Exploration of the Sparse Nonlinear Optimizer Profile (SNOPT) in Astrogator

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The Sparse Nonlinear Optimizer profile, or SNOPT, is a tool that allows STK users, specifically in Astrogator, to minimize and maximize objectives. There are a number of ***key takeaways*** *in regards to how SNOPT functions in STK. The first one involves the Decision Variable section. The lower and upper bounds of a variable can be changed if the user wants to limit the freedom SNOPT has to find a solution. The next takeaway explains how to minimize and maximize problem constraints and objectives, which is done in each goal section shown in the results window. Another key piece of information involves when to change the Iteration and Tolerance values. These values can be changed depending on whether or not the user desires a more accurate solution, or for the optimizer to converge faster. Further SNOPT option customization can be done through the use of a specifications file. This file is used to change any number of the SNOPT profile options, and a very helpful case is to customize the log by changing the print and summary settings. There are also a number of general tips and tricks involving ways to improve performance and convergence. These tips involve how to use the differential corrector to locally optimize, how to scale variables and constraints, how to bound variables and constraints, and how to change iteration and tolerance values. All of this information is demonstrated in a mission to the Moon. The goal of this scenario was to optimize different mission parameters, and for this specific case, those objectives were to minimize the total delta-v and to minimize the travel time to the Moon. Under the specific bounds and constraints that were applied to the problem, SNOPT was able to save roughly 61 m/sec of delta-v, and decrease the trip duration by almost 43 hours. Future research can be done in order to investigate how the SNOPT profile runs under different propagators, as well as targeting different constraints and variables. This information would be beneficial to STK users because it would allow for a deeper understanding on which constraints work better under specific conditions.*

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1. Introduction

The Sparse Nonlinear Optimizer profile, or SNOPT, is a tool that allows STK users, specifically in Astrogator, to minimize and maximize objectives. SNOPT was introduced into STK in order to provide a powerful optimization solution that can be applied across the domain of space operation and mission planning. SNOPT separates itself from other optimizers because it is able to handle both linear and nonlinear functions. SNOPT uses a sequential quadratic programming algorithm that obtains search directions from quadratic programming sub problems. A Langrangian function is then reduced along each search direction to determine convergence. The mathematics and programming behind SNOPT is extensive, and the information presented above is just a small portion of the complex calculation process. While this knowledge is useful in terms of understanding how SNOPT operates in the background, the goal of this paper is to provide STK users with a guide to demonstrate how SNOPT functions within Astrogator specifically. Ever since SNOPT was introduced into STK, the AGI team has been gathering feedback, both internal and external, on a number of topics. These topics cover a variety of concepts including how to setup a SNOPT targeting profile, how to customize SNOPT options, how to interpret the iteration log, and general tips and tricks to improve performance and convergence. All of these concepts, and more, are developed, explored, and integrated into an example STK scenario focused on the optimization of a lunar mission.

2. STK Use Case

2.1 SNOPT Targeting Profile

SNOPT optimization is applied in STK through the use of targeting profiles, which are found in target sequences in Astrogator. There are plenty of targeting profiles to choose from, and SNOPT is one of the profiles used to optimize a mission. Inside of the SNOPT profile, there are five different tabs along the top of the window. These are the Variables, Options, Log, Graphs and Scripting tabs. A summary for the Variables, Options and Log tabs is provided below, which includes a **key takeaway** for each section, while a more in depth description of each piece of information, including the Graphs and Scripting tabs, can be found on the [SNOPT Profile help page] at help.agi.com.

2.1.1 Variables

This tab is where any Decision Variables (Controls), and Objectives and Constraints (Results), are fully defined. There needs to be at least one Decision Variable and one Objective in a SNOPT targeting profile in order for it to run properly. For each Decision Variable, the following information is displayed: Use, Name, Initial Value, Current Value, Lower Bound, Upper Bound, Object, Custom Display Unit, Display Unit, and below, the Scaling Value. In summary, some of the information is only for display, but some of it can be changed. The user can activate or deactivate each variable, change the lower and upper bounds, and change the display unit and current value. The information that is display-only includes the name, object, and the initial values.

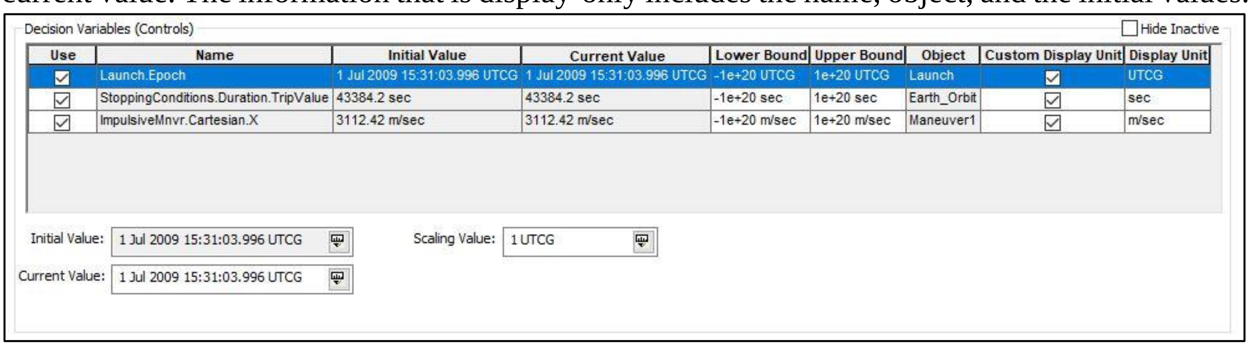
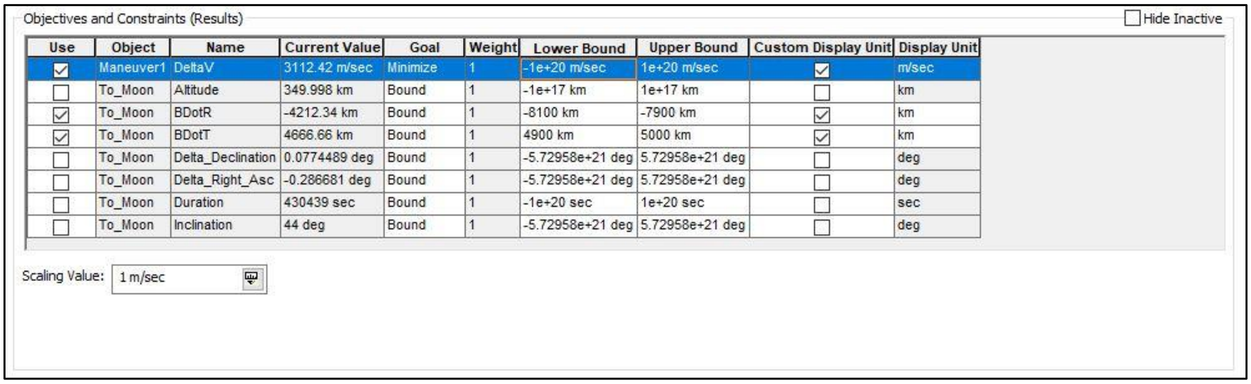


Figure 1: Decision Variables (Controls) Window

The **key takeaway** for the Decision Variable section has to deal with the upper and lower bounds. These values should be changed if the user wants to limit the freedom SNOPT has to complete the mission. One example would be to place an upper bound on a delta-v magnitude control if a minimum time is desired. Another instance would be to place bounds on a launch epoch if a mission has a specific launch window.

For each Objective and Constraint, the following information is displayed: Use, Object, Name, Current Value, Goal, Weight, Lower Bound, Upper Bound, Custom Display Unit, Display Unit, and below, the Scaling Value. In summary, some of the information is only for display, but some of it can be changed. The user can activate or deactivate each result, change the goal and weight, change the lower and upper bounds, and change the display unit. The information that is display-only includes the object, name, and the current value.



Use	Object	Name	Current Value	Goal	Weight	Lower Bound	Upper Bound	Custom Display Unit	Display Unit
☑	Maneuver1	DeltaV	3112.42 m/sec	Minimize	1	-1e+20 m/sec	1e+20 m/sec	☑	m/sec
☐	To_Moon	Altitude	349.998 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☑	To_Moon	BDotR	-4212.34 km	Bound	1	-8100 km	-7900 km	☑	km
☑	To_Moon	BDotT	4666.66 km	Bound	1	4900 km	5000 km	☑	km
☐	To_Moon	Delta_Declination	0.0774489 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg
☐	To_Moon	Delta_Right_Asc	-0.286681 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg
☐	To_Moon	Duration	430439 sec	Bound	1	-1e+20 sec	1e+20 sec	☐	sec
☐	To_Moon	Inclination	44 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg

Figure 2: Objectives and Constraints (Results) Window

The **key takeaway** for the Objective and Constraint section has to deal with the goal and weight information. The default setting for the goal is bound, which allows you to change the upper and lower bounds. If the goal is changed to minimize, SNOPT will ignore the bounds, and change the controls, in order to make the selected result as small as possible. In order to maximize a result, the weight needs to be changed from 1 to -1.

