

Trajectories Design

SPACE
INFORMATICS

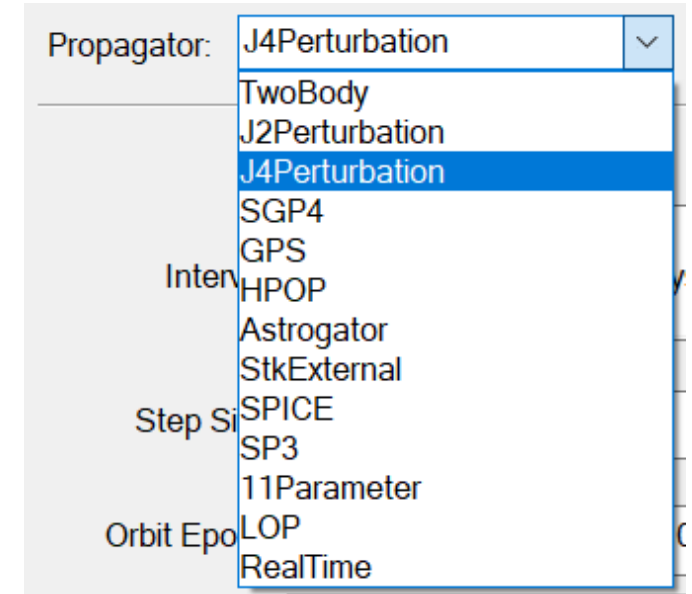
Propagators

Types of Propagators

- Propagators on STK
 - **Two Body:** Analytical
 - **J2/J4 Perturbation:** Analytical
 - **SGP4:** Analytical (TLE)
 - **GPS:** Two-Body propagator
 - **11Parameter:** GEO propagation
 - **LOP:** Long-Term orbit
 - **HPOP:** High-Precision Propagator
 - **External:** From ephemeris file
 - **SPICE:** From SPICE toolkit (JPL)
 - **SP3:** From NGS file
 - **Real Time:** From feed of telemetry

Fixed
orbit
type

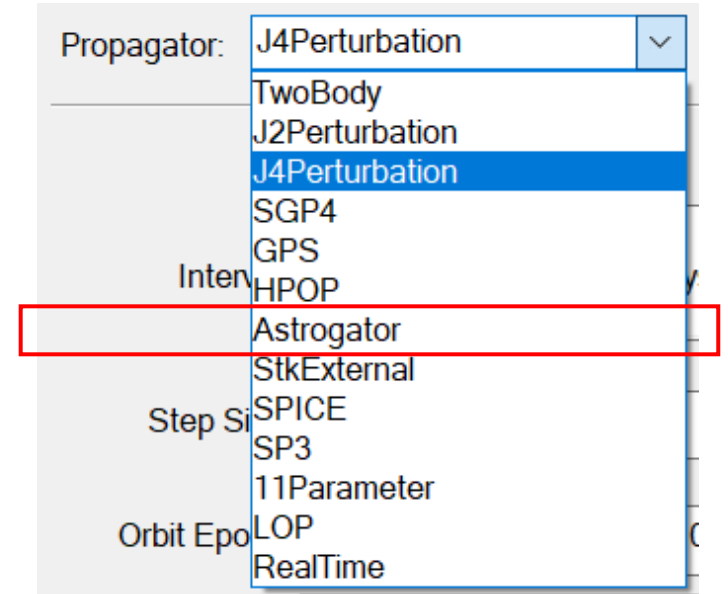
External
input



Astrogator

Introduction

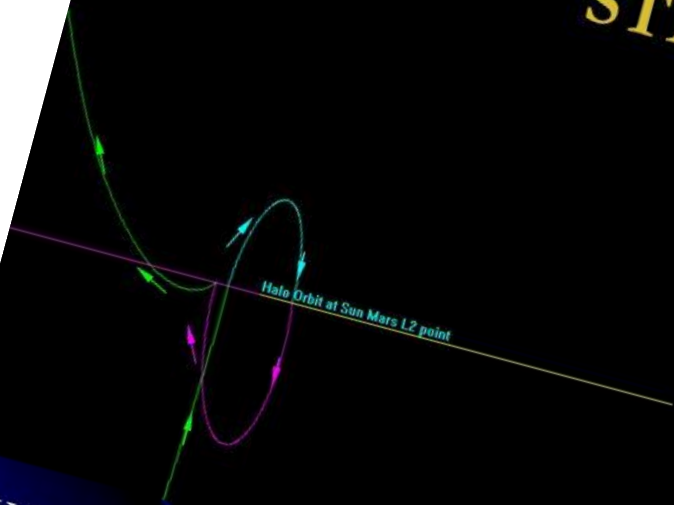
- Astrogator
 - Interactive orbit maneuver and trajectory design
 - **Events** for modeling and targeting trajectories
 - **Impulsive** and **finite** burns
 - High-fidelity orbit **propagation**
 - **Target** specified and optimized orbit states



Astro

Introdu

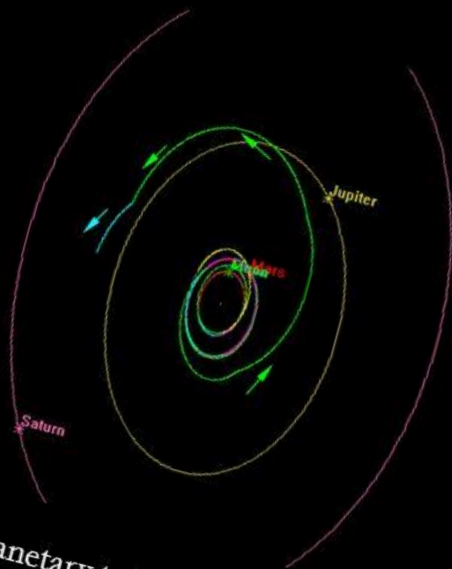
Halo Orbit Targeting methods using STK/Astrogator



Halo Orbit around Sun-Mars L2 Lagrangian point in Sun-Mars rotating frame of reference as seen in X - Y plane



Interplanetary trajectory from Sun-Mars L2 to Sun-Jupiter L2 in Sun-centered inertial frame of reference as seen in X - Y plane

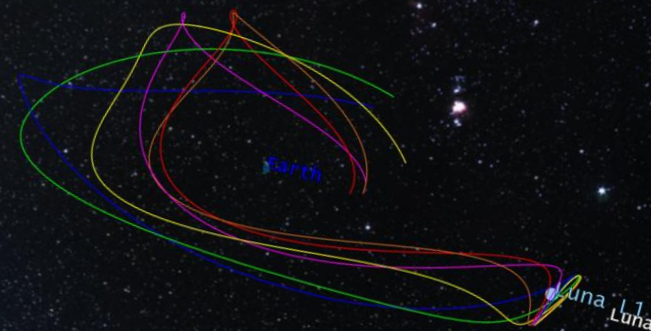


15th AAS/AIAA Space Flight Mechanics Meeting, Copper Mountain, Colorado

Не удаётся отобразить...

LEVERAGING CIS-LUNAR EXPERIENCE

Parameter



Astrogator

Mission Control Sequence

- **Mission Control Sequence**
 - Defines the **trajectory** as a **sequence** of events a.k.a. “segments”
 - Functions as a **graphical programming** language
 - Each segment dictates how Astrogator calculates the trajectory before passing the spacecraft’s state on the next segment

Astrogator

Mission Control Sequence

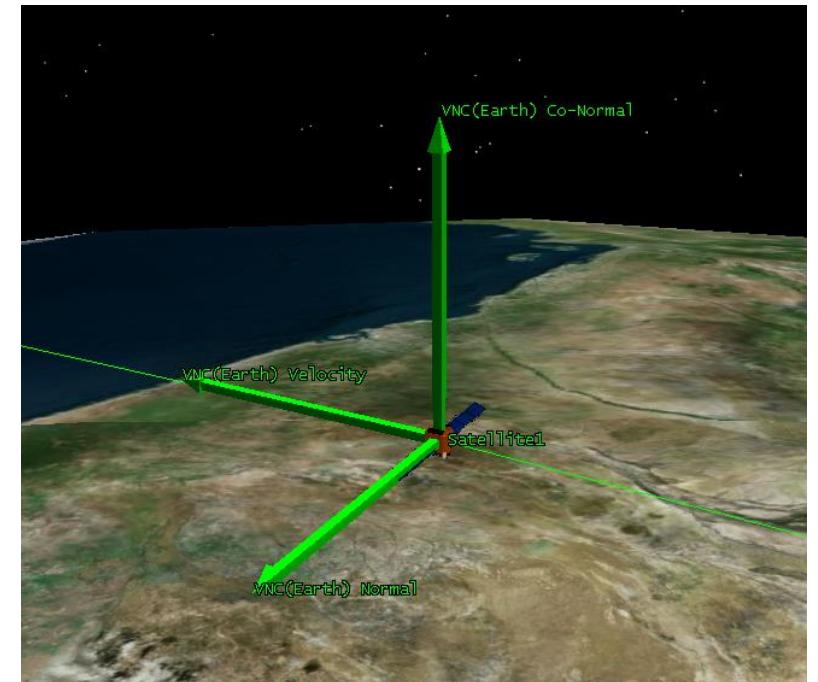
- Mission Control Sequence Segments
 - **Initial State** (📍) – This segment can be used to define the initial conditions of your MCS or a subsequence within the MCS.
 - **Launch** (🚀) – This segment can be used to model a simple spacecraft launch from Earth or another central body.
 - **Follow** (👁️) – This segment can set the spacecraft to follow another vehicle and separate from that vehicle upon meeting specified conditions.
 - **Maneuver** (🎯) – This segment can be used to model a spacecraft maneuver.
 - **Propagate** (🌀) – This segment can be used to model the movement of the spacecraft along its current trajectory until meeting specified stopping conditions

Astrogator

Mission Control Sequence - Maneuver 

■ Maneuver Attitude Control.

- **Along Velocity Vector:** Attitude is such that the delta-V vector is aligned with the spacecraft's inertial velocity vector.
- **Anti-Velocity Vector:** Attitude is such that the delta-V vector is opposite to the spacecraft's inertial velocity vector.
- **Attitude:** Attitude is defined using Euler Angles or a Quaternion.
- **File:** Import an attitude file to set the maneuver.
- **Thrust Vector:** The total delta-V can be specified in cartesian or spherical form with respect to the thrust axes.
 - **VNC** = Velocity, Normal, Co-Normal



Astrogator

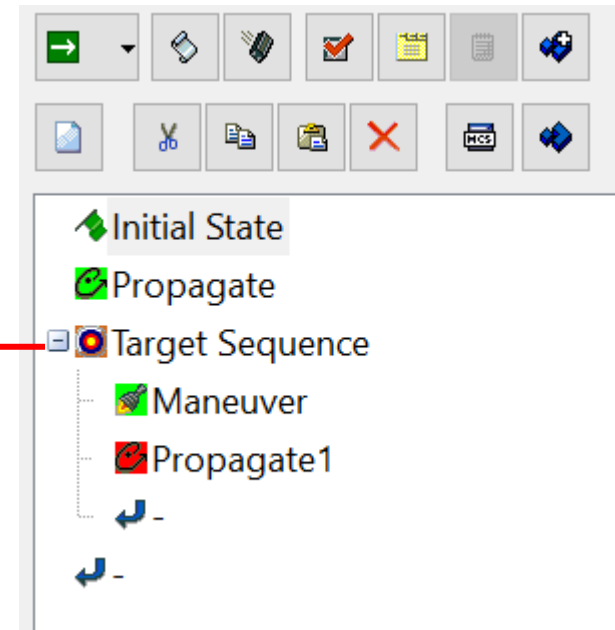
Target Sequences

- **Target Sequences** are used to
 - Calculate and define the required maneuver characteristics...
 - **to meet specified or search for optimal mission parameters.**

A target sequence runs the **segments nested within it**

Applies **profiles** to the run according to its configuration.

Like a “for” loop in a programming language



Astrogator

Target Sequences – Control Parameters

To define **control parameters** configuration fields from elements within a target sequence can be selected and enabled

The screenshot shows the Astrogator software interface. On the left, a tree view shows a hierarchy: 'Initial State' (green arrow), 'Propagate' (green checkmark), 'Target Sequence' (blue circle), 'Maneuver' (green checkmark, highlighted with a blue box), and 'Propagate1' (red checkmark). Below the tree is a 'Results...' button. On the right, the 'Maneuver Type' is set to 'Impulsive' with a dropdown arrow. Next to it is a button 'Seed Finite From Impulsive'. Below these are two tabs: 'Attitude' and 'Engine'. The 'Engine' tab is selected. Under the 'Engine' tab, 'Attitude Control' is set to 'Along Velocity Vector' with a dropdown arrow, and there is a 'More Options...' button. Below this, 'Delta V Magnitude' is set to '1000 m/sec' in a text box with a unit icon. At the bottom, 'Initial:' and 'Final:' are both set to '1 Jan 2019 11:30:22.941 UTCG' with unit icons. A red line connects the 'Maneuver' element in the tree to the 'Delta V Magnitude' field. Another red line connects the 'Delta V Magnitude' field to the text on the right.

These are the **independent variables**... what we allow the target sequence to **change**.

The configured value is taken as **initial search value**... it is important to help with a good guess!

Astrogator

Target Sequences – Control Parameters

To define **control parameters** configuration fields from elements within a target sequence can be selected and enabled



Maneuver Type: Seed Finite From Impulsive

Attitude

Attitude Control: More Options...

Delta V Magnitude:

Initial: Final:

Results...

We can select as many control parameters as we want... but that is the processing price we will pay

These are the **independent variables**... what we allow the target sequence to **change**.

