen in STK. The differential corrector was able to get the inclination value within the set tolerance but not the eccentricity.



**Figure 19: Non-convergent Zero Eccentricity and Zero Inclination Change**

### 4.1.2 Solution

The solution to this issue is to add flight-path angle as an additional constraint in order to help the differential corrector achieve convergence. From orbital mechanics, if an orbit is circular then the flight-path angle will be equal to zero degrees at every point on the orbit. A flight-path angle constraint is therefore used to help drive the eccentricity to zero in particular. This constraint was given a tolerance of  $1e-05$ . Figure 20 below shows the successful convergence of the differential corrector to both circularize and reduce the orbit's inclination to zero as the satellite crosses the equatorial plane.



**Figure 20:** Convergent Zero Eccentricity and Zero Inclination Change

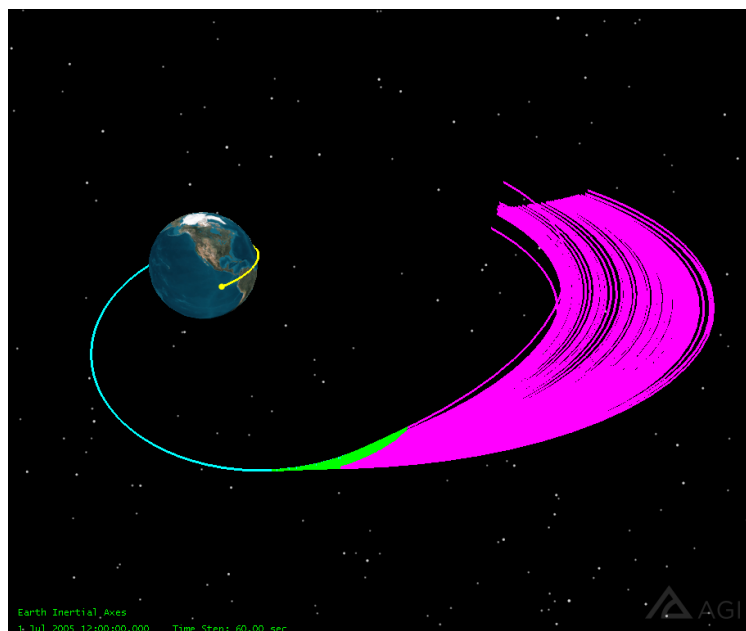
## 4.2 Targeting Zero Eccentricity and Zero Inclination with a Finite Burn

### 4.2.1 Problem and Setup of Orbit

Many users may be interested in modeling a finite burn in Astrogator rather than an impulsive burn. Realistically, it is impossible to do a large instantaneous burn to modify an orbit; therefore, a finite burn will be a closer approximation in reality. The first step to creating a finite burn in Astrogator is to obtain a solution for an impulsive burn. This solution is then seeded into a finite burn to provide a good initial guess for both the burn direction as well as the burn duration. This process is fairly straightforward. The difficulty that users face when targeting conditions for a finite burn is that more controls and constraints need to be added to the differential corrector in order for it to converge. These additional parameters may not be obvious to the user.

For example, when targeting zero eccentricity and zero inclination using the X, Y, and Z directions of the burn as controls and using eccentricity, flight-path angle, and inclination as the constraints will not produce a convergent solution. This is a solution when using an impulsive burn as seen in Section 4.1.2 but it does not work for the case of using a finite burn.

