An Interactive Trajectory Design Environment Leveraging Dynamical Structures in Multi-Body Regimes

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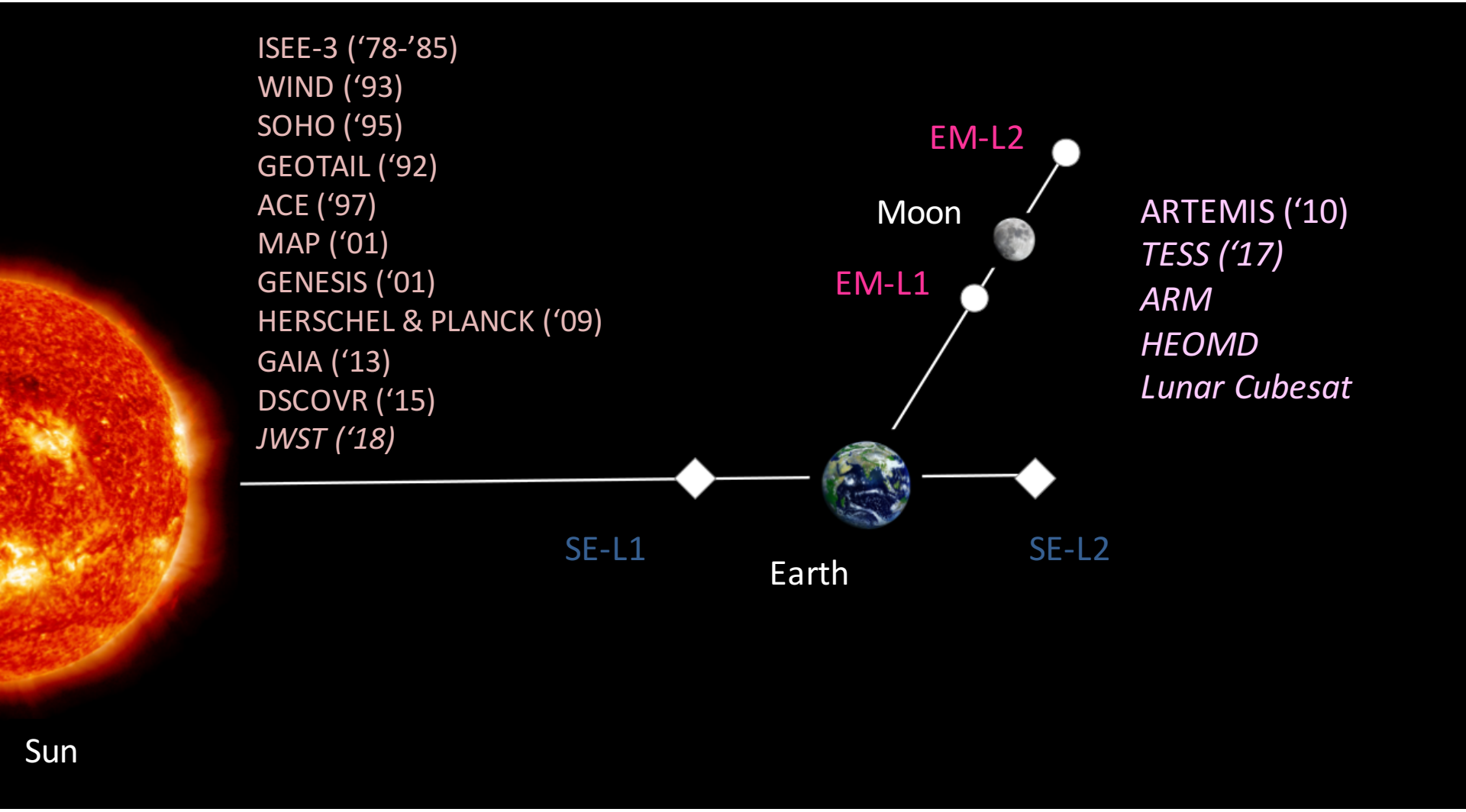
Motivation


ISEE-3 (‘78-’85)
WIND (‘93)
SOHO (‘95)
GEOTAIL (‘92)
ACE (‘97)
MAP (‘01)
GENESIS (‘01)
HERSCHEL & PLANCK (‘09)
GAIA (‘13)
DSCOVR (‘15)
JWST (‘18)
EM-L2
Moon
EM-L1
ARTEMIS (‘10)
TESS (‘17)
ARM
HEOMD
Lunar Cubesat
SE-L1
Earth
SE-L2
Sun

Sample Design Tools

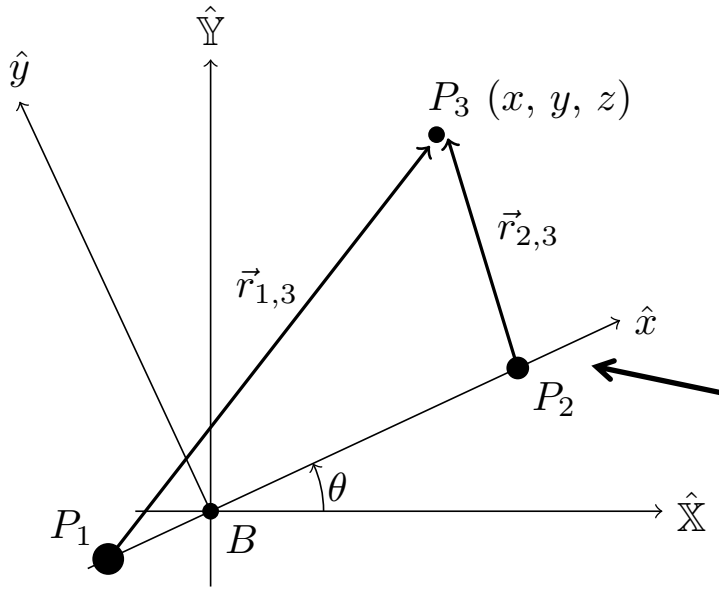
and many more…

- Provide full suite of capabilities for mission planning and operational support
- Increasingly complex environments present design challenges
  - Point solutions can be designed
  - Process to leverage complex dynamical structures may not be intuitive

Trajectory Design Framework

- Purdue University – NASA Goddard Space Flight Center collaboration: **Adaptive Trajectory Design (ATD)**
- Identify and manipulate dynamical structures within simplified Circular Restricted 3-Body Problem
- Prototype interactive graphical interface in Matlab

Circular Restricted 3-Body Problem

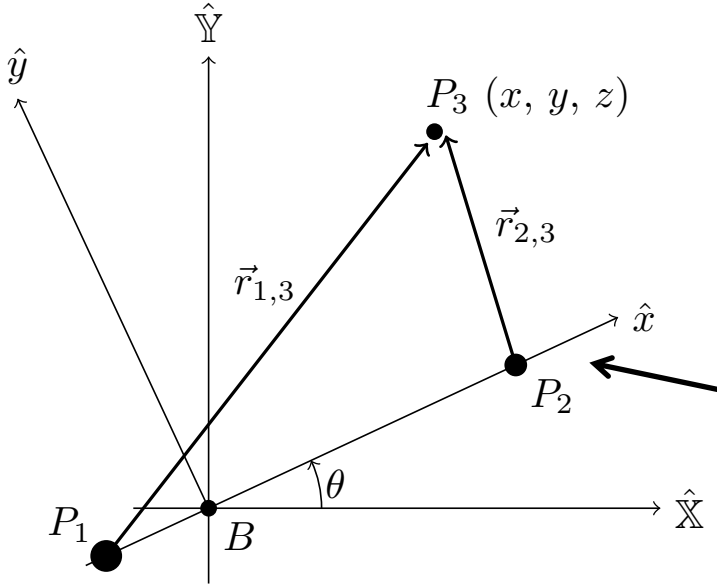


Assumptions

1. $m_3 << m_2 < m_1$
2. P_1 and P_2 in circular orbits about B
3. P_1 and P_2 act as point masses

Rotating Frame (Working Frame)

Circular Restricted 3-Body Problem



Assumptions

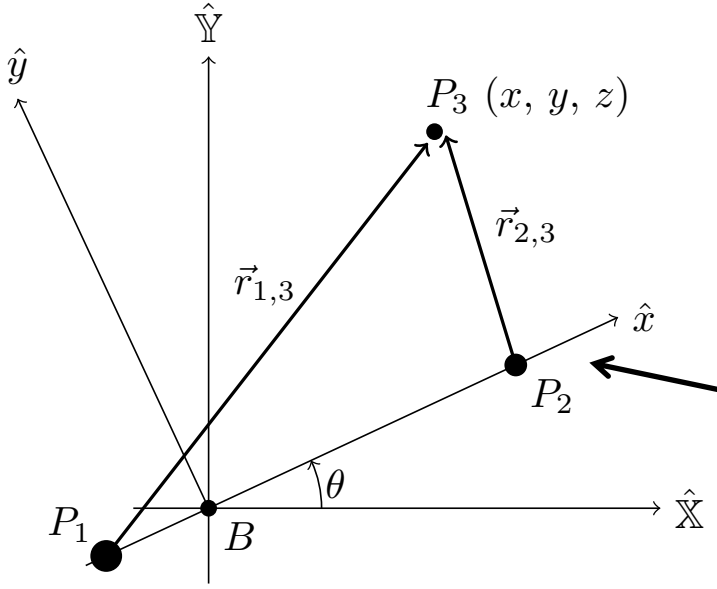
1. $m_3 << m_2 < m_1$
2. P_1 and P_2 in circular orbits about B
3. P_1 and P_2 act as point masses

Rotating Frame (Working Frame)

$$\ddot{x} - 2\dot{y} = \Omega_x \qquad \ddot{y} + 2\dot{x} = \Omega_y \qquad \ddot{z} = \Omega_z$$

$$\Omega = \frac{1-\mu}{r_{1,3}} + \frac{\mu}{r_{2,3}} + \frac{1}{2}(x^2 + y^2)$$

Circular Restricted 3-Body Problem



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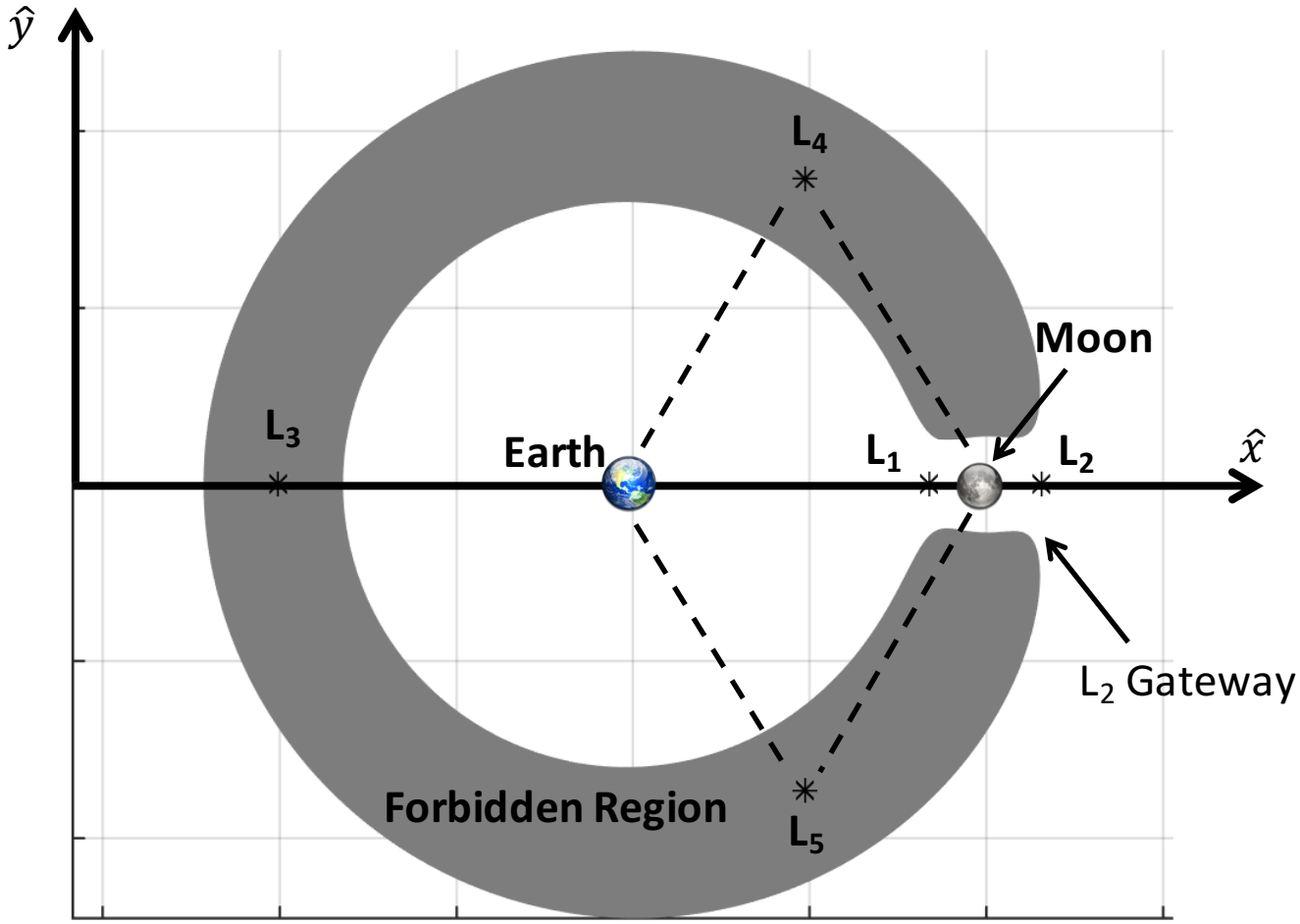
$$\Omega = \frac{1-\mu}{r_{1,3}} + \frac{\mu}{r_{2,3}} + \frac{1}{2}(x^2 + y^2)$$

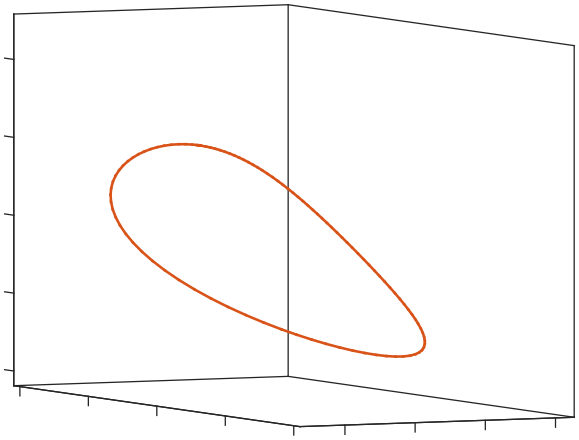
Energy-like constant: $C = 2\Omega - v^2$

"Jacobi Constant"