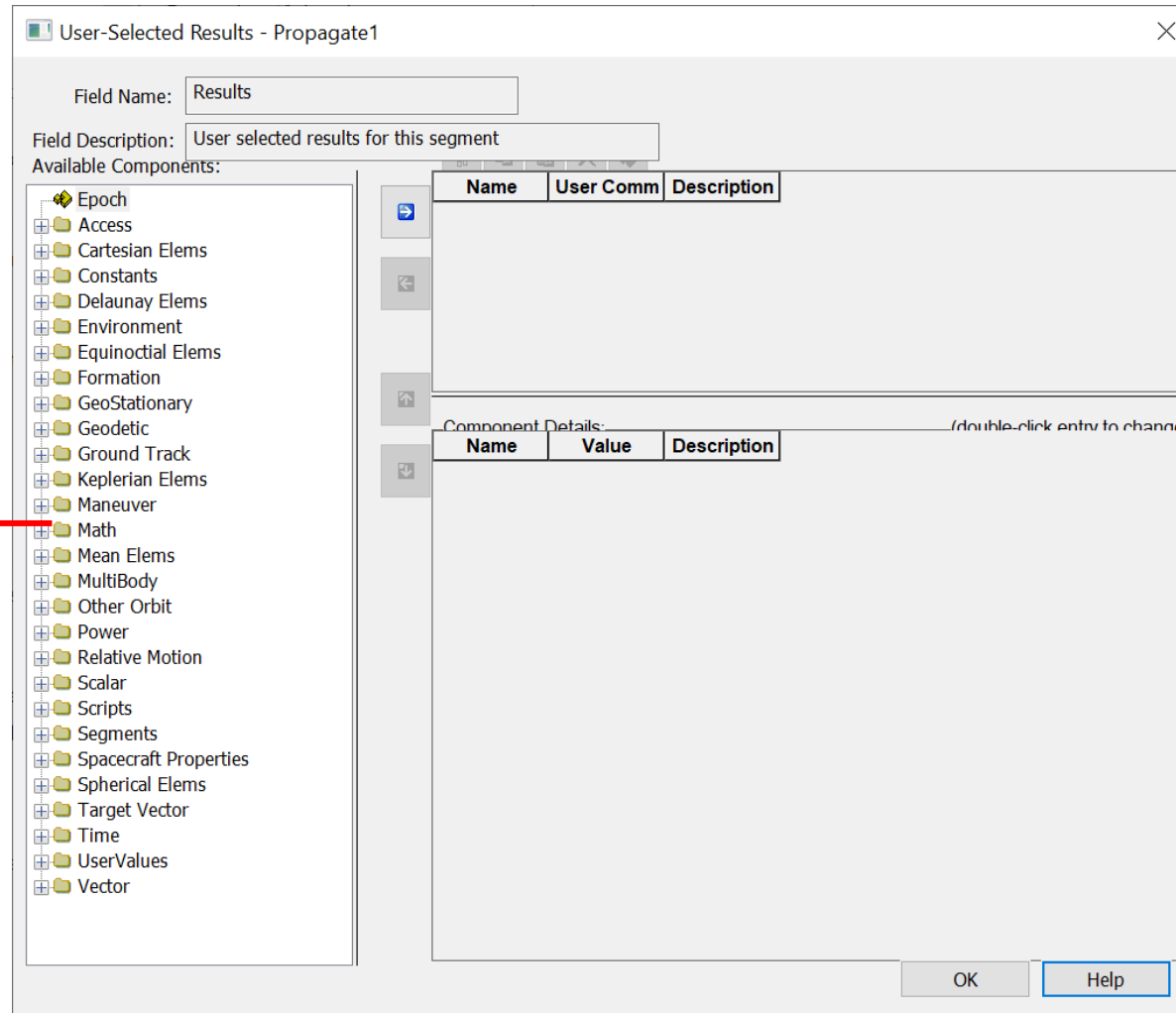
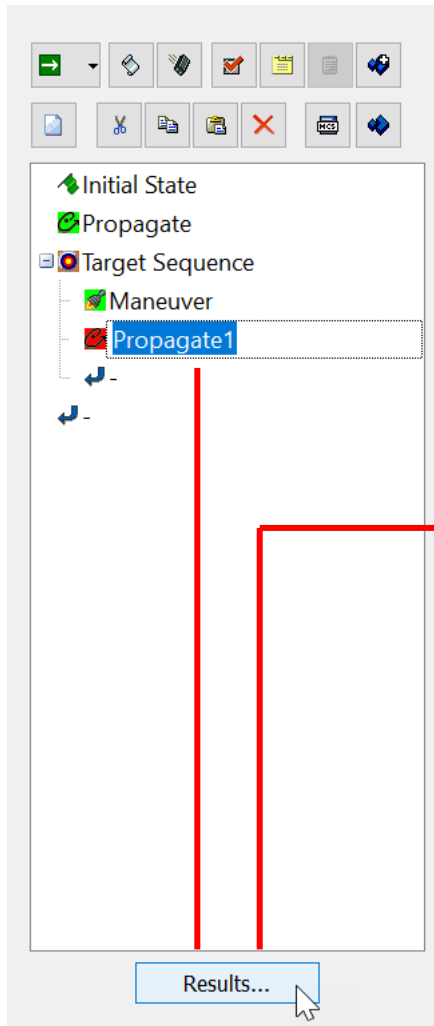
The configured value is taken as **initial search value**... it is important to help with a good guess!

Astrogator

Target Sequences – Results

To define the target sequence objective:

- 1) Select the segment where the objective is expected to happen
- 2) Open “Results” menu on the bottom



Multi-component select window

This are our **dependent variables**.

Astrogator

Target Sequences – Results

To define the target sequence objective:

- 1) Select the segment where the objective is expected to happen
- 2) Open “Results” menu on the bottom

Field Name: Results

Field Description: User selected results for this segment

Available Components:

Name	User Comm	Description
Environment		
Equinoctial Elms		
Formation		
GeoStationary		
Geodetic		
Ground Track		
Keplerian Elms		
Altitude Of Apoapsis		
Altitude Of Periapsis		
Argument of Latitude		
Argument of Periapsis		
Eccentric Anomaly		
Eccentricity		
Inclination		
Longitude Of Ascending Node		
Mean Motion		
Mean Anomaly		
Orbit Period		
RAAN		
Radius Of Apoapsis		
Radius Of Periapsis		
Semimajor Axis		
Time Past Asc Node		
Time Past Periapsis		
True Anomaly		
Maneuver		
Math		
Mean Elms		
MultiBody		

Component Details: (double-click entry to change)

Name	Value	Description
------	-------	-------------

Results...

OK Help

Multi-component select window

- Keplerian elements should be familiar

Select elements which corresponds to our target objective and close.

This are our **dependent variables**.

Astrogator

Target Sequences – Profiles

To define the target sequence behavior a **profile** need to be defined.

Select the target sequence segment and configure it

The screenshot displays the 'Target Sequences – Profiles' configuration window in the Astrogator software. The interface is divided into two main panes. The left pane shows a hierarchical tree view of the target sequence segments: 'Initial State', 'Propagate', 'Target Sequence', 'Maneuver', and 'Propagate1'. The 'Target Sequence' segment is selected, and a red line points to it from the text 'Select the target sequence segment and configure it'. The right pane shows the configuration options for the selected profile. At the top, there are dropdown menus for 'Action: Run nominal sequence' and 'When Profiles Converge: Run to RETURN and continue'. Below these are checkboxes for 'Continue if profiles don't converge' and 'Reset inner targeters before each run'. A 'Profiles and Corrections' section contains 'Apply Changes' and 'Reset' buttons. The 'Profiles' section features a table with columns: Name, Reset, Apply, Mode, Status, and User Comment. The 'Differential Corrector' profile is highlighted in the table. At the bottom, there is an 'Enable Logging' checkbox and 'Initial: -Not Set-' and 'Final: -Not Set-' fields.

Initial: -Not Set- Final: -Not Set-

Astrogator

Target Sequences – Profiles

To define the target sequence behavior a **profile** need to be defined.

Select the target sequence segment and configure it

The screenshot displays the Astrogator software interface for configuring target sequences and profiles. On the left, a tree view shows the sequence structure: Initial State, Propagate, Target Sequence, Maneuver, and Propagate1. The 'Target Sequence' segment is selected. On the right, the 'Profiles and Corrections' panel is active. It features a dropdown menu for 'Action' with options: 'Run nominal sequence', 'Run active profiles', 'Run active profiles ONCE', and 'Run nominal sequence'. Below this, there are checkboxes for 'Continue if profiles don't converge' and 'Reset inner targeters before each run'. A table lists the profiles, with 'Differential Corrector' selected. The table has columns for Name, Reset, Apply, Mode, Status, and User Comment. At the bottom, there are fields for 'Initial' and 'Final' states, both currently set to '-Not Set-'. A red line connects the 'Target Sequence' segment in the tree to the 'Action' dropdown menu.

Profiles and Corrections

Action: Run nominal sequence
Run active profiles
Run active profiles ONCE
Run nominal sequence

When Profiles Converge:

☐ Continue if profiles don't converge

☐ Reset inner targeters before each run

Profiles

Name	Reset	Apply	Mode	Status	User Comment
Differential Corrector	Reset	Apply	Iterate	Not Initialized	-Differential Corrector Description-

☐ Enable Logging

Initial: -Not Set- Final: -Not Set-

Action:

- Run nominal sequence
- Run active profiles
- Run active profiles once

Astrogator

Target Sequences – Profiles

To define the target sequence behavior a **profile** need to be defined.

Select the target sequence segment and configure it

The screenshot displays the Astrogator software interface for configuring target sequences and profiles. On the left, a tree view shows the sequence structure: Initial State, Propagate, Target Sequence (selected), Maneuver, and Propagate1. A red line points from the 'Target Sequence' segment to the 'Profiles' section on the right. The 'Profiles' section contains a table with one profile, 'Differential Corrector', which is highlighted. A red box highlights the 'Add' icon (a document with a plus sign) in the toolbar above the table. Another red line points from the 'Differential Corrector' row to the 'User Comment' column. The 'Profiles and Corrections' panel on the right shows the 'Action' set to 'Run nominal sequence' and the 'When Profiles Converge' set to 'Run to RETURN and continue'. The 'Initial' and 'Final' fields at the bottom are both set to '-Not Set-'.

Initial: -Not Set- Final: -Not Set-

Name	Reset	Apply	Mode	Status	User Comment
Differential Corrector	Reset	Apply	Iterate	Not Initialized	-Differential Corrector Description-

By default, a **differential corrector** will be present as a profile.

Astrogator

Target Sequences – Profiles – Differential Corrector

- The differential corrector profile targets specific values defined as **independent variables**
- The target sequence will change the value of independent variables as needed to achieve the goal defined by the **dependent variables**
- STK will utilize a **differential correction algorithm**
 - Numerical search algorithm

Astrogator

Target Sequences – Profiles – Differential Corrector

Differential corrector config:

- List of **independent variables**
- List of **dependent variables**

Differential Corrector

VariablesConvergenceAdvancedLogGraphsScripting

Control Parameters

Use

Name

Final Value

Last Update

Object

Custom Display Unit

Display Unit

☐

ImpulsiveMnvr.Spherical.MagnitudeSDU

1000 m/sec

0 m/sec

Maneuver

m/sec

Initial Value:

1000 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)

Use

Name

Desired Value

Current Value

Object

Custom Display Unit

Display Unit

☐

Altitude_Of_Apoapsis 0 km

5548.71 km

Propagate1

km

Difference:

5548.71 km

Tolerance:

0.1 km

Scaling

Method: By desired value

Value: 0.001 km

Weight:

1

OK

Help

Astrogator

Target Sequences – Profiles – Differential Corrector

Differential corrector config:

- List of **independent variables**
- List of **dependent variables**

The screenshot shows the 'Differential Corrector' dialog box with the 'Variables' tab selected. It contains two main sections: 'Control Parameters' and 'Equality Constraints (Results)'. Red lines connect specific fields to explanatory text on the right.

Control Parameters

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	ImpulsiveMnvr.Spherical.MagnitudeSDU	1000 m/sec	0 m/sec	Maneuver		m/sec

Initial Value: 1000 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 type="checkbox"/>	Altitude_Of_Apoapsis 0 km	5548.71 km	Propagate1			km

Difference: 5548.71 km Tolerance: 0.1 km Scaling Method: By desired value Value: 0.001 km Weight: 1

Buttons: OK, Help

The final calculated value of the dependent variable

Initial value

The value we want to achieve

The current value with the final value of the independent variable

Astrogator

Target Sequences – Profiles – Differential Corrector

Differential corrector config:

- List of **independent variables**
- List of **dependent variables**

USE!

Set to 7500 km and run the sequence...

The screenshot shows the 'Differential Corrector' dialog box with the 'Variables' tab selected. The 'Control Parameters' section contains a table with one row: 'ImpulsiveMnvr.Spherical.MagnitudeSDU' with a 'Final Value' of '1000 m/sec'. Below this are input fields for 'Initial Value' (1000 m/sec), 'Correction' (0 m/sec), 'Perturbation' (0.1 m/sec), 'Max. Step' (100 m/sec), and 'Scaling' (Method: By initial value, Value: 1 m/sec). The 'Equality Constraints (Results)' section contains a table with one row: 'Altitude_Of_Apoapsis' with a 'Desired value' of '0 km' and a 'Current Value' of '5548.71 km'. Below this are input fields for 'Difference' (5548.71 km), 'Tolerance' (0.1 km), and 'Scaling' (Method: By desired value, Value: 0.001 km, Weight: 1). Red lines and boxes highlight specific elements: a box around the 'Use' checkbox in the 'Control Parameters' table; a line from the 'independent variables' text to the 'Name' column; a line from the 'dependent variables' text to the 'Final Value' column; a line from the 'USE!' text to the 'Use' checkbox in the 'Equality Constraints' table; a line from the 'Set to 7500 km' text to the 'Desired value' column; and lines from the explanatory text on the right to the 'Final Value', 'Initial Value', 'Desired value', and 'Current Value' columns.