2.1.2 Options

This tab is where SNOPT options are set. The most common options, Iteration Limits and Tolerances, can be changed in the options tab, while the entire set of options can be changed through a SNOPT option specifications file. For the Iteration Limits and Tolerances options, the following settings can be changed: Maximum major iterations, Major feasibility tolerance, Major optimality tolerance, Maximum minor iterations, Minor feasibility tolerance, and Minor optimality tolerance. All of these allow for the user to customize the iterative process that SNOPT undergoes.

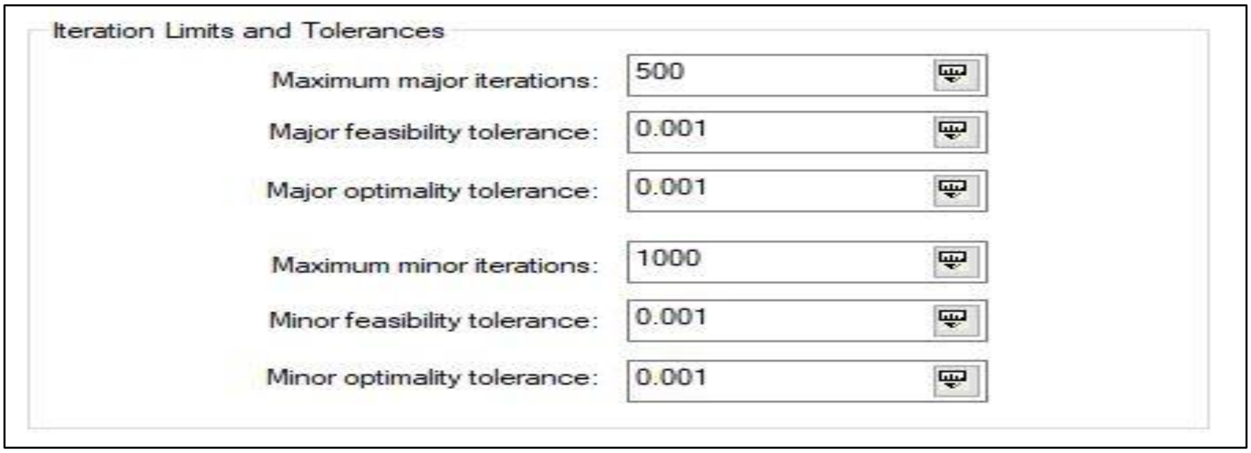


Figure 3: Iteration Limits and Tolerances Window

The **key takeaway** for the Iteration Limits and Tolerances has to deal with when to change the option values. If the user desires an extremely accurate solution, and is willing to wait for a longer amount of time, then the iteration values can be increased, and the tolerance values should be decreased. If the user does not want to wait for a longer amount of time, and is willing to sacrifice accuracy for speed, then the iteration values can be decreased, and the tolerance values should be increased. The value for both iterations and tolerances is dependent on the problem the user is trying to solve, and if one set of values is not providing good enough answers, or is not converging, then they can always be changed to better suit the problem at hand.

The Iteration Limits and Tolerances section allows the user to change the most common settings, but a SNOPT option specifications file can change all of SNOPT's options. A sample file, which contains all of the possible options, and their default values, can be found in the published SNOPT manual starting on page 63. The entire list of possible options, along with their descriptions, can be found starting on page 68 of the SNOPT manual.

```
BEGIN checklist of SPECS file parameters and their default values
* Printing
  Major print level              1        * 1-line major iteration log
  Minor print level              1        * 1-line minor iteration log
  Print   file                   ?        * specified by subroutine snInit
  Summary file                   ?        * specified by subroutine snInit
  Print   frequency            100        * minor iterations log on Print file
  Summary frequency            100        * minor iterations log on Summary file
  Solution                     Yes        * on the Print file
* Suppress options listing                * options are normally listed
  System information            No        * Yes prints more system information
```

Figure 4: Beginning of Sample Specifications File from SNOPT Manual

The **key takeaway** for the SNOPT option specifications file has to deal with how and why an options file would be used. A specifications file starts with the keyword Begin, and stops with the keyword End. It is written in free-format, with each line specifying a single option. Any line with an asterisk (*) signifies a comment. The file can include any number of options that the user desires, so the sample file from the manual can be shortened significantly if a user is only interested in a few options. If a user wants to customize further, these files provide many options that can tailor SNOPT to a user's specific needs. In terms of STK specifically, the default values in the sample file are used every time SNOPT is run, unless an options file is used that changes those values. These default settings are not shown in the options tab because generally the only values that need to be changed are the iteration and tolerance values. A beneficial reason to use the specifications file would be to shorten and user specify the Log. An example of this is provided in the key takeaway information in the Log section.

2.1.3 Log

This tab is where the SNOPT iteration log is displayed. The log is made up of Print and Summary files, which are generated internally by SNOPT when it is run. When SNOPT is using the default specification options, there are six key features of the log that can be easily identified. The first important piece of the default log is the Parameters section. This section displays all of the specification options, and their values, that were used by SNOPT.

```
Parameters
==========

Files
-----
Solution file..........       0      Old basis file ........       0      Standard input.........       5
Insert file............       0      New basis file ........       0      (Printer)..............      11
Punch file.............       0      Backup basis file......       0      (Specs file)...........       0
Load file..............       0      Dump file..............       0      Standard output........       6

Frequencies
-----------
Print frequency........     100      Check frequency........      60      Save new basis map.....     100
Summary frequency......     100      Factorization frequency      50      Expand frequency.......   10000

QP subproblems
--------------
QPsolver Cholesky......
Scale tolerance........   0.900      Minor feasibility tol..  1.00E-03    Iteration limit........   10000
Scale option...........       0      Minor optimality  tol..  1.00E-03    Minor print level......       1
Crash tolerance........   0.100      Pivot tolerance........  3.25E-11    New superbasics........      99
Crash option...........       3      Elastic weight.........  1.00E+05
```

Figure 5: Parameters Section of Log with Default Specification Values

The second important section of the default log is the Matrix Statistics section. This section displays the number of nonlinear constraints, nonlinear variables, linear constraints, and linear variables, along with other matrix information.

```
 Matrix statistics
 -----------------
               Total      Normal        Free       Fixed     Bounded
 Rows              3           0           1           0           2
 Columns           3           0           3           0           0

 No. of matrix elements                    6     Density     66.667
 Biggest  constant element        0.0000E+00  (excluding fixed columns,
 Smallest constant element        0.0000E+00   free rows, and RHS)

 No. of objective coefficients             0

 Nonlinear constraints       2     Linear constraints       1
 Nonlinear variables         3     Linear variables         0
 Jacobian  variables         3     Objective variables      1
 Total constraints           3     Total variables          3
1
```