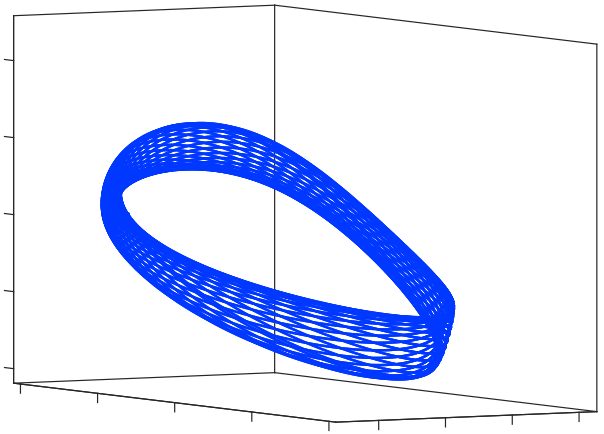
Equilibrium Points



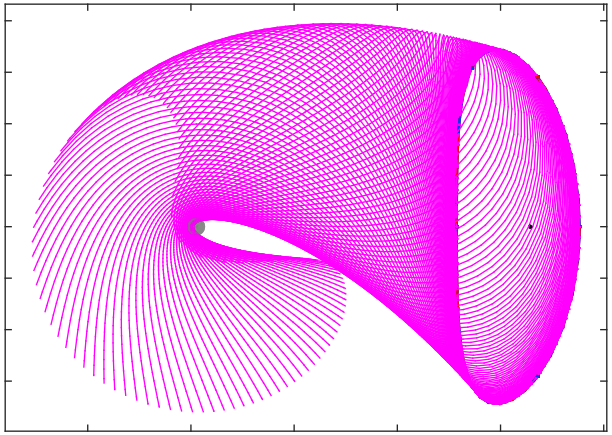
CR3BP Dynamical Structures



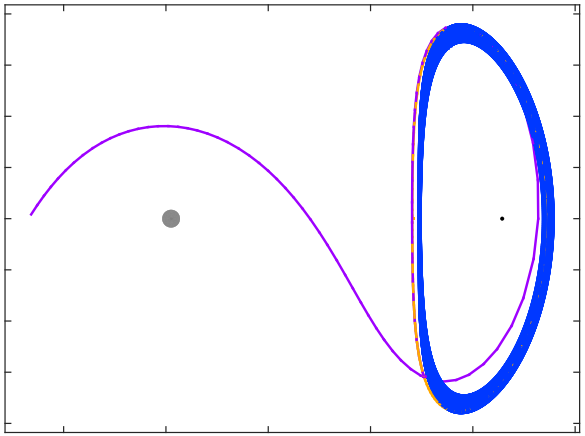
Periodic Orbits



Quasi-Periodic Orbits

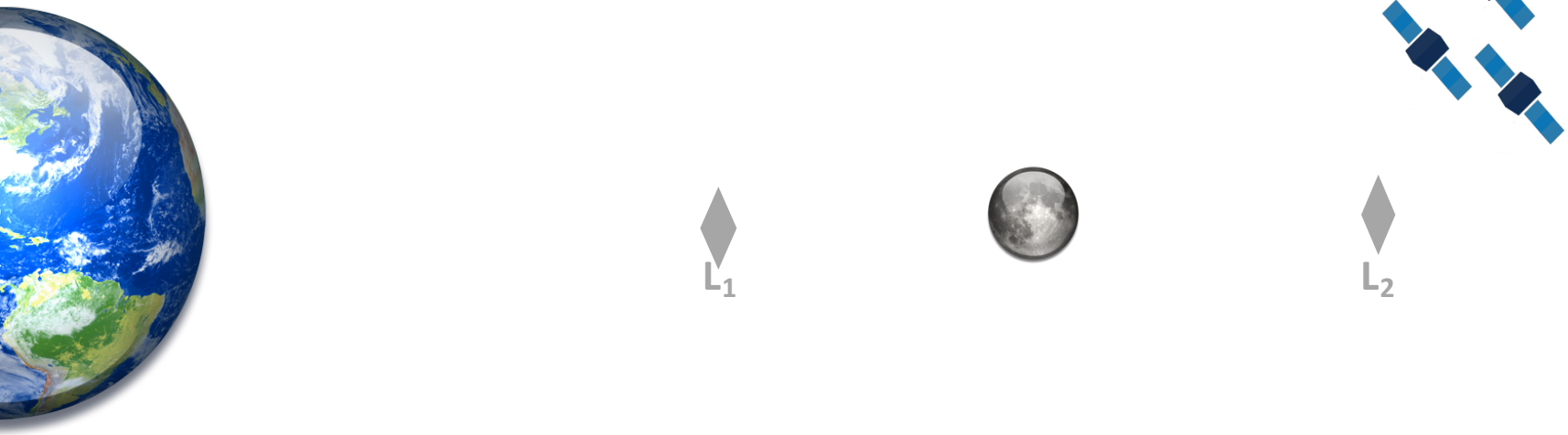


Manifold Arcs



Combined Segments

Sample Mission Scenario



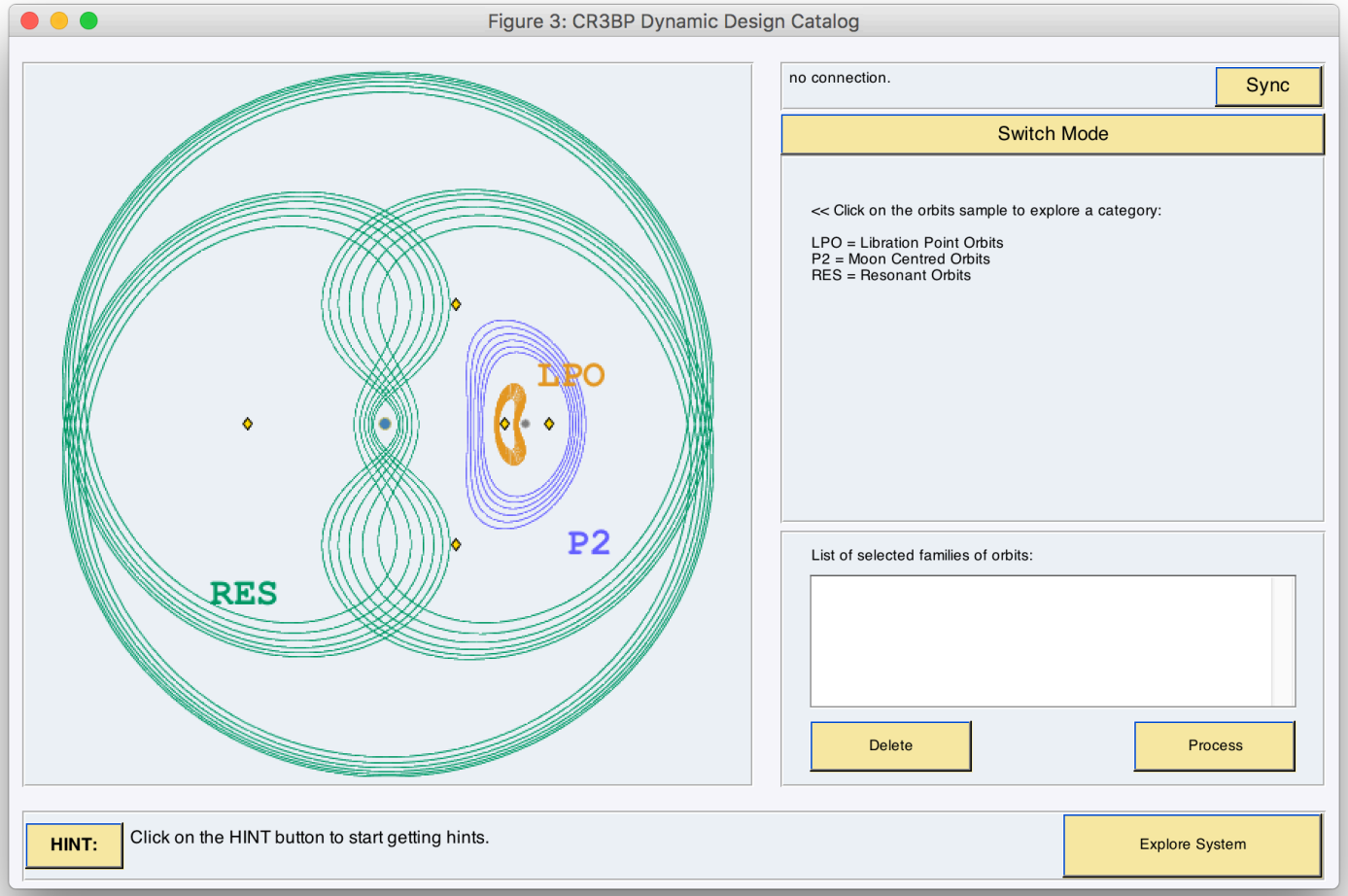
- Multi-purpose formation to service cislunar and interplanetary space
- In parking orbit, require constant communications with Earth

Parking Orbit Selection

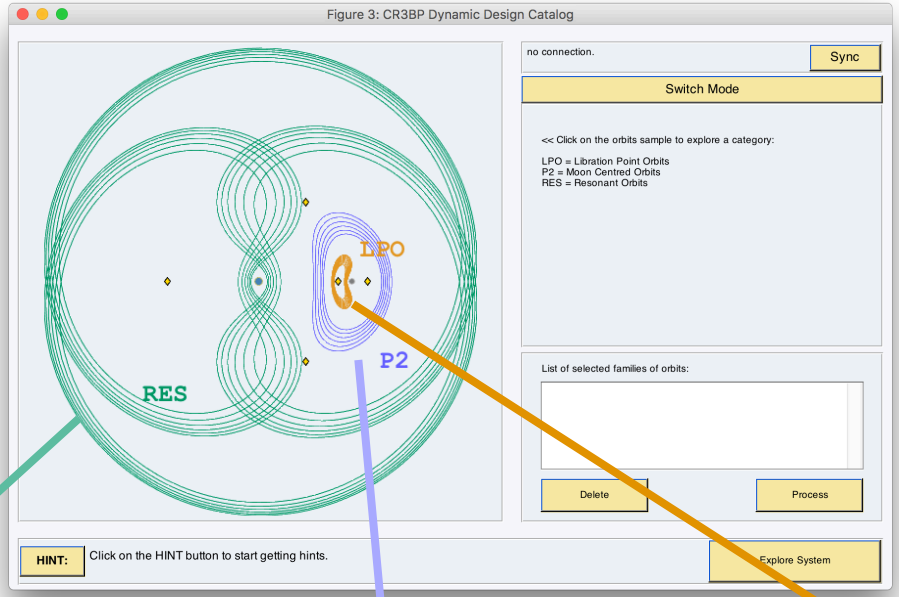
Design Constraints

- Formation of service satellites
  - **Constraint #1:** Use quasi-periodic orbit
- Service interplanetary destinations
  - **Constraint #2:** Located at the L2 gateway
- Service L1 destinations
  - **Constraint #3**: Energy level comparable to L1
- Continuous comm. to Earth, no occultation w/ Moon
  - **Constraint #4:** Angular deviation from x-axis > 0.26 deg

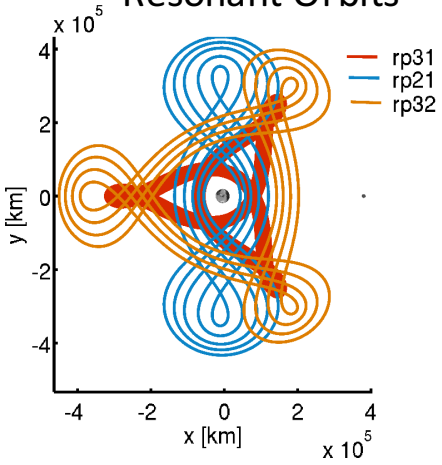
Catalog of Periodic Solutions



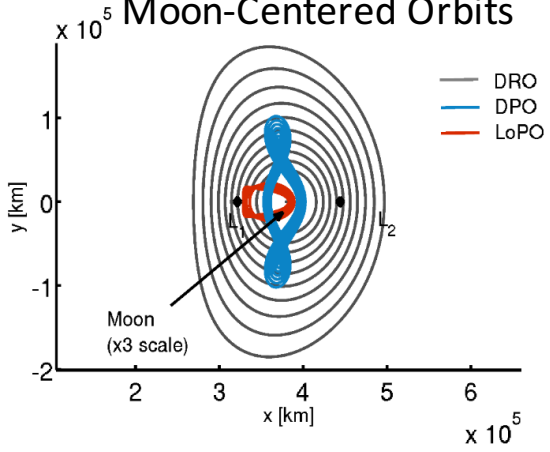
Families of Periodic Orbits



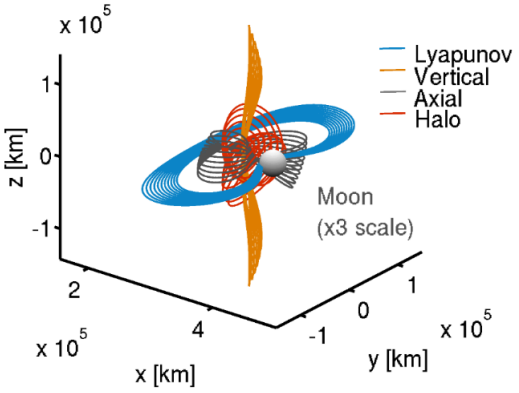
Resonant Orbits



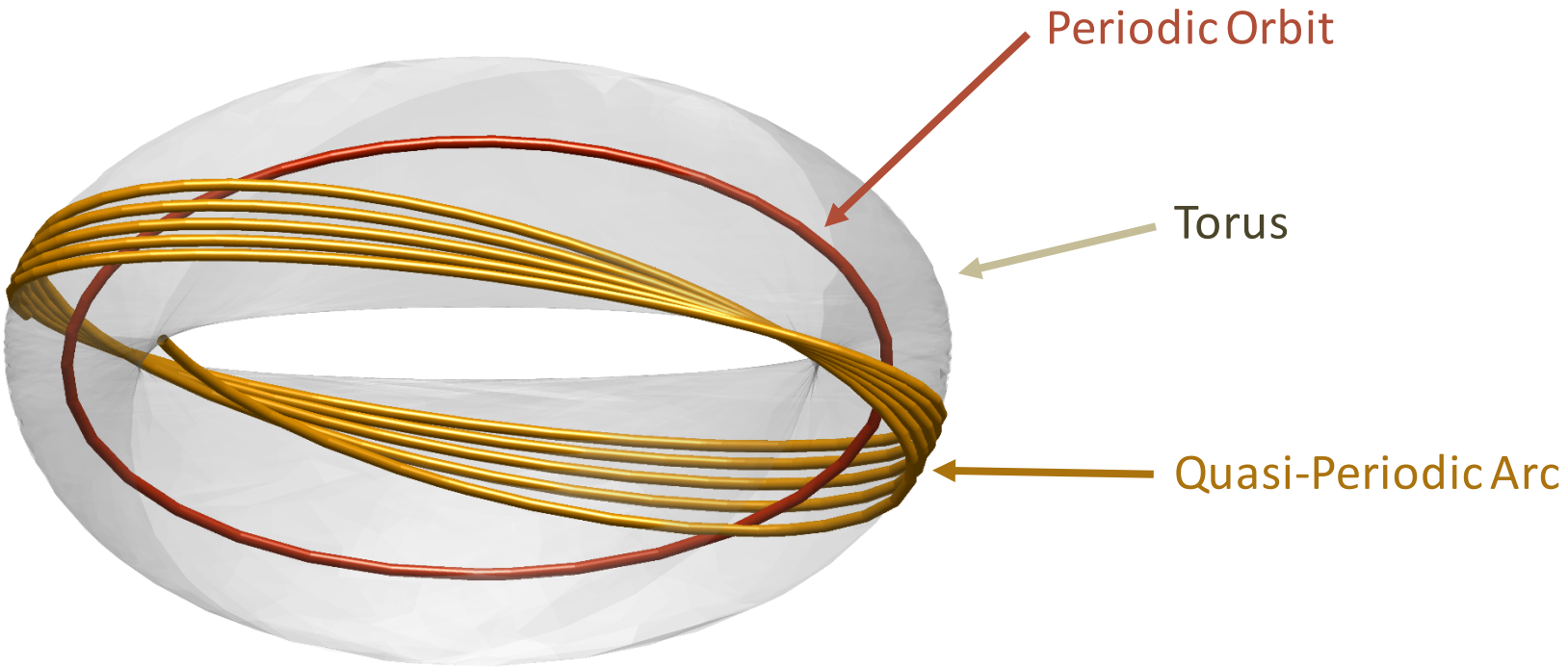
Moon-Centered Orbits



Libration Point Orbits



Quasi-Periodic Motion

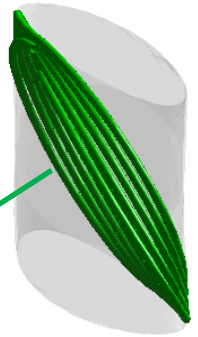


- Module available to explore existence and characteristics of quasi-periodic solutions, selection of segments

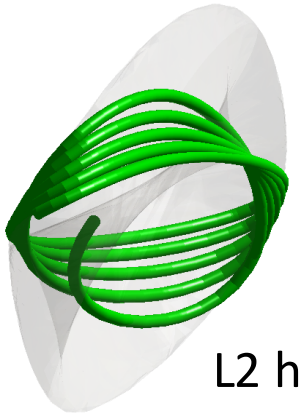
Parking Orbit Selection

Explore Trade Space

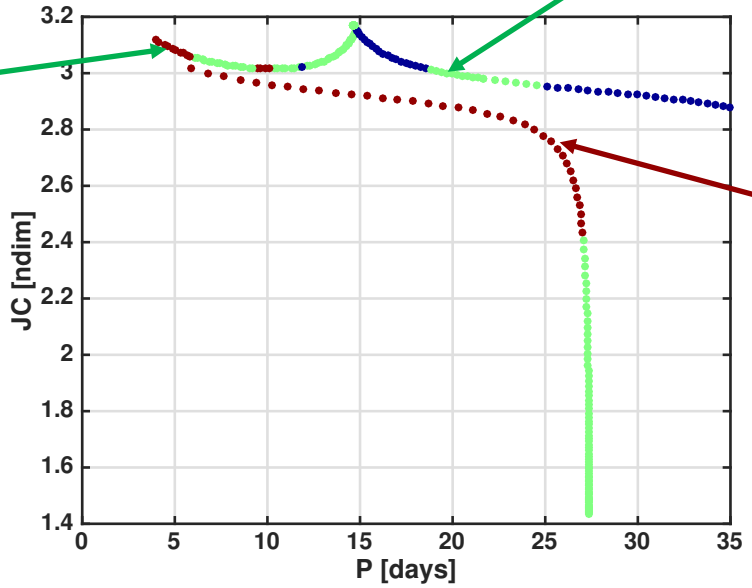
- ✓ Use quasi-periodic orbit
- ❑ Located at the L2 gateway
- ❑ Energy level comparable to L1
- ❑ Angular deviation from x-axis > 0.26°