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	ImpulsiveMnvr.Spherical.MagnitudeSDU	1000 m/sec	0 m/sec	Maneuver		m/sec

Initial Value: 1000 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

Use	Name	Desired value	Current Value	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	Altitude_Of_Apoapsis	0 km	5548.71 km	Propagate1		km

Difference: 5548.71 km Tolerance: 0.1 km
Scaling Method: By desired value Value: 0.001 km Weight: 1

The final calculated value of the dependent variable

Initial value

The value we want to achieve

The current value with the final value of the independent variable

Astrogator

Target Sequences – Profiles – Differential Corrector

After running the corrector...

Differential Corrector

Variables

Convergence

Advanced

Log

Graphs

Scripting

Control Parameters

☐ Hide Inactive

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Spherical.MagnitudeSDU	1229.33 m/sec	0.0301523 m/sec	Maneuver	<input type="checkbox"/>	m/sec

Initial Value: 1000 m/sec

Perturbation: 0.1 m/sec

Correction: 229.325 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 checked="" type="checkbox"/>	Altitude_Of_Apoapsis	7500 km	7500 km	Propagate1	<input type="checkbox"/>	km

Difference: -0.000295895 km

Tolerance: 0.1 km

Scaling

Method: By desired value

Value: 0.001 km

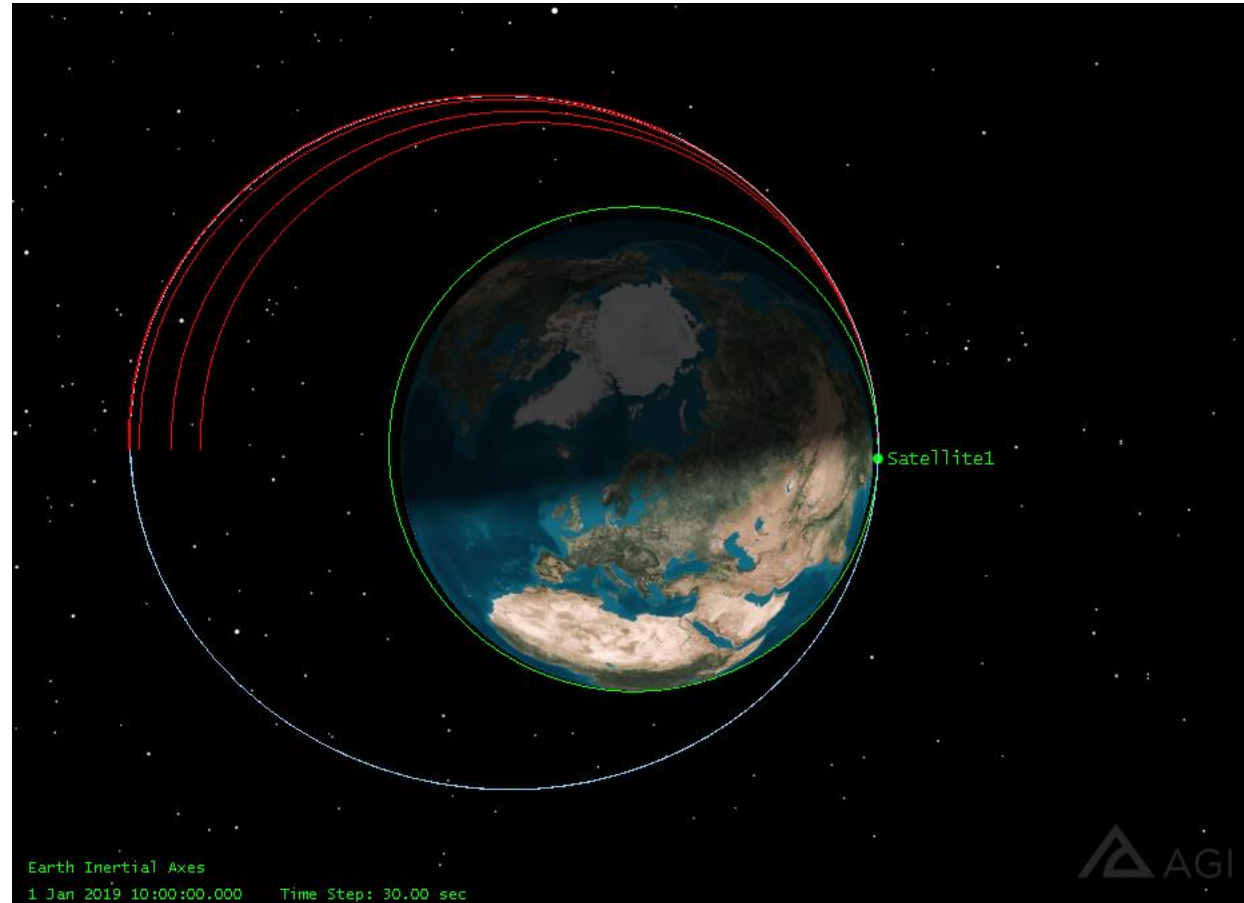
Weight: 1

OK

Help

Astrogator

Target Sequences – Profiles – Differential Corrector

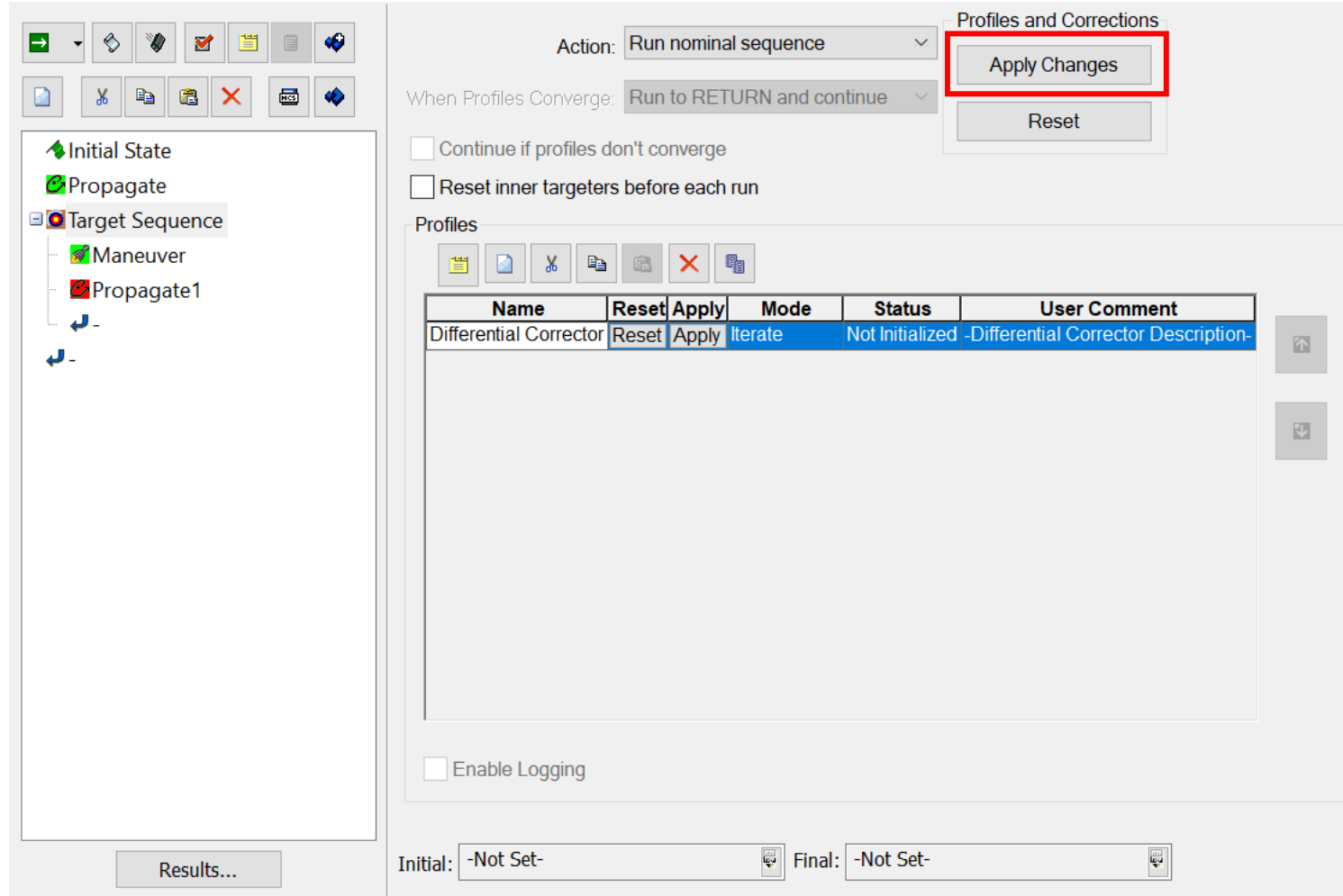


Astrogator

Target Sequences – Profiles – Differential Corrector

Happy with the result? **Apply!**

- Otherwise, reset and restart
- Set action to **Run nominal sequence** and proceed with the MCS...



The screenshot shows the Astrogator software interface. On the left, a tree view displays the sequence: Initial State, Propagate, Target Sequence, Maneuver, and Propagate1. The 'Target Sequence' is selected. Below the tree is a 'Results...' button. On the right, the 'Profiles and Corrections' panel is active. It features a dropdown menu for 'Action' set to 'Run nominal sequence', a dropdown for 'When Profiles Converge' set to 'Run to RETURN and continue', and two checkboxes: 'Continue if profiles don't converge' and 'Reset inner targeters before each run'. The 'Apply Changes' button is highlighted with a red rectangle. Below these are 'Profiles' and 'Enable Logging' checkboxes. A table lists the profiles, with the 'Differential Corrector' profile selected. The table has columns for Name, Reset, Apply, Mode, Status, and User Comment. At the bottom, there are 'Initial' and 'Final' dropdown menus, both set to '-Not Set-'.

Name	Reset	Apply	Mode	Status	User Comment
Differential Corrector	Reset	Apply	Iterate	Not Initialized	-Differential Corrector Description-

The target sequence will remember the last found value.

Unless a reset is applied, the target will converge immediately

Astrogator

Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration

The screenshot shows the 'Differential Corrector' window with the 'Advanced' tab selected. It contains two main sections: 'Control Parameters' and 'Equality Constraints (Results)'. Red lines point from external text boxes to specific fields in these sections.

Control Parameters

Use	Name	Final Value	Last Update	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	ImpulsiveMnvr.Spherical.MagnitudeSDU	1000 m/sec	0 m/sec	Maneuver		m/sec

Initial Value: 1000 m/sec
Correction: 0 m/sec
Perturbation: 0.1 m/sec
Max. Step: 100 m/sec
Scaling Method: By initial value
Value: 1 m/sec

Equality Constraints (Results)

Use	Name	Desired Value	Current Value	Object	Custom Display Unit	Display Unit
<input type="checkbox"/>	Altitude_Of_Apoapsis	0 km	5548.71 km	Propagate1		km

Difference: 5548.71 km
Tolerance: 0.1 km
Scaling Method: By desired value
Value: 0.001 km
Weight: 1

Buttons: OK, Help

Value to be used in calculating numerical derivatives

Maximum increment to make to the value of the parameter in any one step

The smallest update to the parameter to be made before the targeter stops

Astrogator

Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration

Differential Corrector

VariablesConvergenceAdvancedLogGraphsScripting

Maximum Iterations: 50

☒ Display Status

Status: Converged

Convergence Criteria: Equality constraints within tolerance

OKHelp

After this, the search stops

Result is within tolerance bounds
and
Last update within tolerance for convergence

Target Sequence.Differential Corrector: Finished: *CONVERGED* in 5 iterations. *Constraints Met*

Control	New Value	Last Update	Constraint	Desired	Achieved	Difference	Tolerance
...cal.MagnitudeSDU	1229.33 m/	0.03017 m/s	...Altitude Of Apoapsis	7500 km	7500 km	-0.000296	0.1 km

Astrogator

Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration

Limit cycles: independent variables are the same as two iteration earlier

The screenshot shows the 'Differential Corrector' window with the 'Advanced' tab selected. The window has tabs for 'Variables', 'Convergence', 'Advanced', 'Log', 'Graphs', and 'Scripting'. The 'Advanced' tab contains several sections: 'Root-Finding Algorithm' with radio buttons for 'Newton-Raphson Method' and 'Secant Method' (selected), a 'Derivative Calculation Method' dropdown set to 'Forward Difference', checkboxes for 'Clear Corrections Before Each Run' and 'Stop Targeting on Limit Cycle Detection' (checked), an 'Output' section with checkboxes for 'Update B-Planes for nominal run on all iterations' (checked) and 'Update B-Planes for perturbations on all iterations', a 'Line Search' section with a 'Use' checkbox, 'Maximum Iterations' set to 10, 'Lower Bound' and 'Upper Bound' text boxes, and a 'Tolerance' text box. The 'Homotopy' section has a 'Use' checkbox and 'Number Of Steps' set to 1. Red lines and text annotations highlight specific features: a red box around the 'Advanced' tab; a red line from the 'Secant Method' radio button to the text 'Will come back to this later'; a red line from the 'Update B-Planes for nominal run on all iterations' checkbox to the text 'On each step, explore the line of the step (use when no converging)'; and a red line from the 'Number Of Steps' text box to the text 'Attempt to reach the target in stages (recommended for non linear searches)'.

