EMTG Tutorial: Propagation and Force Models

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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

MONTE Mission analysis, Operations, and Navigation Toolkit Environment

SNOPT Sparse Nonlinear OPTimizer

SRP solar radiation pressure

AU Astronomical Unit

NLP Nonlinear Program

MBH Monotonic Basin Hopping

MGALT Multiple Gravity Assist with Low-Thrust

MGAnDSMs Multiple Gravity Assist with n Deep-Space Maneuvers using shooting

PSFB Parallel Shooting with Finite-Burn

PSBI Parallel Shooting with Bounded Impulses

FBLT Finite-Burn Low-Thrust

DSM deep-space maneuver

1 Introduction

Previous tutorials did not account for forces beyond the point-mass gravity of the central body. In this tutorial, you're going to update a few of the previous Evolutionary Mission Trajectory Generator (EMTG) options files to account for additional forces.

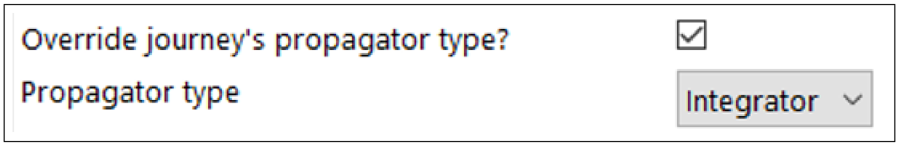

Figure 1: Journey Options Propagator Type Selection.

2 Propagation in EMTG

EMTG has two main methods for performing propagation of the spacecraft: Kepler and Integrator. Kepler uses Kepler's equation to analytically propagate the spacecraft's orbit state between delta-v events. The "Integrator time step size option" does not matter for Kepler propagation since it is analytical. Kepler propagation is compatible with Multiple Gravity Assist with Low-Thrust (MGALT), Coast Phase, and Multiple Gravity Assist with n Deep-Space Maneuvers using shooting (MGAnDSMs). (It is also compatible with the more advanced phase types Parallel Shooting with Bounded Impulses (PSBI) and Probe Entry Phase, which have not been covered in the tutorials yet.)

EMTG's Integrator option propagates the spacecraft by integrating the full equations of motion, whether they are simple two-body equations or more complex N-body equations with additional perturbations. As a result, Integrator propagation is slower than Kepler propagation but can model more realistic forces. Integrator is compatible with Finite-Burn Low-Thrust (FBLT), Coast Phase, and MGAnDSMs. (It is also compatible with the more advanced phase types Parallel Shooting with Finite-Burn (PSFB), Probe Entry Phase, and Control Law Thrust Phase, which have been covered in the tutorials yet.)

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

The propagation type can be selected for the whole mission in the "Physics Options" tab or set on a Journey-by-Journey basis in the "Journey Options" tab by selecting "Override journey's propagator type?" As the options text indicates, setting the propagator type on the "Journey Options" tab overrides the "Physics Options" selection for that particular journey as is shown in Figure 1. The "Integrator time step size option" can also be overridden on a per-Journey basis from the "Journey Options" tab, as well.

3 Perturbation Modeling in EMTG

Through the "Physics Options" tab, EMTG can model perturbing forces due to solar radiation pressure (SRP), gravitational forces other than those from the central body known as third-body or n-body forces, forces due to the oblateness of the central body with the J2 zonal coefficient, spherical harmonics gravity, and atmospheric drag. Spherical harmonics and drag require additional input files and are beyond the scope of this tutorial.

Perturbation effects (i.e., non-two-body forces) are modeled in different ways depending on the

"Mission Type" or transcription method selected in either the "Global Mission Options" (or "Journey Options" tab when using variable "Mission Types"). Perturbations are modeled differently or may not be available depending on the "Mission Type" in use. Table 1 shows a summary of compatible perturbations and "Mission Types". This section will go over the differences for the major transcription methods you've used so far and more detail on how they model perturbations.

