

National Aeronautics and Space Administration

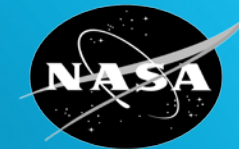
Global Search and Trajectory Optimization in Interplanetary and Cislunar Space



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NAVIGATION & MISSION DESIGN BRANCH
NASA GSFC

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Outline

- Introduction to the interplanetary mission design problem
- Brief (incomplete) history of the field
- Trajectory transcriptions
- Physics models
- Boundary conditions
- Optimization and global search
- Hybrid Optimal Control
- Lucy: Exploring the Diversity of the Jupiter Trojans
- Other examples

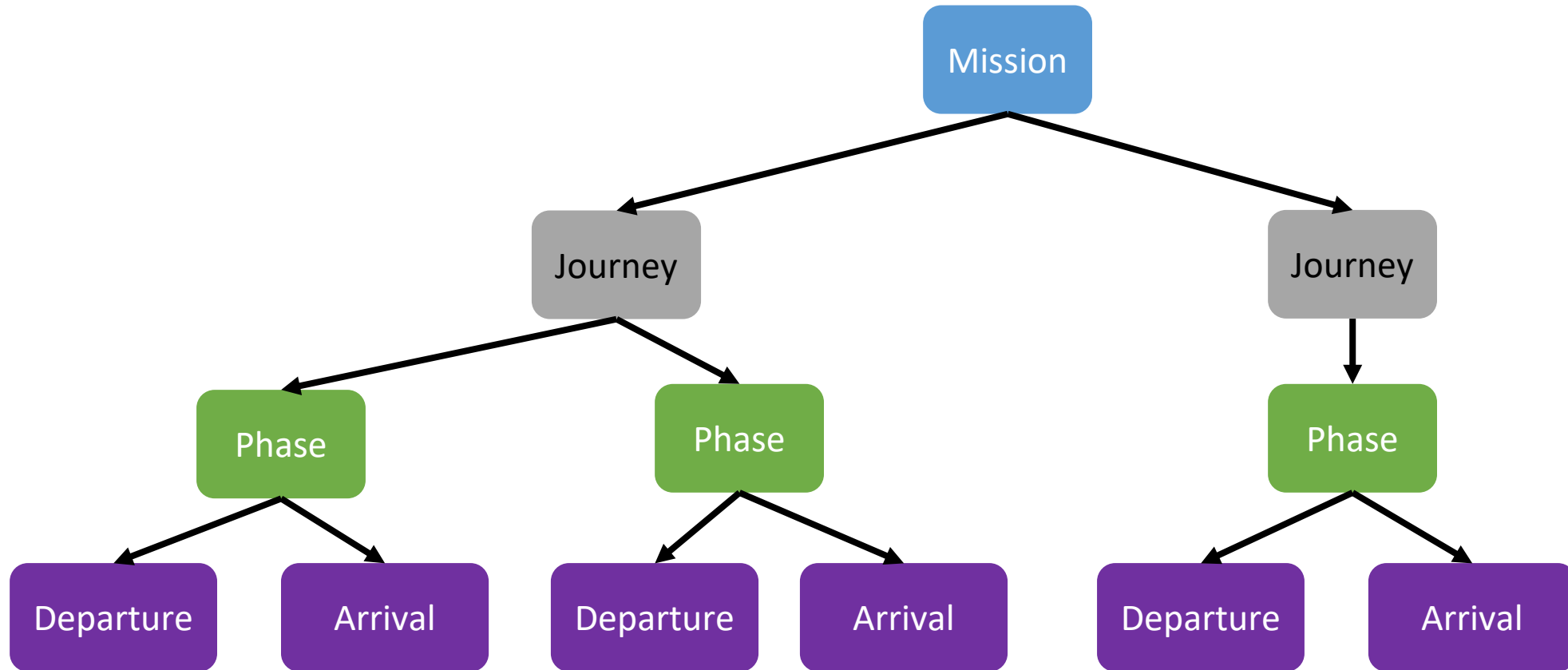
Introduction to the General Interplanetary Mission Design Problem

- The interplanetary design problem is composed of both discrete and real-valued decision parameters:
 - Choice of destination(s), number of planetary flybys, identities of flyby planets, propulsion, power, launch vehicle...
 - Launch date, flight time(s), epochs of maneuvers, control history, flyby altitudes, etc.
- For example, for a main-belt asteroid mission, the designer must choose:
 - The optimal asteroid from a set of scientifically interesting bodies provided by the customer
 - Whether or not to perform planetary flybys on the way to the main belt and, if so, at which planets
 - Optimal trajectory from the Earth to the chosen asteroid by way of the chosen flyby planets

Brief (incomplete) History of Automated Interplanetary Mission Design

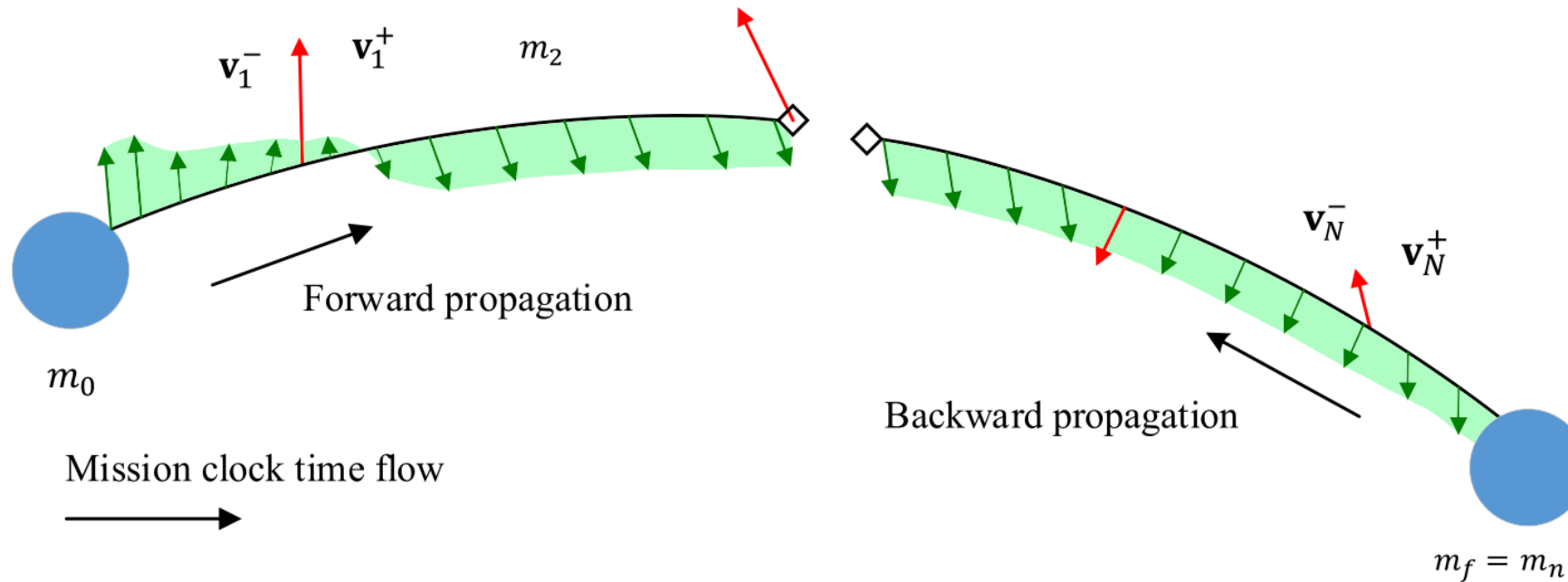
- Gage, Braun, and Kroo, 1994 – autonomous chemical design with variable mission sequence (no deep-space maneuvers)
- Vasile and de Pascale, 2005 – autonomous chemical design for fixed mission sequence
- Vinko and Izzo, 2008 – autonomous chemical design for fixed mission sequence
- Wall and Conway, 2009 – autonomous low-thrust design for fixed mission sequence (no planetary flybys)
- Chilan and Conway, 2009 – autonomous low-thrust and chemical design for fixed mission sequence (no planetary flybys)
- Yam, di Lorenzo, and Izzo, 2011 – autonomous low-thrust design for fixed mission sequence
- Abdelkhalik and Gad, 2011, 2012, and 2013 – autonomous chemical design with variable mission sequence
- Englander, Conway, and Williams, 2012 – autonomous chemical design with variable mission sequence
- Englander (dissertation) 2013 – autonomous low-thrust design with variable mission sequence
- Englander, Vavrina, and Ghosh (2015) – multi-objective low-thrust trajectory and system design with variable mission sequence
- Vavrina, Englander, and Ellison (2016) – Multi-objective chemical mission design with variable mission sequence
- Ellison, Englander, Ozimek, and Conway (2018) – analytical partial derivatives

