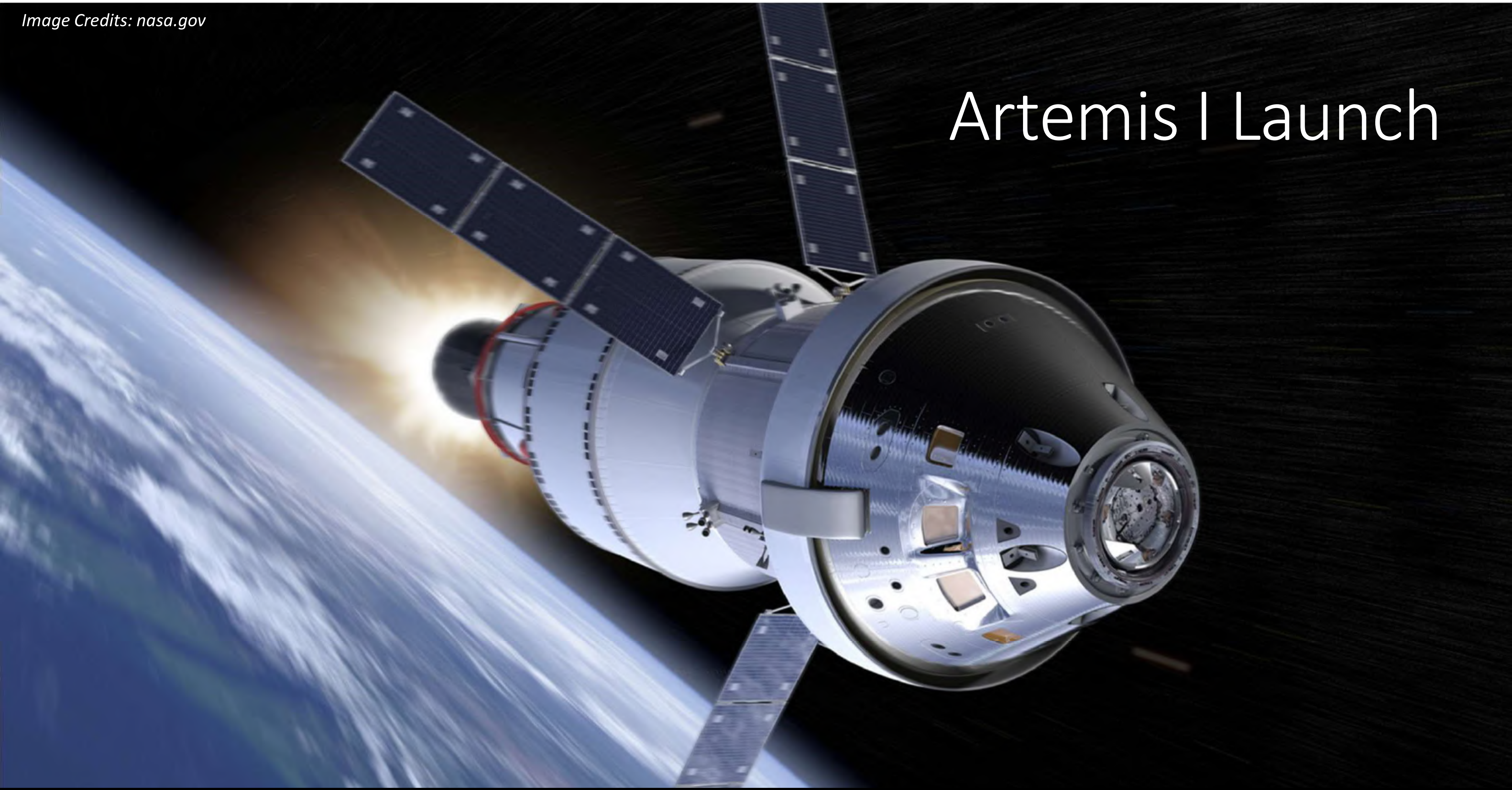
A Trajectory Design Framework Leveraging Low-Thrust for the Lunar IceCube Mission