Mission Type	Propagation	Perturbation Modeling
Coast Phase	Integrator or Kepler	Only with Integrator
MGAnDSMs	Integrator or Kepler	Only with Integrator
MGALT	Kepler	Yes
FBLT	Integrator	Yes

Table 1: Journey Options Propagator Type Selection.

3.1 MGALT

Multiple Gravity Assist with Low-Thrust (MGALT) models each Journey using the Sims-Flanagan transcription and Kepler propagation. A bounded-impulse delta-v is applied at each segment to model the spacecraft's thrust; the magnitude of the impulse is limited to the maximum delta-v that could be achieved by thrusting constantly across the segment. If any perturbations are turned on, they are applied in a similar manner: the perturbing force(s) are evaluated at the point at which each propulsive delta-v is applied. The effect of the perturbing acceleration(s) across the segment is approximated by multiplying the acceleration by the time between segments. The perturbing "delta-v" is then added to the propulsive delta-v to get the full impulse applied to the spacecraft. As a result, MGALT can approximate the effect of perturbing accelerations without using Integrator propagation. Figure 2 shows a diagram of the MGALT model.

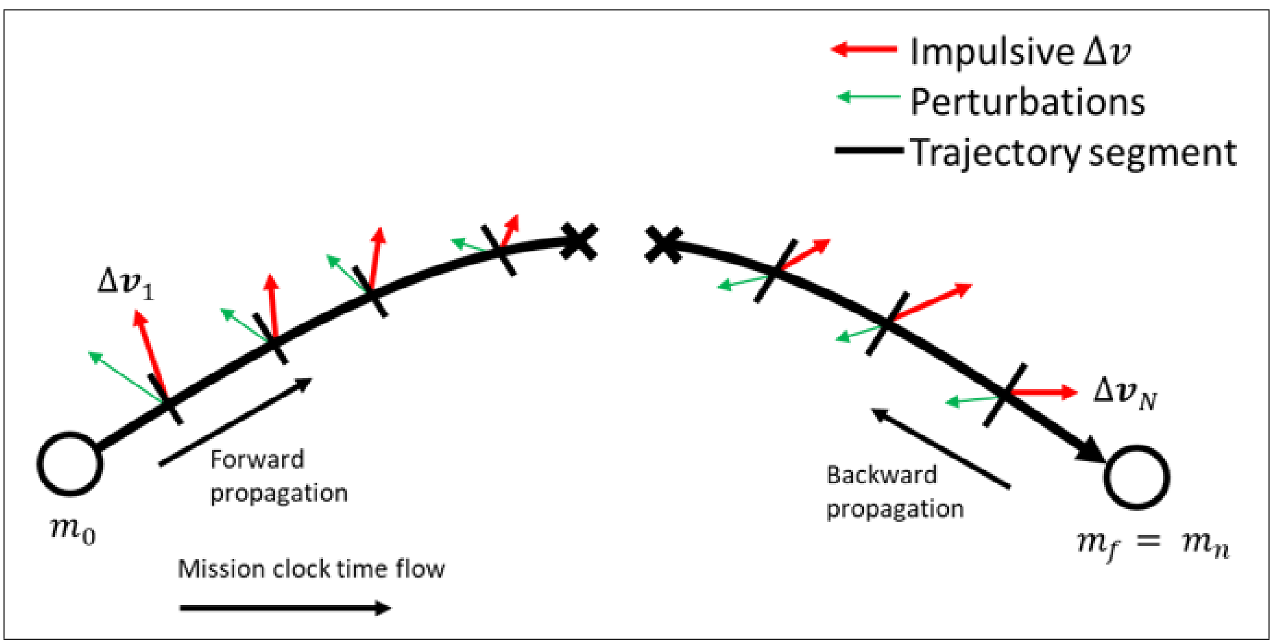

Figure 2: MGALT Mission Type.

