

National Aeronautics and Space Administration



Rapid Preliminary Design of Interplanetary Trajectories Using the Evolutionary Mission Trajectory Generator



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NAVIGATION & MISSION DESIGN BRANCH
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www.nasa.gov

code 595



EMTG: The Team

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Why an automated design tool?

- Interplanetary mission design is highly complex. Analysts must design maneuvers and choose launch dates, flight times, encounter epochs, and in many cases a flyby sequence or even a set of science targets.
- This process is even more complex for missions employing low-thrust electric propulsion because each possible spacecraft design dramatically affects the trajectory.
- Designing even a single interplanetary trajectory is an expensive process. It is even more expensive to explore a broad trade space of missions to find the relationship between science return, cost, and risk.
- An automated tool shifts much of the work from the analyst to a computer, allowing the analyst to spend more time collaborating with the science team and better understand their needs.

EMTG Design Capabilities

▪ Propulsion Types

- High-thrust chemical
- Low-thrust electric

▪ Mission Components

- Deep-space maneuvers
- Gravity Assists
- Asteroid Rendezvous/Flyby
- Sample Return/Planetary Landing
- Launch Vehicle selection

▪ Spacecraft Systems

- Power system sizing
- Propulsion system sizing

▪ Mission Objectives

- Maximize science payload
- Minimize flight time
- Visit as many diverse bodies as possible
- Maximize encounter energy (for planetary defense)

▪ Operational and Science Constraints

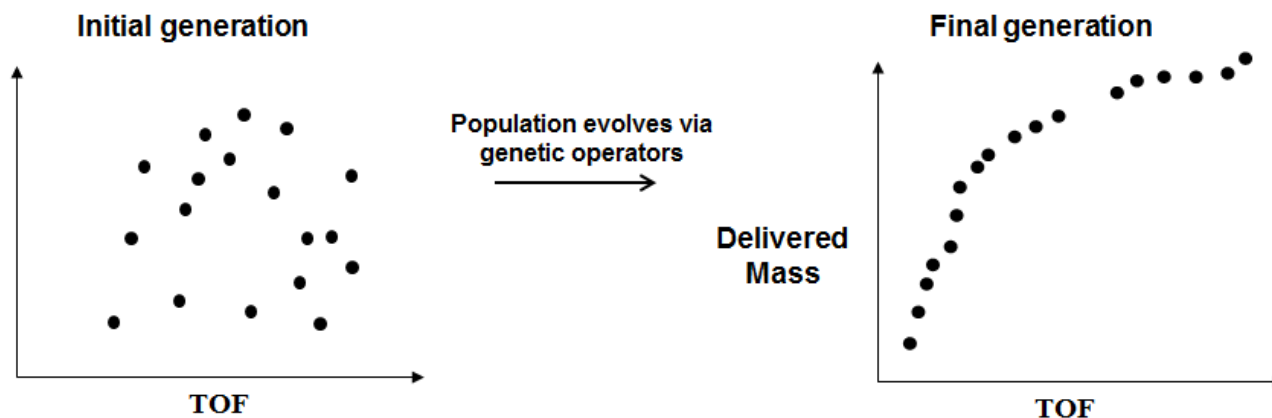
- Atmospheric entry
- Solar distance
- Any other constraints on final orbit

Mission and Systems Design via Hybrid Optimal Control

- The interplanetary mission design problem has two types of variables:
 - *Discrete* variables encoding the mission sequence and choice of spacecraft systems (launch vehicle, power, propulsion)
 - *Continuous* variables defining the trajectory
- In *Hybrid Optimal Control*, the problem is divided into two nested loops.
 - The *outer-loop* solves the discrete problem and identifies candidate missions.
 - The continuous *inner-loop* then finds the optimal trajectory for each candidate mission.
- But in this tutorial, due to time constraints, we will focus solely on the inner-loop solver

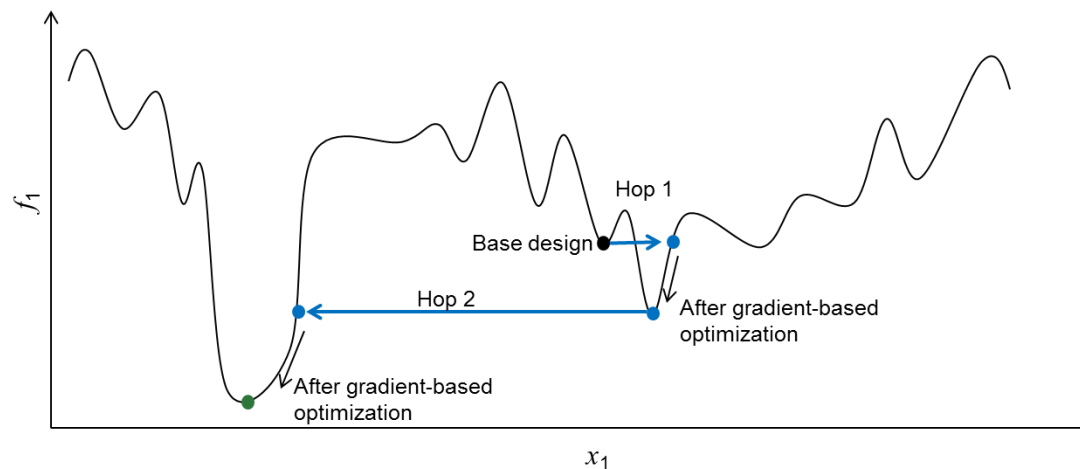
Discrete Optimization of the Mission Sequence and Spacecraft Systems

- EMTG's outer-loop finds the non-dominated set of missions, those which are not strictly better or worse than other missions in the set based on all of the analyst's chosen objective functions
- EMTG uses a version of the Non-Dominated Sorting Genetic Algorithm II (NSGAI) which can evolve to the final non-dominated trade front despite starting from complete randomness. No *a priori* knowledge of the solution is required.



Trajectory Optimization via Monotonic Basin Hopping and Nonlinear Programming

- EMTG's inner-loop finds the optimal trajectory using a stochastic global search method called Monotonic Basin Hopping (MBH) coupled with a gradient-based local search supplied by the third-party Sparse Nonlinear Optimizer (SNOPT).
- EMTG does not require an initial guess and can find the global optimum autonomously.



Some nuts and bolts

- EMTG is available open-source at <https://sourceforge.net/projects/emtg/>
- EMTG is written in C++ and the user interface, PyEMTG, is written in Python 2.7
 - Why Python 2.7? That's what I started with. We welcome collaborators who want to take on the challenge of migrating us to Python 3!
- EMTG is script-driven; all PyEMTG does is write scripts and read output files
- To compile EMTG, one also needs the Boost C++ extensions, the CSPICE ephemeris library, and most importantly SNOPT.
- PyEMTG depends on wxPython
- If one is using the outer-loop, it is possible to link EMTG to MPI for parallel processing. The inner-loop is serial.
- EMTG is happily cross-platform and is used operationally on OSX, Windows, and Linux.

Let's play with EMTG...

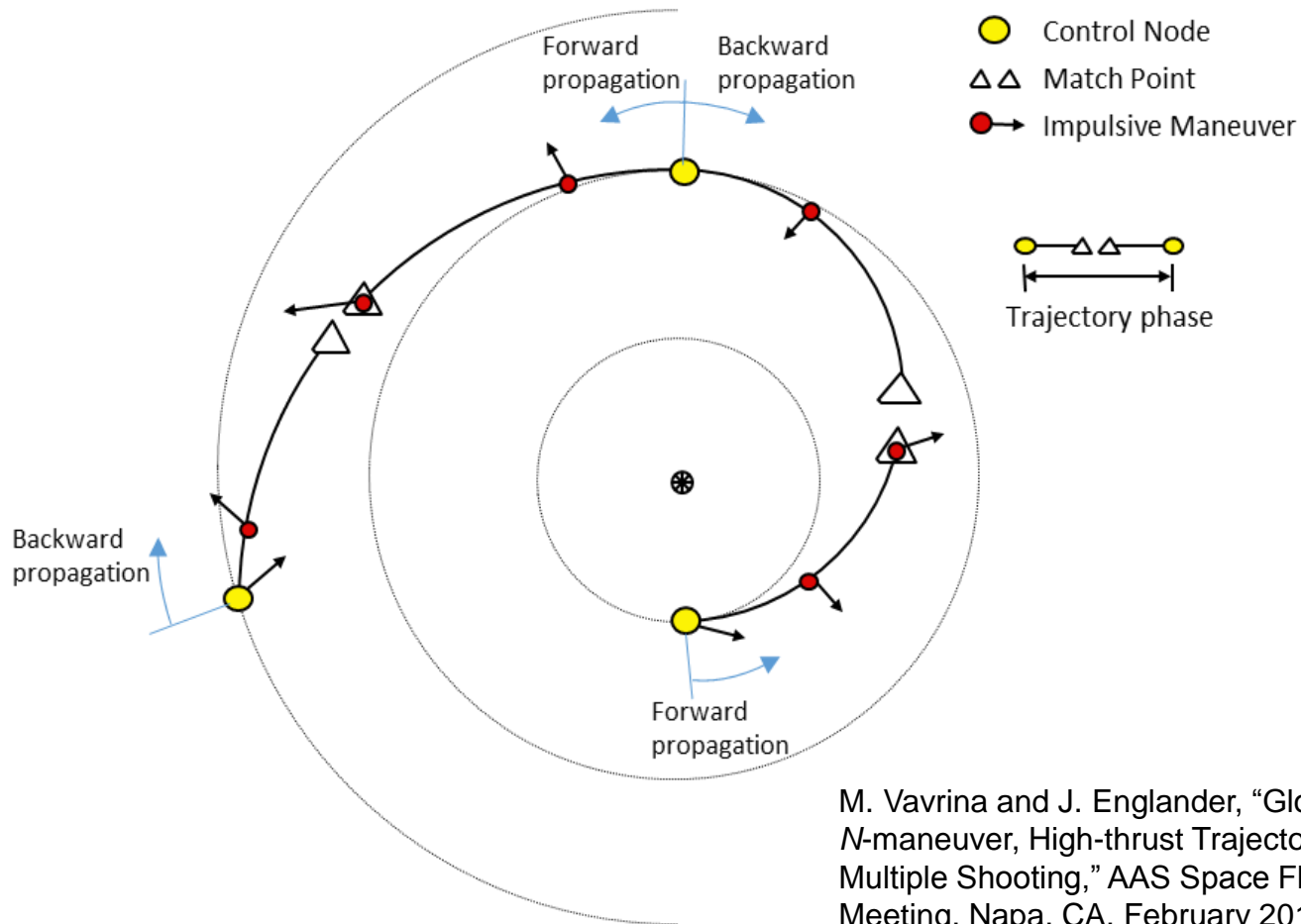
- Today we are going to design two missions in EMTG
 - OSIRIS-REx
 - A New Frontiers class mission to acquire a sample from near-Earth asteroid Bennu and return it to Earth
 - LowSIRIS-REx
 - Academic problem which is very similar to OSIRIS-REx but uses low-thrust electric propulsion
- In the next several slides, we will walk you through how to create these missions in EMTG
- Start your PyEMTG...