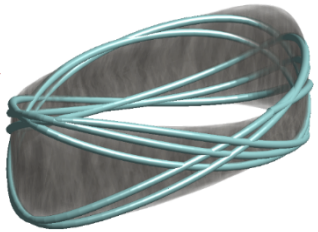


L2 Lyapunov



L2 halo



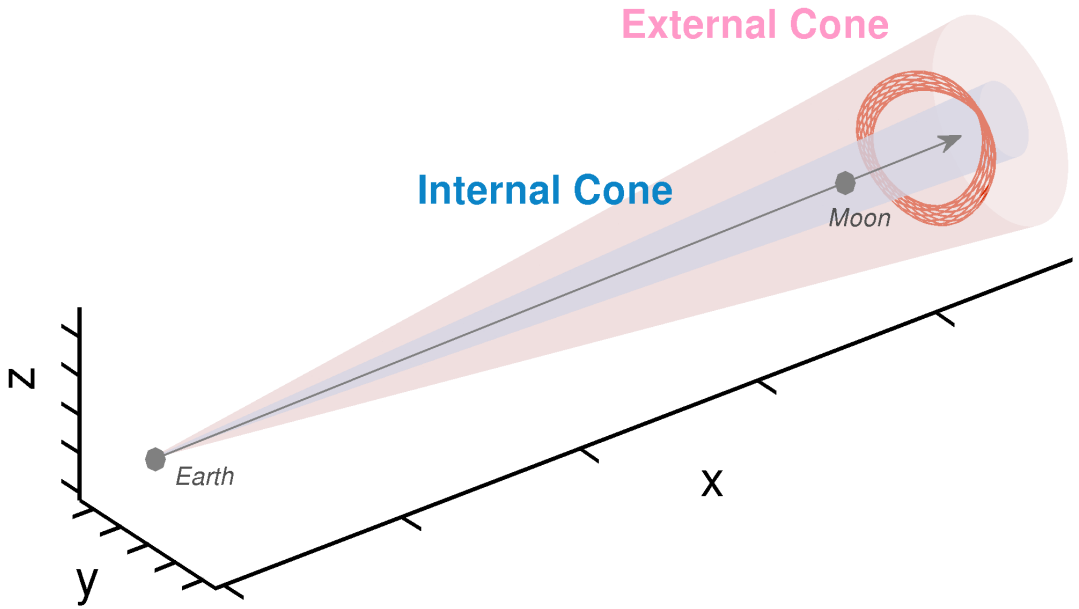


DRO

Parking Orbit Selection

Explore Trade Space

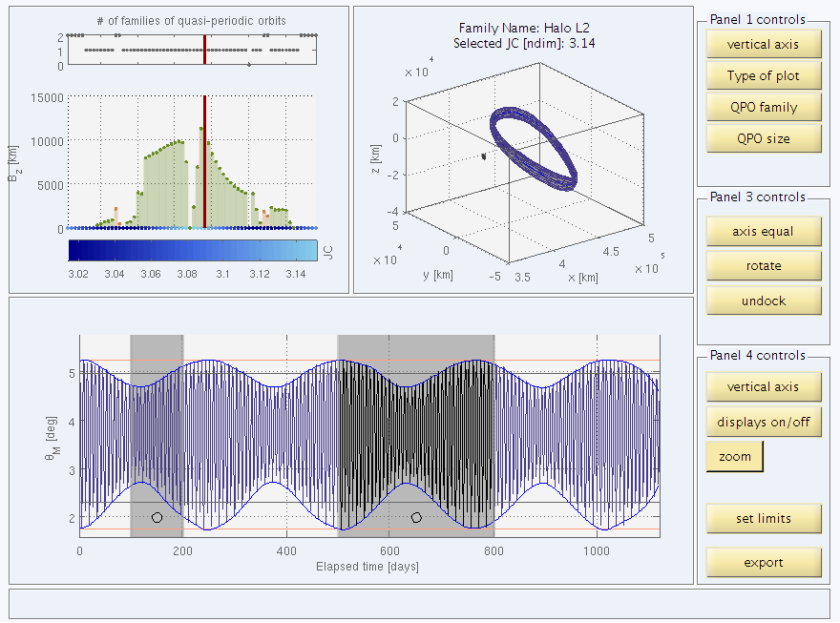
- ✓ Use quasi-periodic orbit
- ✓ Located at the L2 gateway
- ✓ Energy level comparable to L1 ($C \approx 3.14$)
- ❑ Angular deviation from x-axis > 0.26°

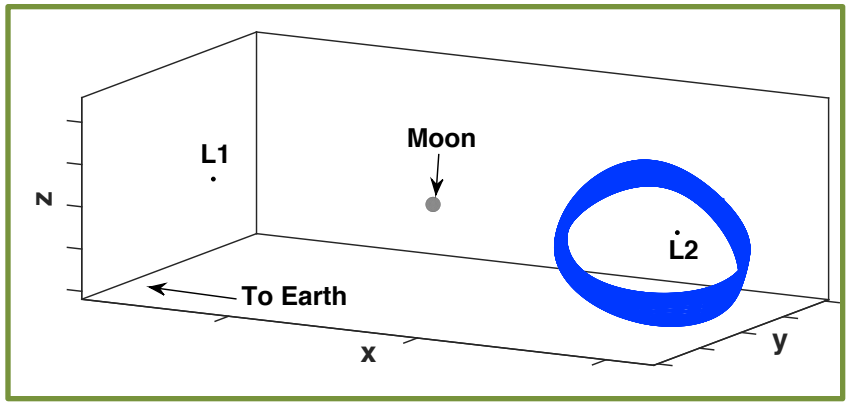


Parking Orbit Selection

Select L_2 Quasi-Halo

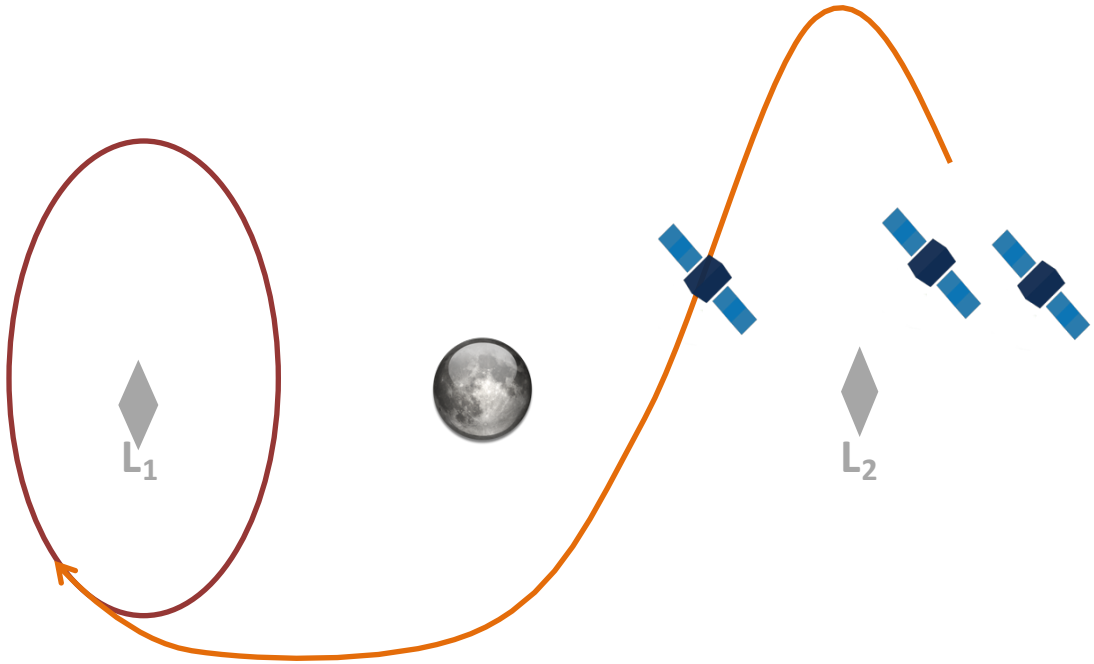
- ✓ Use quasi-periodic orbit
- ✓ Located at the L2 gateway
- ✓ Energy level comparable to L1 ($C \approx 3.14$)
- ✓ Angular deviation from x-axis > 0.26°





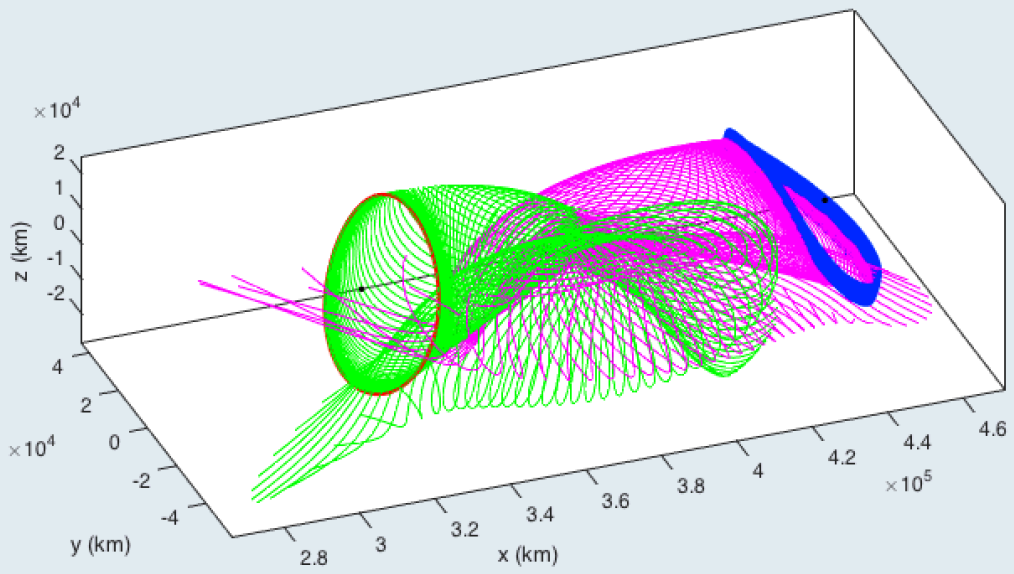
Transfer to Earth-Moon L_1

Mission Description



- Service a malfunctioning spacecraft or restock depot
- Design transfer in ATD CR3BP Design Module

CR3BP Design Environment



CR3B Orbits and Manifolds

Earth-Moon

Select Orbit Family

Plot Family

Explore Catalog

Select Trajectory

Period 12.0685 days

Jacobi Value 3.14448

Stability eig_u = 1377.675, eig

Hide Unselected Orbits

Clear All Families

Compute Manifolds

Stable

Unstable

- Step

+ Step

Manifolds 50

Prop. Time (days) 19

Propagate Manifolds

Select Manifold

Hide Unselected Manifolds

Clear All Manifolds

Assemble Arc Segments

Select Arc Color

Enter Arc Label...

Save to List

Delete from List

Arc List

EM L2 Quasi-Halo
L2 Halo
EM L1 Halo

Highlight Arc List selection

Plot Tools

Undock Plot

Set Axis Limits

Zoom Reset

Additional Tools

Get Conic

Get Libration Point Orbit

Import Trajectory

Select from Arc List

Clip Selected

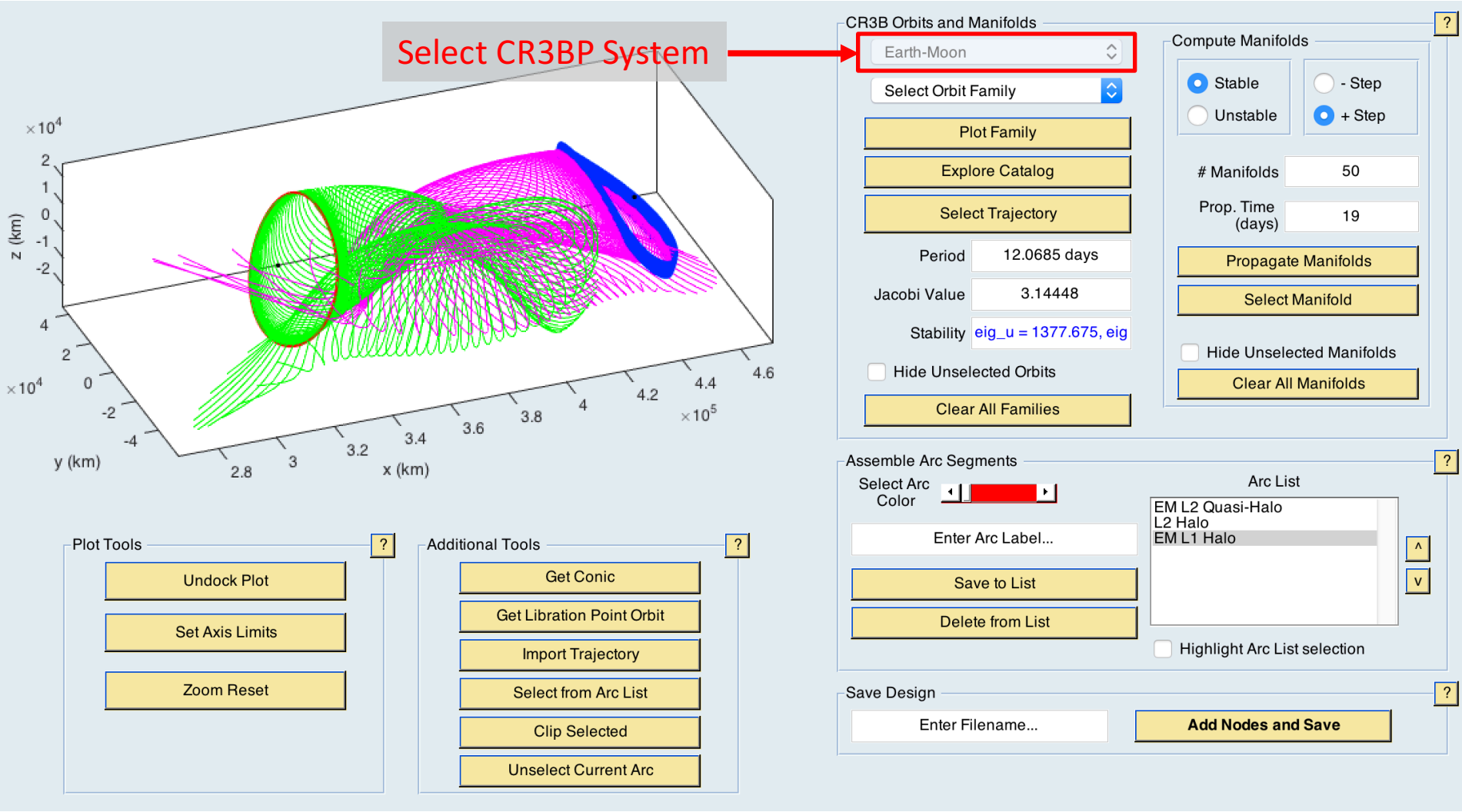
Unselect Current Arc

Save Design

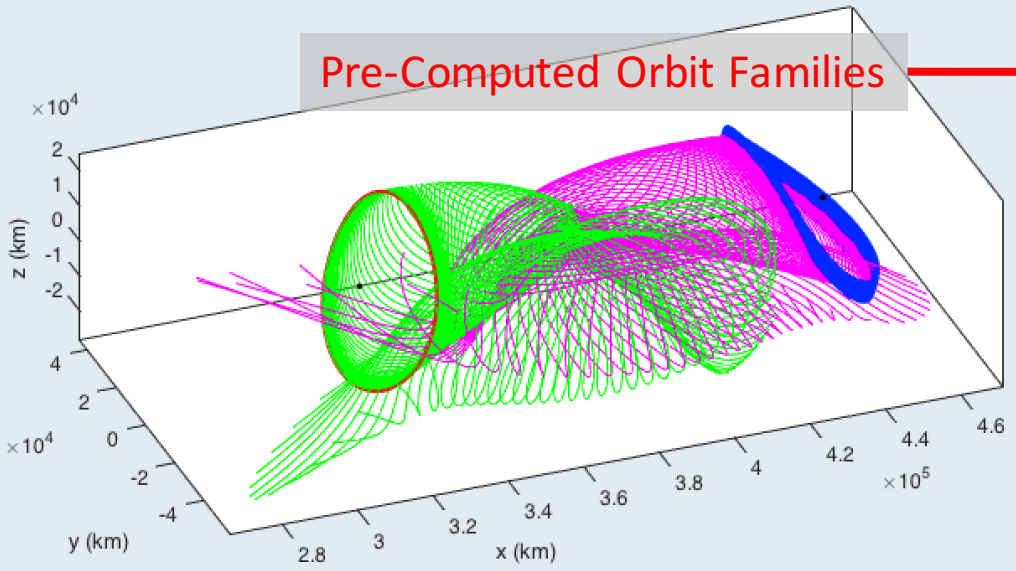
Enter Filename...