ROBERT PRITCHETT, KATHLEEN HOWELL, DAVID FOLTA

Artemis I Launch



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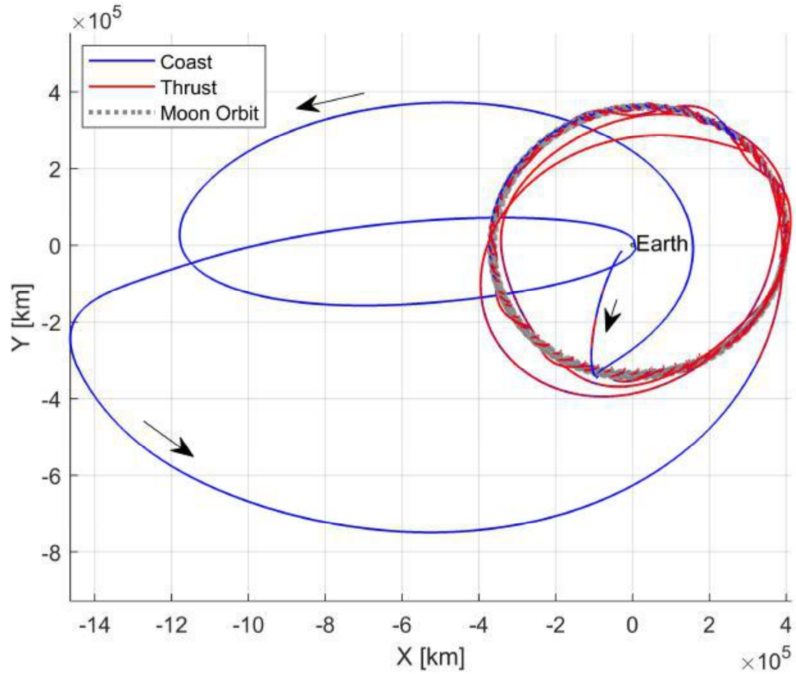
Lunar IceCube

- Goal: Study water transport on lunar surface
- Destination: 100-km x 5000-km lunar orbit
- Physical Specifications: 6U CubeSat, with Busek BIT-3 ion engine.

Spacecraft Parameter	Nominal Value
Initial Mass, m_0	$14\ kg$
Maximum Thrust, T_{max}	$1.24\ mN$
Maximum Acceleration, a_{max}	$8.857 \times 10^{-5}\ m/s^2$
Specific Impulse, I_{sp}	2640 sec

Challenges and Approach

- Challenges:
  - Large change in energy
  - Primary payload takes priority
- Goal: Develop *adaptable* and *robust* design framework
- Approach – Key Elements:
  - Bicircular Restricted Four-Body Problem
  - Staging orbit
  - Direct collocation



Lunar IceCube baseline trajectory in the J2000 inertial frame.