Configuring PyEMTG

- Edit your PyEMTG.options to ensure that PyEMTG has paths to:
 - EMTG executable
 - Universe folder (where all ephemeris-related things live)
 - Your small bodies file (optional file for searching for targets of opportunity)

```
EMTG_path D:\Projects\EMTgV8_sourceforge\branch\Jacob_MGANDSM_and_GMAT\bin\emtg.exe  
default_universe_path D:\Projects\EMTgV8_sourceforge\EMTG_libraries\Universe  
default_small_bodies_file D:\Projects\EMTgV8_sourceforge\EMTG_libraries\Universe\ephemeris_files\AllAsteroids.SmallBody
```

Chemical Mission Modeling in EMTG



M. Vavrina and J. Englander, "Global Optimization Of N -maneuver, High-thrust Trajectories Using Direct Multiple Shooting," AAS Space Flight Mechanics Meeting, Napa, CA, February 2016.

OSIRIS-REx Step 1a: Acquire body ephemeris data

- EMTG is most accurate when a SPICE kernel is provided for each body of interest
- You can create a SPICE kernel for any body in the HORIZONS database at: <http://ssd.jpl.nasa.gov/x/spk.html>
 - Place SPICE kernels in your 'EMTG_root/Universe/ephemeris_files/' directory
- Alternatively you may specify Keplerian orbit elements. This results in faster EMTG execution but less accuracy.

OSIRIS-REx Step 1b: Create a Universe file to teach EMTG about your body(ies)

- Users make EMTG aware of a body by putting entering it into a “Universe” file
- Every journey in an EMTG mission can have a different Universe file if you so desire but you can use on Universe file for the whole mission.
- Create a body and tell EMTG your new body’s SPICE ID and name. If you are using SPICE, all you need to enter is name, shortname, and SPICE_ID.

Universe Properties	Universe Body Properties
Universe name	<input type="text" value="Sun"/>
Central body SPICE ID	<input type="text" value="10"/>
Central body radius (km)	<input type="text" value="4379000.0"/>
μ (km ³ /s ²)	<input type="text" value="1.32712440018e+11"/>
characteristic length unit (km)	<input type="text" value="149597870.691"/>
sphere of influence radius (km)	<input type="text" value="747989353500"/>
minimum safe distance from origin (km)	<input type="text" value="20000000.0"/>
alpha0	<input type="text" value="-90.0"/>
alphadot	<input type="text" value="0"/>
delta0	<input type="text" value="66.5607090000000003"/>
deltadot	<input type="text" value="0"/>
W0	<input type="text" value="84.176"/>
Wdot	<input type="text" value="14.1844000"/>
Reference frame for body orbit elements	<input type="text" value="ICRF"/>

Universe Properties	Universe Body Properties	
Earth	name	Bennu
Mars	shortname	Bennu
Jupiter	SPICE_ID	2101955
Saturn		
Uranus		
Neptune	minimum flyby altitude	-1
Pluto	mass	1000.0
Vesta	radius	1000.0
Ceres	ephemeris_epoch	51544
Bennu	alpha0 (deg)	0.0
	alphadot (deg/century)	0.0
	delta0 (deg)	0.0
	deltadot (deg/century)	0.0
	W (deg)	0.0
	Wdot (deg/century)	0.0
	SMA (km)	150000000.0
	ECC	0.0
	INC (deg)	1e-06
	RAAN (deg)	1e-06
	AOP (deg)	1e-06
	MA (deg)	0.0

OSIRIS-REx Step 2: The Global Options Tab

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | Physics Options | Output Options

Global mission options

Mission Name: OSIRISREx

Mission Type: MGA-nDSM-s

Maximum number of DSMs per phase: 1

Objective function: 14: maximize log₁₀(final mass)

Maximum number of phases per journey: 8

Launch window open date: 57388.0

Number of time-steps: 40

Global mission constraints

DLA bounds (degrees): -28.5 to 28.5

Enable mission time bounds:

Global flight time bounds (days): 0.0 to 2556.75

Forced post-launch coast duration (days): 0.0

Forced pre-flyby coast duration (days): 0.0

Forced post-flyby coast duration (days): 0.0

Enable fixed final mass?

Enable minimum dry mass?

Enable fixed dry mass?

- We recommend the MGA-nDSMs transcription for chemical missions
- There are many objective functions. Log₁₀(final mass) works very well for chemical missions.
- PyEMTG does math! You can, for example, write “365.25 * 7” in the flight time bounds field.
- For chemical missions, the “number of time-steps” field only affects the resolution of the final trajectory plot and not the solution itself.

OSIRIS-REx Step 3: The Physics Options Tab

EMTG Python Interface

File

Global Mission Options | **Spacecraft Options** | Journey Options | Solver Options | **Physics Options** | Output Options

Ephemeris settings

Ephemeris Source: SPICE

Leap seconds kernel: naif0011.tls

Frame kernel: pck00010.tpc

Universe folder: D:\Projects\EMTgv8_sourceforge\EMTG_libraries\Un... Default

Spiral settings

Spiral model type: Edelbaum

Number of spiral segments: 10

Lambert settings

Lambert solver type: Arora-Russell

Flyby settings

MGADSM/MDAnDSMk Flyby transcription: single beta angle

Propagator type for MGAnDSMs: Keplerian

Perturbation settings

Enable SRP:

Enable third body:

- Make sure your script points to the correct Universe folder or else nothing will work. If you configured PyEMTG.options correctly you can just click the “Default” button.
- Third body and solar radiation pressure perturbations only work if your propagator is set to “Integrator.” This is very slow and unnecessary for this stage of design.

OSIRIS-REx Step 4: The Spacecraft Options Tab

EMTG Python Interface

File

Global Mission Options | **Spacecraft Options** | Journey Options | Solver Options | Physics Options | Output Options

Spacecraft and Launch vehicle options

Maximum mass (kg)

Allow initial mass to vary

Launch vehicle type

Launch vehicle adapter mass (kg)

Propulsion options

Chemical Isp (s)

Margins and Constraints

Propellant margin (fraction)

Launch vehicle margin (fraction)

enable maximum propellant constraint?

enable chemical propulsion propellant tank constraint?

- In this case we are optimizing mass, not Δv , so a suitable launch vehicle model and chemical thruster I_{sp} must be chosen. EMTG will trade between the thruster and the launch vehicle to deliver the most mass to the target.
- The “maximum mass” field in this case just scales the optimization problem; the actual launch mass is limited to whatever the launch vehicle can carry to the C3 that the optimizer chooses.

OSIRIS-REx Step 5a: The Journey Options Tab (Journey 1)

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | **Journey Options** | Solver Options | Physics Options | Output Options

Earth_to_Bennu
Bennu_to_Earth

New Journey
Delete Journey
Move Journey Up
Move Journey Down

Journey name: Earth_to_Bennu

Central body: SunOSIRIS

Destination list: [3, 10]

Starting mass increment (kg): 0.0

Variable mass increment:

Wait time bounds (days): 0.0 | 365.25

Journey time bounds: unbounded

Journey initial impulse bounds (km/s): 1e-08 | 5.4101755978

Journey departure type: 0: launch or direct insertion

Enable journey DSM magnitude constraint?

