PURDUE ENGINEERING
AERONAUTICS AND ASTRONAUTICS

Trajectory Design for a Cislunar CubeSat Leveraging Dynamical Systems Techniques: The Lunar IceCube Mission

AAS 17-286

Natasha Bosanac, Andrew Cox, Kathleen C. Howell, David Folta
Purdue University and NASA Goddard Space Flight Center

Motivation

How to design complex path for CubeSat beyond LEO with limited propulsion and constrained deployment state?

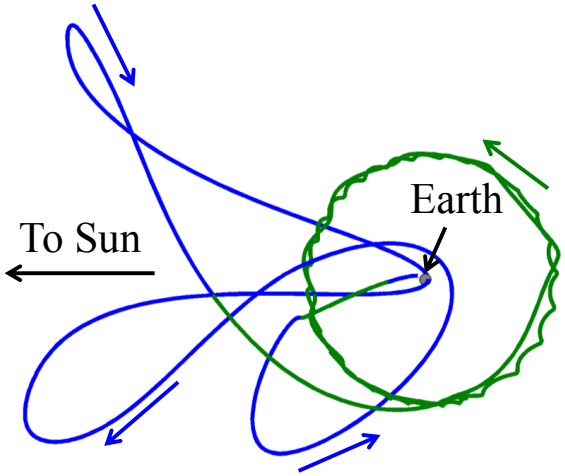
- CubeSats: low-cost, rapidly-developed platform for exploration in cislunar space and beyond
- Deployment uncertainty and updates, limited propulsion create trajectory design challenges
- Leverage dynamical systems approach to construct framework for rapid and guided transfer design

Lunar IceCube

- 6U CubeSat led by Morehead State University
- Secondary payload on EM-1 (to launch in late 2018)
- Objective: observe water and lunar volatiles
- Lunar science orbit, highly inclined
- Busek Ion Thruster system, $T = 0.9$ mN, $I_{sp} = 2500$ s
- Initial spacecraft mass of 14 kg

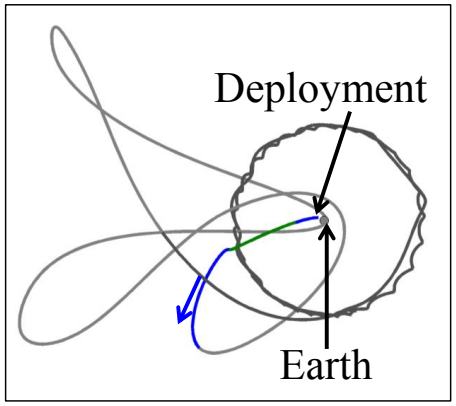
Lunar IceCube spacecraft concept
Credit: Morehead State University