Outline

I. Background

II. Trajectory Design Framework

III. Sample Trajectory Design

IV. Concluding Remarks

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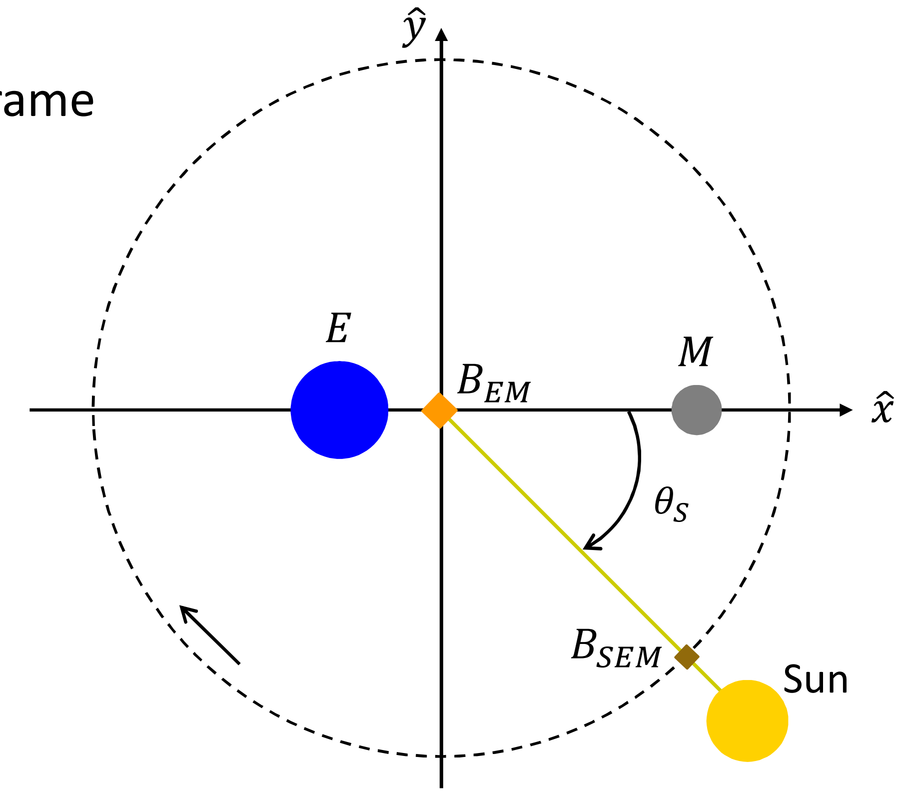
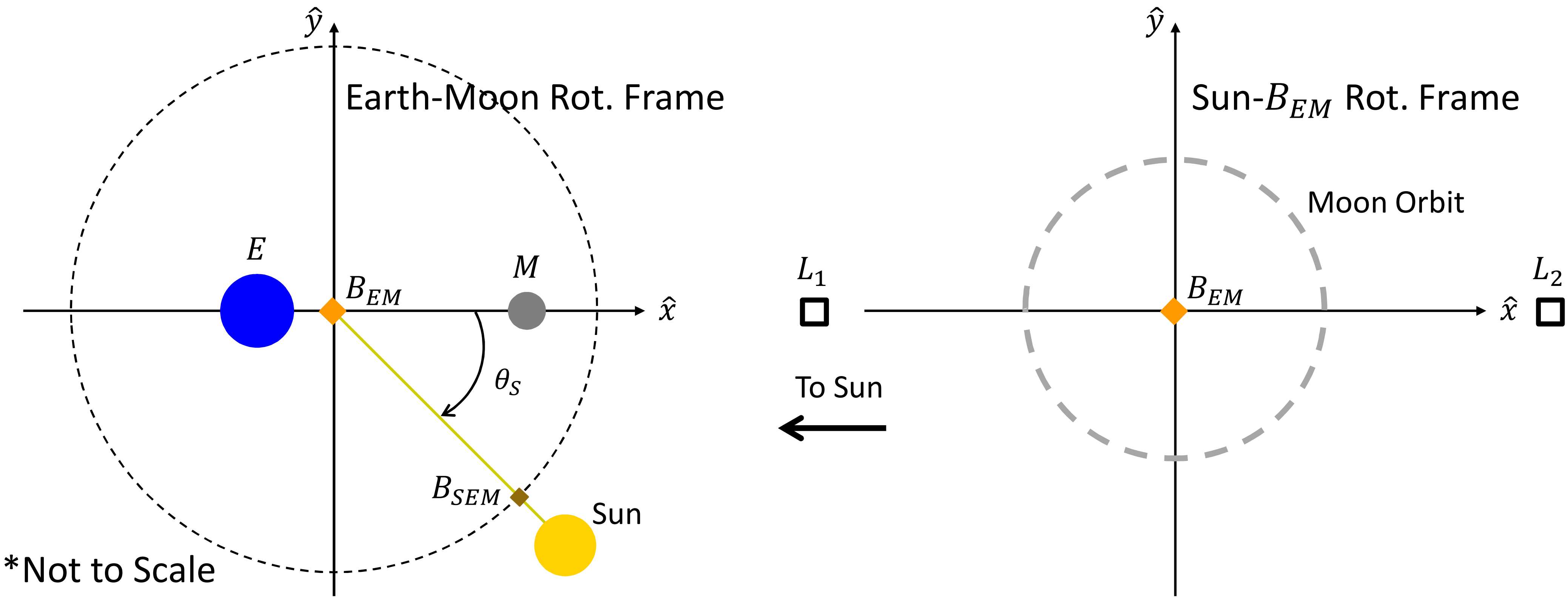
Background – Dynamical Model: BCR4BP