Differential Corrector

Variables Convergence **Advanced** Log Graphs Scripting

Root-Finding Algorithm

☐ Newton-Raphson Method

☒ Secant Method

Derivative Calculation Method: Forward Difference

☐ Clear Corrections Before Each Run

☒ Stop Targeting on Limit Cycle Detection

Output

B-Planes

☒ Update B-Planes for nominal run on all iterations

☐ Update B-Planes for perturbations on all iterations

Draw perturbations in: Segment Color

Line Search

☐ Use Maximum Iterations: 10

Lower Bound: 0.000001

Upper Bound: 10.000000

Tolerance: 0.000001

Homotopy

☐ Use Number Of Steps: 1

OK Help

Will come back to this later

Root-Finding algorithm – secant is known to converge faster

On each step, explore the line of the step (use when no converging)

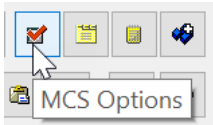
Attempt to reach the target in stages (recommended for non linear searches)

Astrogator

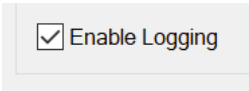
Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration

Enable logging 1)
In the MCS options



2) In the target sequence config window



Differential Corrector

VariablesConvergenceAdvancedLogGraphsScripting

Run	Status	Iterations	Cost	Start Time	Elapsed Time
1	Converged	5 of 50	3.948863421877e-08	8 Sep 2019 12:53:04.072	2.851999998093
IterationCostElapsed Time					
0	0.2601788328108	0			
1	0.1539008580235	0.7569999694824			
2	0.03669624676824	0.2869999408722			
3	0.00251383086161	0.2950000762939			
4	3.835913110673e-05	0.2999999523163			
5	3.948863421877e-08	0.3039999008179			
Control Paramete					
Name	Value	Last Update	Tolerance	Segment	
Maneuver : Imp	1229.332414644 m/sec	0.03016970475278 m/sec	1e-06 m/sec	Maneuver	
Equality Constrai					
Name	Value	Difference	Tolerance	Segment	
Propagate1 : AI	7499.999703835 km	-0.0002961647566408 km	0.1 km	Propagate1	

<

Delete RunRestore IterationClear Log

Maximum Number Of Runs To Keep In The Log: 25

>

OKHelp

Cost is a simple function computed as the **square root of the sum of the squares of the scaled differences** between the achieved and desired values of the equality constraints.

Astrogator

Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration

Differential Corrector

VariablesConvergenceAdvancedLogGraphsScripting

Name	Generate on run	User Comment
Graph1	<input checked="" type="checkbox"/>	Targeter Graph

Graph Properties

Independent variable: Iteration

☐ Label Iterations☐ Show Desired Value☐ Show Tolerance Band

Active Controls

Name	Object	Graph Value	Line Color	Point Style	Y Axis
ImpulsiveMnvr.Spherical.MagnitudeSDU Maneuver		<input checked="" type="checkbox"/>		Solid Dot	Y1

Results

Name	Object	Graph Option	Show Desired Value	Line Color	Point Style	Y Axis	Show Tolerance Band
Altitude_Of_Apoapsis	Propagate1	Graph value	<input checked="" type="checkbox"/>		Solid Dot	Y2	<input checked="" type="checkbox"/>

Generate Report

Generate Graph

OK

Help

Plot the values vs

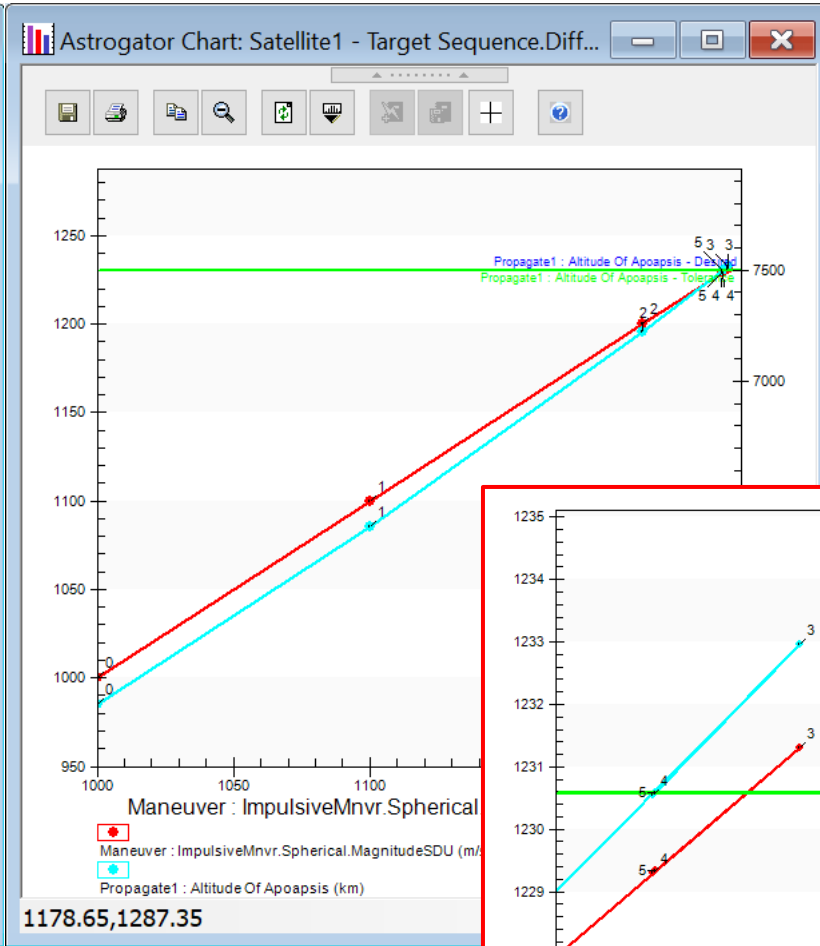
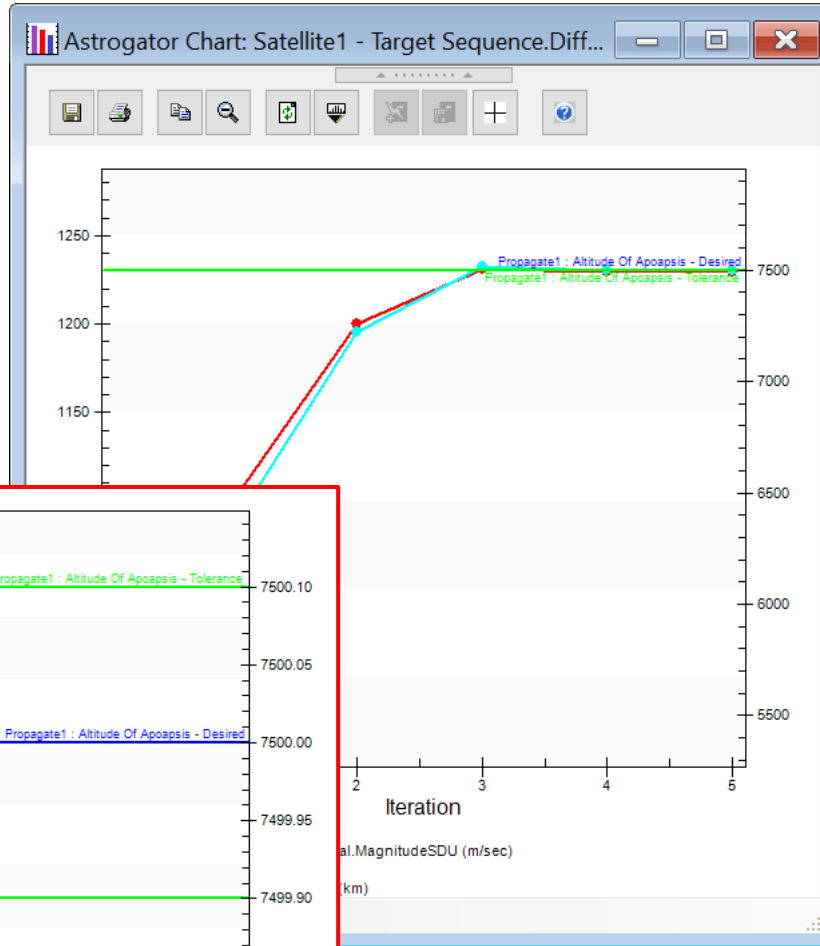
- Iteration
- Independent variables
- Dependent variables

In real time as
astrogator
calculates!

Astrogator

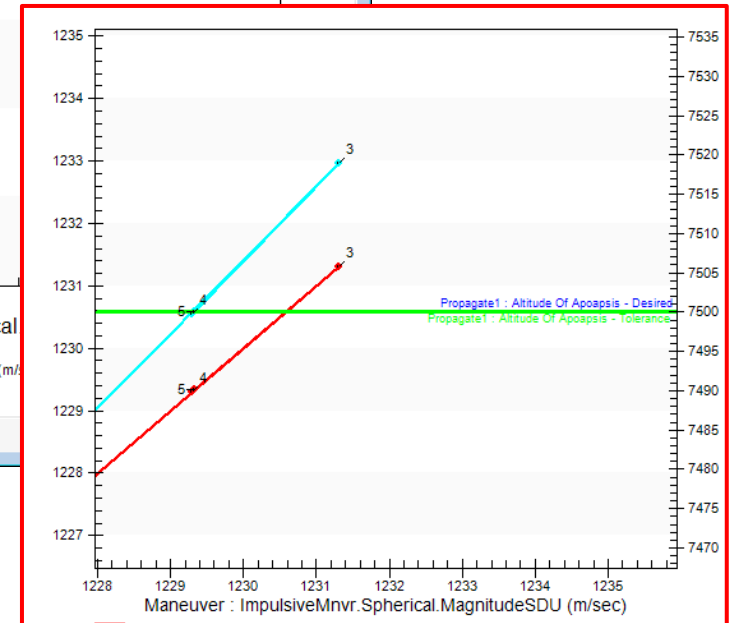
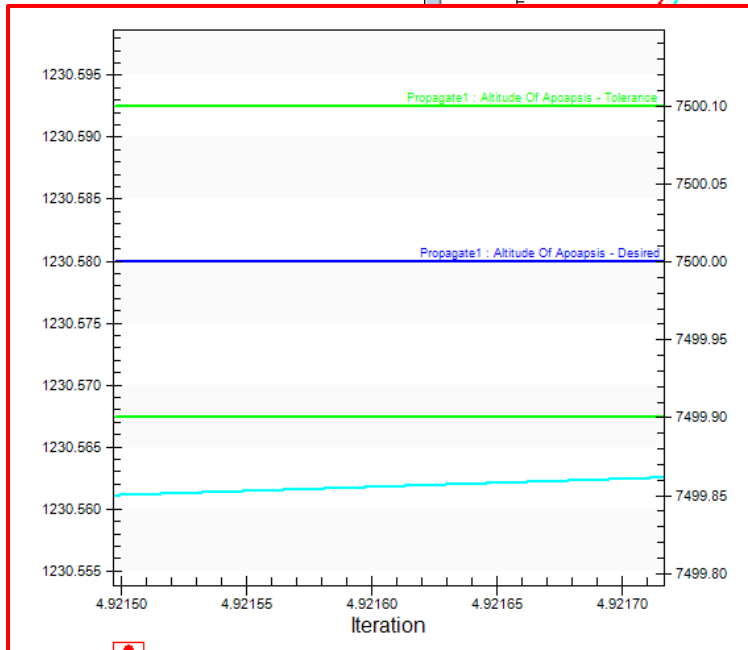
Target Sequences – Profiles – Differential Corrector - Details

Some details of the Differential Corrector configuration



Plot the values vs

- Iteration
- Independent variables
- Dependent variables



Astrogator

Target Sequences – Profiles – Differential Corrector - Under the Hood

■ Root-Finding Algorithms

Root-Finding Algorithm

☐ Newton-Raphson Method

☒ Secant Method

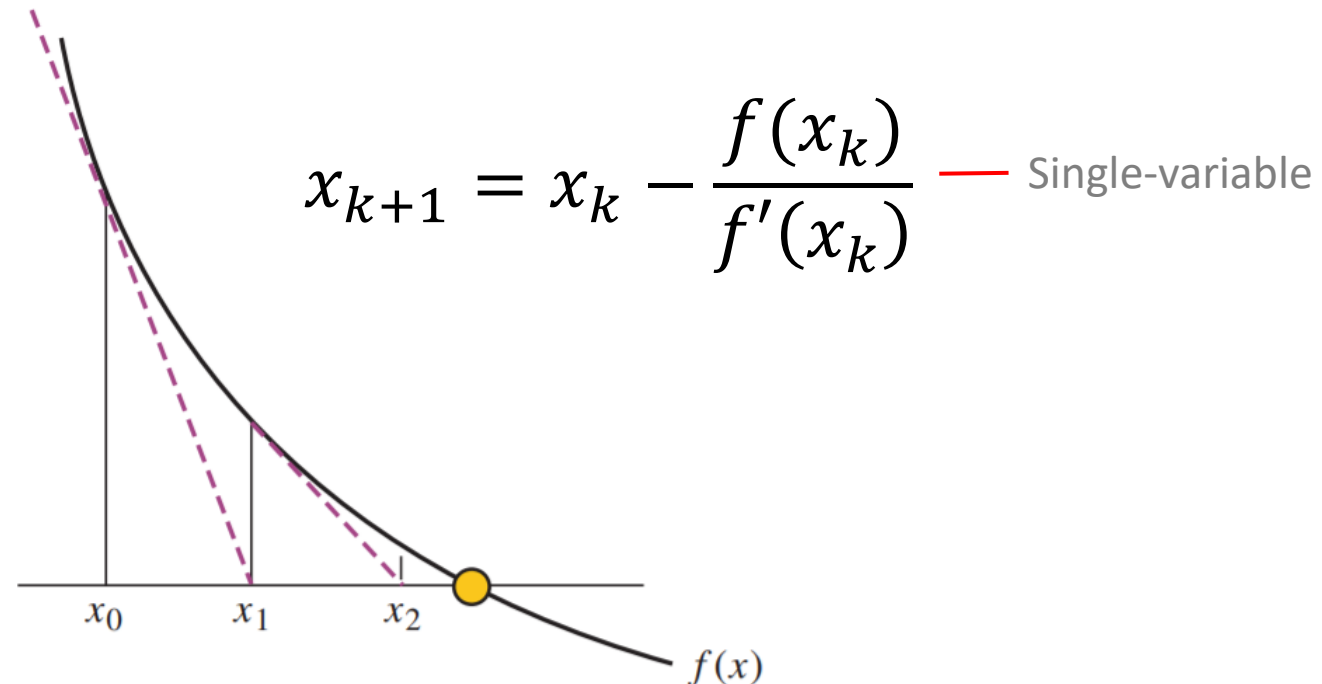
Derivative
Calculation Method: Forward Difference