Trajectory Design Framework

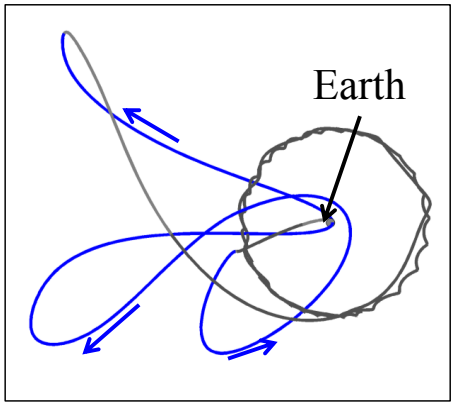


Transfer for original deployment state
Credit: David Folta

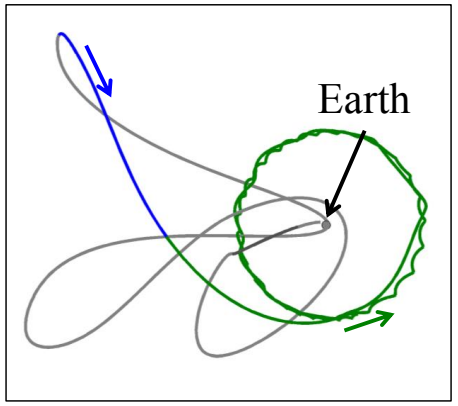
I: Earth Outbound



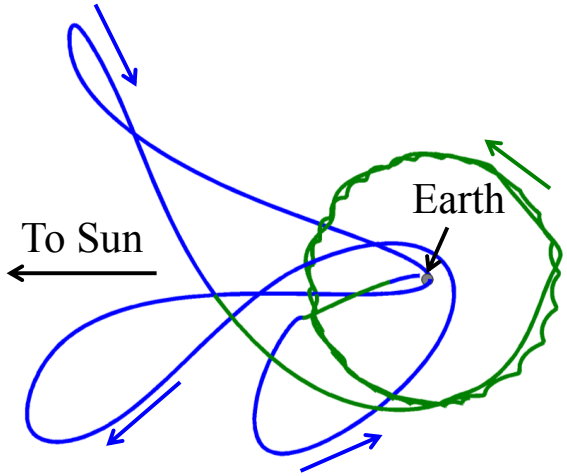
II: Phasing & Energy Adjustment



III: Lunar Approach & Capture

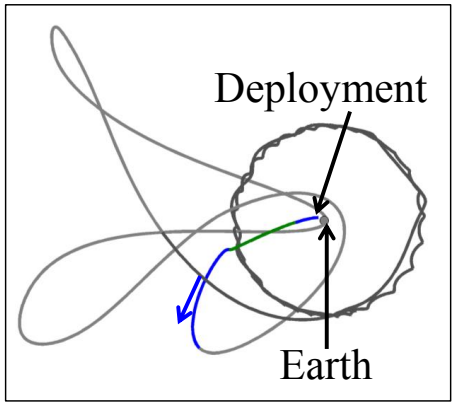


Trajectory Design Framework



Transfer for original deployment state
Credit: David Folta

I: Earth Outbound



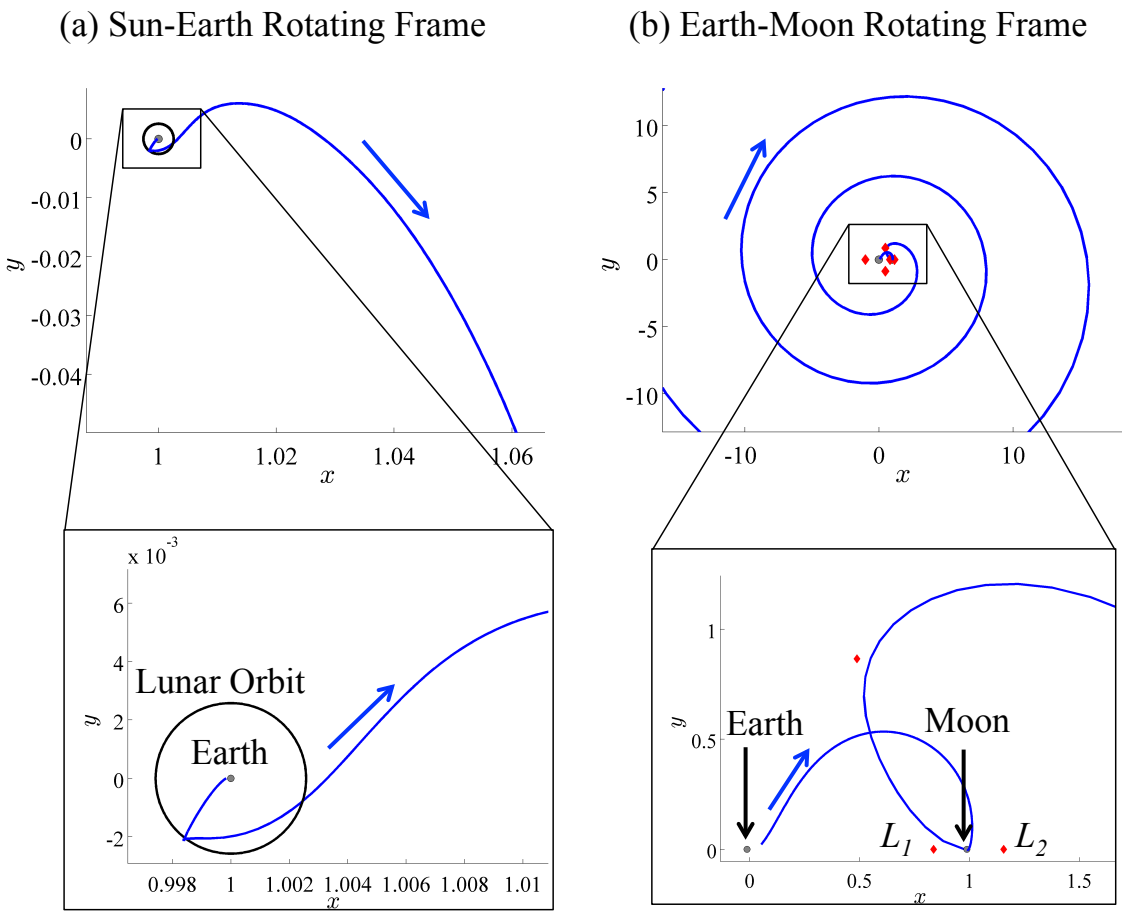
II: Phasing & Energy Adjustment

III: Lunar Approach & Capture

Earth Outbound Segment

Naturally, trajectories would depart

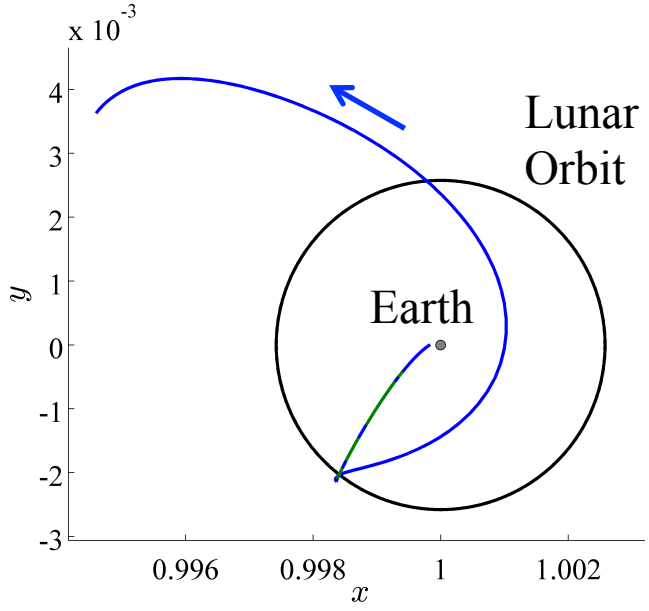
Deployment:
Oct 7, 2018



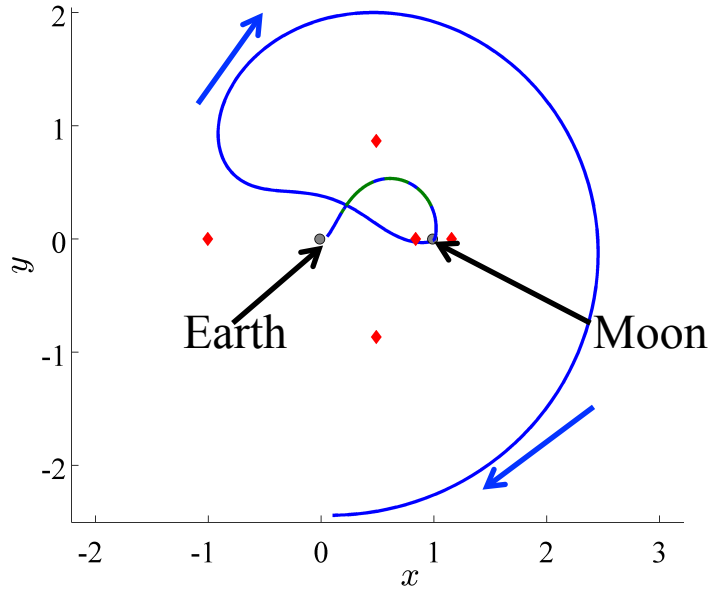
Earth Outbound Segment

Low-thrust engine and lunar flyby prevents spacecraft from departing Earth vicinity