Evolutionary Mission Trajectory Generator (EMTG) Architecture of an Optimization Problem

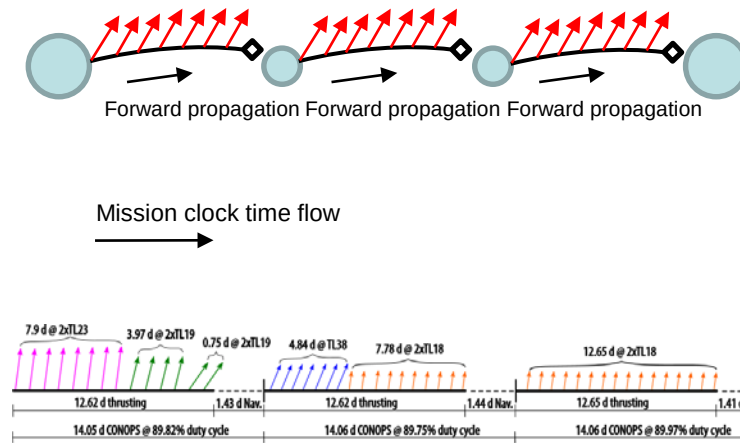
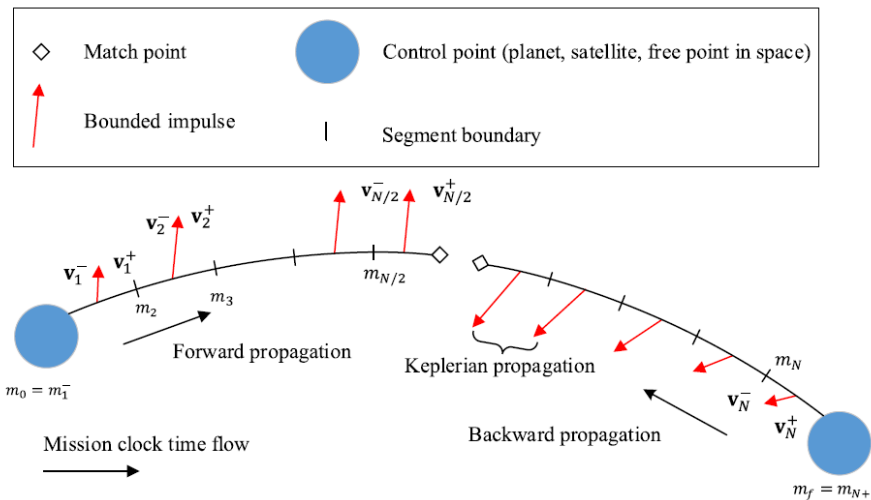


- Mission: A high-level container of the entire problem. Contains journeys.
- Journey: A mid-level container that expresses a complete user-defined thought, *i.e.* “OSIRIS-REx goes to Bennu.”
- Phase: A low-level container created by EMTG to express the trajectory from one boundary to another.
- Departure event: A class defining the left-hand boundary of a phase. Derived classes for different applications.
- Arrival event: A class defining the right-hand boundary of a phase. Derived classes for different applications.

High-thrust chemical propulsion trajectory transcription



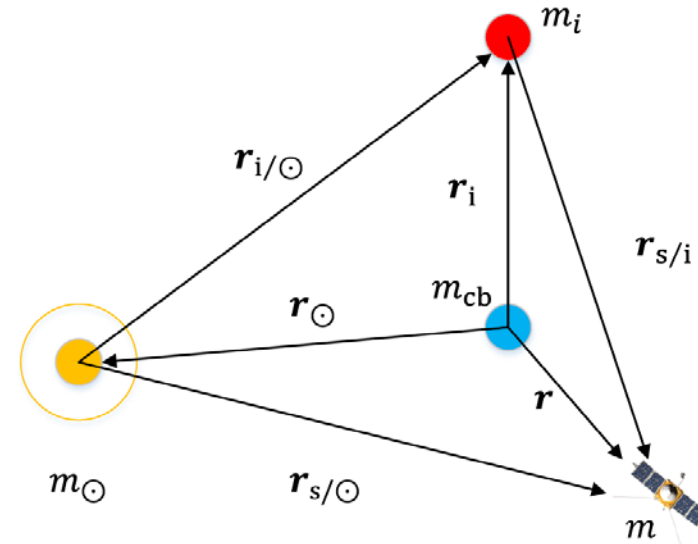
Low-thrust electric propulsion trajectory transcription



Low-Fidelity (Two Point Shooting Sims-Flanagan) High-Fidelity (Parallel Shooting Finite Burn)

Physics Models

- EMTG models 3rd body gravity, solar radiation pressure, and the J2 non-spherical gravity term.
- Thruster modeling in EMTG can be any of:
 - Constant thrust/Isp
 - Polynomial fit to thrust/mass flow rate as a function of power
 - High-fidelity smoothed-discrete model of actual thruster throttle points
- Launch vehicles are modeled as a polynomial fit to tabulated data from NASA Launch Services Program (LSP).
- Hardware (power, propulsion, launch vehicle) models are provided to EMTG via user-supplied text files.