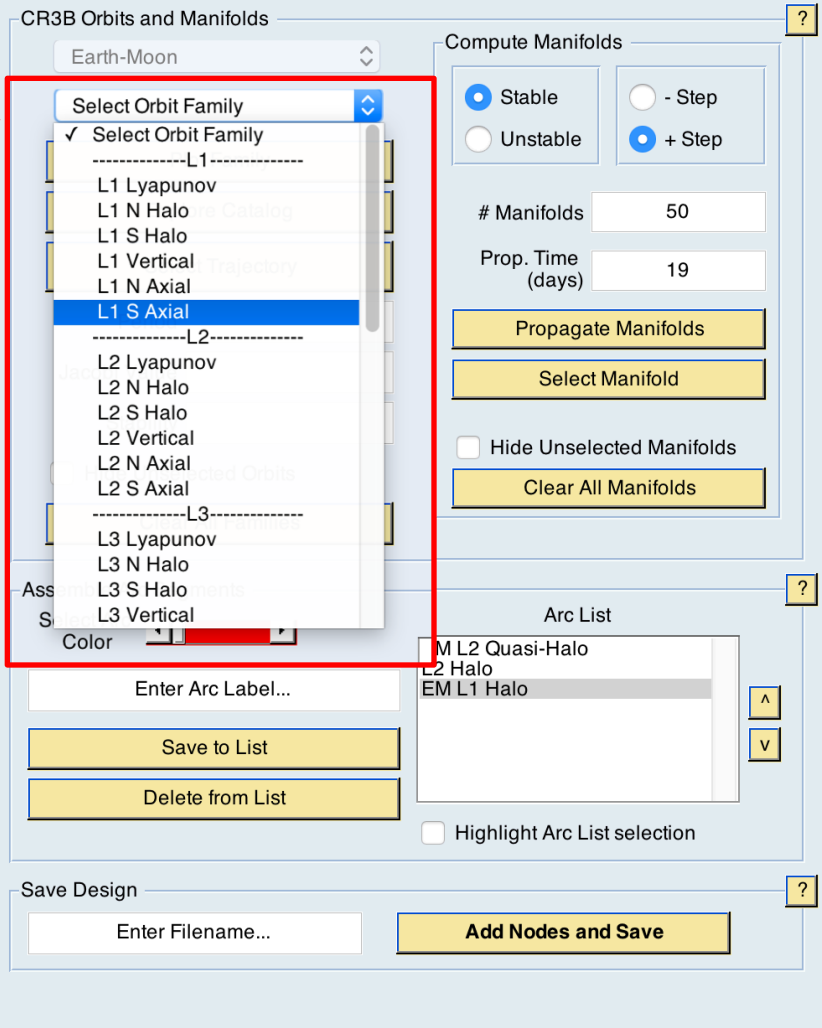
Add Nodes and Save

CR3BP Design Environment

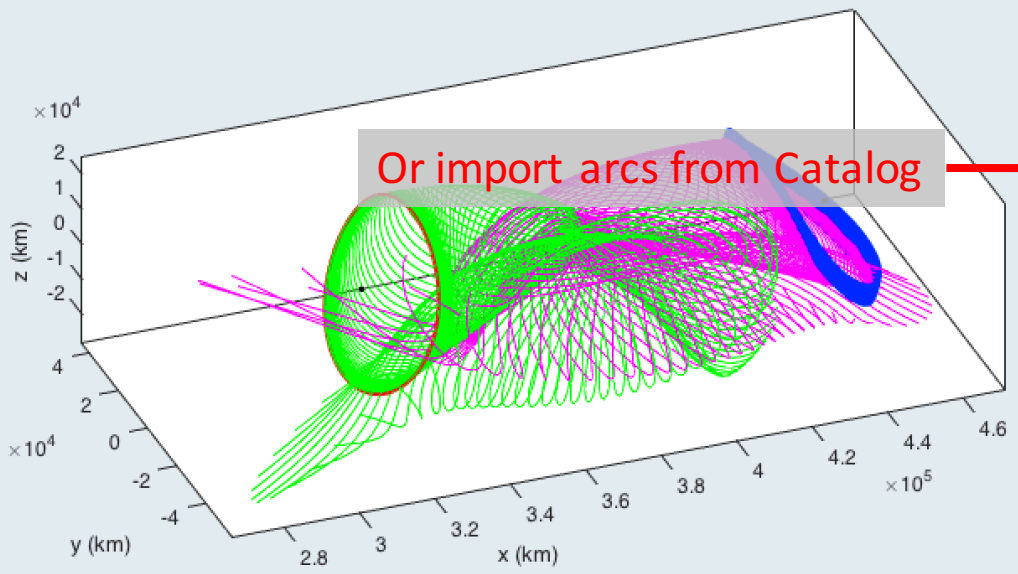


CR3BP Design Environment





CR3BP Design Environment



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Stable / Unstable

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EM L2 Quasi-Halo
L2 Halo
EM L1 Halo

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Set Axis Limits

Zoom Reset

Additional Tools

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Get Libration Point Orbit

Import Trajectory

Select from Arc List

Clip Selected

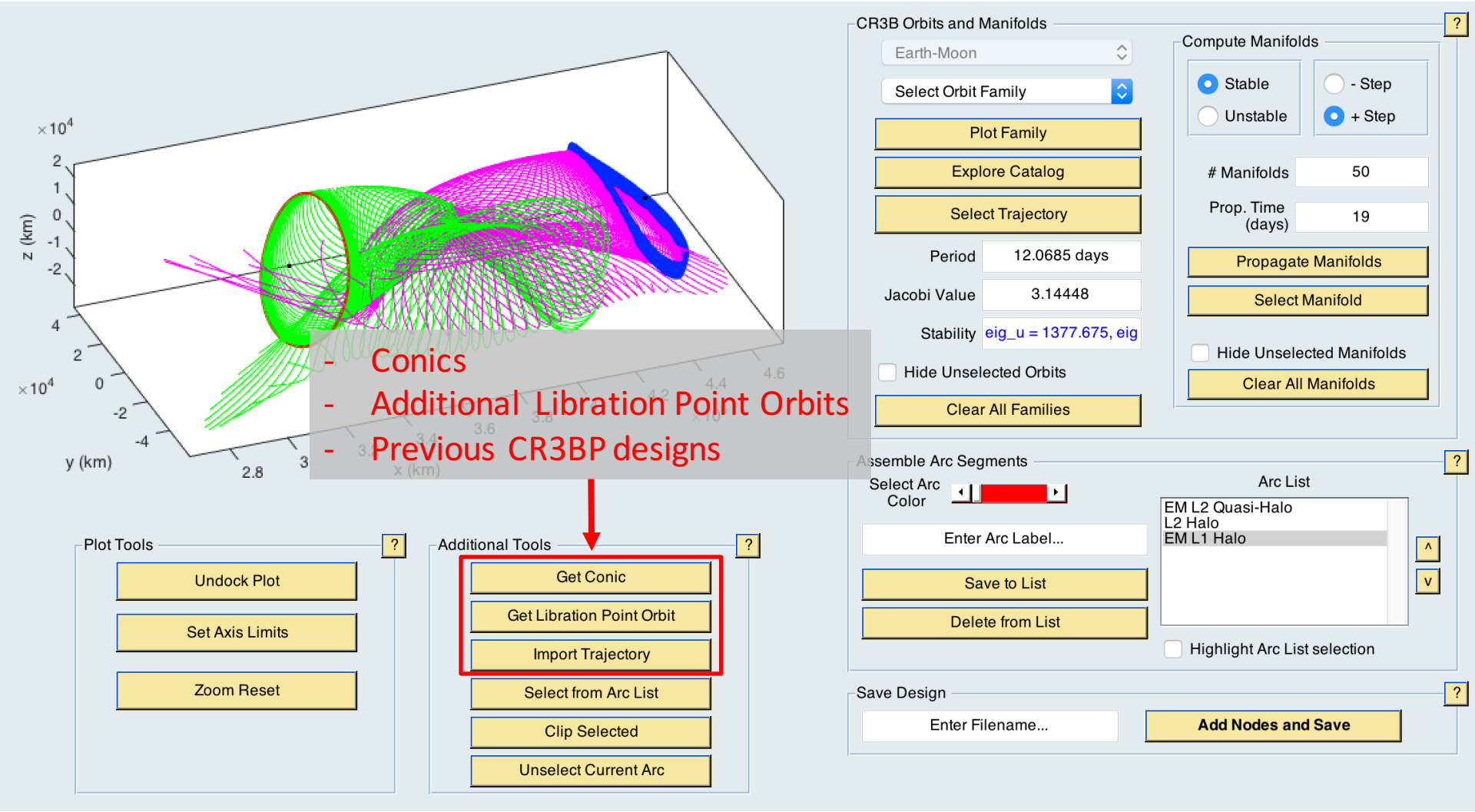
Unselect Current Arc

Save Design

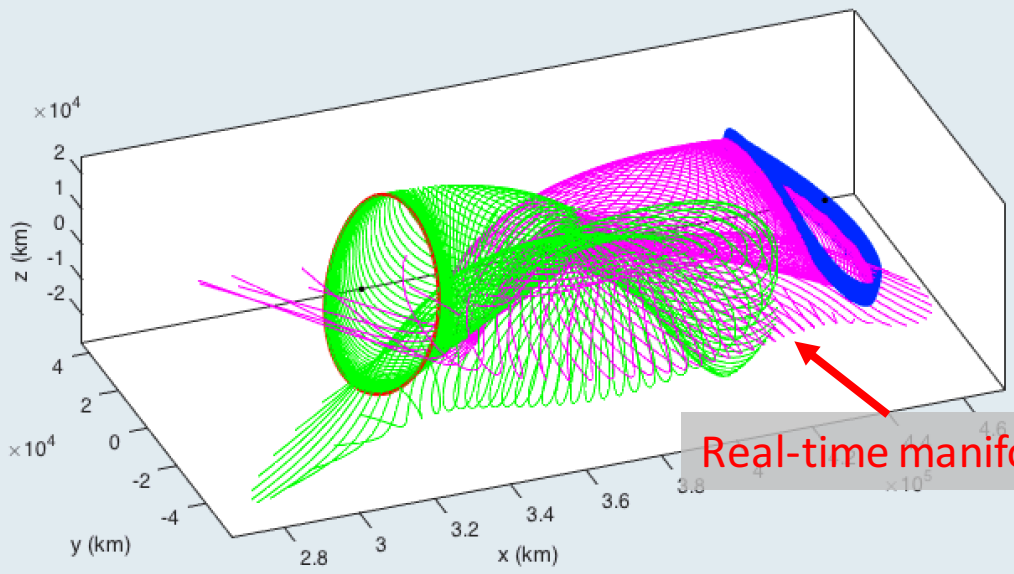
Enter Filename...

Add Nodes and Save

CR3BP Design Environment



CR3BP Design Environment



Real-time manifold generation

CR3B Orbits and Manifolds

Earth-Moon

Select Orbit Family

Plot Family

Explore Catalog

Select Trajectory

Period 12.0685 days

Jacobi Value 3.14448

Stability eig_u = 1377.67[illegible]5, eig

Hide Unselected Orbits

Clear All Families

Compute Manifolds

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Unstable

- Step

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Manifolds 50

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Enter Arc Label...

Save to List

Delete from List

Arc List

EM L2 Quasi-Halo
L2 Halo
EM L1 Halo

Highlight Arc List selection

Save Design

Enter Filename...

Add Nodes and Save

Plot Tools

Undock Plot

Set Axis Limits

Zoom Reset

Additional Tools

Get Conic

Get Libration Point Orbit

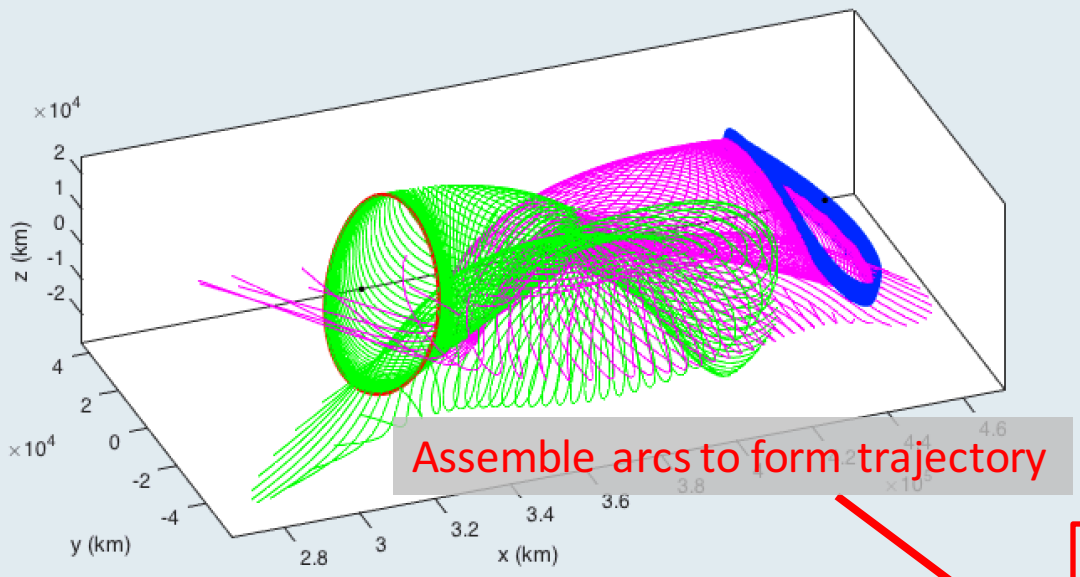
Import Trajectory

Select from Arc List

Clip Selected

Unselect Current Arc

CR3BP Design Environment



Assemble arcs to form trajectory

CR3B Orbits and Manifolds

Earth-Moon

Select Orbit Family

Plot Family

Explore Catalog

Select Trajectory

Period 12.0685 days

Jacobi Value 3.14448

Stability eig_u = 1377.675, eig

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Stable / Unstable

- Step / + Step

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Prop. Time (days) 19

Propagate Manifolds

Select Manifold

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Clear All Manifolds

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Select Arc Color

Enter Arc Label...

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Delete from List

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EM L2 Quasi-Halo
L2 Halo
EM L1 Halo

Highlight Arc List selection

Plot Tools

Undock Plot

Set Axis Limits

Zoom Reset

Additional Tools

Get Conic

Get Libration Point Orbit

Import Trajectory

Select from Arc List

Clip Selected

Unselect Current Arc

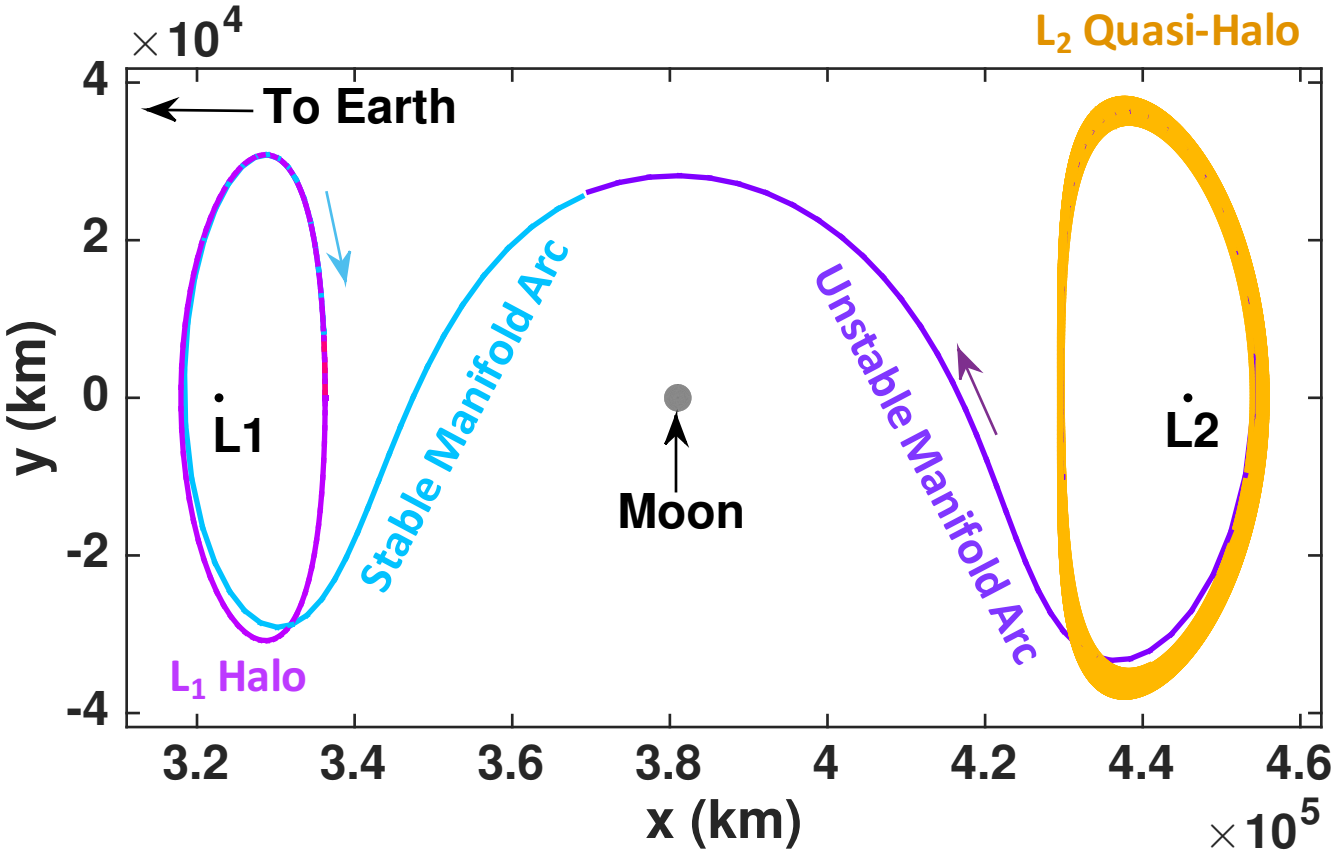
Save Design

Enter Filename...