(a) Sun-Earth Rotating Frame



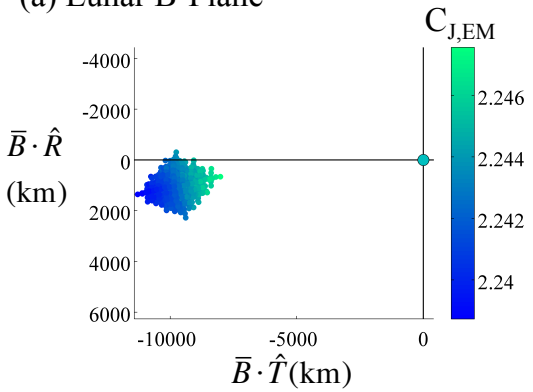
(b) Earth-Moon Rotating Frame



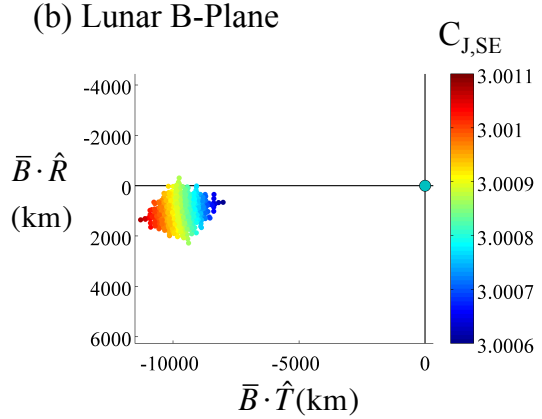
Earth Outbound Segment

Pre-flyby thrust direction can be used to adjust flyby and apogee conditions

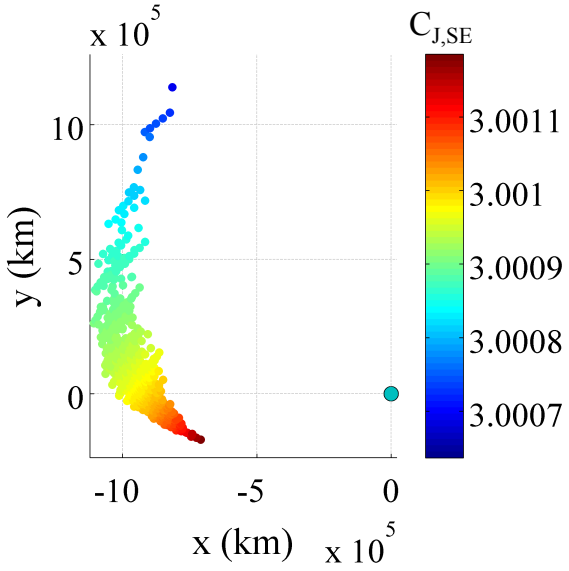
(a) Lunar B-Plane



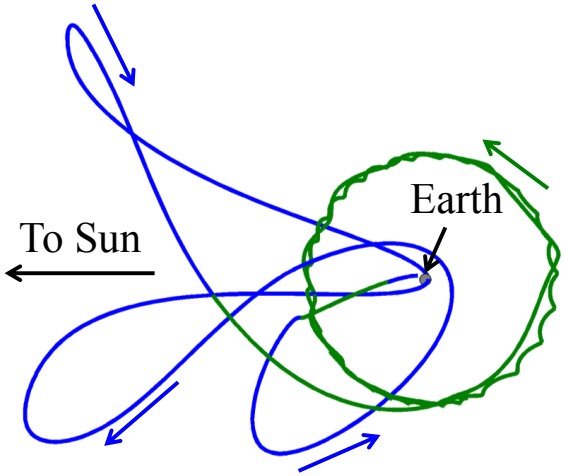
(b) Lunar B-Plane



(c) Sun-Earth Rotating Frame



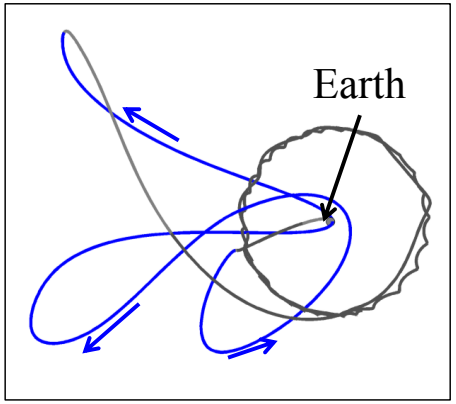
Trajectory Design Framework



Transfer for original deployment state
Credit: David Folta

I: Earth Outbound

II: Phasing & Energy Adjustment



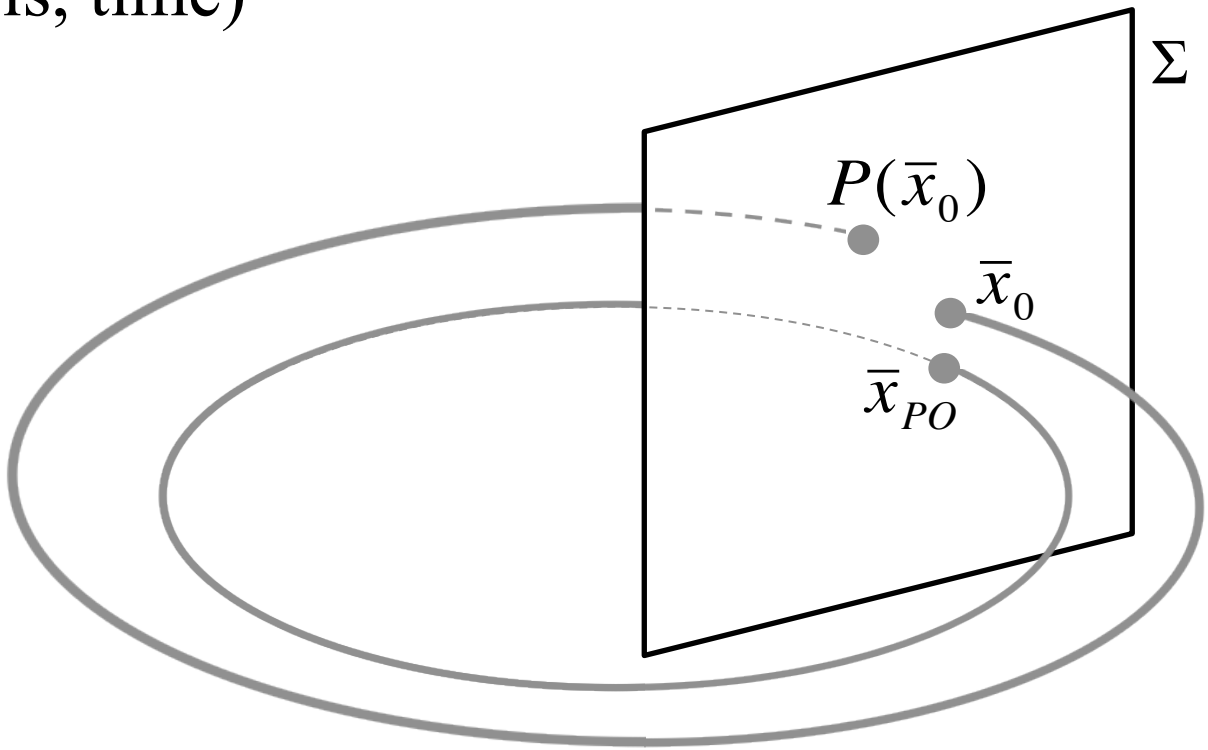
III: Lunar Approach & Capture

Phasing and Energy Adjustment Segment

- Identify connection between bounding segments
  - Leverage natural structures from Sun-Earth CR3BP
- Explore transfer arcs via apoapsis maps
  - Assume planar motion
  - Supports prediction of geometry, regions of existence
- Selected arc impacts TOF, communications feasibility

