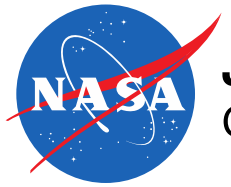


Jet Propulsion Laboratory
California Institute of Technology

Low-Thrust Transfer Design Based on Collocation Techniques: Applications in the Restricted Three-Body Problem

Robert Pritchett

Purdue University

Advisor: Professor Kathleen Howell

Mentor: Dr. Daniel Grebow

August 22nd, 2017

Outline

I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Outline

I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Motivation

- NASA and private companies seek to establish an enduring human presence in cis-lunar space, and this vision is aided by:
  - Efficient low-thrust propulsion.
  - Stable orbits that can be maintained at low-cost for long time spans.
- Thus, low-thrust transfers between stable periodic orbits will also be advantageous.

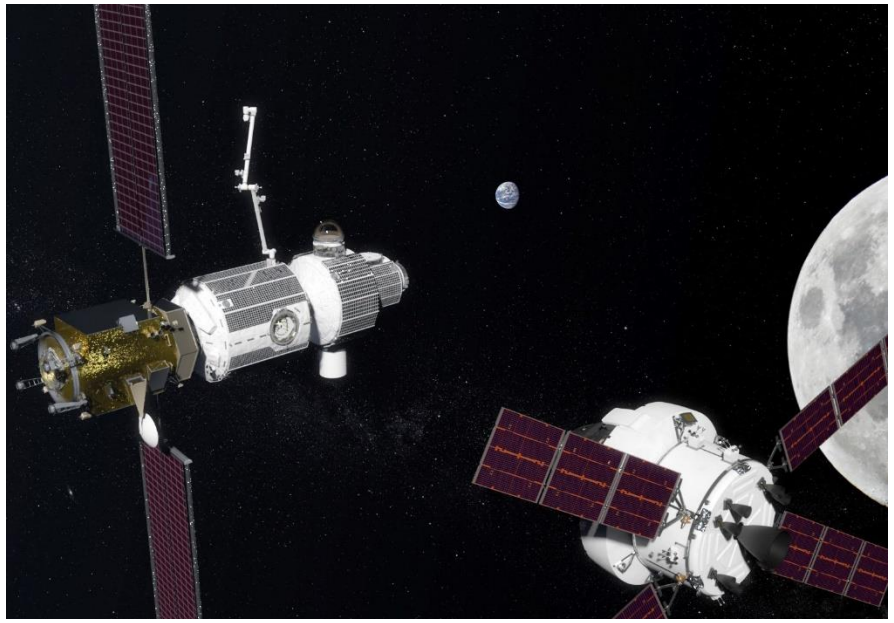


Image Courtesy of nasa.gov

Deep Space Gateway Concept

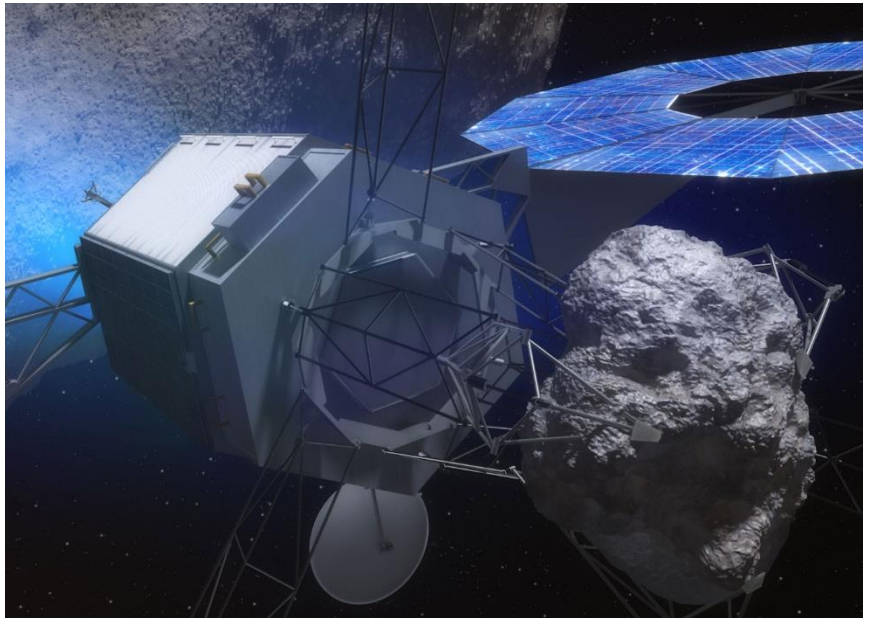
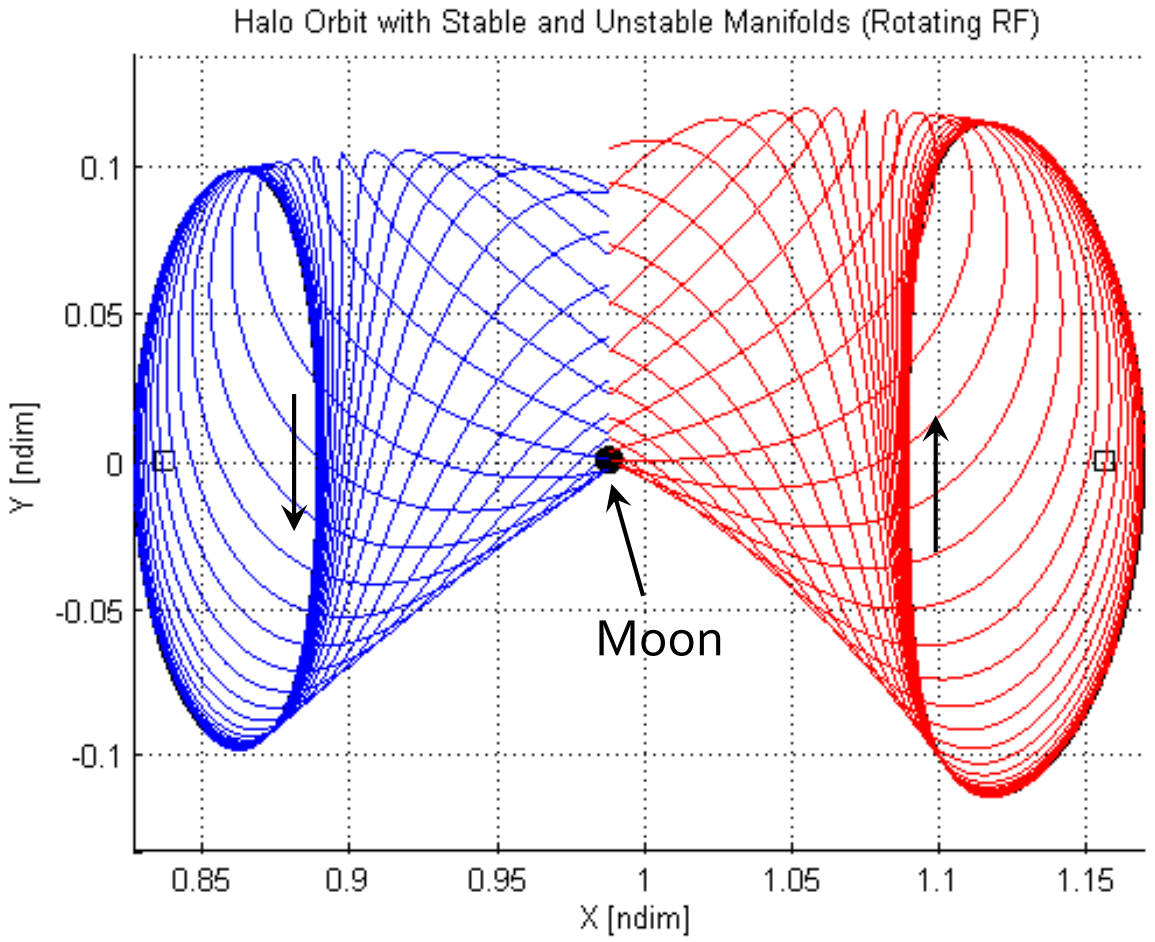


Image Courtesy of nasa.gov

Asteroid Robotic Redirect Mission Concept

Motivation

- Invariant manifold structures offer efficient paths into and out of periodic orbits.
- Therefore, manifolds may assist low-thrust transfer design.
- However, stable and near-stable periodic orbits do not possess manifolds that can assist with trajectory design.
- Thus, additional techniques for low-thrust trajectory design are required



Motivation

- Collocation is a method for numerically integrating ordinary differential equations.
- This method has been successfully employed to compute low-thrust trajectories when little intuition is available for constructing an initial guess.
  - Grebow, Ozimek, and Howell, 2010
  - Herman, 2015
  - Parrish, et al., 2016

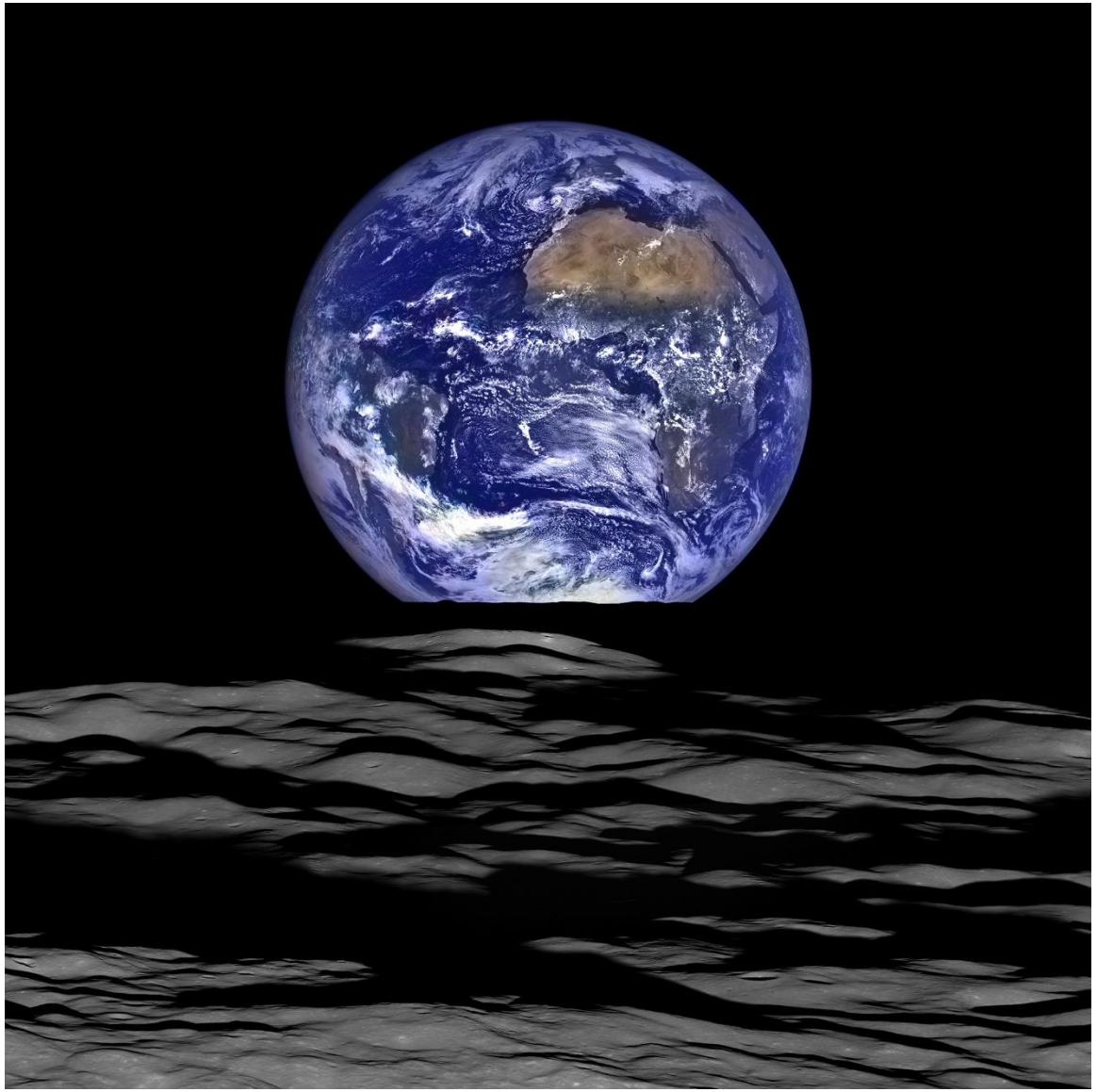
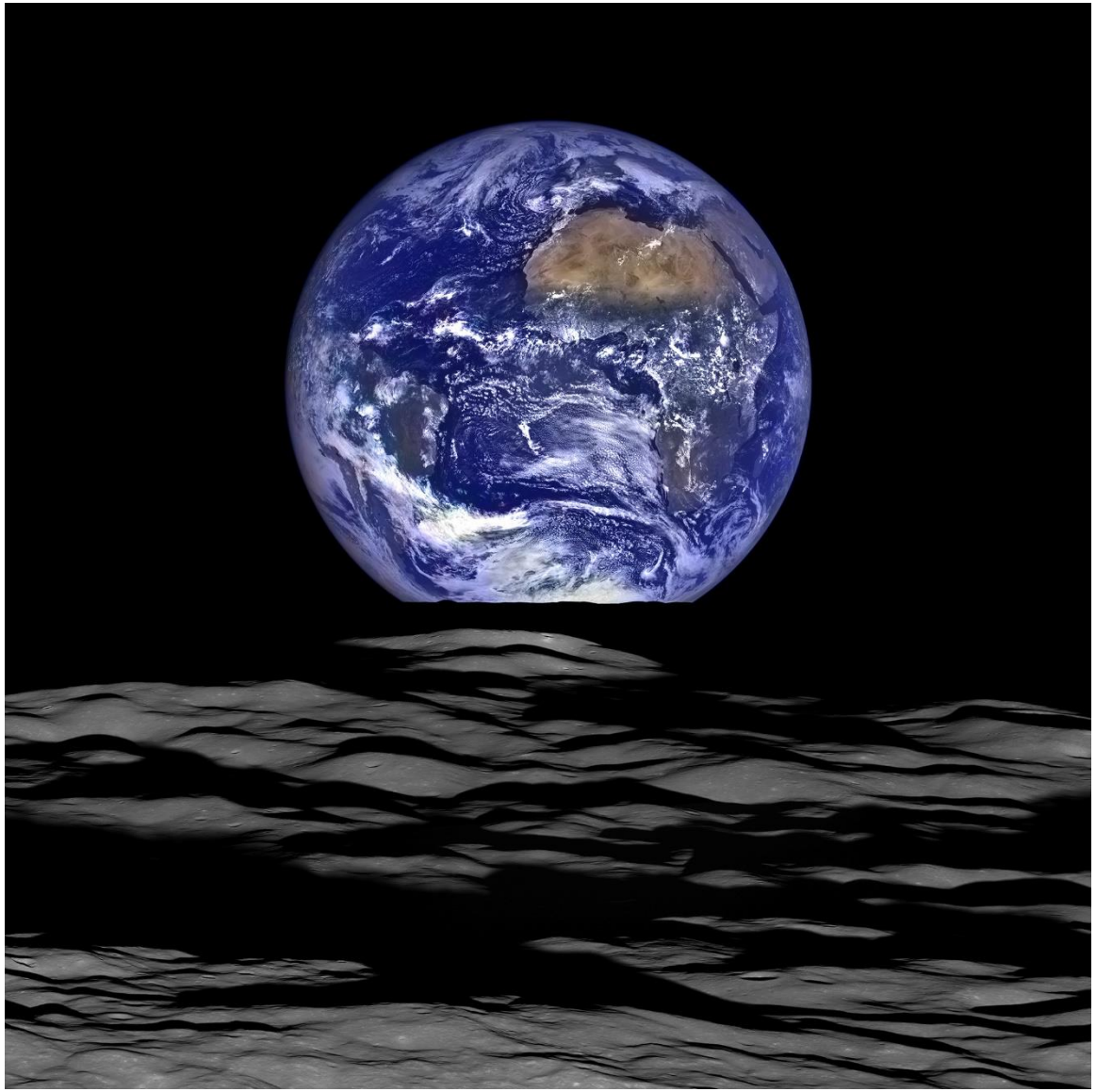


Image Courtesy of nasa.gov

Motivation

Goal: Develop additional techniques for conducting low-thrust trajectory design that leverage collocation to compute optimal trajectories when little intuition is available for the construction of an initial guess.

Sample Application: Low-thrust transfer design between stable and near-stable periodic orbits in the Earth-Moon system.

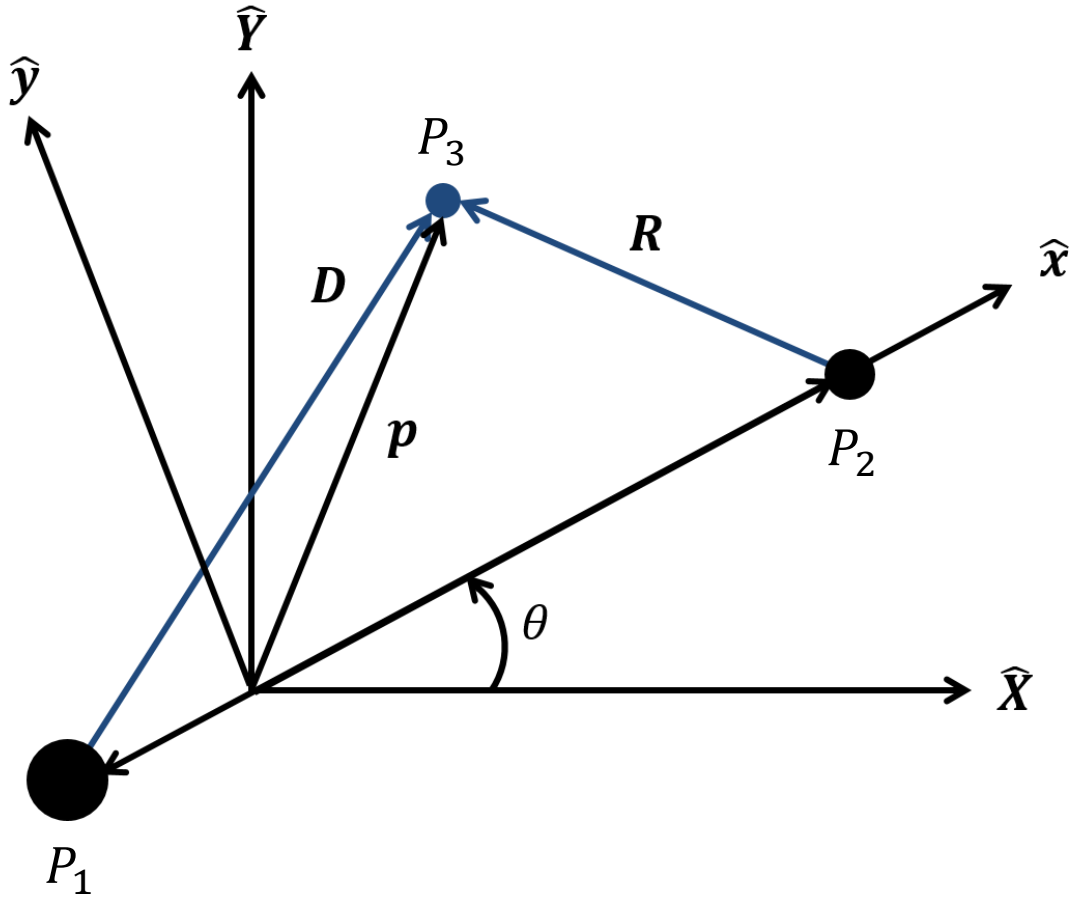


Outline

I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

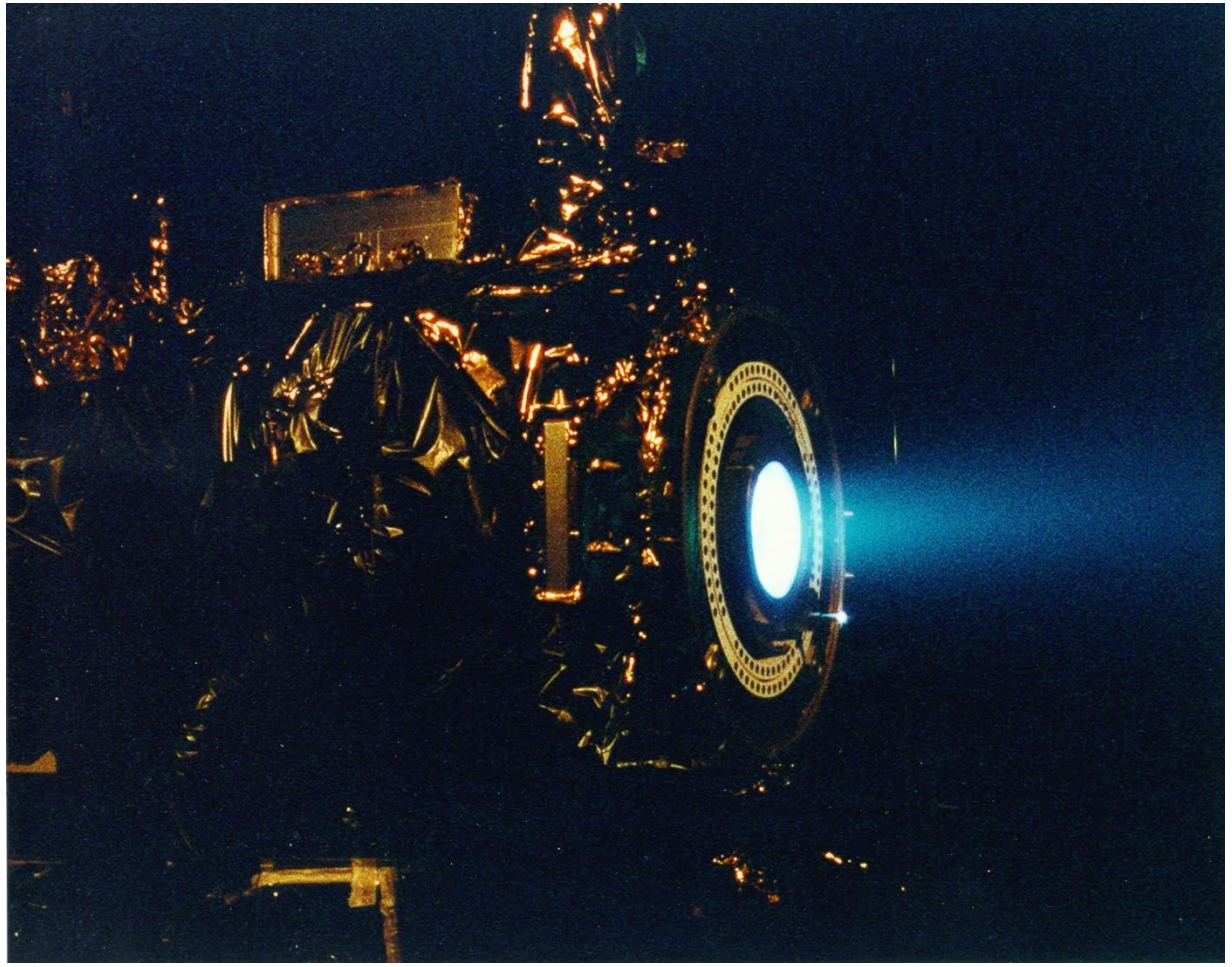
Background

- The circular restricted three-body problem (CR3BP) is employed for initial trajectory design.
  - Gravitational interaction of primaries may be leveraged to compute low-energy trajectories.
  - Avoids complexity of ephemeris model:
    - Time dependence
    - Additional gravitational perturbations



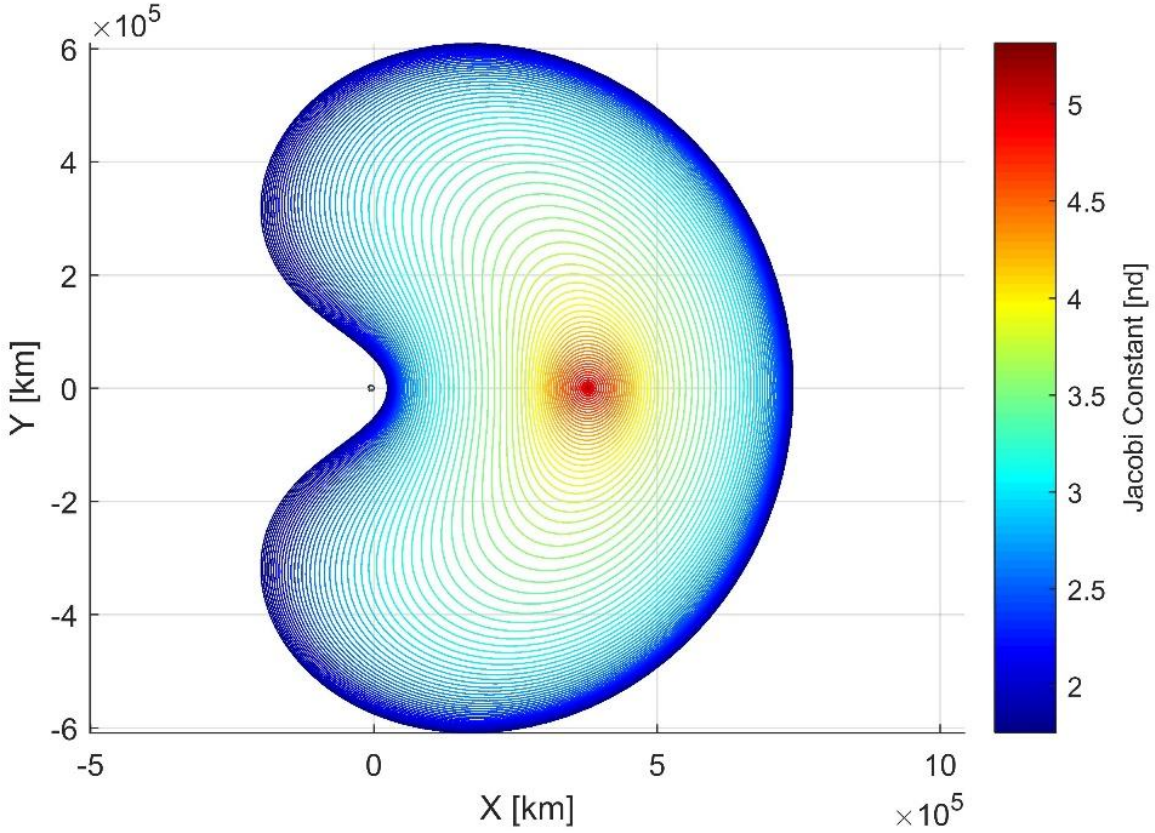
Background

- A low-thrust engine representative of current technological capabilities is employed for all transfers
  - $m_0 = 500\ kg$
  - $I_{sp} = 2000\ sec$
  - $T_{max} = 100\ mN$
- These trajectory design techniques are applicable to a wide-range of engine parameters



Background

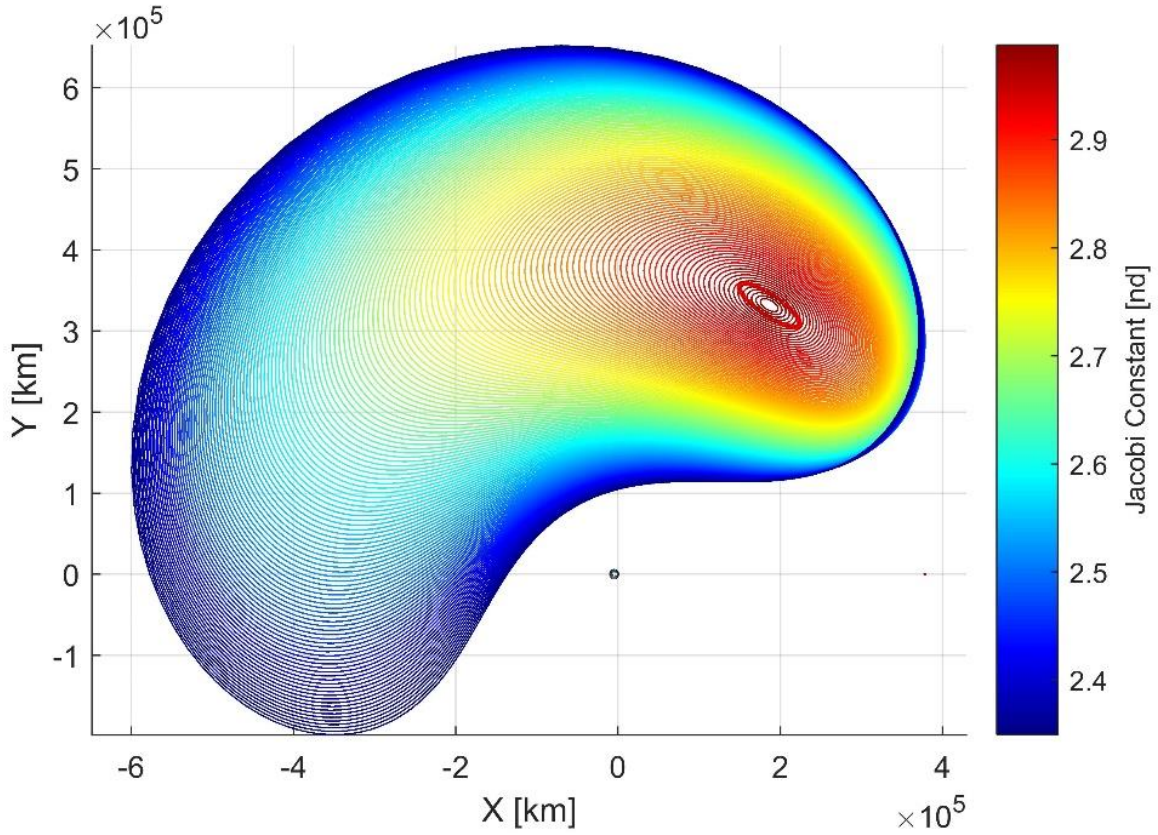
- A variety of stable or near-stable periodic orbits are available in the Circular Restricted Three-Body Problem (CR3BP)
  - Distant Retrograde Orbits (DRO)



Lunar DRO Family

Background

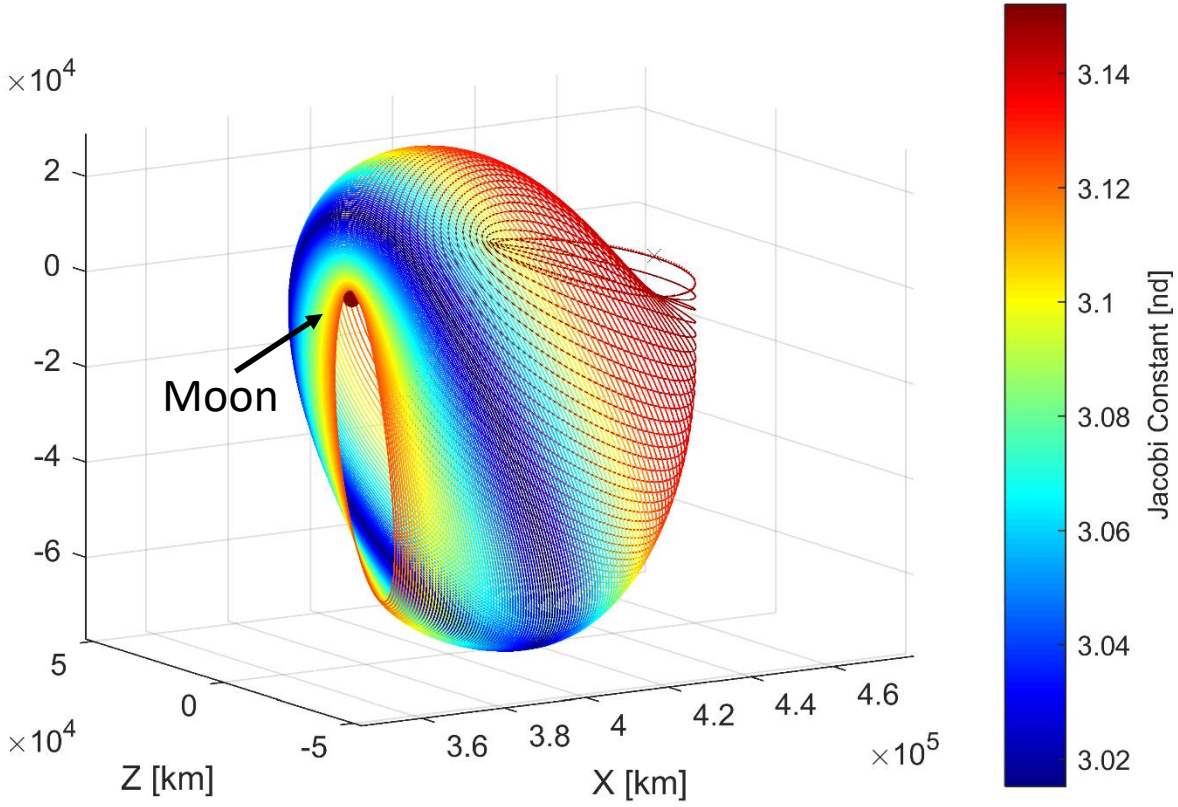
- A variety of stable or near-stable periodic orbits are available in the Circular Restricted Three-Body Problem (CR3BP)
  - Distant Retrograde Orbits (DRO)
  - $L_{4/5}$ Short Period Orbits (SPO)



L_4 SPO Family

Background

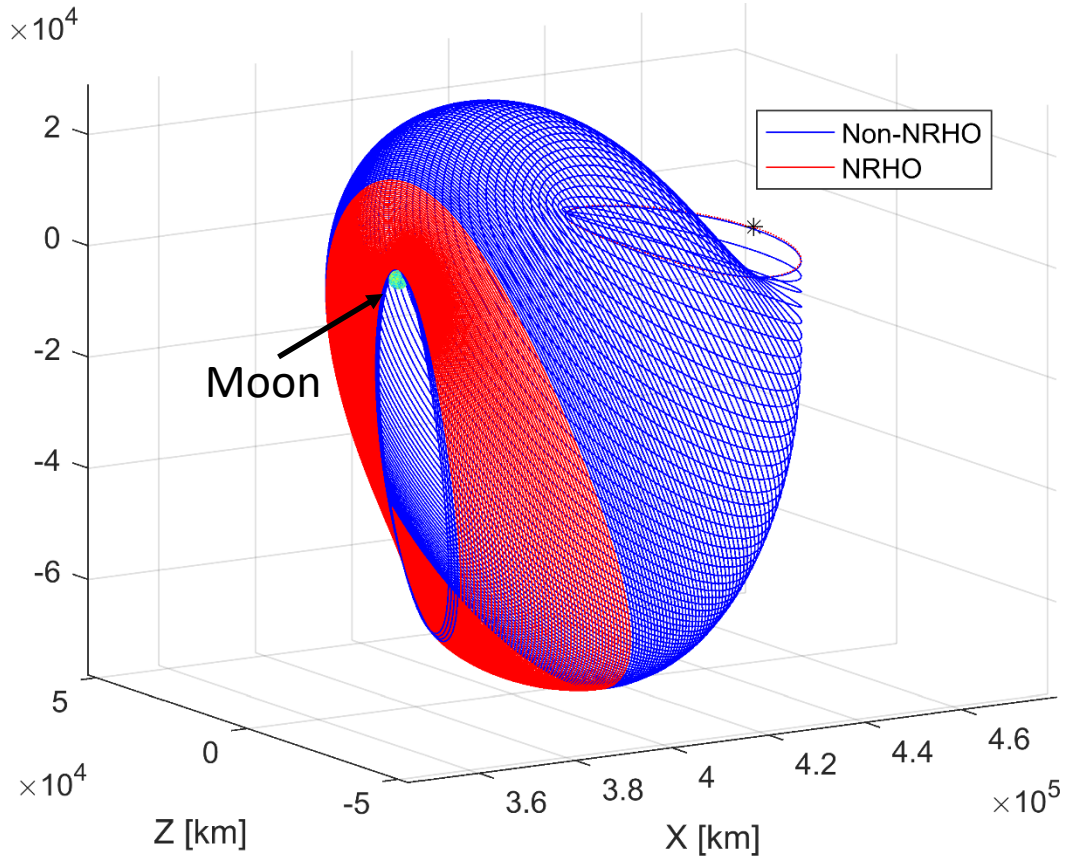
- A variety of stable or near-stable periodic orbits are available in the Circular Restricted Three-Body Problem (CR3BP)
  - Distant Retrograde Orbits (DRO)
  - $L_{4/5}$ Short Period Orbits (SPO)
  - Near-Rectilinear Halo Orbits (NRHO)