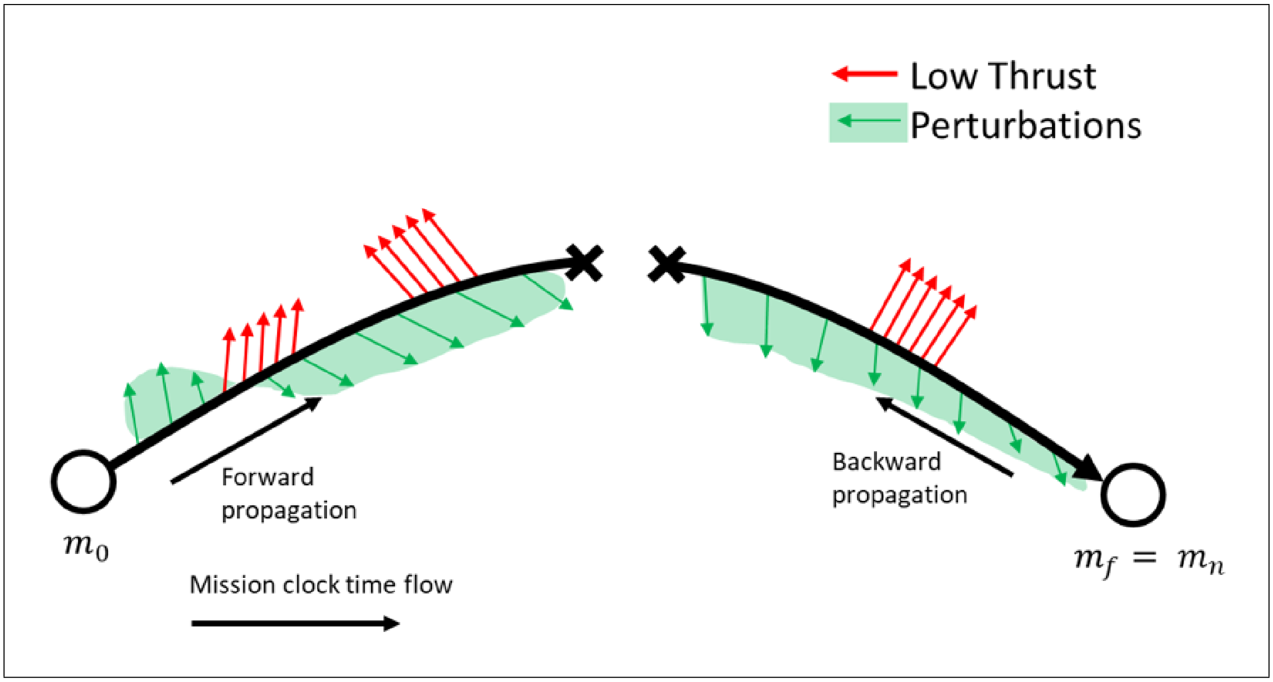

Figure 3: FBLT Mission Type.

3.2 FBLT

Finite-Burn Low-Thrust (FBLT) is similar to MGALT except numerical integration is used to propagate the equations of motion for the spacecraft rather than Sims-Flanagan transcription. The central body, thrust, and perturbing forces sum to apply a net acceleration to the spacecraft, which is integrated with a Runge-Kutta method to generate the spacecraft trajectory. This gives a more realistic trajectory than MGALT. A diagram of the FBLT model is shown in Figure 3.

3.3 MGAnDSMs

Multiple Gravity Assist with n Deep-Space Maneuvers using shooting (MGAnDSMs) allows for some user-selectable number of impulsive maneuvers during each Journey. Spacecraft propagation can be modeled with Kepler or Integrator between instantaneous delta-v events at each deep-space maneuver (DSM). Perturbations can only be applied with Integrator propagation by adding the perturbing forces to the central body gravitational force. Figure 4 shows a diagram of the MGAnDSMs model.