- A root of a function $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$, is a vector of n **independent** variables \mathbf{x} such that $\mathbf{y} = f(\mathbf{x}) = \mathbf{0}$, where \mathbf{y} is a vector of m **dependent** variables.
- In most cases, \mathbf{x} cannot be computed exactly, but approximated typically starting from some **initial guess** \mathbf{x}_0 and iterating to hopefully converge in the root
- On each cycle a step is computed for \mathbf{x} and evaluated at least once

Newton-Raphson Method

STK Method 1)

- Uses the **first derivative** of f to determine the step to take in x
- At each iteration, the x values for the next iteration are chosen such that the root would be reached if $f(x)$ were linear



Newton-Raphson Method

STK Method 1)

- Uses the **first derivative** of f to determine the step to take in x
- Since the first derivative cannot be computed analytically, it can be obtained numerically by using a **perturbation** δx

Perturbation:

$$x_{k+1} = x_k - \frac{f(x_k)}{f(x_k + \delta x) - f(x_k)} \delta x \quad \text{— Single-variable}$$

Newton-Raphson Method

STK Method 1)

- In **multivariable problems**, the Newton-Raphson method is

$$\mathbf{x}_{k+1} = \mathbf{x}_k - \mathbf{J}_n^{-1}(\mathbf{f}(\mathbf{x}_k)) \quad (\text{Pseudo-inverse if } \mathbf{J} \text{ not squared})$$

- To compute \mathbf{J} numerically \mathbf{x} variables are **perturbed** by $\delta\mathbf{x}$. Every i column of \mathbf{J} is given by

$$\mathbf{J}_i = \frac{1}{\delta x_i} (\mathbf{f}(\mathbf{x} + \delta\mathbf{x}_i) - \mathbf{f}(\mathbf{x}))$$

Column vector with δx_i in i^{th} column, zero on the rest

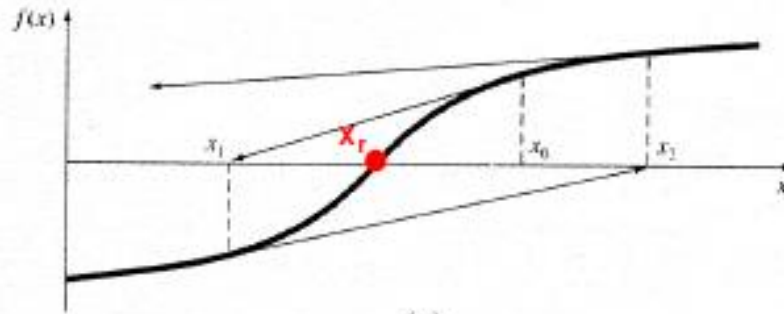
meaning that n evaluations of \mathbf{f} are required per iteration

- A **maximum step** size Δx_i can be configured to avoid overshooting

Max. Step:

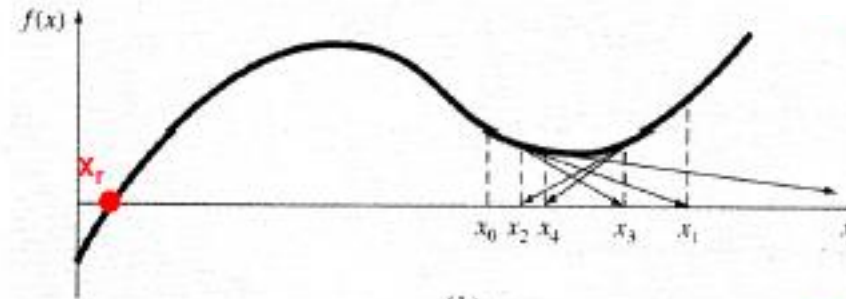
Newton-Raphson Method

STK Method 1) - Problems



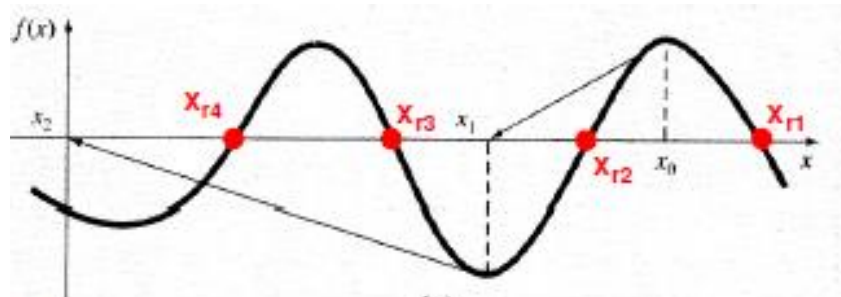
(a)

Case-a: Case where an inflection point ($f''(x)=0$) occurs in the vicinity of a root. Iterations begins at x_0 progressively diverge from the root.



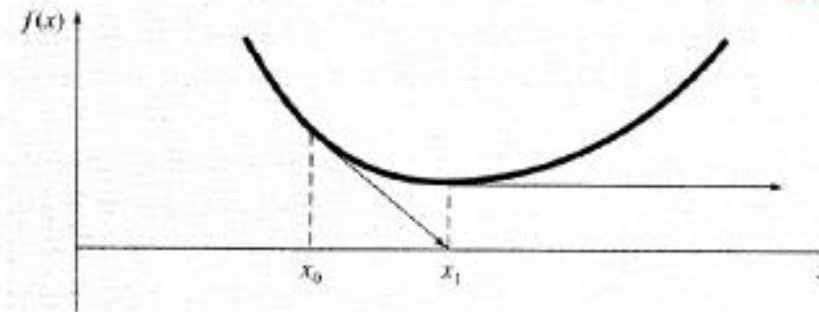
(b)

Case-b: Case shows the tendency of the Newton's method to oscillate around a local maximum or minimum.



(c)

Case-c: Case shows how an initial guess that is close to one root can jump to a location several roots away. This is due to near zero slope.



(d)

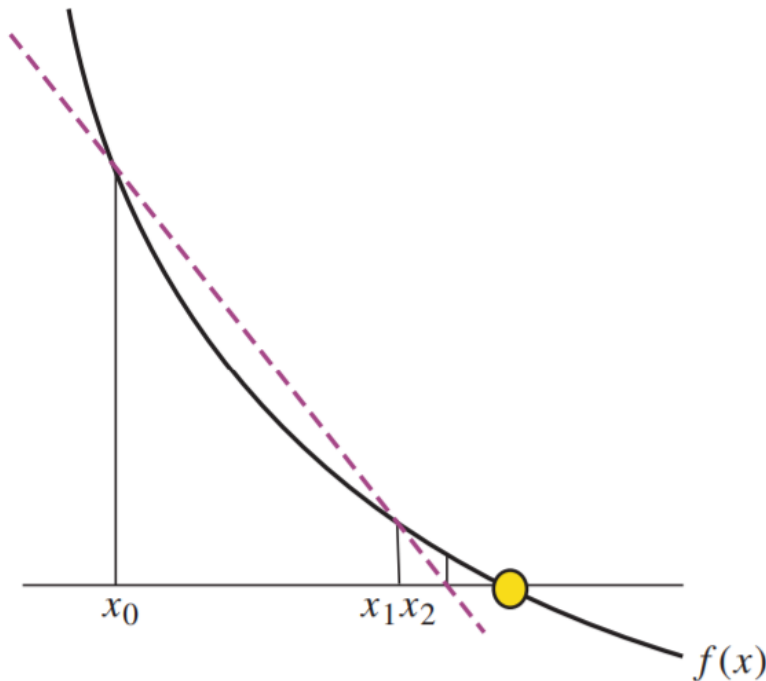
Case-d: Case shows an encounter of zero slope ($f'(x)=0$). In this case the solution shoots off horizontally and never hits the x-axis. (diverge- a disaster)

Secant Method (Broyden's Method)

STK Method 2)

- Uses **successive values** of x (wider range than with perturbations)

$$x_{k+1} = x_k - f(x_k) \frac{x_k - x_{k-1}}{f(x_k) - f(x_{k-1})} \quad \text{--- Single-variable}$$



Secant Method (Broyden's Method)

STK Method 2)

- **Broyden's** method is a generalization of the secant method for multi-variable problems.
- Instead of evaluating **J** on every iteration, it uses an **estimate**

$$\mathbf{J}_k = \mathbf{J}_{k-1} + \frac{f(\mathbf{x}_k) - f(\mathbf{x}_{k-1}) - \mathbf{J}_{k-1}(\mathbf{x}_k - \mathbf{x}_{k-1})}{\|\mathbf{x}_k - \mathbf{x}_{k-1}\|^2}$$

meaning that only 1 evaluation of f is required per iteration, but more iterations might be required to converge

Secant Method (Broyden's Method)

STK Method 2)

- Broyden's

v

- In

meaning
iteration

AAS 11-480

COMPARISONS BETWEEN NEWTON-RAPHSON AND BROYDEN'S METHODS FOR TRAJECTORY DESIGN PROBLEMS

Matthew M. Berry*

Broyden's method, a generalized-secant method for root-finding, was recently added as an option in the STK/Astrogator maneuver planning and trajectory design software module. The software previously used a Newton-Raphson approach with numerical partials to solve shooting problems. In this paper, the two methods are compared for a wide variety of problems, including station-keeping, orbit transfers, and interplanetary trajectories. For most use-cases, Broyden's method has a faster performance than Newton-Raphson.

INTRODUCTION

Root-finding algorithms, such as Newton-Raphson and Broyden's methods, are useful in solving trajectory design problems. These algorithms are used to adjust the problem's independent variables, such as the time, direction, and magnitude of maneuvers, to achieve certain desired orbital characteristics, such as the final orbital characteristics. The STK/Astrogator maneuver design software module has used a Newton-Raphson algorithm to solve a variety of problems since it was first released. Recently, an option was added to the software to use Broyden's method. This paper describes the two algorithms, compares using them to solve a variety of problems, and discusses the results.