L_2 Southern Halo Family

Background

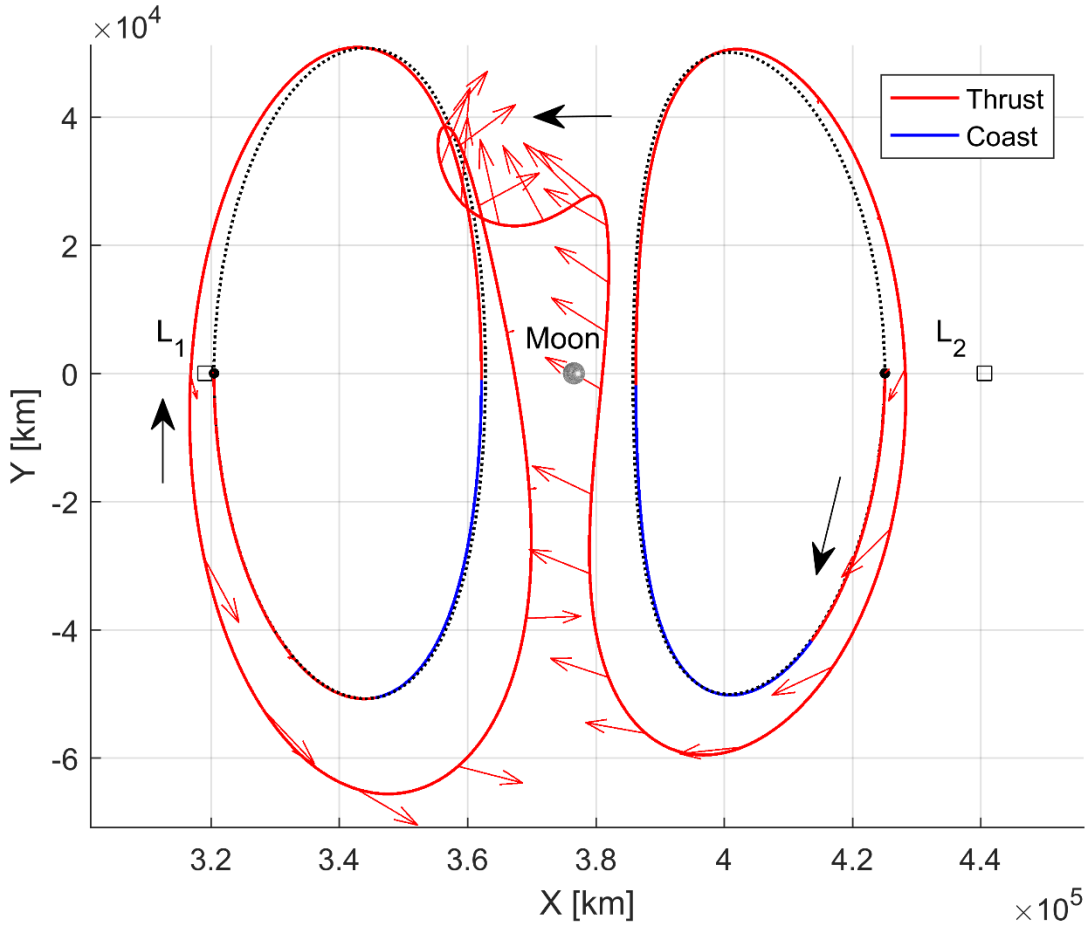
- A variety of stable or near-stable periodic orbits are available in the Circular Restricted Three-Body Problem (CR3BP)
  - Distant Retrograde Orbits (DRO)
  - $L_{4/5}$ Short Period Orbits (SPO)
  - Near-Rectilinear Halo Orbits (NRHO)



L_2 Southern Halo Family

Background

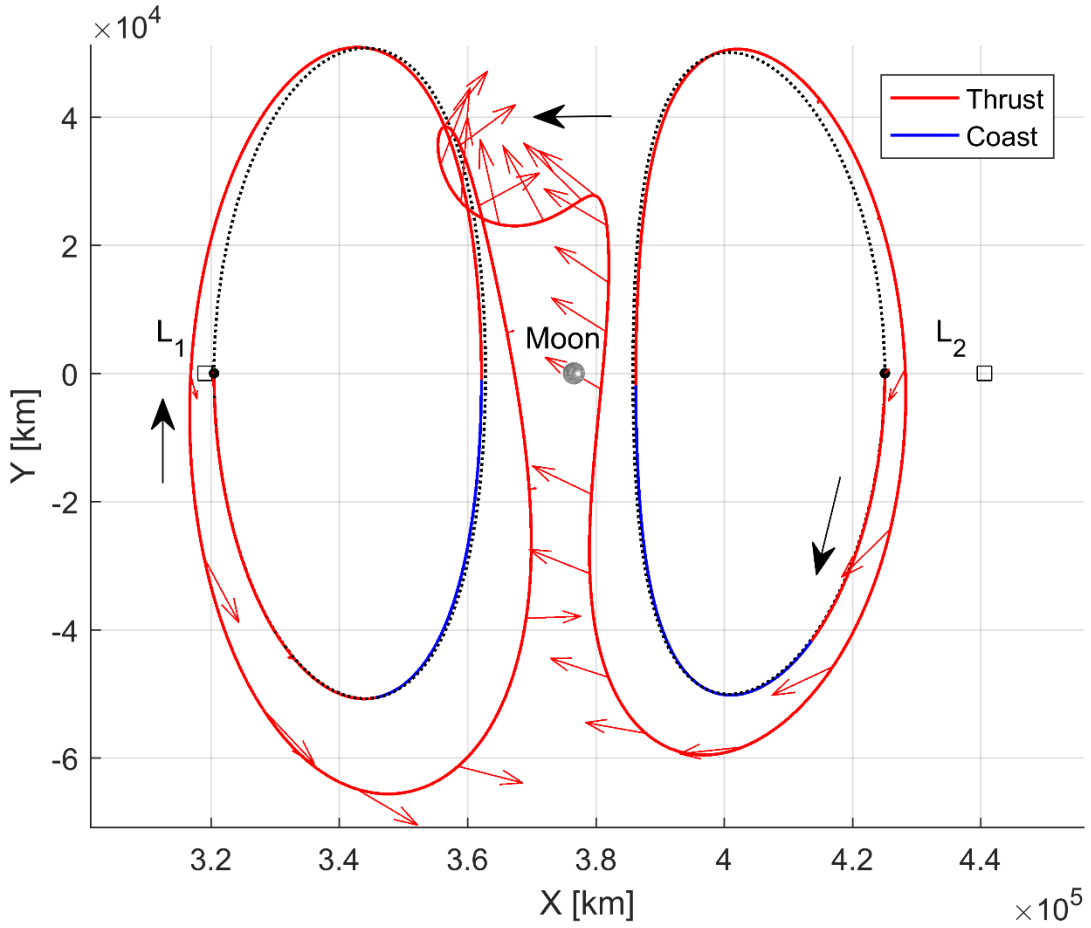
- Low-thrust trajectory design is a continuous optimal control problem, where common objectives are maximization of final mass or minimization of time of flight.
- Direct transcription is a robust method for solving optimal control problems using collocation.
  - Canon, Cullum, and Polak, 1970
  - Hargraves and Paris, 1987
  - Betts and Huffman, 1997



L_2 Halo to L_1 Halo Orbit Transfer

Background

- Two software packages that implement direct transcription for low-thrust trajectory design are employed:
  - Collocation with Optimization for Low-Thrust (COLT)
  - MColl
- MColl enables low-thrust trajectory design within MONTE (Mission Analysis Operation and Navigation Toolkit Environment)

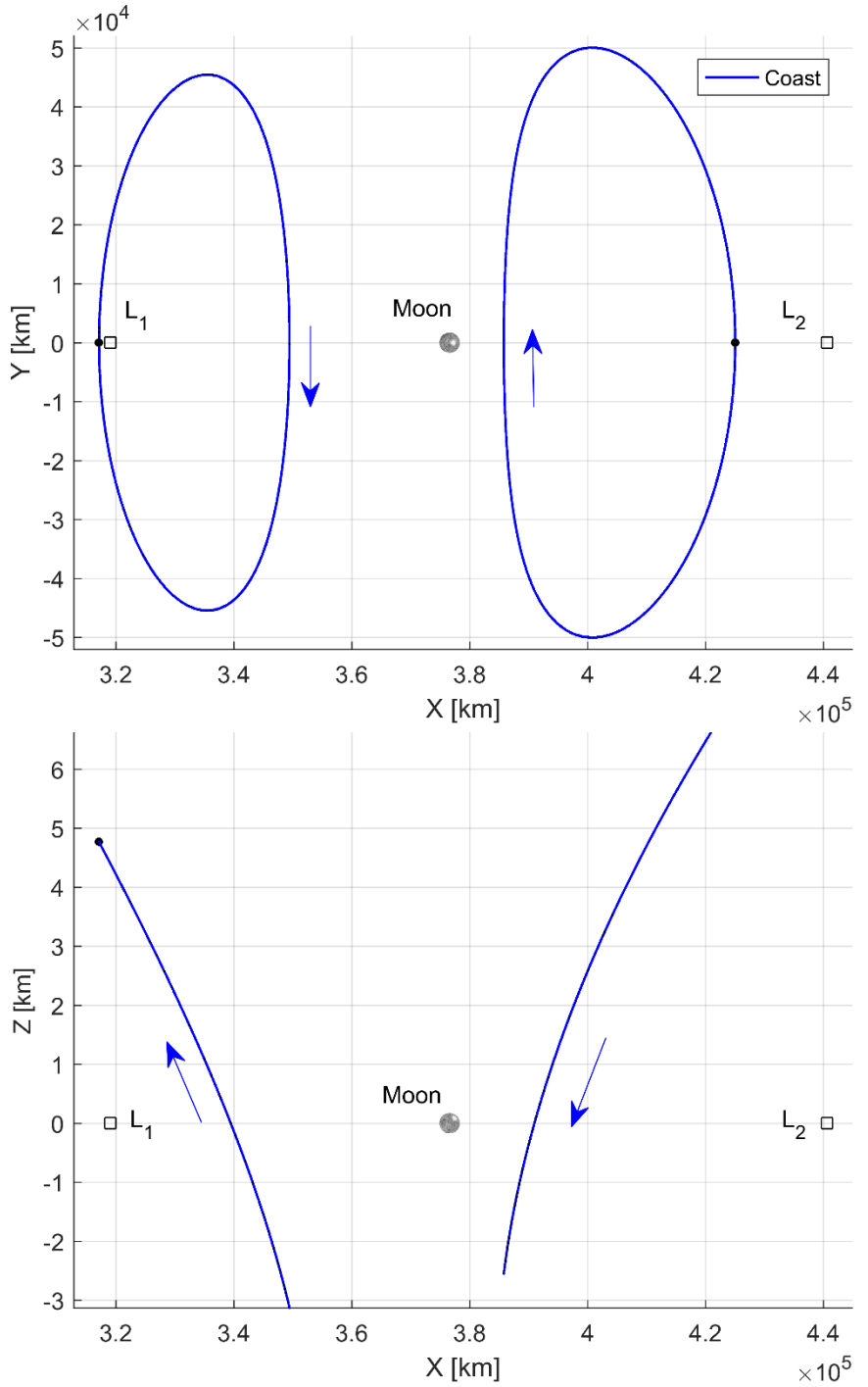


L_2 Halo to L_1 Halo Orbit Transfer

Background

Trajectory Design with Direct Transcription Steps:

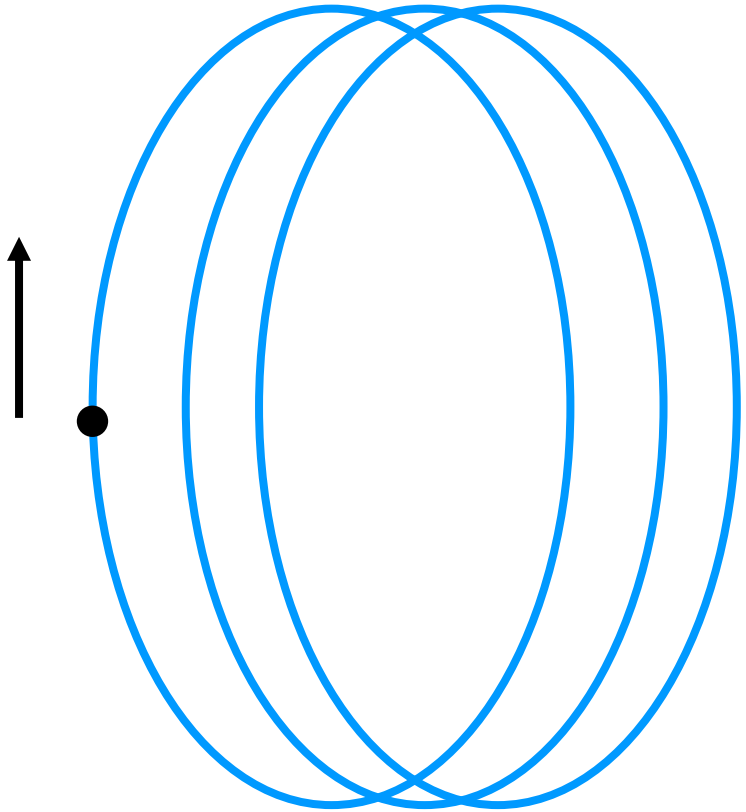
1. Construct initial guess with trajectory stacking technique



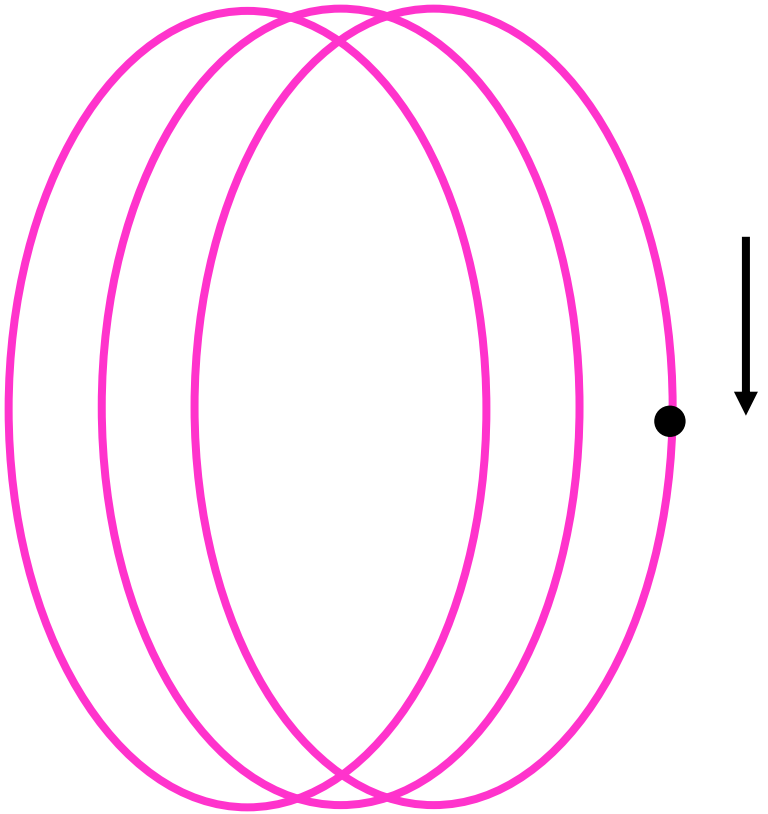
Background

Trajectory Stacking:

$$\mathrm{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



3 Revolution

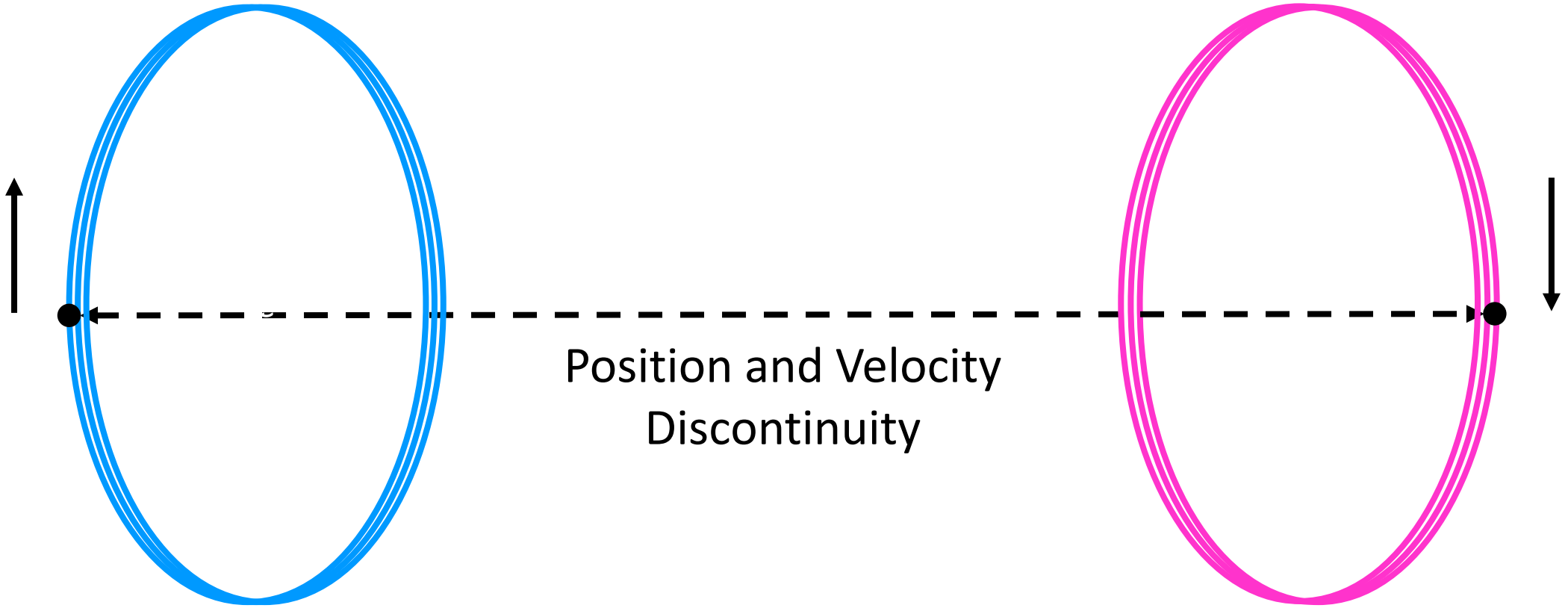


3 Revolution

Background

Trajectory Stacking:

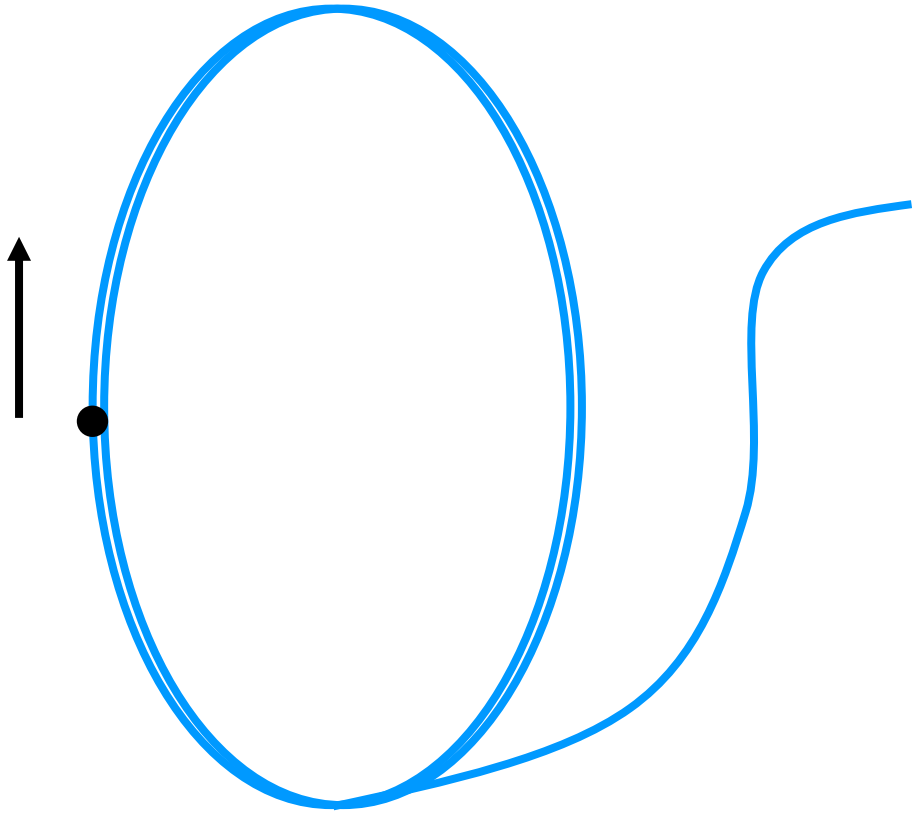
$$\text{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



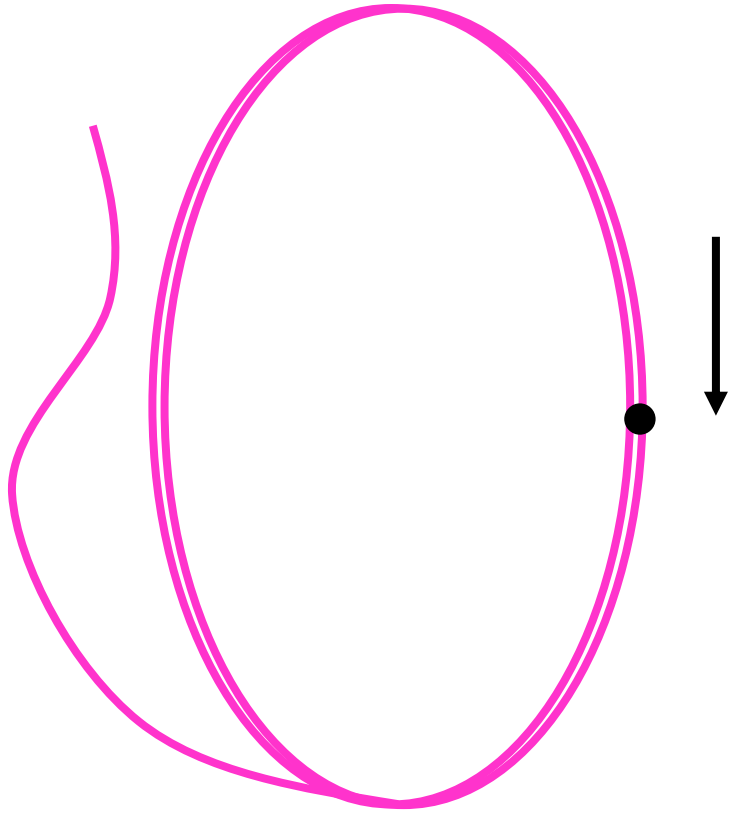
Background

Trajectory Stacking:

$$\mathrm{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



3 Revolution

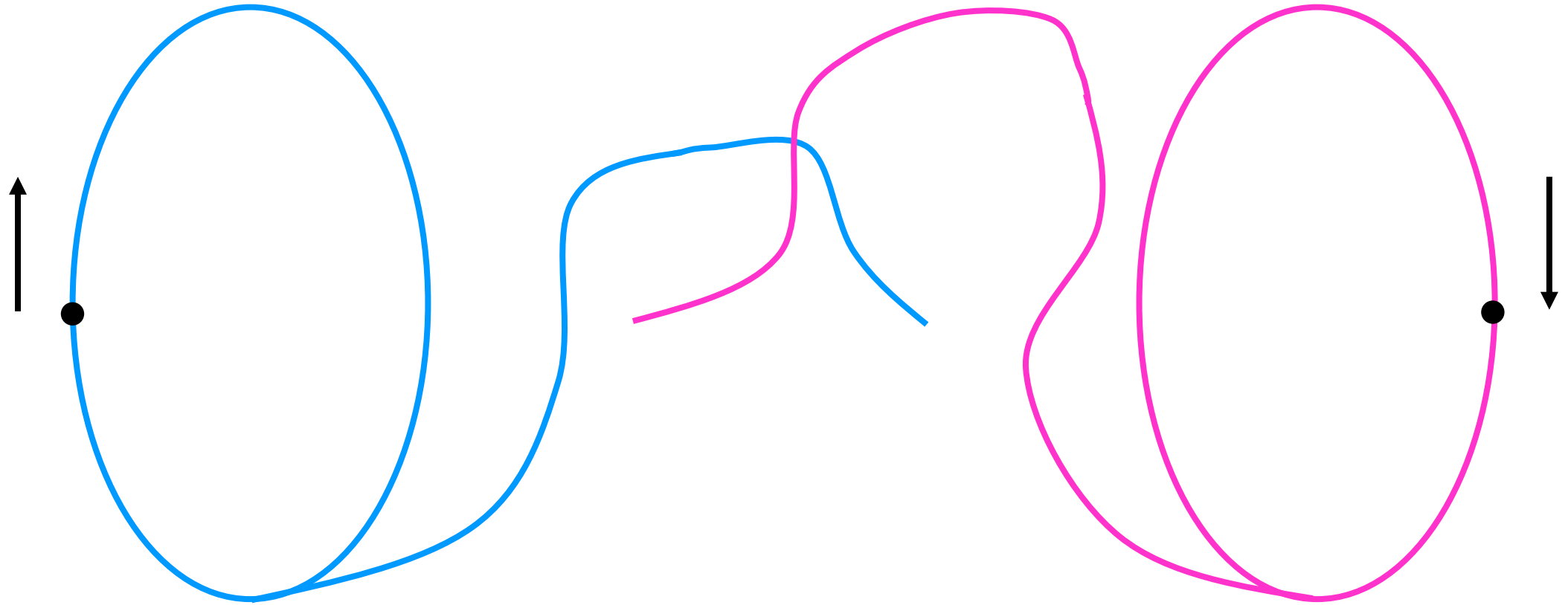


3 Revolution

Background

Trajectory Stacking:

$$\mathrm{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



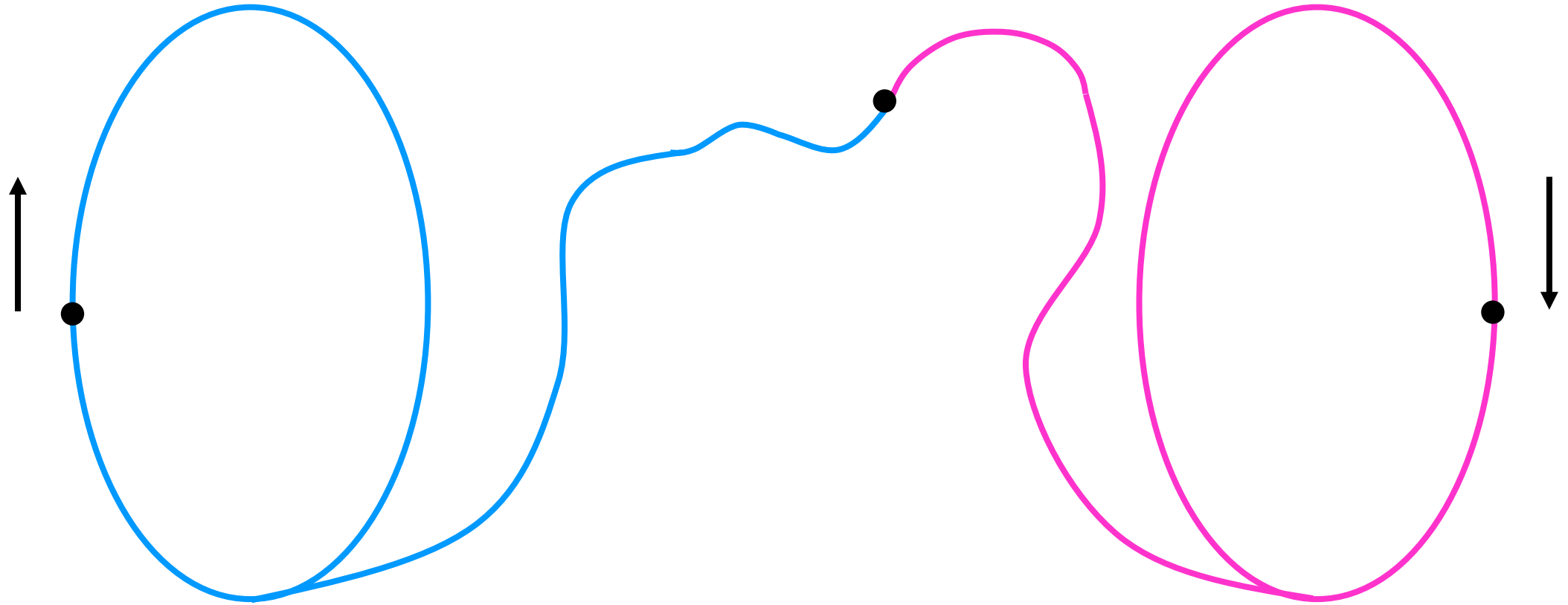
3 Revolution

3 Revolution

Background

Trajectory Stacking:

$$\mathrm{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



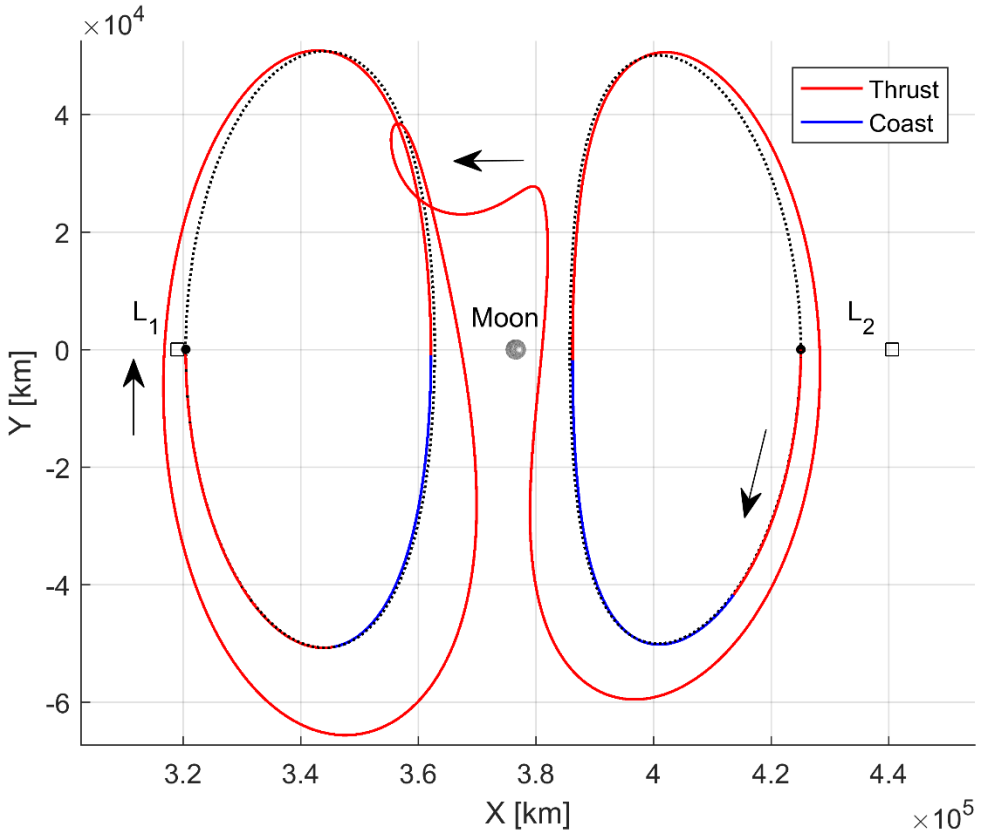
3 Revolution

3 Revolution

Background

Trajectory Design with Direct Transcription Steps:

1. Stack revolutions on departure and arrival orbits to construct initial guess.
2. Converge feasible solution.

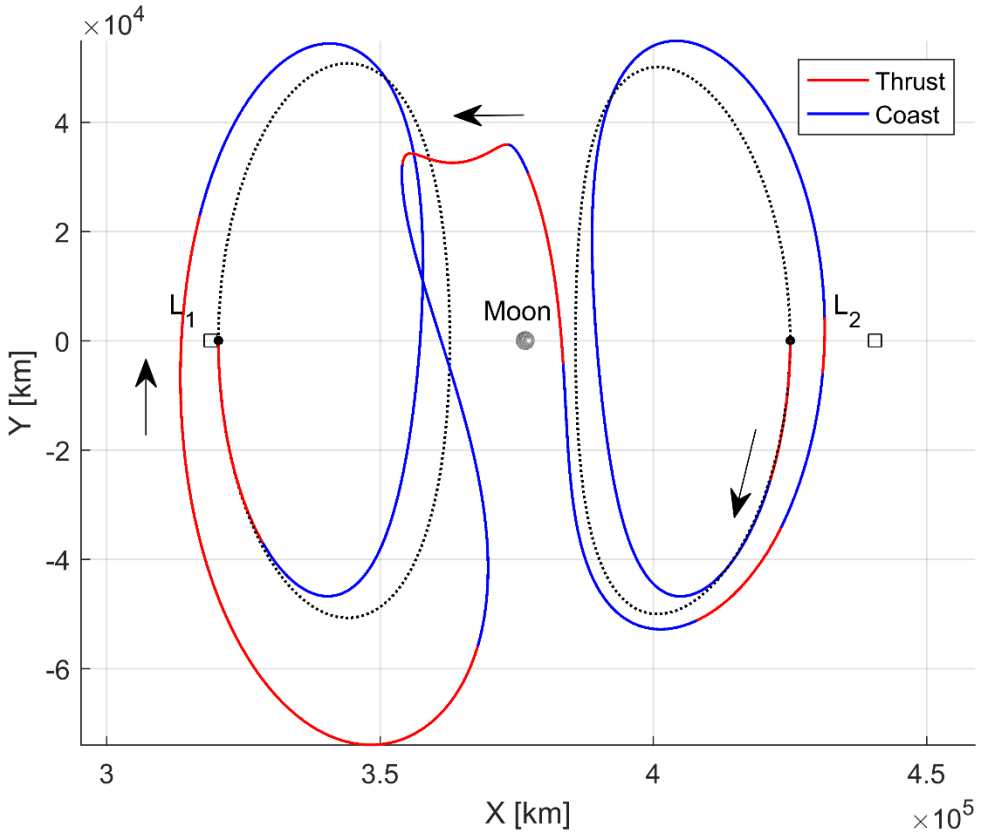


Feasible Transfer

Background

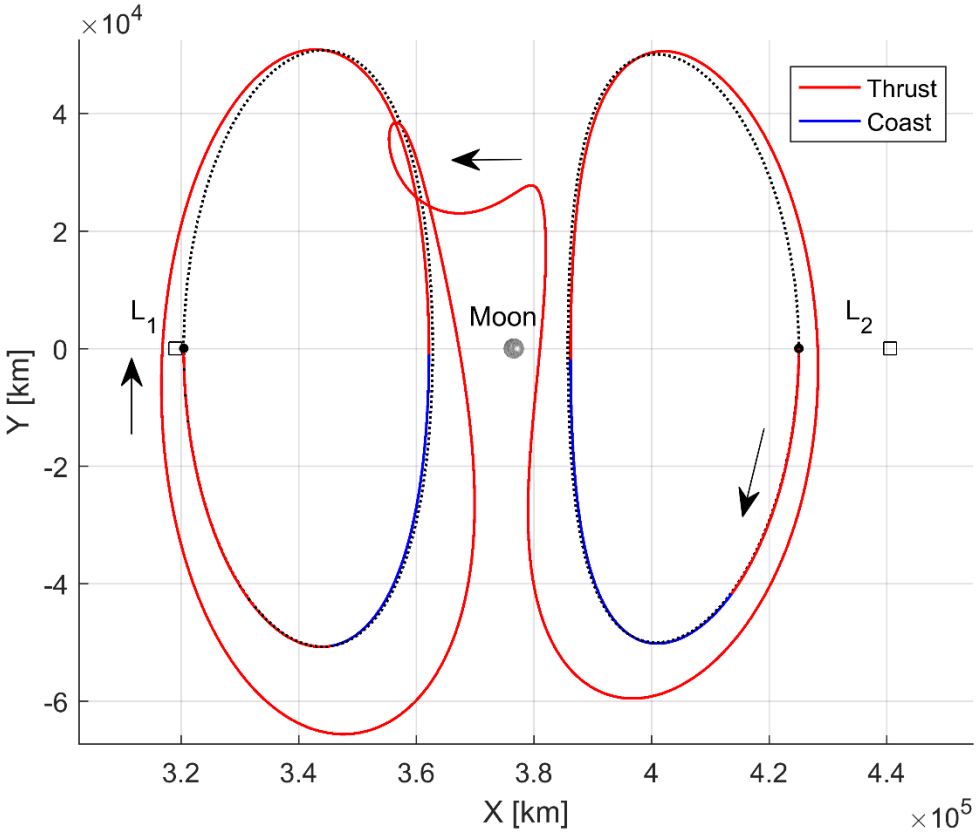
Trajectory Design with Direct Transcription Steps:

1. Stack revolutions on departure and arrival orbits to construct initial guess.
2. Converge feasible solution.
3. Pass feasible solution to optimization algorithm