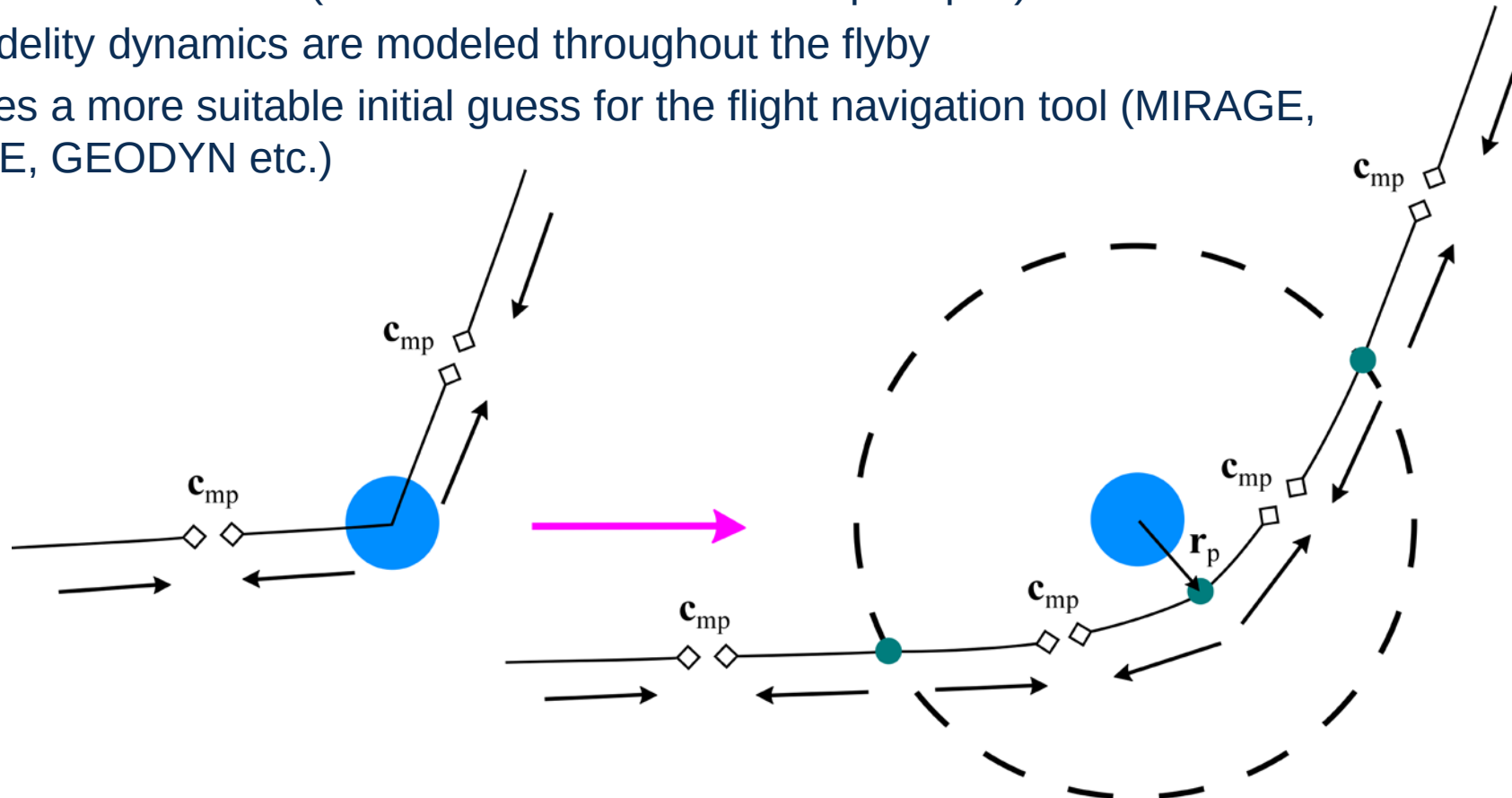


Boundary conditions

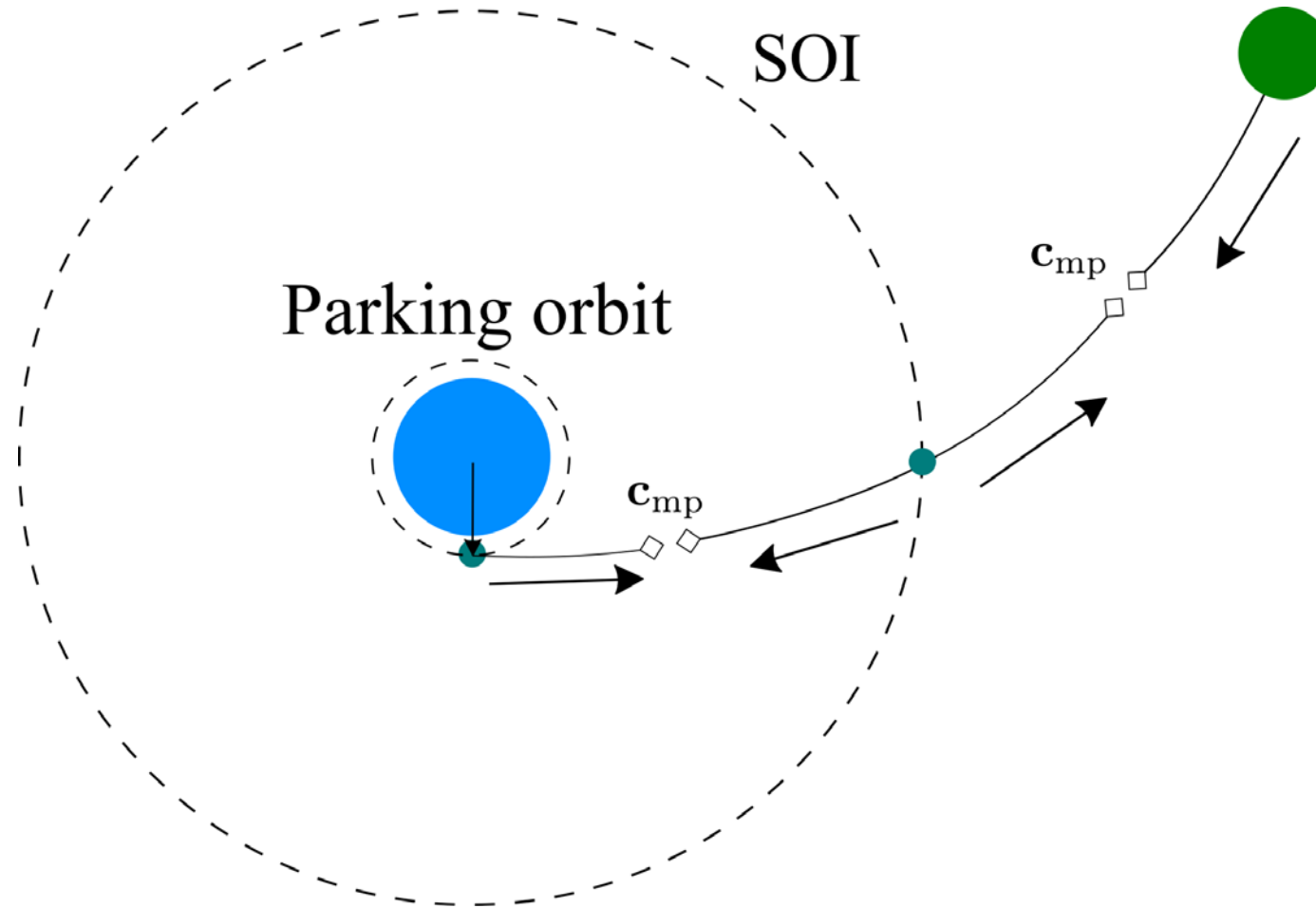
- EMTGv9 supports four classes of boundary condition:
 - *Ephemeris pegged* – base boundary states match a body's ephemeris,.
 - *Ephemeris referenced* – base boundary states lie on a triaxial ellipsoid centered on a body's ephemeris.
 - *Free point* – base boundary states are decision variables bounded by the user. Free point may be specified in Cartesian or COE. EMTG can propagate the free point if necessary.
 - *Periapse* – base point state is periapse of an orbit in Spherical RADEC or AZFPA coordinates. Useful for gravity assists and launch.
- Each boundary class supports multiple boundary types, including but not limited to:
 - Departure with or without $\mathbf{v}_\infty$ vector, with or without launch model.
 - Arrival with or without $\mathbf{v}_\infty$ vector, with or without arrival maneuver.
 - Edelbaum escape and capture spirals (ephemeris pegged only).
- A wide variety of boundary *constraints* may be attached to boundary conditions via a scripting interface. It is very easy to code new constraints.