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re

Methods Comparison

In Depth Analysis

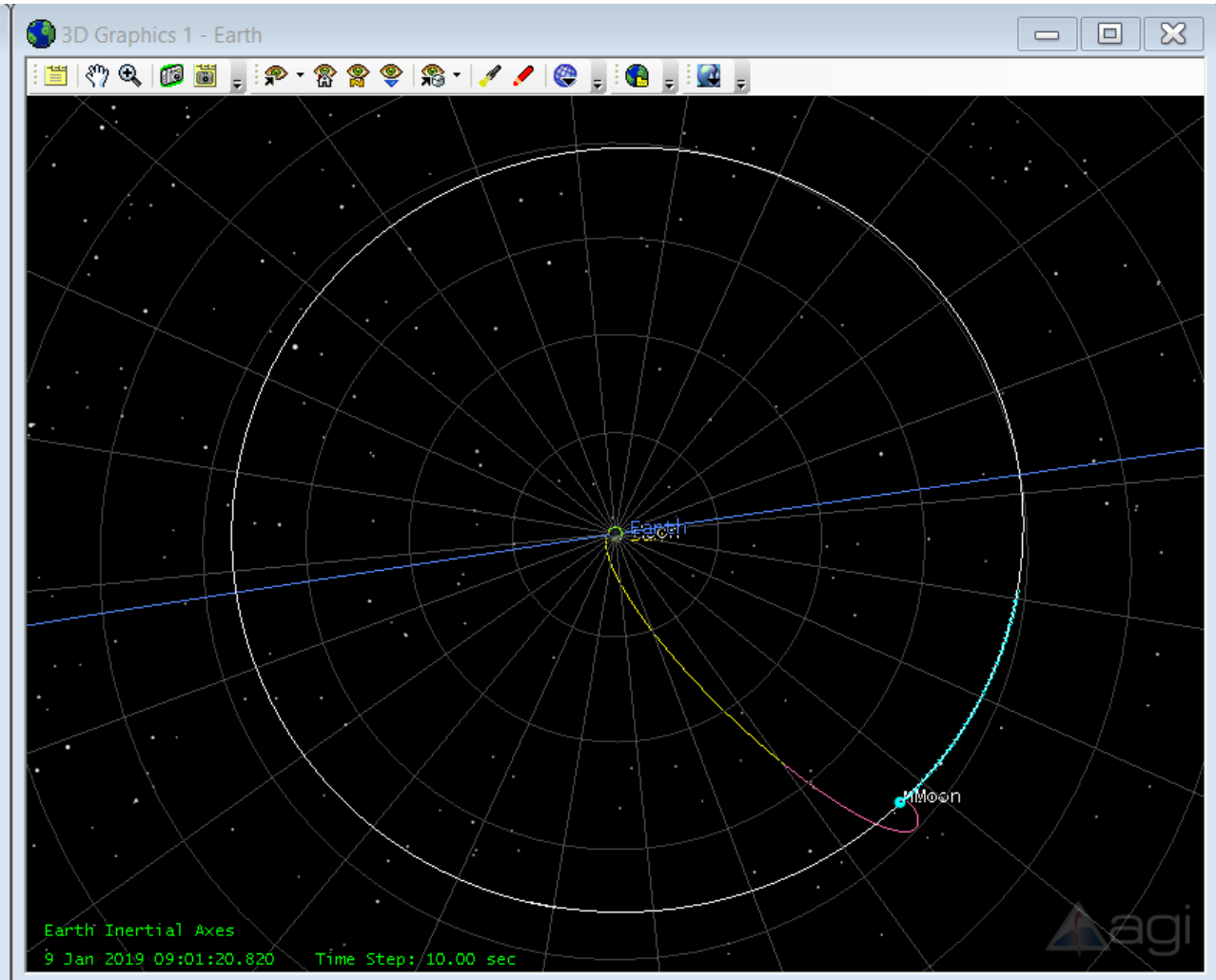
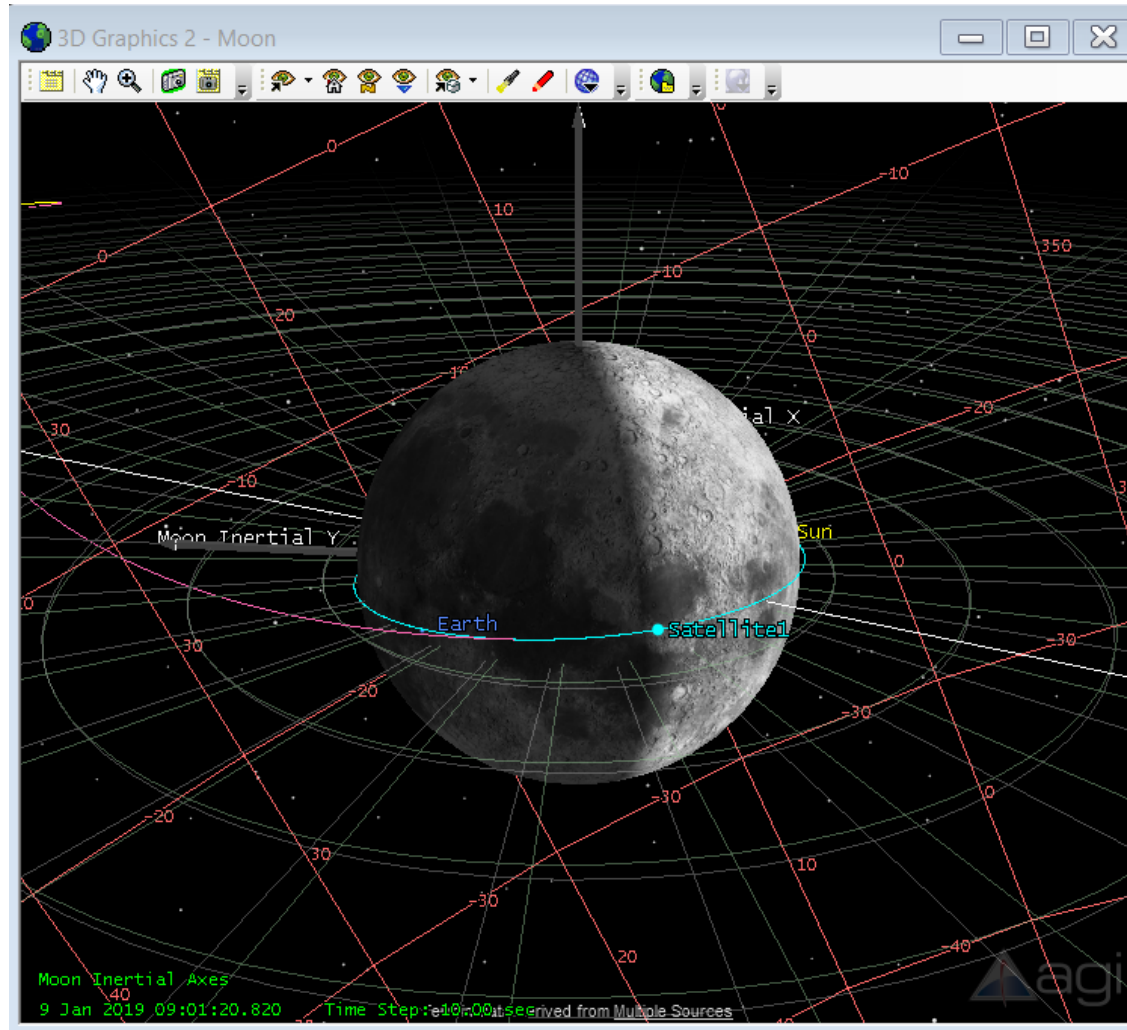
- The paper shows that in several test cases Broyden’s method uses fewer evaluations in multiple different cases

Table 3: Iterations and evaluations needed in Earth to Moon example

Profile	Newton-Raphson method		Broyden’s method	
	Iterations	Evaluations	Iterations	Evaluations
RA Dec	5	16	7	10
B-plane	3	13	5	9
Altitude and inclination	3	13	2	6
Total		42		25

Astrogator

Lunar Mission Tutorial (STK Moon Mission with B-Plane Targeting Tutorial)



Astrogator

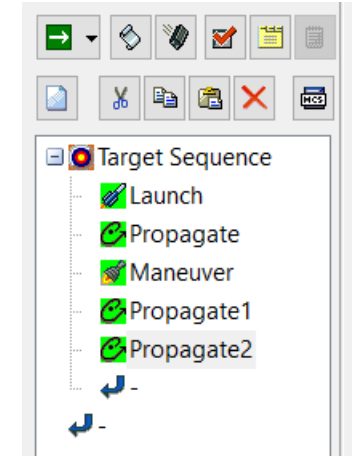
Lunar Mission Tutorial (STK Moon Mission with B-Plane Targeting Tutorial)

- Create scenario **1st Jan 2018 + 30 days** ([link to tutorial](#))
- Scenario properties
 - Basic, time: **Step size 3 min**
 - 2D graphics, global: show **planet orbit**, not show **ground tracks** and **markers**
- Add planet, default planet, repeat 3 times
 - Set them to **Sun, Earth** and **Moon**
- 3D window
 - Grids, view **ECI coordinates**
 - Advanced, **view distance** 1e+10 km
- View, duplicate 3D graphics window, center on moon

Astrogator

Lunar Mission Tutorial – Setting the Context

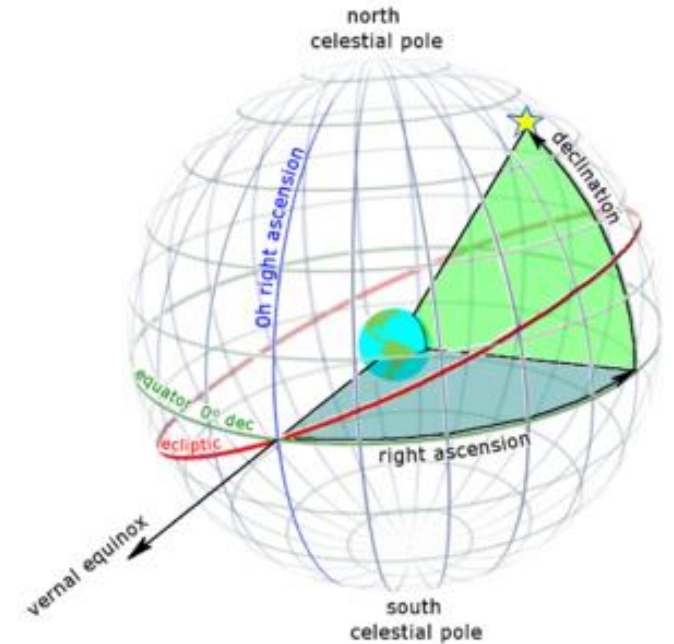
- Add default **satellite** (Lunar Probe), set Astrogator
- In Astrogator
 - Delete all segments
 - Add **target sequence**
 - **Launch** (set to **initial analysis time**)
 - Propagate (**Coast**): **90 min** trip
 - Maneuver (**TransLunarInjection**): set to **Thrust vector, VNC Earth, X=3120 m/sec**
 - Propagate (**ToSwingBy**): set propagator to **Cis-Lunar, R Mag** stopping condition, **trip=300000 km**
 - Propagate (**ToPeriselene**): set propagator to **Cis-Lunar**, Stop condition 1 duration to **10 days**, Stop condition 2 **altitude trip 0km**, moon central, Stop condition 3 **periapsis**, moon central
- **Run** the sequence to see how it looks like



Astrogator

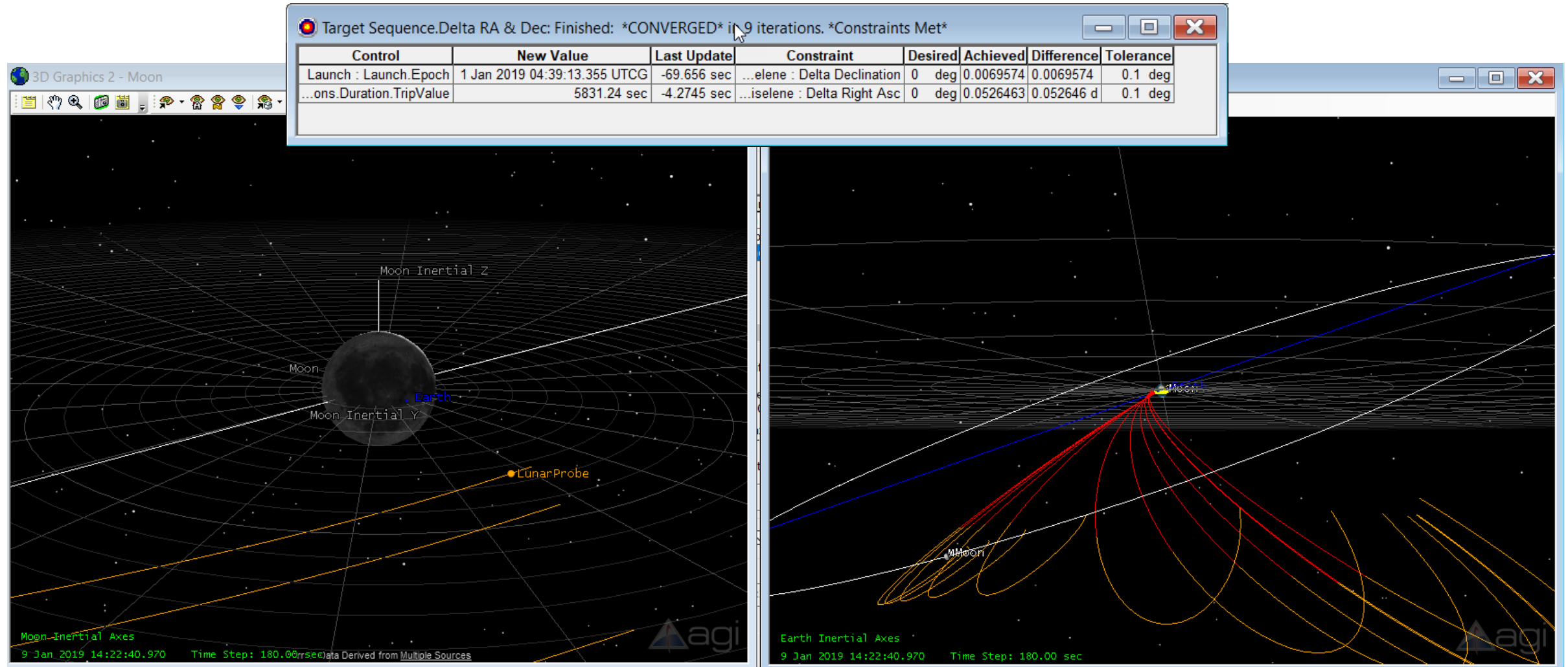
Lunar Mission Tutorial – 1) Launch and Coast Times

- Set **independent** variables
 - Launch: **Epoch (set time)**
 - Propagate (Coast): **Trip time**
- Set **dependent** variables (results)
 - Propagate (ToPeriselene): multibody, **delta right ascension** and **delta declination**, verify central body is the Moon
- Name this profile as **Delta RA & Dec** and set
 - Enable **both independent** variables
 - Launch: perturbation=1 min, Max step=1 hr
 - StopCond.Duranton.Trip: perturbation=1 min, Max step=5 min
 - Enable both **dependent** variables (results)
 - Set iterations to 100
 - Target sequence: Run Active Profiles



Astrogator

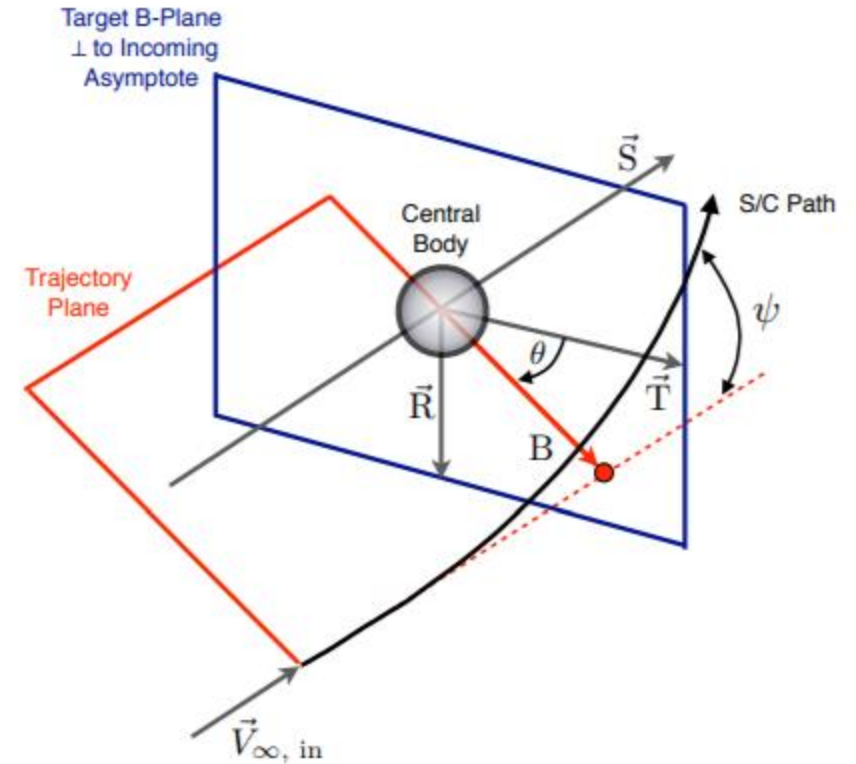
Lunar Mission Tutorial – 1) Launch and Coast Times