Poincaré Mapping

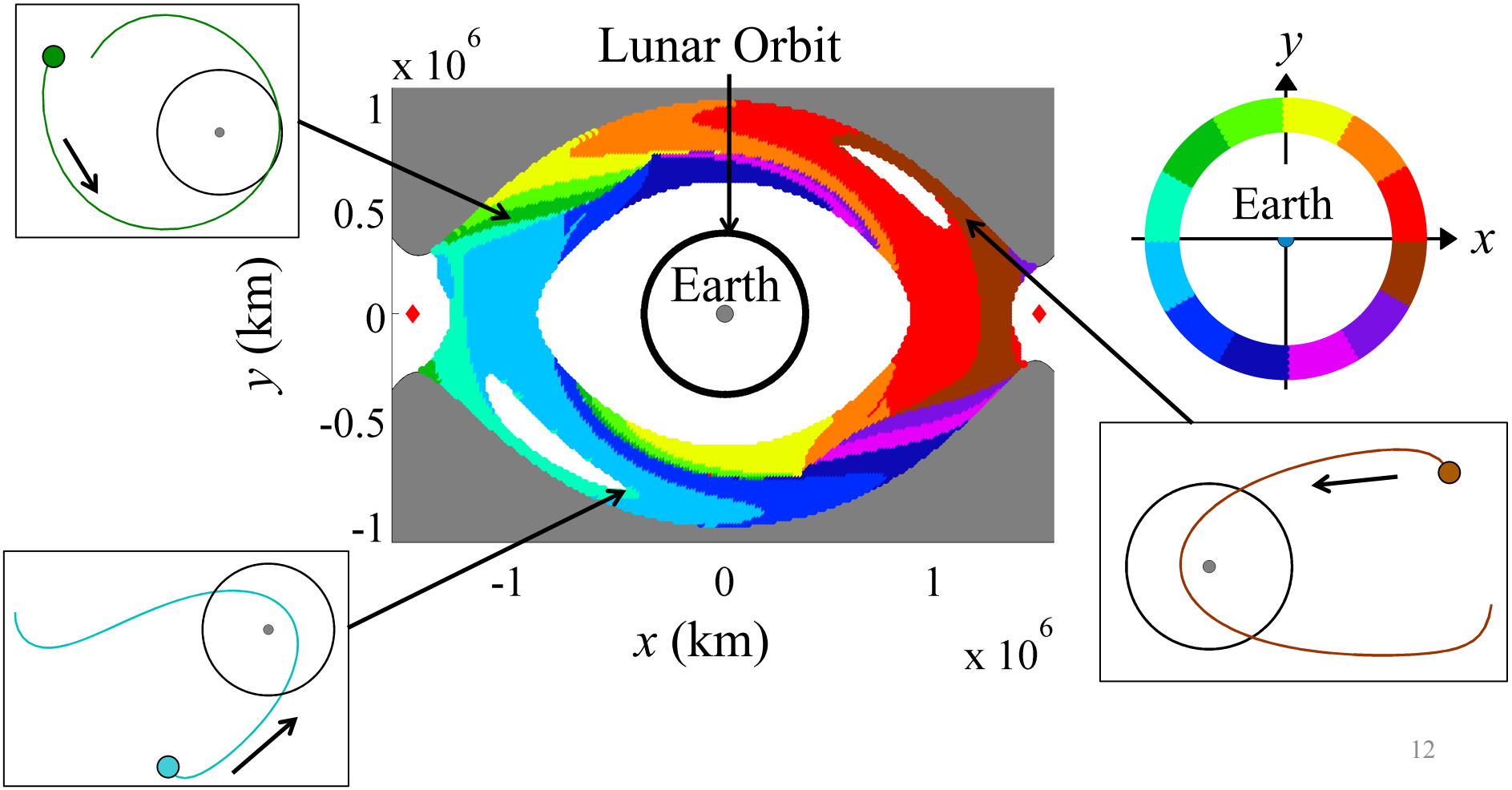
Hyperplanes can take physical forms (e.g. $y = 0$) or events (e.g. apsis, time)



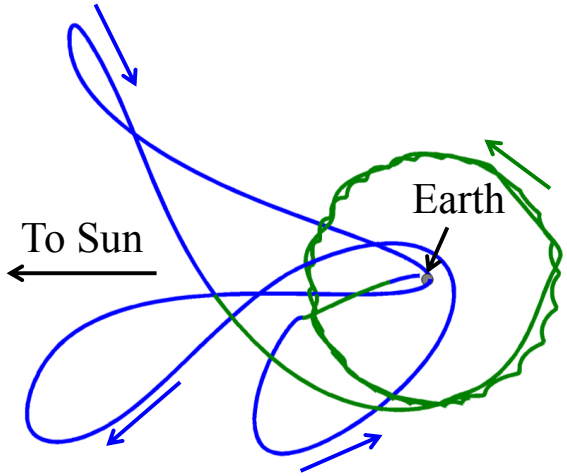
Examples:
Koon, Lo, Marsden, Ross
Villac, Scheeres
Paskowitz, Scheeres
Davis, Howell
Haapala, Howell