Journey arrival type: 1: rendezvous (use chemical Isp)

Constrain the spacecraft-target-sun angle at arrival?

Constrain the spacecraft-sun-Earth angle at departure?

Constrain the spacecraft-sun-Earth angle at flybys?

Constrain the spacecraft-sun-Earth angle at arrival?

Constrain the spacecraft-sun-Earth angle at DSMs?

Constrain true anomaly at departure?

Constrain true anomaly at arrival?

Journey-end delta-v (km/s): 0.0

Flyby sequence: [[3, 0, 0, 0, 0, 0, 0, 0]]

Powered flyby flags: [0, 0, 0, 0, 0, 0, 0, 0]

- Each “journey” represents a set of events with user-defined boundary conditions – in this case launch from Earth and arrival at Bennu.
- There are many types of journey departure and arrival conditions. The ones shown here are appropriate for a small body rendezvous.
- Each journey can contain any number of phases. If a journey has more than one phase, they are separated by planetary flybys. In this case we have selected an Earth flyby.

OSIRIS-REx Step 5b: The Journey Options Tab (Journey 2)

Journey name	Bennu_to_Earth
Central body	SunOSIRIS
Destination list	[10, 3]
Starting mass increment (kg)	0.0
Variable mass increment	<input type="checkbox"/>
Wait time bounds (days)	365.25 730.5
Bounded journey departure date?	<input type="checkbox"/>
Journey time bounds	unbounded
Journey initial impulse bounds (km/s)	1e-08 10.0
Journey departure type	0: launch or direct insertion
Enable journey DSM magnitude constraint?	<input type="checkbox"/>
Journey arrival type	2: intercept with bounded V_infinity
Forced pre-intercept coast (days)	0.0
Journey final velocity bounds	0.0 10
Apply arrival declination constraint?	<input type="checkbox"/>
Atmospheric interface flight path angle (degrees)	-8.0
Atmospheric entry interface radius (km)	6503.0
Atmospheric entry latitude (degrees)	40.0
Apply atmospheric entry interface azimuth constraint?	<input type="checkbox"/>
Apply atmospheric entry interface sun angle constraint?	<input type="checkbox"/>
Apply atmospheric entry interface longitude constraint?	<input type="checkbox"/>
Apply entry velocity with respect to rotating atmosphere constraint?	<input checked="" type="checkbox"/>
Bounds on entry interface velocity with respect to rotating atmosphere (km/s)	0.0 12.4

- We constrain OSIRIS-REx to spend between 1 and 2 years at Bennu.
- OSIRIS-REx ends with a landing on Earth. EMTG can constrain – using a simplified geometric model – the conditions at which the spacecraft intersects the Earth’s atmosphere.
- In this example, we constrain the velocity of the spacecraft relative to the rotating atmosphere at interface.
- We must specify flight path angle, altitude, and latitude.

OSIRIS-REx Step 6: The Solver Options Tab

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | Physics Options | Output Options

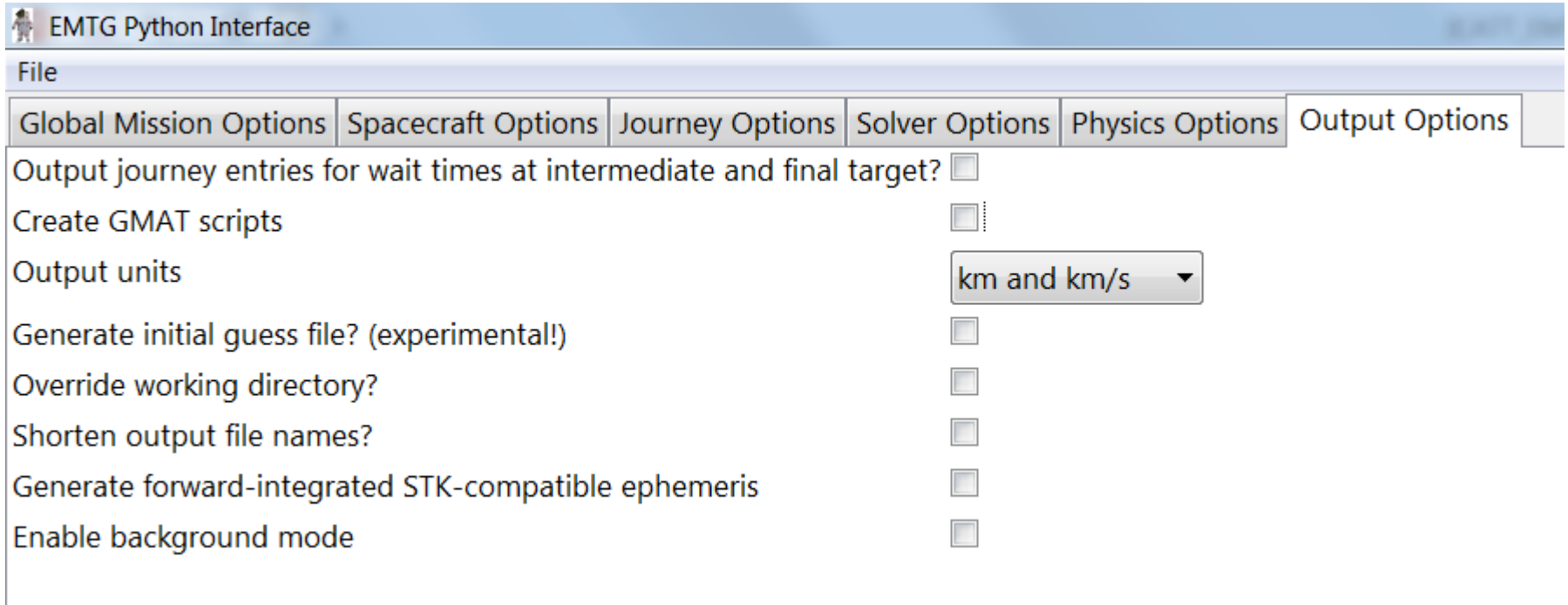
Inner Loop Solver Parameters

Inner-loop Solver Mode	Monotonic Basin Hopping
NLP solver	SNOPT
NLP solver mode	Optimize
Quiet NLP solver?	<input checked="" type="checkbox"/>
Quiet MBH solver?	<input type="checkbox"/>
Two-step MBH?	<input type="checkbox"/>
Finite differencing step size	1.5e-08
Enable ACE feasible point finder?	<input checked="" type="checkbox"/>
MBH Impatience	100000
Maximum number of innerloop trials	100000
Maximum run-time (s)	3600
MBH hop probability distribution	Pareto
MBH hop scale factor	1.0
MBH Pareto distribution alpha	1.4
Probability of MBH time hop	0.05
Feasibility tolerance	1e-05
SNOPT major iterations limit	8000
SNOPT maximum run time (s)	30
Derivative calculation method	Analytical all but time
Check derivatives via finite differencing?	<input type="checkbox"/>
Seed MBH?	<input type="checkbox"/>

- For this example we will use Monotonic Basin Hopping (MBH) with a Pareto distribution. For chemical missions we recommend setting the “Pareto alpha” to 1.4 or, if the problem has many local optima, 1.3.
- The ACE feasible point finder allows MBH to compare infeasible solutions and search for minimum infeasibility before it finds its first feasible solution and begins to search for optimality.
- EMTG has full analytical derivatives for the MGAnDSMs transcription. However we recommend that you run with time derivatives turned off because, since SPICE does not provide smooth derivatives and must be finite-differenced, the analytical time derivatives are not accurate unless SPICE is not used.

OSIRIS-REx Step 7

The Output Options Tab



The screenshot shows the EMTG Python Interface window with the 'Output Options' tab selected. The interface includes a menu bar with 'File' and a series of tabs: 'Global Mission Options', 'Spacecraft Options', 'Journey Options', 'Solver Options', 'Physics Options', and 'Output Options'. The 'Output Options' tab contains the following settings:

- Output journey entries for wait times at intermediate and final target?
- Create GMAT scripts
- Output units:
- Generate initial guess file? (experimental!)
- Override working directory?
- Shorten output file names?
- Generate forward-integrated STK-compatible ephemeris
- Enable background mode

- We don't need any of these right now.
- For the purpose of this tutorial it is sufficient to know that “background mode” means “close EMTG as soon as it is done executing.” If you are running EMTG from PyEMTG then you should leave background mode off so that you can see your results more easily.

