EMTG Tutorial: LowSIRIS-REx

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Revision Date	**Author**	**Description of Change**
December 2, 2022	Tim Sullivan	Initial revision.
June 30, 2023	Joseph Hauerstein	Conversion to LaTeX.
August 4, 2023	Joseph Hauerstein	Addition of Known Issues section.

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Contents

List of Known Issues

List of Acronyms

EMTG Evolutionary Mission Trajectory Generator

SNOPT Sparse Nonlinear OPTimizer

SRP solar radiation pressure

NASA National Aeronautics and Space Administration

NLP Nonlinear Program

MBH Monotonic Basin Hopping

MGALT Multiple Gravity Assist with Low-Thrust

FBLT Finite-Burn Low-Thrust

1 Introduction

This tutorial assumes that you have already completed the OSIRIS-REx chemical propulsion mission tutorial, `1_OSIRIS-REx`.

This tutorial changes the chemical mission of the OSIRIS-REx tutorial to a low-thrust version that is called LowSIRIS-REx. Low-thrust electric propulsion is characterized by high power requirements and low thrust acceleration, but also very high specific impulse (Isp), leading to very good mass fractions. However, low-thrust trajectory design is a very different process from chemical trajectory design. Like chemical design, the optimal launch date, flight time, and dates of each flyby (if applicable) must be found. Unlike chemical design, low-thrust missions must find a time-history of thrust control for the entire mission; low-thrust propulsion events cannot be modeled as a small number of discrete deep space maneuvers (DSMs). A consequence of this is that low-thrust electric propulsion mission design requires accurate modeling of propulsion and power systems. As a result, every spacecraft design drives a unique trajectory design!

First, create a new directory for this mission. It will be very similar to the one used in the OSIRIS-REx tutorial. Name the new directory LowSIRIS-REx. Copy/paste the contents of the OSIRIS-REx directory into the new LowSIRIS-REx directory except for any results subdirectories you have created by executing Evolutionary Mission Trajectory Generator (EMTG).

Open the new copy of the emtgopt file in PyEMTG. Anytime you copy an EMTG mission directory, you will need to ensure that all relevant paths in the EMTG Options file are changed by using PyEMTG or a text editor. For the new LowSIRIS-REx mission, ensure the "Hardware library path" in the "Spacecraft Options" tab is updated to the location of the new directory for this mission you created such as `C:\EMTG\Tutorials\LowSIRIS-REx\hardware_models\` (Do not forget the trailing slash in this path or EMTG will throw an error at run time). Do the same for the "Working directory" in the "Output Options" tab. (Create a new results folder like you did for OSIRIS-REx.) You do not need to create a new copy of the Universe folder since the same Universe folder is being used, so the path in the "Physics Options" tab should not need to be changed.

2 LowSIRIS-REx Options

Make the following changes to the new LowSIRIS-REx EMTG options file.

2.1 Global Options

Switch to the "Global Options" tab and set the following options as shown in Figure 1:

- **Mission name:** "LowSIRIS-REx"
  - Save the options file. Note that the default save name changed to match the new mission name. Keep the updated mission name as the save name.
- **Mission type:** "Multiple Gravity Assist with Low-Thrust (MGALT)"
  - The MGALT transcription is EMTG's implementation of the Sims-Flanagan transcription, which is a low-fidelity model of low-thrust trajectories suitable for preliminary mission design.
- **Objective function:** "2: maximum final mass"

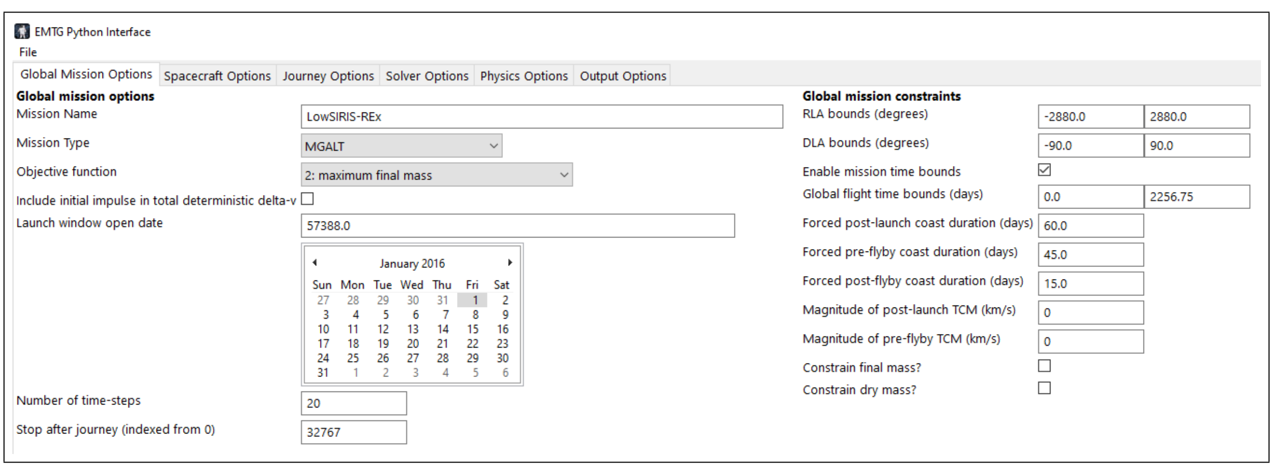

Figure 1: Global Options.