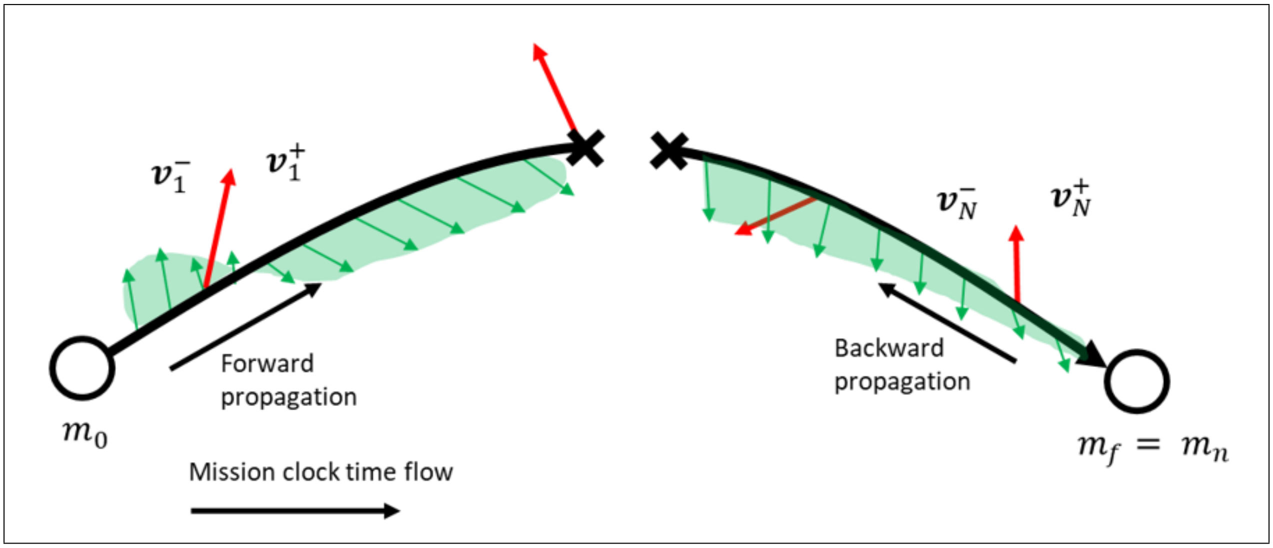

Figure 4: MGAnDSMs Mission Type. Integrator propagation is required to model perturbations.

3.4 Coast Phase

Like the name implies, Coast Phase has no spacecraft thrust. It can be propagated with either Kepler (and no perturbing forces) or Integrator with optional perturbing forces. For a Coast Phase, the "Integrator time step size" set on the "Physics Options" tab is always overridden by the forward/backward half-phase step size values on the "Journey Options" tab.

4 Tutorial Problem Setup

Begin by making a copy of the LowSIRIS-REx tutorial working directory. Call the new directory `Force_Models`. Create a results directory in `Force_Models`. Open the LowSIRIS-REx.emtgopt file with PyEMTG. Update the path to the Universe folder in the "Physics Options" tab if you are not using a Universe folder that is shared between multiple tutorials. Update the hardware library path in the "Spacecraft Options" tab (don't forget the trailing slash). Switch to the "Output Options" tab and select the "Override working directory?" check box. Change the path to `Force_Models/results`. Save the .emtgopt file in `Force_Models`, keeping the same filename.

4.1 Initial Run

Run the LowSIRIS-REx EMTG options file (File ->run, or Ctrl+r). You will compare the solutions you generate with additional forces modeled to this two-body, MGALT solution. After executing the first run, with the EMTG options file still open in PyEMTG, switch to the "Global Options" tab and rename the file to `LowSIRIS-REx_forcemodel`. Save the file (File ->save, or Ctrl + s).