Finite Radius SOI Gravity-Assists

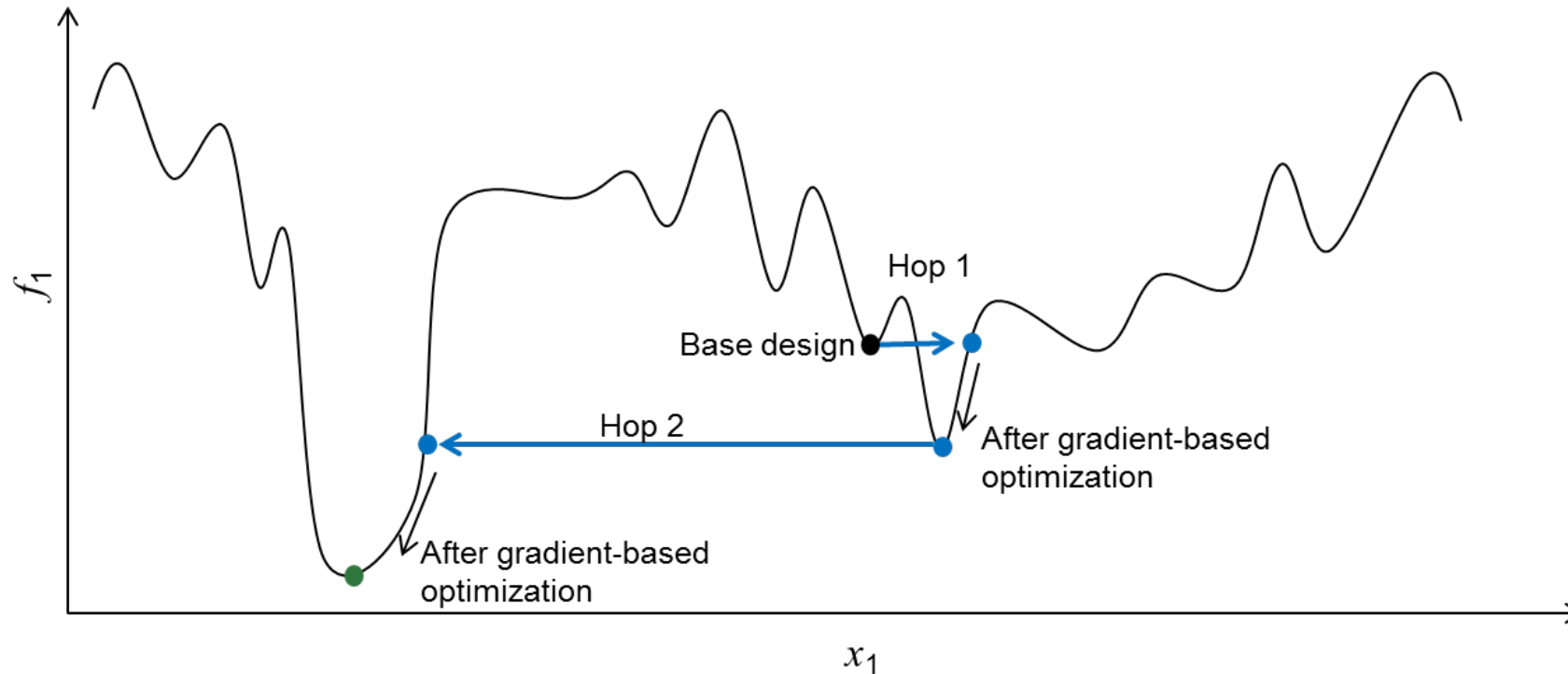
- EMTG can model two types of flyby boundary events
- Ephemeris-pegged (ZSOI, collision model)
- Ephemeris-referenced (shooters on the SOI and at periapse)
- High-fidelity dynamics are modeled throughout the flyby
- Provides a more suitable initial guess for the flight navigation tool (MIRAGE, MONTE, GEODYN etc.)



Departure From a Parking Orbit



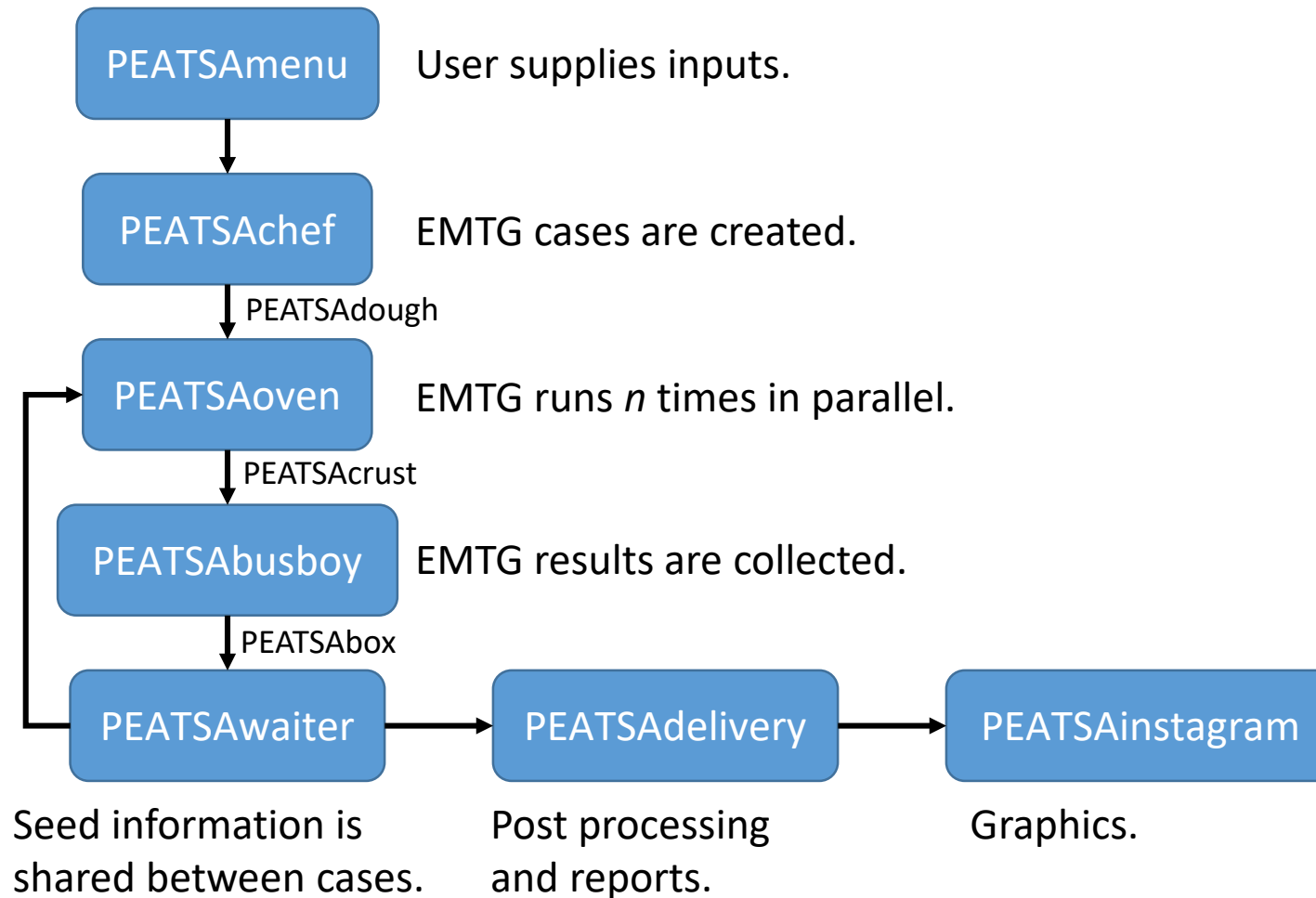
Optimization via Nonlinear Programming and Monotonic Basin Hopping