Earth-Moon Rot. Frame

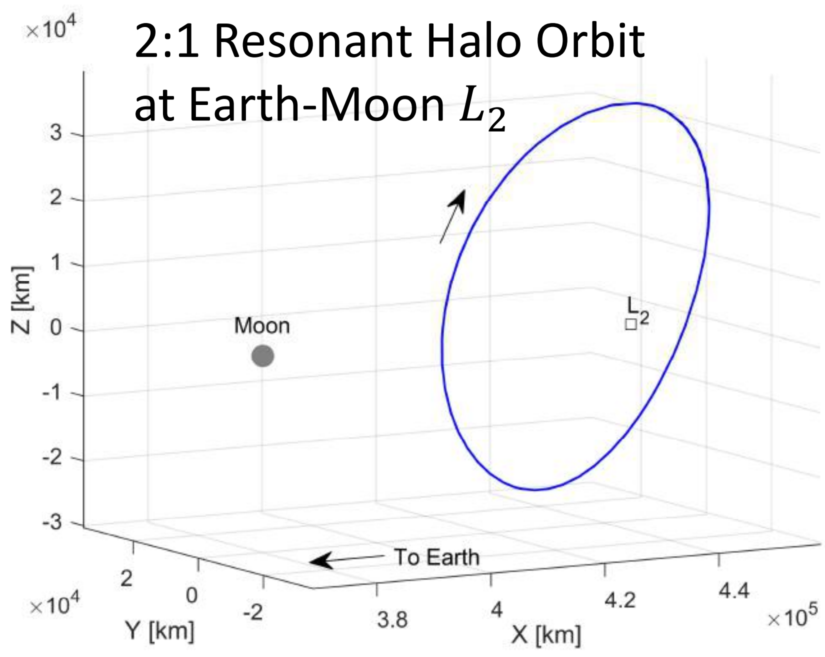


*Not to Scale

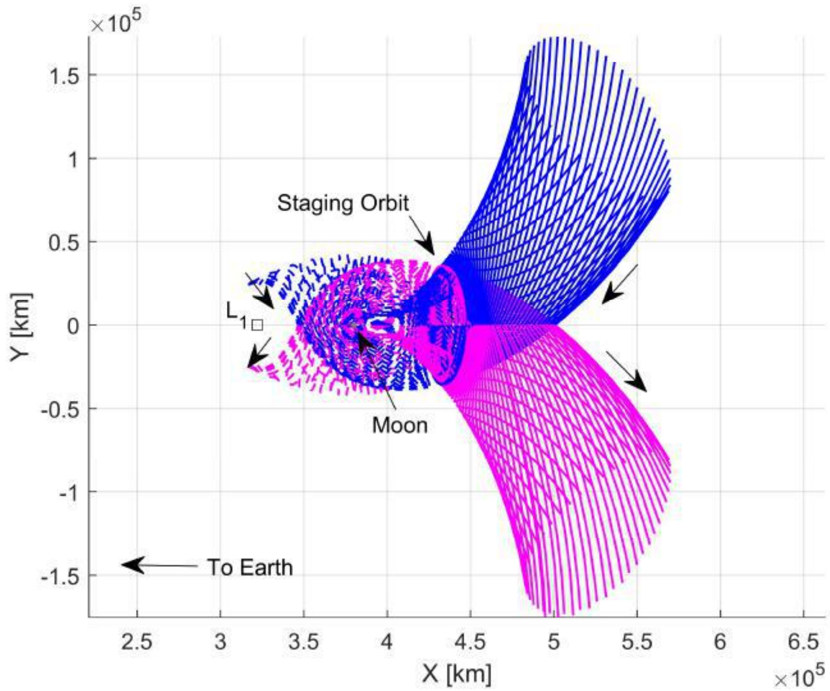
Background – Dynamical Model: BCR4BP