2.2 Spacecraft Options

Switch to the "Spacecraft Options" tab and set the following options as shown in Figure 2:

- **Allow initial mass to vary:** "On"
  - Lets EMTG use less initial mass than the launch vehicle can inject to a given C3 if that results in a higher final mass. Even with this checked, EMTG will not allow the initial mass to be greater than the capabilities of the launch vehicle.
- **Power margin (fraction):** "0.15"
  - This effectively decreases the power made available to the propulsion system, compared to what is theoretically available.
- **Thruster duty cycle:** "0.9"
  - This is a multiplier on the calculated thrust acceleration and is used to approximately take into account the fact that low-thrust spacecraft must periodically coast to allow for activities like navigation to take place. Both this setting and that for the previous option are standard for NASA preliminary design.
- **Power and Propulsion Coefficients:** Use Table 1

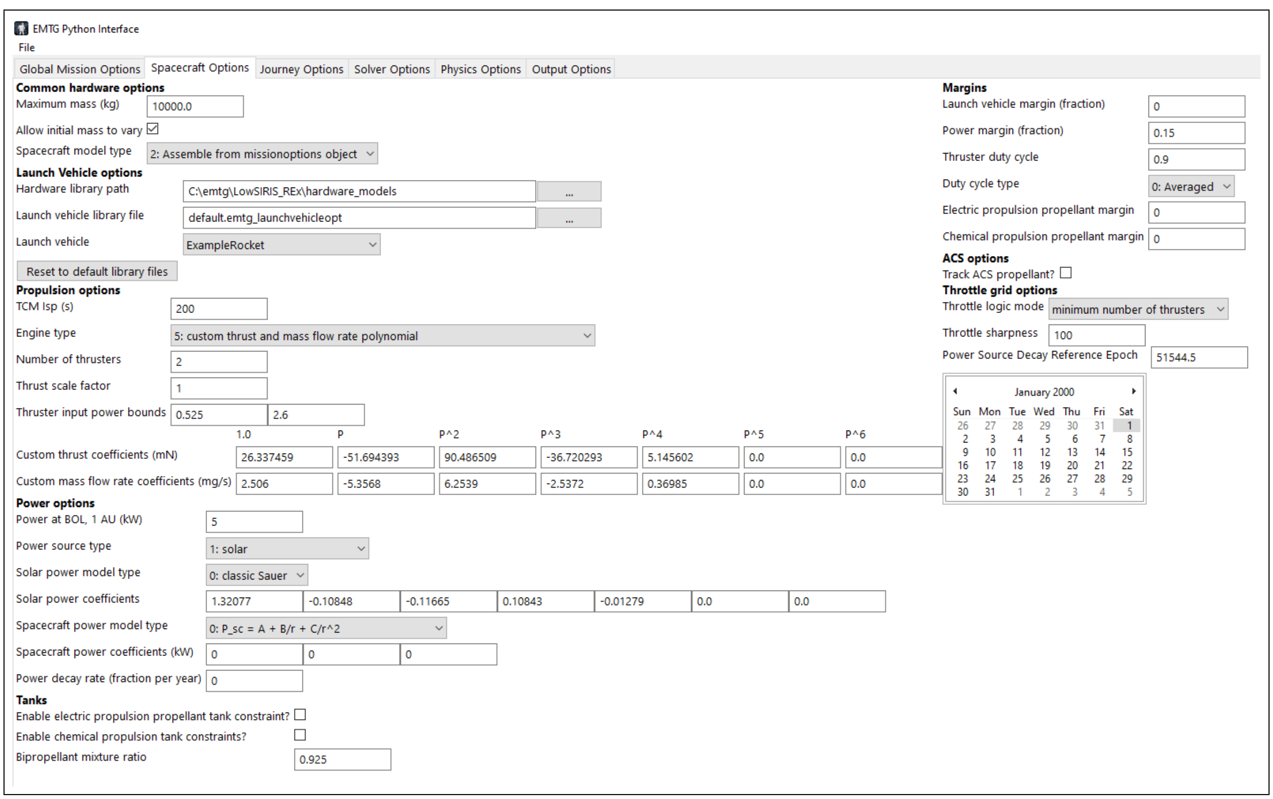

Figure 2: LowSIRIS-REx Thruster Settings.

Parameter	1.0	P	P2	P3	P4
Custom thrust coefficient (mN)	26.337459	-51.694393	90.486509	-36.720293	5.145602
Custom mass flow rate coefficients (mg/s)	2.506	-5.3568	6.2539	-2.5372	0.36985

Table 1: Spacecraft Propulsion Coefficients.

2.3 Journey Options

Switch to the "Journey Options" tab and, starting with the "Earth_to_Bennu" Journey, set the following options as shown in Figure 3:

- **Journey arrival type:** "3: rendezvous (no maneuver)"
  - This means that the spacecraft is not allowed to perform an impulse at arrival (because it does not have a chemical engine). Instead, the low-thrust propulsion system will be required to gradually change the speed of the spacecraft to match the position and velocity of Bennu at arrival.
- **Flyby sequence** "[]"
  - For LowSIRIS-REx, the Earth flyby should be removed because it is less optimal than a direct-to-Bennu trajectory.

Switch to the "Bennu_to_Earth" Journey and make the following changes as shown in Figure 4:

- **Departure type:** "2: free direct departure"
  - This means that the spacecraft starts with the position and velocity of Bennu and no initial impulse.
- **Forced terminal cost (days:** "90" days
  - This means that no thrust is allowed 90 days prior to Earth return. The spacecraft can make small adjustments using chemical thrusters during that time, but the electric propulsion system will not be used. (The small adjustments with chemical maneuvers are statistical maneuvers and are not modeled in this tutorial.)