Figure 6: Matrix Statistics Section of Log with Default Specification Values

The third important section of the default log is the Major Iteration Log section. This section displays information regarding the step size, feasibility, and optimality, as a function of cumulative minor iterations. The Major Iteration Log section, and all of the labels and values, are described in full detail on page 86 of the SNOPT manual.

```
 Itns Major Minors    Step    nCon Feasible  Optimal  MeritFunction     L+U BSwap     nS condZHZ Penalty
    2     0      2               1  8.3E+02  3.0E+01  3.1259234E+03       5              1 5.1E+03         _  r
    3     1      1 6.7E-02       2  7.7E+02  2.6E+01  3.5709785E+03       5              1 2.6E+03 7.3E-13 _  rl
    4     2      1 7.4E-02       4  7.1E+02  2.4E+00  3.5387117E+03       5              1 1.5E+02 7.3E-13 _sm l
    5     2      2 7.4E-02       4  7.1E+02  2.4E+00  3.5387117E+03       5              1 2.2E+02 7.3E-13 _sm    c
    6     3      1 1.0E+00       6  1.3E+02  8.5E-01  3.1127180E+03       5              1 9.4E+01 7.3E-13 _      c
    7     4      1 1.0E+00       7  4.0E-02  2.4E-03  3.1132703E+03       5              1 9.9E+01 9.6E-13 _      c
    8     5      1 1.0E+00       8 (7.5E-06) 2.4E-03  3.1132646E+03       5              1 2.6E+01 9.6E-13 _      c
    9     6      1 1.0E+00      10 (6.0E-05) 1.3E-02  3.1132645E+03       5              1 2.7E+01 9.6E-13 _ M    c
   10     7      1 1.0E+00      11  4.2E-02  2.7E-01  3.1131831E+03       5              1 5.7E+02 9.6E-13 _      c
   11     8      1 2.1E-01      12  8.2E-01  4.7E-01  3.1128772E+03       5              1 7.1E+02 9.6E-13 _      c
   12     9      1 2.1E-01      13  1.4E+00  2.2E-01  3.1127250E+03       5              1 7.9E+02 9.6E-13 _      c
   13    10      1 3.4E-01      14  2.9E+00  1.5E-01  3.1125648E+03       5              1 8.9E+02 9.6E-13 _      c
   14    11      1 1.0E+00      15  7.3E+00  4.5E-02  3.1124507E+03       5              1 1.0E+03 9.6E-13 _      c
   15    12      1 1.0E+00      16  4.7E-02  2.3E-02  3.1123699E+03       5              1 8.8E+02 9.6E-13 _      c
   16    13      1 1.0E+00      17  7.4E-02  1.7E-02  3.1123613E+03       5              1 2.2E+03 9.6E-13 _      c
   17    14      1 1.0E+00      18  9.6E-02  1.2E-03  3.1123569E+03       5              1 2.1E+03 9.6E-13 _      c
   18    15      1 5.3E-03      20  9.5E-02  1.3E-03  3.1123587E+03       5              1 2.1E+03 2.1E-10 _      c
   19    16      1 6.4E-03      21  9.5E-02 (9.6E-05) 3.1123587E+03       5              1 9.7E+01 2.1E-10 _      c
   20    17      1 2.8E-03      22  9.4E-02 (8.6E-05) 3.1123588E+03       5              1 3.2E+01 2.1E-10 _      c
   21    17      1              22  9.4E-02 (7.4E-05) 3.1123570E+03       5              1 3.5E+01         _  R   c
   22    18      1 1.3E-08      23  9.4E-02 (7.6E-04) 3.1123588E+03       5              1 3.1E+01 2.1E-10 _sm    c
   23    18      1              23  9.4E-02  4.3E-03  3.1123570E+03       5              1 2.0E+01         _smR   c
   24    19      1 4.0E-03      24  9.4E-02 (4.8E-05) 3.1123588E+03       5              1 1.6E+00 2.1E-10 _s     c
```

Figure 7: Major Iteration Log Section with Default Specification Values

The fourth important section of the default log is the Exit Summary section. This section provides the SNOPT exit condition and information, as well as the number of iterations and the value of the objective. The Exit Summary section of the log, and all of the labels and values, are described in full detail on page 94 of the SNOPT manual.

```
SNOPTA EXIT   0 -- finished successfully
SNOPTA INFO   1 -- optimality conditions satisfied

Problem name                 AstgProb
No. of iterations                  59   Objective            3.1123605478E+03
No. of major iterations            50   Linear    obj. term  0.0000000000E+00
Penalty parameter           3.448E-09   Nonlinear obj. term  3.1123605478E+03
User function calls (total)       724   Calls with modes 1,2 (known g)      73
Calls for forward differencing    222   Calls for central differencing     210
No. of superbasics                  1   No. of basic nonlinears              2
No. of degenerate steps             0   Percentage                        0.00
Max x                       3 4.3E+04   Max pi                       3 1.0E+00
Max Primal infeas           0 0.0E+00   Max Dual infeas              3 1.1E-04
Nonlinear constraint violn    0.0E+00
```

Figure 8: Exit Summary Section of Log with Default Specification Values

The fifth important section of the default log is the Constraints section. This section displays information regarding the state, value, and upper and lower bounds of the constraints in the problem. The Constraints section of the log, and all of the labels and values, are described in full detail on page 99 of the SNOPT manual.

```
Section 1 - Constraints

 Number   ...Row.. State   ...Value......   Slack Value...  ..Lower Limit.  ..Upper Limit.  .Dual Variable    ..i

      4  r      1    BS           .                 .            None            None          -1.0           1
      5  r      2 A  UL    350000.65912        0.65912    250000.00000    350000.00000       -0.00000         2
      6  r      3    LL        44.00001        0.00001        44.00000        46.00000        0.01666         3
1
```

Figure 9: Constraints Section of Log with Default Specification Values

The sixth important section of the default log is the Variables section. This section displays information regarding the state, value, and upper and lower bounds of the variables in the problem. The Variables section of the log, and all of the labels and values, are described in full detail on page 101 of the [SNOPT manual].

```
Section 2 - Variables

 Number   .Column. State   ...Value......   .Obj Gradient.  ..Lower Limit.  ..Upper Limit.  .Dual Variable     m+j

      1  x      1   SBS      1790.74793           .              None            None          -0.00001          4
      2  x      2    BS     43384.20742           .              None            None          -0.00007          5
      3  x      3    BS      3112.41708        1.00000           None            None           0.00033          6
```

Figure 10: Variables Section of Log with Default Specification Values

The **key takeaway** for the Log section has to deal with how to customize the log using a SNOPT option specifications file. As previously mentioned, all six of the important sections are included in the log because the default specifications option file has included them. It is very possible for a user to create a log that displays user specified information, which is done by creating a custom options file. A sample custom options file is shown (Figure 11), which can be used to toggle the six important sections on and off. If this file was used as is in the options tab, the Exit Summary, Constraints, and Variables would all be displayed in the log, while the Major Iteration Log, Parameters, and Matrix Statistics would not be displayed. This is because the three sections that would not displayed are embedded in the Major print level function, which has a value of zero, while the Constraints and Variables are embedded in the Solution function. The Exit Summary is always displayed unless a Print file function is called with a zero value. In that case, the Exit Summary is not displayed, and the entire log will be empty. In order to only display the Exit Summary, the Major print level function value needs to be zero, and the Solution function needs to be No. If the user changed the Major print level function value to 1, while the Solution function was Yes, then all six important sections will be displayed. If the Major print level function value is changed to 1, and the Solution function is changed to No, then only the Parameters, Matrix Statistics, Major Iteration Log, and Exit Summary sections will be displayed.

```
BEGIN TestLogCustomization

   Major print level      0
   Minor print level      0
   Solution               Yes

End TestLogCustomization
```

Figure 11: Sample Custom Option Specification File

2.2 Tips and Tricks

2.2.1 Local Optimality

The SNOPT targeting profile is built to find locally optimal solutions. This means that SNOPT will work best if it is trying to optimize a trajectory that has already been calculated. One way to do this in STK is to first run a target sequence using the Differential Corrector targeting profile. This will provide a SNOPT profile with a known trajectory, and it can then begin to optimize that specific solution. If a SNOPT profile is run on its own, it will be much more difficult to converge unless the initial values are very close to a possible solution.