Apoapsis Map in Sun-Earth CR3BP, $C = 3.00088013$

Prograde initial conditions, encircle Earth once



Trajectory Design Framework

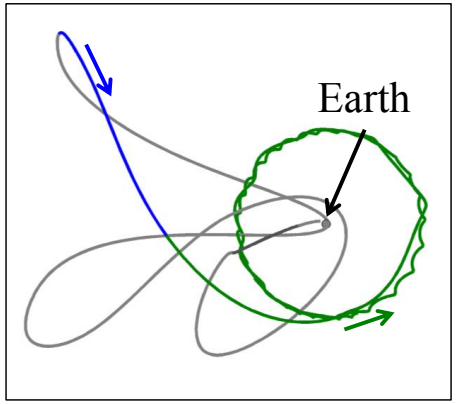


Transfer for original deployment state
Credit: David Folta

I: Earth Outbound

II: Phasing & Energy Adjustment

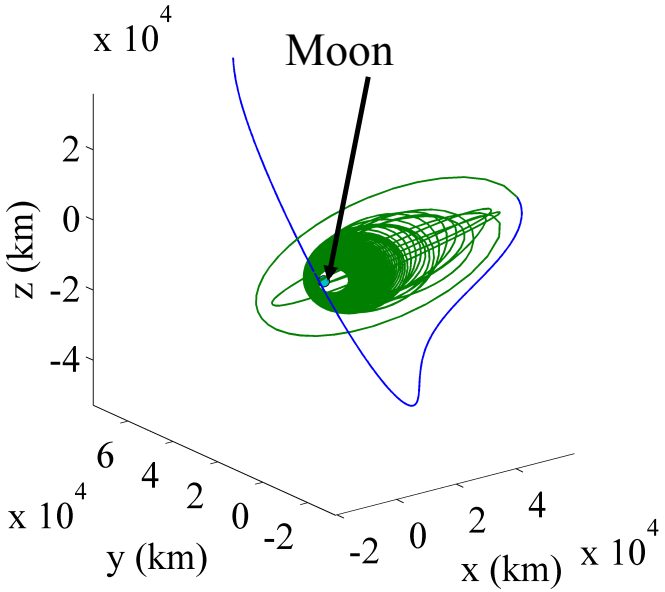
III: Lunar Approach & Capture



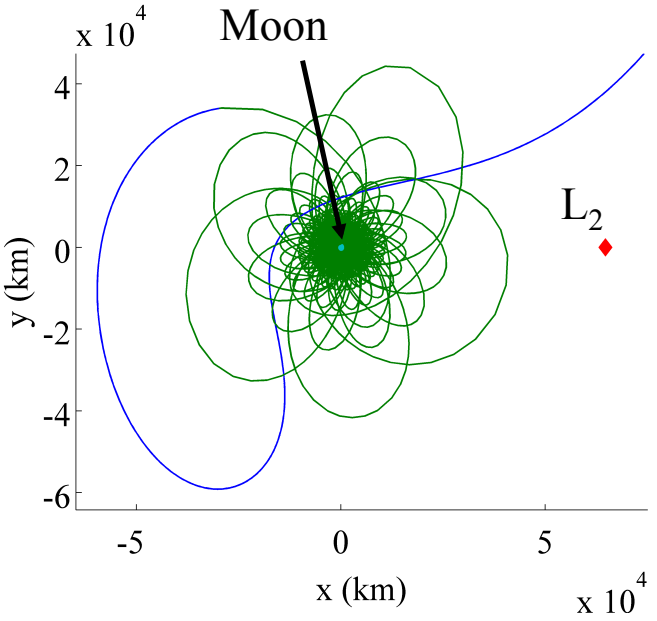
Lunar Approach and Capture Segment

Generate approach arcs through application of manifold computation techniques

(a) Moon-Centered Inertial J2000 Frame

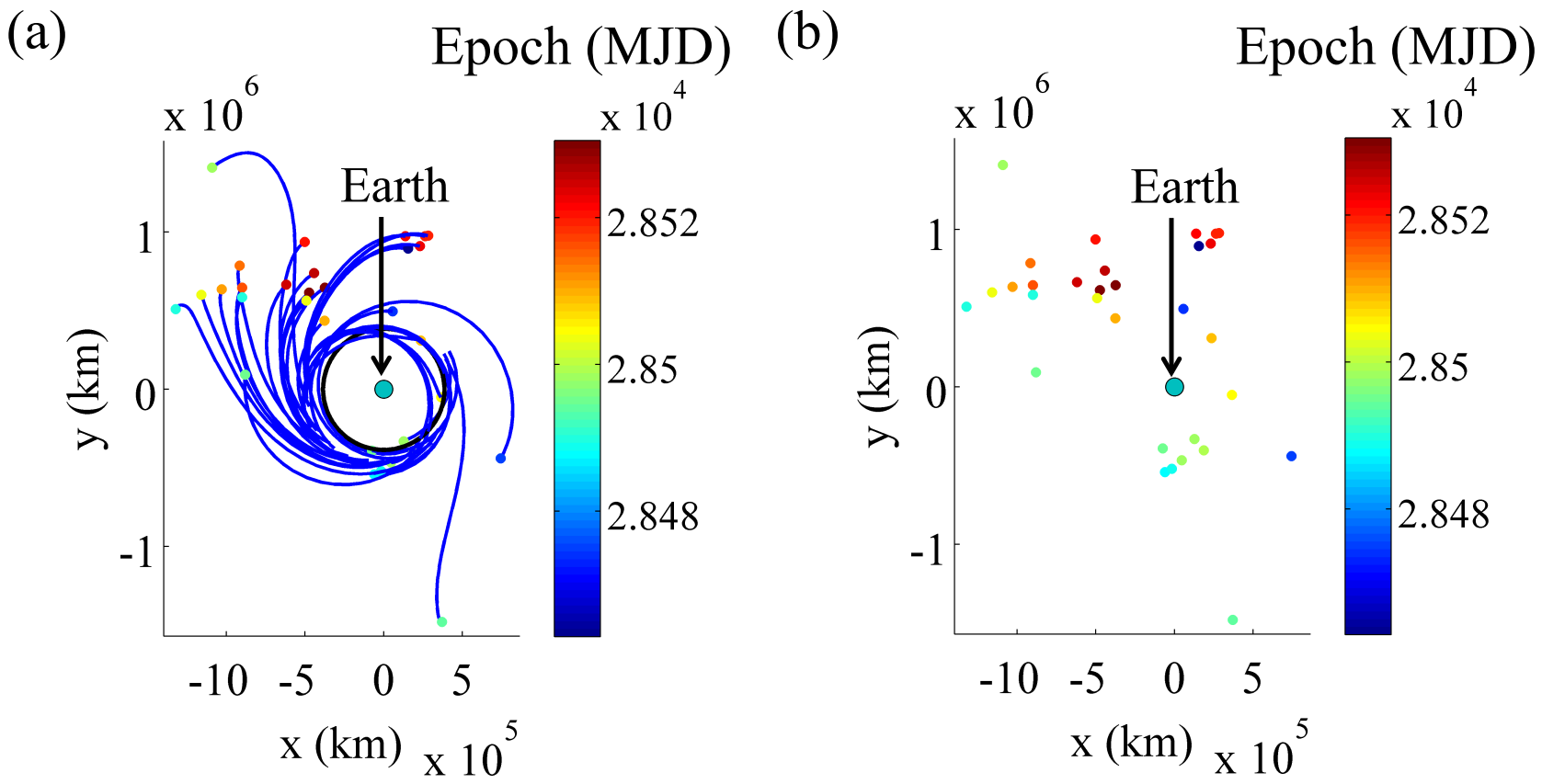


(b) Moon-Centered Earth-Moon Rotating Frame

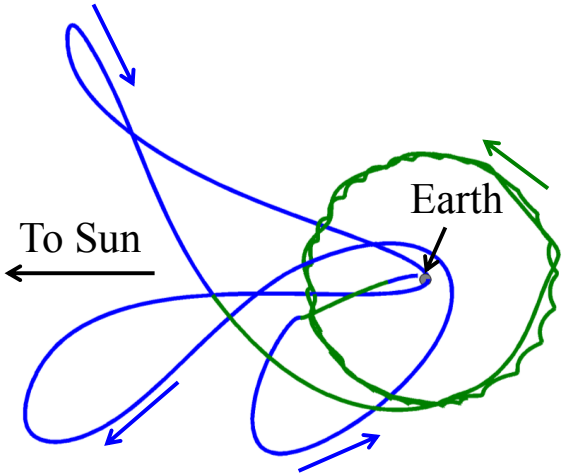


Lunar Approach and Capture Segment