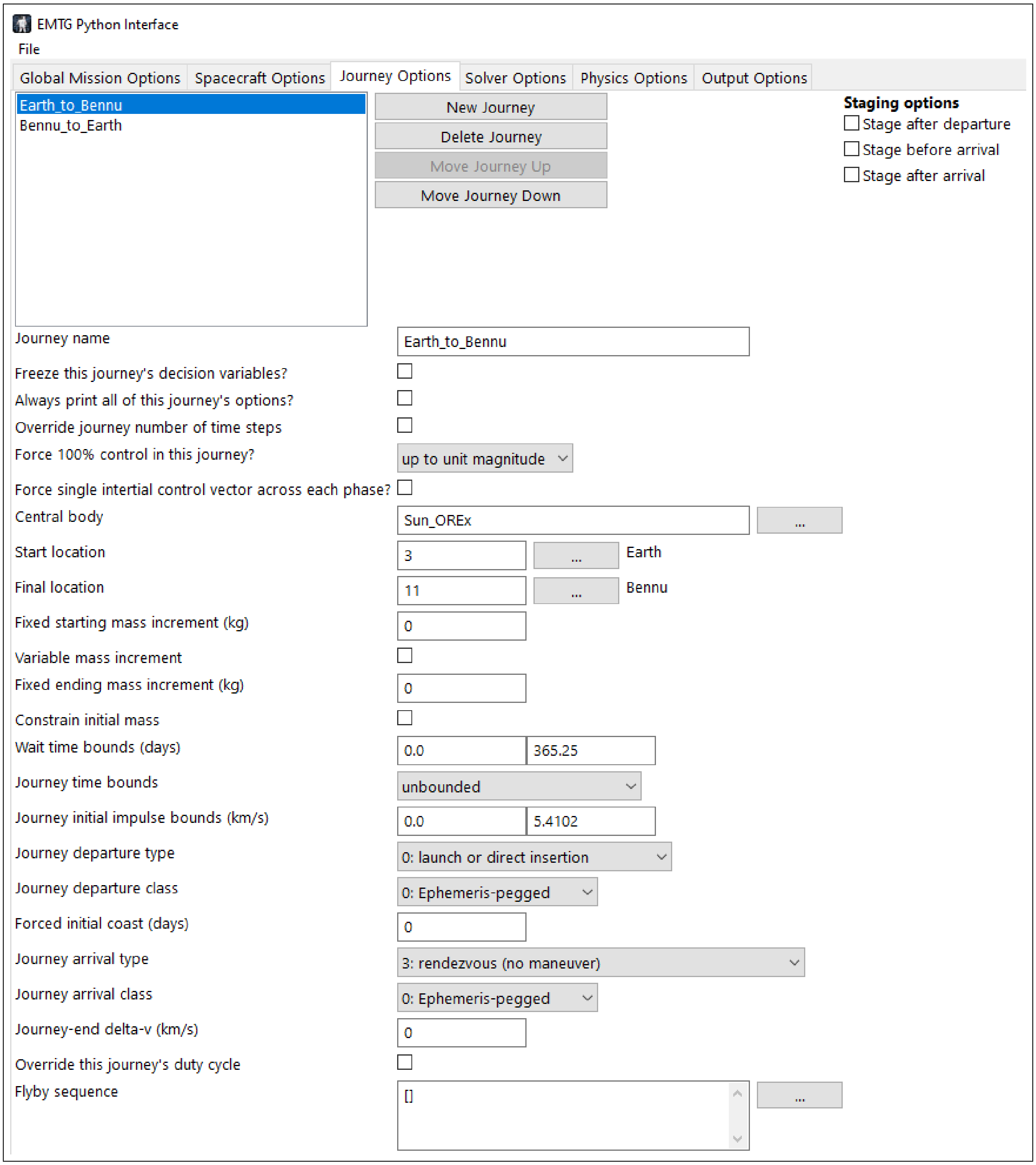

Figure 3: Earth to Bennu Journey.