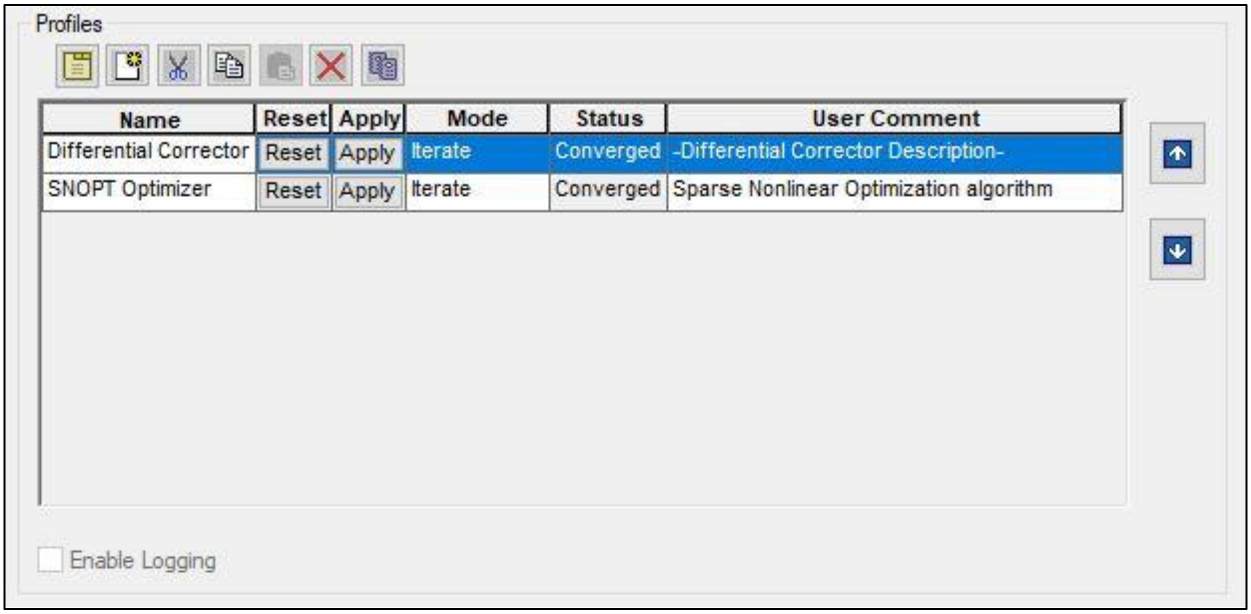
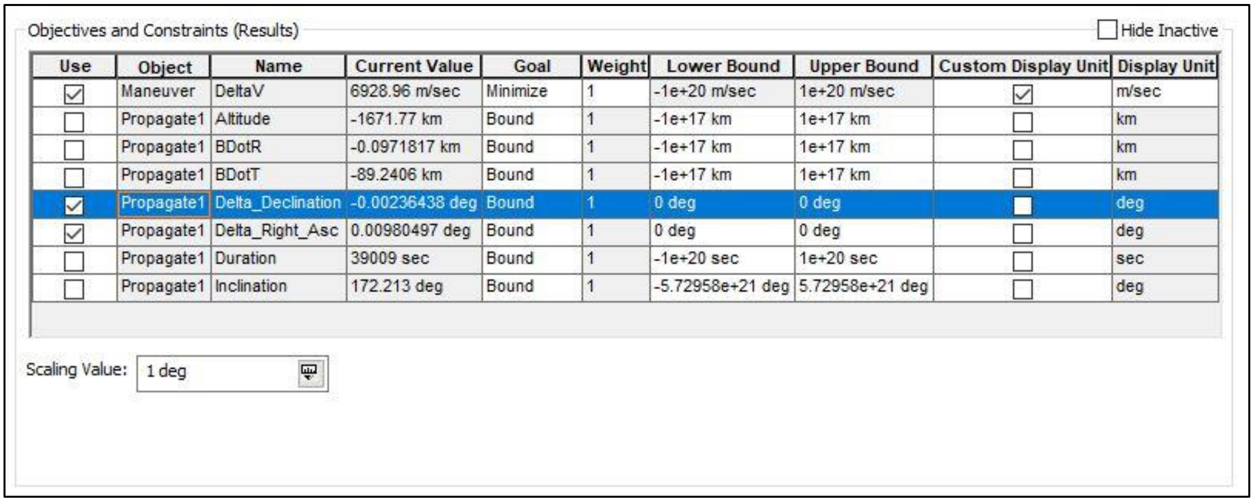


Figure 12: Optimization Setup in Target Sequence Profile Window

2.2.2 Constraints

SNOPT runs better if there are more constraints. The more constraints that a user has defined, the easier it is for SNOPT to converge to a solution. This is because the number of possible solutions is decreased, meaning SNOPT has less room to search for the most optimal solution. There is no limit to the number of constraints that a user can include in a SNOPT targeting profile, so a user should always try to include as many constraints as possible.

Another way that has been shown to decrease convergence time is to bind each constraint to target one value. This is done by setting the lower and upper bounds equal to each other. If a SNOPT profile has difficulty converging, then the user should go to the options tab and increase the tolerance values instead of changing the constraint bounds. If the bounds are changed, then SNOPT will have a wider range of values to test, leading to a longer amount of time. If the tolerance values are changed, SNOPT will only target the desired value, and will converge when the solution is within those tolerance values.



Objectives and Constraints (Results) Hide Inactive

Use	Object	Name	Current Value	Goal	Weight	Lower Bound	Upper Bound	Custom Display Unit	Display Unit
☑	Maneuver	DeltaV	6928.96 m/sec	Minimize	1	-1e+20 m/sec	1e+20 m/sec	☑	m/sec
☐	Propagate1	Altitude	-1671.77 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	Propagate1	BDotR	-0.0971817 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	Propagate1	BDotT	-89.2406 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☑	Propagate1	Delta_Declination	-0.00236438 deg	Bound	1	0 deg	0 deg	☐	deg
☑	Propagate1	Delta_Right_Asc	0.00980497 deg	Bound	1	0 deg	0 deg	☐	deg
☐	Propagate1	Duration	39009 sec	Bound	1	-1e+20 sec	1e+20 sec	☐	sec
☐	Propagate1	Inclination	172.213 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg

Scaling Value: 1 deg

Figure 13: Bounded Constraint Example for Faster Convergence

2.2.3 Major vs. Minor

The SNOPT profile uses two different iteration variants in order to find solutions. These are the major iterations and the minor iterations, which are covered in the Options section. The major iterations generate a sequence of iterates that satisfy the linear constraints, and converges to a point that satisfies the nonlinear constraints and optimality conditions. Each iterate generates a search direction toward what will be the next iterate through a sub problem. The minor iterations are used to solve the sub problems. This information can be used to further customize the SNOPT options, specifically the major iterations and tolerances, and the minor iterations and tolerances. If a user is more concerned with the accuracy of the search direction towards the next iteration, then the minor values could be changed. If a user is more concerned with the accuracy to which the constraints are satisfied, then the major values could be changed. It is common to set the major and minor values equal to each other, but if the user wants to speed up a slow calculation, prioritizing one category over another could be beneficial.

2.2.4 Scaling

Another way to improve SNOPT performance is to scale variables and constraints. Scaling should be used if the parameters in a SNOPT profile have very different magnitudes. Scaling is done internally by dividing the current value by the scaling value, which passes along a unit less value through the algorithm. In the Variables tab, the scaling value for every variable and constraint can be changed so that all parameters in a SNOPT profile have similar orders of magnitude. On example would be to scale an altitude constraint to match an inclination constraint. If the desired inclination is zero degrees, and the desired altitude is 10,000 km, then the altitude constraint scaling value could be set to 10,000 km in order to match the magnitude of the inclination constraint.

2.2.5 Epoch Control

Epoch is commonly used as a control in Astrogator, and there are some helpful tips to know if a user wants to use it in a SNOPT profile. The default bound units for epoch are UTCG, however, instead of accepting a date as a bound value, SNOPT only recognizes numerical values. This is not very intuitive as most people would think to enter a date into the bound field, but then SNOPT will request a numerical value. If the user wants to bind the epoch between specific dates, then it is recommended to change the units from the UTCG unit, to any of the epoch units: EpSec, EpMin, EpHr, EpDay, or EpYr. For all of these units, a numerical value is entered, which represents the time ahead of, or behind, the initial value defined by the user. An example would be to define a launch window for a spacecraft. If the launch window was to be from March 1st to March 31st, an initial value of March 16th would be set, the lower bound would be -15 EpDay, and the upper bound would be +15 EpDay. This will restrict SNOPT to search between these dates to find a solution. If the user is not bounding the epoch, the units do not have to be changed because SNOPT will treat the epoch control as having infinite bounds, in which case the units do not affect the outcome.

Initial Value	Current Value	Lower Bound	Upper Bound	Object
16 Mar 2018 00:00:00.000 UTCG	16 Mar 2018 00:00:00.000 UTCG	-15 EpDay	15 EpDay	Launch
75464.7 sec	75464.7 sec	-1e+20 sec	1e+20 sec	Earth_Orbit
3214.78 m/sec	3214.78 m/sec	-1e+20 m/sec	1e+20 m/sec	Maneuver1

Figure 14: Epoch Control EpDay Unit Example

3. SNOPT Lunar Trajectory

3.1 Mission Outline

This SNOPT application scenario is a lunar trajectory. In this mission, a spacecraft was launched from Cape Canaveral into Earth orbit, underwent an impulsive maneuver to reach the Moon, and then entered lunar orbit. The goal of this scenario was to show how SNOPT can be used to optimize different variables of a deep space mission. This was achieved by creating a spacecraft that used the differential corrector profile in the target sequences to find a solution. This solution was then optimized by creating two new spacecraft from the original one, each using the SNOPT profile to minimize a specific variable. The first spacecraft, *DifferentialCorrector*, uses differential corrector profiles while the other two spacecraft, *SNOPT_DeltaV* and *SNOPT_Time*, use SNOPT profiles. In this scenario, the two variables minimized were impulsive Delta-V and propagation time from Earth to the Moon. For all three spacecraft, the trajectory was calculated through two different targeting sequences, one to target the Moon, and the other to enter lunar orbit. Between all three spacecraft, the setup of the two targeting sequences was mostly the same. All of the commonalities are listed in the next two paragraphs, while the differences are explained in the Differential Corrector, SNOPT Minimum Delta-V and SNOPT Minimum Time sections.