Visualize feasible approach arcs via mapping

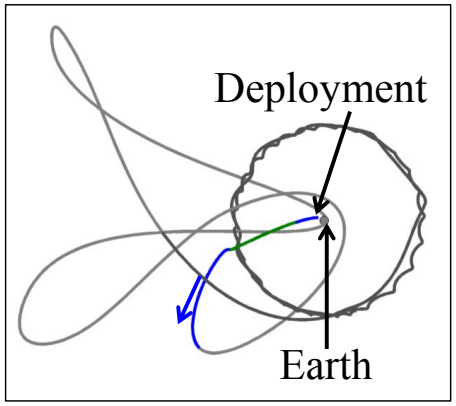


Trajectory Design Framework

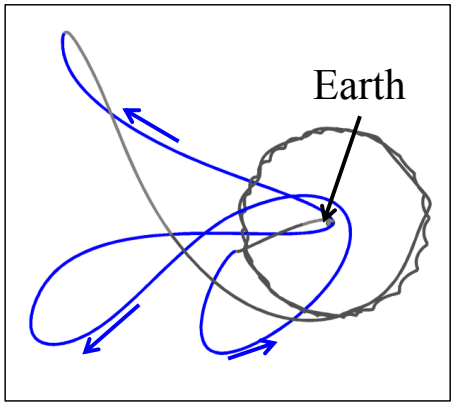


Transfer for original deployment state
Credit: David Folta

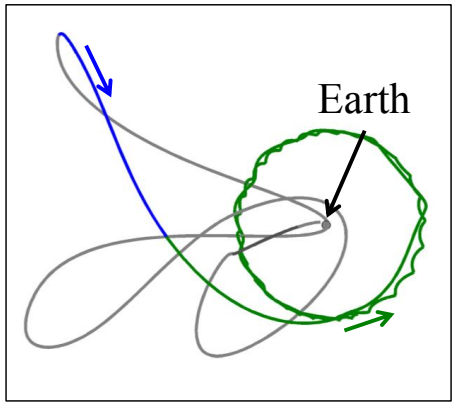
I: Earth Outbound



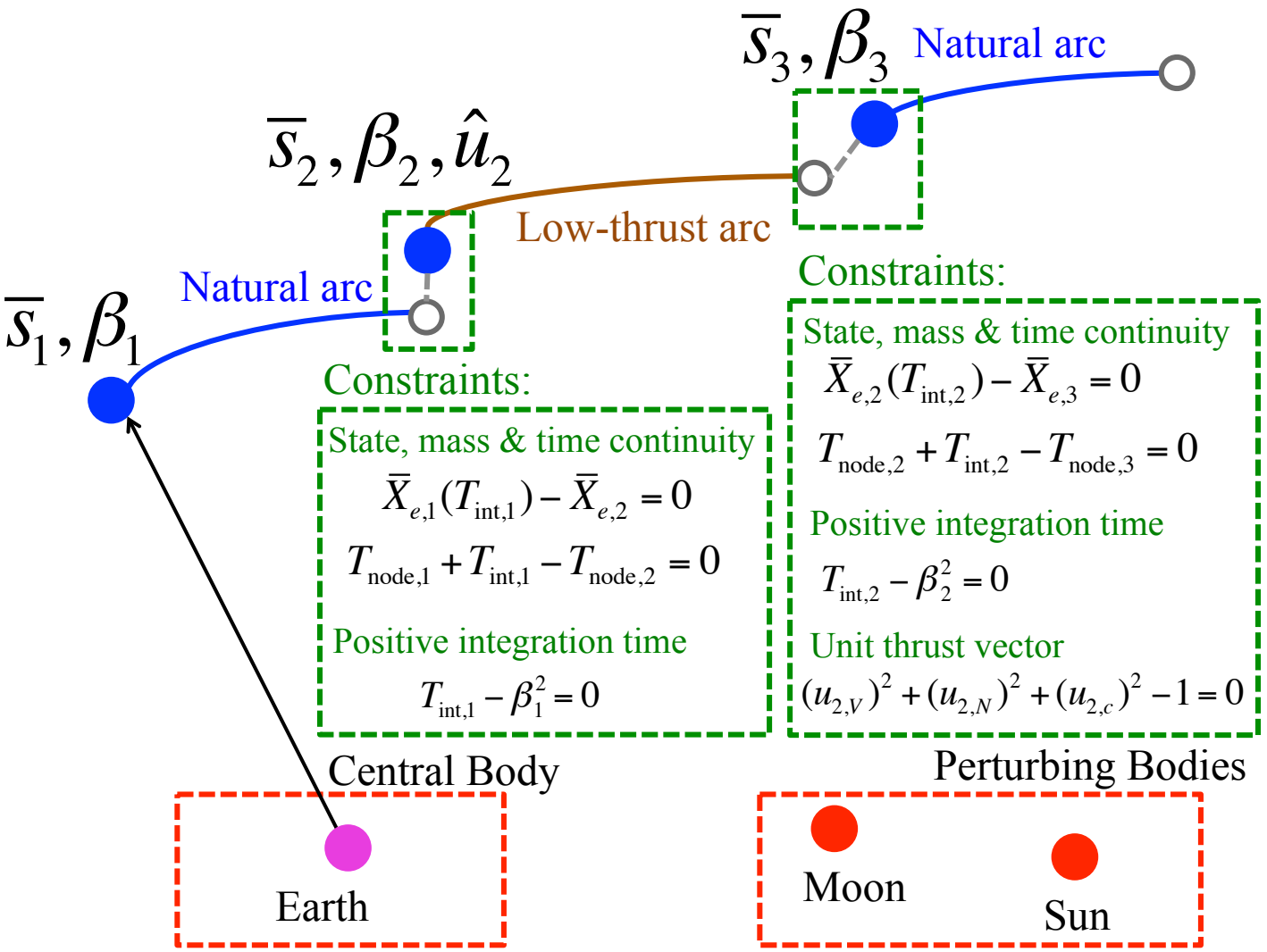
II: Phasing & Energy Adjustment



III: Lunar Approach & Capture

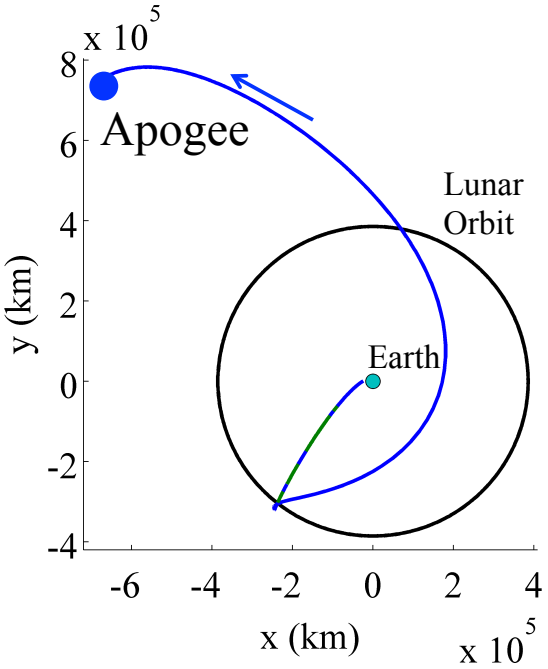


Corrections Algorithm

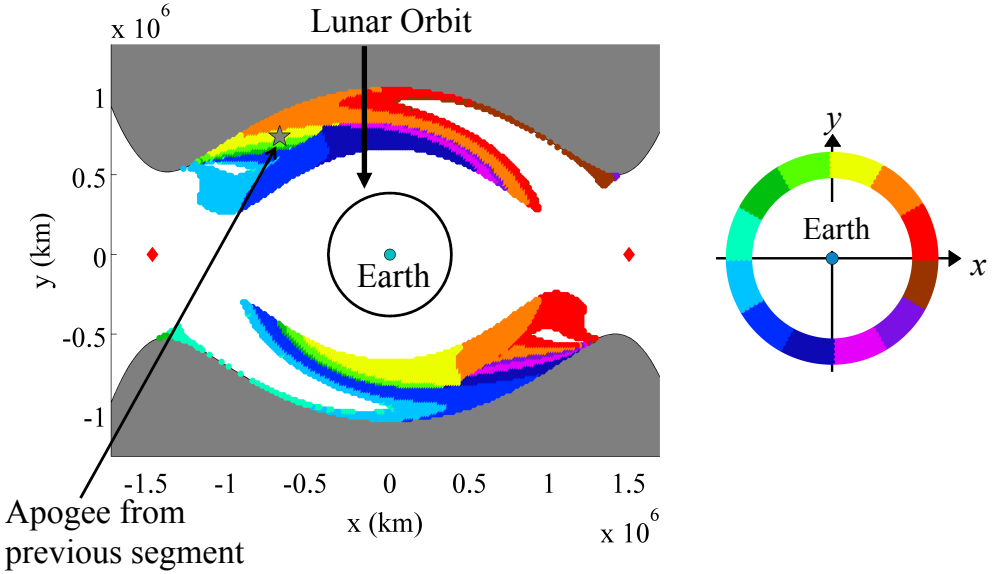


Construction of Initial Guess Trajectory

1. Select Earth outbound arc
   Deployment: Oct 7, 2018

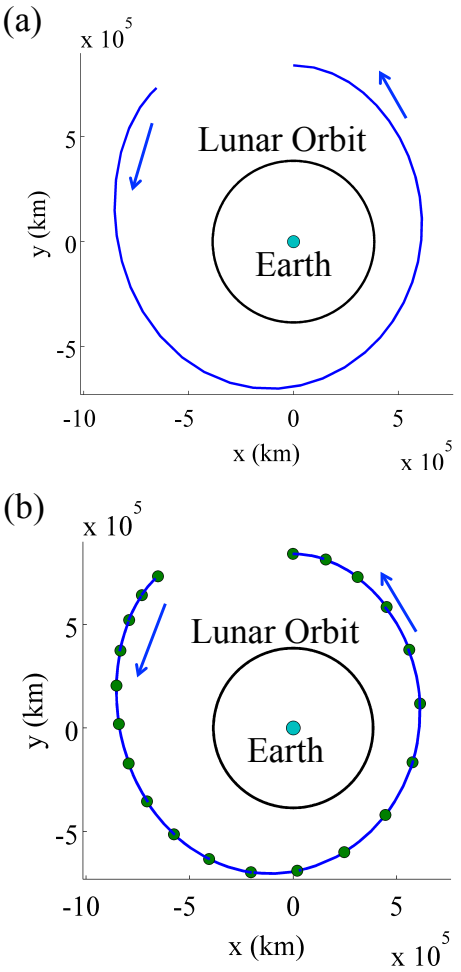


2. Select nearby phasing and energy adjustment arc

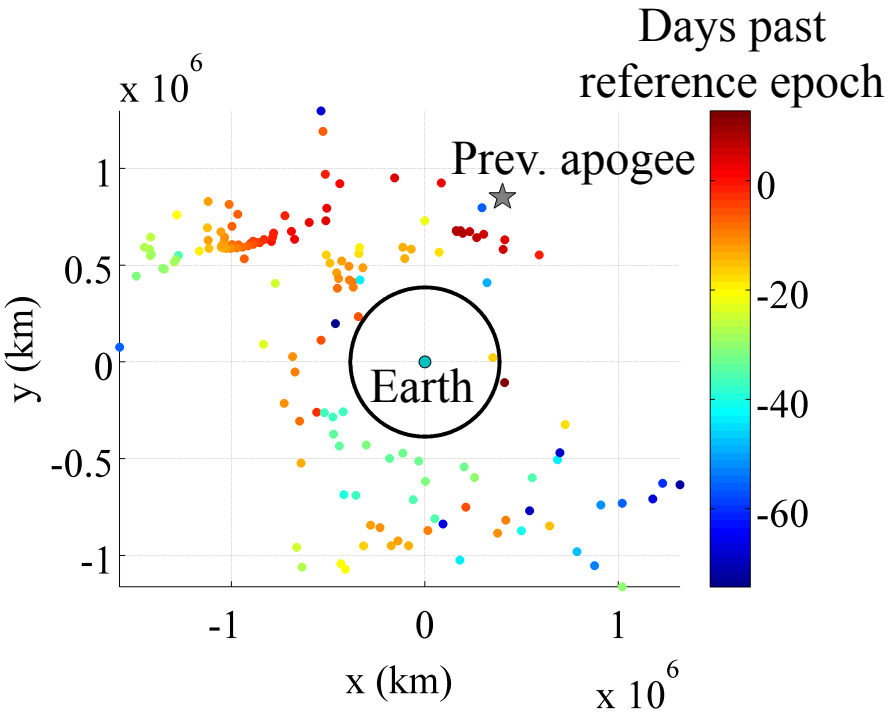