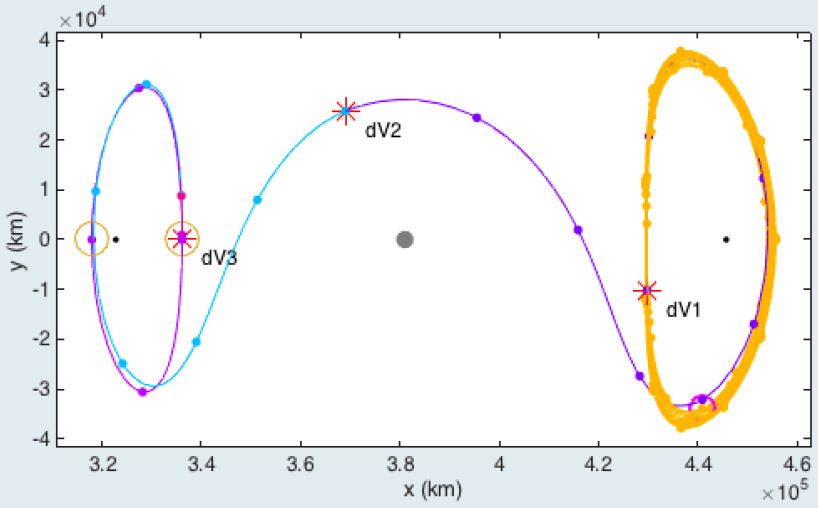
Add Nodes and Save

Transfer to Earth-Moon L_1

Initial Guess Construction



CR3B Corrections Environment



Problem Setup

Earth-Moon

Load Patch Point Data

ICATT_Paper_3BP_Uncor | Browse

Plot Initial Guess | Clear Plot

Differential Corrector

Exit Mode: Save & Continue / Discard

Tolerance: 1e-12 = 0.0003857 m = 1.023e-09 m/s

Max Iter: 20

Use fsolve

Correct Trajectory

Current Error: ||F|| = 1.8861e-14

Plot Converged Path | Clear Plot

Constraints

	Num Nodes	
Fix State	2	Select Nodes
Apsis		Select Nodes
Altitude		Select Nodes
Jacobi Const	1	Select Nodes
Delta-V Allowed	3	Select Nodes

Total dV = m/s

TOF = 312.534 Days

Maneuver Data

dV1 = 15.5532 m/s
dV2 = 109.9647 m/s
dV3 = 3.2661 m/s
Total dV = 128.784 m/s

Plot Tools

Undock Plot

Set Axis Limits

Arc Segment and Node Visibility

EM L1 Halo - 1

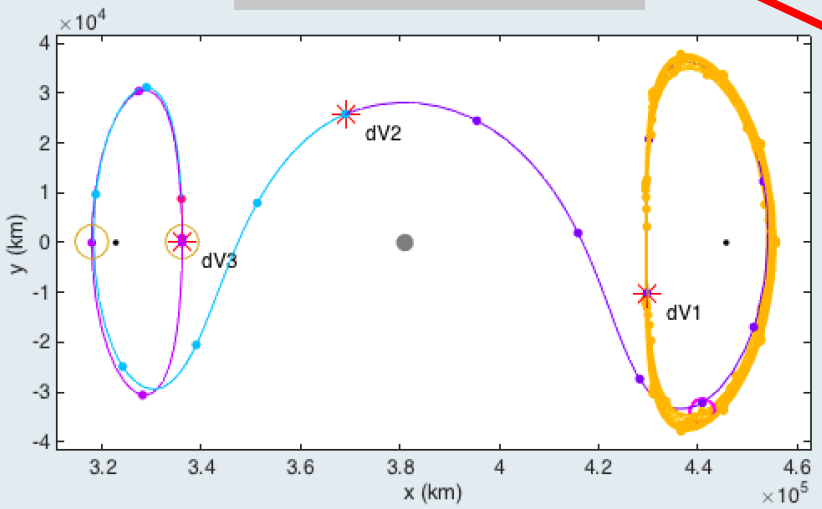
Show Segment | Show All | Hide All

Save Converged Trajectory Data

Enter Filename... | Save

CR3B Corrections Environment

Select system and import design



Problem Setup
Earth-Moon
Load Patch Point Data
ICATT_Paper_3BP_Uncor
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode: Save & Continue / Discard
Tolerance: 1e-12 = 0.0003857 m = 1.023e-09 m/s
Max Iter: 20
Use fsolve
Correct Trajectory
Current Error: ||F|| = 1.8861e-14
Plot Converged Path
Clear Plot

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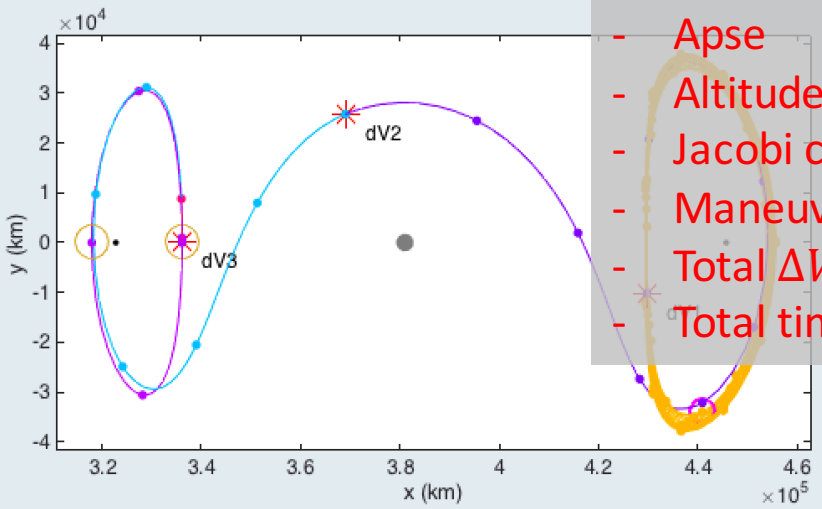
Total dV = 128.784 m/s

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

Save Converged Trajectory Data
Enter Filename...
Save

CR3B Corrections Environment

Constrain design:
- State
- Apse
- Altitude
- Jacobi constant
- Maneuver
- Total ΔV
- Total time-of-flight



Problem Setup
Earth-Moon
Load Patch Point Data
ICATT_Paper_3BP_Uncor
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode:
Save & Continue
Discard
Tolerance: 1e-12
= 0.0003857 m
= 1.023e-09 m/s
Max Iter: 20
Use fsolve
Correct Trajectory
Current Error: ||F|| = 1.8861e-14
Plot Converged Path
Clear Plot

Constraints

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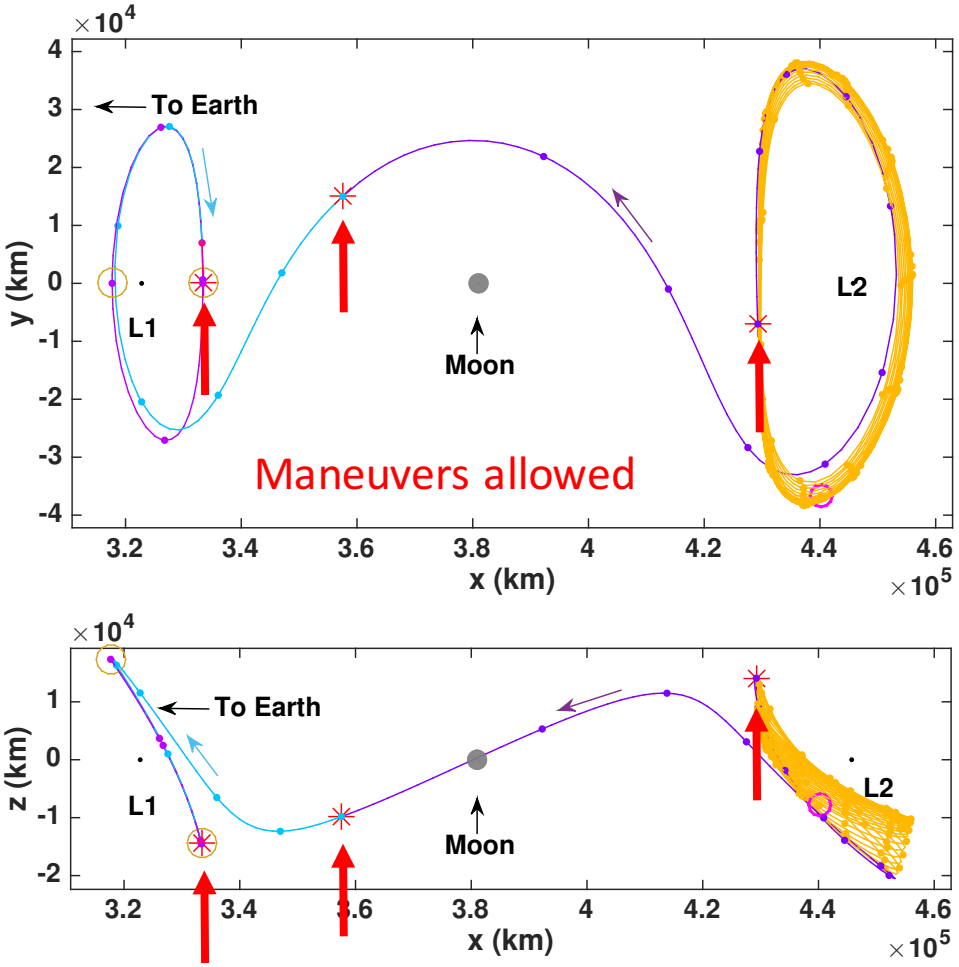
dV1 = 15.5532 m/s
dV2 = 109.9647 m/s
dV3 = 3.2661 m/s
Total dV = 128.784 m/s

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

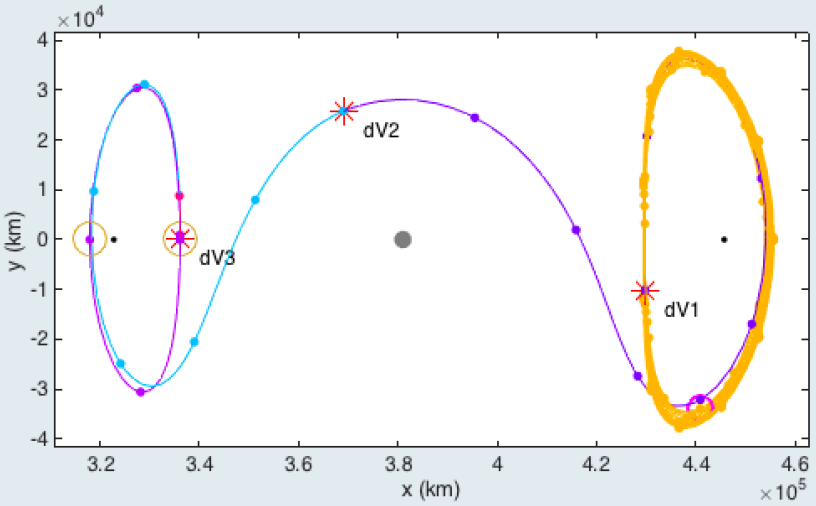
Save Converged Trajectory Data
Enter Filename...
Save

Transfer to Earth-Moon L_1

Constrained Design



CR3B Corrections Environment



Run multiple shooting differential corrections algorithm

Problem Setup
Earth-Moon
Load Patch Point Data
ICATT_Paper_3BP_Uncor
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode: Save & Continue / Discard
Tolerance: 1e-12 = 0.0003857 m = 1.023e-09 m/s
Max Iter: 20
Use fsolve
Correct Trajectory
Current Error: ||F|| = 1.8861e-14
Plot Converged Path
Clear Plot

Constraints
Num Nodes

Fix State	2	Select Nodes
Apsis		Select Nodes
Altitude		Select Nodes
Jacobi Const	1	Select Nodes
Delta-V Allowed	3	Select Nodes

Total dV = m/s
TOF = 312.534 Days

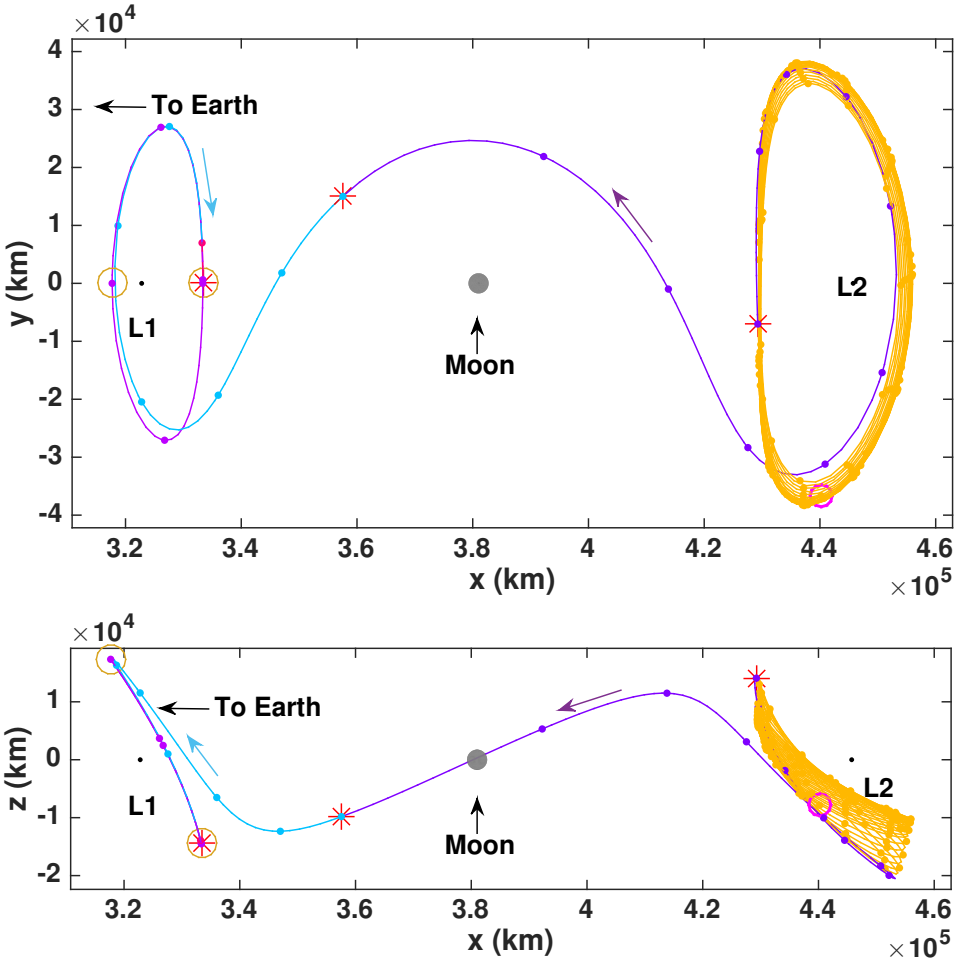
Maneuver Data
dV1 = 15.5532 m/s
dV2 = 109.9647 m/s
dV3 = 3.2661 m/s
Total dV = 128.784 m/s

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

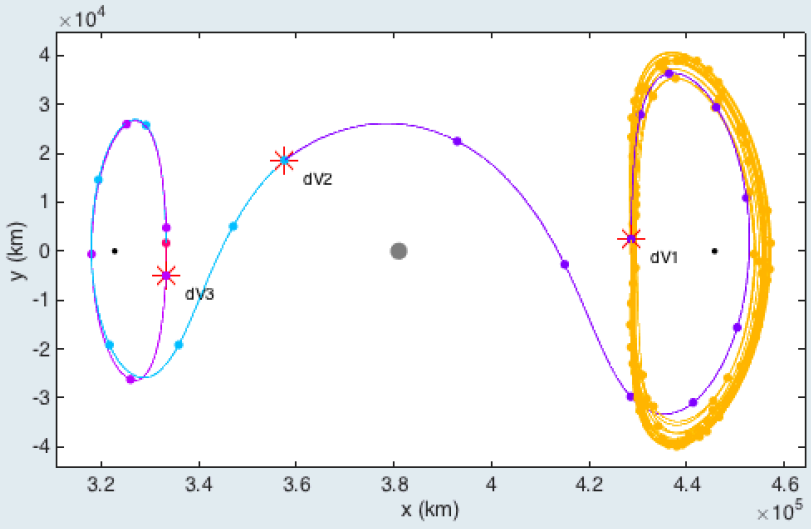
Save Converged Trajectory Data
Enter Filename...
Save

Transfer to Earth-Moon L_1

Corrected Trajectory



Ephemeris Corrections



Plot Tools

Undock Plot

Set Axis Limits

Arc Segment and Node Visibility

EM L1 Halo - 1

Show Segment

Show All

Hide All

Problem Setup

Define Initial Epoch

Earth-Moon

Moon

Perturbing Bodies:

Options: Mercury, Venus, Mars, Jupiter, Saturn, Neptune

Selected: Sun

Import Data

Load Patch Point Data

ICATT_Paper_3BP_Corre

Browse

Plot Initial Guess

Clear Plot

Differential Corrector

Exit Mode: Save & Continue / Discard

Tolerance: 1e-10 = 0.03857 m = 1.023e-07 m/s

Max Iter: 30

Use fsolve

Compute Derivatives: Analytically

Correct Trajectory

Current Error: ||F|| = 1.3374e-11

Plot Converged Path

Clear Plot

Save Converged Trajectory Data

Enter Filename...

Save

Constraints

Num Nodes

Fix State — Select Nodes

Apsis — Select Nodes

Altitude — Select Nodes

Inclination — Select Nodes

Epoch — Select Nodes

Delta-V Allowed: 3 — Select Nodes

Total dV = Desired d m/s

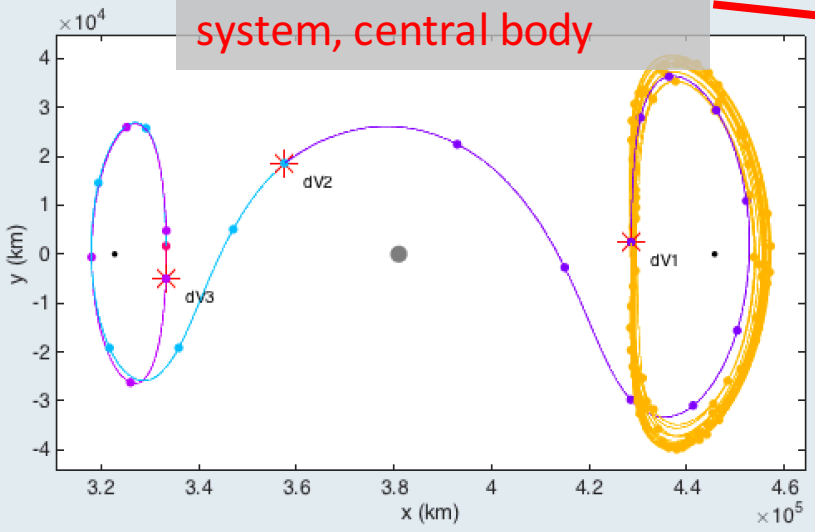
TOF = 311.645 Days

Maneuver Data

dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

Ephemeris Corrections

Define epoch, originating system, central body



Problem Setup
Define Initial Epoch
Earth-Moon
Moon

Perturbing Bodies:
Options: Mercury, Venus, Mars, Jupiter, Saturn, Neptune
Selected: Sun

Import Data
Load Patch Point Data
ICATT_Paper_3BP_Corre
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode: Save & Continue / Discard
Tolerance: 1e-10 = 0.03857 m = 1.023e-07 m/s
Max Iter: 30
Use fsolve
Compute Derivatives: Analytically
Correct Trajectory
Current Error: ||F|| = 1.3374e-11
Plot Converged Path
Clear Plot

Save Converged Trajectory Data
Enter Filename...
Save

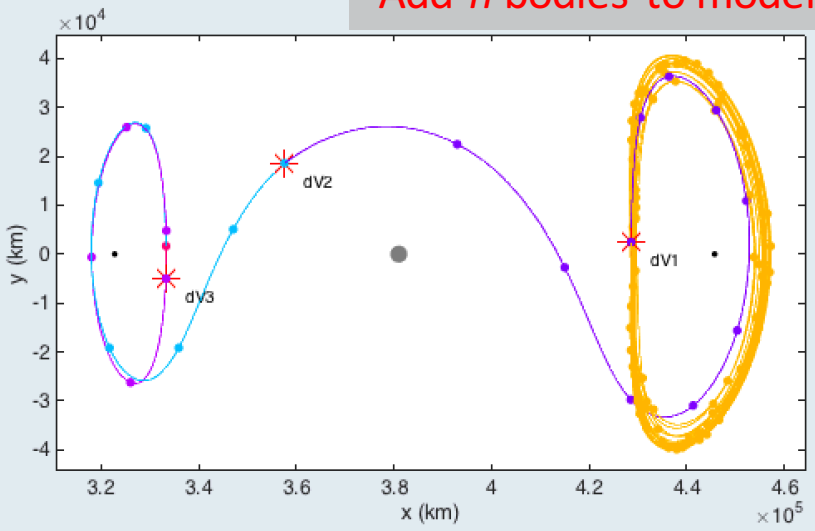
Constraints
Num Nodes
Fix State — Select Nodes
Apsis — Select Nodes
Altitude — Select Nodes
Inclination — Select Nodes
Epoch — Select Nodes
Delta-V Allowed: 3 — Select Nodes
Total dV = Desired d m/s
TOF = 311.645 Days

Maneuver Data
dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

Ephemeris Corrections

Add *n* bodies to model



Problem Setup

Define Initial Epoch

Earth-Moon

Moon

Perturbing Bodies:

Options: Mercury, Venus, Mars, Jupiter, Saturn, Neptune

Selected: Sun

Import Data

Load Patch Point Data

ICATT_Paper_3BP_Corre

Browse

Plot Initial Guess

Clear Plot

Differential Corrector

Exit Mode: Save & Continue / Discard

Tolerance: 1e-10 = 0.03857 m = 1.023e-07 m/s

Max Iter: 30 Use fsolve

Compute Derivatives: Analytically

Correct Trajectory

Current Error: ||F|| = 1.3374e-11

Plot Converged Path

Clear Plot

Save Converged Trajectory Data

Enter Filename...