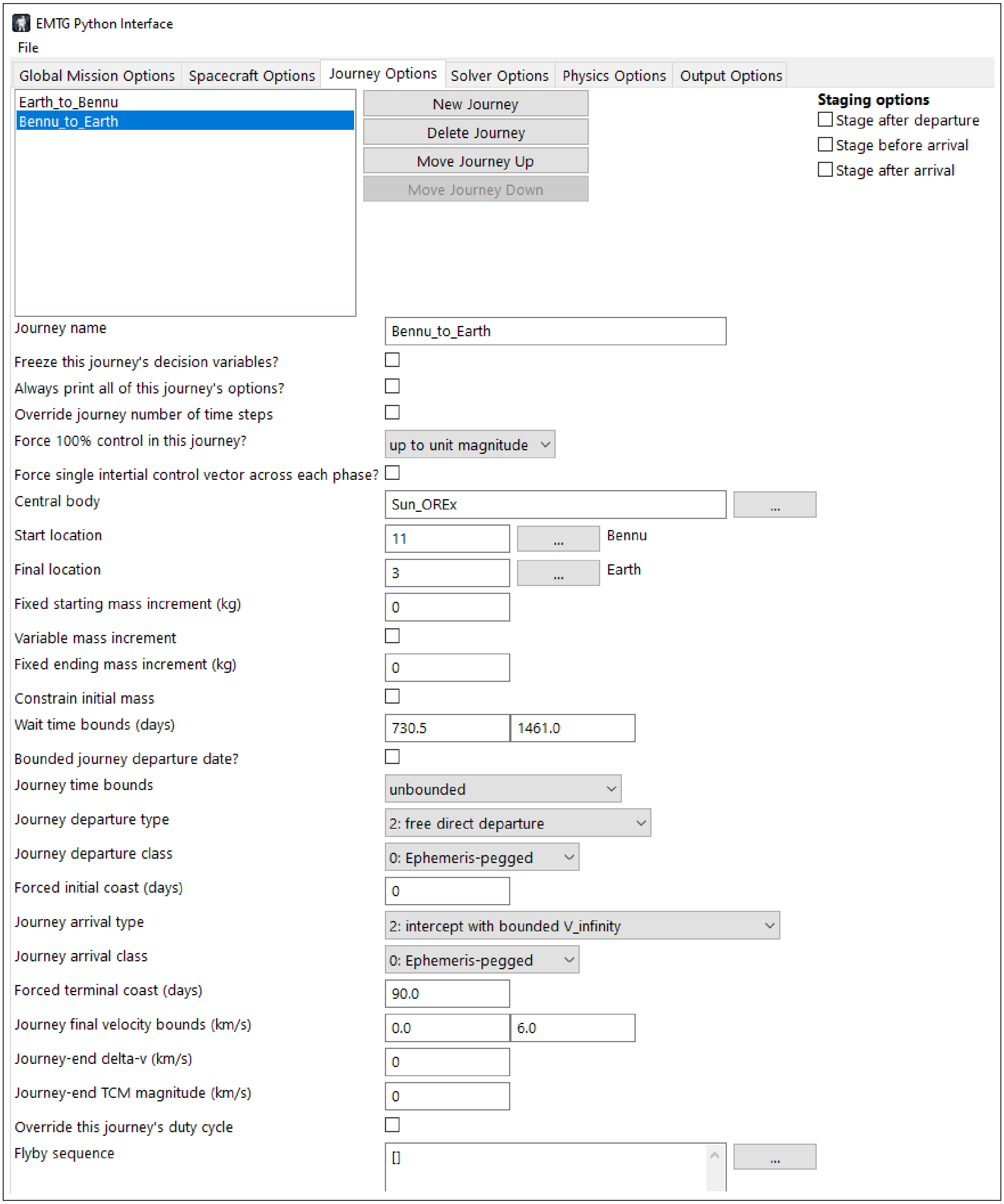

Figure 4: Bennu to Earth Journey.

2.4 Solver Options

No changes are needed to the Solver options here. However, you may want to increase "Maximum run time (s)" from the default 60 to, say, 120, if EMTG does not find a feasible solution using the default value. In general, a low-thrust mission requires more time to find feasible and optimal solutions than a chemical mission because the optimization problem is larger: more decision variables and more constraints. The Solver options can be seen in Figure 5.

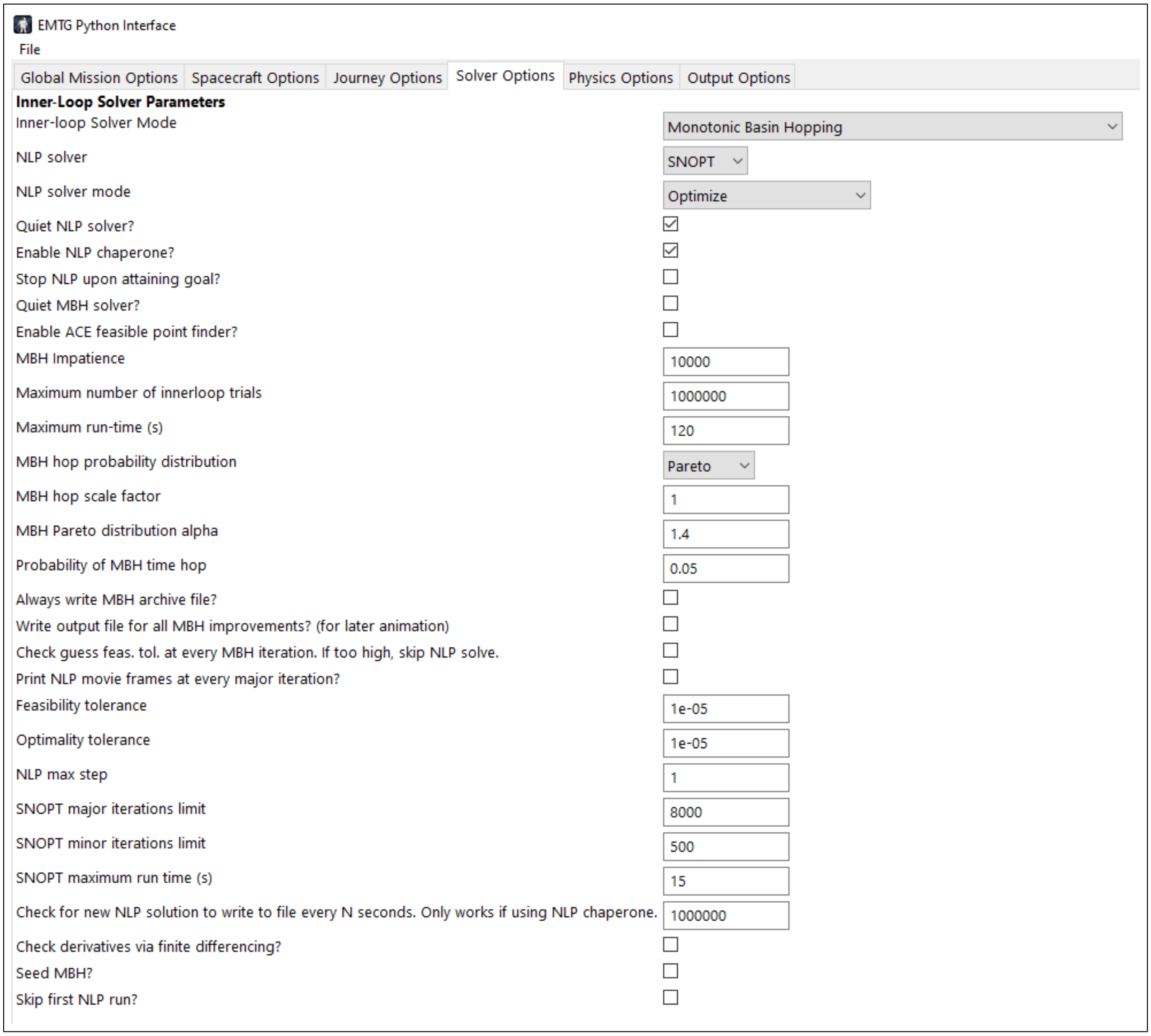

Figure 5: Solver Options.

3 Run and Post-Process

Run the mission (File->Run or Ctrl+r) and plot the trajectory when finished. Keep in mind that the maximum run time is short, and solutions may vary from run to run due to the stochastic nature of monotonic basin hopping. An example plot can be seen in Figure 6.