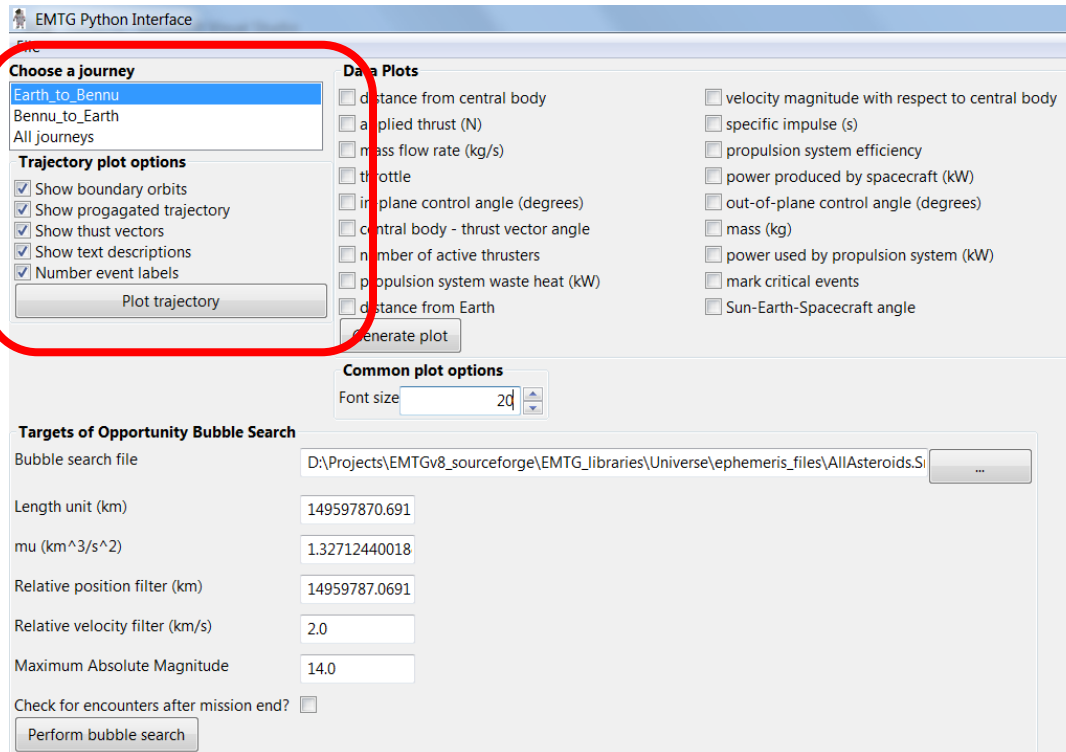
OSIRIS-REx Step 8: Run your mission!

The screenshot shows the EMTG Python Interface with the 'File' menu open and 'Run' highlighted. The interface includes several configuration panels:

- Tabs:** Trajectory Options, Journey Options, Solver Options, Physics Options, Output Options
- Global mission constraints:**
 - DLA bounds (degrees): -28.5, 28.5
 - Enable mission time bounds:
 - Global flight time bounds (days): 0.0, 2556.75
 - Forced post-launch coast duration (days): 0.0
 - Forced pre-flyby coast duration (days): 0.0
 - Forced post-flyby coast duration (days): 0.0
 - Enable fixed final mass?:
 - Enable minimum dry mass?:
 - Enable fixed dry mass?:
- Configuration fields:**
 - OSIRISREx_dv
 - MGA-nDSM-s
 - 1
 - 0: minimum deltaV
 - Include initial impulse in cost:
 - Maximum number of phases per journey: 8
 - Launch window open date: 57388.0
 - Number of time-steps: 40
- Calendar:** January 2016, with the 30th selected.

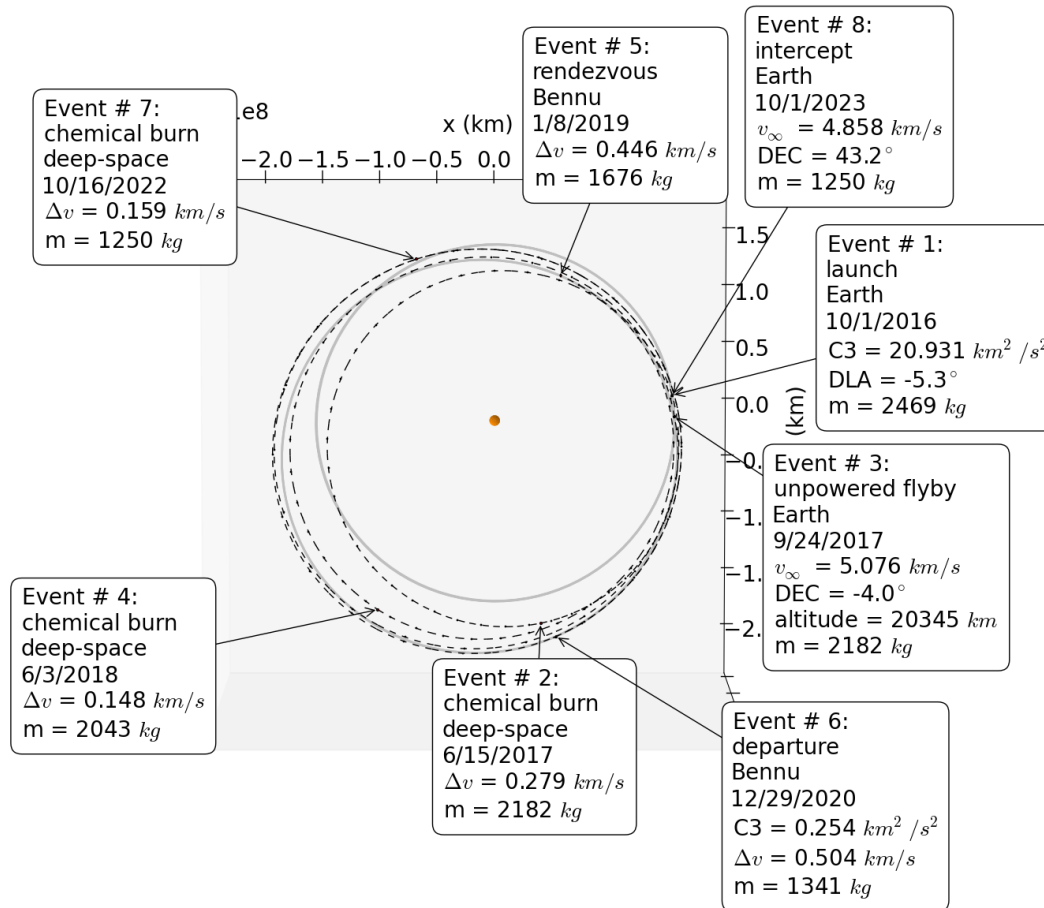
- PyEMTG will prompt you to save a “.emtgopt” options file.
- EMTG will then execute, create a new timestamped subdirectory for your results, and begin solving your problem.

OSIRIS-REx Step 9: Post-Process Your Mission



- PyEMTG can open “.emtg” options files.
- PyEMTG can create trajectory plots and systems summary plots.
- We will focus on the trajectory plot for this example.
- PyEMTG can also search for targets of opportunity along your trajectory. This is out of scope for the tutorial.

OSIRIS-REx Trajectory Plot

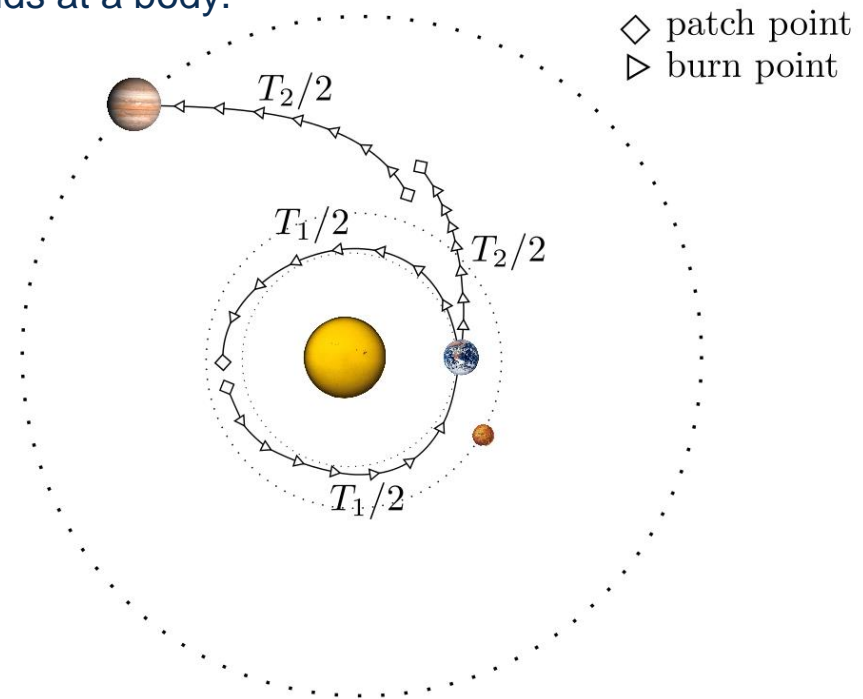


Interlude: What makes Low-Thrust Different?

- Low-thrust electric propulsion is characterized by high power requirements but also very high specific impulse (I_{sp}), leading to very good mass fractions
- Low-thrust trajectory design is a very different process from chemical trajectory design
 - Like chemical design, must find the optimal launch date, flight time, and dates of each flyby (if applicable)
 - Unlike chemical design, must find a time-history of thrust control for the entire mission
- ***Low-thrust electric propulsion mission design requires accurate modeling of propulsion and power systems. Every spacecraft design drives a unique trajectory design!***
- Audience members who are familiar with ESA's PaGMO will see many similarities between it and EMTG. This is intentional. EMTG's inner-loop was very much inspired by PaGMO although EMTG models a much wider range of mission types. If there are any PaGMO team members in the audience, we greatly appreciate you and cite you as often as we can!