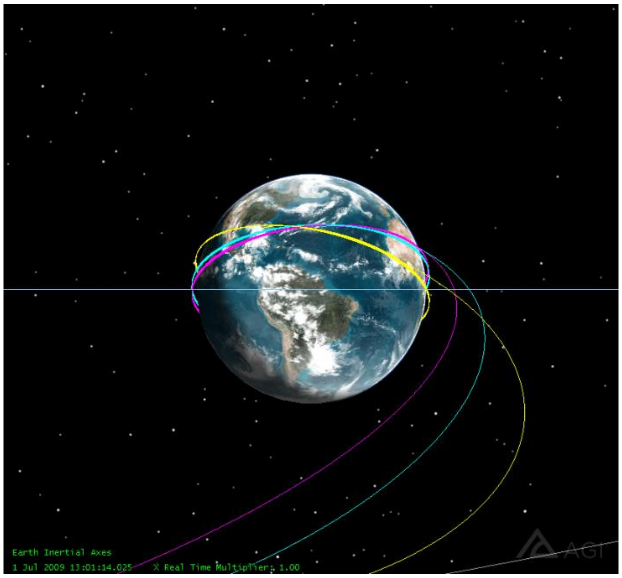


Figure 15: Earth View of Optimized Lunar Mission

The first target sequence (*To Moon*) began with a default launch segment (*Launch*) followed by a propagate segment (*Earth Orbit*), an impulsive maneuver (*Maneuver1*), and a final propagate segment (*To Moon*). The launch segment default values were not changed and the launch epoch was set as a control. The *Earth Orbit* propagate segment used the Earth HPOP propagator and a duration stopping condition where the trip value was set as a control. The impulsive maneuver *Maneuver1* was configured to use thrust vector attitude control with VNC(Earth) thrust axes. The Y and Z axes were set to zero, in order to keep the maneuver within the orbital plane, while the X axis was given

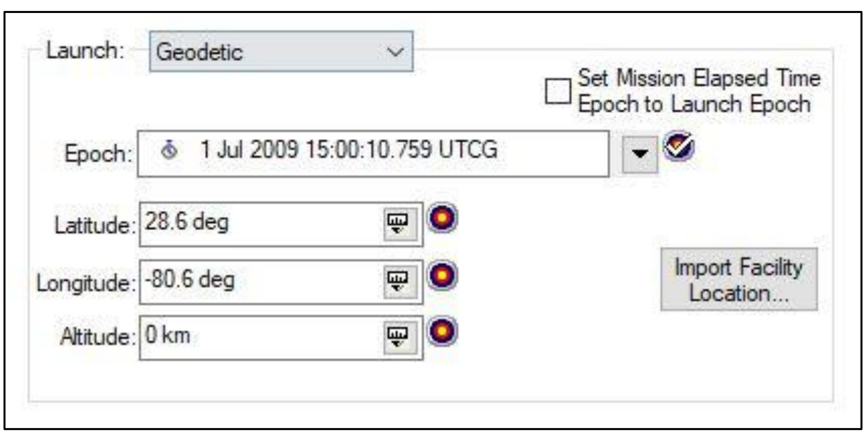


Figure 16: Launch Segment

an initial value of 3.2 km/sec and was set as a control. The *To Moon* propagate segment used the CisLunar propagator and a periapsis stopping condition where the central body was set to be the Moon. In order for the *To Moon* target sequence to target the Moon, seven components were added to the results of the *To Moon* propagate segment. Delta Declination, Delta Right Asc, BDotR and BDotT, found under the MultiBody folder, as well as Inclination, in the Keplerian Elements folder, Altitude, in the Geodetic folder, and Duration, in the Time folder, were all inserted as results. The central/target body for all of the results was changed to Moon, and the coordinate system for the Inclination was changed to Moon TOD. Targeting the moon was done in three phases by adding three different targeting profiles in the *To Moon* target sequence. The first targeting profile, *HitMoon*, used all three controls and used Delta Declination and Delta Right Asc as constraints. Both of those constrains had a desired value of 0 deg. The second targeting profile, *BPlane*, used all three controls and used BDotR and BDotT as constraints. BDotR had a desired value of -8000 km and BDotT had a desired value of 4938.96 km. The third targeting profile, *Approach*, used all three controls and used Altitude and Inclination as constraints. Altitude had a desired value of 300 km and Inclination had a desired value of 45 deg.

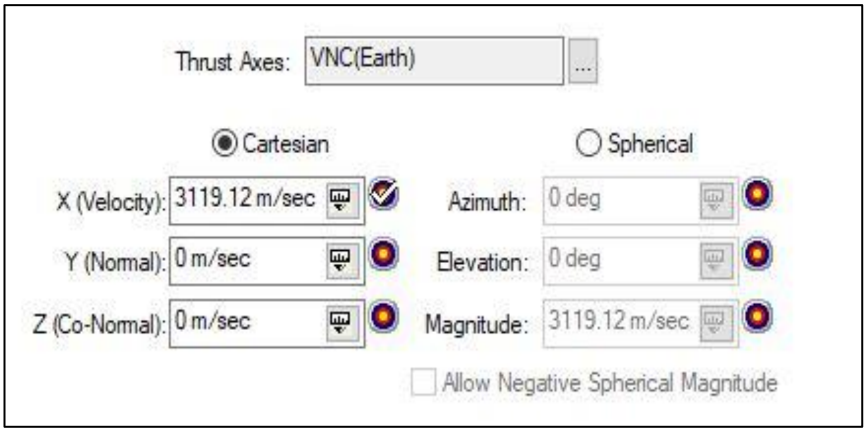


Figure 17: Maeuver1 Segment

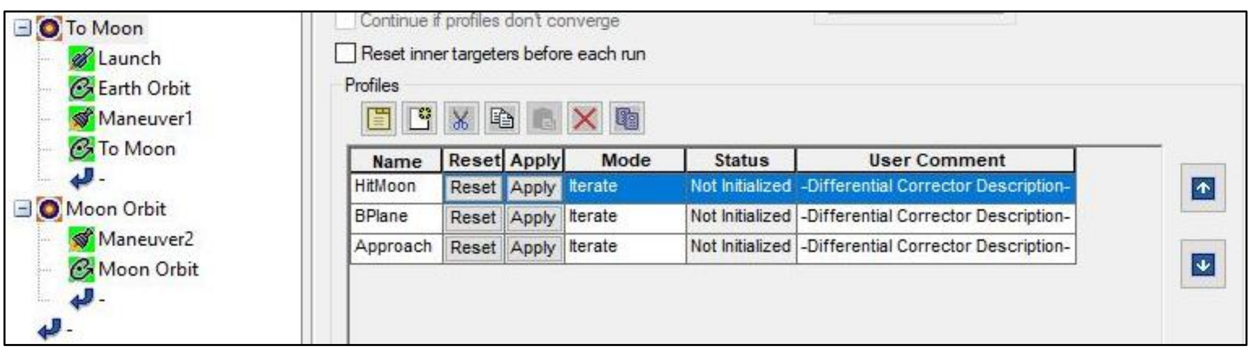


Figure 18: To Moon Target Sequence

The second target sequence (*Moon Orbit*) began with an impulsive maneuver (*Maneuver2*) and ended with a propagate segment (*Moon Orbit*). The impulsive maneuver *Maneuver2* was configured to use thrust vector attitude control with VNC(Moon) thrust axes. The three default Cartesian thrust values were kept and the X axis was set as a control. The *Moon Orbit* propagate segment used the Moon HPOP propagator and a periapsis stopping condition where the central body was set to be the Moon. In order for the *Moon Orbit* target sequence to target lunar orbit, two

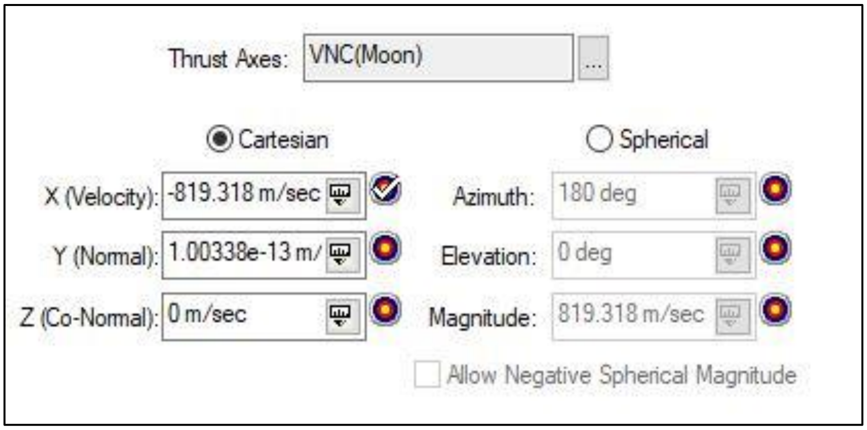


Figure 19: Maneuver2 Segment

components were added to the results of the *Moon Orbit* propagate segment. Eccentricity, in the Keplerian Elements folder, and Flight Path Angle, in the Spherical Elements folder, were both inserted as results. The central body for Eccentricity was changed to be the moon, and the coordinate system for Flight Path Angle was changed to Moon TOD. Targeting lunar orbit was done in one phase by adding a single targeting profile in the *Moon Orbit* target sequence. The targeting profile, *MoonOrbit*, used the maneuvers X value as the control and used Eccentricity and Flight Path Angle as constraints. Eccentricity had a desired value of 0 and Flight Path Angle had a desired value of 0 deg.