Astrogator

Lunar Mission Tutorial – 2) B Plane Targeting

- Duplicate differential corrector
- Set new **dependent** variables (results)
 - Propagate (ToPeriselene): multibody, **BdotT** and **BdotR**, verify central body is the Moon
- Name this profile as **B-PlaneTargeting** and go to properties
 - Enable **BdotT** and **BdotR** as **dependent** variables
 - Set BdotR desired value to 5000 km
- Add new Propagator (Prop3Days) after target sequence
- Target sequence: Run Active Profiles



Astrogator

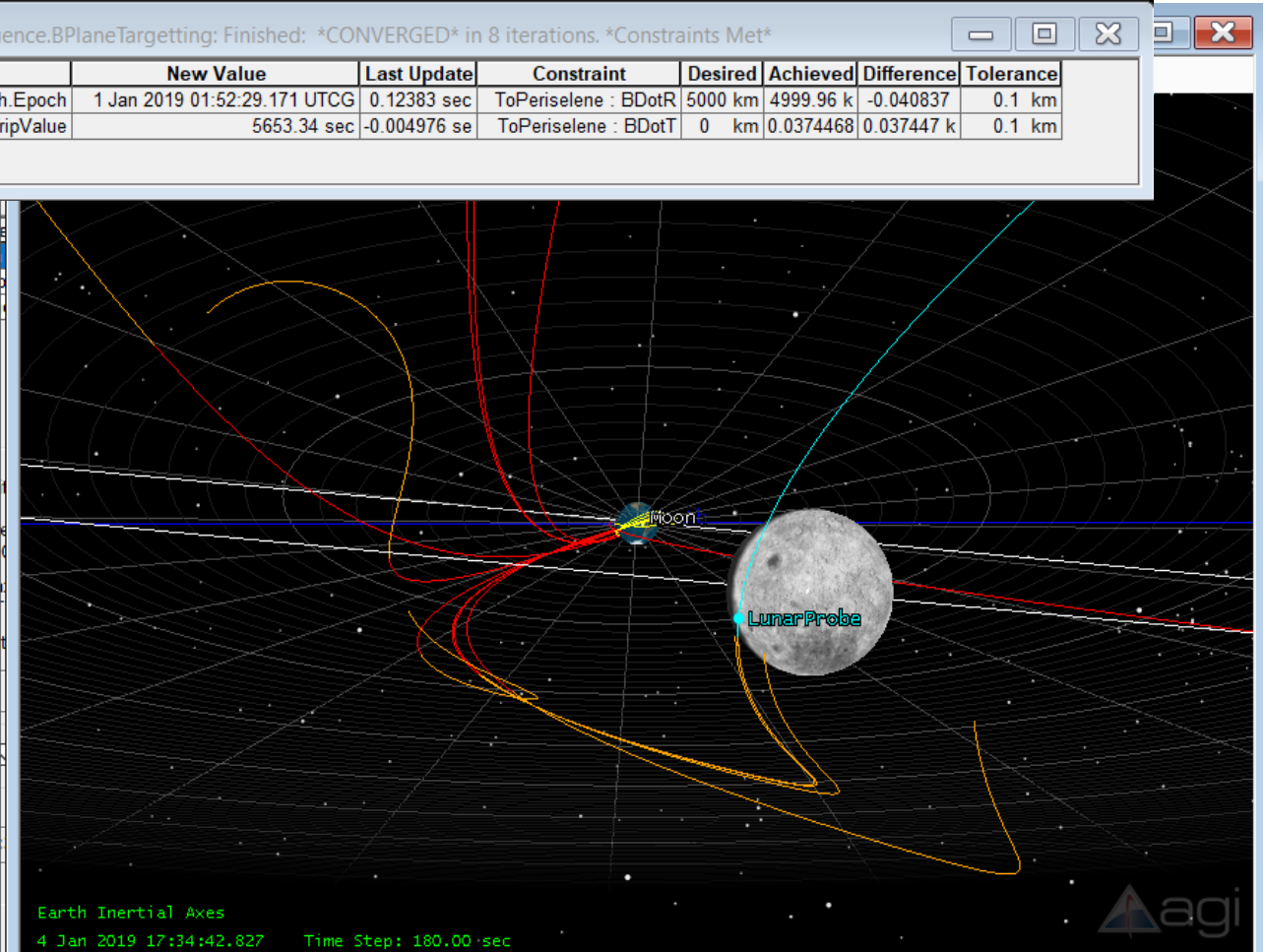
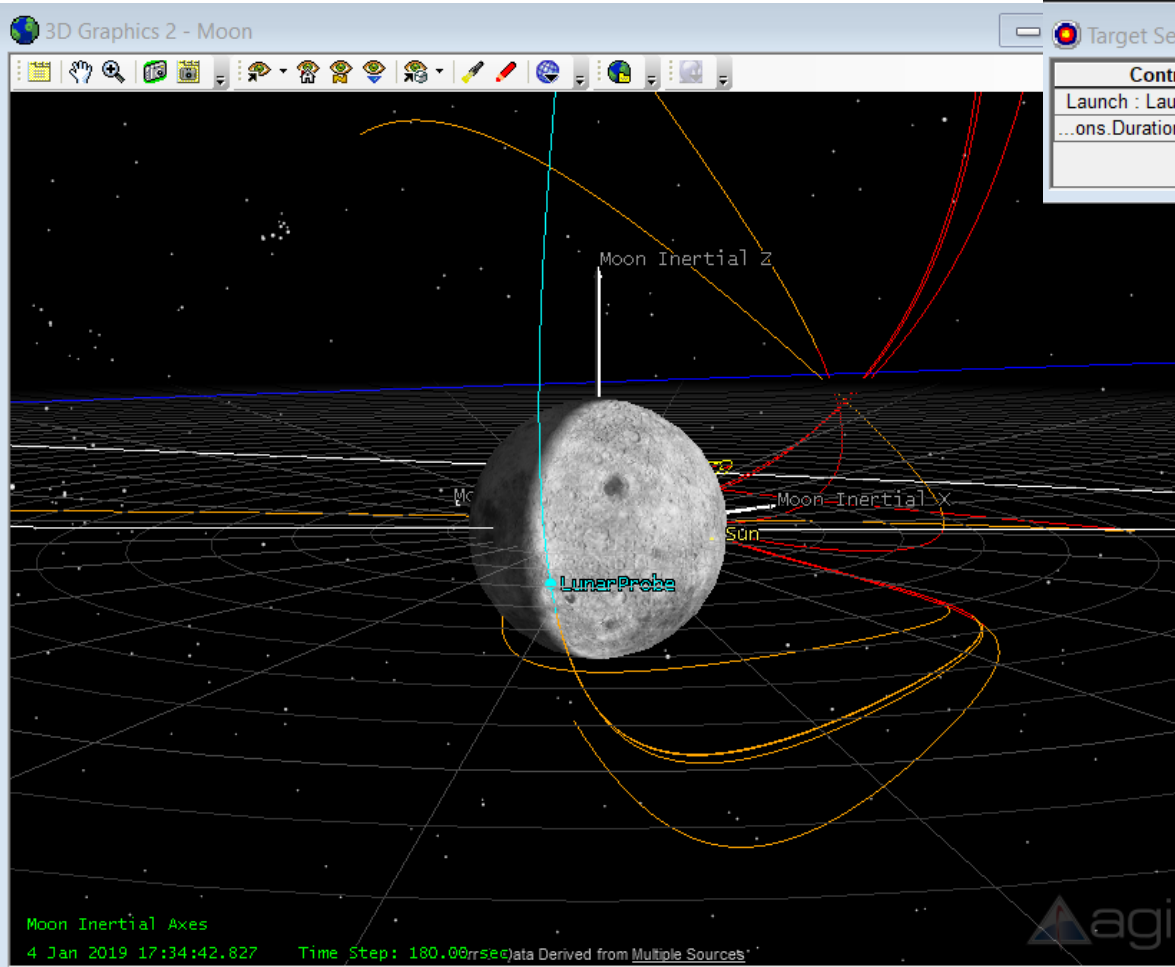
Lunar Mission Tutorial – 2) B Plane Targeting

Target Sequence.Delta RA & Dec: Finished: *CONVERGED* in 0 iterations. *Constraints Met*

Control	New Value	Last Update	Constraint	Desired	Achieved	Difference	Tolerance
Launch : Launch.Epoch	1 Jan 2019 04:39:13.355 UTCG	0 sec	...elene : Delta Declination	0 deg	0.0069574	0.0069574	0.1 deg
...ons.Duration.TripValue	5831.24 sec	0 sec	...iselene : Delta Right Asc	0 deg	0.0526463	0.052646 d	0.1 deg

Target Sequence.BPlaneTargeting: Finished: *CONVERGED* in 8 iterations. *Constraints Met*

Control	New Value	Last Update	Constraint	Desired	Achieved	Difference	Tolerance
Launch : Launch.Epoch	1 Jan 2019 01:52:29.171 UTCG	0.12383 sec	ToPeriselene : BDotR	5000 km	4999.96 k	-0.040837	0.1 km
...ons.Duration.TripValue	5653.34 sec	-0.004976 se	ToPeriselene : BDotT	0 km	0.0374468	0.037447 k	0.1 km