Low-Thrust Modeling in EMTG Transcription

- Break mission into phases. Each phase starts and ends at a body.
- Sims-Flanagan Transcription
 - Break phases into time steps
 - Insert a small impulse in the center of each time step, with bounded magnitude
 - Optimizer Chooses:
 - Launch date
 - For each phase:
 - Initial velocity vector
 - Flight time
 - Thrust-impulse vector at each time step
 - Mass at the end of the phase
 - Terminal velocity vector
- Assume two-body force model; propagate by solving Kepler's problem
- Propagate forward and backward from phase endpoints to a "match point"
- Enforce nonlinear state continuity constraints at match point
- Enforce nonlinear velocity magnitude and altitude constraints at flyby



J. Englander, D. Ellison, and B. Conway, "Global Optimization of Low-Thrust, Multiple-Flyby Trajectories at Medium and Medium-High Fidelity," AAS Space Flight Mechanics Meeting, Santa Fe, NM, January 2014.

Low-Thrust Modeling in EMTG Spacecraft and Launch Vehicle Models

- Medium-fidelity mission design requires accurate hardware modeling
- Launch vehicles are modeled using a polynomial fit

$$m_{delivered} = (1 - \sigma_{LV}) (a_{LV} C_3^5 + b_{LV} C_3^4 + c_{LV} C_3^3 + d_{LV} C_3^2 + e_{LV} C_3 + f_{LV})$$

where σ_{LV} is launch vehicle margin and C_3 is hyperbolic excess velocity

- Thrusters are modeled using either a polynomial fit to published thrust and mass flow rate data

$$\begin{aligned}\dot{m} &= a_F P^4 + b_F P^3 + c_F P^2 + d_F P + e_F \\ T &= a_T P^4 + b_T P^3 + c_T P^2 + d_T P + e_T\end{aligned}$$

or, when detailed performance data is unavailable

$$T = \frac{2 \eta P}{I_{sp} g_0}$$

- Power is modeled by a standard polynomial model

$$\frac{P_0}{r^2} \left(\frac{\gamma_0 + \frac{\gamma_1}{r} + \frac{\gamma_2}{r^2}}{1 + \gamma_3 r + \gamma_4 r^2} \right) (1 - \tau)^t$$

where P_0 is the power at beginning of life at 1 AU and τ is the solar array degradation constant

LowSIRIS-REx Step 1: The Global Options Tab

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | Physics Options | Output Options

Global mission options

Mission Name: LowSIRISREx

Mission Type: MGA-LT

Objective function: 2: maximum final mass

Maximum number of phases per journey: 8

Launch window open date: 57388.0

Number of time-steps: 40

Control coordinate system: Cartesian

Global mission constraints

DLA bounds (degrees): -28.5, 28.5

Enable mission time bounds:

Global flight time bounds (days): 0.0, 2556.75

Forced post-launch coast duration (days): 60.0

Forced pre-flyby coast duration (days): 0.0

Forced post-flyby coast duration (days): 0.0

Enable fixed final mass?

Enable minimum dry mass?

Enable fixed dry mass?

Calendar: January, 2016

Sun	Mon	Tue	Wed	Thu	Fri	Sat
27	28	29	30	31	1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31	1	2	3	4	5	6

- Change the transcription to MGALT
- Change the objective function to “maximum final mass”
- Add a forced coast of 60 days after launch before the electric thrusters can be used to maneuver. This period is used for spacecraft testing and is standard for NASA preliminary design.

LowSIRIS-REx Step 2: The Physics Options Tab

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | **Physics Options** | Output Options

Ephemeris settings

Ephemeris Source: SPICE

Leap seconds kernel: naif0011.tls

Frame kernel: pck00010.tpc

Universe folder: D:\Projects\EMTGV8_sourceforge\EMTG_libraries\Un... Default

Spiral settings

Spiral model type: Edelbaum

Number of spiral segments: 10

Lambert settings

Lambert solver type: Arora-Russell

Flyby settings

MGADSM/MDAnDSMk Flyby transcription: single beta angle

Perturbation settings

Enable SRP

Enable third body

- No changes here.

LowSIRIS-REx Step 3: The Spacecraft Options Tab

EMTG Python Interface

File

Global Mission Options | **Spacecraft Options** | Journey Options | Solver Options | Physics Options | Output Options

Spacecraft and Launch Vehicle options

Maximum mass (kg)

Allow initial mass to vary

Launch vehicle type

Launch vehicle adapter mass (kg)

Propulsion options

Chemical Isp (s)

Engine type

Number of thrusters

Throttle logic mode

Throttle sharpness

Thruster duty cycle

Power options

Power at BOL, 1 AU (kW)

Power source type

Solar power coefficients

Spacecraft power model type

Spacecraft power coefficients (kW)

Power decay rate (fraction per year)

Margins and Constraints

Propellant margin (fraction)

Power margin (fraction)

Launch vehicle margin (fraction)

Enable maximum propellant constraint?

Enable electric propulsion propellant tank constraint?

Enable chemical propulsion propellant tank constraint?

- The choice of propulsion and power model drastically affects the solution.
- The real challenge in designing low-thrust missions is understanding the appropriate spacecraft propulsion and power choices. This is more difficult than learning EMTG.
- In this example we apply a 90% duty cycle, 10% propellant margin, and 15% power margin which are standard for NASA preliminary design.

LowSIRIS-REx Step 4a: The Journey Options Tab

The screenshot shows the EMTG Python Interface with the 'Journey Options' tab selected. The 'Journey arrival type' dropdown menu is highlighted with a red box and set to '3: low-thrust rendezvous (does not work if terminal phase is not low-thrust)'. Other visible options include 'Earth_to_Bennu' as the journey name, 'SunOSIRIS' as the central body, and 'unbounded' for journey time bounds.

Option	Value
Journey name	Earth_to_Bennu
Central body	SunOSIRIS
Destination list	[3, 10]
Starting mass increment (kg)	0.0
Variable mass increment	<input type="checkbox"/>
Wait time bounds (days)	0.0 to 365.25
Journey time bounds	unbounded
Journey initial impulse bounds (km/s)	1e-08 to 10.0
Journey departure type	0: launch or direct insertion
Journey arrival type	3: low-thrust rendezvous (does not work if terminal phase is not low-thrust)
Constrain the spacecraft-sun-Earth angle at departure?	<input type="checkbox"/>
Constrain the spacecraft-sun-Earth angle at flybys?	<input type="checkbox"/>
Constrain the spacecraft-sun-Earth angle at arrival?	<input type="checkbox"/>
Constrain the spacecraft-sun-Earth angle at DSMs?	<input type="checkbox"/>
Constrain true anomaly at departure?	<input type="checkbox"/>
Constrain true anomaly at arrival?	<input type="checkbox"/>
Journey-end delta-v (km/s)	0.0
Flyby sequence	[[0, 0, 0, 0, 0, 0, 0]]
Powered flyby flags	[0, 0, 0, 0, 0, 0, 0]
Freeze this journey's decision variables?	<input type="checkbox"/>

- Change the arrival type from chemical rendezvous to low-thrust rendezvous.
- For LowSIRIS-REx, an Earth flyby is not optimal and so this is a direct mission.
- EMTG can determine the optimal flyby sequence for you by using the outer-loop solver, but that is not part of this tutorial.

LowSIRIS-REx Step 4b: The Journey Options Tab

The screenshot shows the EMTG Python Interface with the Journey Options tab selected. The interface includes a menu bar (File, Global Mission Options, Spacecraft Options, Journey Options, Solver Options, Physics Options, Output Options) and a list of journey options on the left. The 'Bennu_to_Earth' journey is selected. The main area contains various configuration fields for the journey, with the 'Forced pre-intercept coast (days)' field highlighted in red.

Parameter	Value
Journey name	Bennu_to_Earth
Central body	SunOSIRIS
Destination list	[10, 3]
Starting mass increment (kg)	0.0
Variable mass increment	<input type="checkbox"/>
Wait time bounds (days)	365.25 730.5
Bounded journey departure date?	<input type="checkbox"/>
Journey time bounds	unbounded
Journey departure type	2: free direct departure
Journey arrival type	2: intercept with bounded V infinity
Forced pre-intercept coast (days)	90.0
Journey final velocity bounds	0.0 10.0
Apply arrival declination constraint?	<input type="checkbox"/>
Atmospheric interface flight path angle (degrees)	-8.0
Atmospheric entry interface radius (km)	6503.0
Atmospheric entry latitude (degrees)	40.0
Apply atmospheric entry interface azimuth constraint?	<input type="checkbox"/>
Apply atmospheric entry interface sun angle constraint?	<input type="checkbox"/>
Apply atmospheric entry interface longitude constraint?	<input type="checkbox"/>
Apply entry velocity with respect to rotating atmosphere constraint?	<input checked="" type="checkbox"/>
Bounds on entry interface velocity with respect to rotating atmosphere (km/s)	0.0 12.4

- A forced coast of 90 days is inserted 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.