For the setup of this non-convergent orbit the steps outlined in Section 4.1.1 were followed while additionally adding in zero flight-path angle as a constraint on the second impulsive maneuver. The Targeter was run and was able to successfully converge on the same solution seen in Section 4.1.2. The Apply Changes button on the Target Sequence was then clicked in order to update both of the impulsive burns with the values obtained in the solution. Next, the Seed Finite From Impulsive button was clicked on the second impulsive burn in order to seed the impulsive solution into a finite burn (only the second burn was changed to a finite in this example). Immediately trying to run the MCS again resulted in a non-convergence because no differential corrector was added to use the controls for a finite burn. The next step was to create this differential corrector and add in some controls. In the Target Sequence the two previous differential correctors were set to 'Not Active' and a new differential corrector was created and given the name 'Final'. On the finite burn segment Attitude Tab the Attitude Update was changed to Inertial at Start, Spherical was selected instead of Cartesian, and both Azimuth and Elevation were set as controls by clicking the target icon. On the finite burn's propagator tab Trip Value was also set as a control. The Final differential corrector was then updated to include using the finite burn's spherical Az/El directions and the finite burn's duration trip value as controls. For both the Az and El controls the perturbation value was set to 1 deg and the max step was set to 10 deg. For the finite burn duration trip value the perturbation was set to 1 sec and the max step was set to 10 sec. Zero eccentricity, flight-path angle, and inclination were all added as constraints and given the same tolerances seen in the 'Zero Ecc and Inc' differential corrector. To account for a more involved problem the number of iterations in the 'Final' differential corrector was changed to 150. The MCS was re-run. At this point the user may expect a successful convergence but Figure 21 below shows that a non-convergent solution is obtained.



**Figure 21:** Non-convergent Zero Eccentricity and Zero Inclination Change Using a Finite Burn

In this particular case the differential corrector did not converge due to the controls and constraints that it was given. Additionally, if a user decides to keep track of their spacecraft's mass throughout the mission then another issue that users may run into is running out of fuel or having unrealistic

burn times for their finite maneuver. The differential corrector will not converge and will limit itself from iterating to a solution that will cause the spacecraft to use all of its fuel. Users should note that currently the differential corrector will simply say "Did Not Converge" rather than specifying that the spacecraft ran out of fuel. It is up to the user to inspect a Summary report on their maneuver to see if it causes the spacecraft to exhaust its fuel. The additional topics of modifying the spacecraft's mass and changing its engine model to lower the burn duration will be visited in the next subsection.

#### 4.2.2 Solution

The solution demonstrated in this case will examine the missing controls and constraints for the differential corrector and will also account for the situation where a user wishes to modify mass and engine properties for their mission. To start, the 'Final' differential corrector was set to 'Not Active' and the first two differential correctors were set back to 'Iterate'. The finite maneuver was also changed back to an impulsive maneuver. Additionally, the X, Y, and Z values for both of the maneuver were set back to zero in order to erase the previous solution. Since the mass and engine properties were going to be modified, the impulsive solutions had to be re-solved using the new properties. The next step was to change the dry mass and fuel mass of the spacecraft to better reflect the intended mission. On the Initial State segment in the MCS, the dry mass was changed to 1,500 kg within the Spacecraft Parameters tab and both the fuel mass and maximum fuel mass values were changed to 7,000 kg within the Fuel Tank tab. The MCS was then re-run in order to update the segments so that they accounted for the change in mass.

One of the great features in Astrogator is the ability to run a Summary report on any of the segments within the MCS in order to view detailed information relative to the segment. When running a Summary report on an impulsive maneuver there is a section that lists the estimated equivalent finite burn duration as well as the estimated fuel used. Running the Summary report on the first impulsive maneuver inside the Targeter revealed the following information seen in Figure 22:

Estimated Equivalent Finite Burn Duration: 28235.2 sec
Estimated Fuel Used: 4798.65 kg (Update mass OFF)

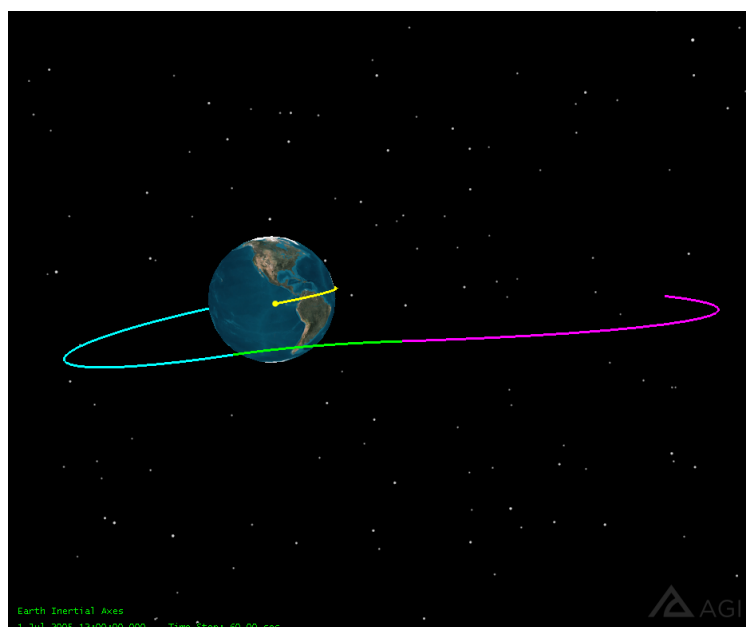
**Figure 22:** Estimated Burn Duration and Estimated Fuel Usage