Automated Mission Design via Hybrid Optimal Control

- How do we solve the coupled discrete and continuous problems together?
- Break the mission design problem into two stages, or “loops”
 - “outer-loop” picks sets of destinations, planetary flybys, sizes the power system, can pick propulsion system – a discrete optimization problem
 - “inner-loop” finds the optimal trajectory for a given candidate outer-loop solution – a real-valued optimization problem
 - **For the outer-loop to work, the inner-loop must function autonomously (i.e. no human interaction)**
- The customer (scientist or project manager) most often does not want just one point solution to the mission design problem. Instead, an exploration of a multi-objective trade space is required.
- To address this question we use a multi-objective discrete outer-loop which defines many single objective real-valued inner-loop problems
- Outer loop optimization is done with a multi-objective genetic algorithm (NSGA-II)

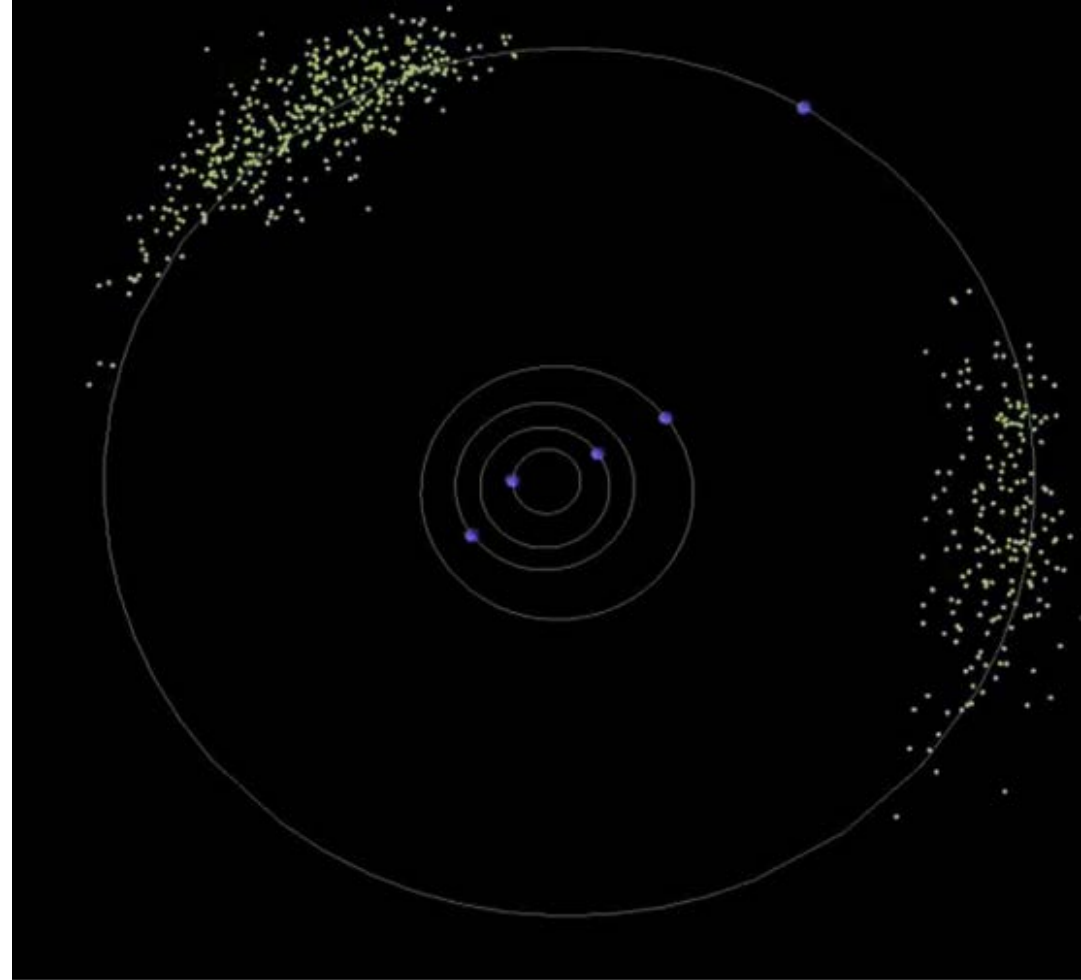
PYTHON EMTG AUTOMATED TRADE STUDY APPLICATION (PEATSA)



EXAMPLES

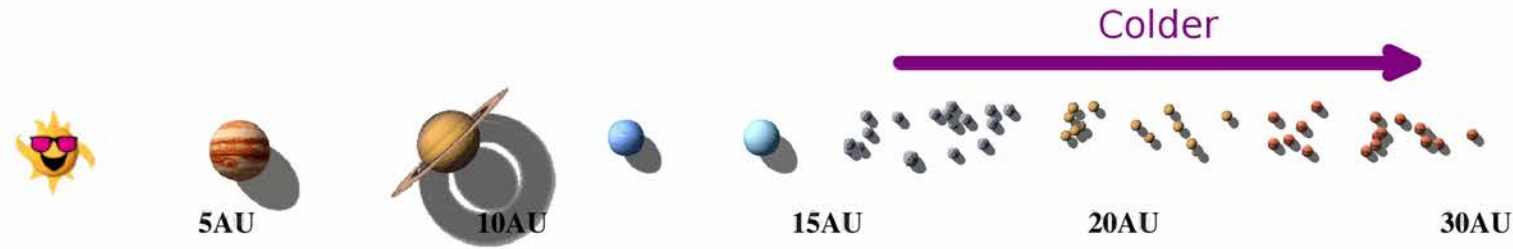
LUCY: EXPLORING THE DIVERSITY OF THE JUPITER TROJANS

- The Lucy mission will launch in 2021 to explore the asteroids trapped in the L4 and L5 regions of the Sun-Jupiter system.
- Lucy will visit four bodies in L4, one in L5, and a main-belt asteroid.