Save

Constraints

Num Nodes

Fix State — Select Nodes

Apsis — Select Nodes

Altitude — Select Nodes

Inclination — Select Nodes

Epoch — Select Nodes

Delta-V Allowed: 3 — Select Nodes

Total dV = Desired d' m/s

TOF = 311.645 Days

Maneuver Data

dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

Plot Tools

Undock Plot

Set Axis Limits

Arc Segment and Node Visibility

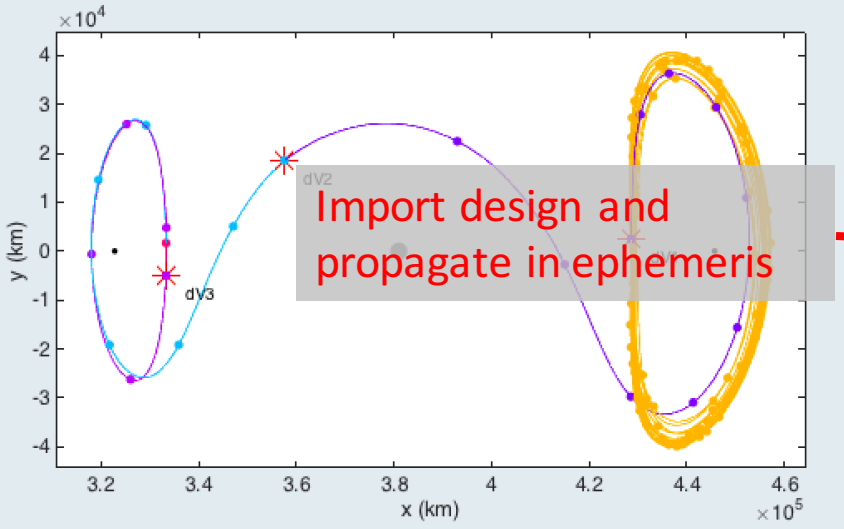
EM L1 Halo - 1

Show Segment

Show All

Hide All

Ephemeris Corrections



Import design and propagate in ephemeris

Problem Setup
Define Initial Epoch
Earth-Moon
Moon
Perturbing Bodies:
Options
Mercury
Venus
Mars
Jupiter
Saturn
Neptune
Selected
Sun

Import Data
Load Patch Point Data
ICATT_Paper_3BP_Corre
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode:
Save & Continue
Discard
Tolerance:
1e-10
= 0.03857 m
= 1.023e-07 m/s
Max Iter:
30
Use fsolve
Compute Derivatives:
Analytically
Correct Trajectory
Current Error:
||F|| = 1.3374e-11
Plot Converged Path
Clear Plot

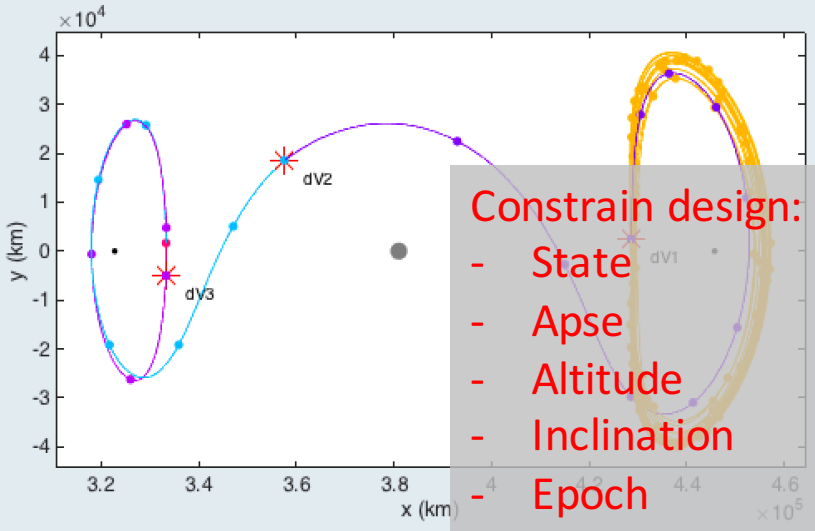
Save Converged Trajectory Data
Enter Filename...
Save

Constraints
Num Nodes
Fix State
Apsis
Altitude
Inclination
Epoch
Delta-V Allowed
3
Select Nodes
Total dV =
Desired d
m/s
TOF =
311.645
Days

Maneuver Data
dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

Ephemeris Corrections



Constrain design:
- State
- Apse
- Altitude
- Inclination
- Epoch
- Maneuver
- Total ΔV
- Total time-of-flight

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

Problem Setup
Define Initial Epoch
Earth-Moon
Moon
Perturbing Bodies:
Options: Mercury, Venus, Mars, Jupiter, Saturn, Neptune
Selected: Sun

Import Data
Load Patch Point Data
ICATT_Paper_3BP_Corre
Browse
Plot Initial Guess
Clear Plot

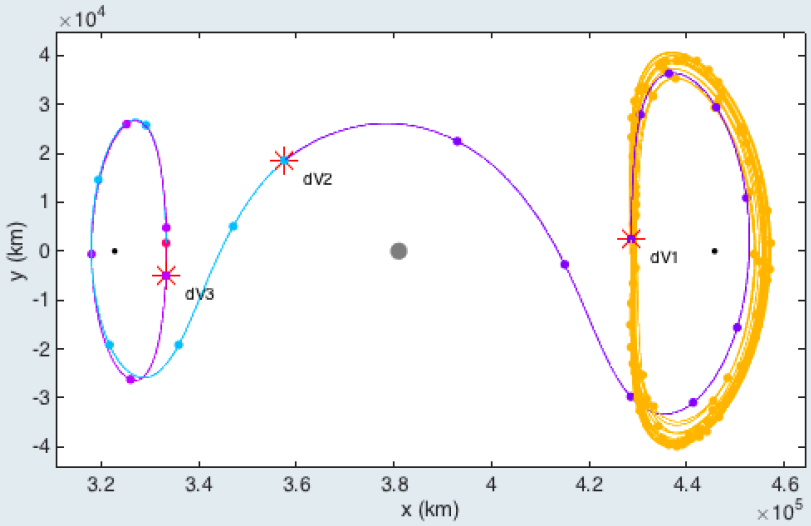
Differential Corrector
Exit Mode: Save & Continue / Discard
Tolerance: 1e-10 = 1.023e-07 m/s
Max Iter: 30
Use fsolve
Compute Derivatives: Analytically
Correct Trajectory
Current Error: ||F|| = 1.3374e-11
Plot Converged Path
Clear Plot

Save Converged Trajectory Data
Enter Filename...
Save

Constraints
Num Nodes
Fix State — Select Nodes
Apsis — Select Nodes
Altitude — Select Nodes
Inclination — Select Nodes
Epoch — Select Nodes
Delta-V Allowed: 3 — Select Nodes
Total dV = Desired d m/s
TOF = 311.645 Days

Maneuver Data
dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

Ephemeris Corrections



Customize and run differential corrector

Plot Tools
Undock Plot
Set Axis Limits
Arc Segment and Node Visibility
EM L1 Halo - 1
Show Segment
Show All
Hide All

Problem Setup
Define Initial Epoch
Earth-Moon
Moon
Perturbing Bodies:
Options: Mercury, Venus, Mars, Jupiter, Saturn, Neptune
Selected: Sun

Import Data
Load Patch Point Data
ICATT_Paper_3BP_Corre
Browse
Plot Initial Guess
Clear Plot

Differential Corrector
Exit Mode: Save & Continue / Discard
Tolerance: 1e-10 = 0.03857 m = 1.023e-07 m/s
Max Iter: 30
Use fsolve
Compute Derivatives: Analytically
Correct Trajectory
Current Error: ||F|| = 1.3374e-11
Plot Converged Path
Clear Plot

Save Converged Trajectory Data
Enter Filename...
Save

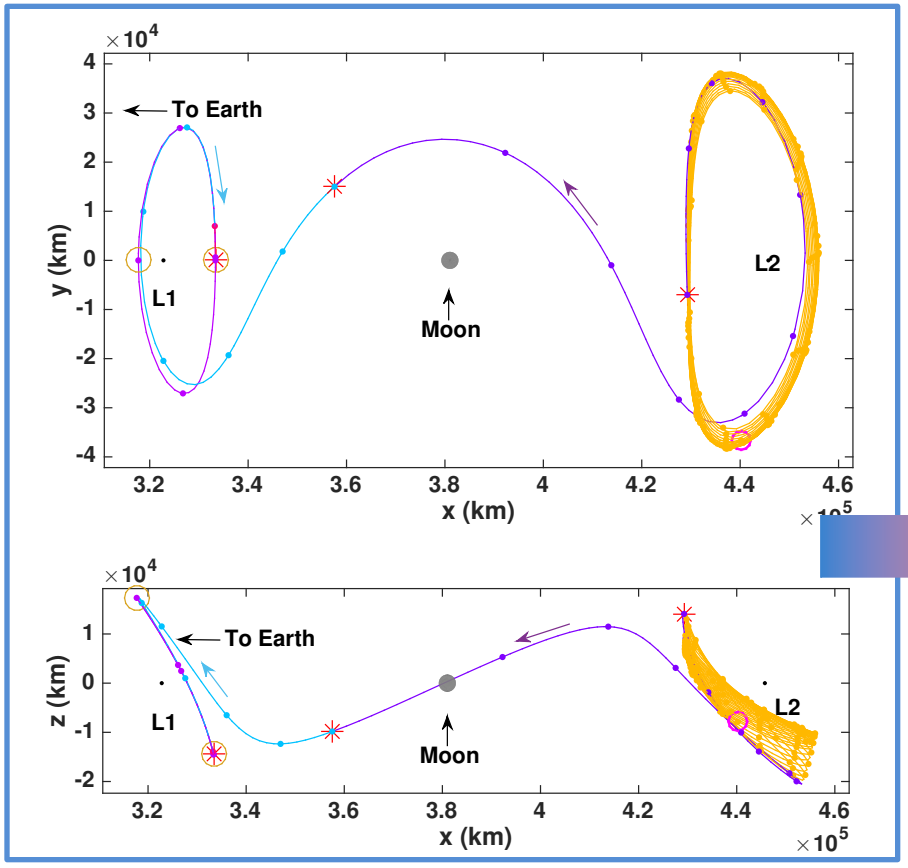
Constraints
Num Nodes
Fix State — Select Nodes
Apsis — Select Nodes
Altitude — Select Nodes
Inclination — Select Nodes
Epoch — Select Nodes
Delta-V Allowed: 3 — Select Nodes
Total dV = Desired d m/s
TOF = 311.645 Days

Maneuver Data
dV1 = 36.498 m/s
dV2 = 43.4861 m/s
dV3 = 7.8265 m/s
Total dV = 87.8106 m/s