LowSIRIS-REx Step 5: The Solver Options Tab

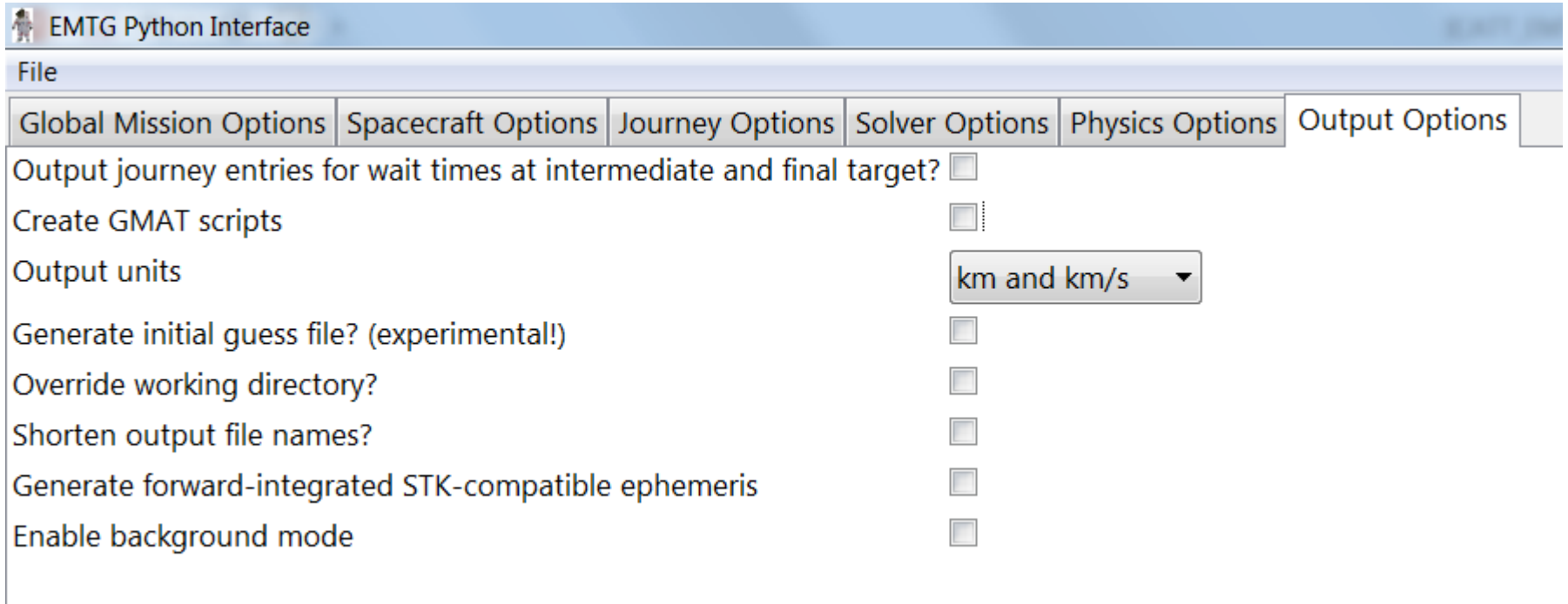
The screenshot shows the 'EMTG Python Interface' window with the 'Solver Options' tab selected. The 'Inner-Loop Solver Parameters' section is expanded, showing various configuration options for the solver. The 'Pareto' distribution is selected for the MBH hop probability distribution, and the MBH Pareto distribution alpha is set to 1.4.

Parameter	Value
Inner-loop Solver Mode	Monotonic Basin Hopping
NLP solver	SNOPT
NLP solver mode	Optimize
Quiet NLP solver?	<input checked="" type="checkbox"/>
Quiet MBH solver?	<input type="checkbox"/>
Two-step MBH?	<input type="checkbox"/>
Finite differencing step size	1.5e-08
Enable ACE feasible point finder?	<input checked="" type="checkbox"/>
MBH Impatience	100000
Maximum number of innerloop trials	100000
Maximum run-time (s)	3600
MBH hop probability distribution	Pareto
MBH hop scale factor	1.0
MBH Pareto distribution alpha	1.4
Probability of MBH time hop	0.05
Feasibility tolerance	1e-05
SNOPT major iterations limit	8000
SNOPT maximum run time (s)	30
Derivative calculation method	Analytical all but time
Check derivatives via finite differencing?	<input type="checkbox"/>
Seed MBH?	<input type="checkbox"/>

- No changes here, although in general a higher value of Pareto alpha – 1.4 or 1.5, is appropriate for low-thrust missions.

LowSIRIS-REx Step 6

The Output Options Tab



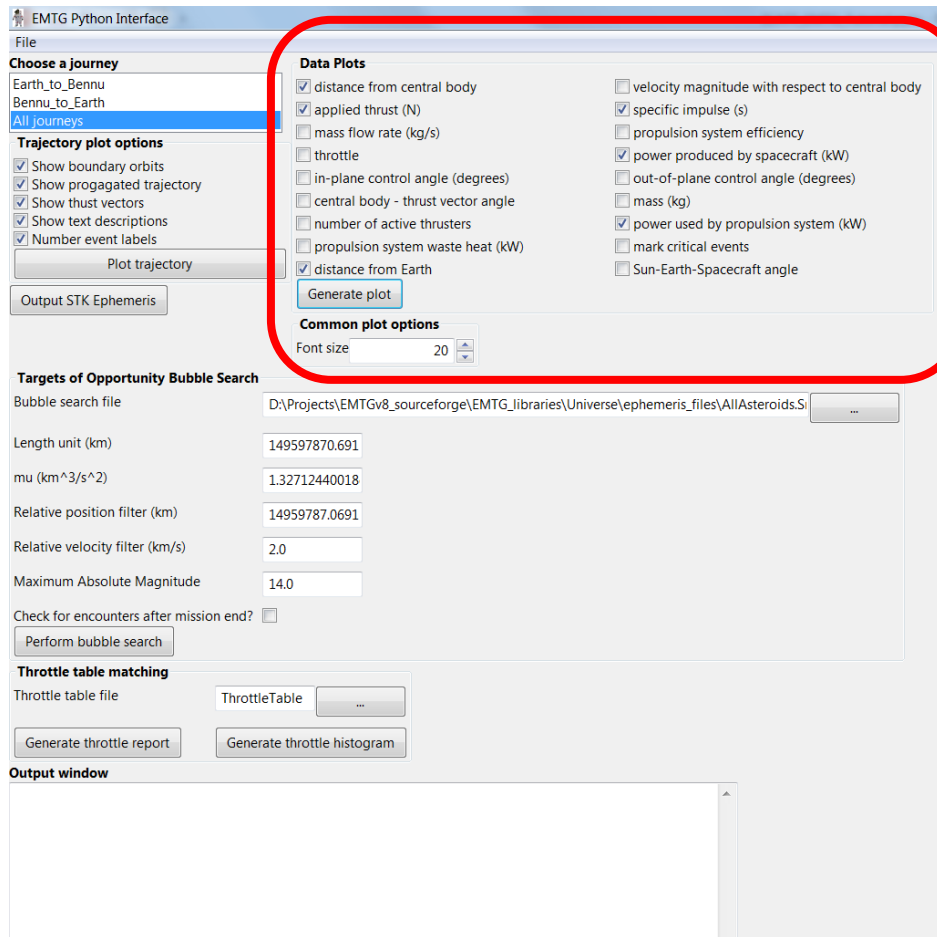
- No changes here.

LowSIRIS-REx Step 7: Run your mission!

The screenshot displays the EMTG Python Interface software. A red circle highlights the 'Run' button in the 'File' menu. The interface includes several tabs: 'Flight Options', 'Journey Options', 'Solver Options', 'Physics Options', and 'Output Options'. The main workspace shows mission parameters for 'LowSIRISREx_FBLT'. A calendar widget is open, showing the month of January 2016, with the 30th highlighted. The 'Global mission constraints' panel on the right lists various parameters and their values.