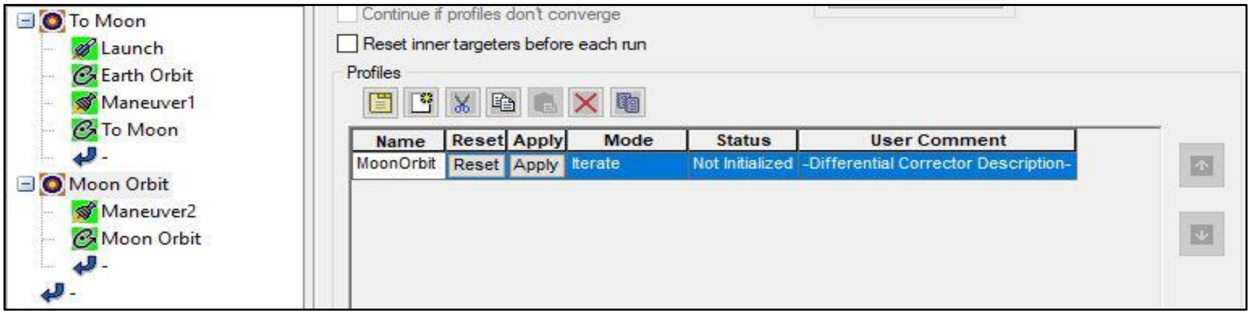


Figure 20: Moon Orbit Target Sequence

3.2 Differential Corrector

The first spacecraft created, *DifferentialCorrector*, used differential corrector targeting profiles to find a trajectory from the Earth, to a circular orbit around the Moon. The MCS for this spacecraft was identical to the setup shown in the Mission Outline because the goal of the differential corrector was to find a possible solution, not necessarily the most optimal solution, so no additional results were required. Once the MCS was properly setup, the action for both target sequences was set to run active profiles, and the entire MCS was run. This action yielded a light blue trajectory, which represented the path that SNOPT would attempt to optimize in the other two spacecraft, *SNOPT_DeltaV* and *SNOPT_Time*.

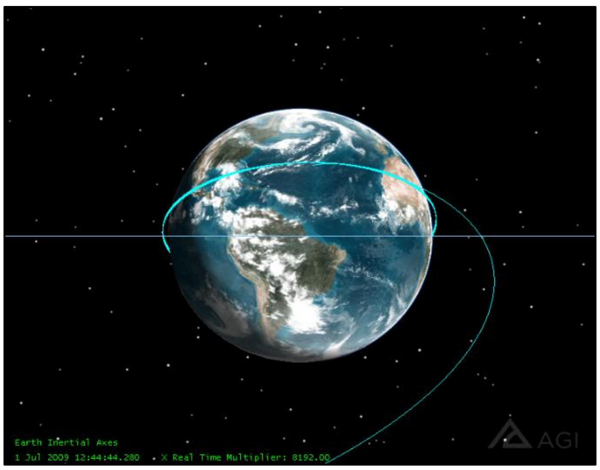


Figure 21: DifferentialCorrector View from Earth

Figure 22: DifferentialCorrector View from Moon

3.3 SNOPT Minimum Delta-V

The second spacecraft, *SNOPT_DeltaV*, used SNOPT targeting profiles to find a similar trajectory to *DifferentialCorrector*. The new spacecraft was able to start from the trajectory of the first spacecraft because the entire first spacecraft was copied and pasted into the object browser. The copy of the first spacecraft was then transformed into *SNOPT*_DeltaV. There are other ways to accomplish this same goal, such as nesting the differential corrector target sequences inside a SNOPT target sequence, but the copy and paste method was chosen to allow for easy visualization of each calculated trajectory. The *SNOPT_DeltaV* trajectory was different from the first trajectory only because a Delta-V result, from the Maneuver folder, was added to the two maneuvers, *Maneuver1* and *Maneuver2*. In this scenario, the Delta-V was minimized in the targeters, and in order for the targeters to acknowledge the minimum Delta-V results, the differential corrector targeting profiles

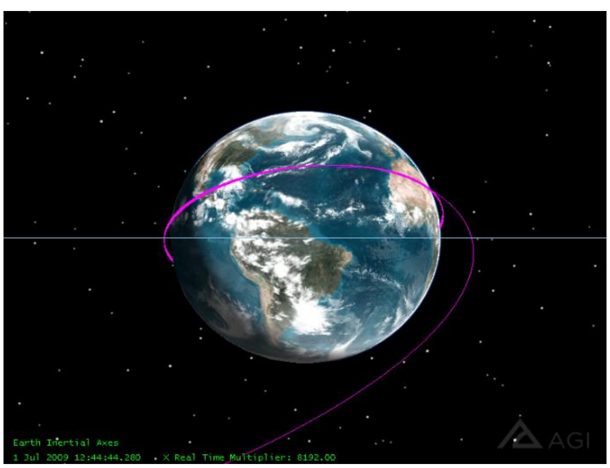


Figure 23: SNOPT_DeltaV View from Earth

in the target sequences had to first be replaced with SNOPT targeting profiles. This process involved manually removing the old differential corrector profiles, and adding in new SNOPT profiles. Since the SNOPT profiles use a bounding system, which is not in the differential corrector profiles, lower and upper bound values had to be considered. In order for SNOPT to converge as fast as possible, the upper and lower bounds were set to the same value, and the tolerance values were changed depending on the profile. For the first targeting profile, *HitMoon*, the default bounds for the controls were left alone, while the lower and upper bounds for Delta Declination and Delta Right Asc were both set to 0 deg. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the second targeting profile, *BPlane*, the default bounds for the controls were left alone, while the BDotR upper and lower bounds were set to -8000 km, and the BDotT upper and lower bounds were set to 4938.96 km. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the third targeting profile, *Approach*, the default bounds for the controls were left alone, while the Altitude upper and lower bounds were set to 300 km, and the Inclination upper and lower bounds were set to 45 deg. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the fourth targeting profile, *MoonOrbit*, in the *Moon Orbit* target sequence, the default bounds for the control were left alone, while the lower and upper bounds for Eccentricity and Flight Path Angle were set to 0 and 0 deg respectively. The major and minor feasibility and optimality tolerance default values of 0.001 were kept. At this point, the SNOPT profiles were fully put into place and the minimum Delta-V results could be activated. The first step was to go into each of the four targeting profiles and to use the Delta-V as a constraint. Then under the goal section for all four targeting profiles, minimize was selected. At this point, the *SNOPT_DeltaV* spacecraft was properly configured. The action for both target sequences was then set to run active profiles, and the entire MCS was run. This action yielded a pink trajectory, which represented the path of minimum Delta-V, from both *Maneuver1* and *Maneuver2*, for the specified bounds and constraints.