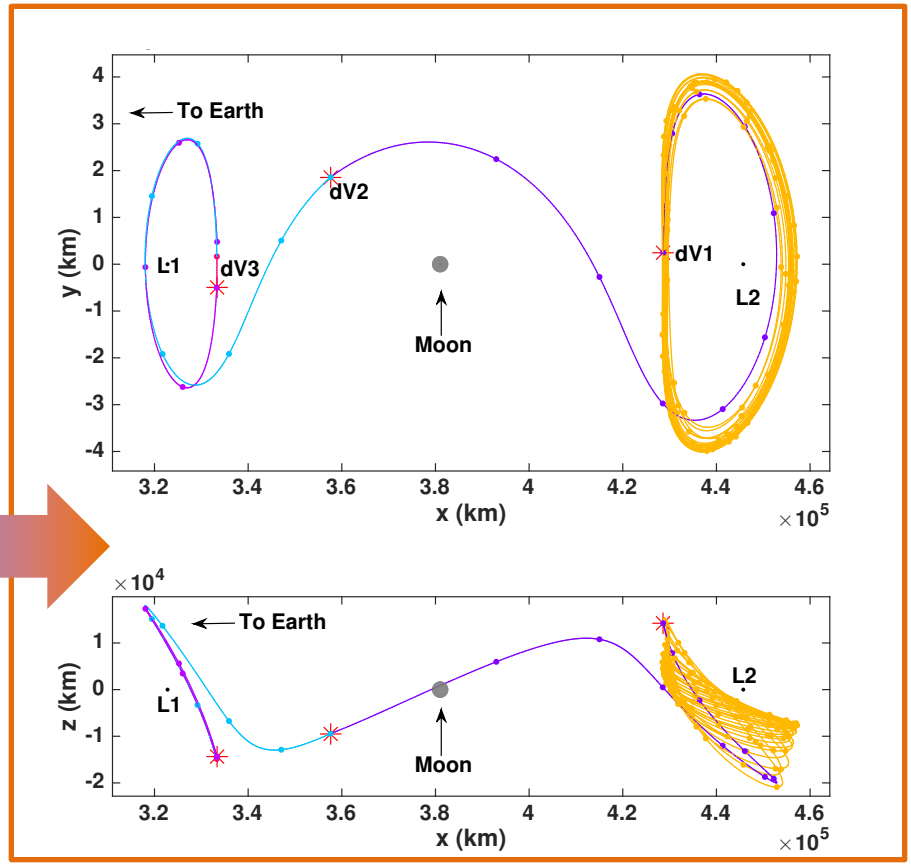
Transfer to Earth-Moon L_1

Continuous Trajectory in Ephemeris

Earth-Moon CR3BP



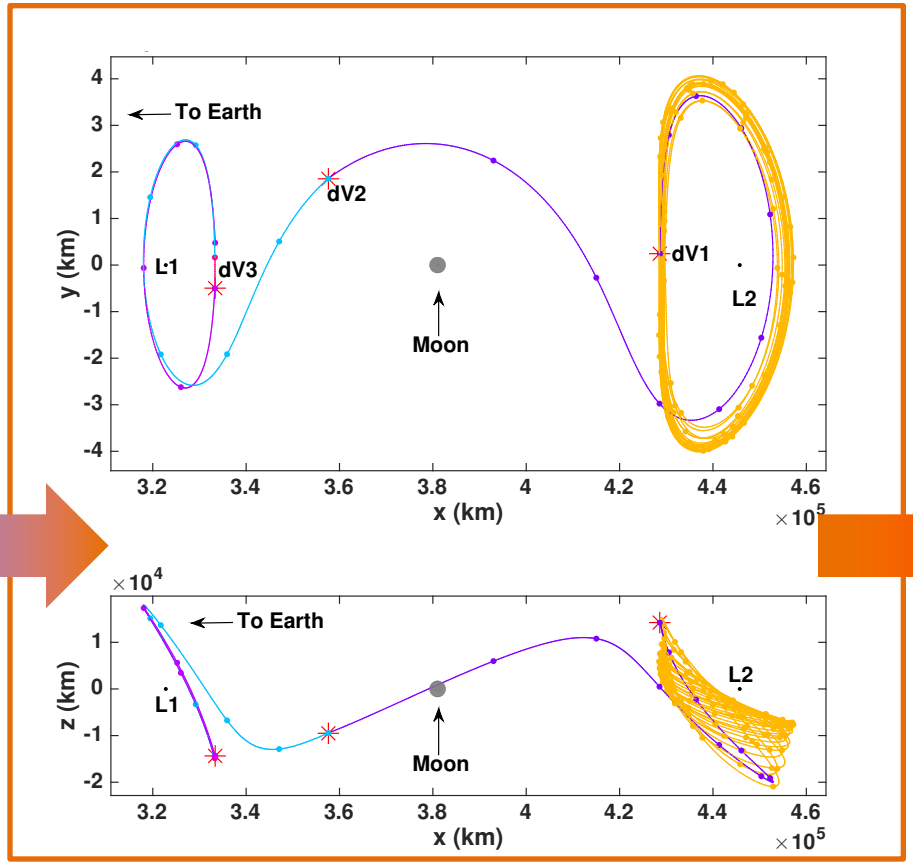
Sun-Earth-Moon Ephemeris



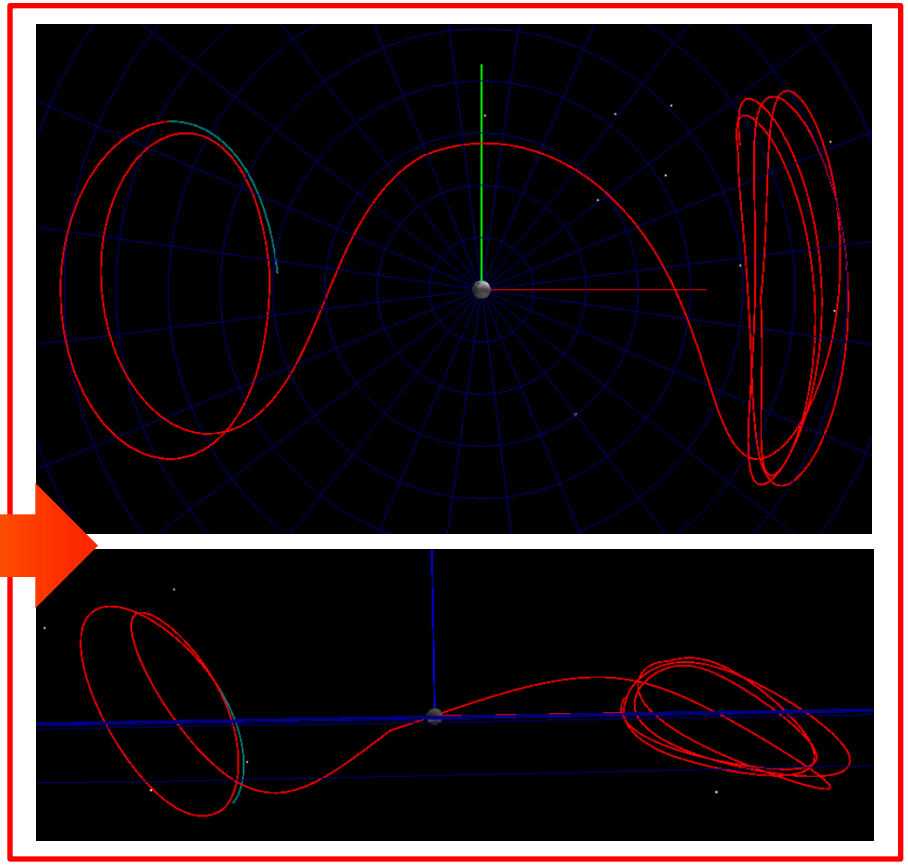
Transfer to Earth-Moon L_1

Continuous Trajectory in Ephemeris

Sun-Earth-Moon Ephemeris



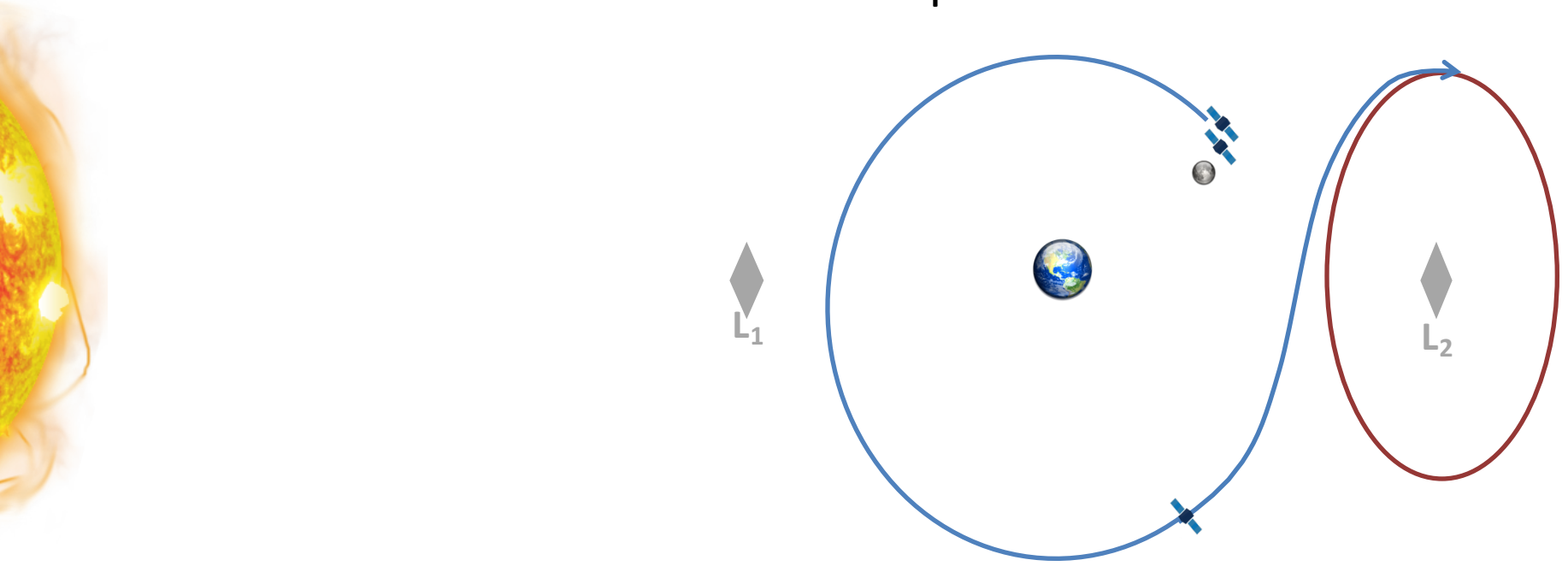
GMAT Ephemeris



Point Masses: Sun, Earth
Harmonics: Moon

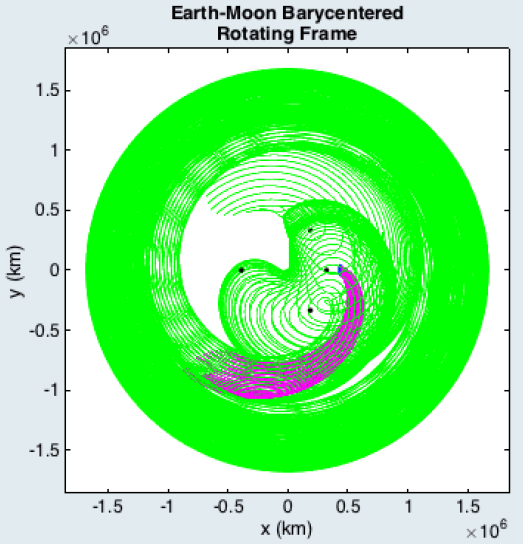
Transfer to Sun-Earth L_2

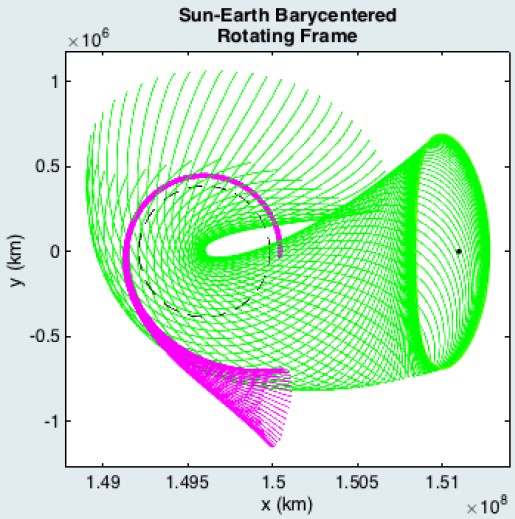
Mission Description



- Service a space observatory at Sun-Earth L_2
- Leverage dynamical structures from Sun-Earth and Earth-Moon systems
- Design transfer in ATD System Blending Module

System Blending Module





EM Trajectory Initial Phase Angle
beta0, deg 0 (Initial phase angle)
Select Transfer and Sync S-E Frame

SE Trajectory Initial Phase Angle
alpha0, deg 0 (Initial phase angle)
Select Transfer and Sync E-M Frame

Procedure
1. Select system transfer
2. Include additional arcs in arc lists
3. Sort arc list segments
4. Save design and determine epoch

Additional Tools
Get Conic | Import Trajectory
Clip Selected | Unselect Current Arc

CR3B Orbits and Manifolds
Sun-Earth
L2 S Halo
Plot Family
Explore Catalog
Select Trajectory
Period 180.301 days
Jacobi Value 3.00081
Stability eig_u = 1649.5308, ei
Hide Unselected Orbits
Clear All Families

Compute Manifolds
Stable / Unstable
- Step / + Step
Manifolds 50
Prop. Time (days) -220
Propagate Manifolds
Select Manifold
Hide Unselected Manifolds
Clear All Manifolds

Assemble Arc Segments
Select Arc Color
SE L2 Halo
Save to List
Select From List
Delete from List
Enter Filename...
Add Nodes and Save

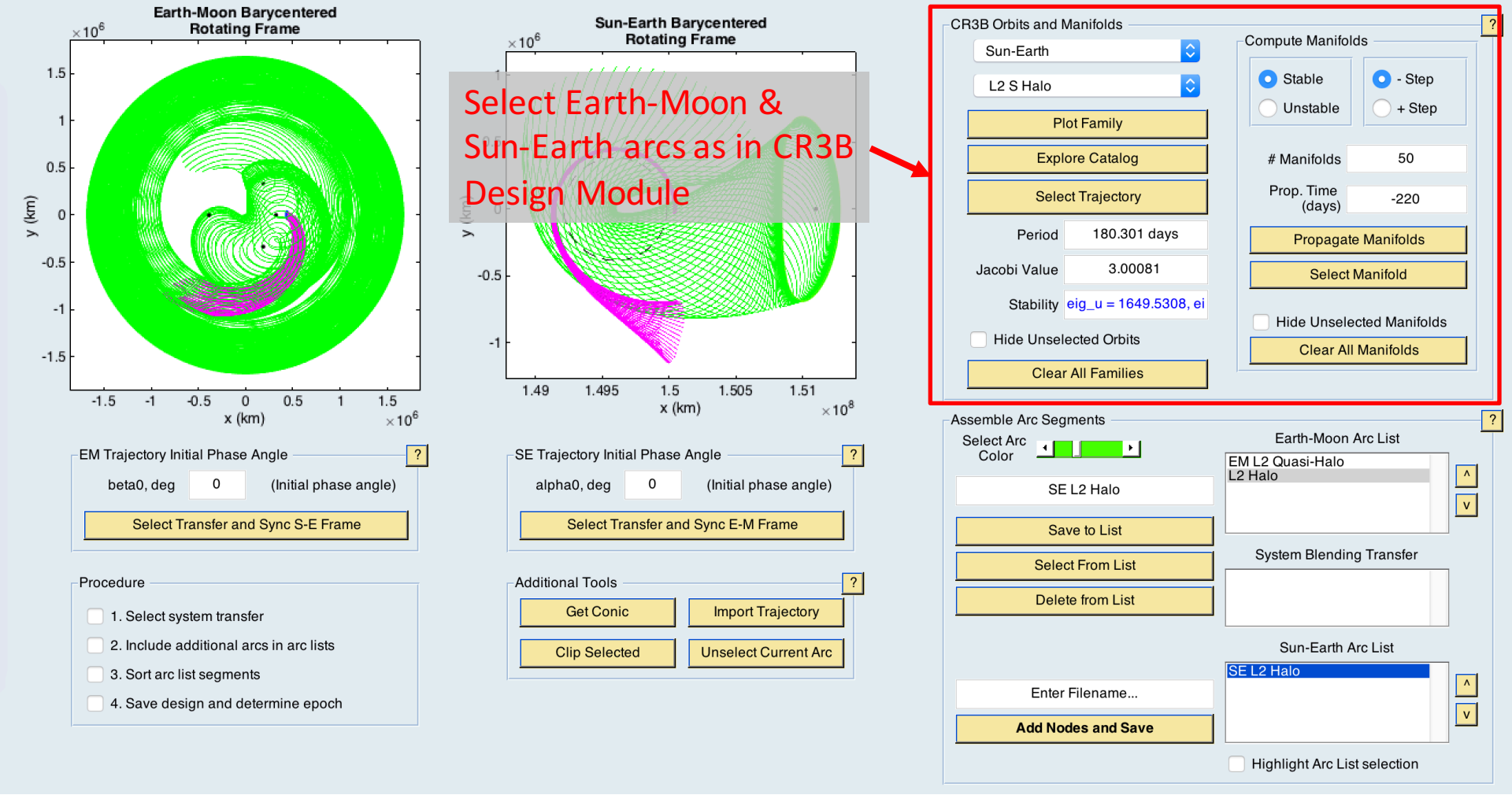
Earth-Moon Arc List
EM L2 Quasi-Halo
L2 Halo