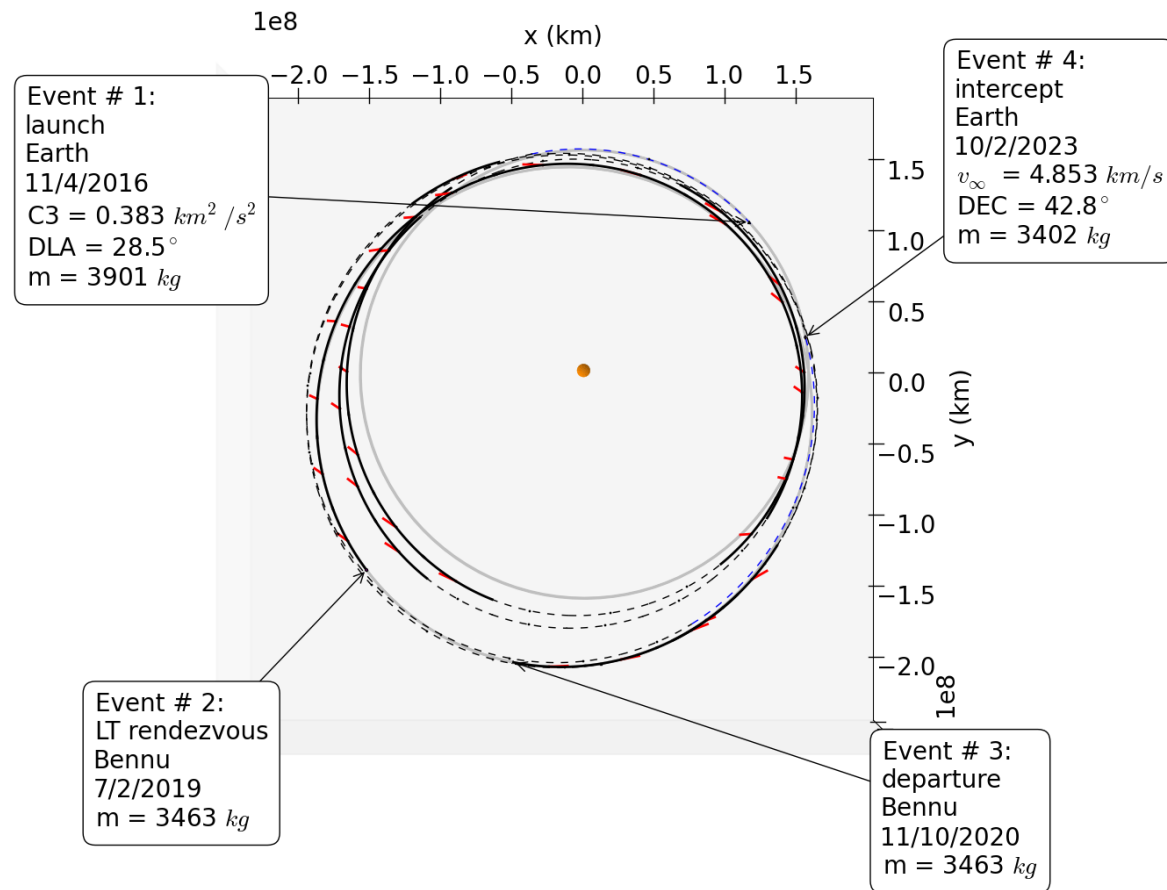
Parameter	Value
DLA bounds (degrees)	-28.5 to 28.5
Enable mission time bounds	<input checked="" type="checkbox"/>
Global flight time bounds (days)	0.0 to 2556.75
Forced post-launch coast duration (days)	60.0
Forced pre-flyby coast duration (days)	0.0
Forced post-flyby coast duration (days)	0.0
Enable fixed final mass?	<input type="checkbox"/>
Enable minimum dry mass?	<input type="checkbox"/>
Enable fixed dry mass?	<input type="checkbox"/>

LowSIRIS-REx Step 8: Post-Process Your Mission

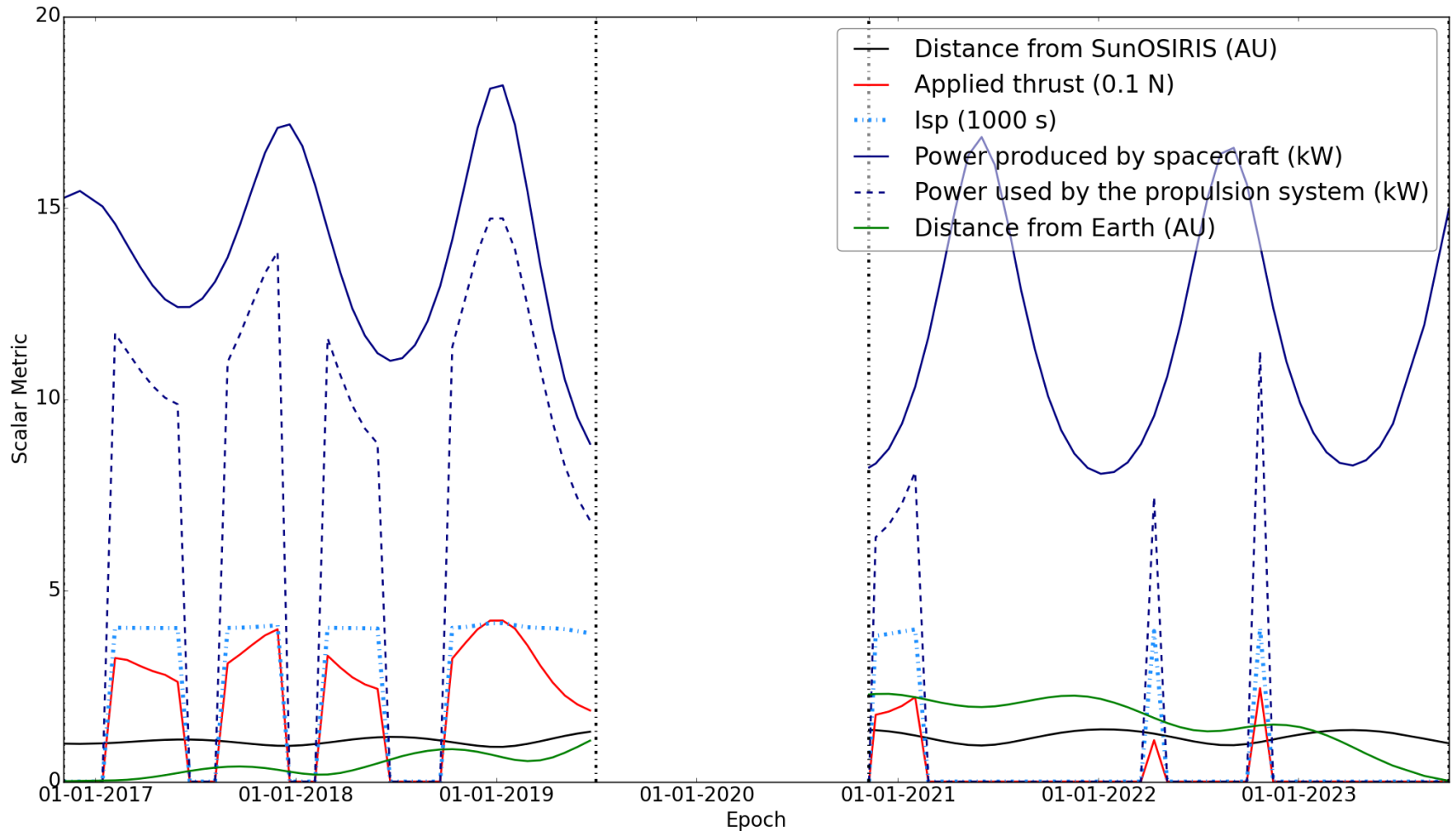


- In addition to trajectory plots, PyEMTG can create plots of systems parameters, such as power, propulsion, and distance from the Sun and Earth.
- Plotting distance from the Earth requires installing the “jplephem” and “de423” Python packages.
- PyEMTG can also map the continuous low-thrust model to a discrete throttle table if you have one. Unfortunately we can’t distribute those.

LowSIRIS-REx Trajectory Plot



LowSIRIS-REx Systems Plot



LowSIRIS-REx in Medium-High Fidelity

- 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
- For a more accurate representation of the trajectory, we migrate to the “Finite-Burn Low-Thrust” (FBLT) transcription which uses a numerical integrator and the true low-thrust equations of motion
- FBLT can support perturbing terms like third body gravity and solar radiation pressure (SRP)
- However the body encounters are still patched-conic
- FBLT is a good intermediate step between the speed of MGALT and the accuracy of GMAT
- Integrated trajectory, accurate force model but flybys are still patched-conic

J. Englander, D. Ellison, and B. Conway, “Global Optimization of Low-Thrust, Multiple-Flyby Trajectories at Medium and Medium-High Fidelity,” AAS Space Flight Mechanics Meeting, Santa Fe, NM, January 2014.

LowSIRIS-REx in Medium-High Fidelity

Step 1: The Global Options Panel

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | Physics Options | Output Options

Global mission options

Mission Name: LowSIRISREx_FBLT

Mission Type: FBLT

Objective function: 2: maximum final mass

Maximum number of phases per journey: 8

Launch window open date: 57388.0

Number of time-steps: 80

Control coordinate system: Cartesian

Global mission constraints

DLA bounds (degrees): -28.5, 28.5

Enable mission time bounds:

Global flight time bounds (days): 0.0, 2556.75

Forced post-launch coast duration (days): 60.0

Forced pre-flyby coast duration (days): 0.0

Forced post-flyby coast duration (days): 0.0

Enable fixed final mass?:

Enable minimum dry mass?:

Enable fixed dry mass?:

January, 2016

Sun	Mon	Tue	Wed	Thu	Fri	Sat
27	28	29	30	31	1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31	1	2	3	4	5	6

- Change the transcription to FBLT
- We want our detailed trajectory in higher resolution, *i.e.* more opportunities to change the control, so increase the number of time-steps to 80.