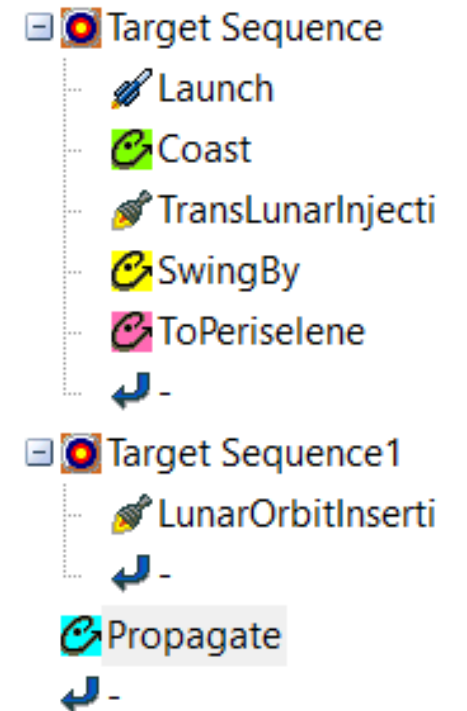


Astrogator

Lunar Mission Tutorial – 3) Lunar Orbit Insertion

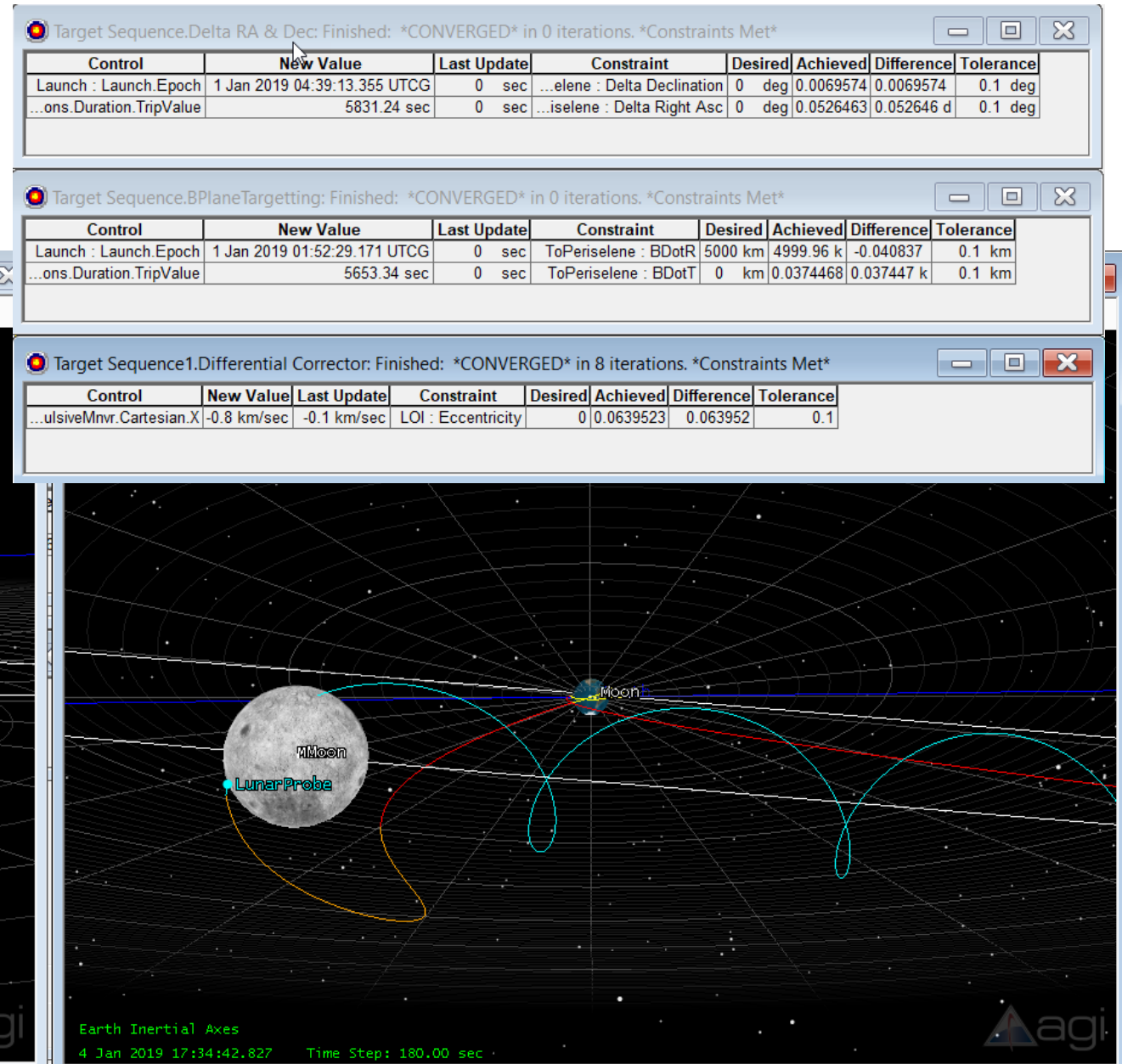
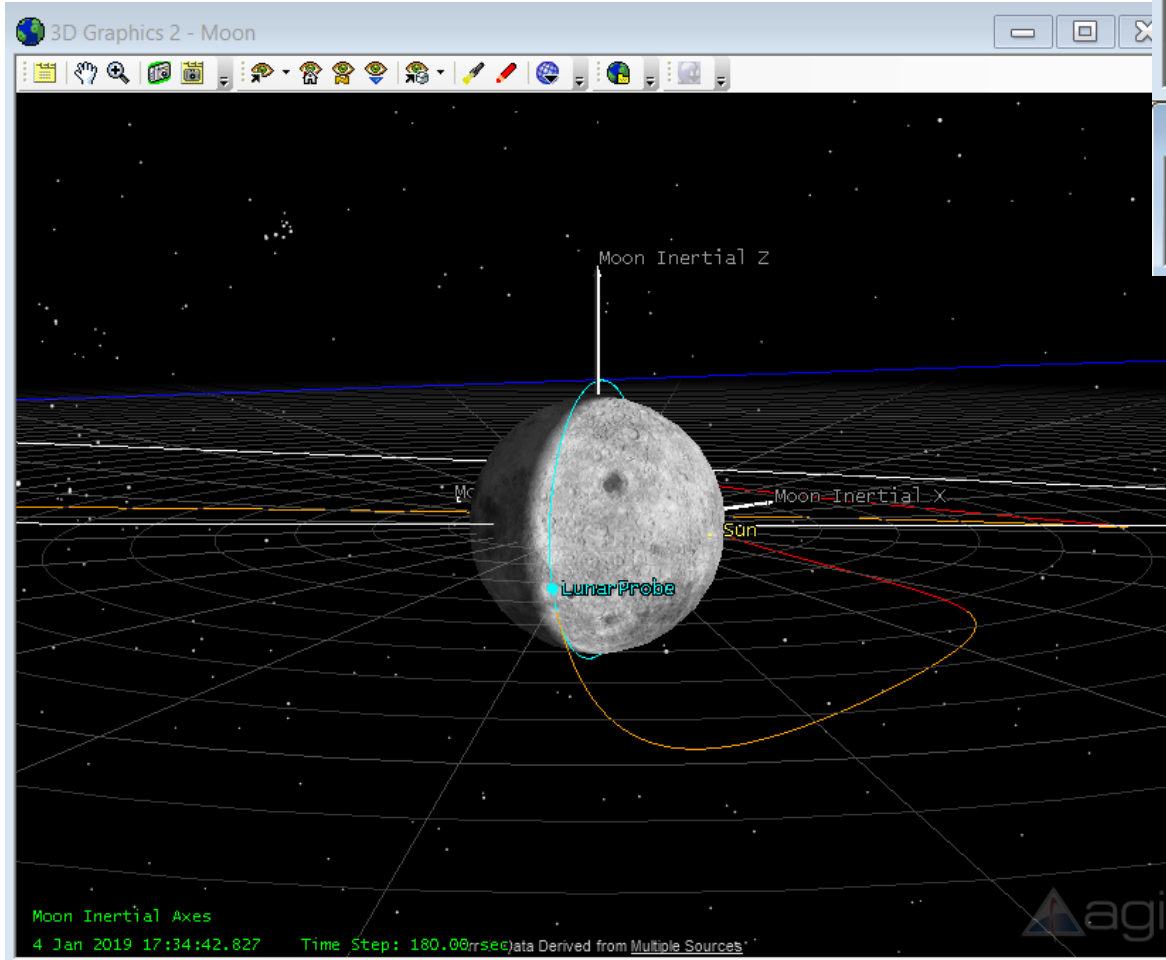
V The X axis is along the velocity vector \vec{V}
N The Y axis is along the orbit normal (\hat{n})
C The Z axis completes the orthogonal triad ($\hat{n} \times \vec{V}$)

- Add new target sequence
 - Add maneuver **LunarOrbitInsertion** (LOI), set **Thrust vector**: [VNC \(Moon\)](#)
- Set new **independent** variables
 - **X Velocity**: leave at 0 to let Astrogator calculate the delta-V
- Set new **dependent** variables (results)
 - Maneuver: Keplerian elements, **eccentricity** (central body: Moon)
- Name this profile as **LOI** and go to properties
 - Enable **X Velocity** as **independent** and **eccentricity** as **dependent** variable
- Target sequence: Run Active Profiles



Astrogator

Lunar Mission Tutorial – 3) Lunar Orbit Insertion



Astrogator

Astrogator Guild - <https://astrogatorsguild.com/>

[SEE Home](#)

The Astrogator's Guild

LUNAR MISSIONS VIDEO BLOG

by Astrogator John | May 16, 2019 | [General Comments](#)

Mike Loucks and I were at agi.com last week in their new studio and we recorded this video blog on YouTube with Josh Poley. We're talking about some Lunar missions we worked on:

Ep6 – Lunar Missions



Recent Posts

[Lunar Missions Video Blog](#)

Great Article about LADEE that somehow didn't get posted here 3 years ago

"Back of the Envelope"

Astrogation: Re-creating the New Horizons Trajectory

Candidate Object on Asteroid Zoo could be "Snoopy" from Apollo 10

Could the Meteorite crater in Nicaragua be related to Asteroid 2014 RC?

Meta

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Astrogator

Target Sequence - Optimizers

- **Differential Corrector**
 - Root-finding
(good to approximate a feasible solution)
- **Interior Point Optimizer (IPOPT)**
 - Interior-point method
(good to obtain a local optimal)
- **Sparse Nonlinear Optimizer (SNOPT)**
 - Sequential quadratic programming
(good to obtain a local optimal)

Independent variables (control) -> Decision variables
Dependent variables (results) -> Objective function

Propagator: Astrogator

Initial State

- Target Sequence
- Maneuver

When Profiles Converge:

- ☐ Continue if profiles don't
- ☐ Reset inner targeters be

Profiles

Name	Reset
SNOPT Optimizer	Reset

New...

Field Name: Profiles

Field Description: Targeting profiles for this

- Change Maneuver Type
- Change Propagator
- Change Return Segment
- Change Stop Segment
- Change Stopping Condition State
- Design Explorer Optimizer
- Differential Corrector
- IPOPT Optimizer
- Run Target Sequence Once
- SNOPT Optimizer
- Scripting Tool
- Seed Finite Maneuver

Decision Variables (Controls)

Use	Name	Initial Value	Current Value
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.X	9.18485e-16 m/sec	9.18485e-16 m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.Y	15 m/sec	15 m/sec
<input checked="" type="checkbox"/>	ImpulsiveMnvr.Cartesian.Z	100 m/sec	100 m/sec

Initial: 9.18485e-16 m/sec

Current: 9.18485e-16 m/sec

Scaling

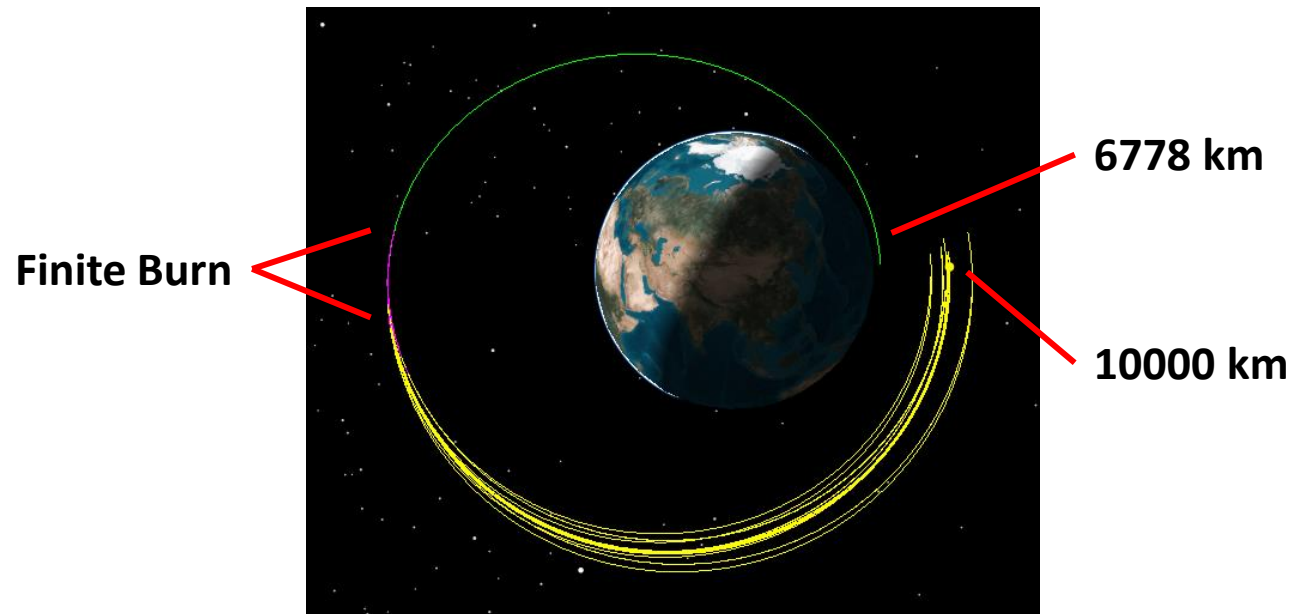
Objectives and Constraints (Results)

Use	Object	Name	CurrentValue	Goal
<input checked="" type="checkbox"/>	Maneuver	C3_Energy	-58.1322 km^2/sec^2	Minimize
<input checked="" type="checkbox"/>	Maneuver	DeltaV	100 m/sec	Bound
<input checked="" type="checkbox"/>	Maneuver	DeltaV_Squared	10000 m^2/sec^2	Minimize

Astrogator

Target Sequence – Optimizers: Trajectory Design with SNOPT [Tutorial](#)

- Initial state (RAAN, Argument of Perigee, and True Anomaly = 0)
 - Radius of Perigee: **6778 km**, Eccentricity: 0.4 km, Inclination: 45 degree
- Objective
 - Propagate the orbit **until** a certain true anomaly (guess = 170 deg)
 - Use **finite** burn with **min delta V** | radius of perigee = **10000 km**



Astrogator

Target Sequence – Optimizers: Trajectory Design with SNOPT [Tutorial](#)

SNOPT Optimizer

VariablesOptionsLogGraphsScripting

Decision Variables (Controls)

Hide Inactive

Use	Name	Initial Value	Current Value	Lower Bound	Upper Bound	Object	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	StoppingConditions.True_Anomaly.TripValue	170 deg	173.091 deg	160 deg	180 deg	Propagate	<input type="checkbox"/>	deg
<input checked="" type="checkbox"/>	FiniteMnvr.StoppingConditions.Duration.TripValue	900 sec	973.717 sec	0 sec	1200 sec	Maneuver	<input type="checkbox"/>	sec

Initial Value: 170 deg

Current Value: 173.091 deg

Scaling Value: 1 deg

Objectives and Constraints (Results)

Hide Inactive

Use	Object	Name	Current Value	Goal	Weight	Lower Bound	Upper Bound	Custom Display Unit	Display Unit
<input checked="" type="checkbox"/>	Maneuver	DeltaV	532.223 m/sec	Minimize	1	1e+20 m/sec	1e+20 m/sec	<input checked="" type="checkbox"/>	m/sec
<input checked="" type="checkbox"/>	Propagate1	R_Mag	10000 km	Bound	1	10000 km	10000 km	<input type="checkbox"/>	km

Scaling Value: 1 m/sec

10000 km

Initial State

Target Sequence

Propagate

Maneuver

Propagate1

Action: Run active profiles

When Profiles Converge: Run to RETURN and continue

☐ Continue if profiles don't converge

☐ Reset inner targeters before each run

Profiles

Profiles and Corrections

Apply Changes

Reset

Name	Reset	Apply	Mode	Status	User Com
SNOPT Optimizer	Reset	Apply	Iterate	Converged	Sparse Nonlinear Optim

Target Sequence.SNOPT Optimizer: Finished successfully: optimality conditions satisfied.

Control	Current Value	Last Update	Result	Goal	Current Value	Status
...ns.True_Anomaly.TripValue	173.091467564 deg	-0.0233113066994 de	Maneuver : DeltaV	Minimize	532.223282073 m/sec	-----
...onditions.Duration.TripValue	973.717038038 sec	0 sec	Propagate1 : R_Mag	Bound	9999.99999601 km	SNOPT feasible

Questions?