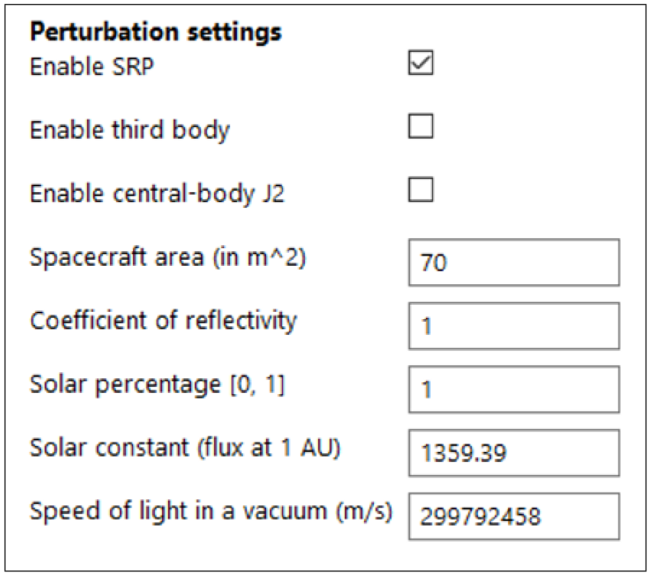

Figure 5: Perturbation Settings.

4.2 Physics Options

Switch to the "Physics Options" tab. On the far right of PyEMTG, there is a section called "Perturbation settings". This section switches on common perturbing forces including SRP, third-body effects, and central-body J2.

4.2.1 SRP

Select "Enable SRP". This will reveal new parameters for the spacecraft and Sun used to configure the SRP force model as shown in Figure 5. The spacecraft parameters you can set are the spacecraft cross-sectional area exposed to the Sun and spacecraft coefficient of reflectivity. EMTG models a consistent surface area exposed to the Sun and does not adjust for spacecraft attitude (i.e., the cannonball model). This should be sufficient for this stage of the mission design.

Additionally, EMTG allows you to set values pertaining to the solar activity by changing the "Solar percentage [0, 1]" or "Solar constant (flux at 1 AU)". These can often be left to their default value but can be adjusted to examine the effects of flying the mission at high or low solar activity levels. Leave the SRP values set to their default.

Selecting "Enable SRP" turns on SRP perturbations for all Journeys whose Journey type supports perturbations.

4.2.2 Third Body Forces

Select "Enable third body". Checking this box reveals a new option in the "Journey Options" tab allowing you to select the additional gravitational bodies that will be modeled on a per-Journey basis. You will set these later.

Selecting "Enable third body" turns on third-body perturbations for all Journeys whose Journey type supports perturbations, but, as mentioned previously, which third bodies, if any, are perturbers is set on a per-Journey basis.

4.2.3 Central-body J2

The final perturbation option is "Enable central-body J2". This will switch on the J2 spherical harmonic gravitational forces for the central body of each Journey. For this force to be included, the Universe file for the central body must contain a value for J2 and a J2 reference radius (units of km) in the central body section of the Universe file. See Figure 6 for an example of how to set these values for Mars. You won't turn J2 perturbations on for this mission.

```
#central body J2
central_body_J2 1960.45e-6
#central_body_J2_reference_radius
central_body_J2_reference_radius 3389.9
```

Figure 6: Mars Universe File J2 Settings.

Selecting "Enable central-body J2" turns on J2 perturbations for all Journeys whose Journey type supports perturbations.

4.3 Journey Options

Switch to the "Journey Options" tab. Notice that there is a new option toward the bottom of the window called "Perturbation_bodies". You can type in the Universe file body numbers from the "menu of bodies" section of the central body universe file or click the "..." button and select the bodies you wish to include in third body effects modeling. Select Venus, Mars, Jupiter, Saturn, Uranus, and Neptune or enter "[2,4,5,6,7,8]" as shown in Figure 7. Do not select the Earth (ID 3) because the Journey departure is an ephemeris-pegged launch or direct insertion from the Earth, meaning the departure state is coincident with the Earth. Thus, you would produce a divide-by-zero error if you attempted to calculate the gravitational force exerted by the Earth on the spacecraft at departure. Follow this procedure for both the "Earth_to_Bennu" Journey and the "Bennu_to_Earth" Journey.