Lucy Link to Planet Formation

Example: The Nice Model

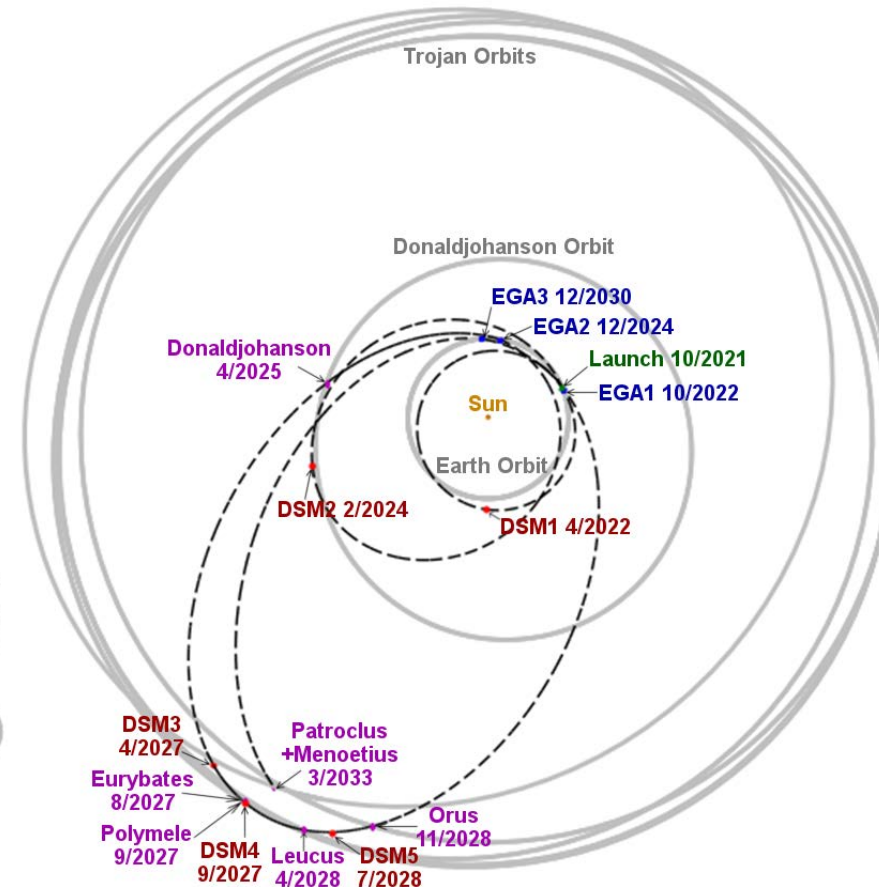
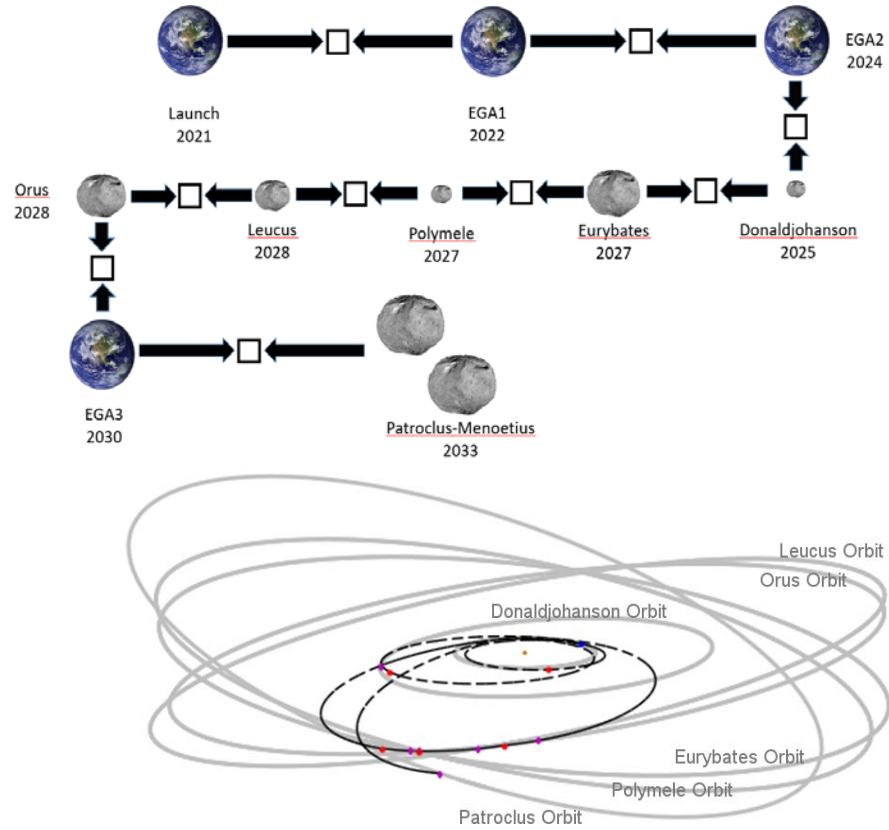


- Trojans were mixed together by planet formation and migration.
- The same process led to their capture in the swarms.

So, Trojans likely harbor objects that formed throughout the outer Solar System. Thus, they present us with a **UNIQUE** opportunity to constrain planet formation and evolution models. **It is only by sampling their diversity that their true scientific potential can be realized.**