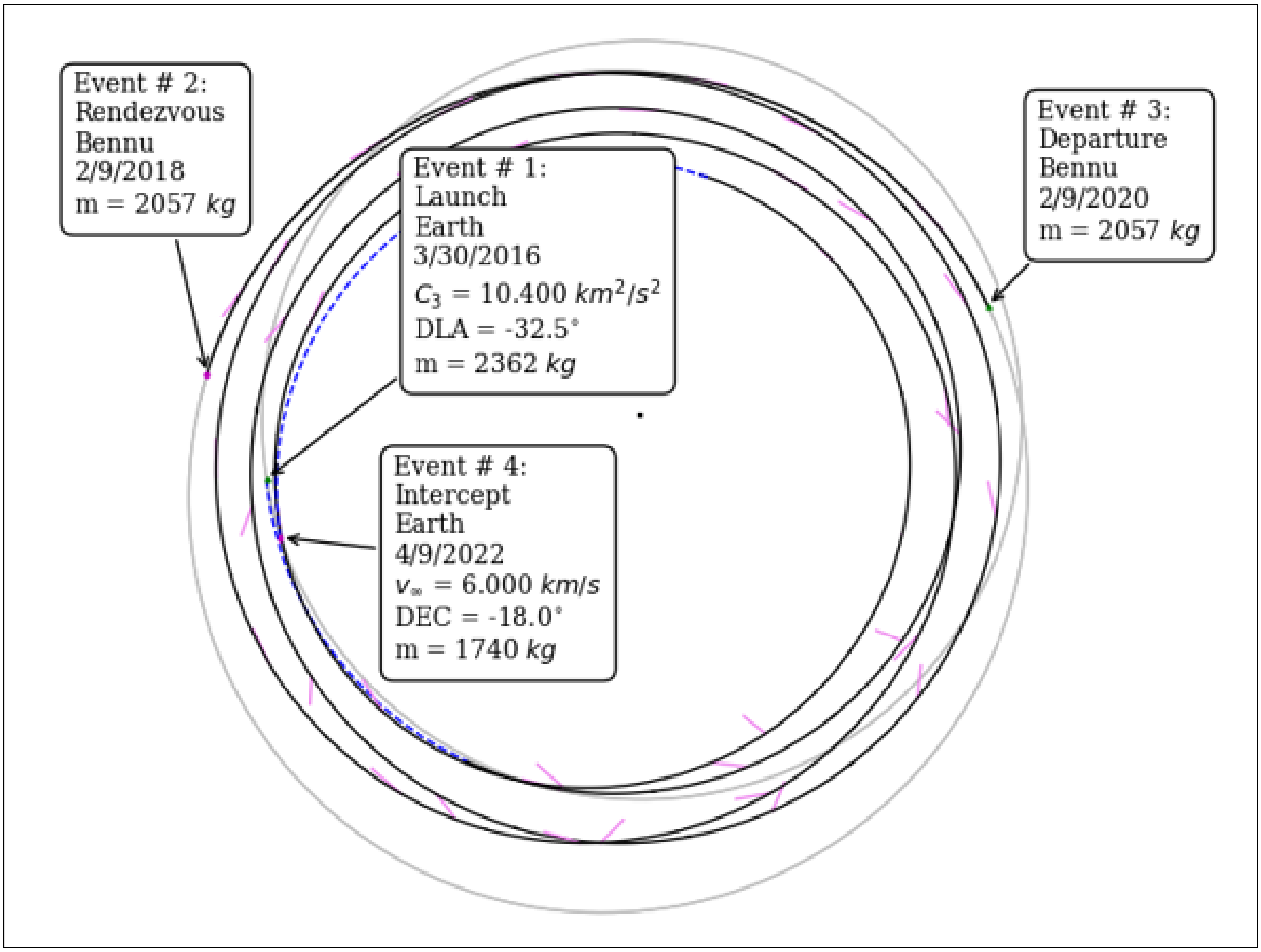

Figure 6: Trajectory Plot.

In addition to trajectory plots, PyEMTG can create plots of systems parameters, such as power, propulsion, and distance from the Sun and Earth. PyEMTG can also map the continuous low-thrust model to a discrete throttle table if you have one. An example data plot can be seen in Figure 7.

Note: Keep in mind that some options, such as "Distance from Earth" will not work without installing additional python packages.