System Blending Transfer

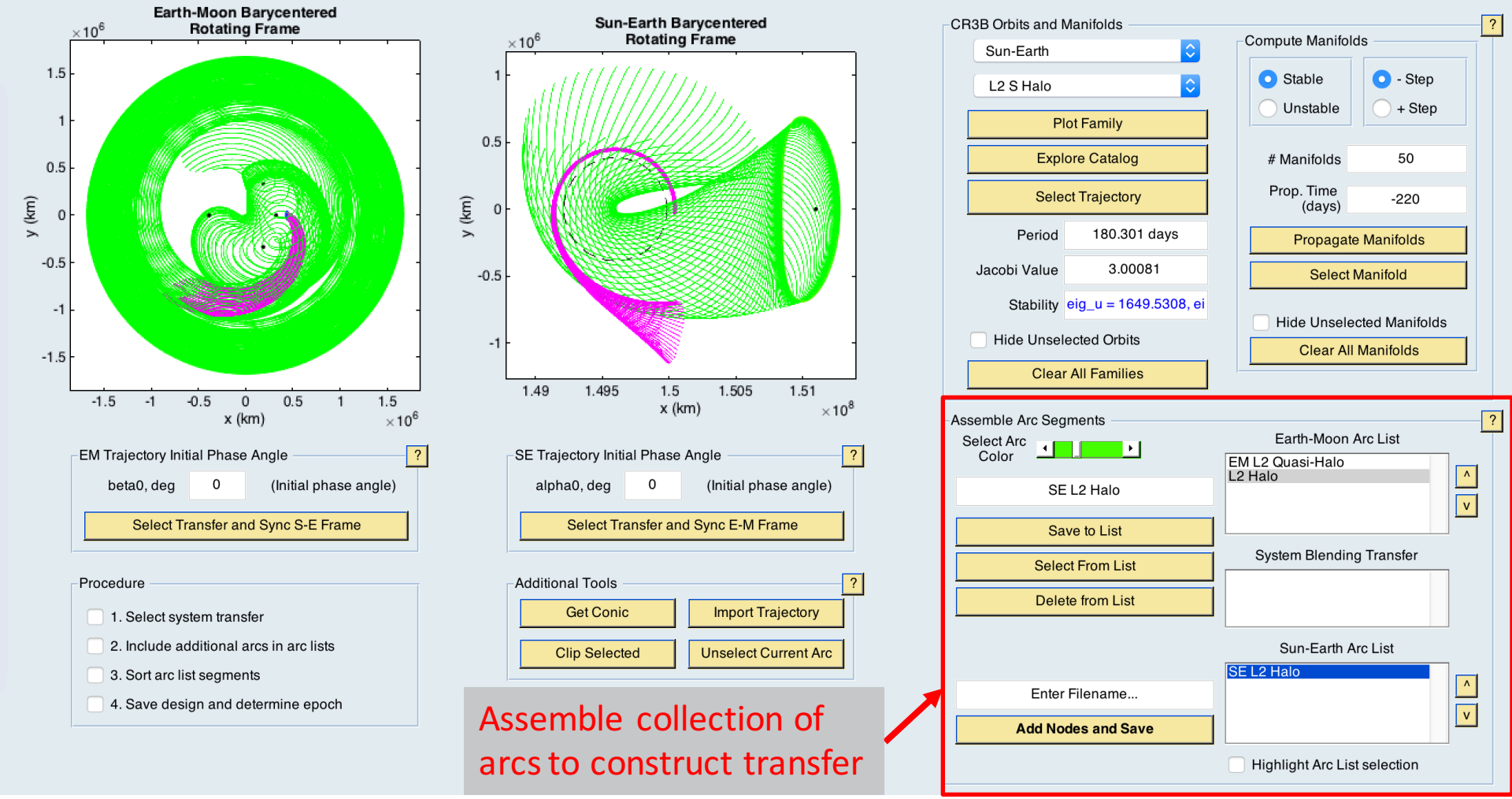
Sun-Earth Arc List
SE L2 Halo

Highlight Arc List selection

System Blending Module



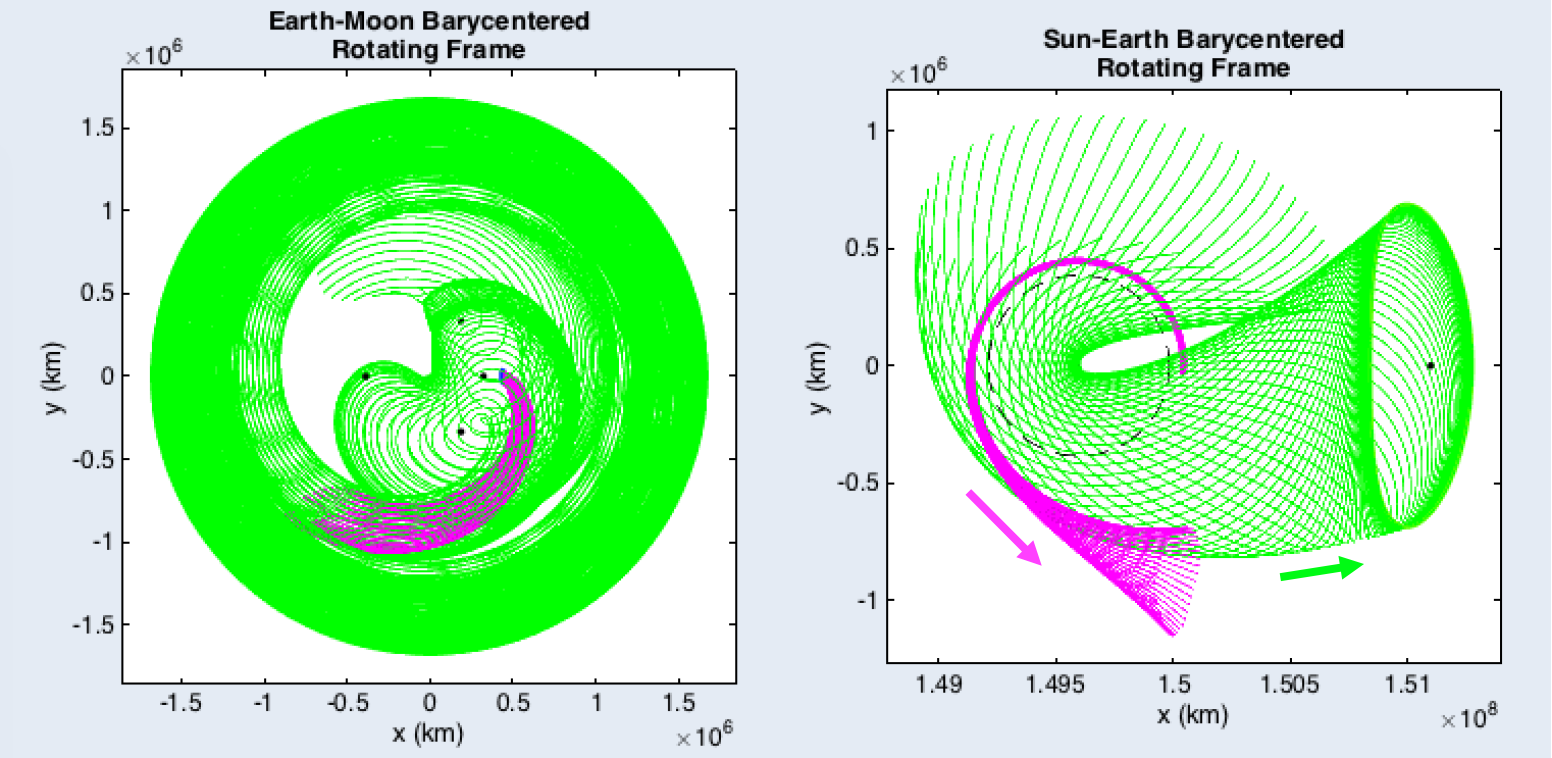
System Blending Module



Assemble collection of arcs to construct transfer

Transfer to Sun-Earth L_2

System-to-System Manifold Connection

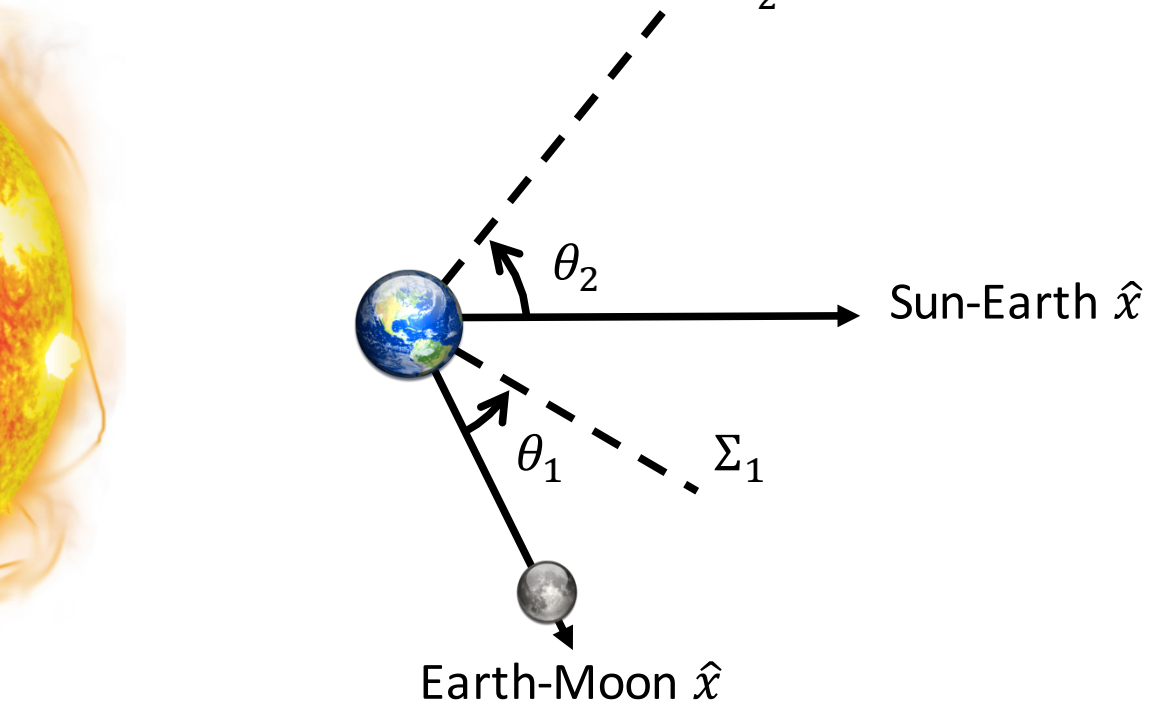


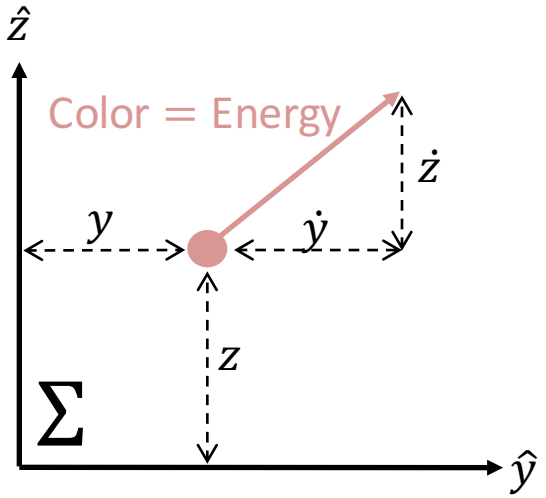
- Manifold arcs from Earth-Moon L_2 to Sun-Earth L_2
- Next step: Identify connection between manifolds

Transfer to Sun-Earth L_2

Locate System Connections

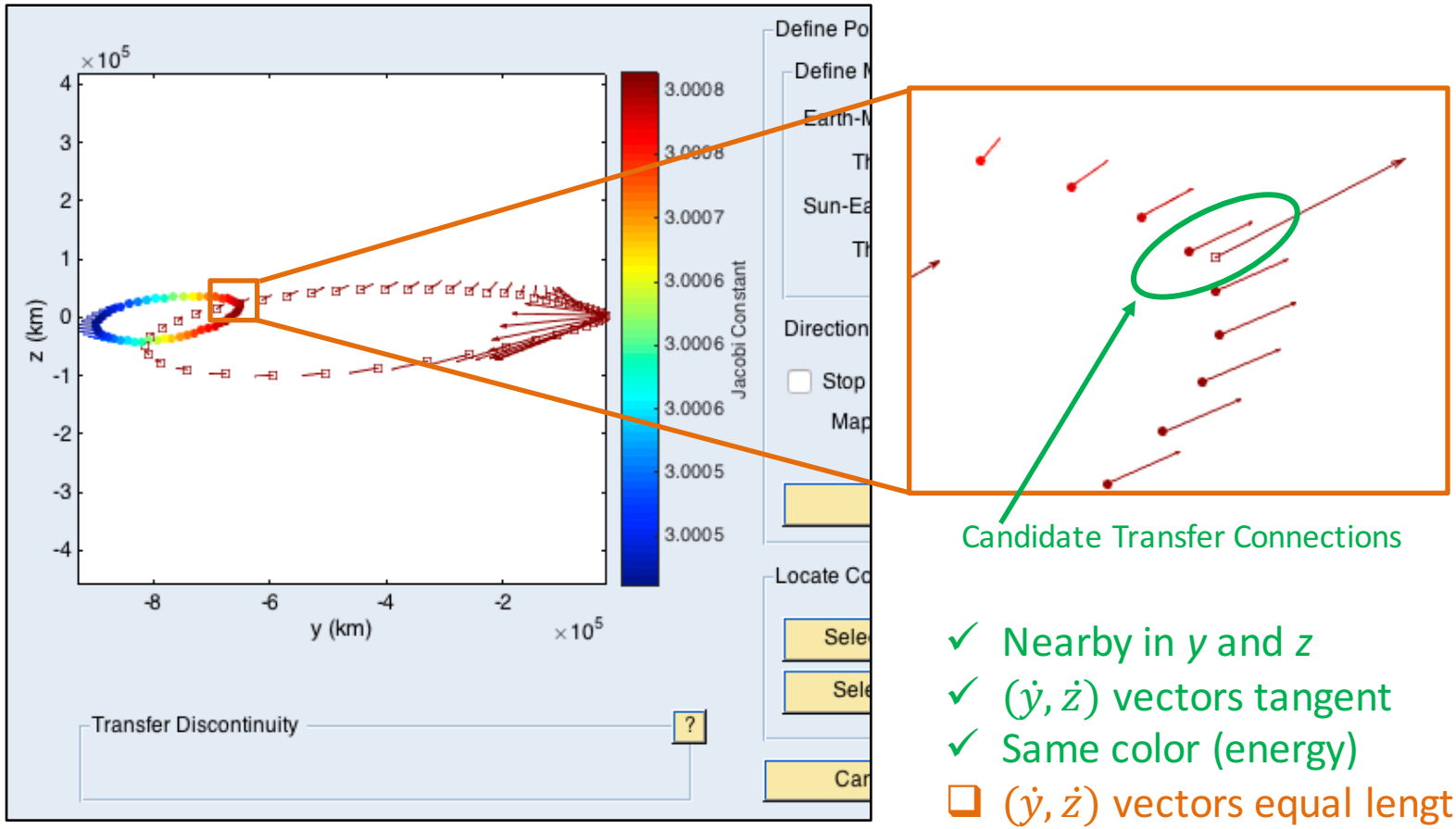
- Employ higher-dimensional Poincaré mapping





Transfer to Sun-Earth L_2

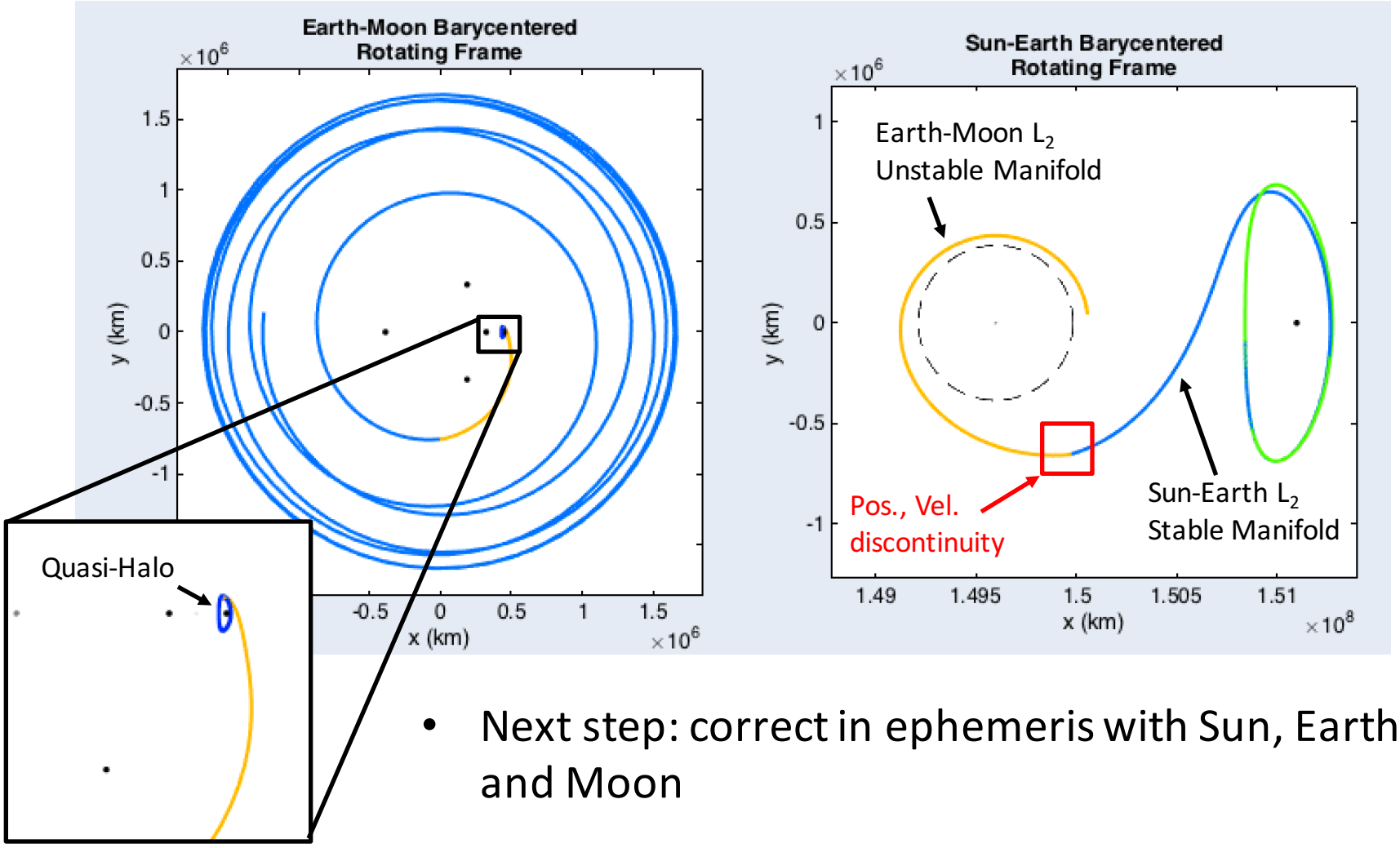
Locate System Connections



- ✓ Nearby in y and z
- ✓ $(\dot{y}, \dot{z})$ vectors tangent
- ✓ Same color (energy)
- ❑ $(\dot{y}, \dot{z})$ vectors equal length

Transfer to Sun-Earth L_2

System-to-System Transfer Design

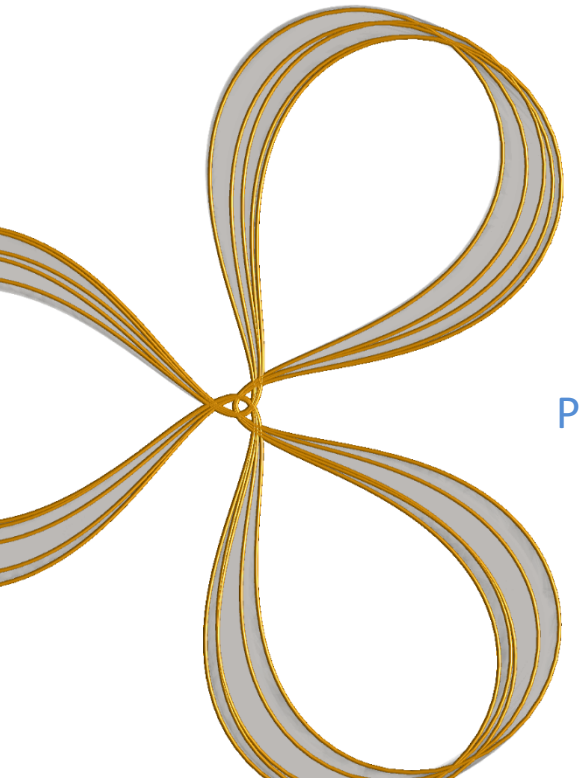


- Next step: correct in ephemeris with Sun, Earth, and Moon

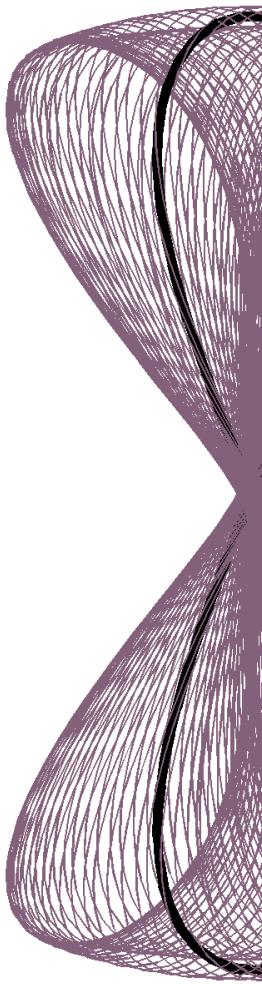
Summary

- ATD offers framework to explore natural dynamical structures in CR3BP
- Interactive design environment to construct transfers leveraging natural structures
- Multiple shooting corrections available in CR3BP, Ephemeris
- Output to operational-level software, e.g., GMAT

An Interactive Trajectory Design Environment Leveraging Dynamical Structures in Multi-Body Regimes



Thank You!



Acknowledgements:

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NASA Goddard Space Flight Center