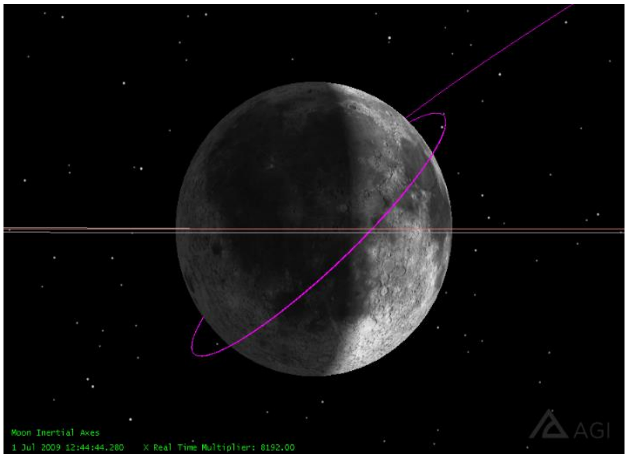


Figure 24: SNOPT_DeltaV View from Moon

Objectives and Constraints (Results) ☐ Hide Inactive

Use	Object	Name	Current Value	Goal	Weight	Lower Bound	Upper Bound	Custom Display Unit	Display Unit
☑	Maneuver1	DeltaV	3112.42 m/sec	Minimize	1	-1e+20 m/sec	1e+20 m/sec	☑	m/sec
☐	To_Moon	Altitude	349.998 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	To_Moon	BDotR	-4212.34 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	To_Moon	BDotT	4666.66 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☑	To_Moon	Delta_Declination	0.0774489 deg	Bound	1	0 deg	0 deg	☐	deg
☑	To_Moon	Delta_Right_Asc	-0.286681 deg	Bound	1	0 deg	0 deg	☐	deg
☐	To_Moon	Duration	430439 sec	Bound	1	-1e+20 sec	1e+20 sec	☐	sec
☐	To_Moon	Inclination	44 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg

Figure 25: Minimized Delta-V Objective

3.4 SNOPT Minimum Time

The third spacecraft, *SNOPT_Time*, used SNOPT targeting profiles to find a similar trajectory to *DifferentialCorrector* and *SNOPT_DeltaV*. The setup for *SNOPT_Time* was nearly identical to the setup of *SNOPT_DeltaV*, except for the different results for optimization that were added. The new spacecraft, *SNOPT_Time*, was able to start from the trajectory of the first spacecraft, *DifferentialCorrector*, because the entire first spacecraft was copied and pasted into the object browser. The copy of the first spacecraft was then transformed into *SNOPT_Time*. The *SNOPT_Time* trajectory was different from the first trajectory only because a Duration result, from the Time folder, was added to the *To Moon* propagate segment. In this scenario, the Duration was minimized in the targeter, *To Moon*, and in order for the targeter to acknowledge the minimum Duration result, the differential corrector targeting profiles in the target sequences had to first be replaced with SNOPT targeting profiles. This process involved manually removing the old differential corrector profiles, and adding in new SNOPT profiles. Since the SNOPT profiles use a bounding system, which is not in the differential corrector profiles, lower and upper bound values had to be considered. In order for SNOPT to converge as fast as possible, the upper and lower bounds were set to the same value, and the tolerance values were changed. For the first targeting profile, *HitMoon*, the default bounds for the controls were left alone, except for an upper bound of 3250 m/sec for the maneuver, while the lower and upper bounds for Delta Declination and Delta Right Asc were both set to 0 deg. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the second targeting profile, *BPlane*, the default bounds for the controls were left alone, except for an upper bound of 3250 m/sec for the maneuver, while the BDotR upper and lower bounds were set to -8000 km, and the BDotT upper and lower bounds were set to 4938.96 km. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the third targeting profile, *Approach*, the default bounds for the controls were left alone, except for an upper bound of 3250 m/sec for the maneuver, while the Altitude upper and lower bounds were set to 300 km, and the Inclination upper and lower bounds were set to 45 deg. The major and minor feasibility and optimality tolerance values were all changed to 0.01. For the fourth targeting profile, *MoonOrbit*, in the *Moon Orbit* target sequence, the default bounds for the control were left alone,

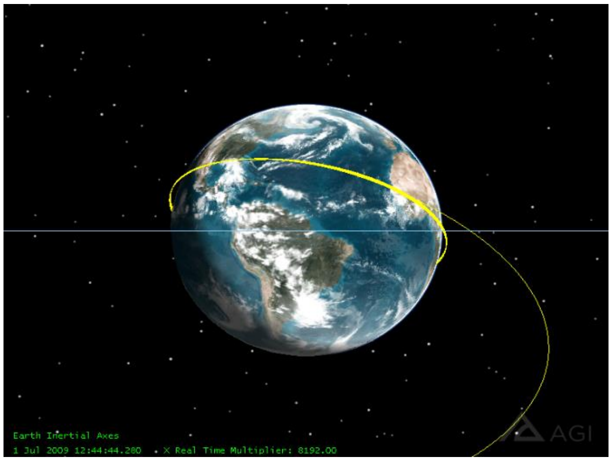


Figure 26: SNOPT_Time View from Earth

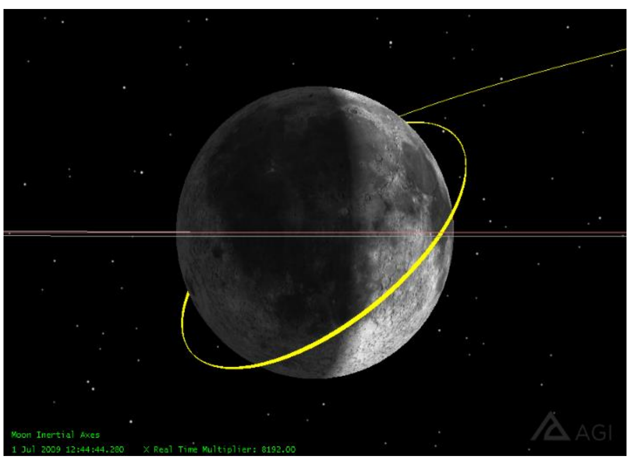


Figure 27: SNOPT_Time View from Moon

while the lower and upper bounds for Eccentricity and Flight Path Angle were set to 0 and 0 deg respectively. The major and minor feasibility and optimality tolerance default values of 0.001 were kept. At this point, the SNOPT profiles were fully put into place and the minimum Duration result could be activated. The first step was to go into the first three targeting profiles, *HitMoon, BPlane, and Approach*, and to use the Duration as a constraint. Then under the goal section for those three targeting profiles, minimize was selected. At this point, the *SNOPT_Time* spacecraft was properly configured. The action for both target sequences was then set to run active profiles, and the entire MCS was run. This action yielded a yellow trajectory, which represented the path of minimum Time, from the Earth to the Moon, for the specified bounds and constraints.

Objectives and Constraints (Results) ☐ Hide Inactive

Use	Object	Name	Current Value	Goal	Weight	Lower Bound	Upper Bound	Custom Display Unit	Display Unit
☐	To_Moon	Altitude	349.994 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	To_Moon	BDotR	-2249.15 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☐	To_Moon	BDotT	2258.08 km	Bound	1	-1e+17 km	1e+17 km	☐	km
☑	To_Moon	Delta_Declination	0.226202 deg	Bound	1	0 deg	0 deg	☐	deg
☑	To_Moon	Delta_Right_Asc	-0.213672 deg	Bound	1	0 deg	0 deg	☐	deg
☑	To_Moon	Duration	167092 sec	Minimize	1	-1e+20 sec	1e+20 sec	☐	sec
☐	To_Moon	Inclination	44.0028 deg	Bound	1	-5.72958e+21 deg	5.72958e+21 deg	☐	deg

Figure 28: Minimized Duration Objective

3.5 Results

After all three spacecraft trajectories had been created, the results were compared in order to determine SNOPT's impact on the optimization of the selected variables. The first variable that was designated to be minimized was the total Delta-V between both maneuvers. A custom Maneuver Summary report was generated for each spacecraft, which showed the Delta-V for both of the maneuvers that took place during the mission. For the first spacecraft, *DifferentialCorrrector*, the *Maneuver1* Delta-V was 3119.12 m/sec and the *Maneuver2* Delta-V was 819.32 m/sec. This meant the total Delta-V for *DifferentialCorrector* was 3938.44 m/sec.

```
Satellite-DifferentialCorrector


                    Maneuver Number          Segment            Delta V (m/sec)
                    ---------------   ---------------------    ----------------
                                  1   To_Moon.Maneuver1             3119.121789
                                  2   Moon_Orbit.Maneuver2           819.318355

Global Statistics
-----------------
Total Delta V                                                       3938.440144
```

Figure 29: DifferentialCorrector Delta-V Results

For the second spacecraft, *SNOPT_DeltaV*, the *Maneuver1* Delta-V was 3112.42 m/sec and the *Maneuver2* Delta-V was 764.81 m/sec. This meant the total Delta-V for *SNOPT_DeltaV* was 3877.23 m/sec.

Satellite-SNOPT_DeltaV

Maneuver Number	Segment	Delta V (m/sec)
1	To_Moon.Maneuver1	3112.417076
2	Moon_Orbit.Maneuver2	764.808941

Global Statistics	
Total Delta V	3877.226017

Figure 30: SNOPT_DeltaV Delta-V Results

For the third spacecraft, *SNOPT_Time*, the *Maneuver1* Delta-V was 3250 m/sec and the *Maneuver2* Delta-V was 1335.84 m/sec. This meant the total Delta-V for *SNOPT_Time* was 4585.84 m/sec.