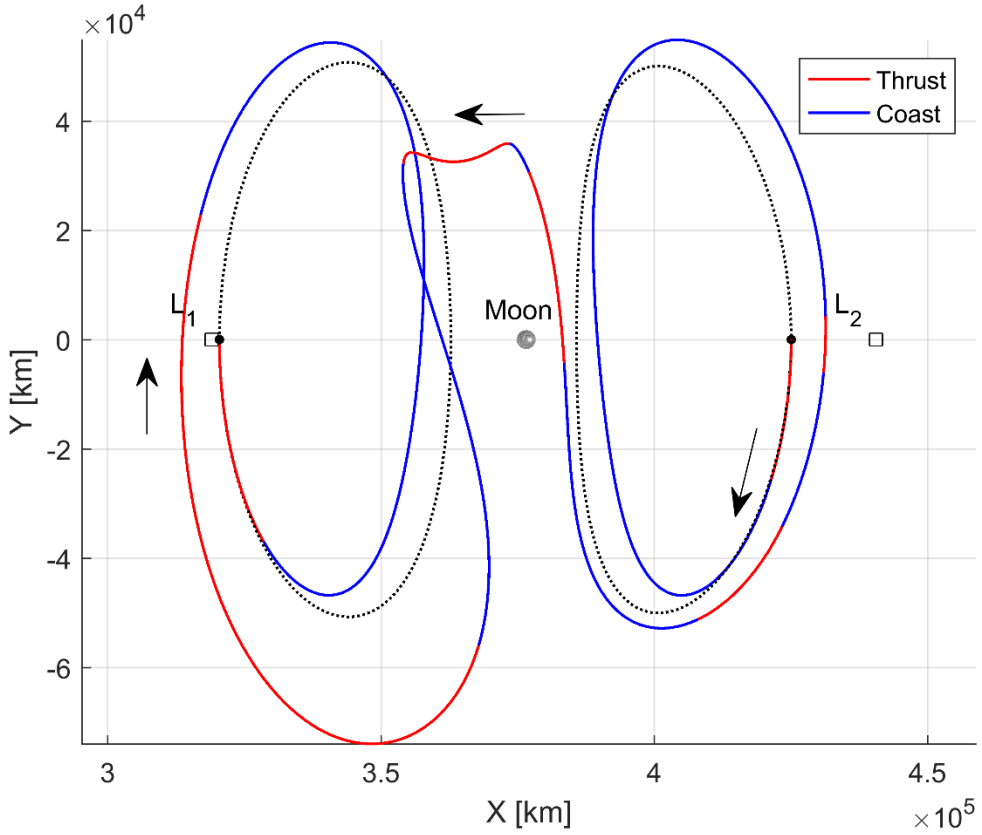
Optimal Transfer

Background



Feasible Transfer

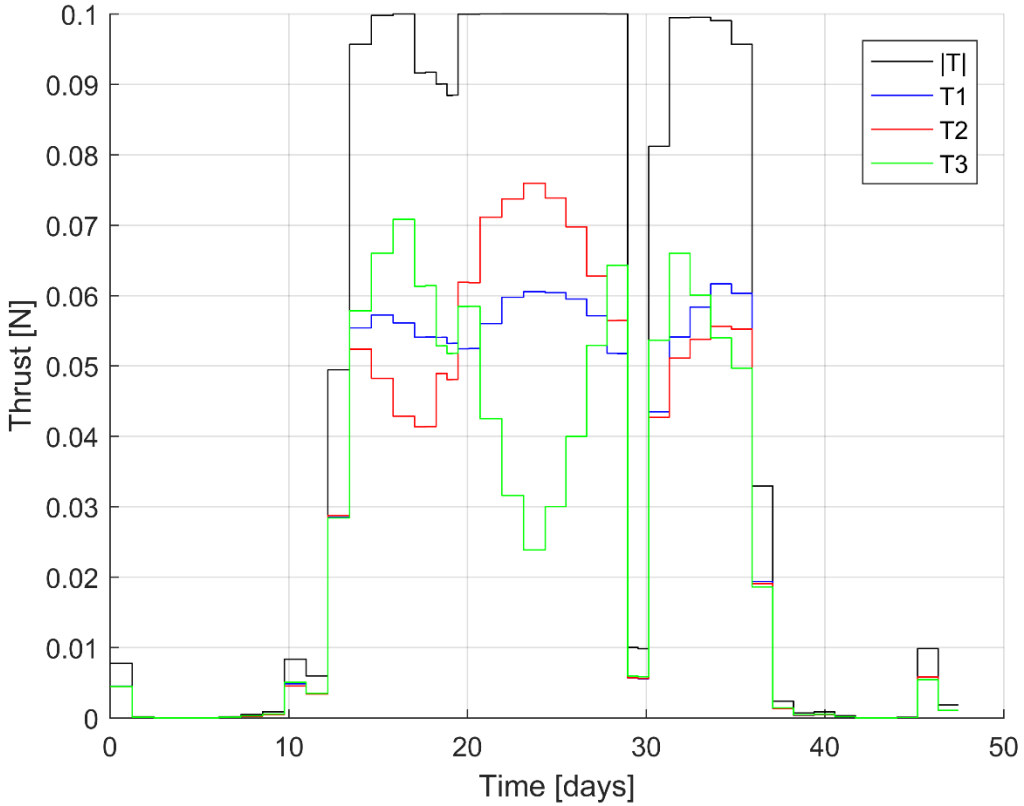
$m_f/m_0 = 490/500$



Optimal Transfer

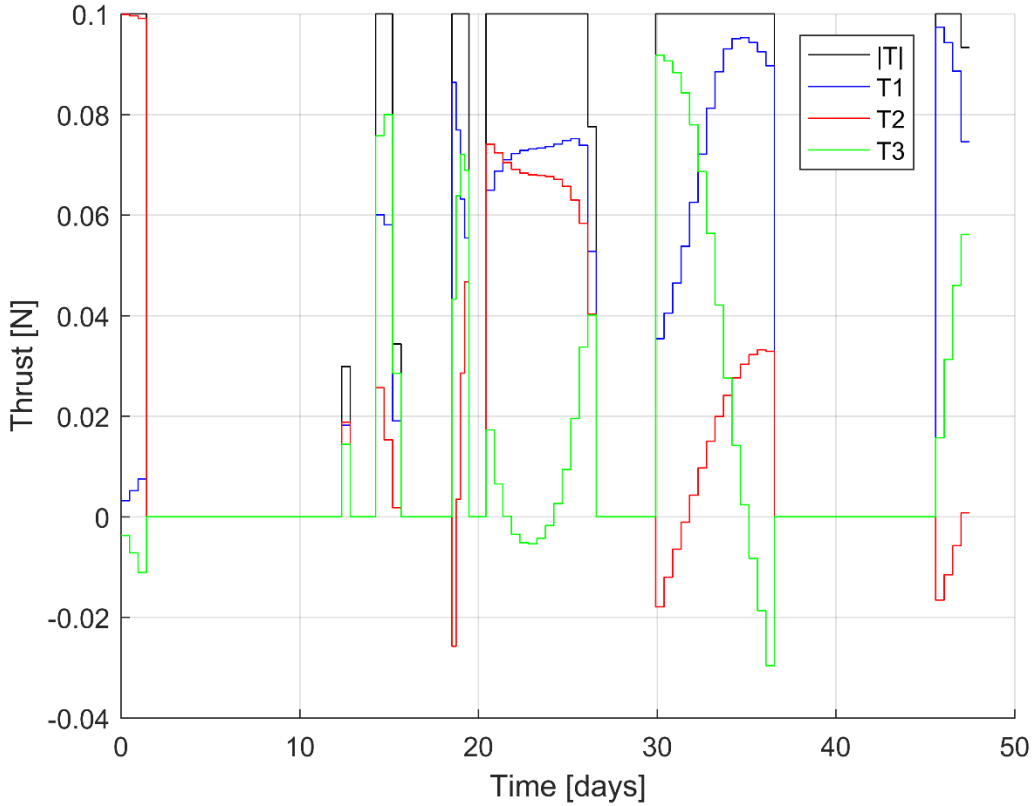
$m_f/m_0 = 492/500$

Background



Feasible Thrust Profile

$m_f/m_0 = 490/500$



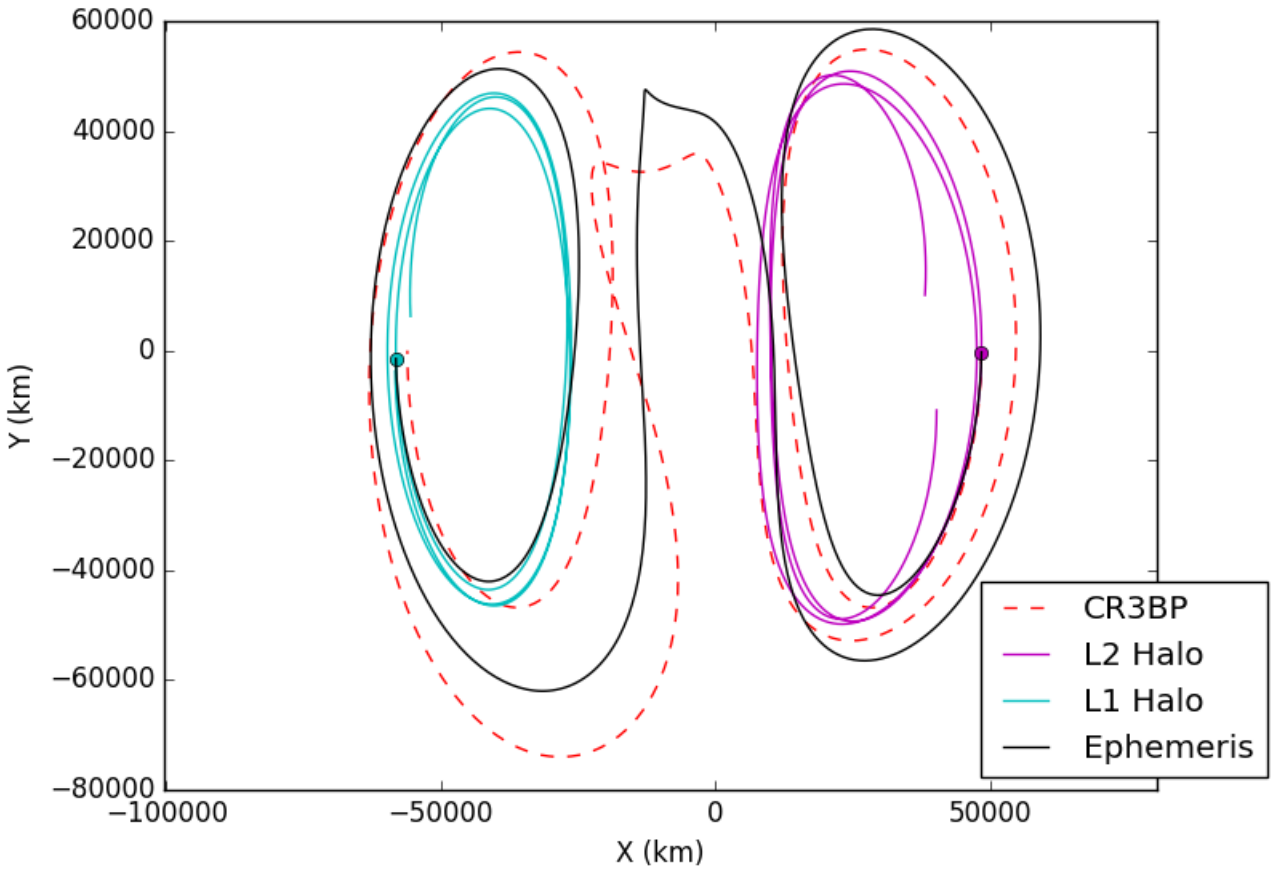
Optimal Thrust Profile

$m_f/m_0 = 492/500$

Background

Trajectory Design with Direct Transcription Steps:

1. Stack revolutions on departure and arrival orbits to construct initial guess.
2. Converge feasible solution.
3. Pass feasible solution to optimization algorithm
4. Transition optimal CR3BP transfer to a high-fidelity model

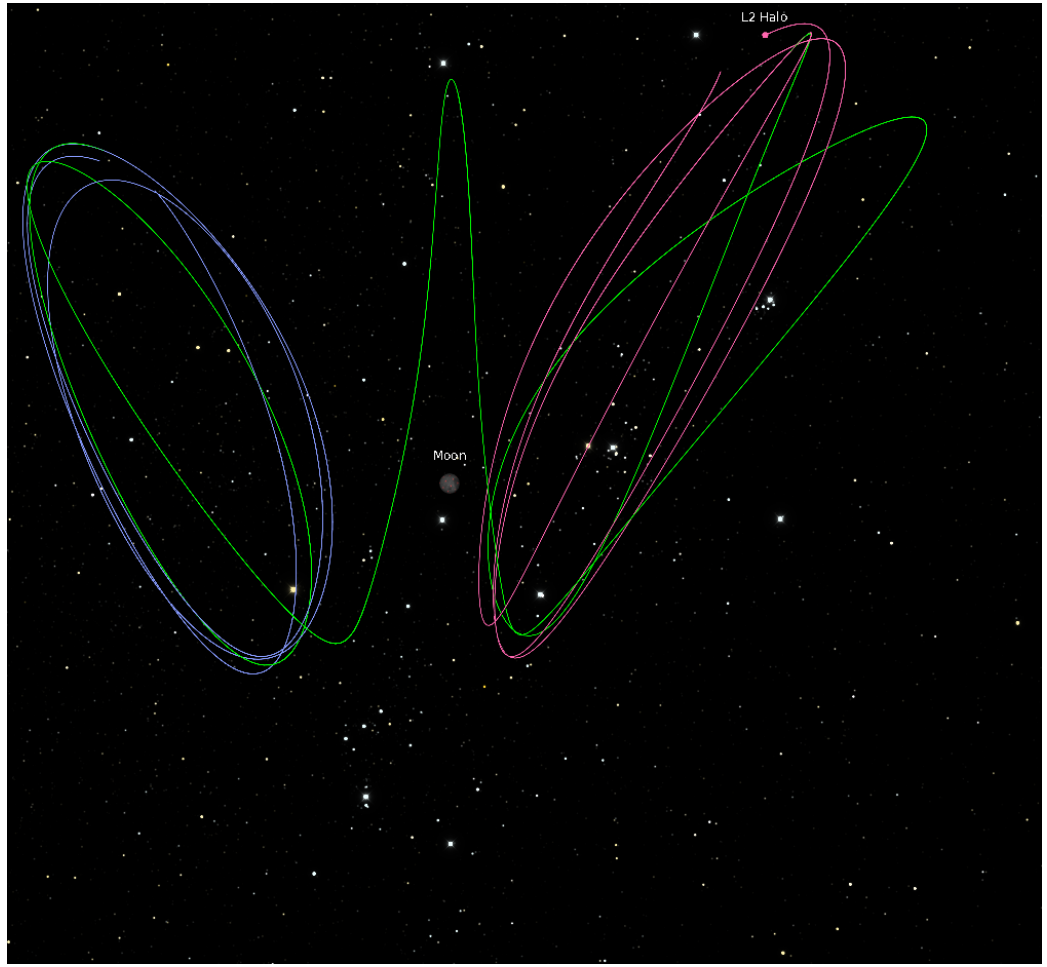


Transfer in a Full Ephemeris Model

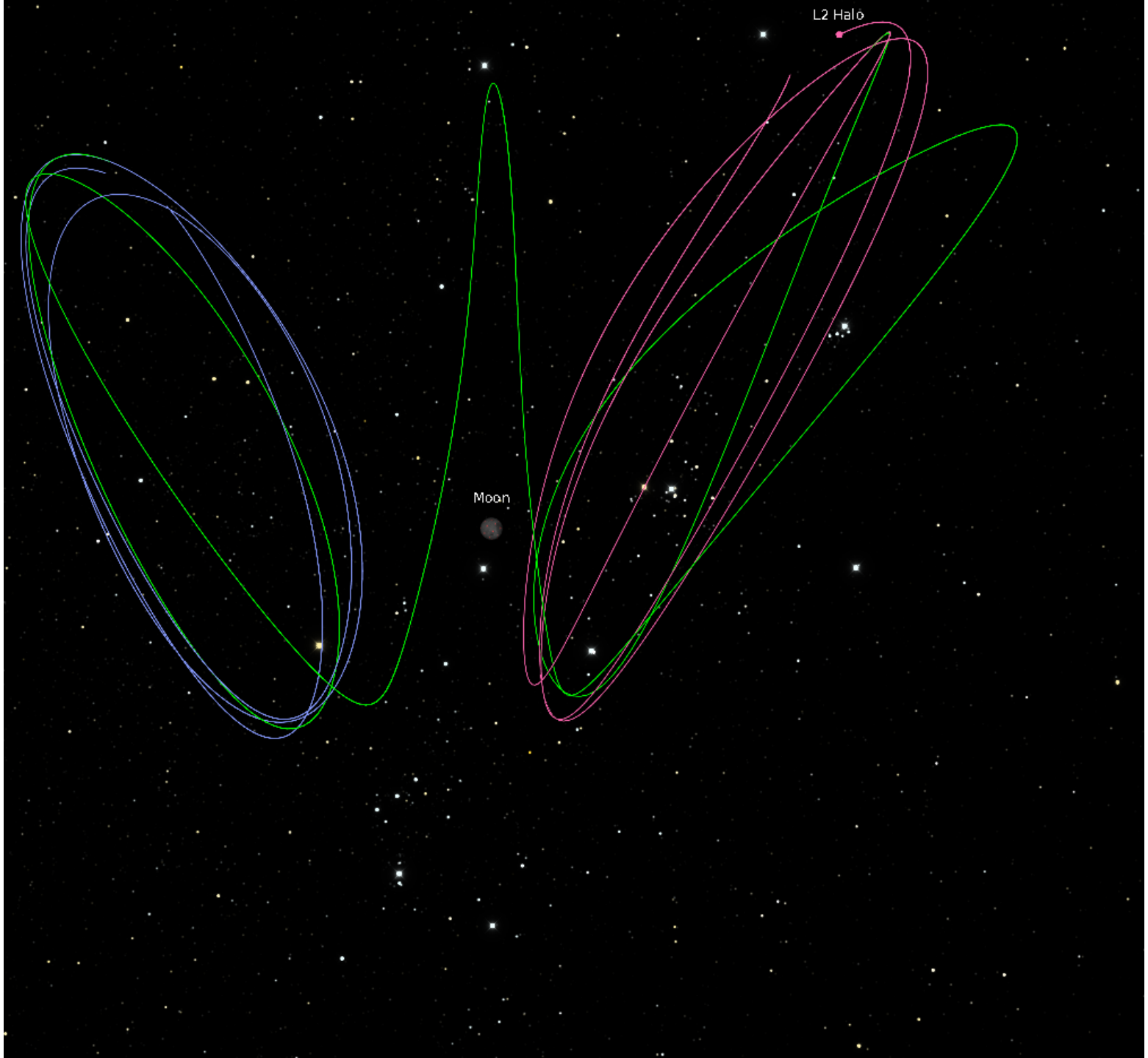
Background

Trajectory Design with Direct Transcription Steps:

1. Stack revolutions on departure and arrival orbits to construct initial guess.
2. Converge feasible solution.
3. Pass feasible solution to optimization algorithm
4. Transition optimal CR3BP transfer to a high-fidelity model



Transfer in a Full Ephemeris Model


L2 Halo
Moon

Outline

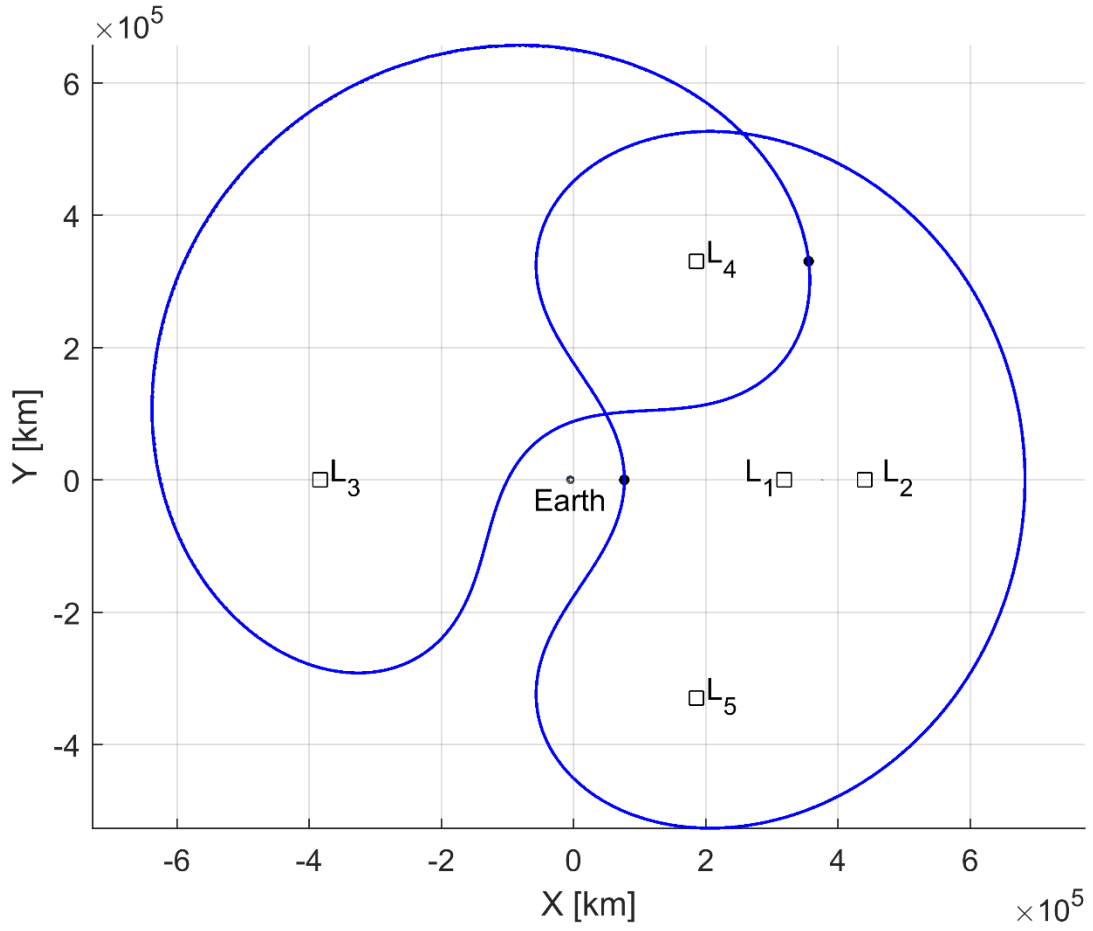
I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$DRO \rightarrow L_4\ SPO$$

- Could facilitate placement of or access to a waystation located at a triangular Lagrange point
- Departure and arrival orbits selected to possess a similar Jacobi constant value



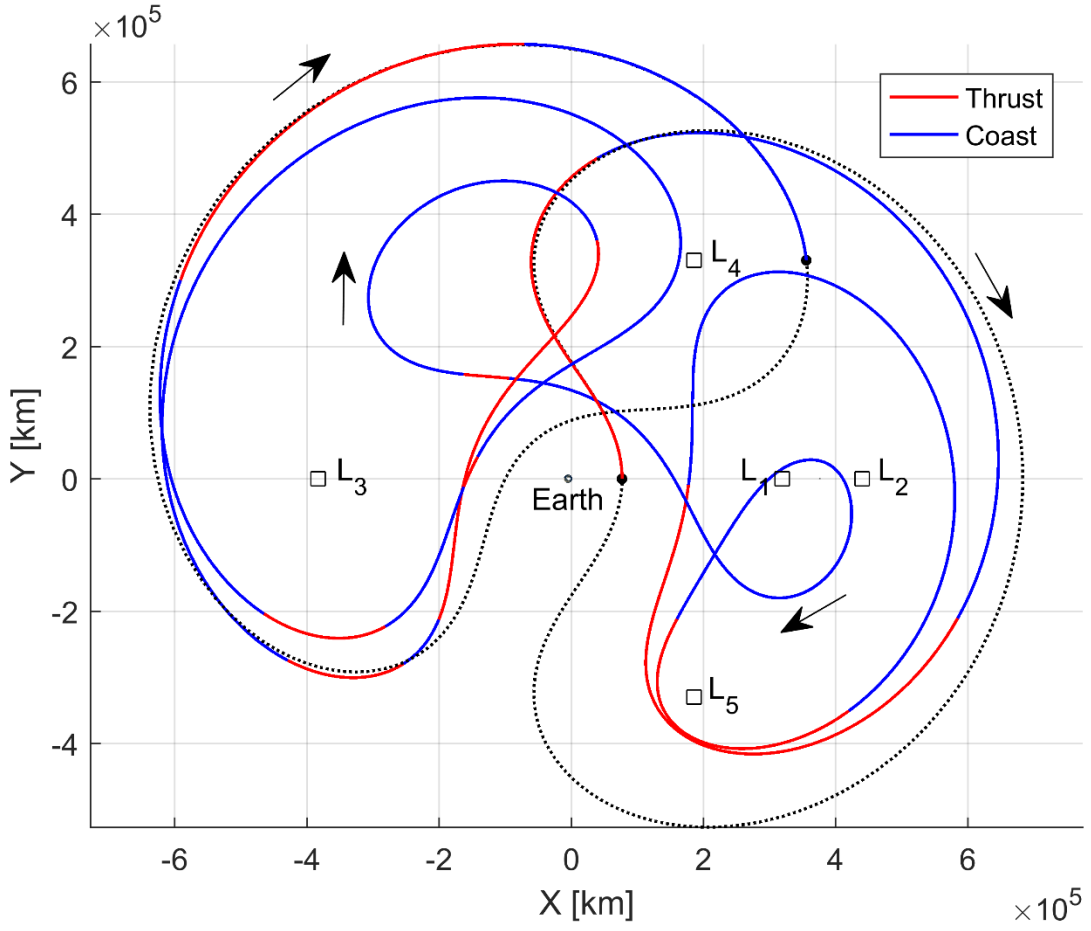
Initial Guess

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$DRO \rightarrow L_4\ SPO$$

- $DRO\ 3\ Rev + L_4\ SPO\ 2\ Rev$
- Transfer Time: $134.8\ days$
- Feasible: $m_f/m_0 = 478/500\ kg$
- Optimal: $m_f/m_0 = 482/500\ kg$



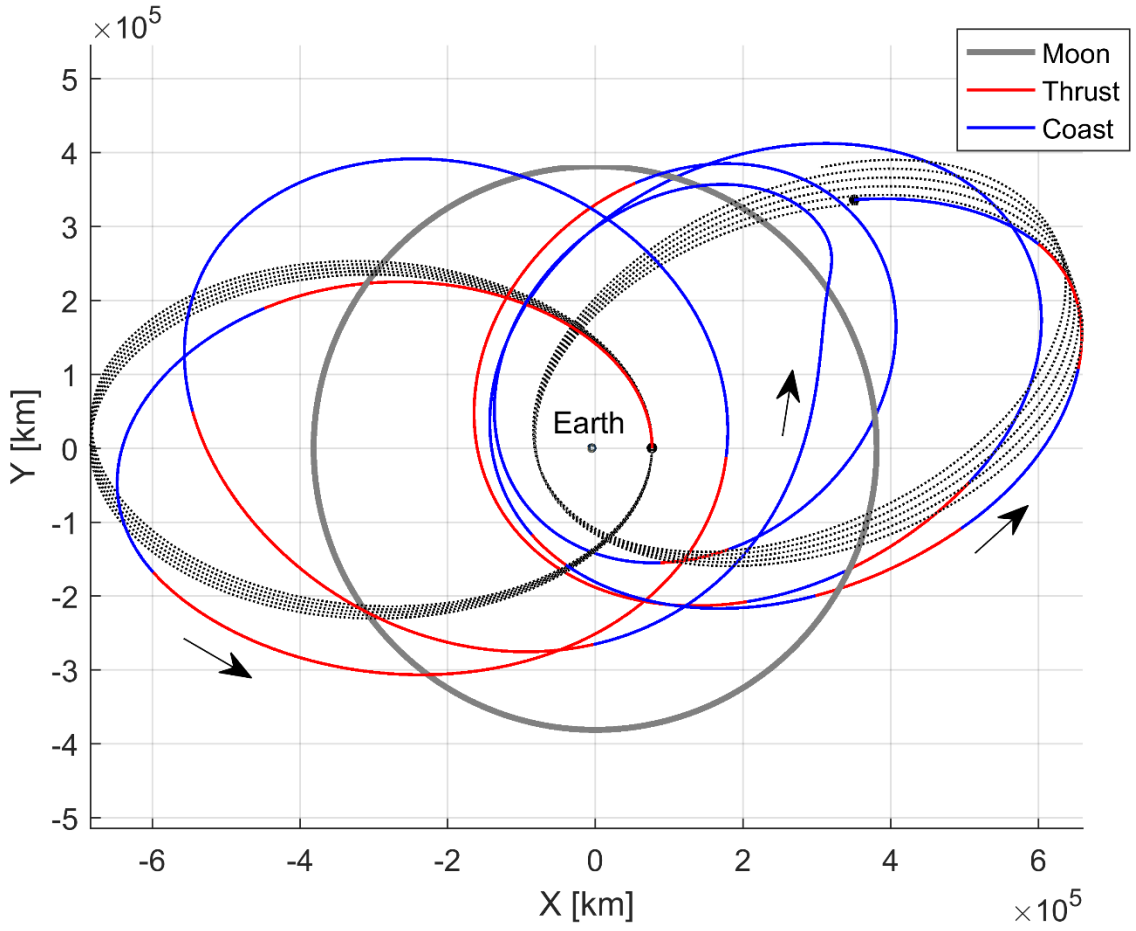
Optimal Transfer – Rotating Frame

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$DRO \rightarrow L_4\ SPO$$

- $DRO\ 3\ Rev + L_4\ SPO\ 2\ Rev$
- Transfer Time: $134.8\ days$
- Optimal: $m_f/m_0 = 482/500\ kg$



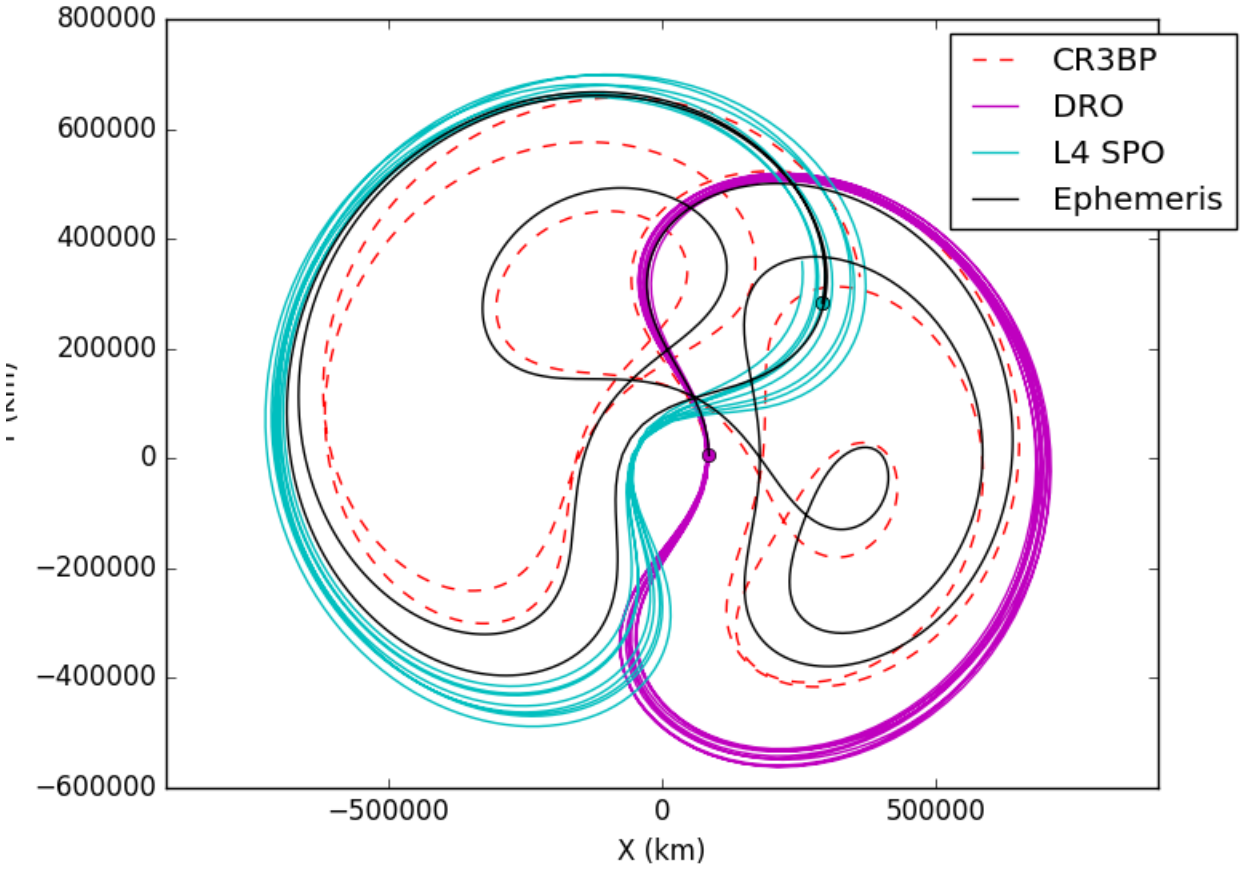
Optimal Transfer – Inertial Frame

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$DRO \rightarrow L_4\ SPO$$

- $DRO\ 3\ Rev + L_4\ SPO\ 2\ Rev$
- Transfer Time: $134.8\ days$



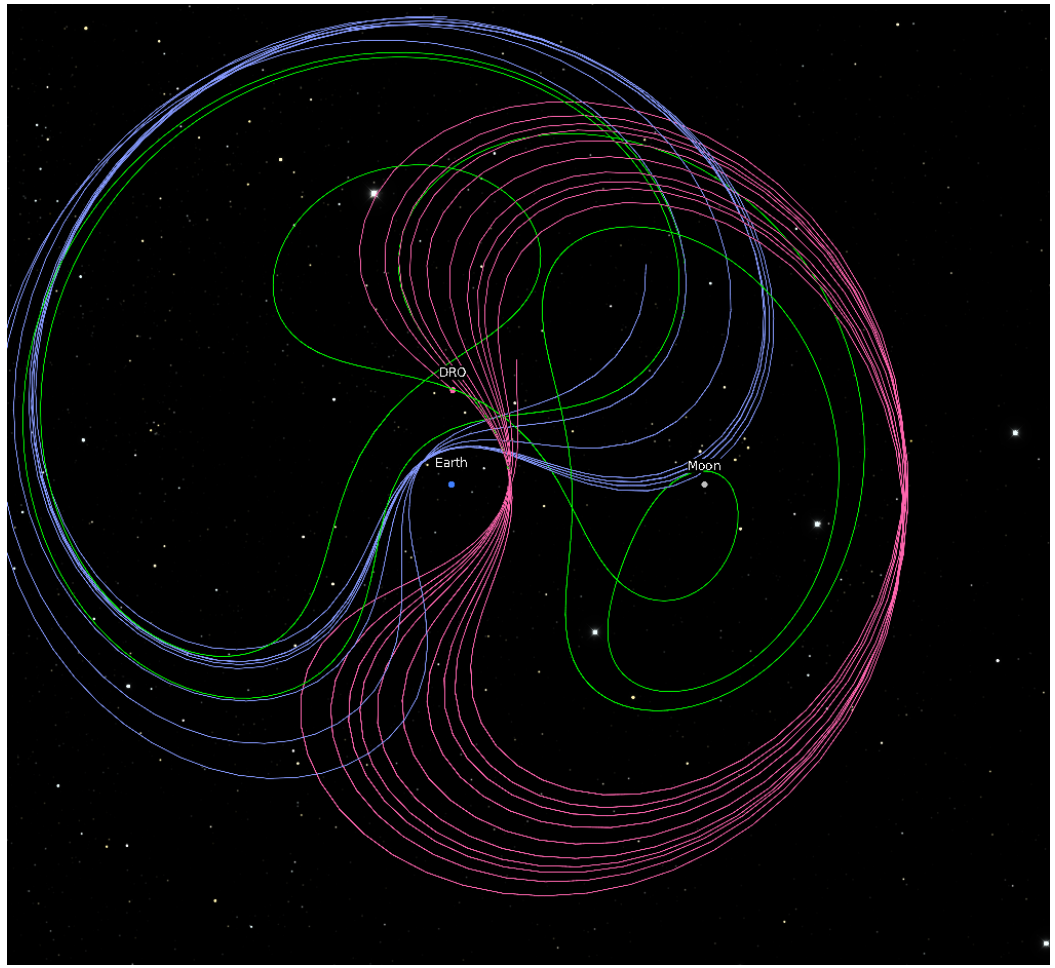
Transfer in a Full Ephemeris Model

Sample Applications – Trajectory Stacking

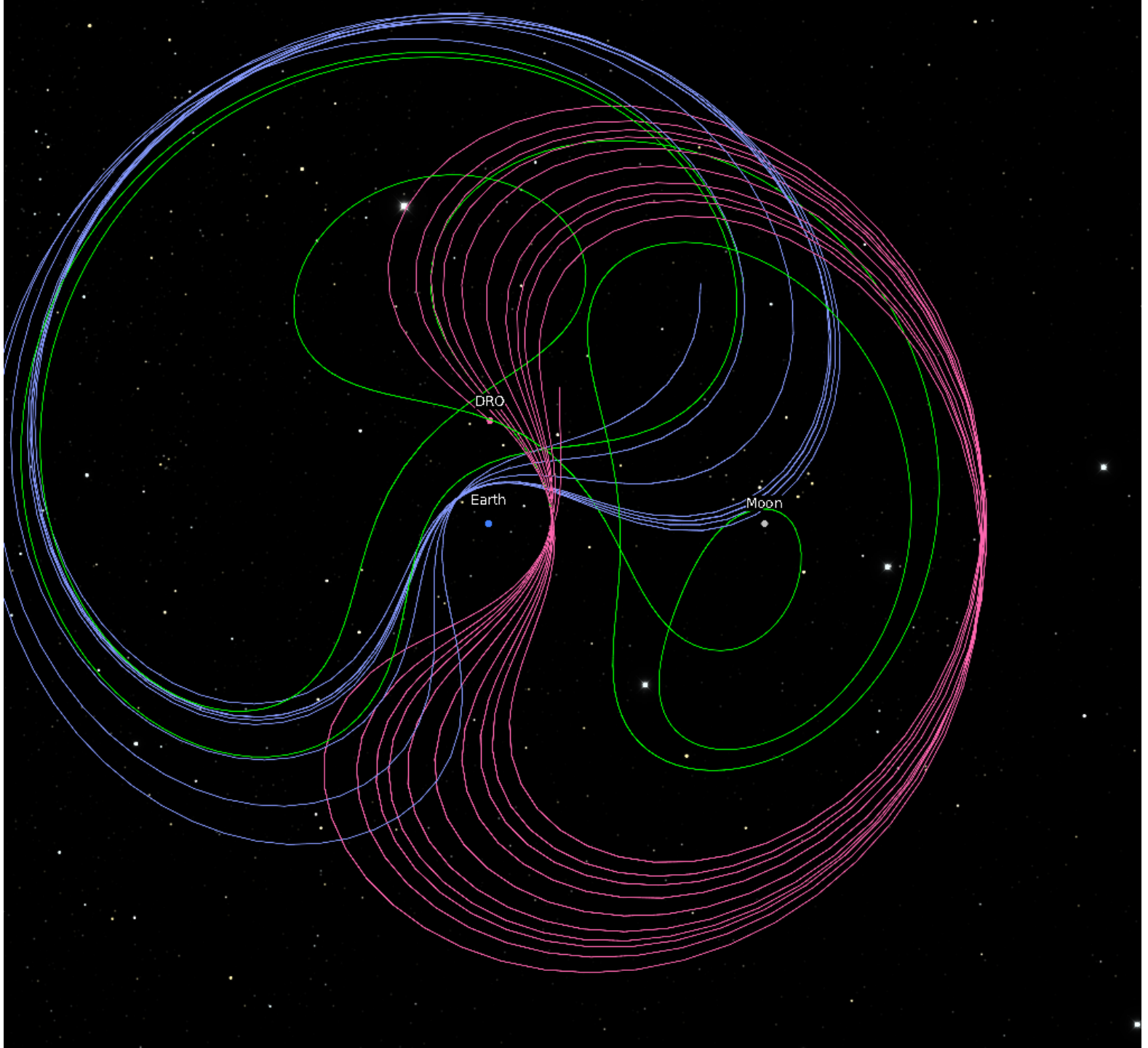
Transfer Scenario:

$$DRO \rightarrow L_4\ SPO$$

- $DRO\ 3\ Rev + L_4\ SPO\ 2\ Rev$
- Transfer Time: $134.8\ days$
- Optimal: $m_f/m_0 = 482/500\ kg$