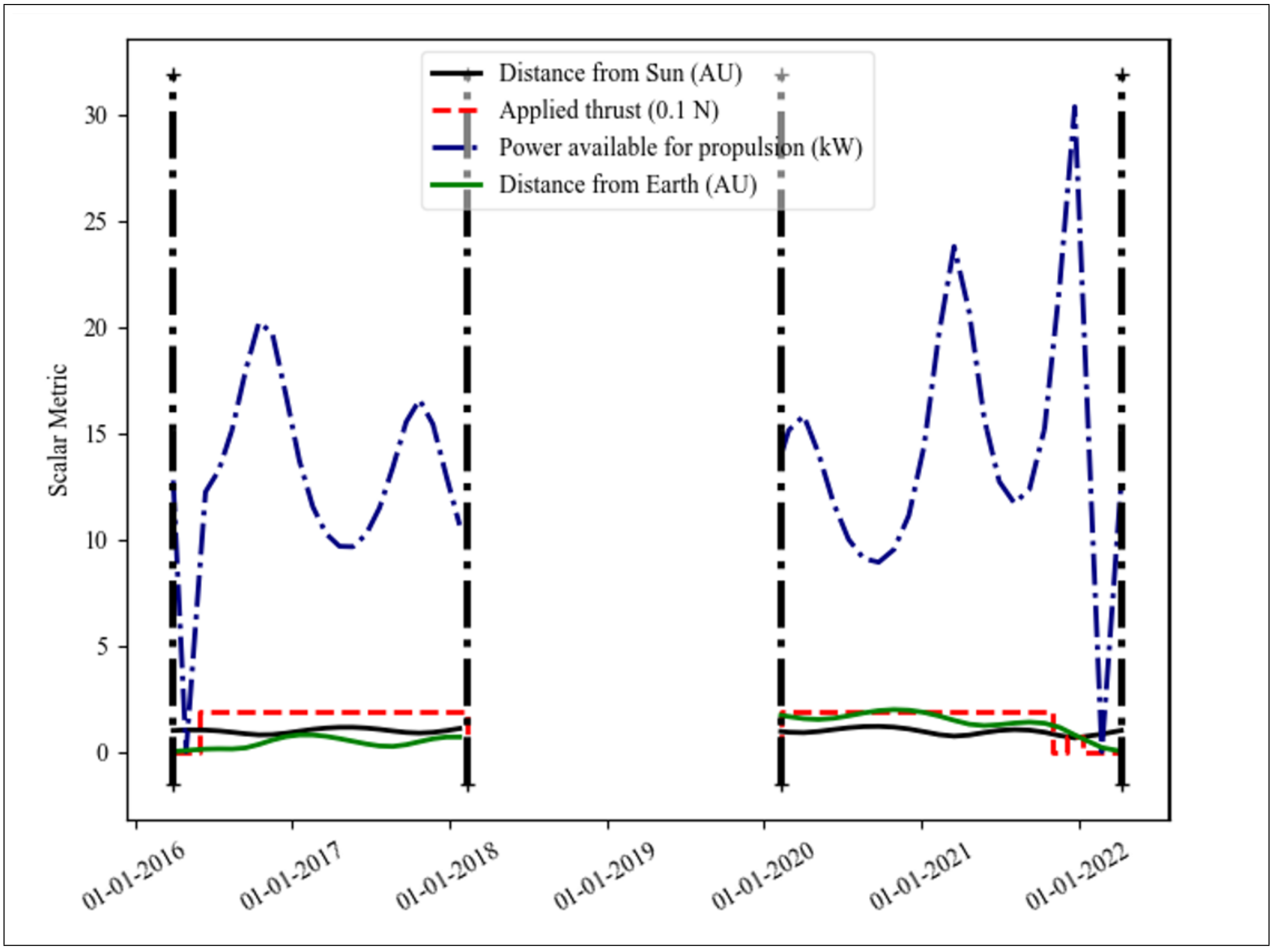

Figure 7: Example Data Plot.

4 LowSIRIS-REx Medium-High Fidelity Options

The MGALT transcription is not adequate for detailed design work because it approximates the true low-thrust trajectory with a sequence of conic arcs and bounded impulses (the Sims-Flanagan model). For a more accurate representation of the trajectory, the Finite-Burn Low-Thrust (FBLT) transcription will be used, which utilizes a numerical integrator and the true low-thrust equations of motion. FBLT can support perturbing accelerations like third-body gravity and solar radiation pressure (SRP). (This is optional and these perturbations will not be turned on in this example.) However, only changing the transcription from MGALT to FBLT does not change the body encounters from patched-conic to "real" encounters. EMTG does support fully integrated gravity assists, orbit insertion, escape, etc., but these are outside the scope of this tutorial.

4.1 Global Options

Change the following options in the "Global Mission Options" tab as shown in Figure 8:

- **Mission name:** “LowSIRIS-REx_FBLT.emtgopt”
  - Perform File->Save (Ctrl+s) and make sure that the save file name and location are correct.
- **Mission type:** “FBLT”
- **Number of time-steps:** “40”
  - A higher resolution trajectory is needed, i.e., more opportunities to change the control. If using as an initial guess a previous EMTG solution with a different number of time steps, EMTG will automatically interpolate the initial guess.

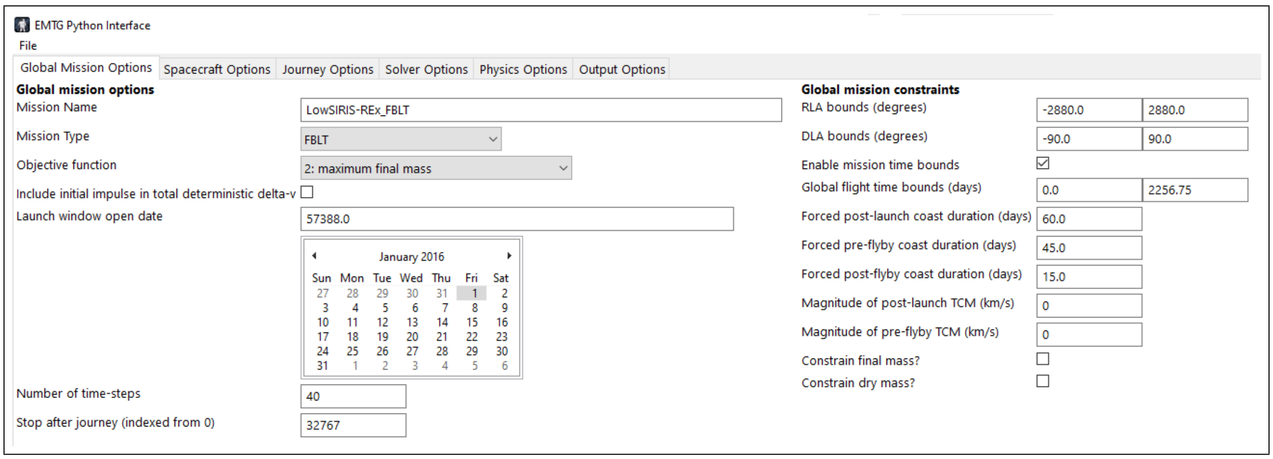

Figure 8: LowSIRIS-REx FBLT Global Mission Options.

4.2 Solver Options

Switch to the “Solver Options” tab and change the following options as shown in Figure 9:

- **Inner-loop Solver Mode:** “NLP with initial guess”
  - Since there is a solution in MGALT, Monotonic Basin Hopping (MBH) does not need to be run. Instead, only the Nonlinear Program (NLP) solver SNOPT will be run, using the MGALT solution as an initial guess.
- **Quiet NLP solver:** “Off”
  - Uncheck this option so you can see SNOPT iterate.
- **SNOPT maximum run time (s):** “600” seconds
  - FBLT is very slow because of the numerical integration of the equations of motion, as compared to MGALT’s Kepler problem solves, so let’s give SNOPT 10 minutes to chew on the problem.