Trojans allow us to study planetesimals from throughout the outer Solar System

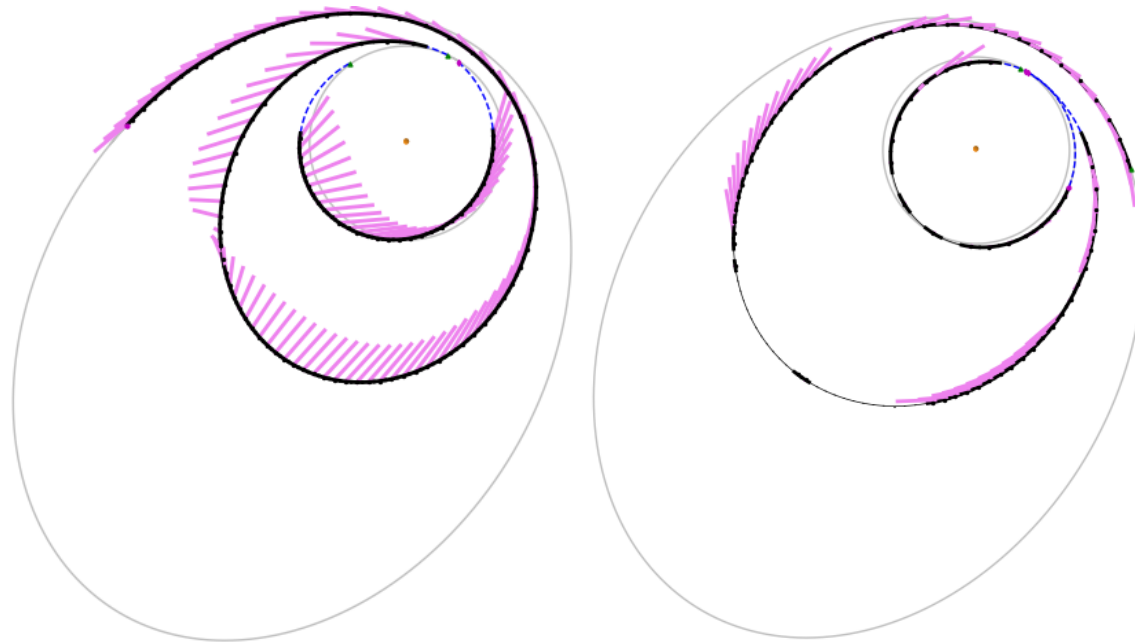
Example: Lucy reference mission design



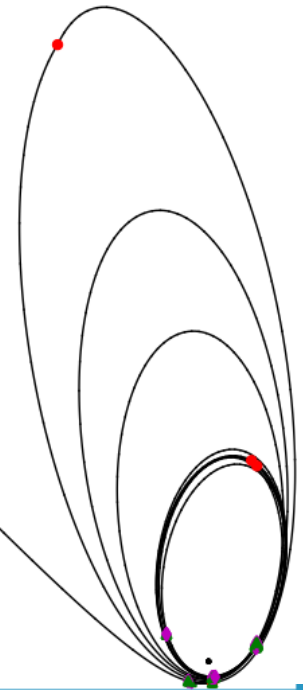
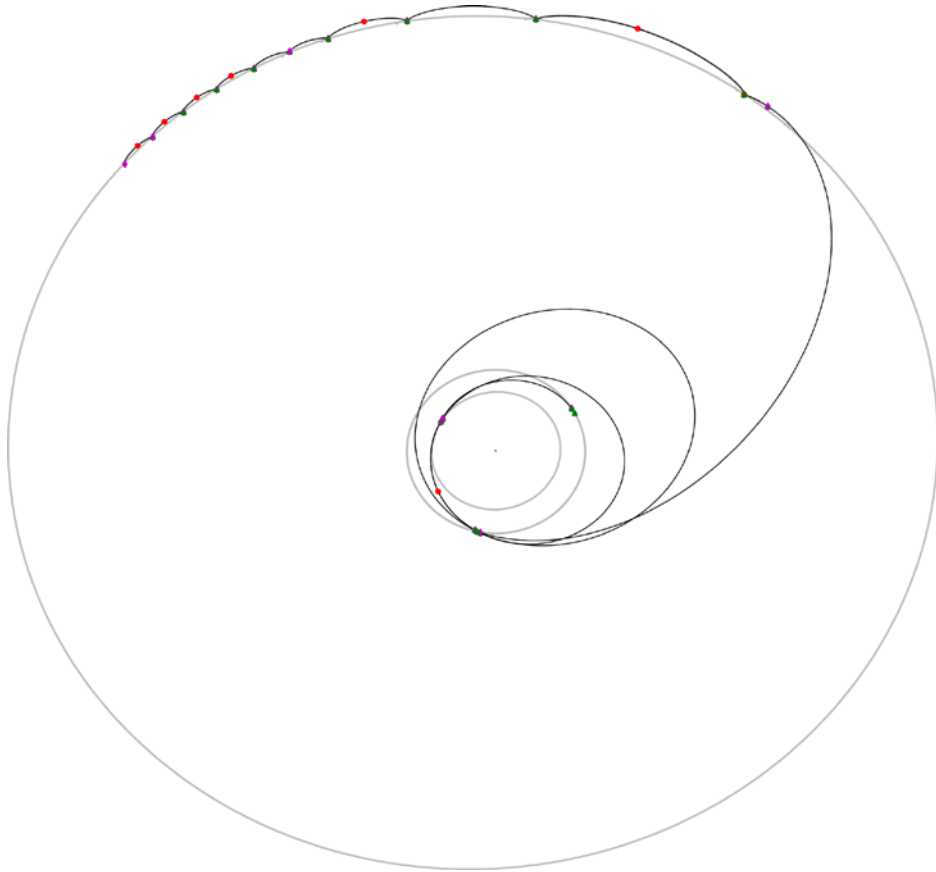
EXAMPLE: LUCY REFERENCE MISSION DESIGN