Construction of Initial Guess Trajectory

3. Discretize initial guess from CR3BP

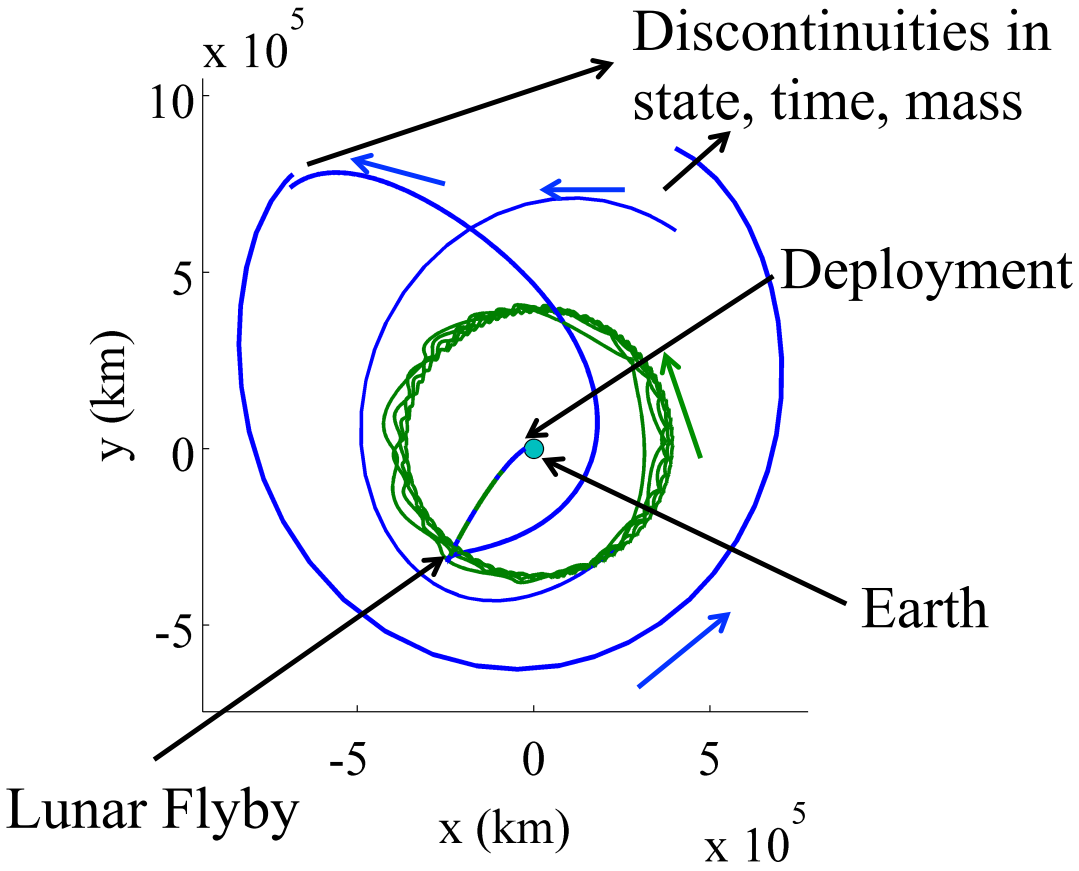


4. Select lunar capture arc nearby in (x,y) and epoch



Construction of Initial Guess Trajectory

Assemble arcs, connect with short low-thrust arcs

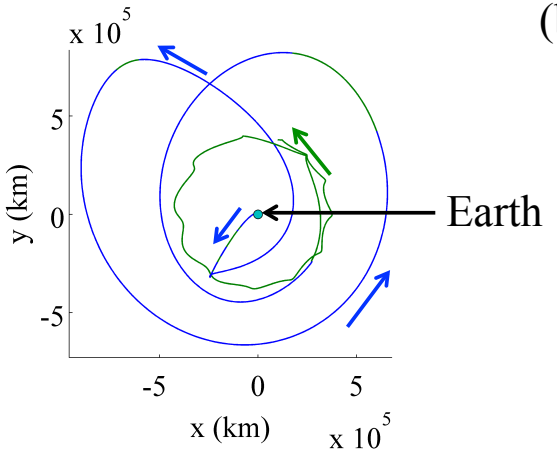


Corrected Trajectory in Ephemeris

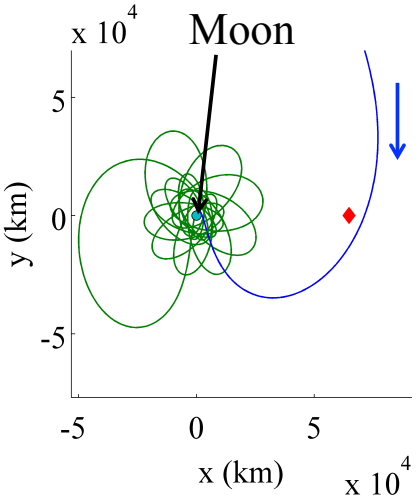
Dynamical model: Earth, Sun, Moon point masses; low-thrust

Earth-centered Sun-Earth rotating frame

(a)



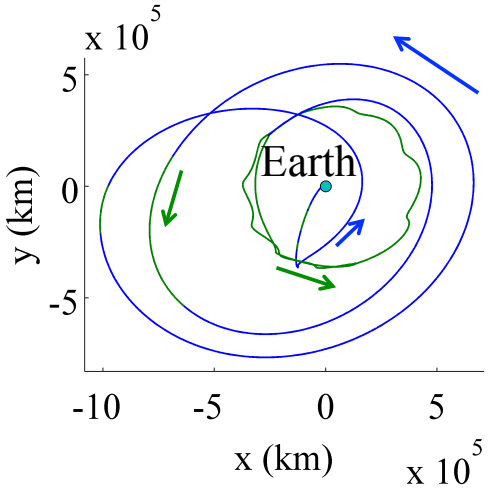
(b)



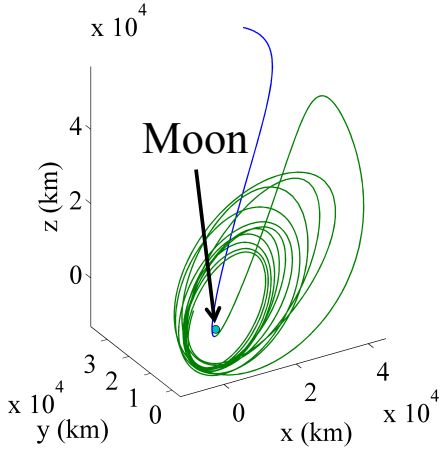
Moon-centered Earth-Moon rotating frame

Earth-centered inertial frame

(c)



(d)



Moon-centered inertial frame

Trajectory Design Framework

How to design complex path for CubeSat beyond LEO with limited propulsion and constrained deployment state?

- Poincare mapping enables identification of individual transfer arcs to assemble initial guess
- Natural particular solutions offer:
  - Initial guess to connect bounding segments
  - Insight into bounds on motion, transfer geometry
- Supports well-informed and rapid evaluation of complex trajectory design space prior to higher-fidelity analysis

PURDUE ENGINEERING
AERONAUTICS AND ASTRONAUTICS

Trajectory Design for a Cislunar CubeSat Leveraging Dynamical Systems Techniques: The Lunar IceCube Mission

AAS 17-286

Natasha Bosanac, Andrew Cox, Kathleen C. Howell, David Folta
Purdue University and NASA Goddard Space Flight Center