Satellite-SNOPT_Time

Maneuver Number	Segment	Delta V (m/sec)
1	To_Moon.Maneuver1	3250.000000
2	Moon_Orbit.Maneuver2	1335.840805

Global Statistics	
Total Delta V	4585.840805

Figure 31: SNOPT_Time Delta-V Results

These results aligned with the expectations because *SNOPT_DeltaV* had the smallest total Delta-V. This meant that SNOPT was able to alter the *DifferentialCorrector* trajectory, within the specified bounds, in order to minimize the amount of total Delta-V throughout the mission, saving roughly 61 m/sec of Delta-V. In terms of the other two spacecraft, *DifferentialCorrector* had a total Delta-V very close to *SNOPT_DeltaV*, while *SNOPT_Time* had a much higher total Delta-V. This is explained by the idea that it takes more fuel, and subsequently, more Delta-V, in order for a spacecraft to complete a trajectory in a shorter amount of time. Since the goal of *SNOPT_Time* was to minimize the amount of time it took for the spacecraft to reach the Moon from Earth, the Delta-V was significantly increased. This is why the upper bounds were all set to 3250 m/sec, as SNOPT would have otherwise infinitely increased the Delta-V.

The second variable that was selected to be minimized was the trip duration between Earth and the moon. An MCS Summary report was generated for each spacecraft, which showed the Duration of the *To Moon* propagate segment. This was found in the Propagate To Moon.To Moon section of the report, under the User-Selected Results at the bottom of the first Satellite State at End of Segment section. For the first spacecraft, *DifferentialCorrector*, the Duration value was 321,543.06 seconds, or 89.32 hours.

```
User-selected results:
    Delta Declination =        0.1217965343890061 deg
    Delta Right Asc =       -0.290882902869013 deg
    BDotR =    -3929.8249394279391709 km
    BDotT =     4053.7685941005079258 km
    Inclination =          44.98958801765566 deg
    Altitude =      300.0250859725551891 km
    Duration =   321543.0612615133868530 sec
```

Figure 32: DifferentialCorrector Duration Results

For the second spacecraft, *SNOPT_DeltaV*, the Duration value was 430,438.82 seconds, or 119.57 hours.

```
User-selected results:
    Delta Declination =       0.07744885993396111 deg
    Delta Right Asc =       -0.2866806370087314 deg
    BDotR =    -4212.3428992819508494 km
    BDotT =     4666.6637733300303807 km
    Inclination =          44.00003122913569 deg
    Altitude =      349.9976035766154610 km
    Duration =   430438.8210168223595247 sec
```

Figure 33: SNOPT_DeltaV Duration Results

For the third spacecraft, *SNOPT_Time*, the Duration value was 167,092.12 seconds, or 46.41 hours.

```
User-selected results:
    Delta Declination =        0.2262020403916084 deg
    Delta Right Asc =       -0.2136721852750377 deg
    BDotR =    -2249.1459966402671853 km
    BDotT =     2258.0847109195492521 km
    Inclination =          44.00278700479348 deg
    Altitude =      349.9935197655744901 km
    Duration =   167092.1234261785866693 sec
```

Figure 34: SNOPT_Time Delta-V Results

These results aligned with the expectations because *SNOPT_Time* had the smallest Duration value. This meant that SNOPT was able to alter the *DifferentialCorrector* trajectory, within the specified bounds, in order to minimize the amount of time it took to reach the Moon from Earth, decreasing the time by almost 43 hours. In terms of the other two spacecraft, *DifferentialCorrector* and *SNOPT_DeltaV* both had much larger duration values, with the *SNOPT_DeltaV* duration being the largest of all three spacecraft. This is explained by the idea that a smaller Delta-V will need a longer amount of time than a higher Delta-V to accomplish the same task. Since the goal of *SNOPT_DeltaV* was to minimize the total Delta-V in the mission, the Duration was significantly increased.

3.6 Future Research

There are two major areas of research that would be important to study in the future. One of these is to try and run this lunar trajectory with different propagators such as point mass, J2, and J4. It would be beneficial to gather data on how the SNOPT profile runs under different propagators, and to see how the results were different from the HPOP propagation that was initially used. The table below represents data that would be collected.

	Total Delta-V (m/sec)			Duration (sec)		
Propagator	*DifferentialCorrector*	*SNOPT_DeltaV*	*SNOPT_Time*	*DifferentialCorrector*	*SNOPT_DeltaV*	*SNOPT_Time*
HPOP	3938.44	3877.22	4585.84	321543.06	430438.82	167092.12
Point Mass						
J2						
J4						

Table 1: Delta-V and Duration Results across Multiple Propagators

Another research opportunity would be to run this lunar trajectory and target different constraints. For example, the result for the *Moon Orbit* propagation could be changed from eccentricity to mean eccentricity, and then to signed eccentricity in order to see how targeting different constraints will affect the results. This type of research, along with testing different propagators, would be extremely beneficial because it would provide Astogator users with more data on which constraints work better under specific conditions.

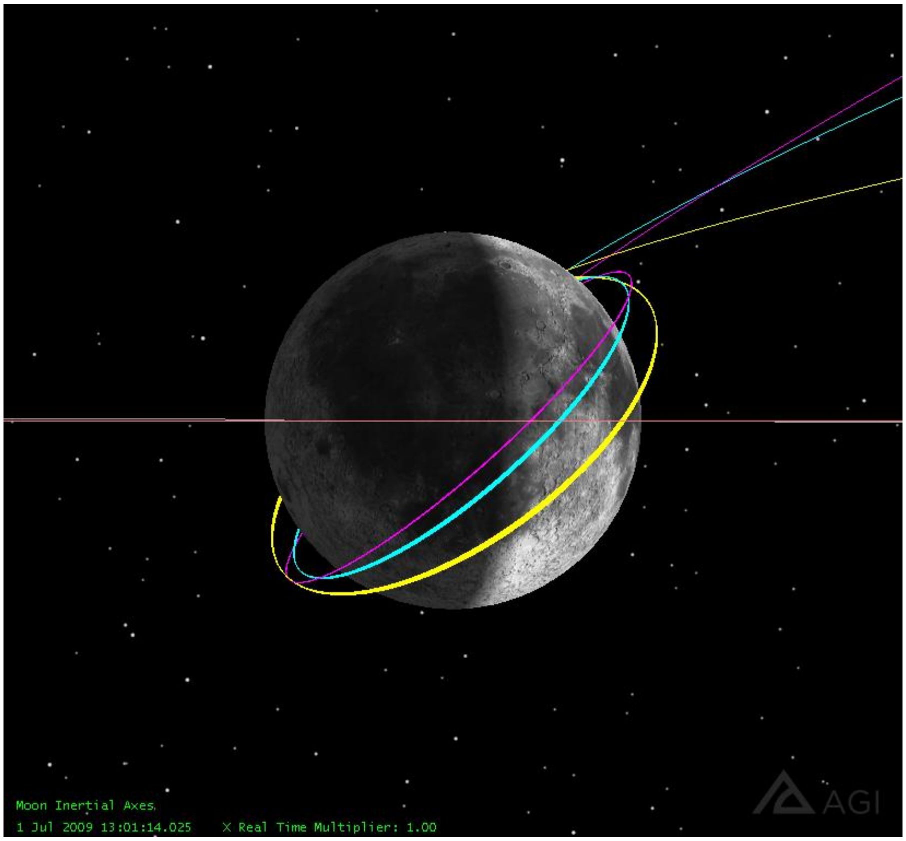


Figure 35: Moon View of Optimized Lunar Mission

4. Conclusion

The SNOPT profile in Astrogator is a tool designed to optimize local solutions. It allows for users to minimize, maximize, and bound objectives in order to optimize their mission. Users of SNOPT can adjust their mission to save fuel, time, and many other aspects, which will ultimately minimize mission costs as well. There are many pieces of advice that should be taken into consideration when using a SNOPT profile. A Differential Corrector profile should be run first in order to provide SNOPT with initial values that are proven to be a solution. This is what SNOPT is built to do, and this practice will lead to better performance. SNOPT was also built to handle as many constraints as possible, so the more constraints that are introduced into the problem, the easier it will be for SNOPT to optimize a solution. Furthermore, if the lower and upper bounds for constraints are set to be equal to each other, SNOPT will target that single value instead of a range of values. This can be taken a step further by changing the iteration and tolerance values, for both minor and major categories, if a user wants to put an emphasis towards performance or accuracy. The ability to customize SNOPT even further is available in the form of the SNOPT option specifications file. This file has a plethora of options that can be changed, and a very useful case involves the customization of the SNOPT log for much easier interpretation. SNOPT will continued to be studied, tested, and documented, as it is a very powerful tool. Optimization is a key aspect of any mission, and SNOPT is a recognized solution.

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Special thanks to….

Pradipto Ghosh, Cody Short, Austin Claybrook, Kyle Kochel, Ethan Whitaker, John Thompson, Jens Ramrath, Kate Lane, and the entire AGI team!