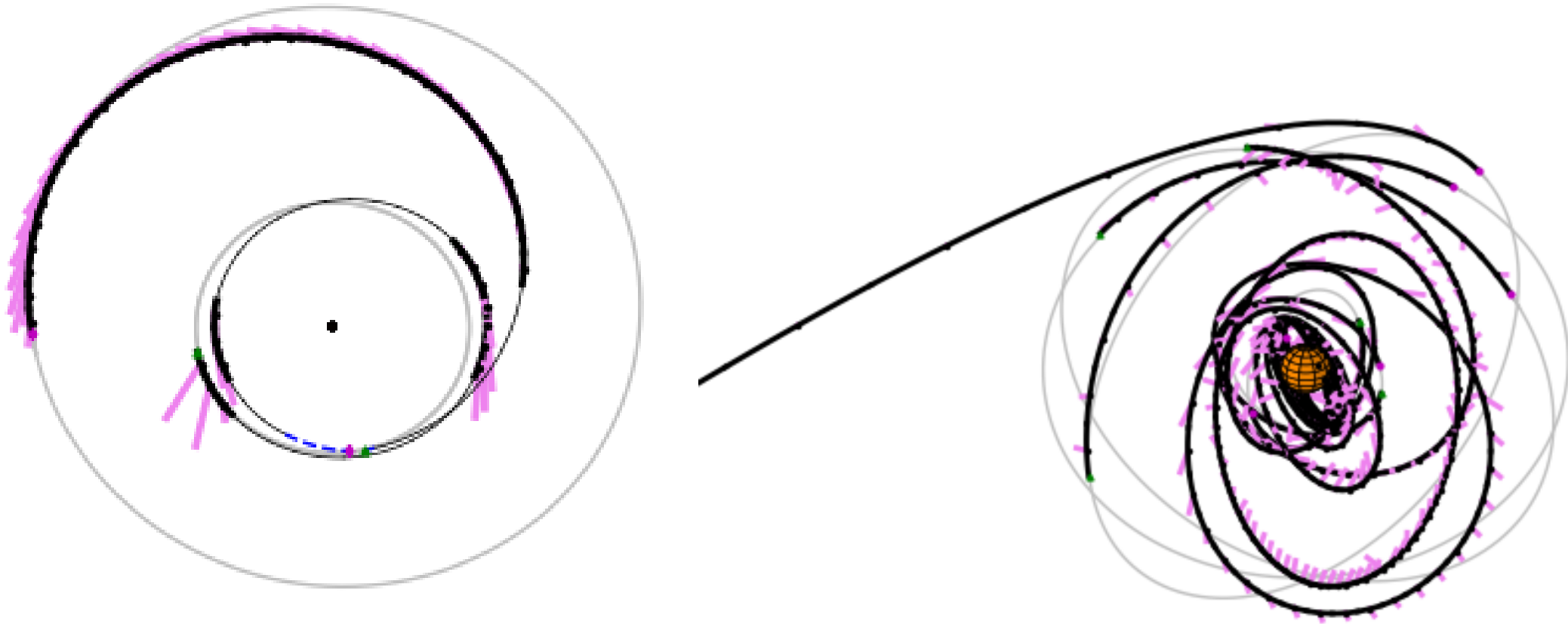
Example: Comet Sample Return



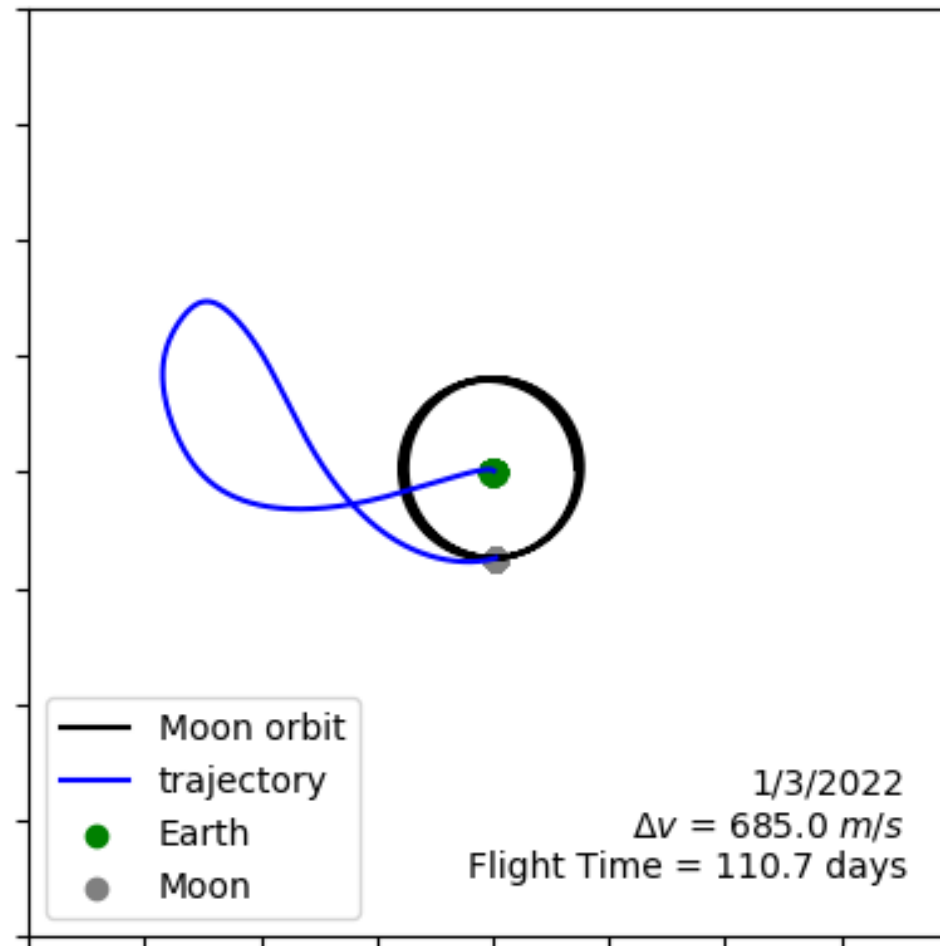
Example: Mission to Europa all in one solve



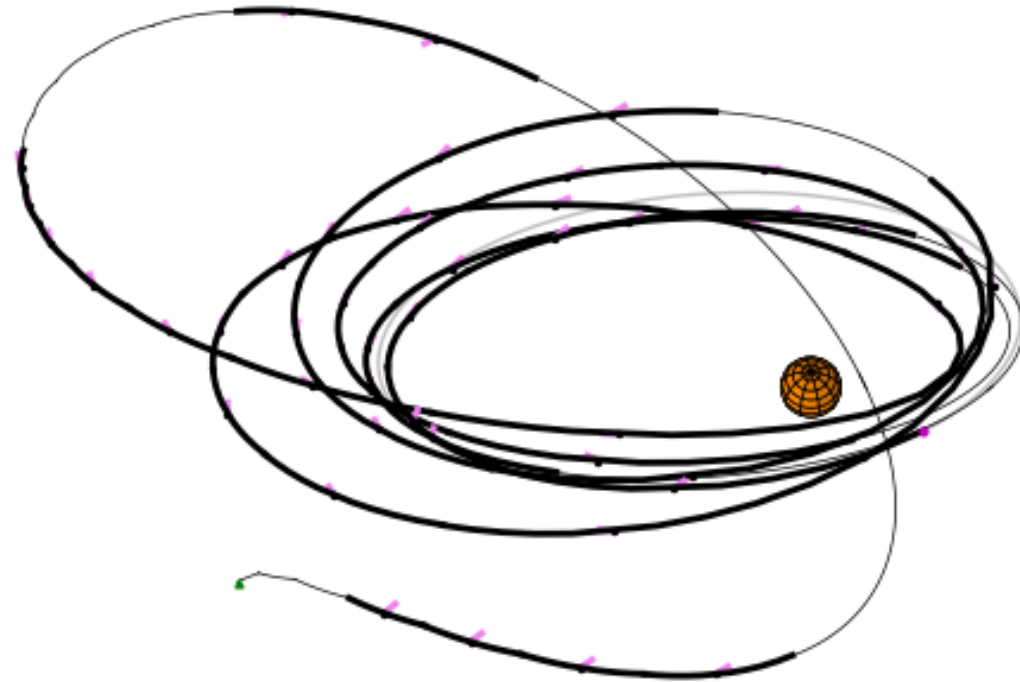
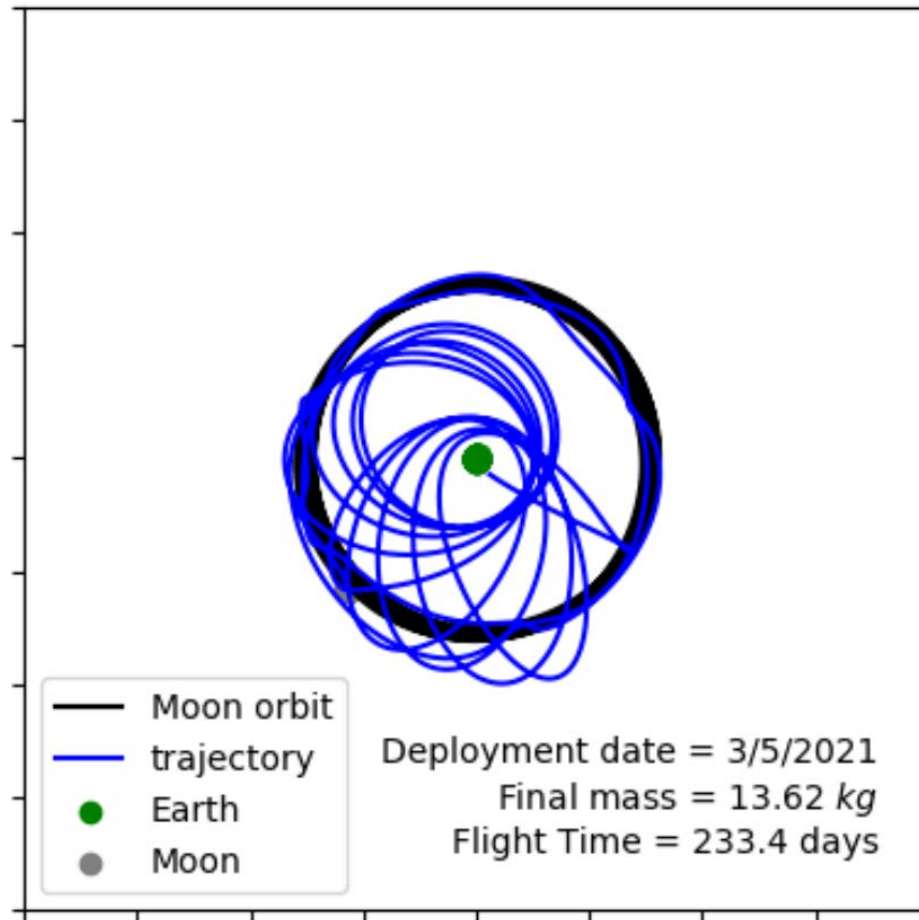
Example: Small Body interplanetary transfer and proximity operations, all in one solve



Example: Ballistic Lunar Transfer



Example: Low-thrust, low-energy lunar transfer and weak capture, all in one solve



Hybrid Optimal Control Example: Asteroid Robotic Redirect Mission (ARRM)