LowSIRIS-REx in Medium-High Fidelity

Step 2: The Solver Options Panel

EMTG Python Interface

File

Global Mission Options | Spacecraft Options | Journey Options | Solver Options | Physics Options | Output Options

Inner-Loop Solver Parameters

Inner-loop Solver Mode: NLP with initial guess

NLP solver: SNOPT

NLP solver mode: Optimize

Quiet NLP solver?

Finite differencing step size: 1.5e-08

Feasibility tolerance: 1e-05

SNOPT major iterations limit: 8000

SNOPT maximum run time (s): 600

Derivative calculation method: Analytical all but time

Check derivatives via finite differencing?

Initial guess control coordinate system: Cartesian

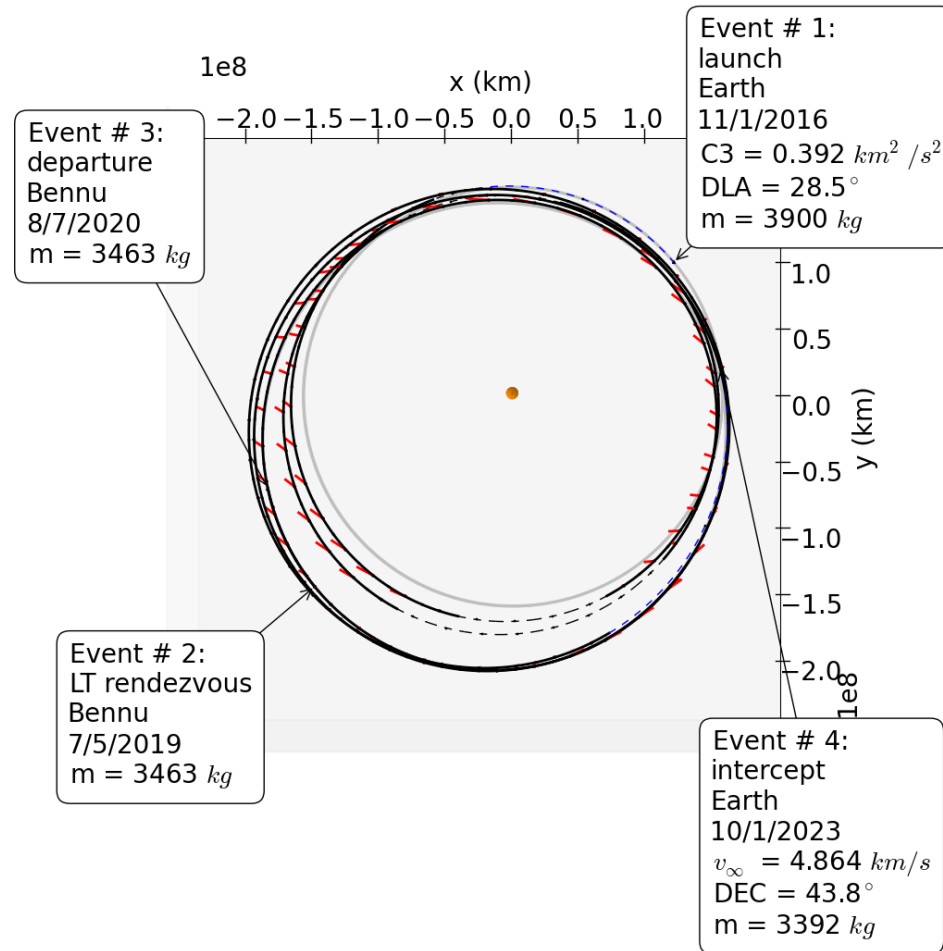
Interpolate initial guess?

Number of timesteps used to create initial guess: 40

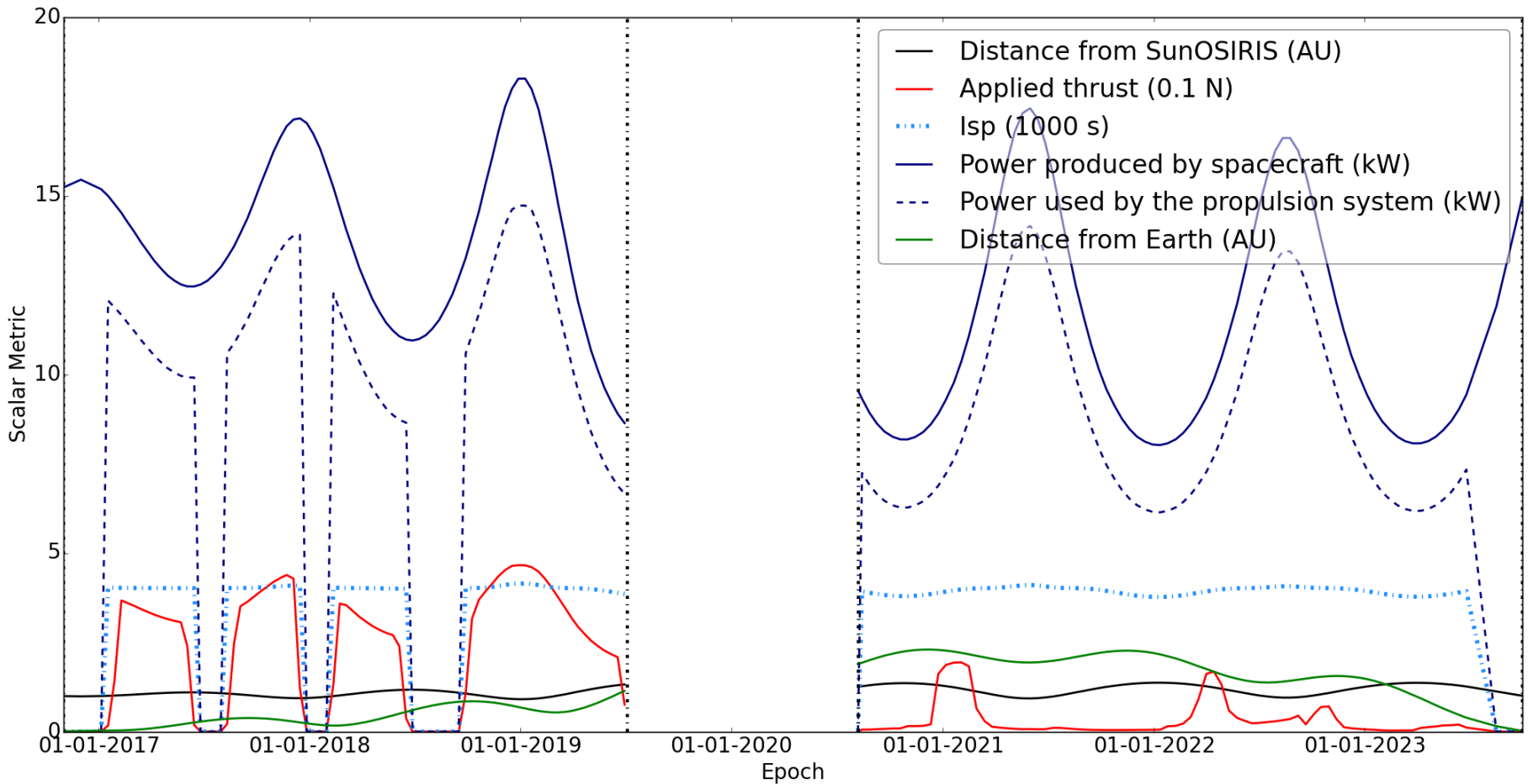
Trial decision vector or initial guess: ...

- Since we already have a solution in MGALT, we do not need to run MBH.
- Instead we will run our NLP solver (SNOPT) directly with the previous solution as an initial guess.
- We can tell EMTG to seed from a previous solution by clicking “...” and selecting the previous .emtg results file.
- The previous solution had only 40 time steps so we have to tell EMTG to interpolate it.
- FBLT is very slow. Let’s give SNOPT 10 minutes to chew on the problem.

LowSIRIS-REx in Medium-High Fidelity Trajectory Plot



LowSIRIS-REx in Medium-High Fidelity Systems Plot



Some of the many things that we did not cover...

- EMTG's outer-loop solver
 - Can choose planetary flyby sequence
 - For small-bodies missions, can choose both the number and the identity of the targets
 - Can design the propulsion and power system for the spacecraft
 - Finds the Pareto-optimal non-dominated front between mission and systems objective functions of the user's choice
- Operational constraints
 - Distance from the sun and other bodies
 - Visibility angles at arrival and departure
- Powered gravity assist
- Low-thrust departure and arrival spirals
- Non-body boundary conditions
- Central bodies other than the sun (EMTG is central body agnostic)
- Automated export to GMAT

Conclusion

- EMTG is a flexible, automated tool for preliminary design of interplanetary trajectories that can find optimal solutions without requiring an initial guess.
- EMTG can design both missions with chemical propulsion and/or low-thrust electric propulsion.
- When operated in hybrid optimal control mode, EMTG can autonomously explore the design space for a mission and can be left to run independently for days while analysts do other work.
- Mission design mathematics may easily be automated. Communication and understanding cannot be. EMTG's automation allows analysts to focus their attention on understanding the needs of the customers (scientists) and the capabilities of the spacecraft while leaving the repetitive work to the computer.

Thank You

EMTG is available open-source at
<https://sourceforge.net/projects/emtg/>