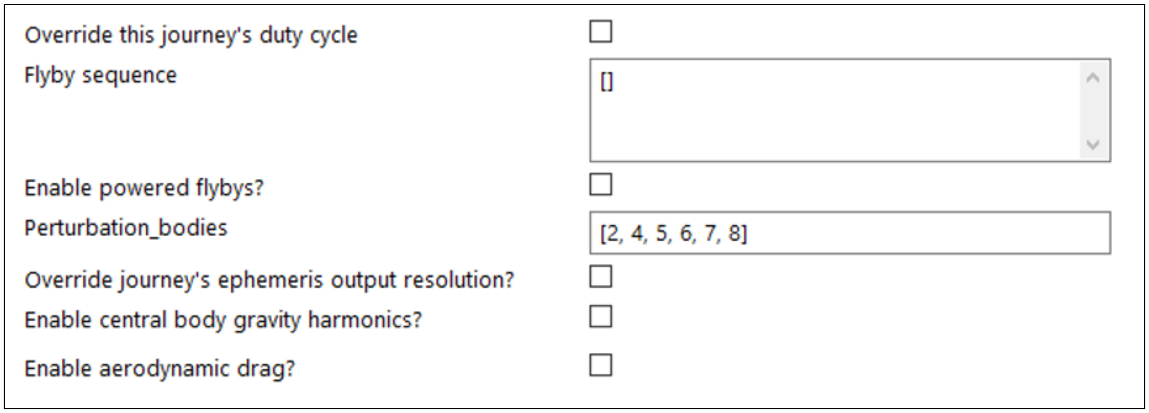

Figure 7: Journey Options - Perturbation Bodies.

4.3.1 Other Perturbing Forces

Two other types of perturbations can be turned on and off on a per-Journey basis: aerodynamic drag and central body gravity harmonics (beyond J2). The check boxes for these options are at the bottom of the "Journey Options" tab. Use of either of these perturbations requires an additional input file describing the coefficients used to evaluate the atmospheric density or spherical harmonics model, respectively. You will not use these perturbers in the current example, and further description is beyond the scope of this tutorial.

4.4 Solver Options

The easiest way to see the effects of the perturbing forces you just added is to evaluate the previous, two-body solution using this updated EMTG options file. Switch to the "Solver Options" tab and change "Inner-loop Solver Mode" to "Evaluate trialX". Select the `LowSIRIS-REx.emtg` file you created earlier in this tutorial by solving the unperturbed problem as the "Trial decision vector or initial guess" using the "…" button.

5 Run

5.1 Evaluate Trial X

Run this mission (File ->run, or Ctrl+r) and open the resulting EMTG file in a text editor. Notice that the results file is called `FAILURE_LowSIRIS-REx_forcemodel_Sun(EB)_Sun(BE).emtg`. Near the bottom of the file, you can see that the decision vector you used as an initial guess does not produce a feasible solution now that the force model is different. Below the objective function and worst constraint section, you should see:

```
Number of solution attempts: 1
```

```
Solution attempt that produced a feasible solution with the best objective
value (0 if no feasible solutions): 0
```

Look at the final state of Journey 0 (Earth to Bennu) of the `LowSIRIS-REx_forcemodel` solution compared to the final state of the LowSIRIS-REx trial solution. They're the same value, shouldn't this solution be feasible? Didn't they both arrive at Bennu? The answer is no. The state you're seeing is the same because EMTG integrates forwards *and* backwards from the Journey departure and arrival states, respectively. Since you didn't change the Bennu arrival epoch in the decision vector, you're trying to rendezvous with Bennu at the same ephemeris point. This is the state shown in the EMTG solution file. To see the problem, you must examine the constraint vector. This is the section at the bottom of the EMTG solution file starting with `Fupperbounds`. The row starting with `Fdescriptions` contains the labels for each entry, and the row starting with `Constraint_Vector` contains the scaled constraint values. You're interested in the values for `j_p_MGALT: match point` where "j" and "p" are followed by Journey and phase numbers, respectively, and the parameter after "match point" is the state parameter being matched. (Constraint values and bounds, as well as decision vector values and bounds, may also be viewed in a more user-friendly format in the `XFfile.csv` produced in the output directory of each EMTG run.)