Transfer in a Full Ephemeris Model

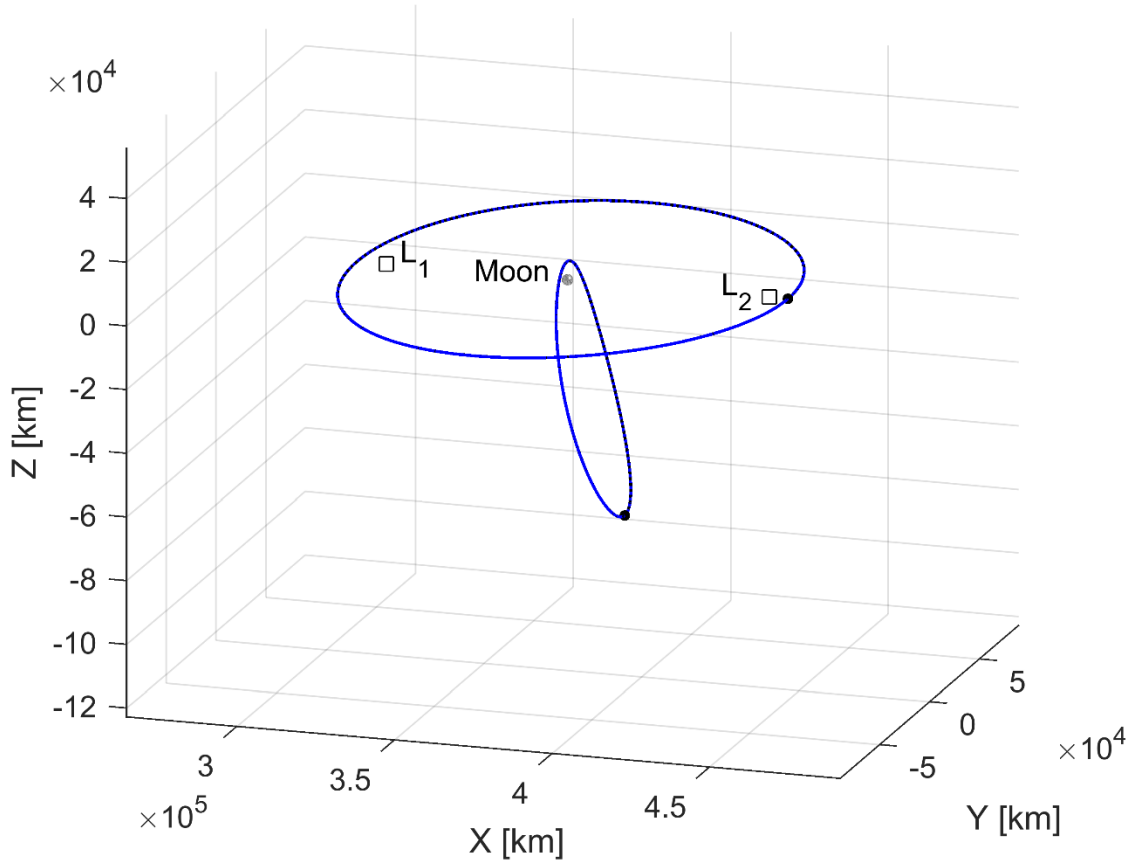

DRO
Earth
Moon

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$L_2\ NRHO \rightarrow DRO$$

- Could facilitate transfer of space station or communications satellite between two types of lunar orbits
- Orbits have different Jacobi constant values and very different orbital planes.



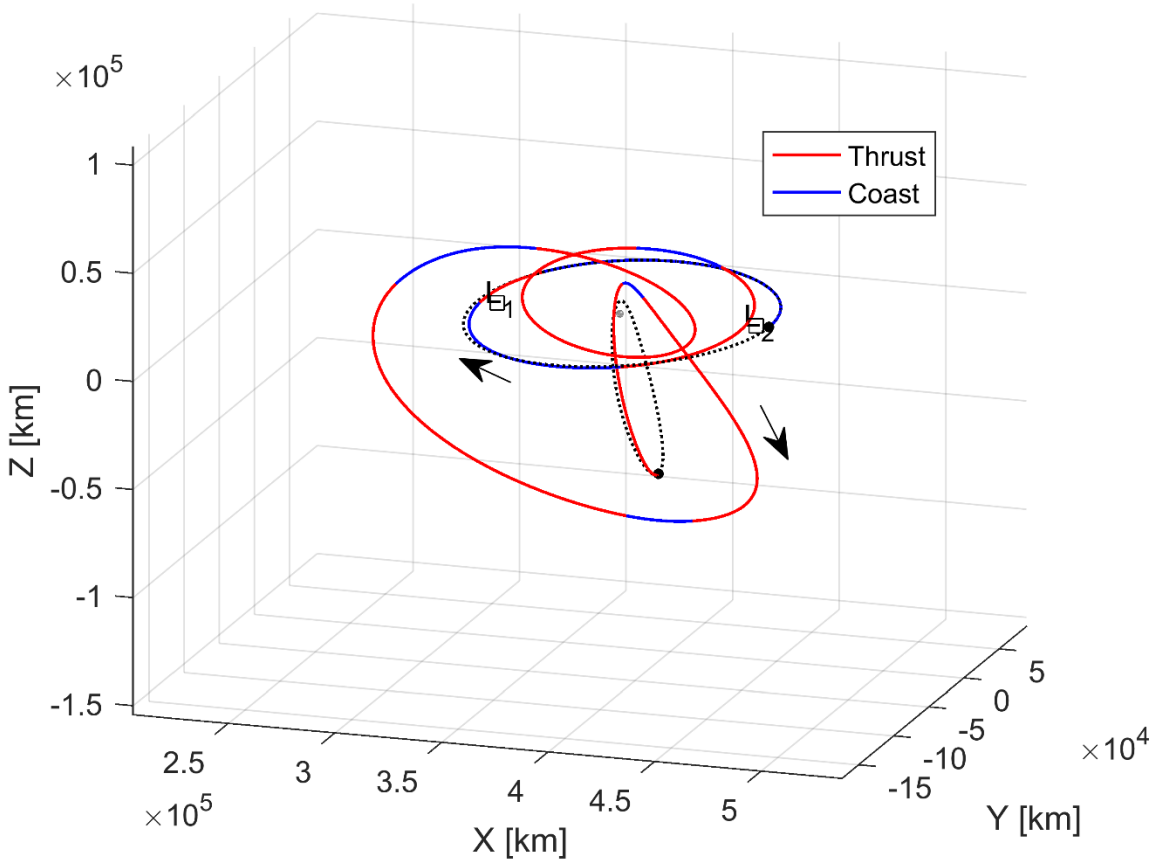
Initial Guess

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$L_2\ NRHO \rightarrow DRO$$

- $NRHO\ 1\ Rev + DRO\ 3\ Rev$
- Transfer Time: $46.7\ days$
- Feasible: $m_f/m_0 = 483/500\ kg$
- Optimal: $m_f/m_0 = 486/500\ kg$



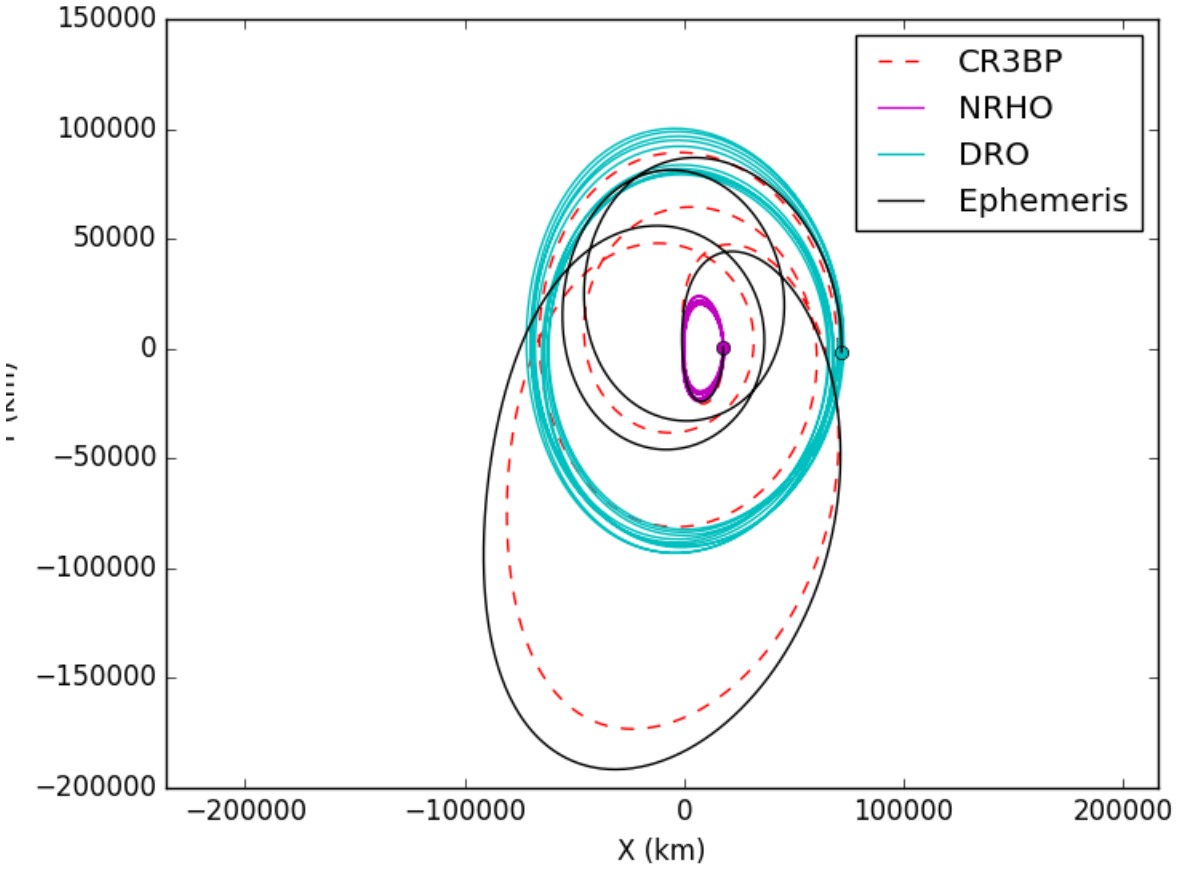
Optimal Transfer – Rotating Frame

Sample Applications – Trajectory Stacking

Transfer Scenario:

$$L_2\ NRHO \rightarrow DRO$$

- $NRHO\ 1\ Rev + DRO\ 3\ Rev$
- Transfer Time: $46.7\ days$



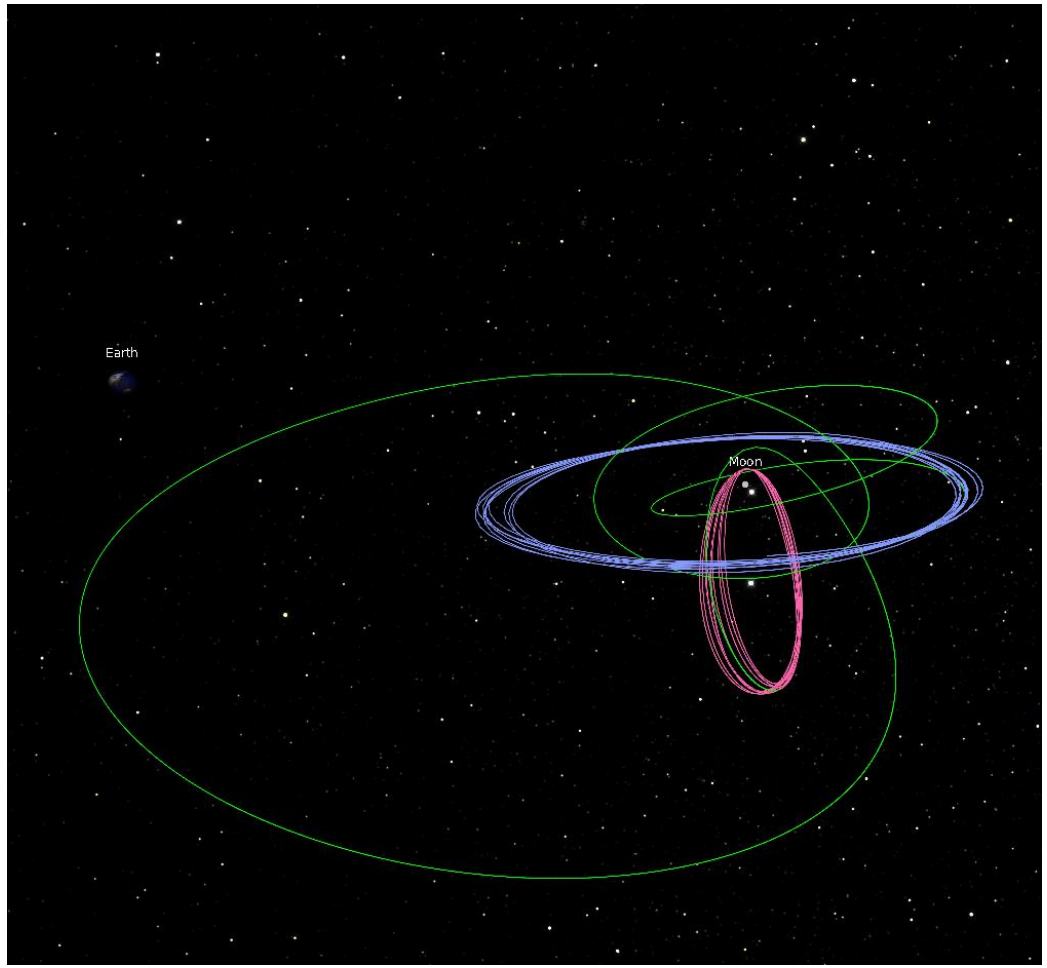
Transfer in a Full Ephemeris Model

Sample Applications – Trajectory Stacking

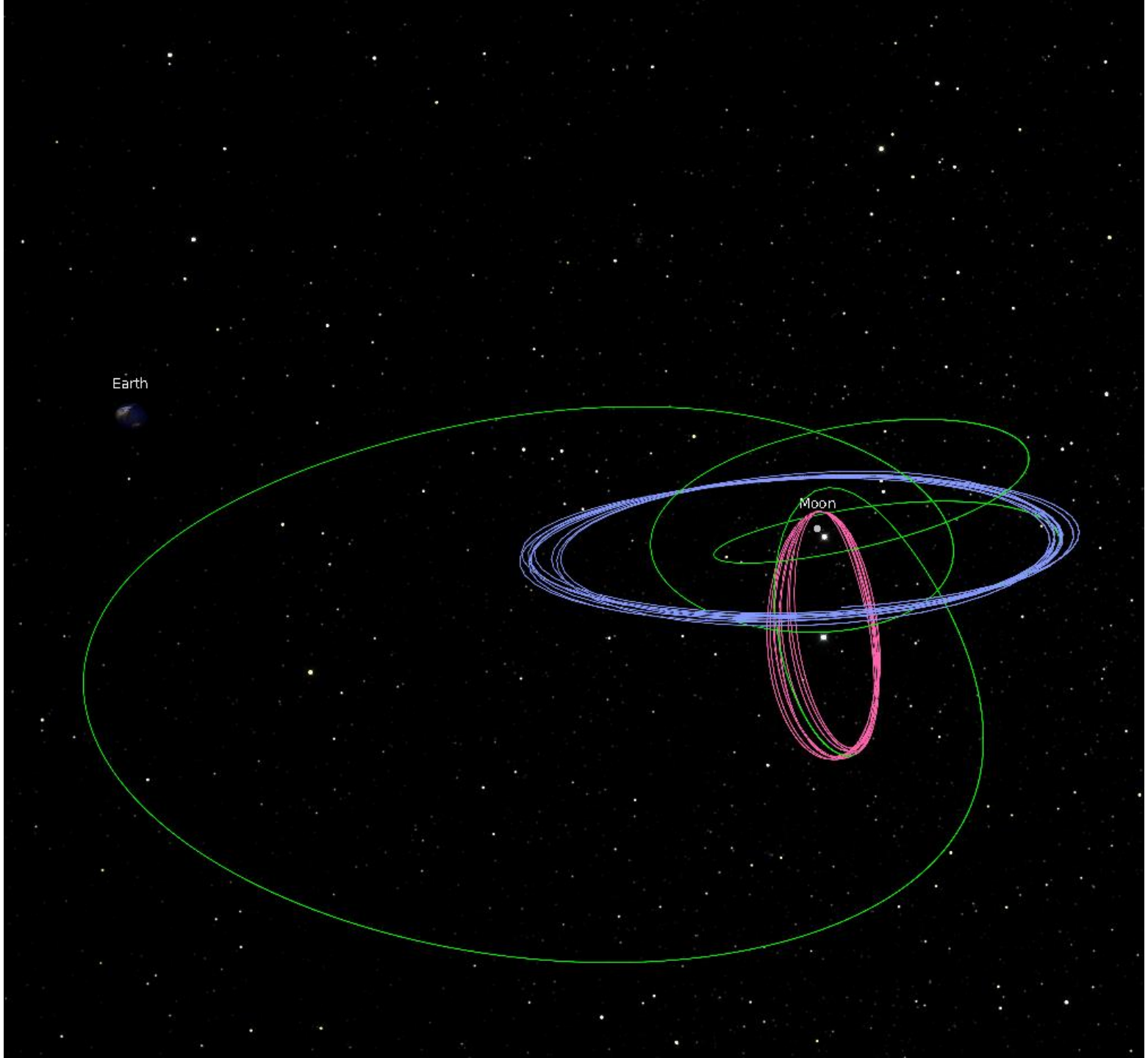
Transfer Scenario:

$$L_2\ NRHO \rightarrow DRO$$

- $NRHO\ 1\ Rev + DRO\ 3\ Rev$
- Transfer Time: $46.7\ days$
- $m_f/m_0 = 486/500\ kg$



Transfer in a Full Ephemeris Model


Earth
Moon

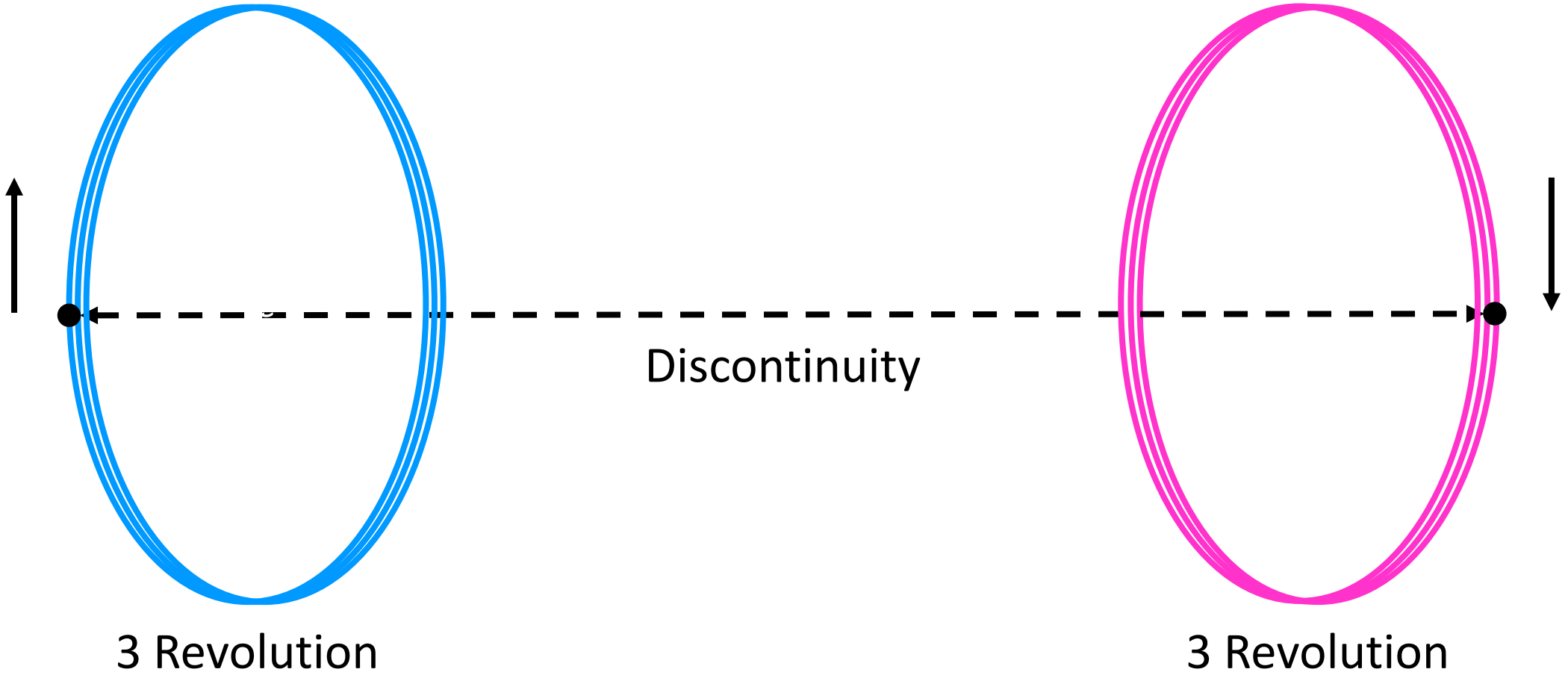
Outline

I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Sample Applications – Orbit Chaining

Orbit Chaining:

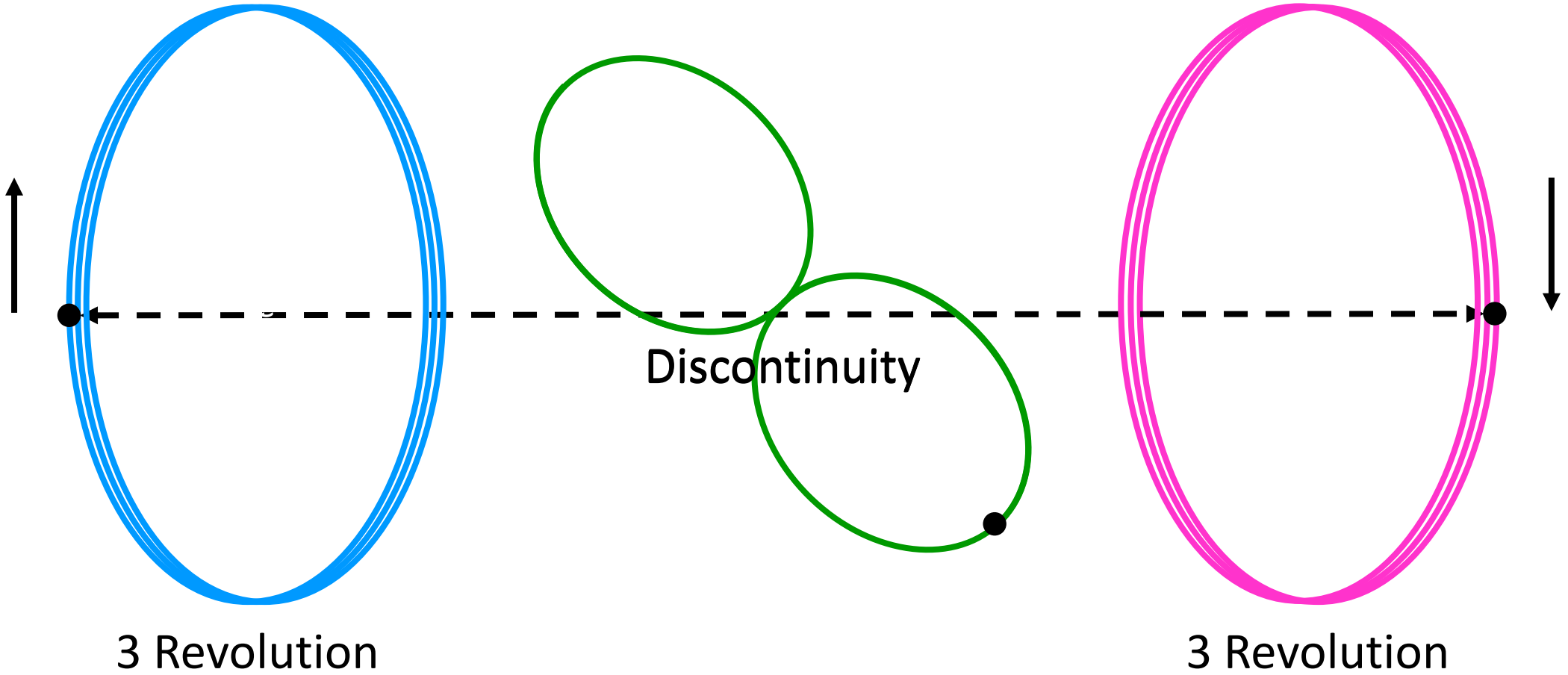
$$\text{TOF} = 3\,rev * \tau_0 + 3\,rev * \tau_f$$



Sample Applications – Orbit Chaining

Orbit Chaining:

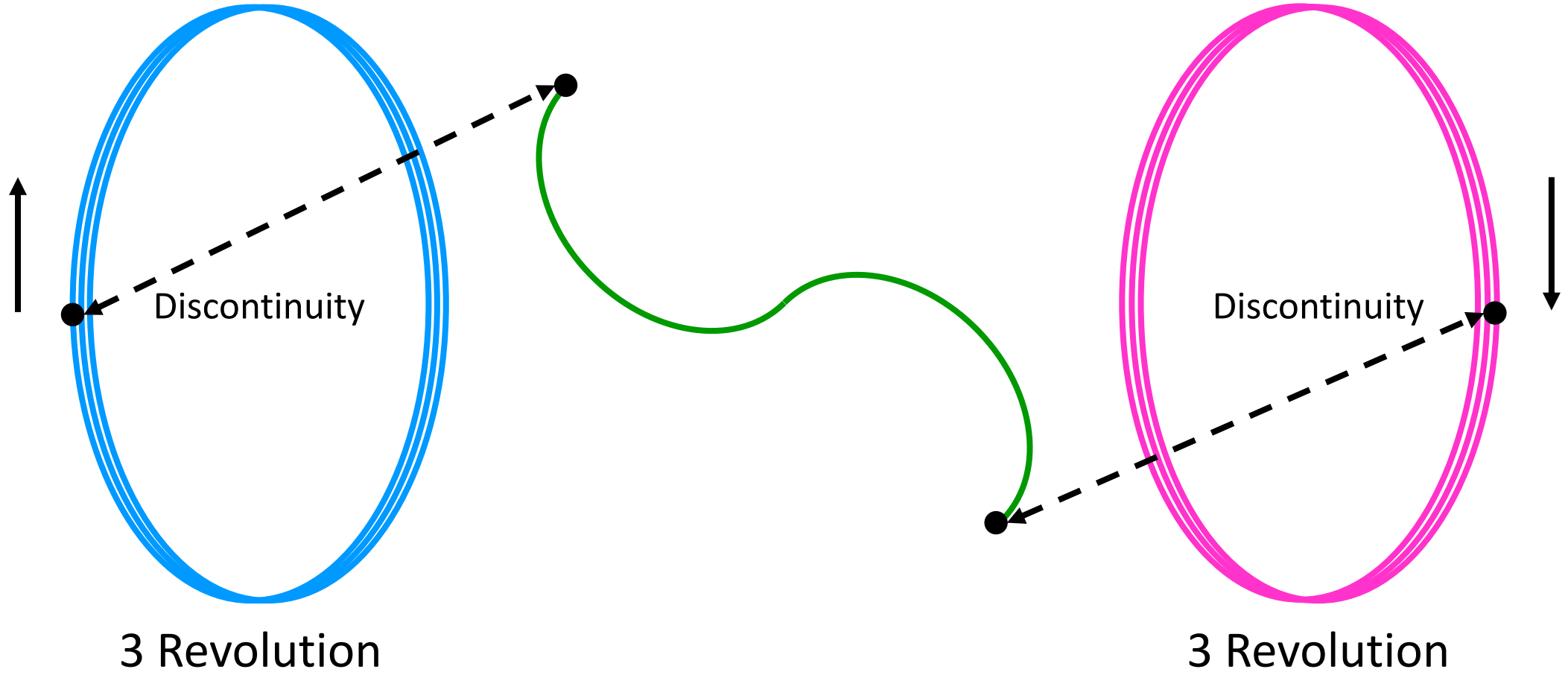
$$\mathrm{TOF} = 3\,rev * \tau_0 + \boldsymbol{\tau_{int}} + 3\,rev * \tau_f$$



Sample Applications – Orbit Chaining

Orbit Chaining:

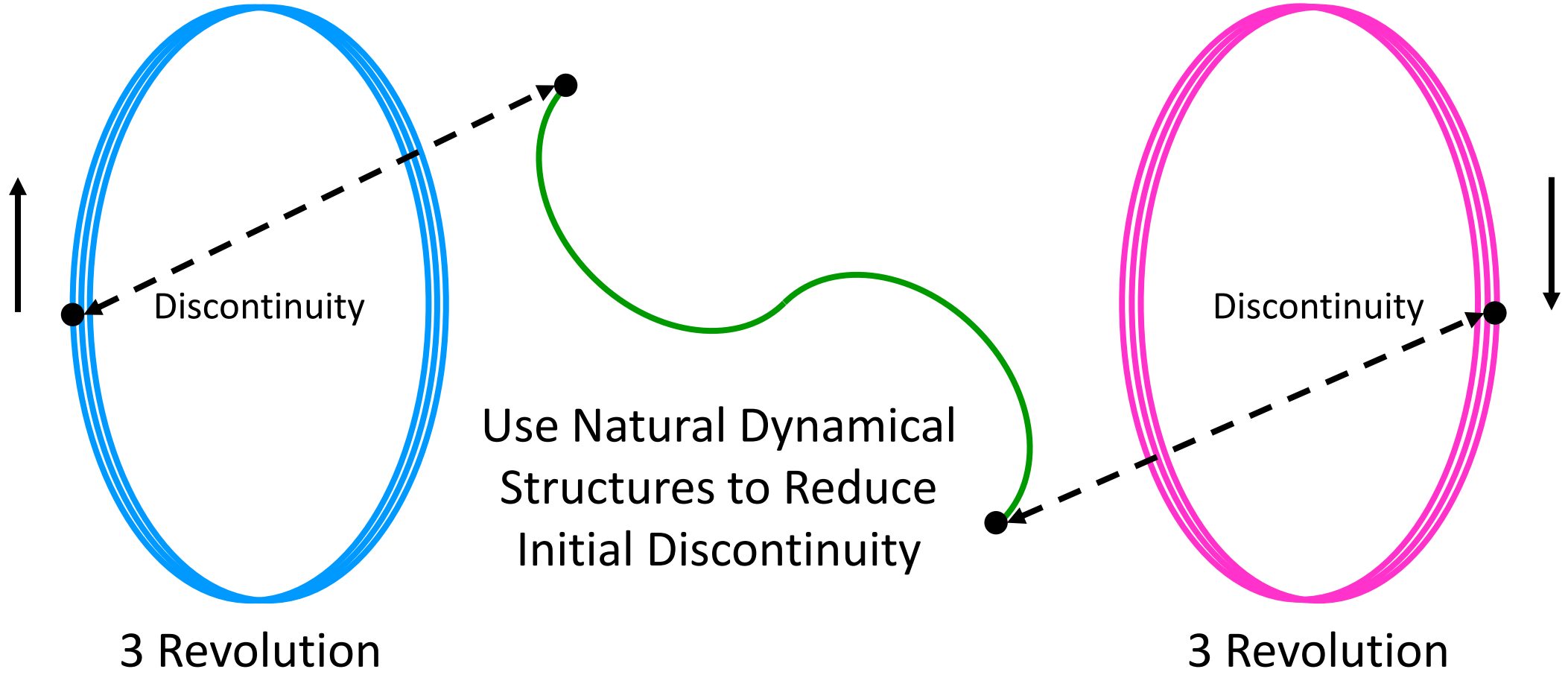
$$\mathrm{TOF} = 3\,rev * \tau_0 + \boldsymbol{\tau_{int}} + 3\,rev * \tau_f$$



Sample Applications – Orbit Chaining

Orbit Chaining:

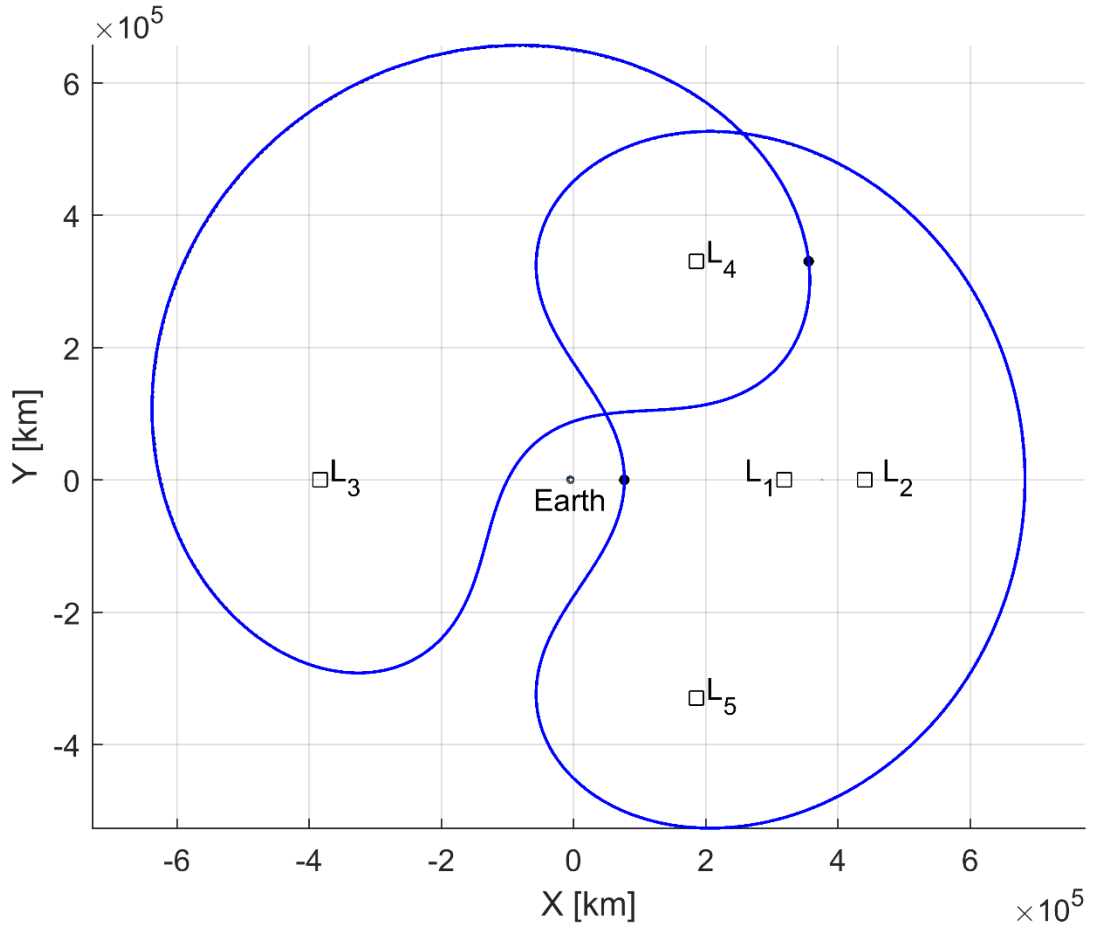
$$\mathrm{TOF} = 3\,rev * \tau_0 + \boldsymbol{\tau_{int}} + 3\,rev * \tau_f$$



Sample Applications – Orbit Chaining

Transfer Scenario:

$$DRO \rightarrow ??? \rightarrow L_4\ SPO$$

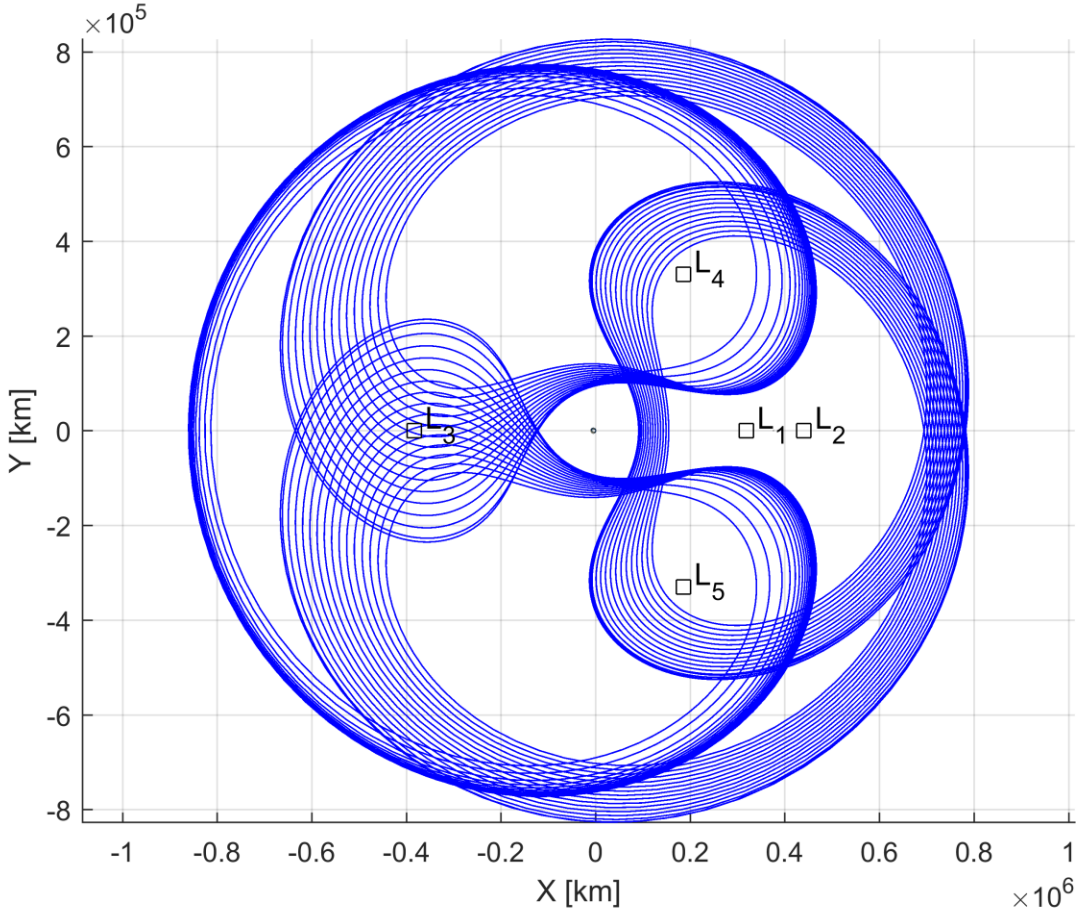


Departure and Arrival Orbits

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$



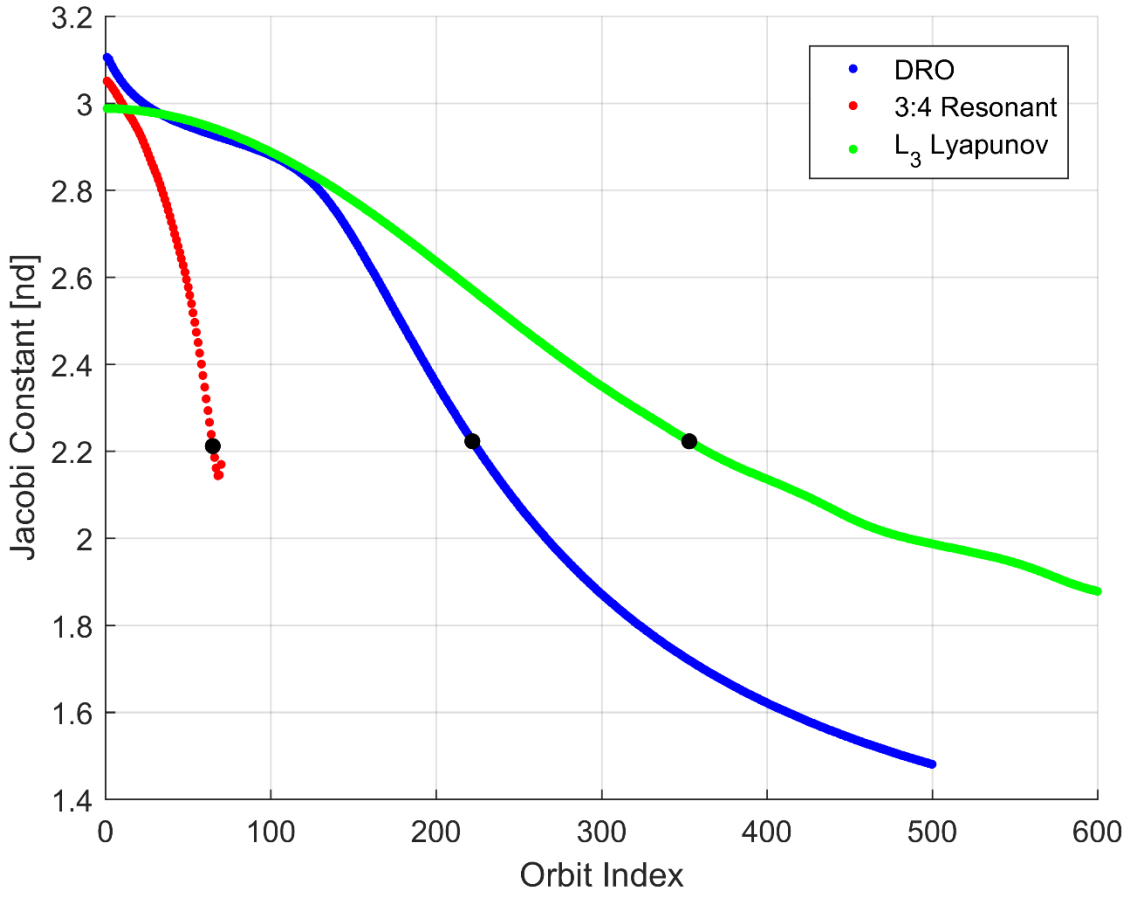
3:2 Resonant Orbit Family

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- Select resonant orbit with similar Jacobi constant value



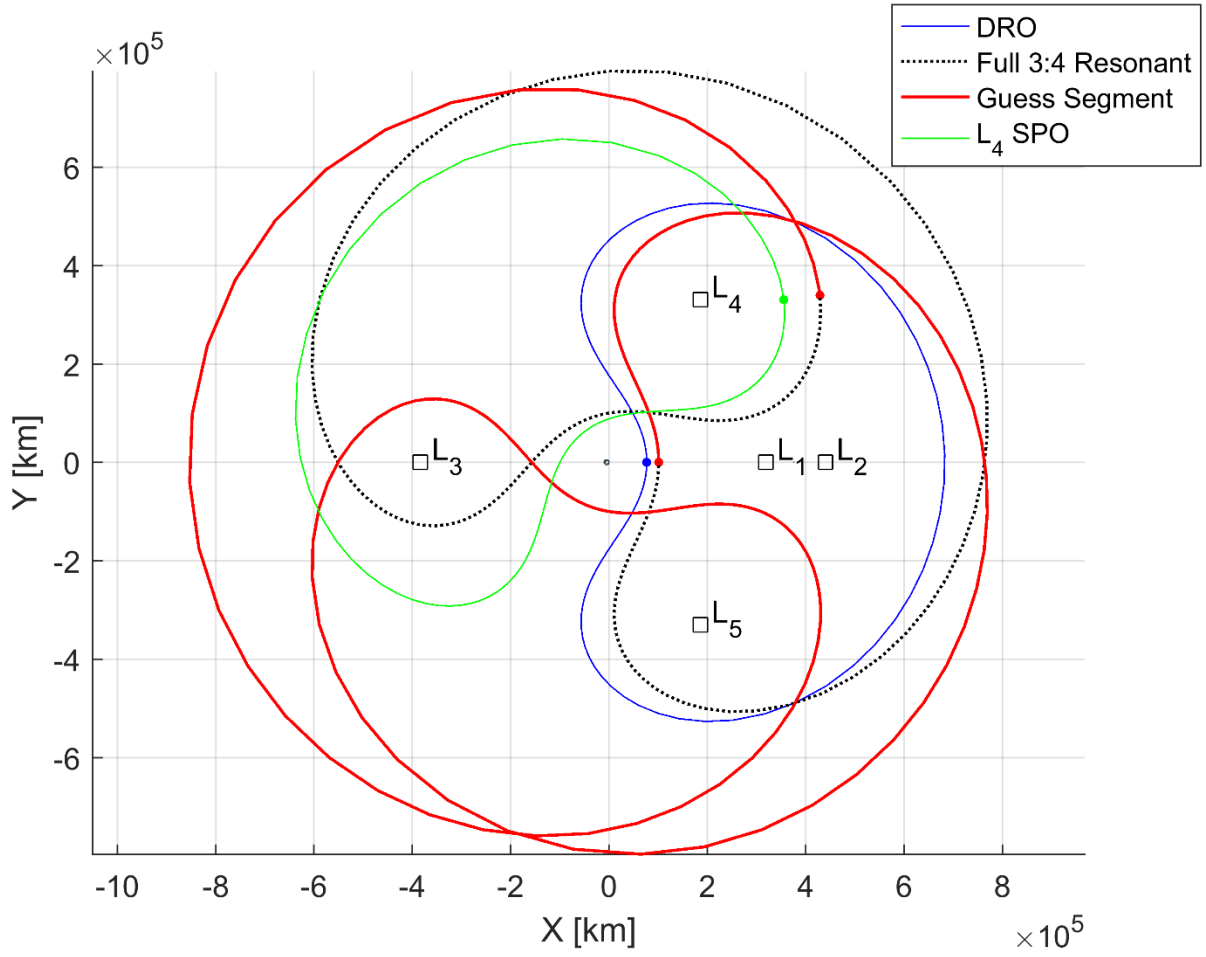
Jacobi Constant vs. Orbit Index

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- Select resonant orbit with similar Jacobi constant value
- Trim resonant orbit near departure and insertion points



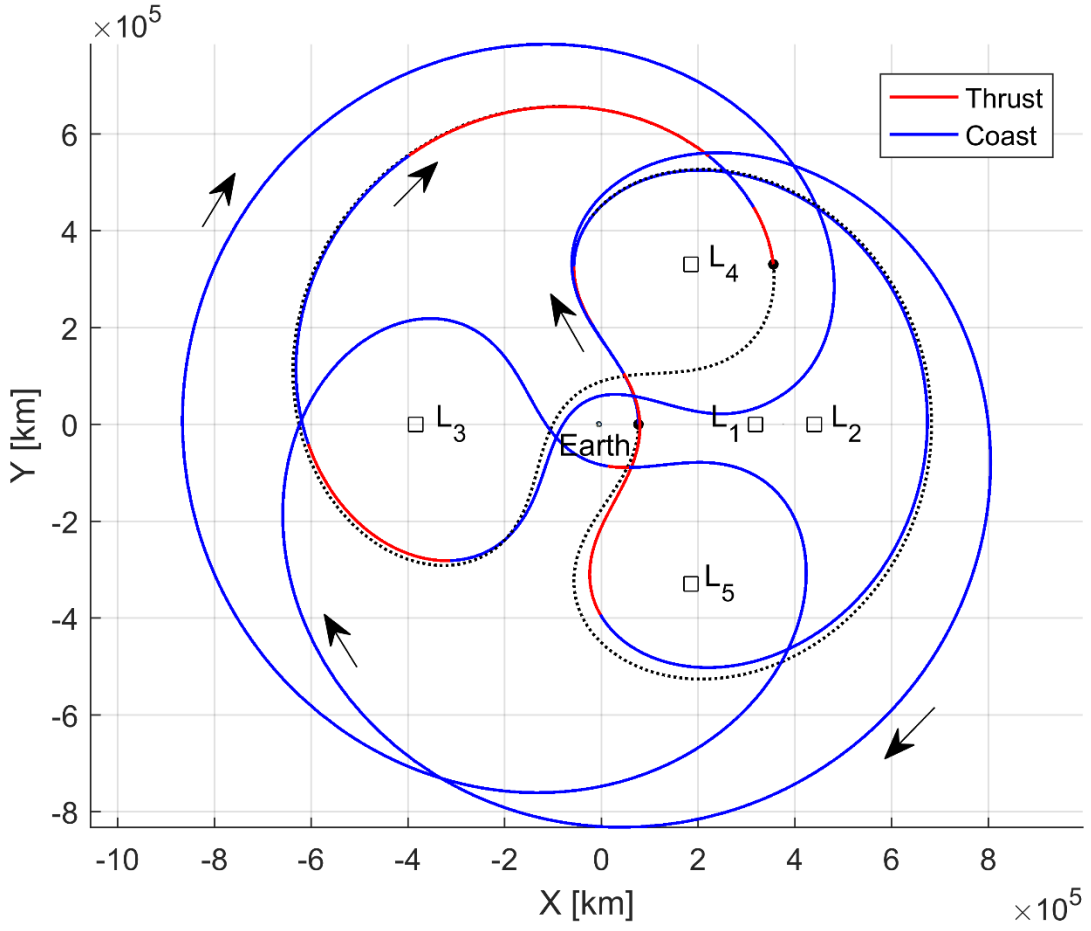
Initial Guess

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- $DRO\ 1\ Rev + 3{:}2\ Res\ 1\ Rev +$ $L_4\ SPO\ 1\ Rev$
- Transfer Time: $121.3\ days$
- Feasible: $m_f/m_0 = 492/500\ kg$
- Optimal: $m_f/m_0 = 497/500\ kg$



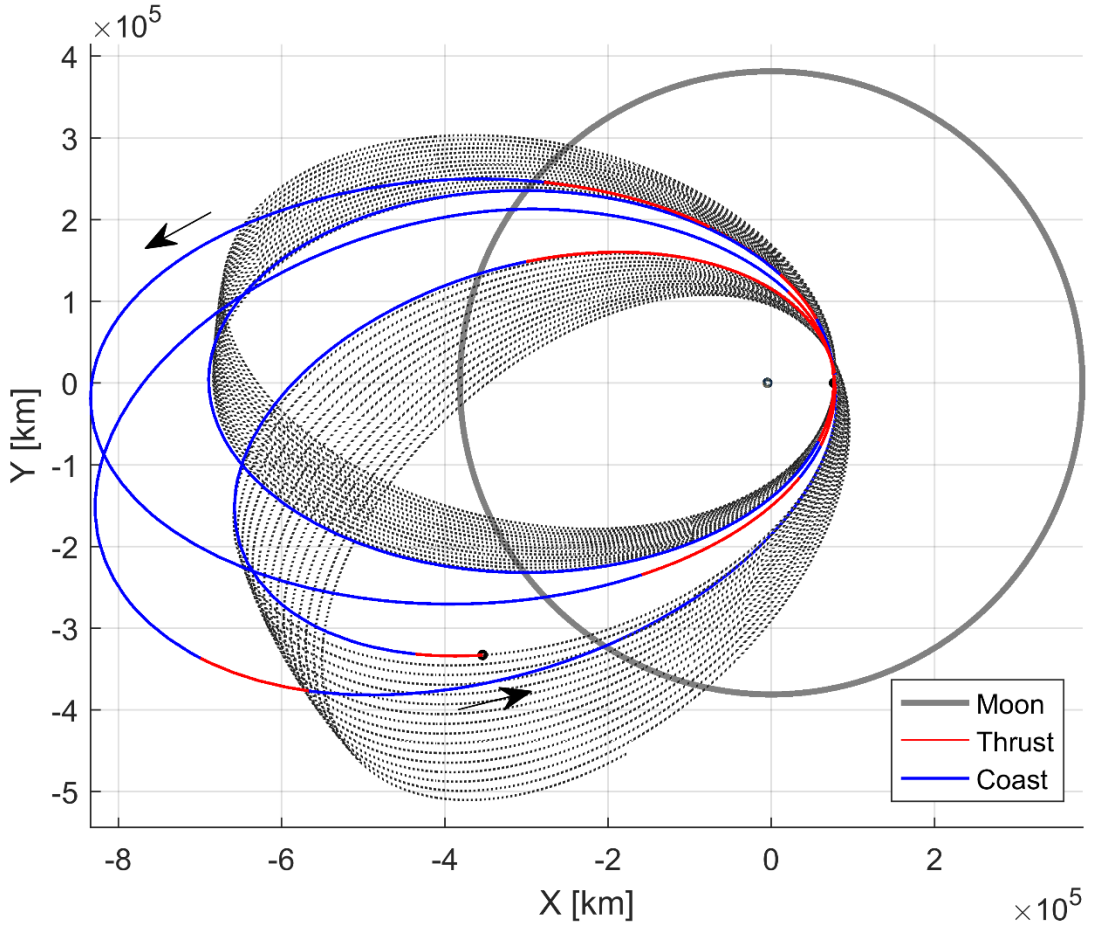
Optimal Transfer

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- $DRO\ 1\ Rev + 3{:}2\ Res\ 1\ Rev +$ $L_4\ SPO\ 1\ Rev$
- Transfer Time: $121.3\ days$
- Optimal: $m_f/m_0 = 497/500\ kg$



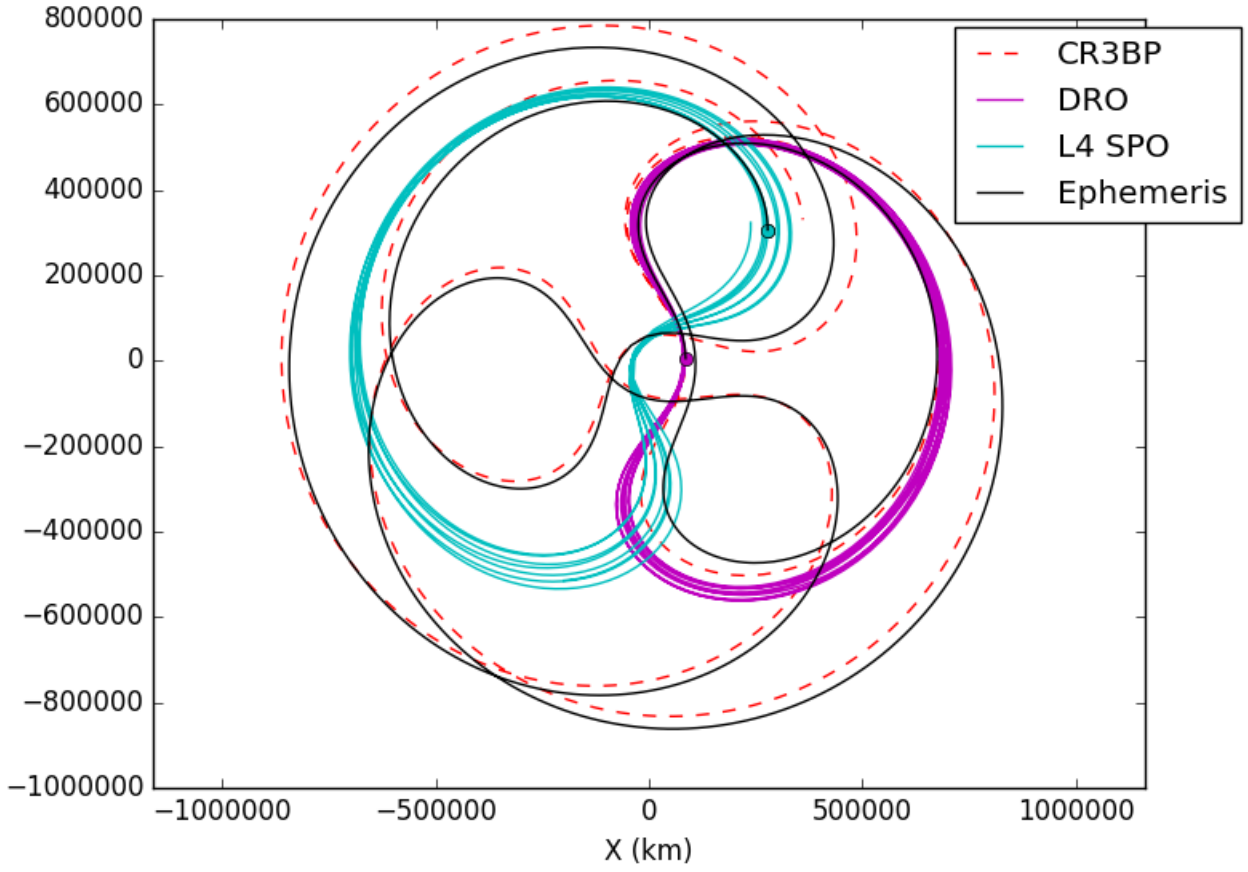
Optimal Transfer – Inertial Frame

Sample Applications – Orbit Chaining

Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- $DRO\ 1\ Rev + 3{:}2\ Res\ 1\ Rev +$ $L_4\ SPO\ 1\ Rev$
- Transfer Time: 121.3 $days$



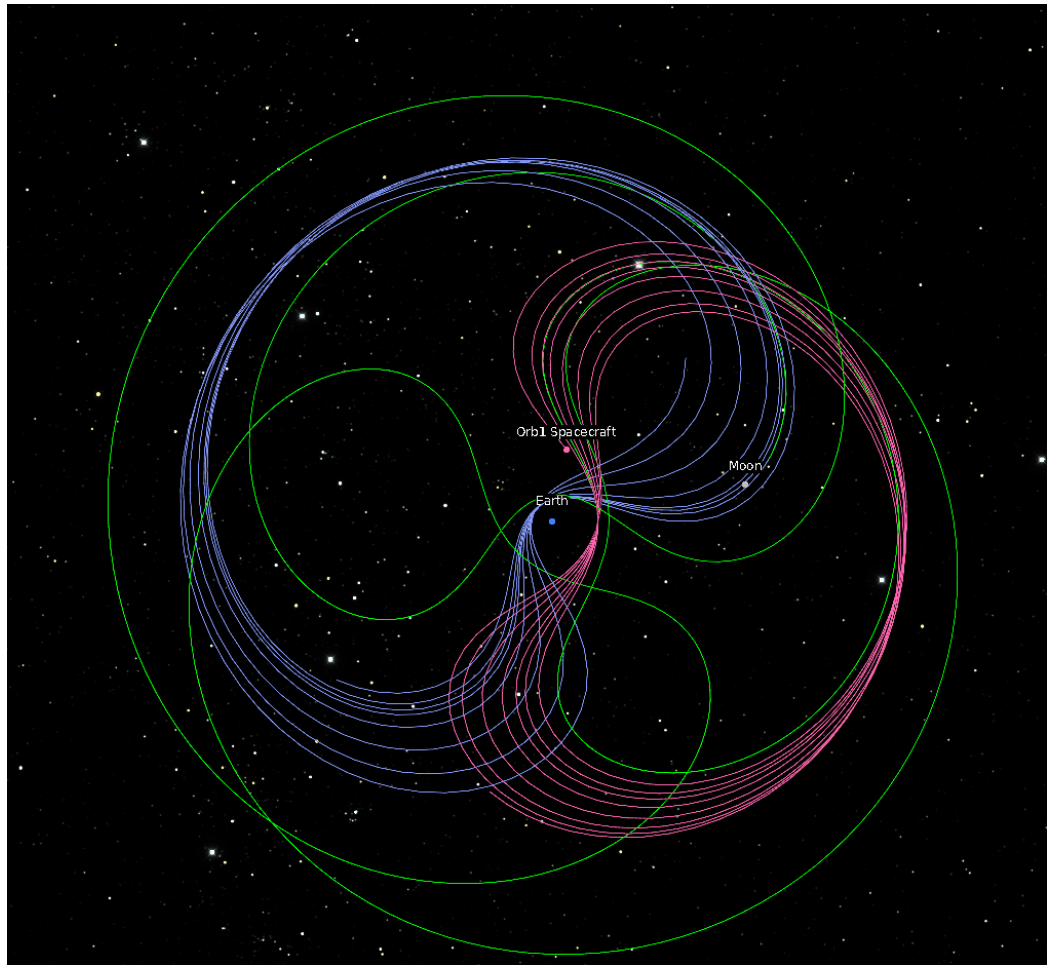
Transfer in a Full Ephemeris Model

Sample Applications – Orbit Chaining

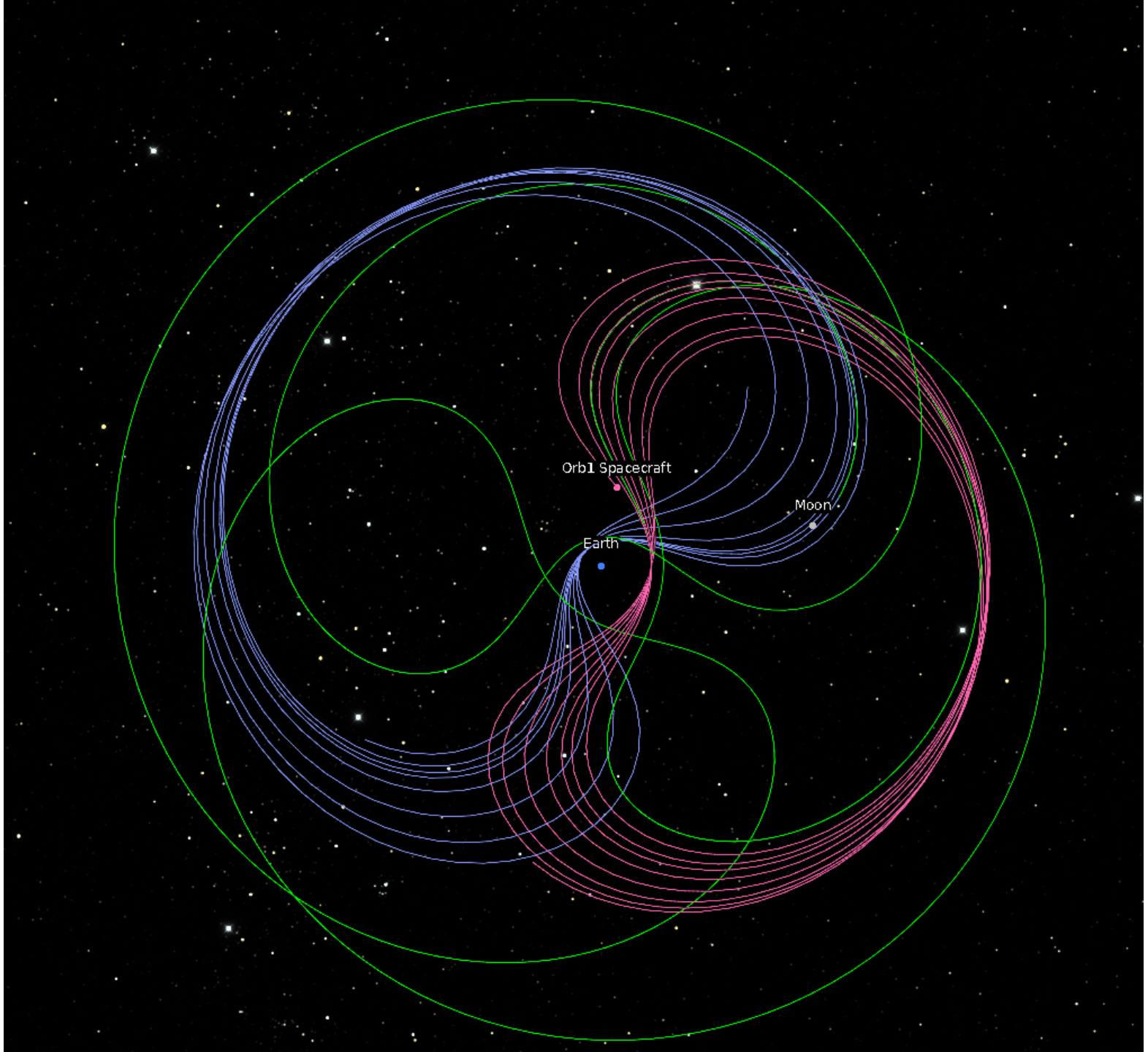
Transfer Scenario:

$DRO \rightarrow 3{:}2\ Resonant \rightarrow L_4\ SPO$

- $DRO\ 1\ Rev + 3{:}2\ Res\ 1\ Rev +$ $L_4\ SPO\ 1\ Rev$
- Transfer Time: $121.3\ days$
- Optimal: $m_f/m_0 = 497/500\ kg$



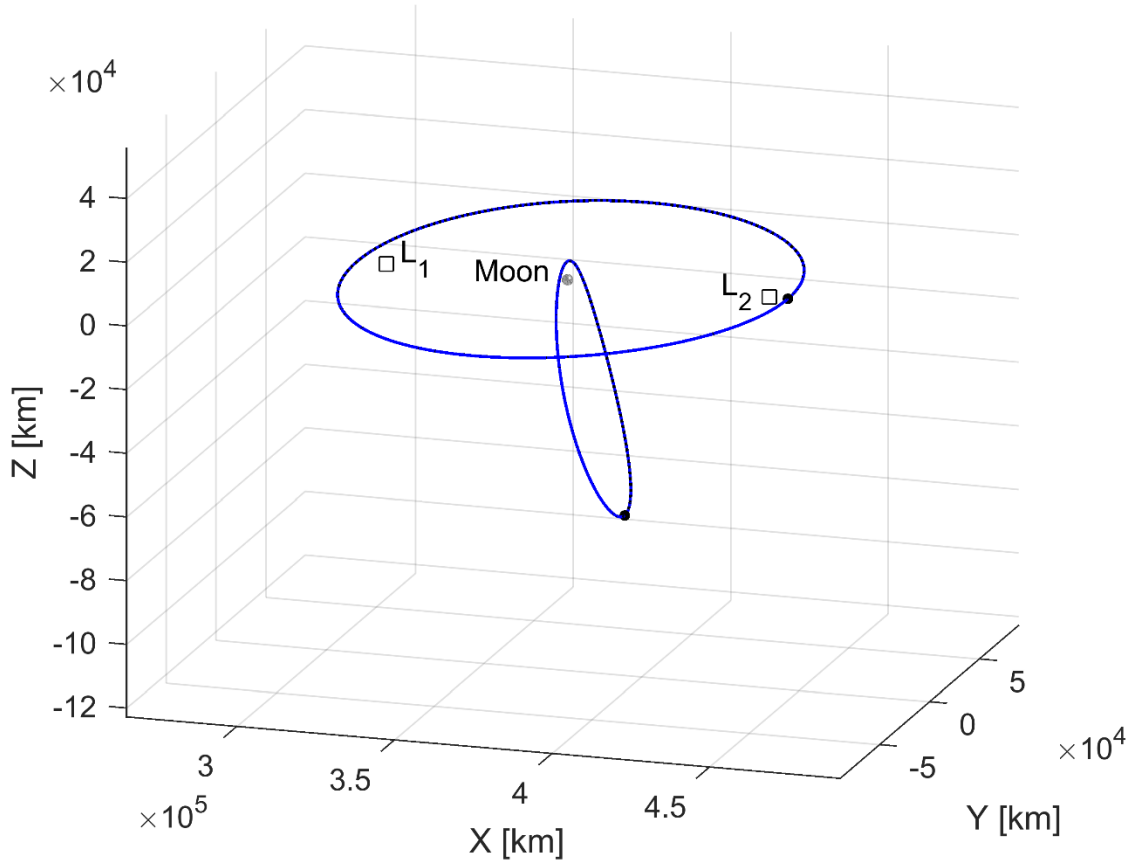
Transfer in a Full Ephemeris Model


Orbit Spacecraft
Moon
Earth

Sample Applications – Orbit Chaining

Transfer Scenario:

$$NRHO \rightarrow ??? \rightarrow DRO$$

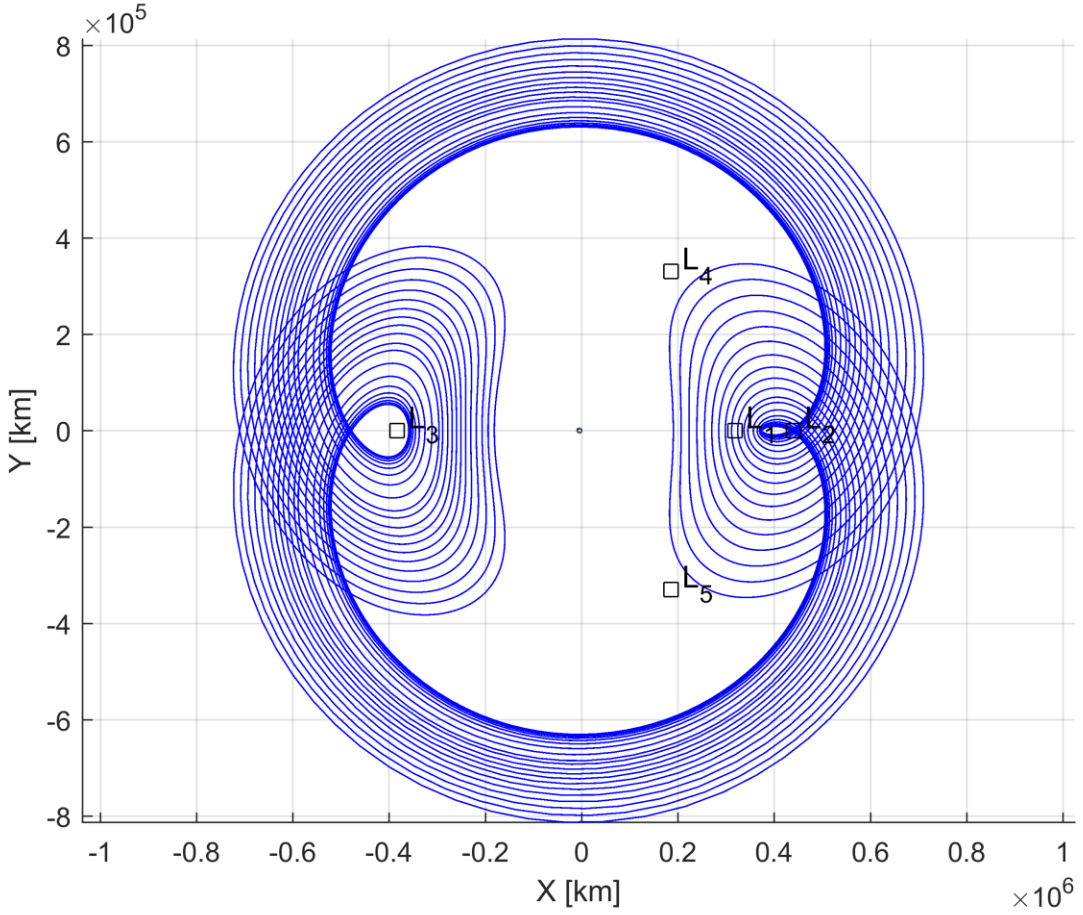


Departure and Arrival Orbits

Sample Applications – Orbit Chaining

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$



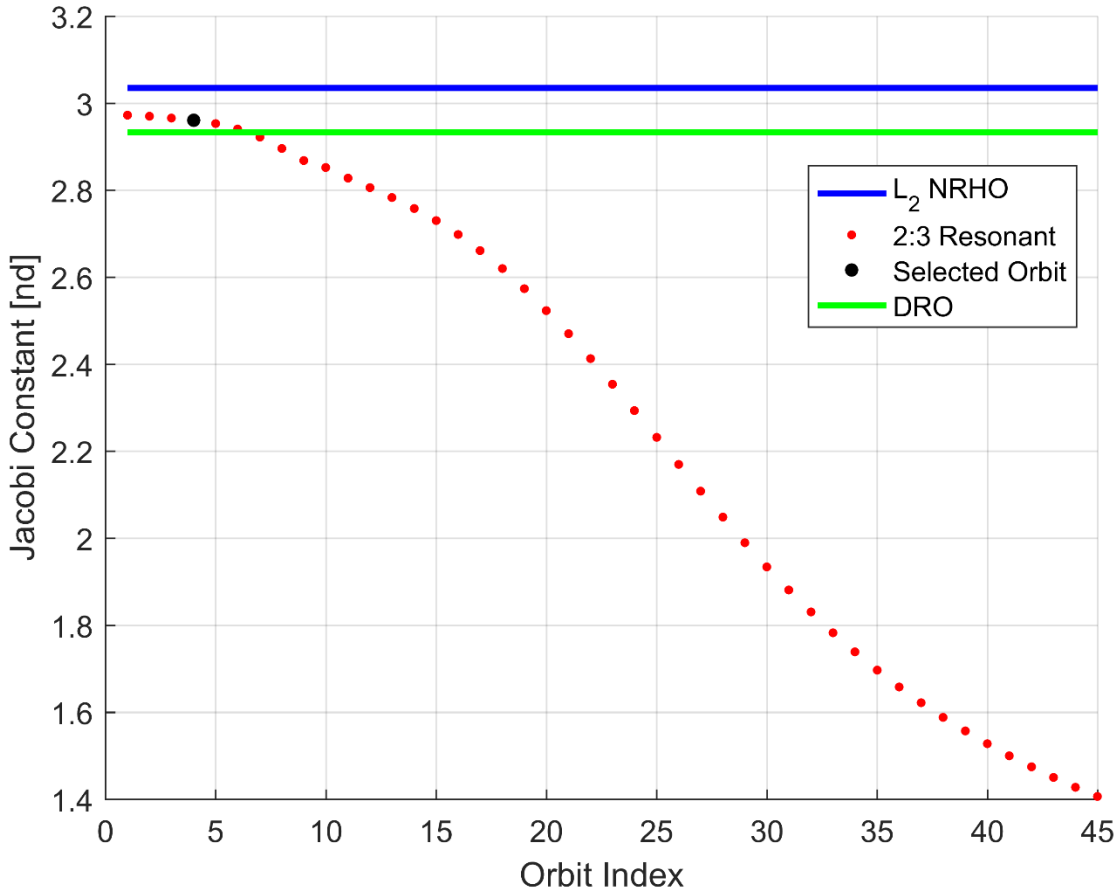
2:3 Resonant Orbit Family

Sample Applications – Orbit Chaining

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- Select resonant orbit with similar Jacobi constant value