Examination of the above figure showed that with the current setup of the spacecraft, a finite burn duration of 28,235.2 seconds was estimated. This is quite high and not very realistic for a chemical engine. In order to bring this time down the engine properties for both of the maneuvers were modified. First, the Component Browser was opened from within Astrogator and the Engine Models folder was selected. The Constant Thrust and Isp model was selected and then the Duplicate button was clicked to create a copy of this model. The model was given the name 'Solid Thrust and Isp'. The model was then double-clicked to bring up its properties. The thrust field was changed to 20,000 lbf and the Isp was changed to 280 sec to better model an engine capable of transferring the spacecraft from a LEO to a GEO. Another copy of the Constant Thrust and Isp model was made and was given the name 'Solid Thrust and Isp V2'. This engine was given a thrust of 1,000 N and an Isp of 300 sec to better model the intended finite burn into a circularized, zero inclination orbit at geostationary radius. Both of these engines were then applied to their respective maneuvers by changing the model on the Engine tab of the maneuver. Also on the Engine tab,

the Update Mass Based on Fuel Usage option was checked for both of the maneuvers. The MCS was re-run and converged right away. The Summary report was run again on the first maneuver and the estimated finite burn duration was reduced down to 154.681 sec.

Now that a solution was obtained using impulsive maneuvers with the modified spacecraft properties, a finite burn could properly be set up. First, the Apply Changes button on the Target Sequence was clicked to update both of the burn maneuvers with the solved values. The first two differential correctors were set back to 'Not Active' and the last one was set back to 'Iterate'. The second maneuver was also seeded back into a finite maneuver again using the Seed Finite From Impulsive button. Next, the additional controls and constraints were added in order to successfully achieve convergence.

The Az/EI direction of the finite maneuver and the finite maneuver burn duration were already selected as controls. One more control that was necessary was to control the starting location of the finite burn. This was done by adding and changing to a True Anomaly stopping condition on the first propagate segment within the Targeter. The trip value was set to 170 deg as an initial guess and the target icon was selected to use this condition as a control. As far as constraints, latitude and velocity azimuth were added as constraints on the finite burn maneuver by using the Results... button as before. Latitude helped target the end of the finite burn so that it ended in the equatorial plane. Velocity azimuth was added because it was used to target zero inclination rather than using inclination itself. This is because the inclination function is heavily dependent upon latitude and using both as constraints at the same time prevents the differential corrector from converging. The next step was to setup these parameters in the 'Final' differential corrector. The true anomaly control was selected and was given a perturbation value and max step value of 1 deg and 10 deg, respectively. The latitude constraint was set to 0 deg and given a tolerance of 0.01 deg. Inclination was removed and velocity azimuth was added and set to 90 deg with a tolerance of 0.001 deg. The MCS was run one more time and was able to successfully converge. Figure 23 below shows this convergence.



**Figure 23:** Convergent Zero Eccentricity and Zero Inclination Change Using a Finite Burn

## 5 Conclusion

There are many more cases where a user may have issues with the Targeter but some of the most common ones have been examined here. Additionally, there are more solutions to some of these common cases that could be explored with further research. One example would be to target mean elements rather than the osculating elements. Especially in the case of osculating eccentricity, the function can produce shallow, high frequency slopes near zero which make it difficult for the Targeter to find the desired solution. Using mean eccentricity may provide a more stable and predictable function that allows the Targeter to converge more easily. A solution could be obtained using mean elements which could then be used to seed the Targeter before iterating for a solution using osculating elements. This likely isn't necessary for the common case of targeting eccentricity alone but may prove beneficial when dealing with more advanced problems.