5.2 NLP with Initial Guess

The mission needs some refinement in order to be feasible now that you have changed the force model. Luckily, the two-body solution is a good initial guess, and you only need to refine it with SNOPT. In other words, with a good initial guess, you usually do not need Monotonic Basin Hopping (MBH) to produce a feasible solution, though MBH can still be used to try to find a more optimal trajectory. Switch to the "Solver Options" tab. Change the "Inner-loop Solver Mode" to "NLP with initial guess". Rename the file `LowSIRIS-REx_forcemodel_nlp.emtg` in the "Global Options" tab and run it (File ->run, or Ctrl+r). If you are interested in watching SNOPT iterate in real time, you can uncheck the "Quiet NLP solver?" checkbox on the "Solver Options" tab.

Open the solution in a text editor and check that EMTG has found a feasible solution. An example set of constraint match points for this resolved EMTG options file is shown in the last column in Table 2.

		Two-Body Solution	Two-Body Solution Evaluated with Perturbations	Two-Body Solution with Perturbations Resolved With SNOPT
j0p0MGALT: point x	match	-5.52E-06	1.27E-02	-4.16E-06
j0p0MGALT: point y	match	-2.02E-07	-1.63E-03	2.05E-07
j0p0MGALT: point z	match	6.88E-07	-7.01E-04	3.75E-07
j0p0MGALT: point xdot	match	-1.78E-06	1.10E-03	-9.56E-07
j0p0MGALT: point ydot	match	-6.21E-06	1.11E-02	-4.60E-06
j0p0MGALT: point zdot	match	-2.67E-06	6.38E-03	-2.14E-06

Table 2: LowSIRIS-REx Match Point Constraint Values.

You can apply the same perturbations to the FBLT LowSIRIS-REx solution. Since FBLT integrates the full equations of motion, this will be the most accurate method for modeling the low-thrust trajectory. An important thing to keep in mind here is that an MGALT solution can be used as an initial guess for an FBLT problem (and vice versa) using the same "Trial decision vector or initial guess" option previously described. EMTG recognizes that the initial guess decision variables are MGALT but that the new problem is FBLT, and internally adapts the decision variables accordingly. To add perturbations to the FBLT LowSIRIS-REx solution, perform the same modifications to the `.emtgopt` file as to the LowSIRIS-REx_forcemodel solution in this tutorial.

This concludes the tutorial on force modeling in EMTG. You can now apply accurate modeling of the forces on your spacecraft during each Journey. As you've seen, the typical EMTG workflow is to begin with a low-fidelity but easy-to-solve version of the mission, then progressively increase the realism before arriving at a highly realistic solution that is ready for implementation in Mission analysis, Operations, and Navigation Toolkit Environment (MONTE) or another system for designing the flight-ready mission. Table 3 gives example EMTG progressions for chemical and low-thrust missions. The next tutorials will go over how to model spacecraft hardware like thrusters and power systems and how to trade different options to find the best combination for the mission.

Chemical	Low Thrust
1. MGAnDSMs with flyby sequence	1. MGALT with flyby sequence with perturbing forces
2. MGAnDSMs with single-phase Journeys	2. MGALT with single-phase Journeys with perturbing forces
3. MGAnDSMs with propagated flybys	3. MGALT with propagated flybys with perturbing forces
4. MGAnDSMs with propagated flybys with perturbing forces	4. FBLT with propagated flybys with perturbing forces

Table 3: Example Low to High-Fidelity Progression. Particularly for low-thrust missions, you may need to adapt these steps for your particular use case.