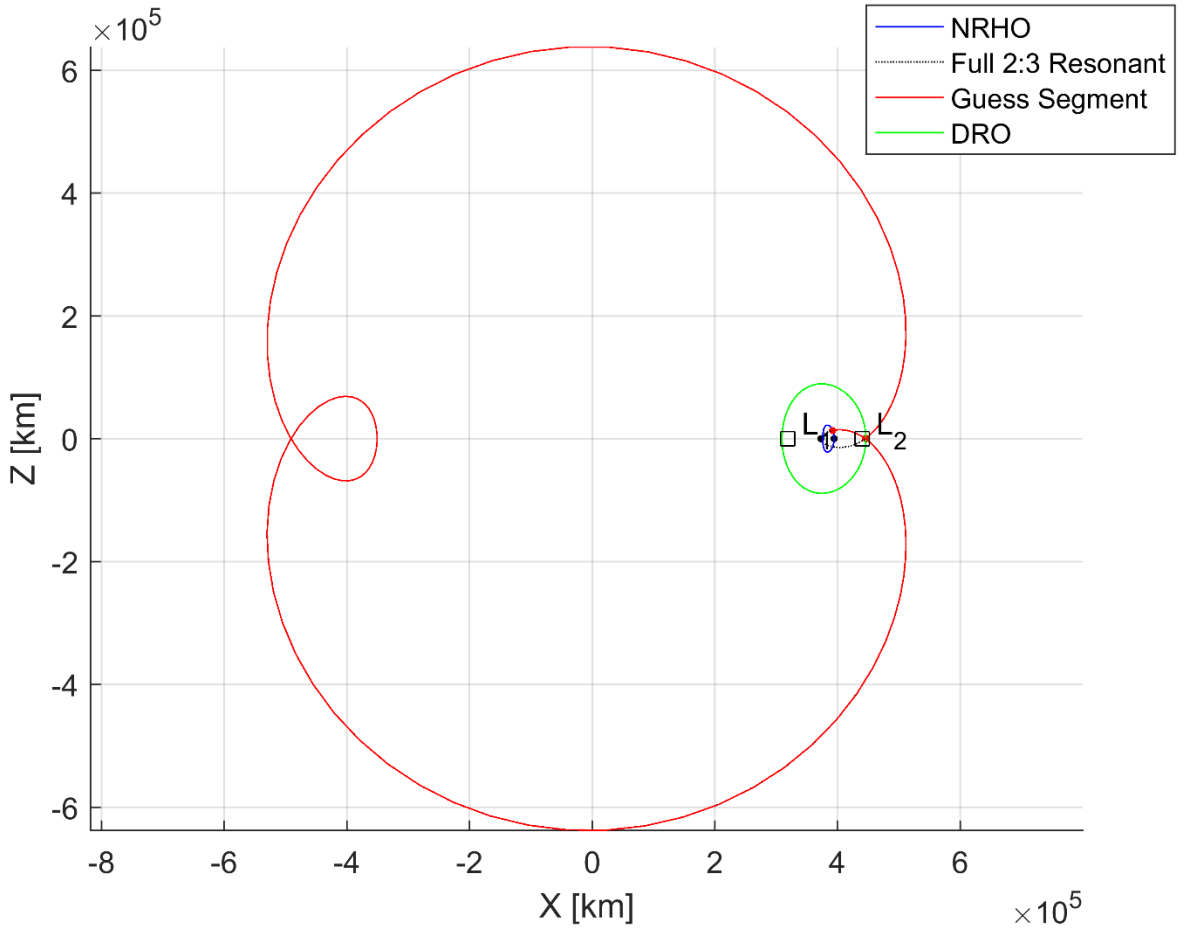
Jacobi Constant vs. Orbit Index

Sample Applications – Orbit Chaining

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- Select resonant orbit with similar Jacobi constant value
- Trim resonant orbit near departure and insertion points



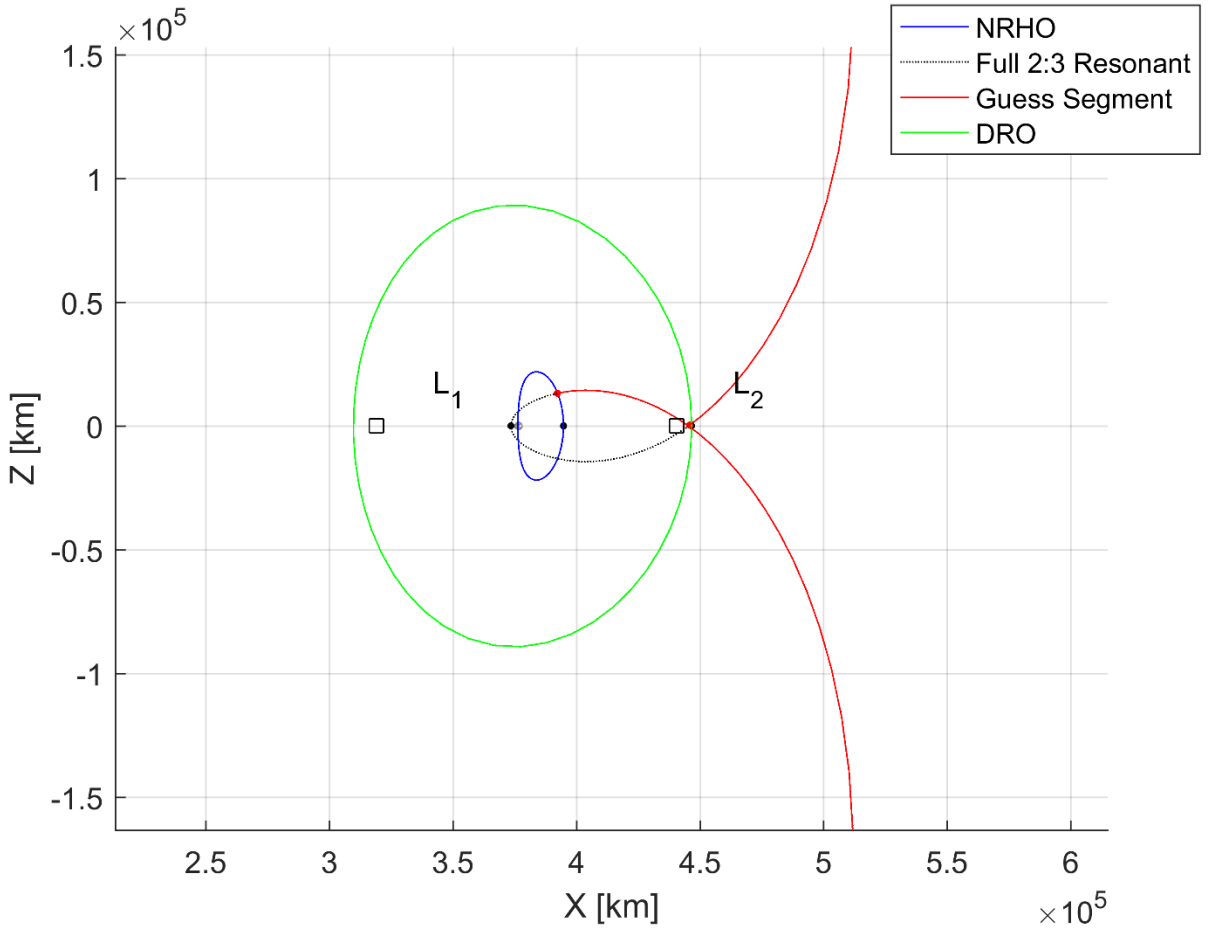
Initial Guess

Sample Applications – Orbit Chaining

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- Select resonant orbit with similar Jacobi constant value
- Trim resonant orbit near departure and insertion points



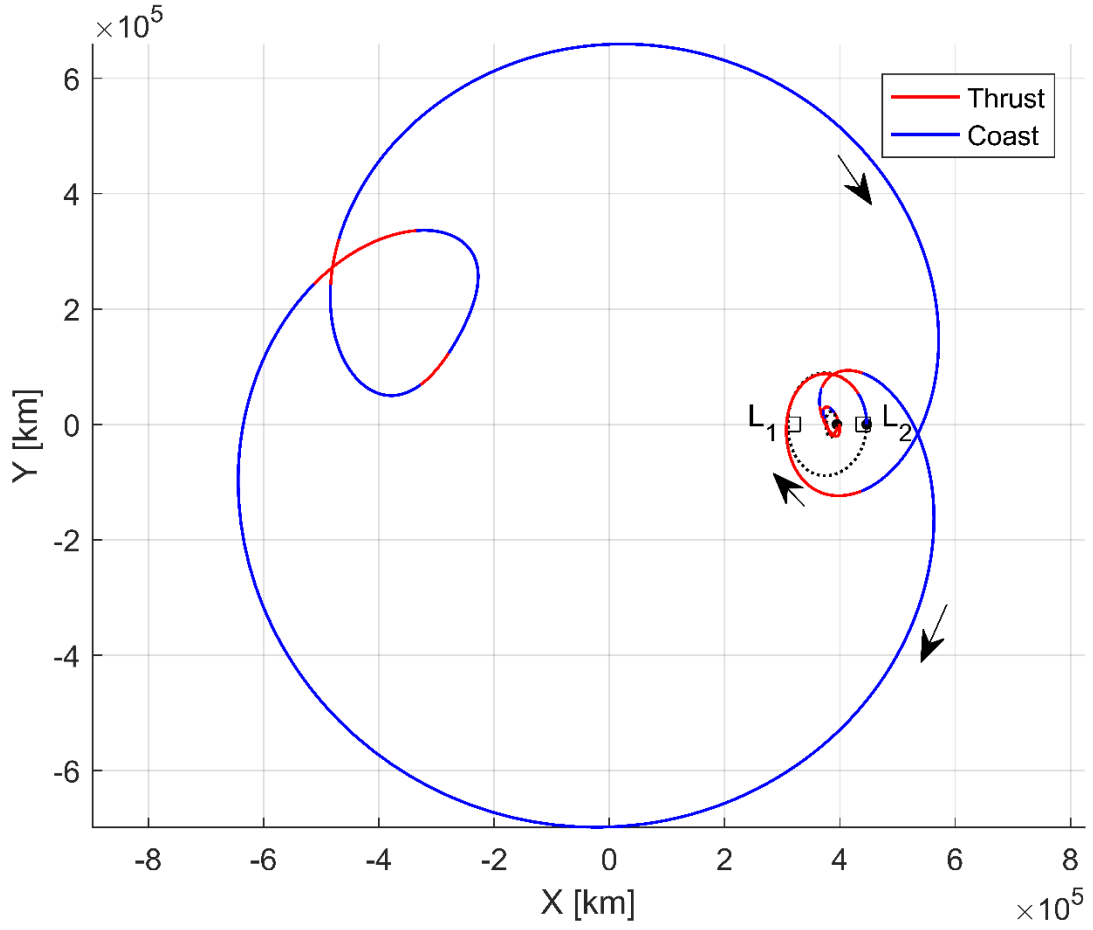
Initial Guess – Zoom View

Sample Applications – Orbit Chaining

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev + 2{:}3\ Res\ 1\ Rev +$ $DRO\ 1\ Rev$
- Transfer Time: $96.8\ days$
- Feasible: $m_f/m_0 = 485/500\ kg$
- Optimal: $m_f/m_0 = 487/500\ kg$



Optimal Transfer

Sample Applications – Orbit Chaining

Transfer Scenario:

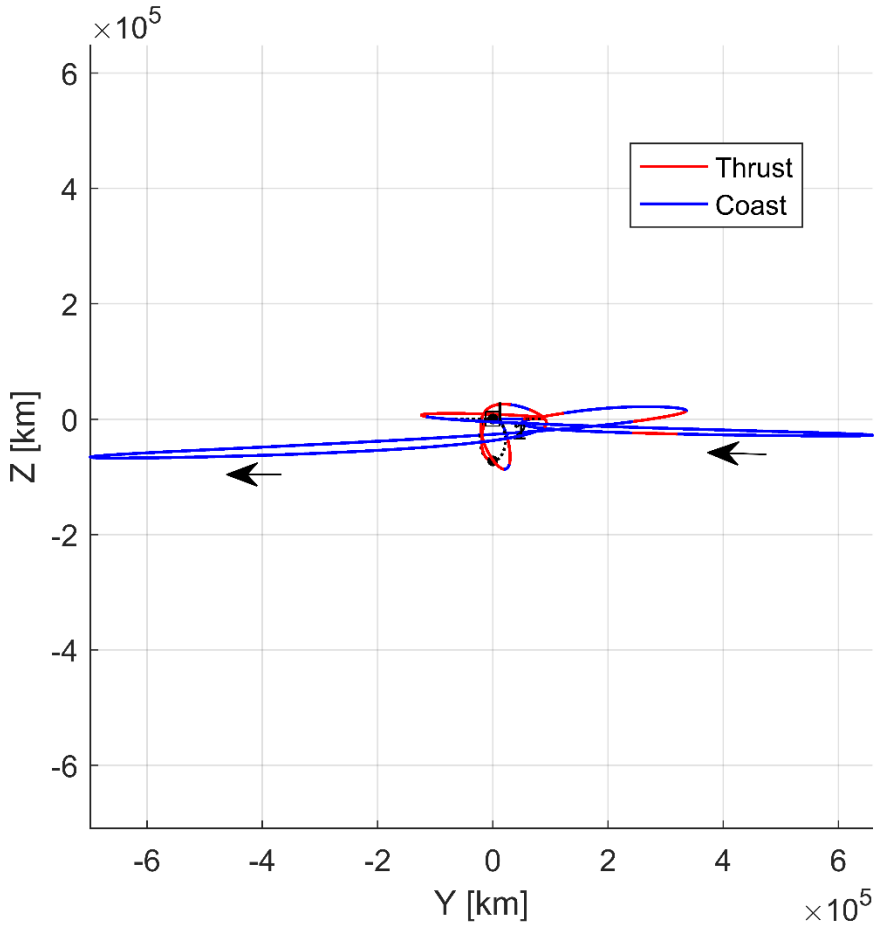
$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev +$

  $2{:}3\ Res\ 1\ Rev + DRO\ 1\ Rev$

- Transfer Time: $96.8\ days$

- Optimal: $m_f/m_0 = 487/500\ kg$



Optimal Transfer

Sample Applications – Orbit Chaining

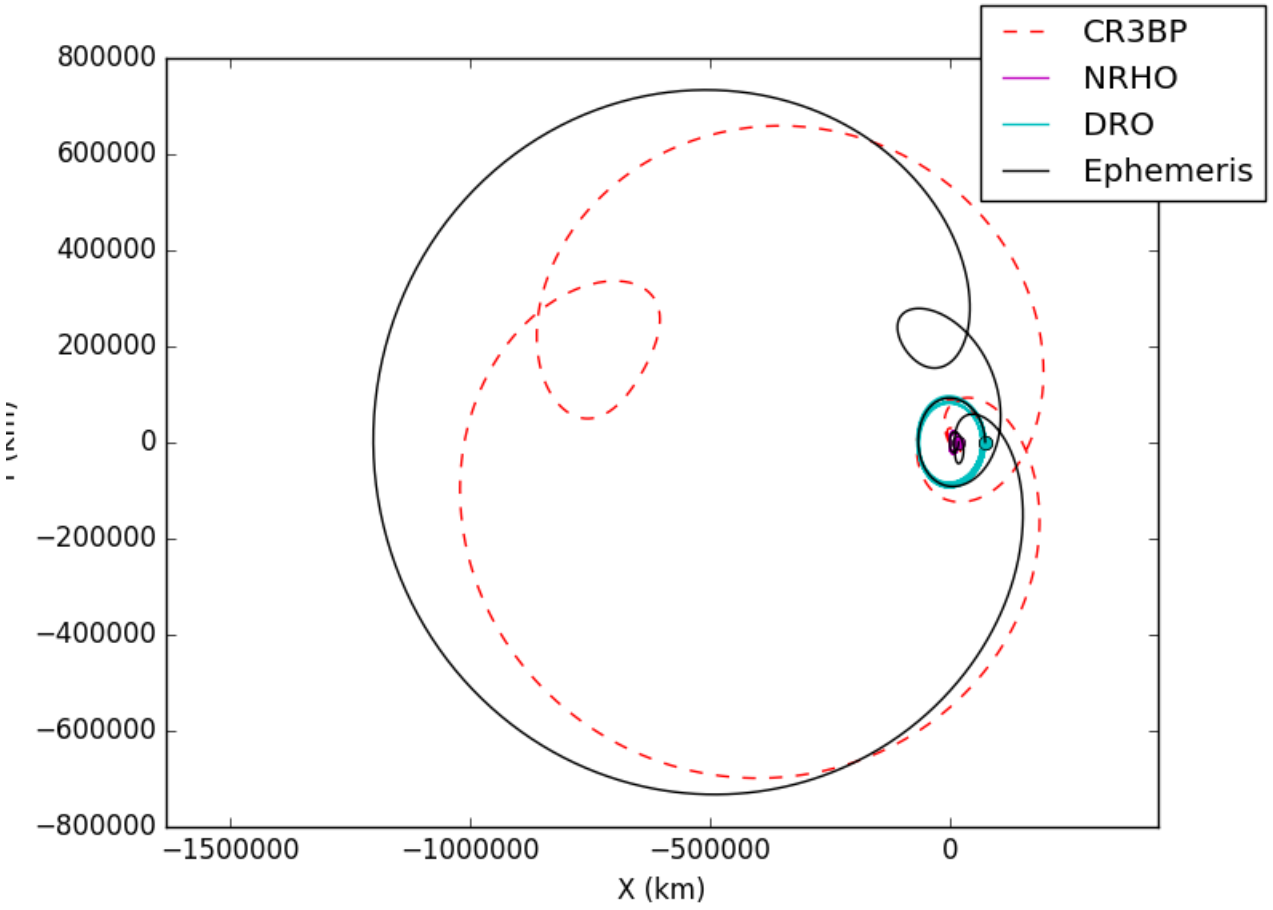
Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev +$

  $2{:}3\ Res\ 1\ Rev + DRO\ 1\ Rev$

- Transfer Time: 96.8 $days$



Transfer in a Full Ephemeris Model

Sample Applications – Orbit Chaining

Transfer Scenario:

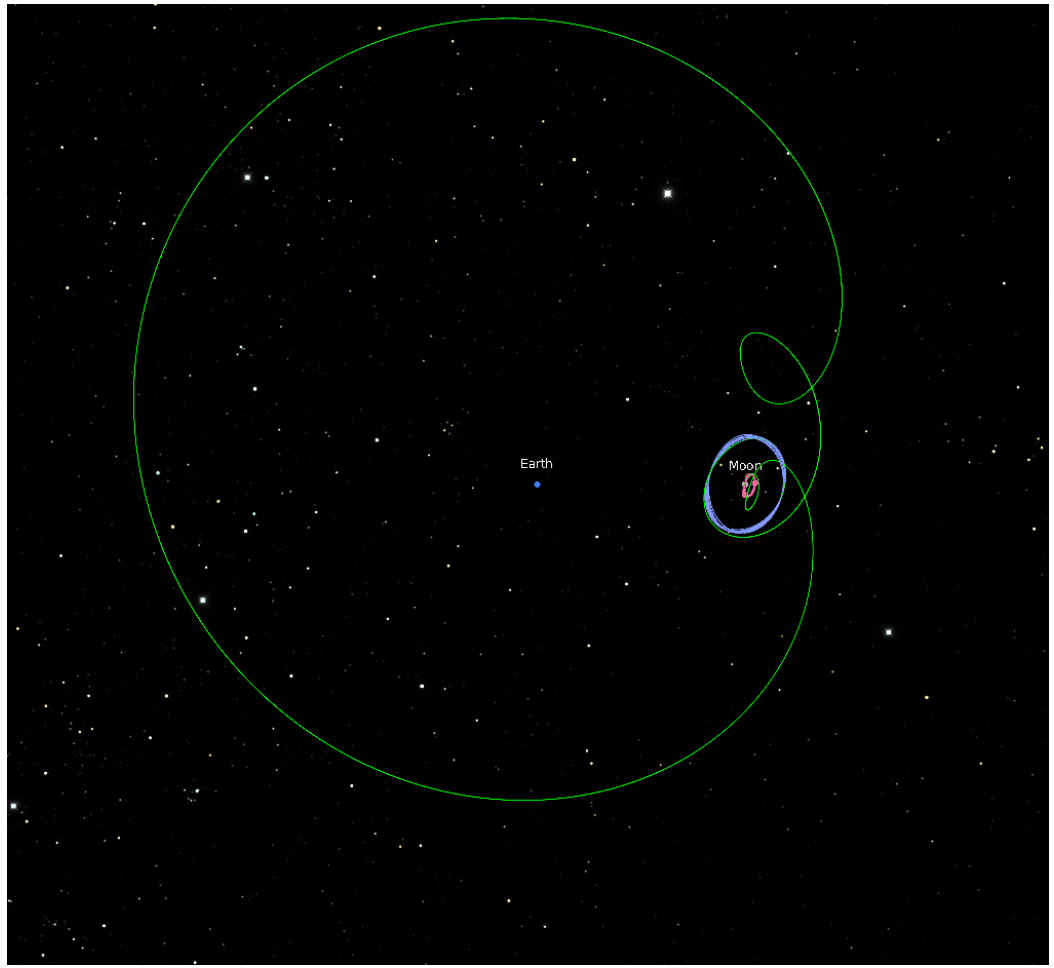
$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev +$

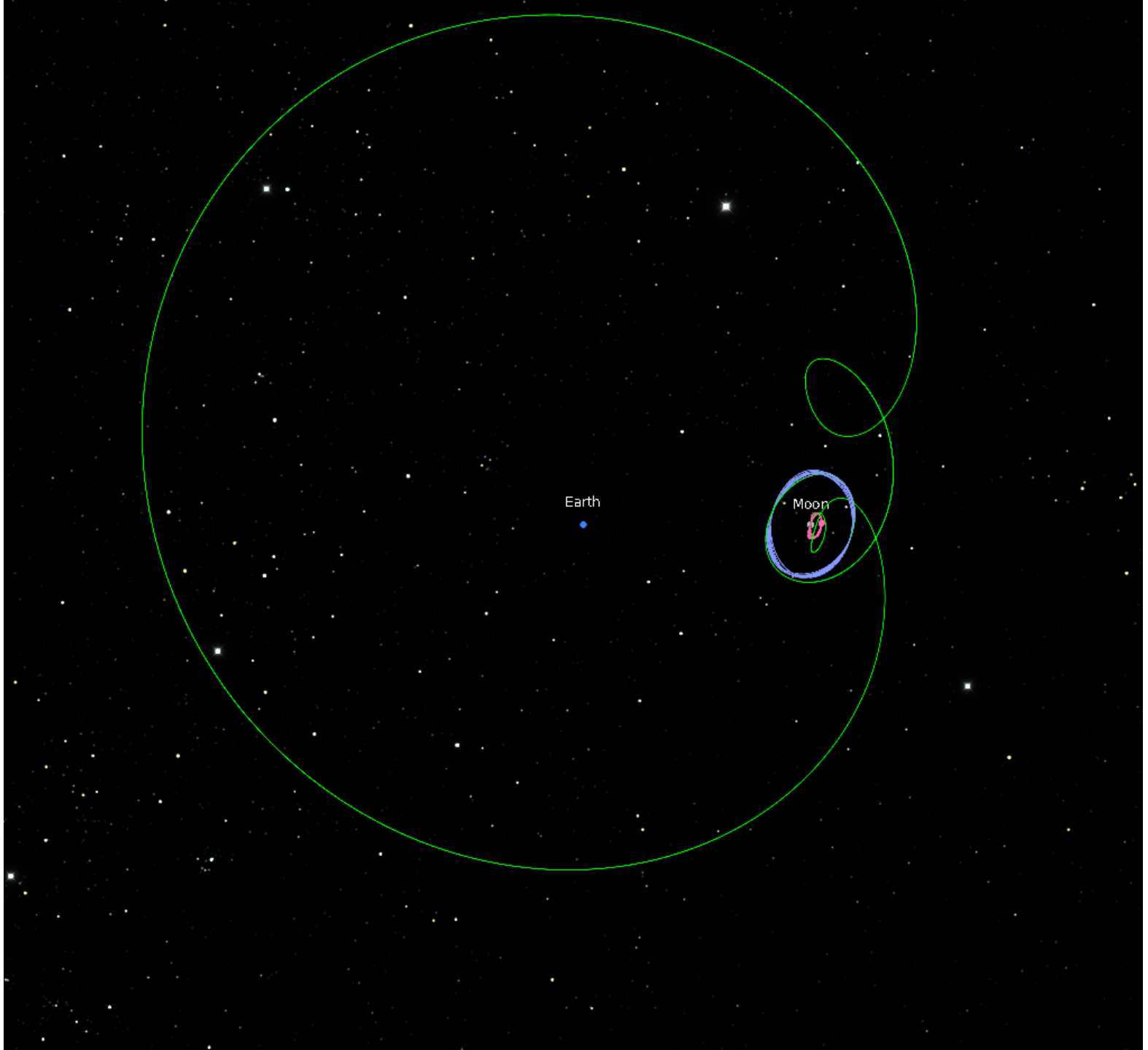
  $2{:}3\ Res\ 1\ Rev + DRO\ 1\ Rev$

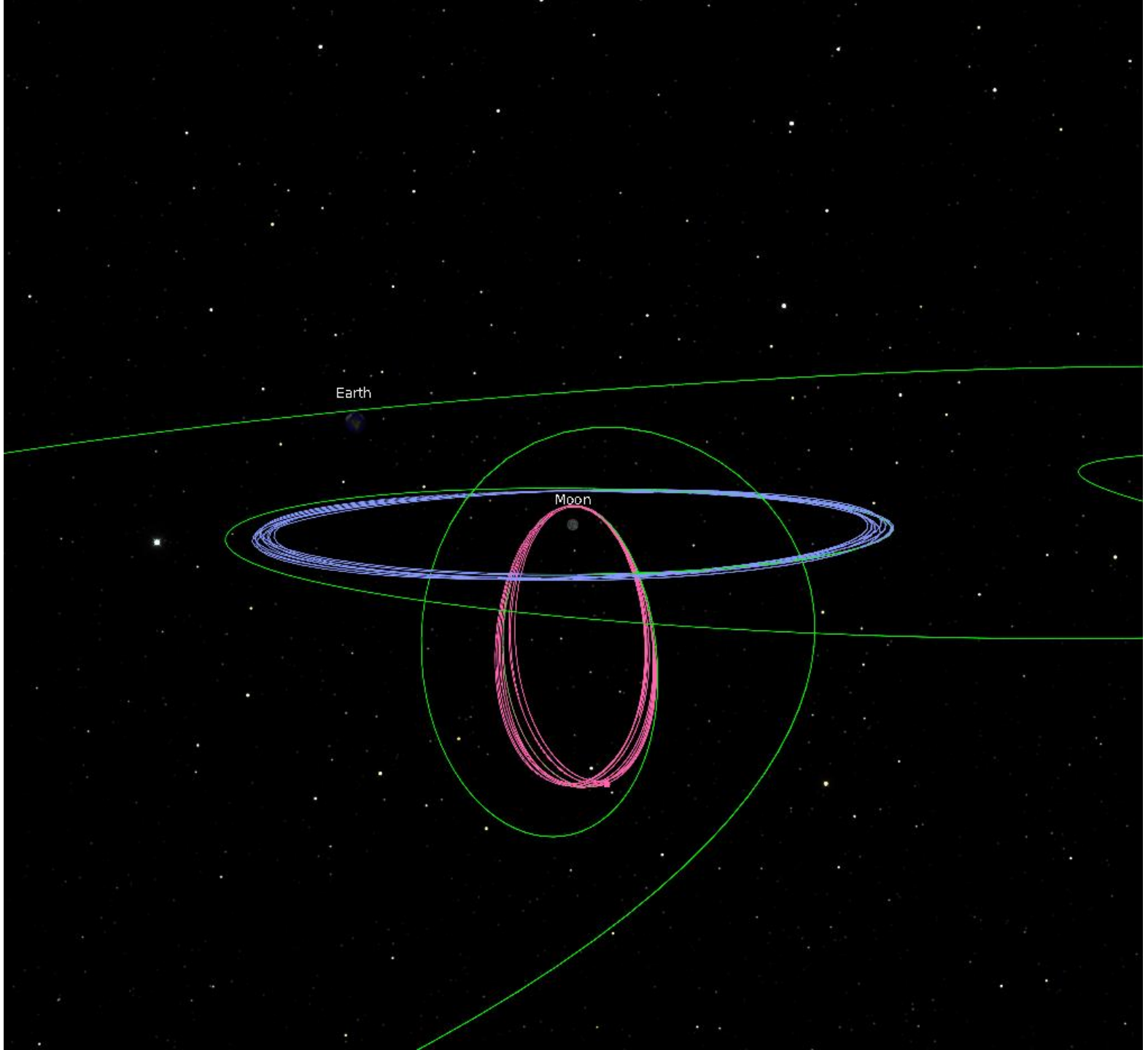
- Transfer Time: $96.8\ days$

- Optimal: $m_f/m_0 = 487/500\ kg$



Transfer in a Full Ephemeris Model


Earth
Moon


Earth
Moon

Sample Applications – Orbit Chaining

Transfer Type	CR3BP Model		Ephemeris Model
	$TOF\ (days)$	$m_f\ (kg)$	$m_f\ (kg)$
L_2 Halo → L_1 Halo	47.5	491.98	491.73
DRO → L_4 SPO	134.8	482.03	*463.83
DRO → 3:2 Resonant → L_4 SPO	121.3	497.04	*472.75
NRHO → DRO	46.7	486.14	488.33
NRHO → 2:3 Resonant → DRO	96.8	487.15	495.00

*Ephemeris transfer not optimized

Sample Applications – Orbit Chaining

Transfer Type	CR3BP Model		Ephemeris Model
	$TOF\ (days)$	$m_f\ (kg)$	$m_f\ (kg)$
L_2 Halo → L_1 Halo	47.5	491.98	491.73
DRO → L_4 SPO	134.8	482.03	*463.83
DRO → 3:2 Resonant → L_4 SPO	121.3	497.04	*472.75
NRHO → DRO	46.7	486.14	488.33
NRHO → 2:3 Resonant → DRO	96.8	487.15	495.00

*Ephemeris transfer not optimized

Outline

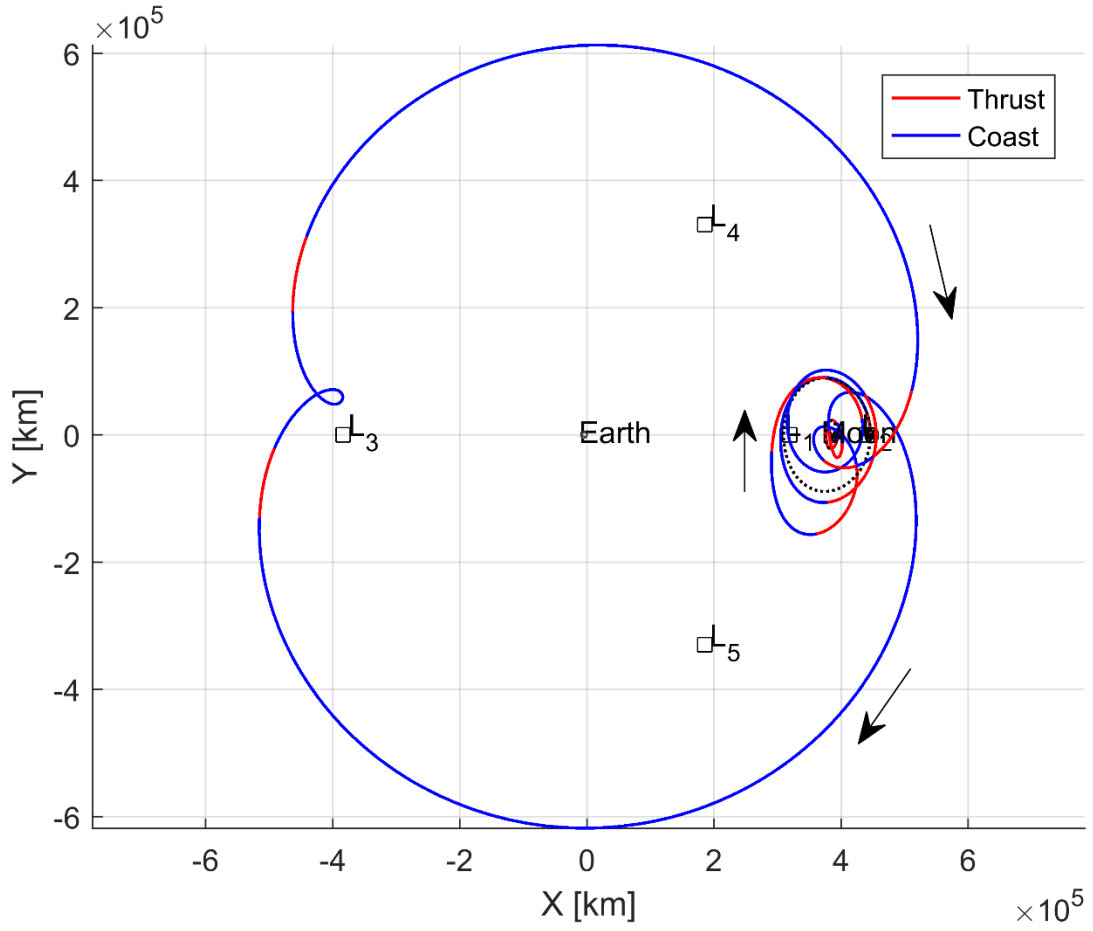
I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Sample Applications – Deep Space Gateway

Transfer Scenario:

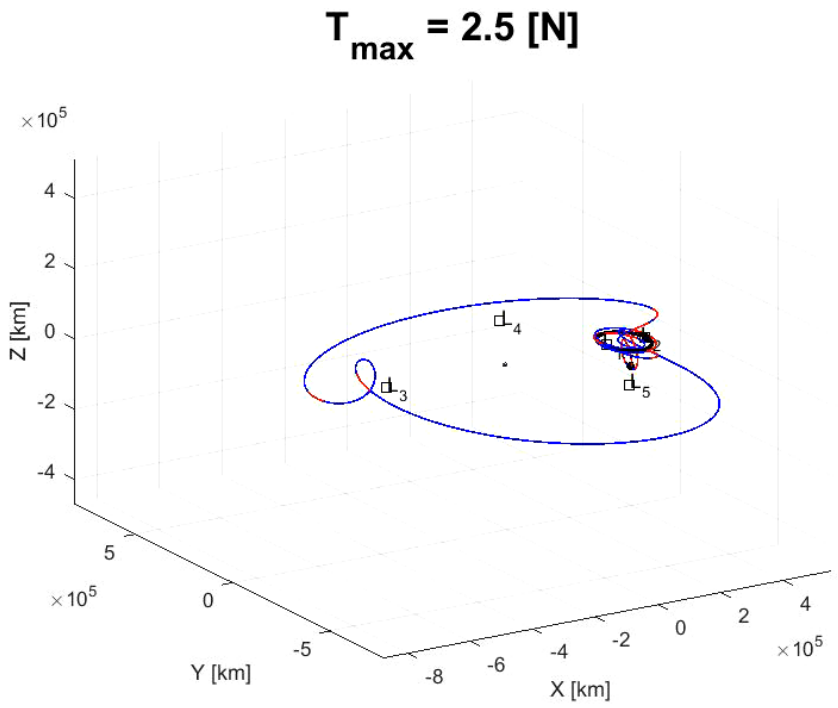
$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

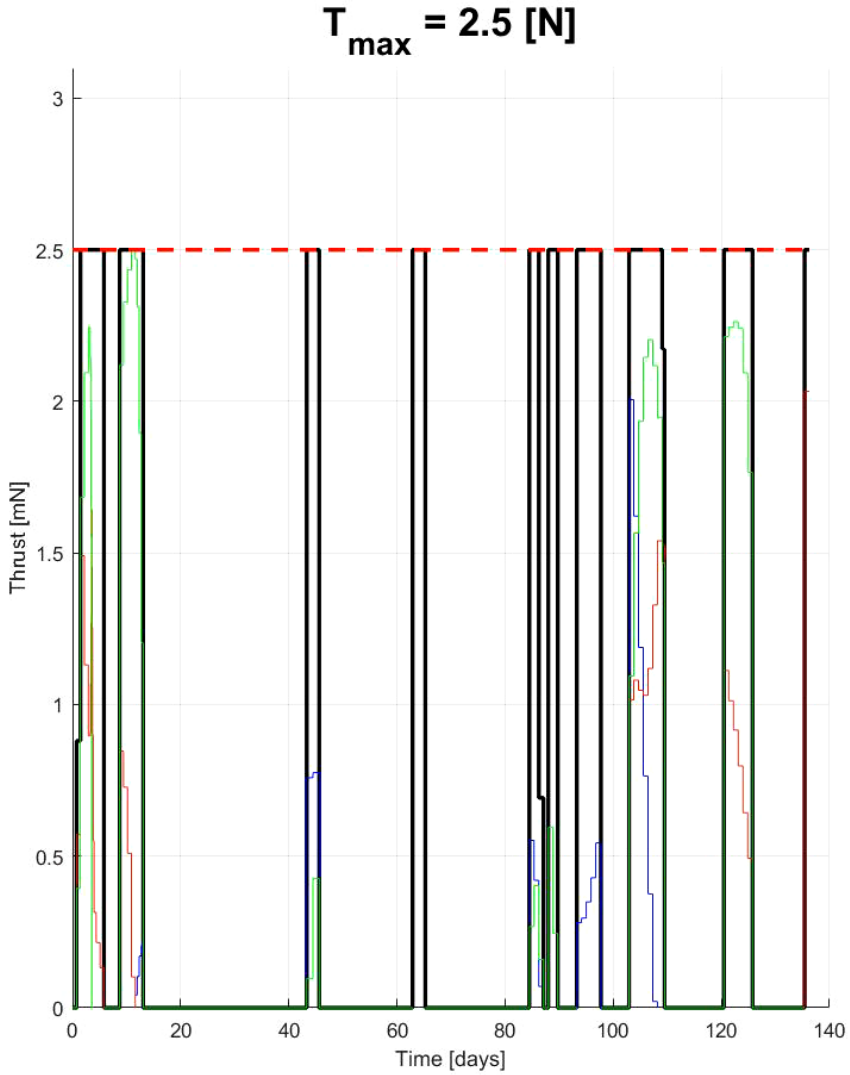
- Now using spacecraft with space station parameters:
  - $m_0 = 30{,}000\ kg$
  - $I_{sp} = 3000\ sec$
- Expected Thrust/Weight ratio:
  - $T/W = 1 \times 10^{-6}$ to 6×10^{-6}
  - $T_{max} = 0.29 - 1.77\ N$



Optimal Transfer with $T_{max} = 2.5\ N$

Sample Applications – Deep Space Gateway



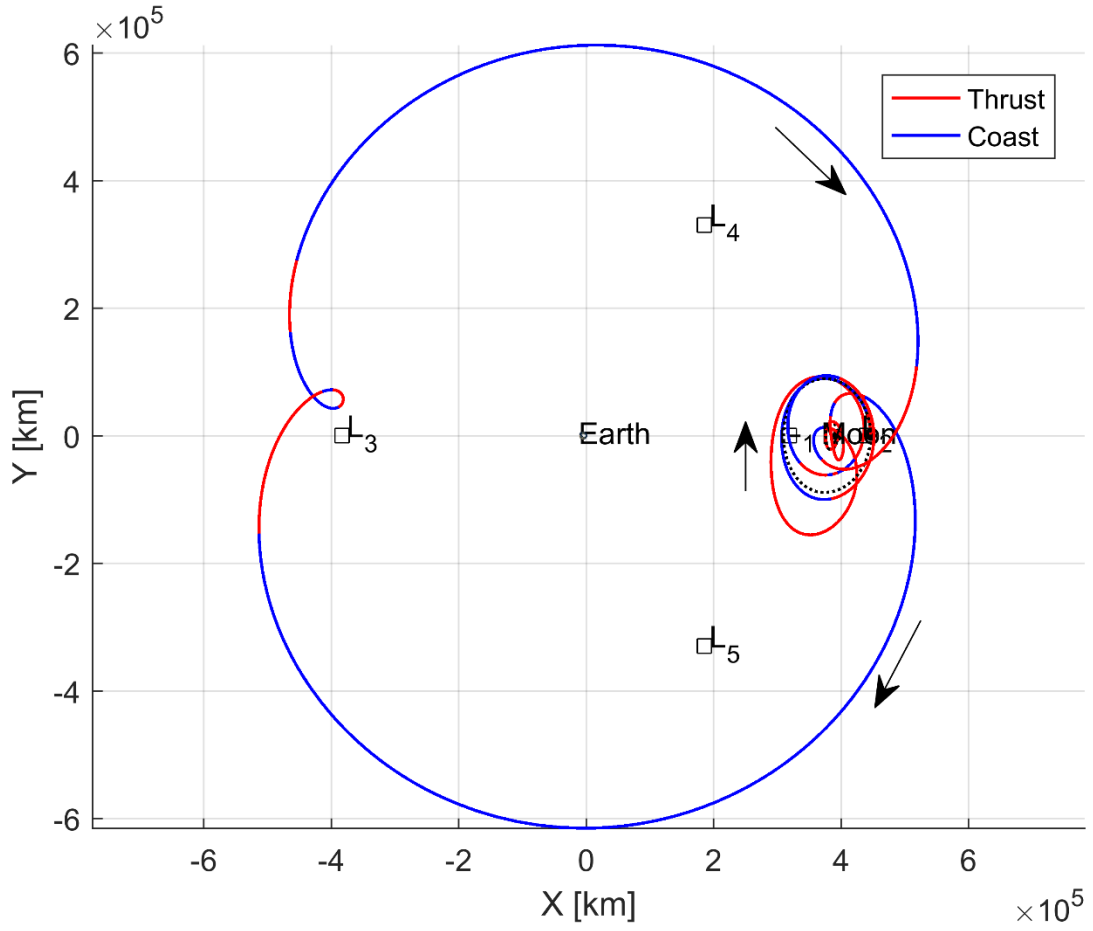


Sample Applications – Deep Space Gateway

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev + 2{:}3\ Res\ 1\ Rev +$ $DRO\ 1\ Rev$
- Transfer Time: $136.24\ days$
- Feasible: $m_f/m_0 = 29.66/30\ mT$
- Optimal: $m_f/m_0 = 29.69/30\ mT$



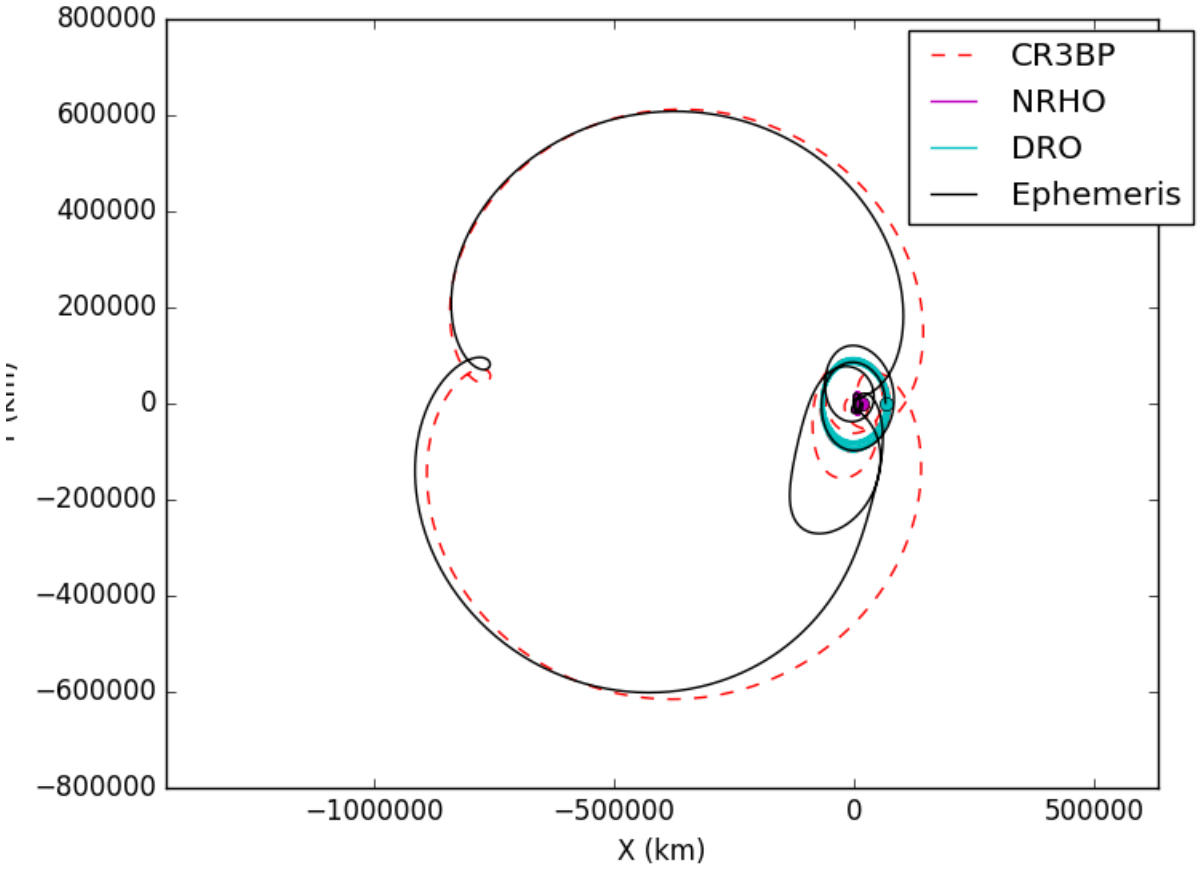
Optimal Transfer with $T_{max} = 1.7\ N$

Sample Applications – Deep Space Gateway

Transfer Scenario:

$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev + 2{:}3\ Res\ 1\ Rev + DRO\ 1\ Rev$
- Transfer Time: $136.24\ days$
- Optimal: $m_f/m_0 = 29.69/30\ mT$



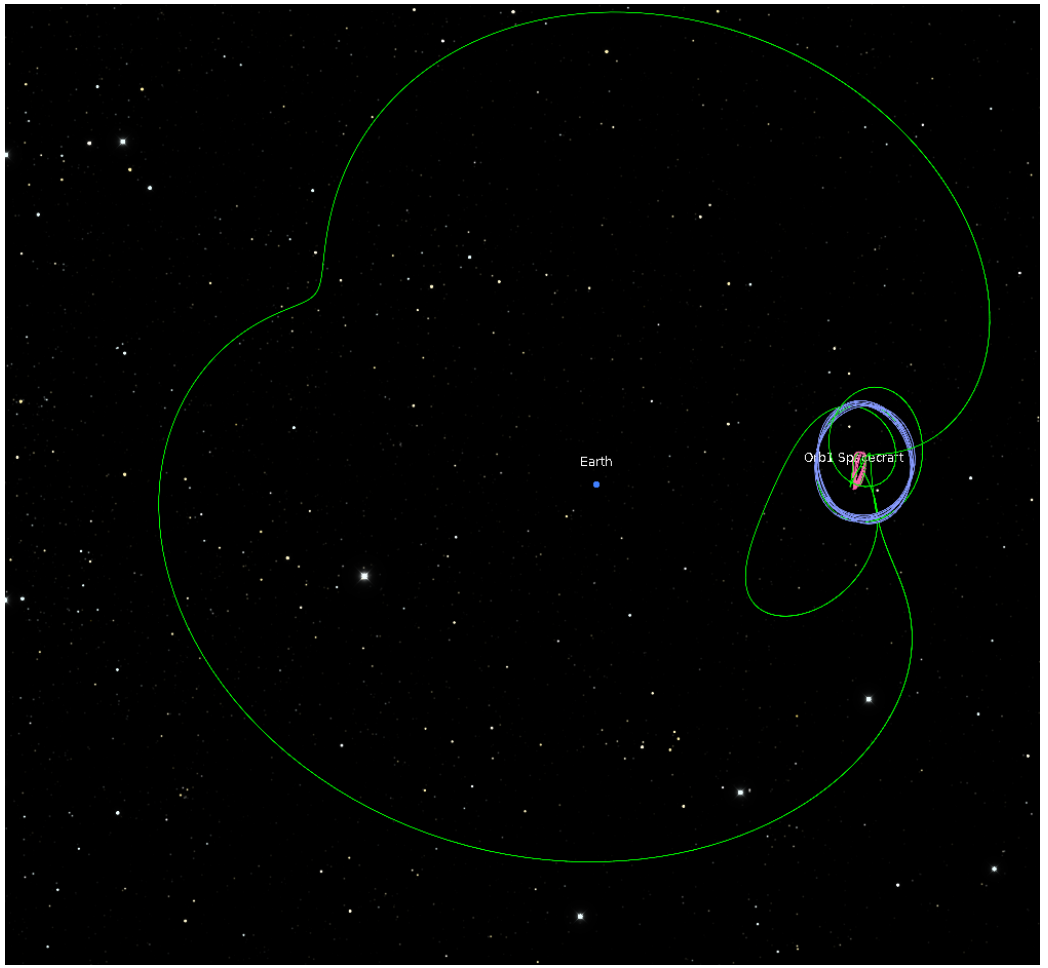
Optimal Transfer with $T_{max} = 1.7\ N$

Sample Applications – Deep Space Gateway

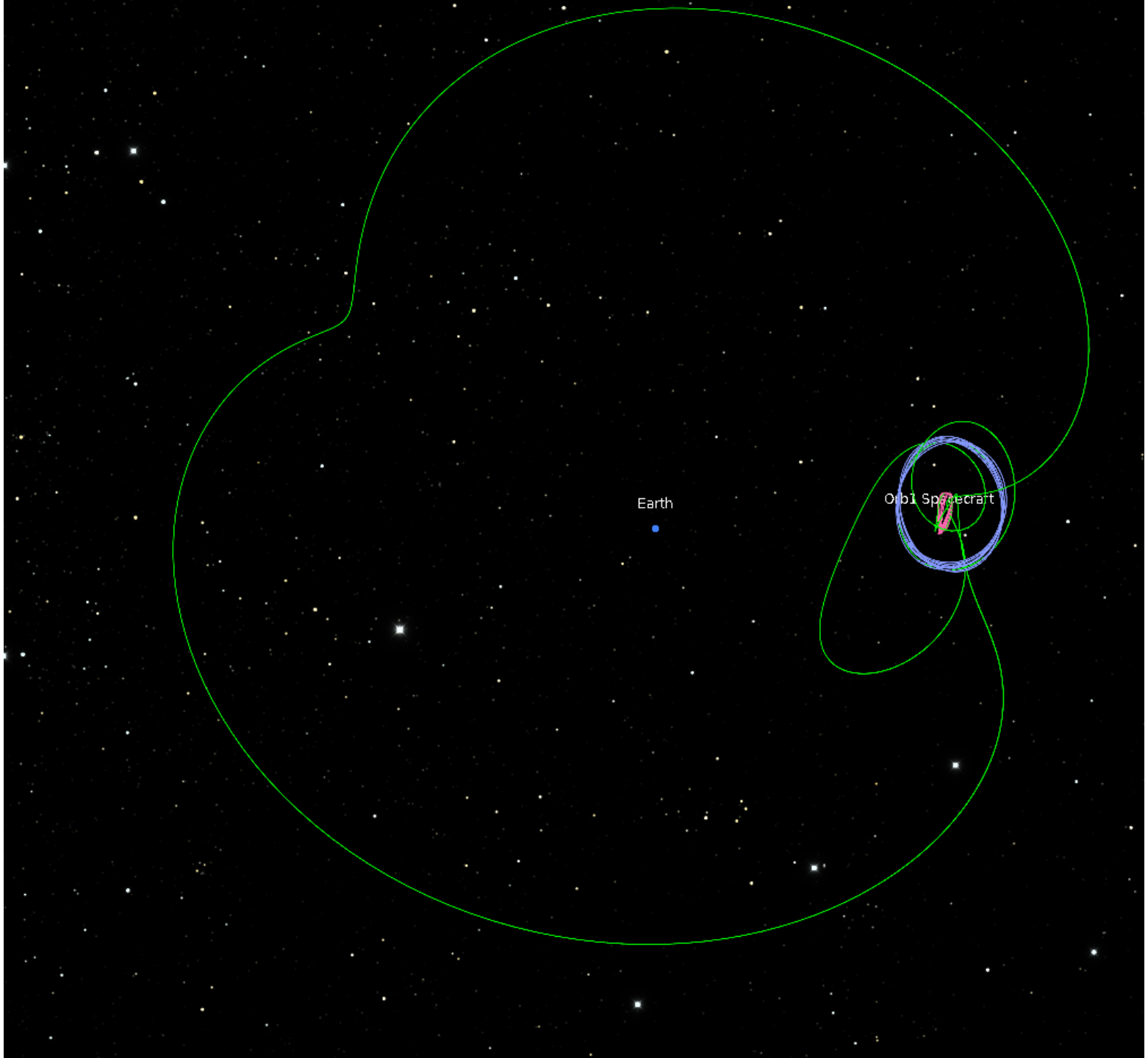
Transfer Scenario:

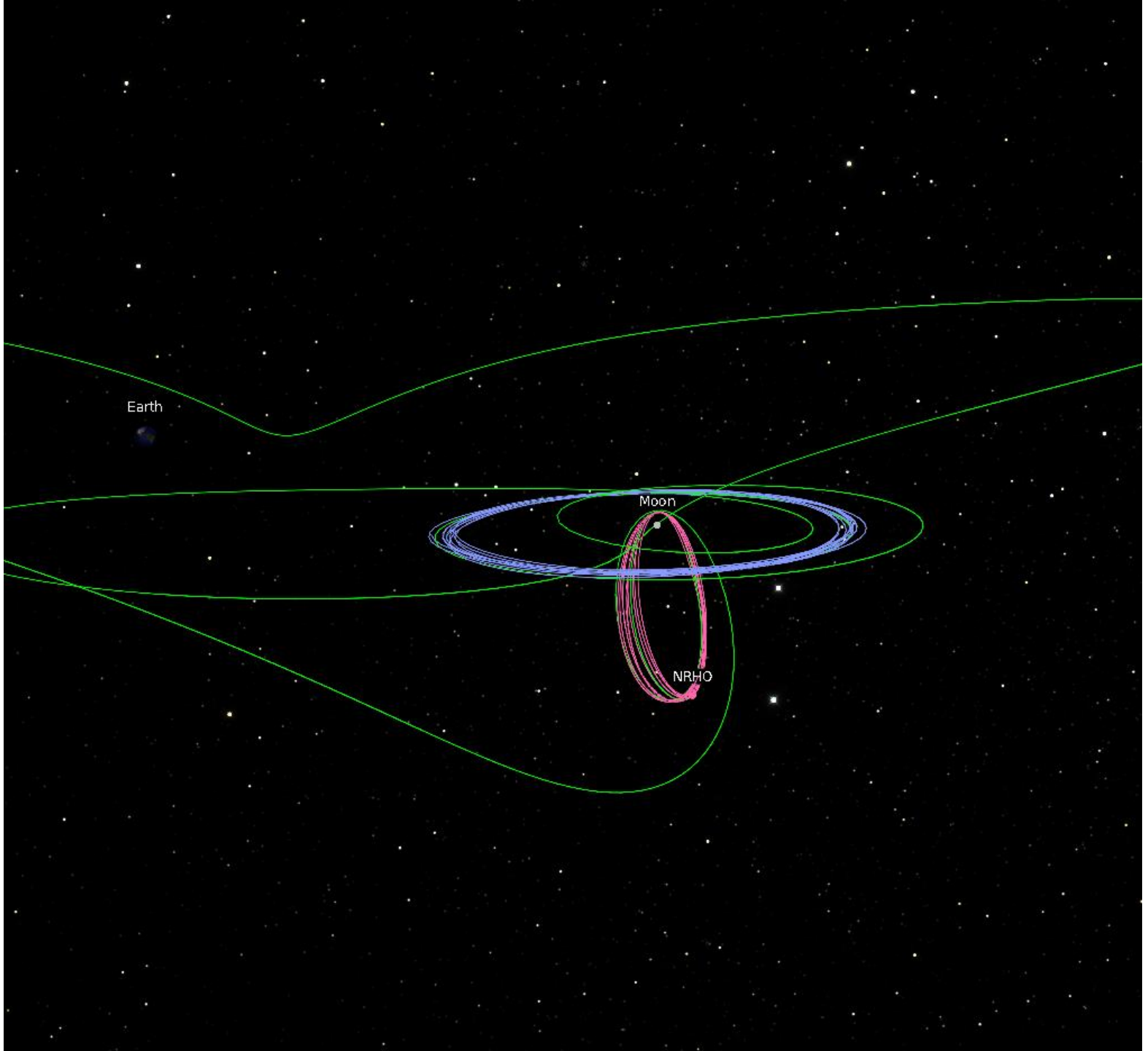
$NRHO \rightarrow 2{:}3\ Resonant \rightarrow DRO$

- $NRHO\ 1\ Rev + 2{:}3\ Res\ 1\ Rev +$ $DRO\ 1\ Rev$
- Transfer Time: $136.24\ days$
- Optimal: $m_f/m_0 = 29.69/30\ mT$



Optimal Transfer with $T_{max} = 1.7\ N$

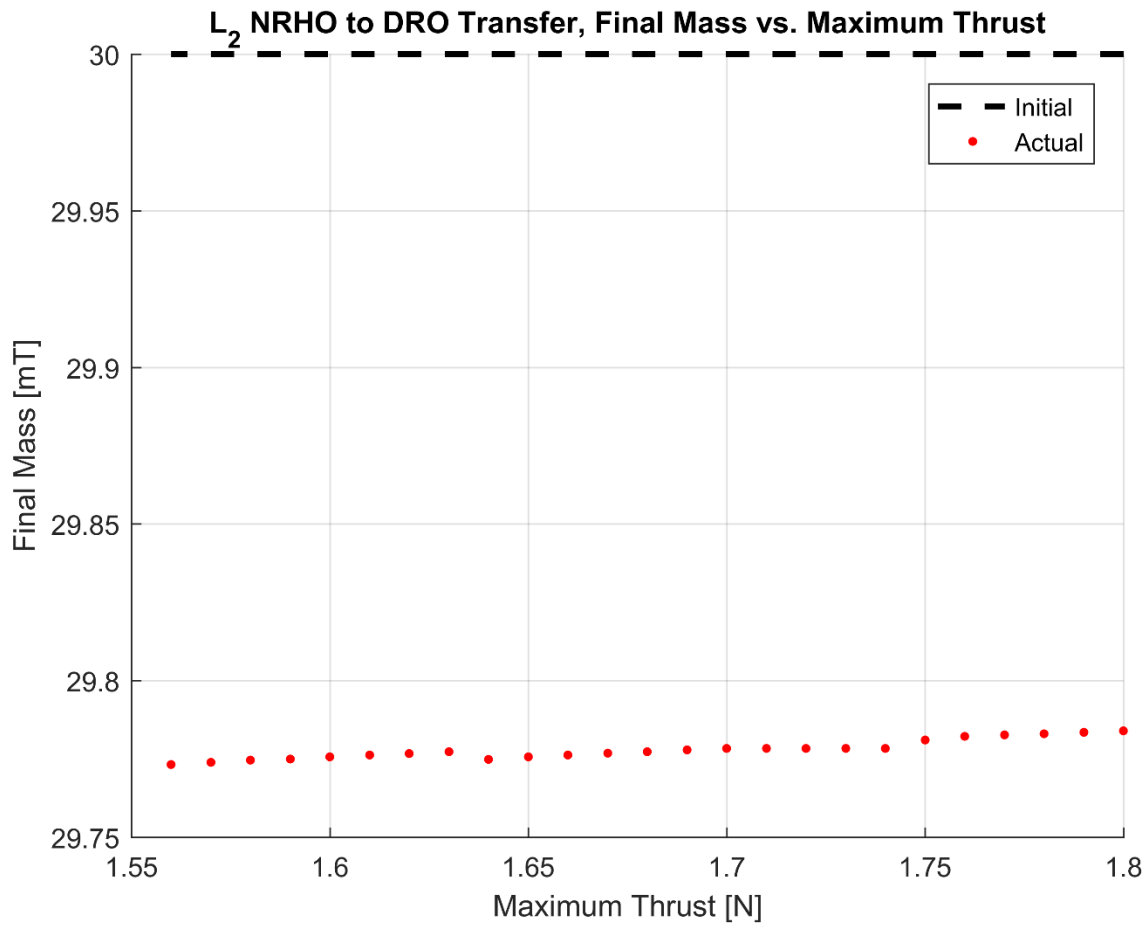

Earth
Orbi Spacecraft


Earth
Moon
NRHO

Sample Applications – Deep Space Gateway

Transfer Scenario:

- Can also continue optimal solutions with respect to T_{max}, TOF, or Jacobi of departure and arrival orbits.

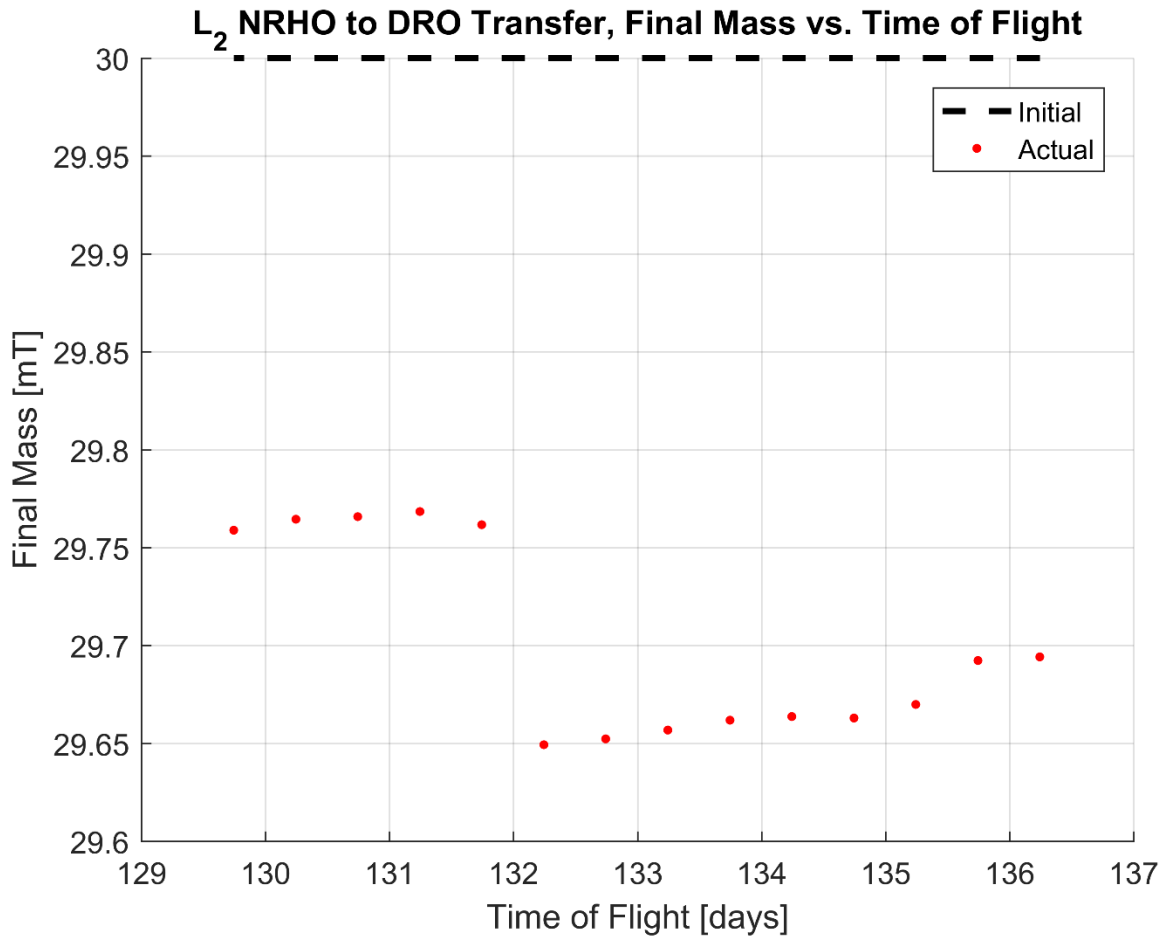


Final Mass vs. Maximum Thrust

Sample Applications – Deep Space Gateway

Transfer Scenario:

- Can also continue optimal solutions with respect to T_{max}, TOF, or Jacobi of departure and arrival orbits.



Final Mass vs. Time of Flight

Outline

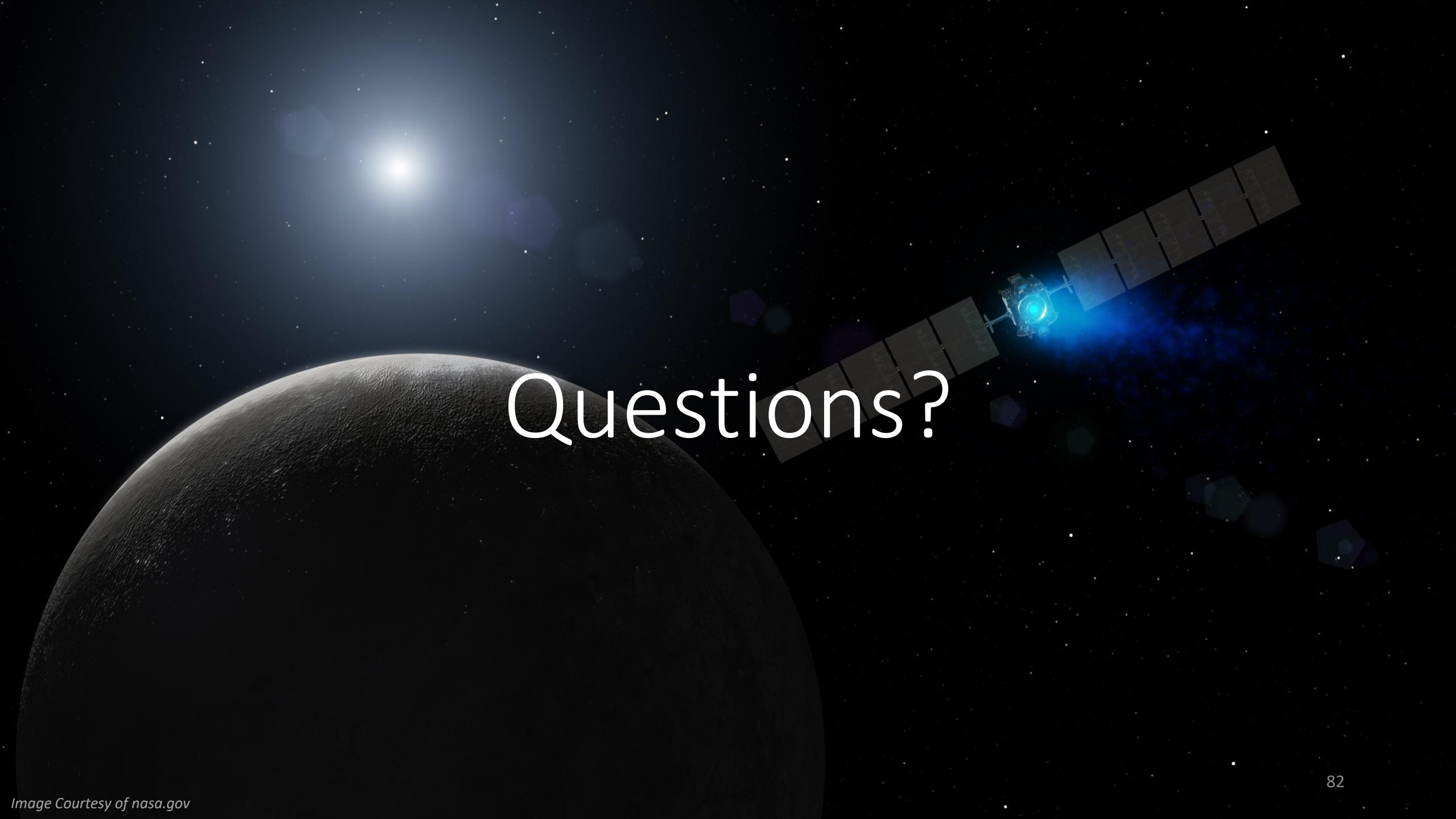
I. Motivation
II. Background
III. Sample Applications
    I. Trajectory Stacking Technique
    II. Orbit Chaining Technique
    III. Deep Space Gateway Transfer
IV. Concluding Remarks

Concluding Remarks

- Demonstrated techniques for conducting low-thrust trajectory design that leverage collocation to compute optimal trajectories.
- Showed how natural dynamical structures in the CR3BP may be “chained” together to construct an initial guess.
- Applied these strategies in a continuation process to compute a transfer for a space station sized vehicle.
- Future Work:
  - Further develop orbit chaining technique
  - Explore application of these techniques to other scenarios where little information is available to construct an initial guess
  - Improve efficiency of direct transcription algorithms

Thank You!

- Dr. Daniel Grebow and Dr. Thomas Pavlak
- Professor Kathleen Howell
- Dr. Juan Senent for SNOPT assistance
- Dr. Jeff Stuart for SparQ assistance
- Emily Zimovan for intermediate trajectory arc discussions
- Section 392 and JPL
- This work was supported by a NASA Space Technology Research Fellowship

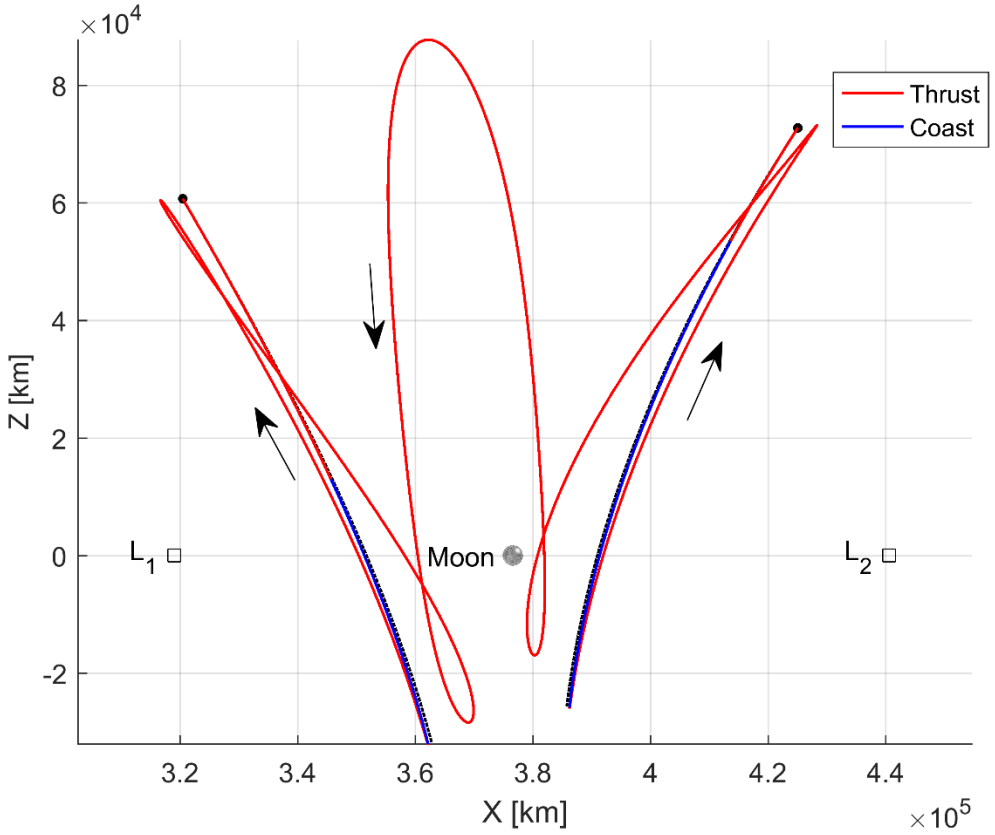


Questions?