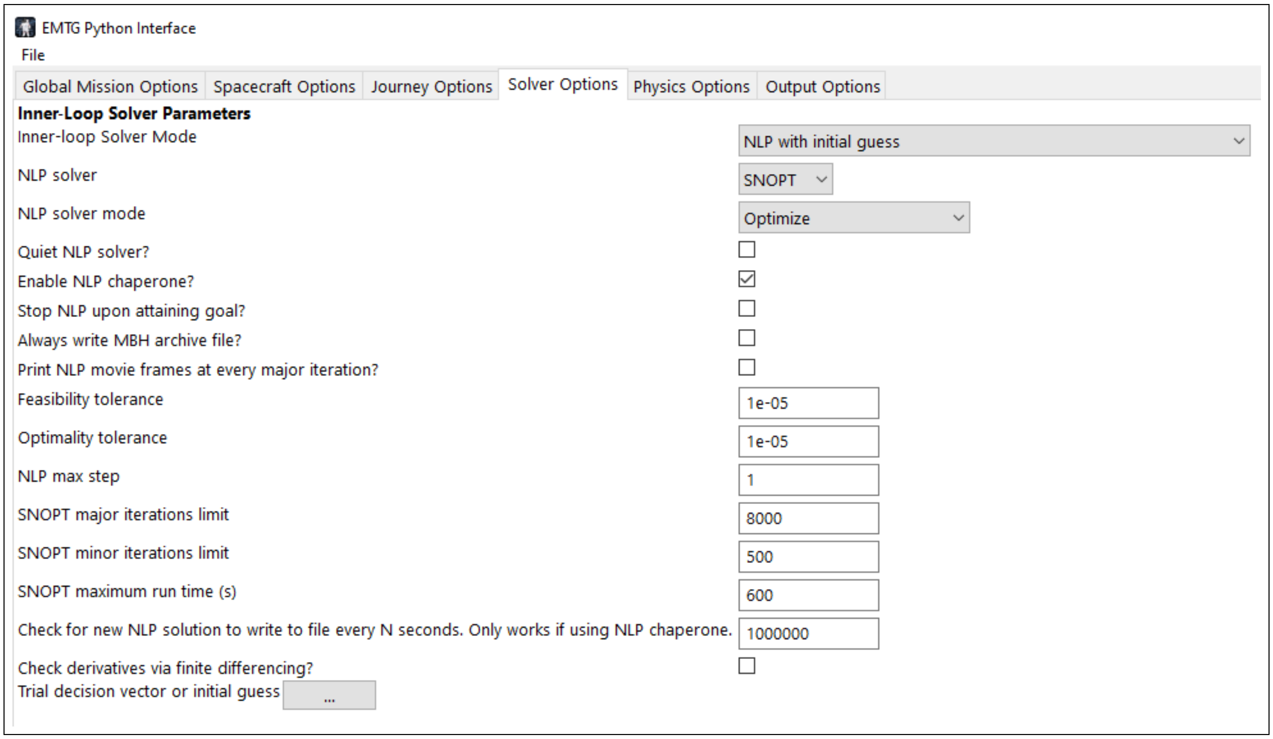

Figure 9: FBLT Solver Options.

4.3 Physics Options

Switch to the "Physics Options" tab and set the following options:

- **Integrator type:** "rk8 fixed step"

The default integrator time step of 86400 seconds is appropriate for this run.

Note: The "rk7813M adaptive step" option does not work.

5 Run and Post-Process

Run the mission as before. This time the SNOPT output will be displayed to the terminal. After the EMTG run finishes, plot the journeys and experiment with some of the Data Plots. If you examine the .emtg solution files in a text editor, you'll see that the journeys are represented by more data points than before due to the increased number of time-steps set in Global Options. Figure 10 shows an example trajectory plot, while Figure 11 shows an example Data Plot.

You now know how to use EMTG to refine an initial MGALT solution into a higher-fidelity FBLT solution. Additional steps to creating a "real" trajectory include turning on non-two-body forces and explicitly modeling launch, flybys, and arrival, but these are outside the scope of this tutorial.