Image Courtesy of nasa.gov

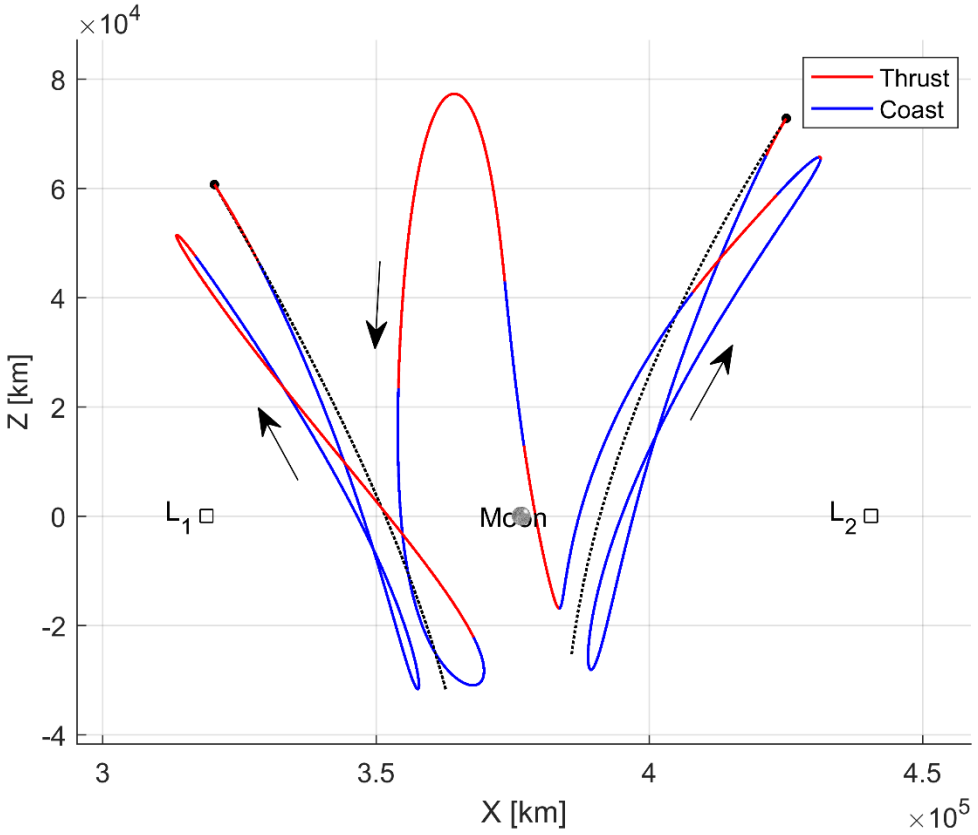
Backup Slides

Background



Feasible Transfer

$m_f/m_0 = 490/500$



Optimal Transfer

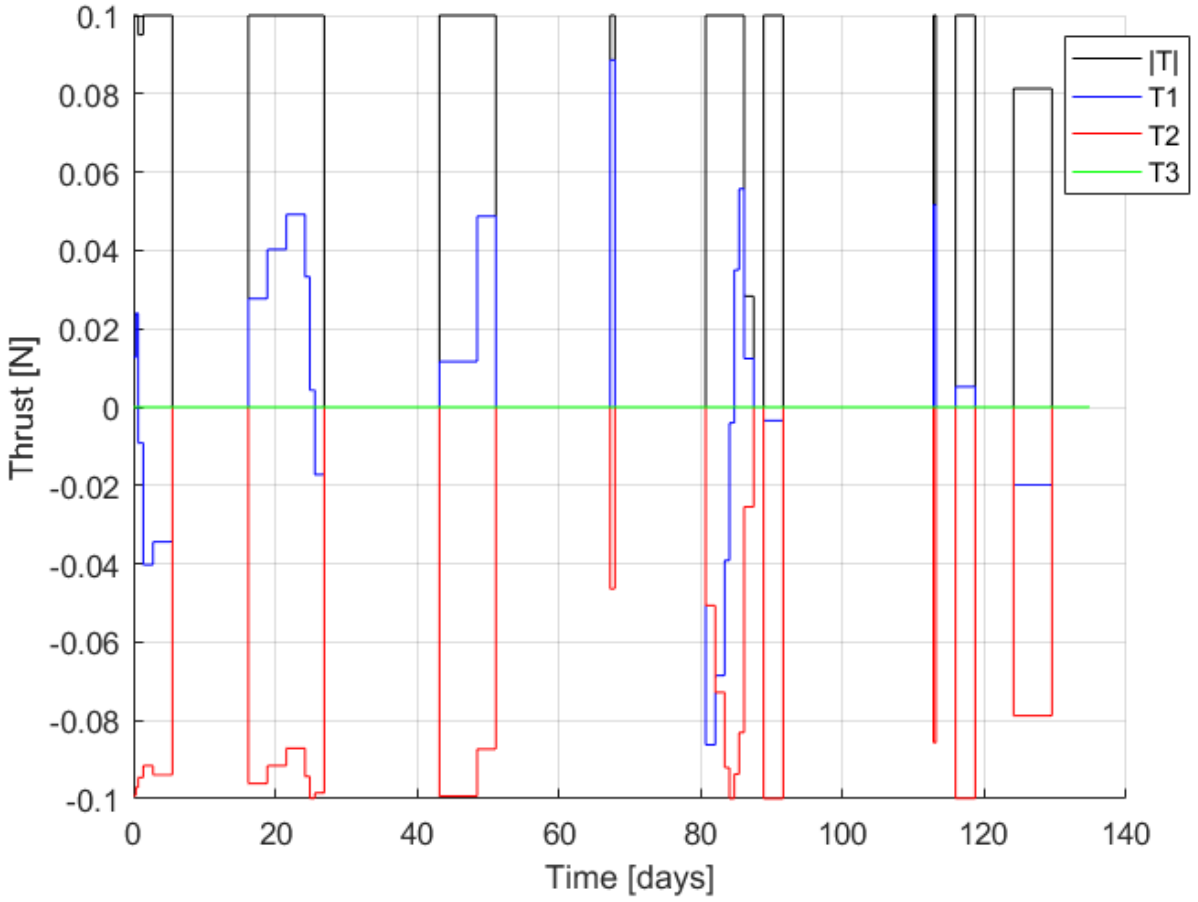
$m_f/m_0 = 492/500$

Sample Applications – Trajectory Stacking

Transfer Scenario:

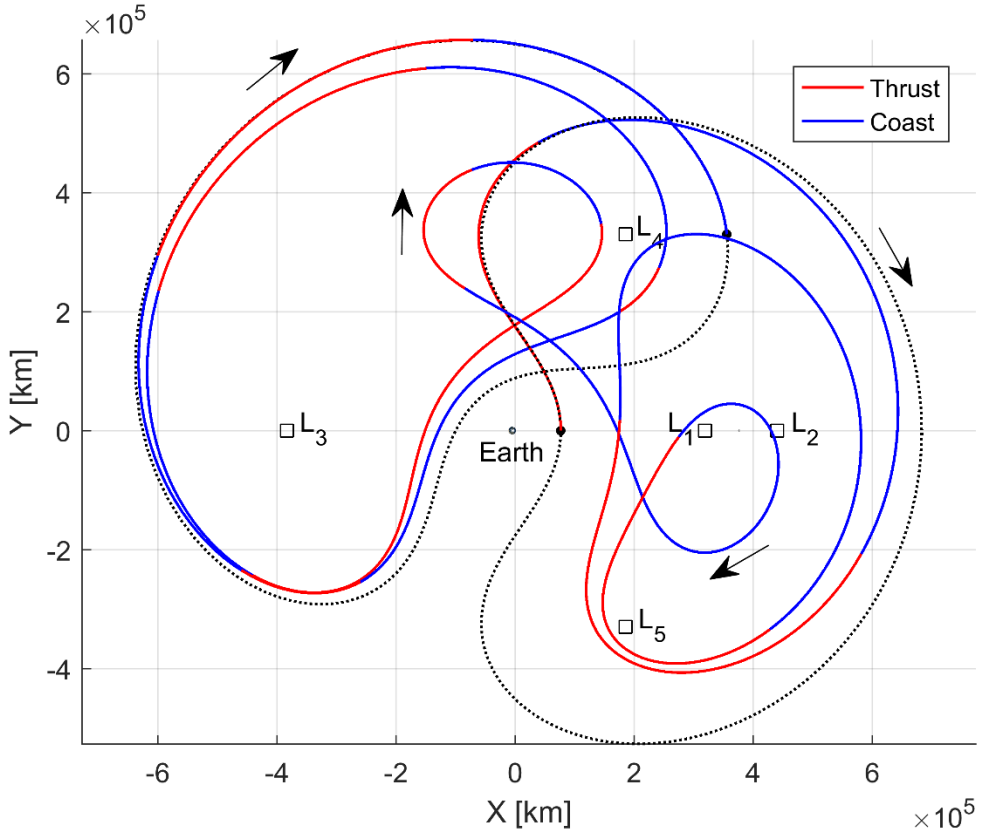
$$DRO \rightarrow L_4\ SPO$$

- $DRO\ 3\ Rev + L_4\ SPO\ 2\ Rev$
- Transfer Time: $134.8\ days$
- Optimal: $m_f/m_0 = 482/500\ kg$



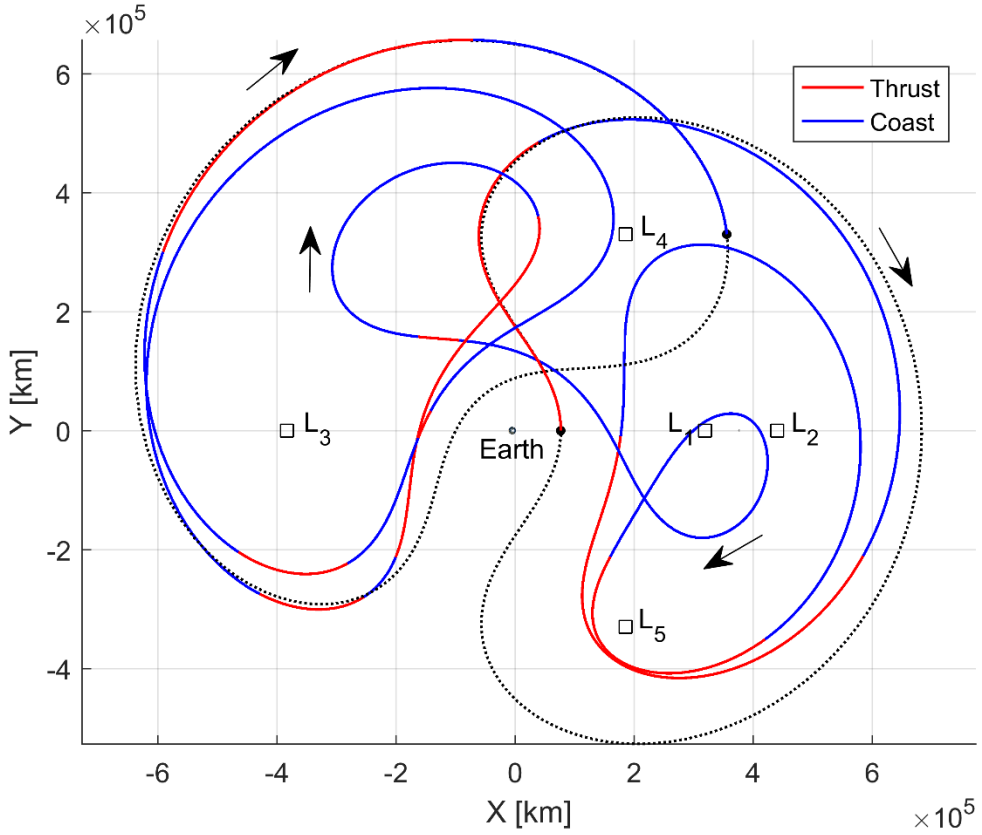
Optimal Thrust Profile

Background



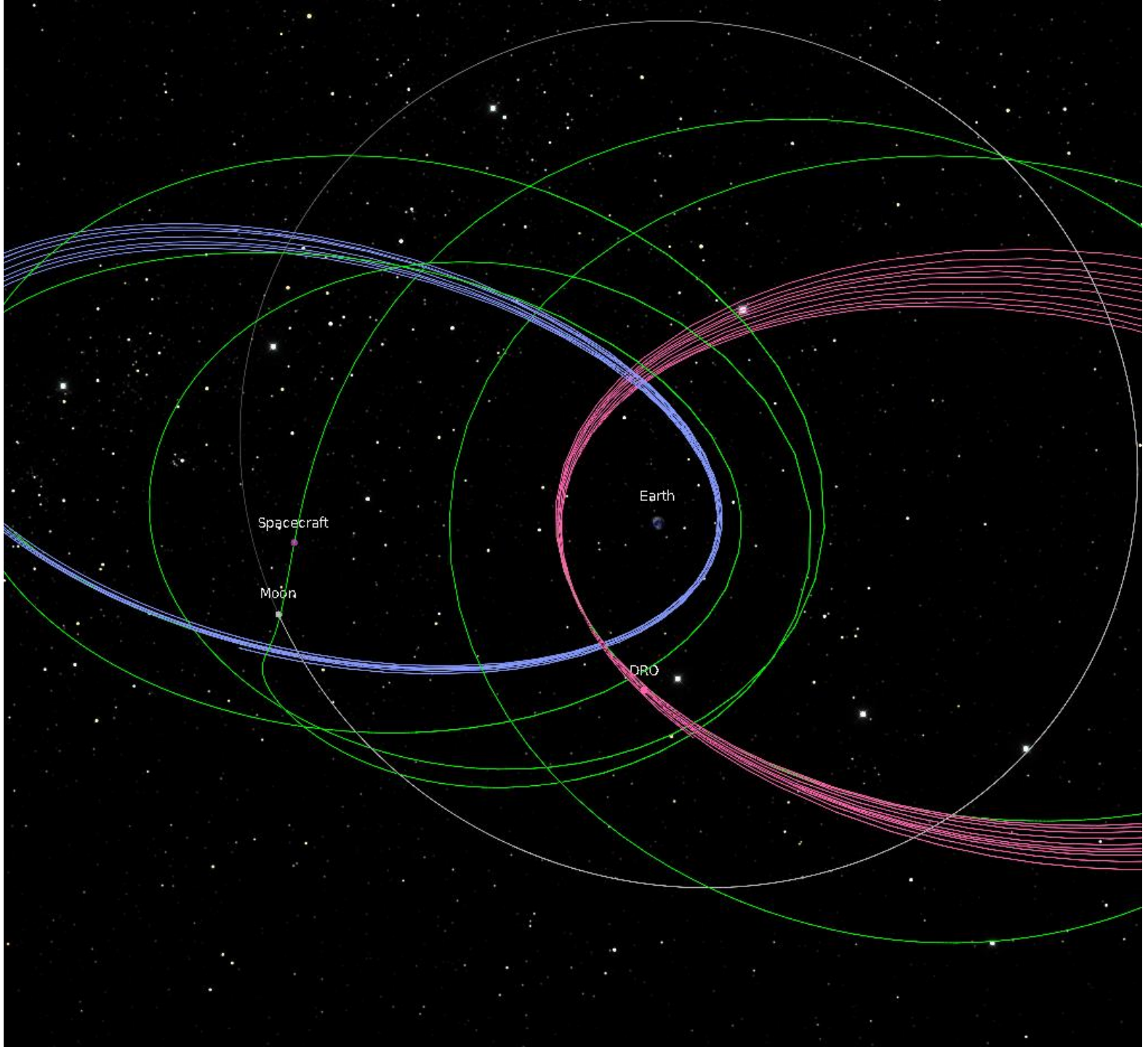
Feasible Transfer

$m_f/m_0 = 478/500$



Optimal Transfer

$m_f/m_0 = 482/500$

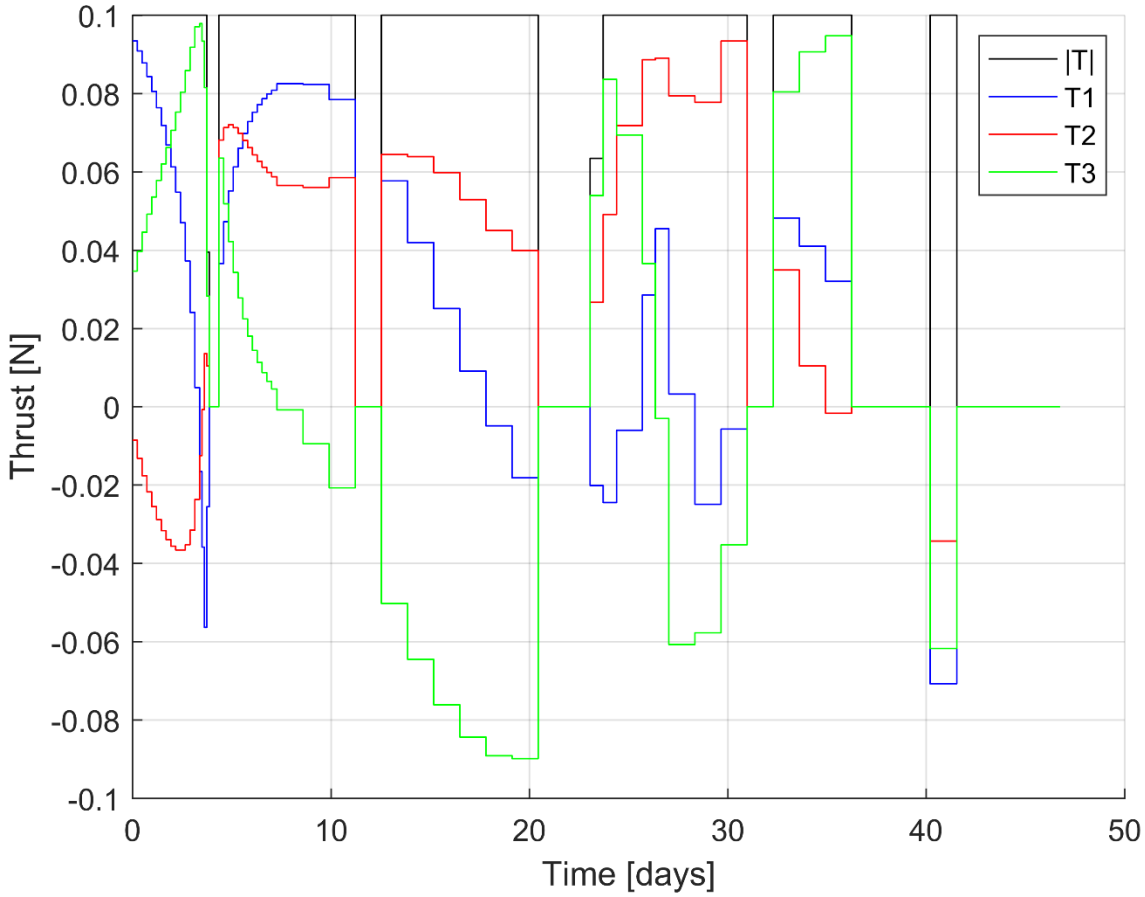

Earth
Spacecraft
Moon
DRO

Sample Applications – Trajectory Stacking

Transfer Scenario:

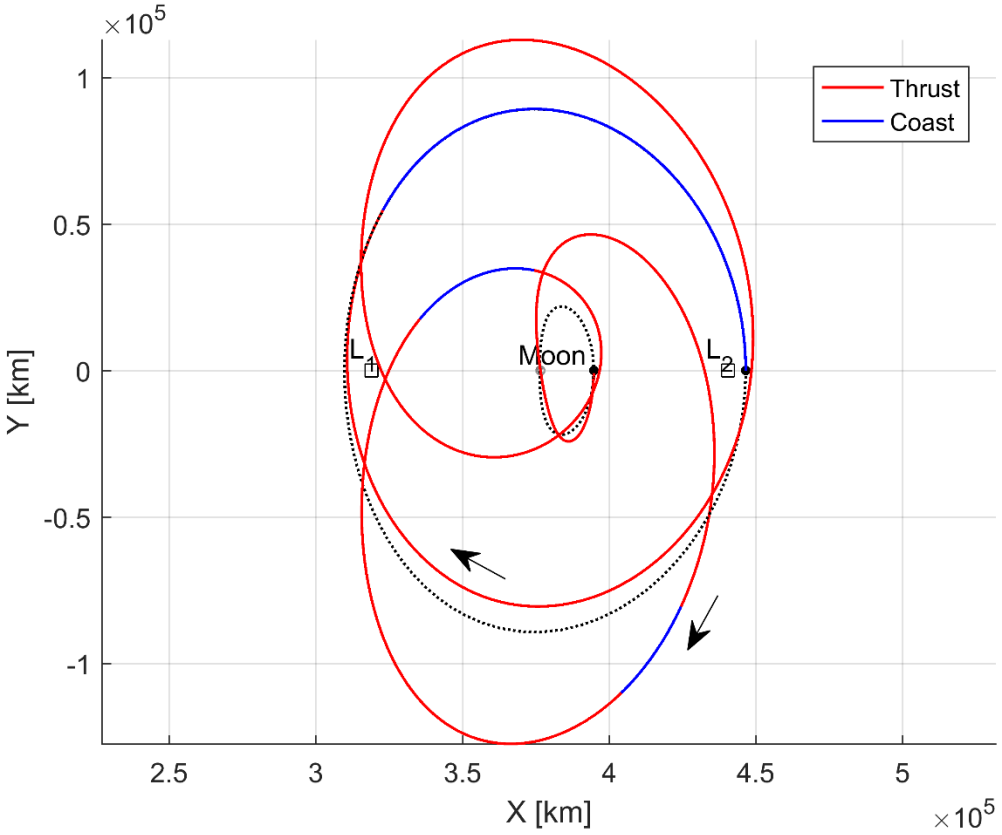
$$L_2\ NRHO \rightarrow DRO$$

- $NRHO\ 1\ Rev + DRO\ 3\ Rev$
- Transfer Time: $46.7\ days$
- $m_f/m_0 = 486/500\ kg$



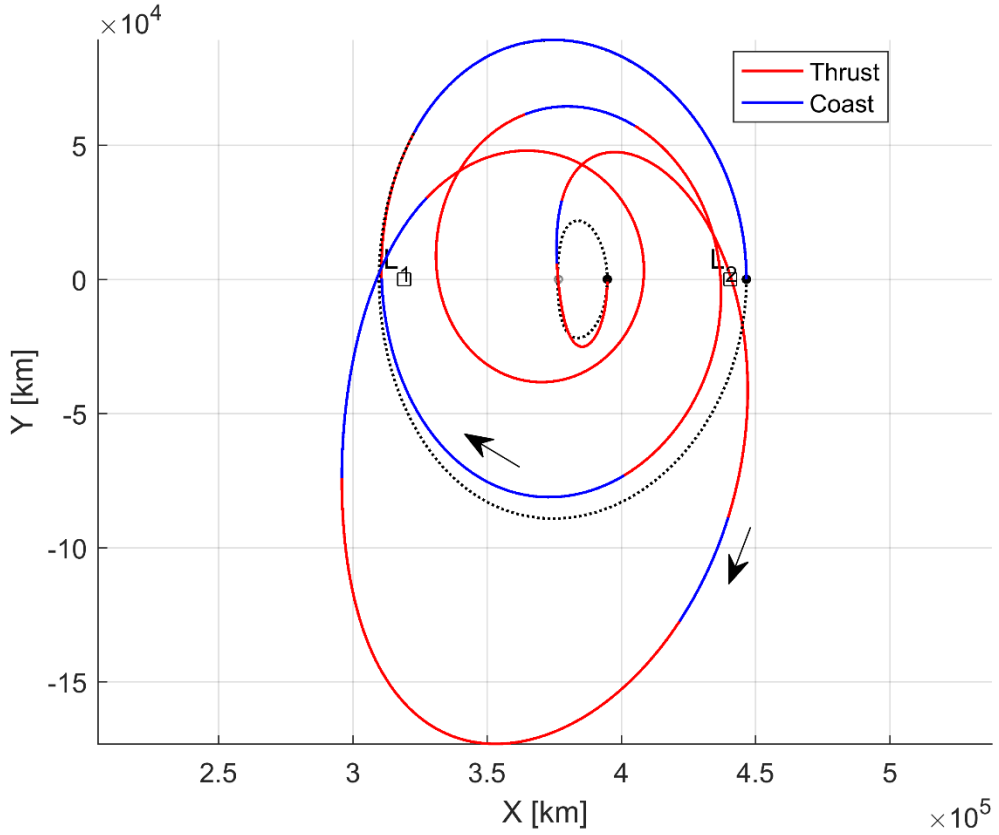
Optimal Thrust Profile

Background



Feasible Transfer

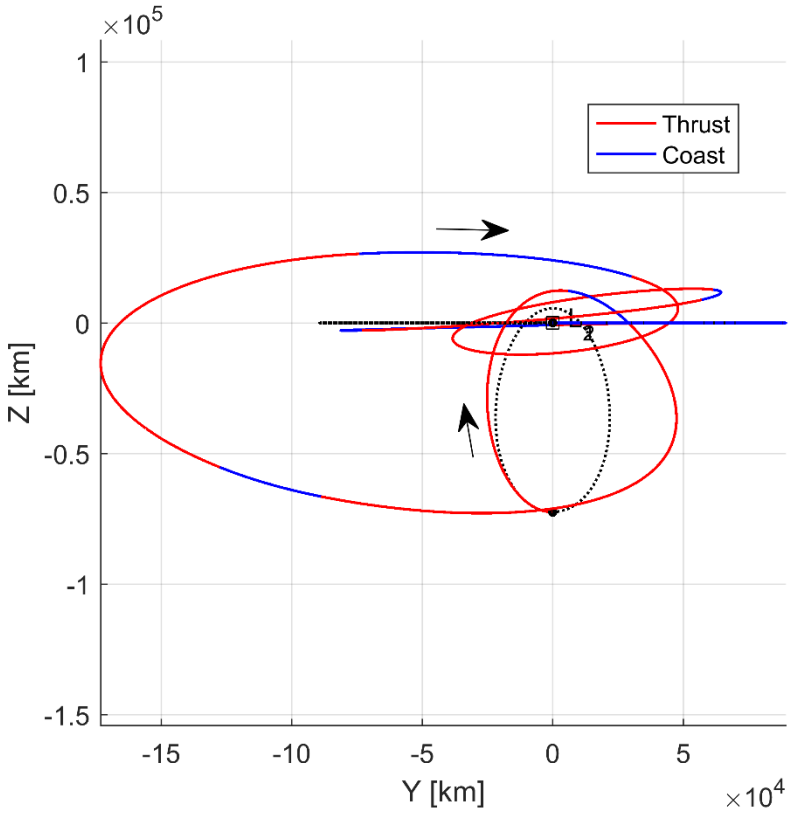
$m_f/m_0 = 483/500$



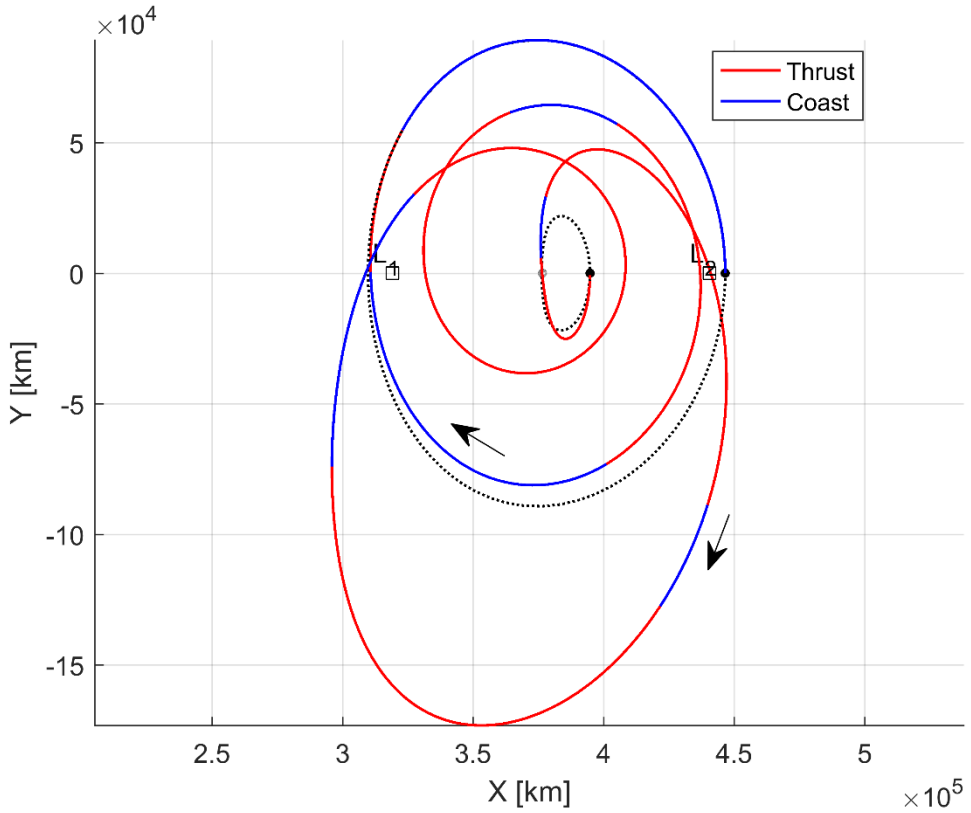
Optimal Transfer

$m_f/m_0 = 486/500$

Sample Applications – Trajectory Stacking

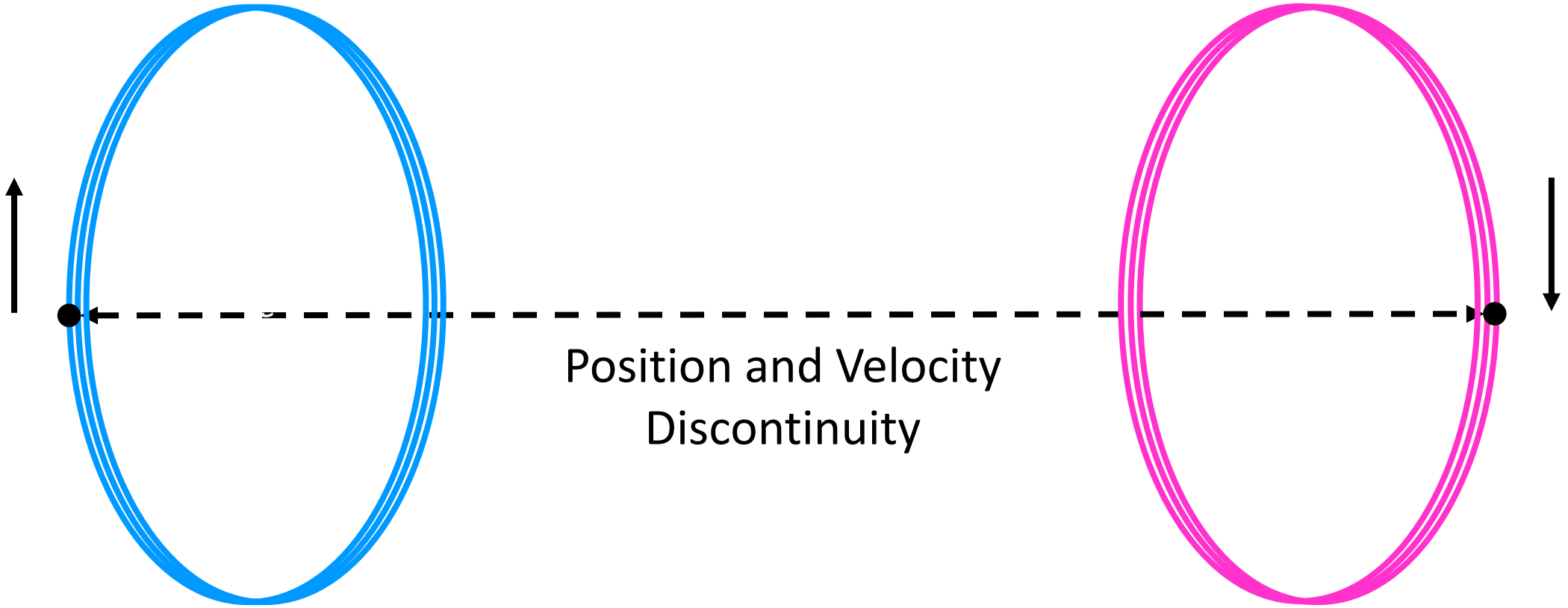


YZ View

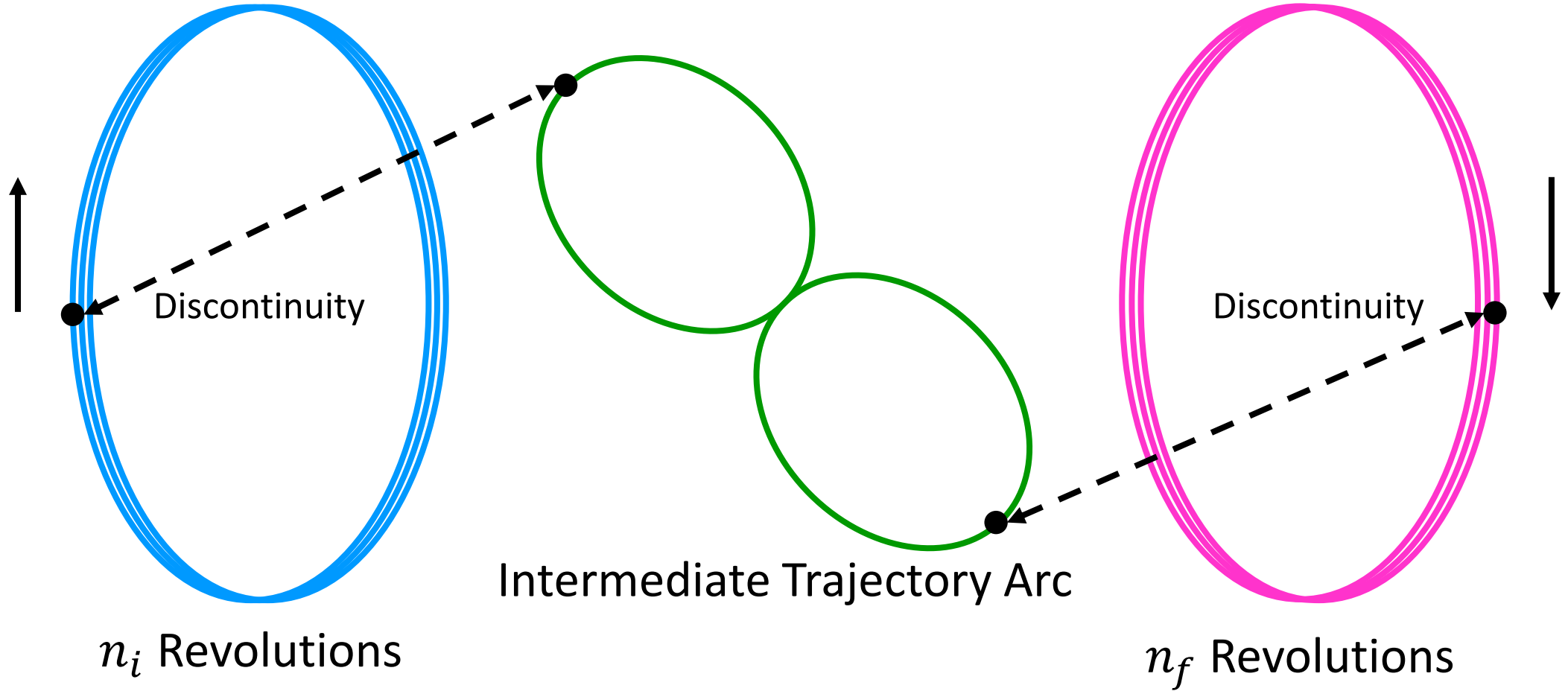


XY View

Background


Position and Velocity
Discontinuity
3 Revolution
3 Revolution

Background


Discontinuity
Discontinuity
Intermediate Trajectory Arc
n_i Revolutions
n_f Revolutions