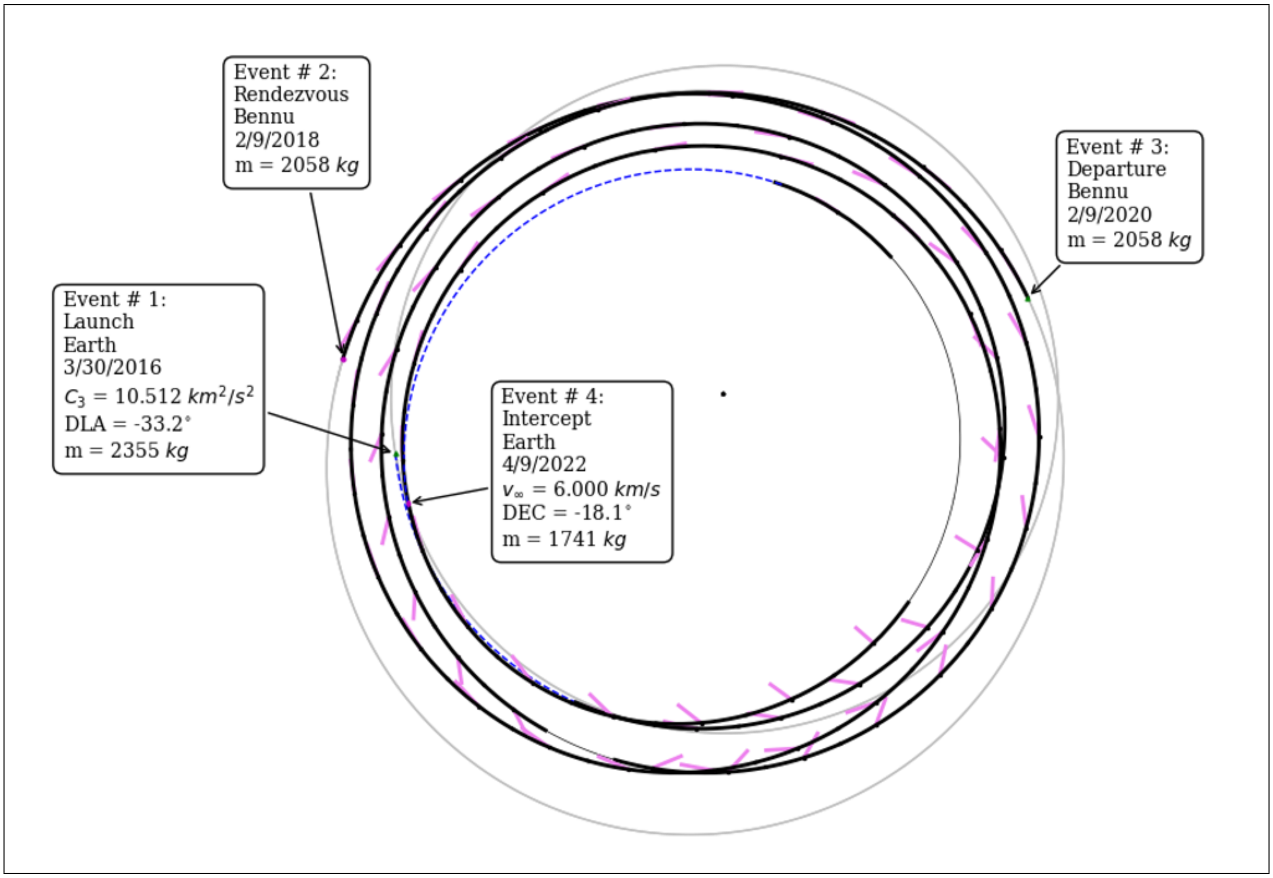

Figure 10: FBLT Example Solution.

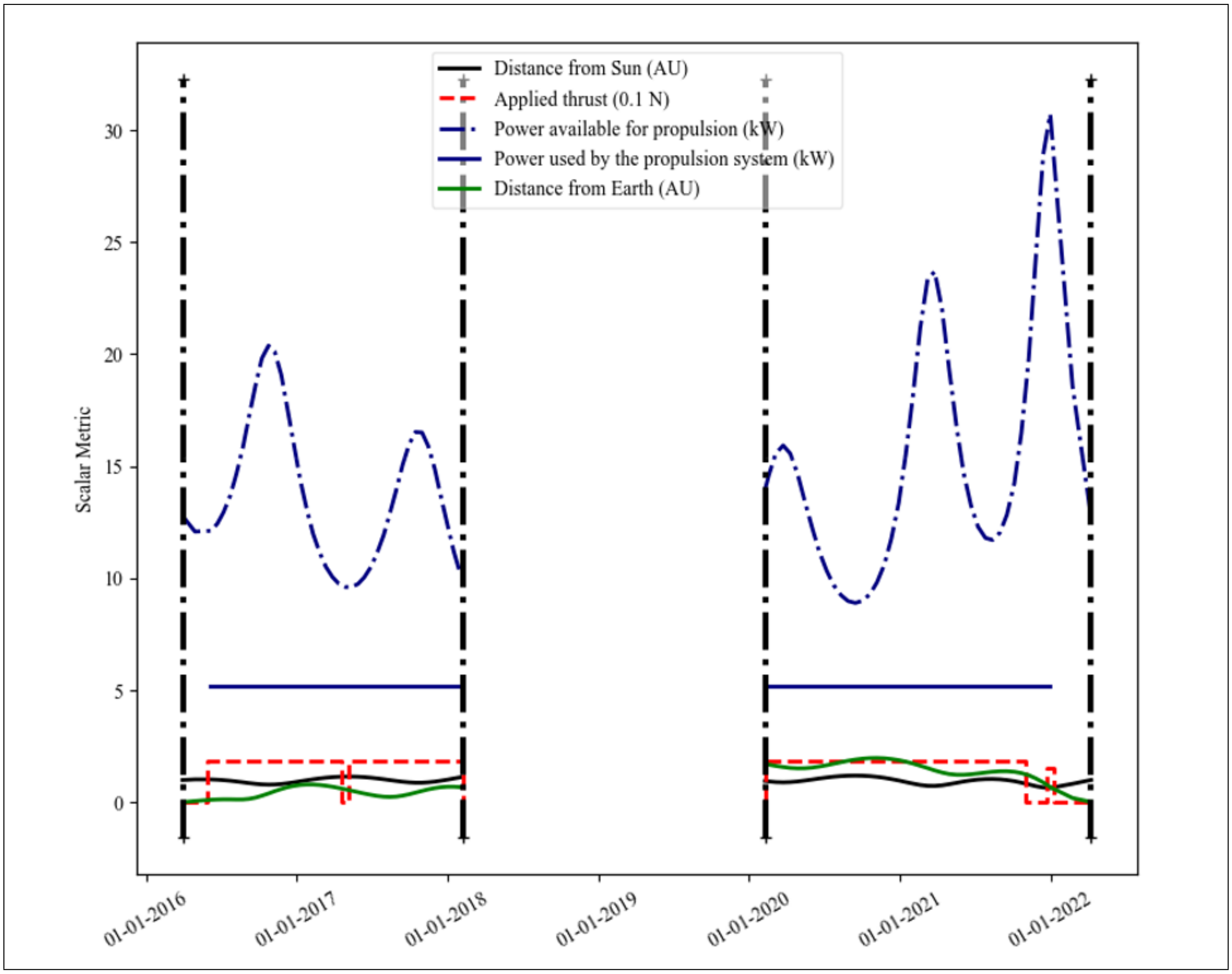

Figure 11: FBLT Example Data Plot.