Background – Dynamical Model: BCR4BP



Staging Orbit



Manifolds of Staging Orbit

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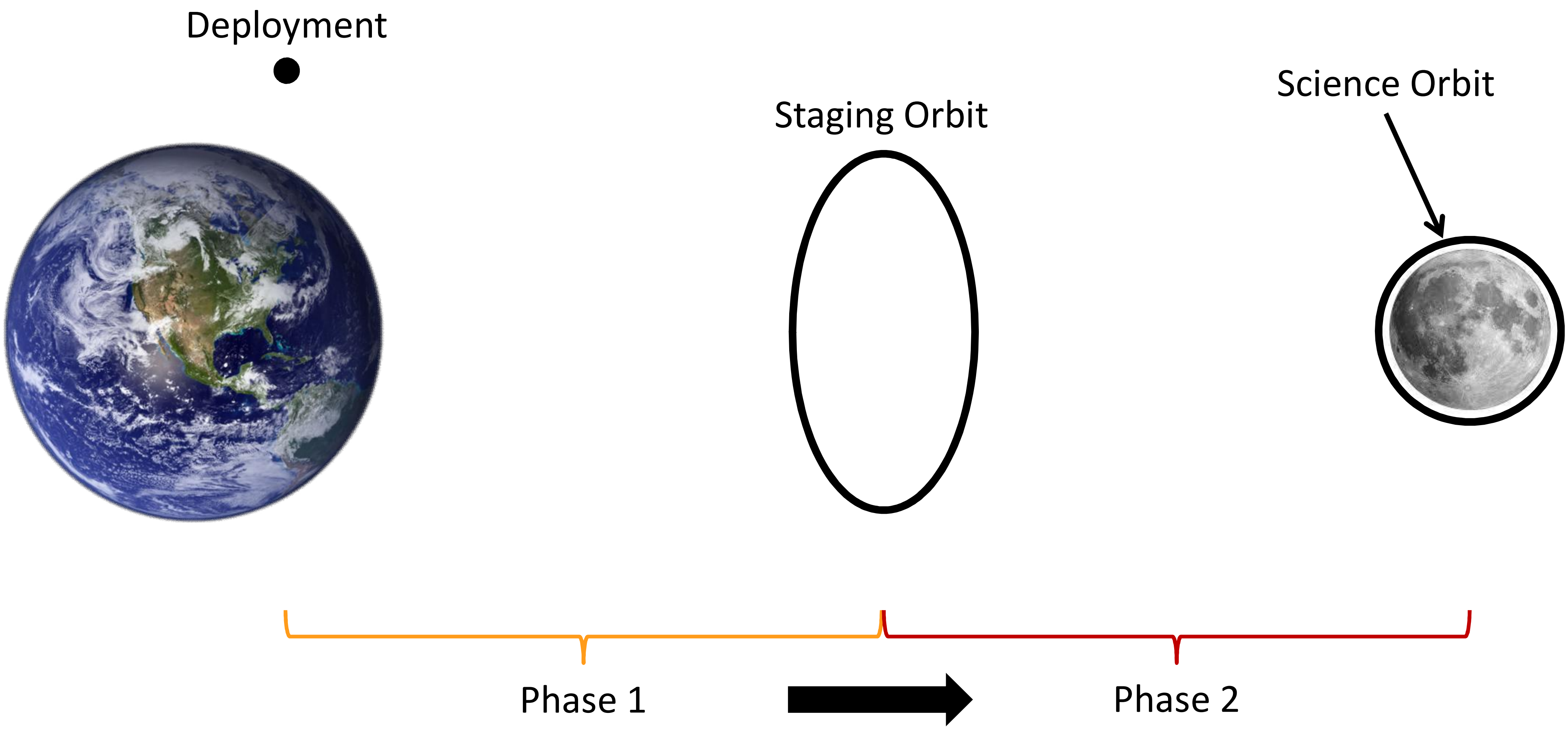
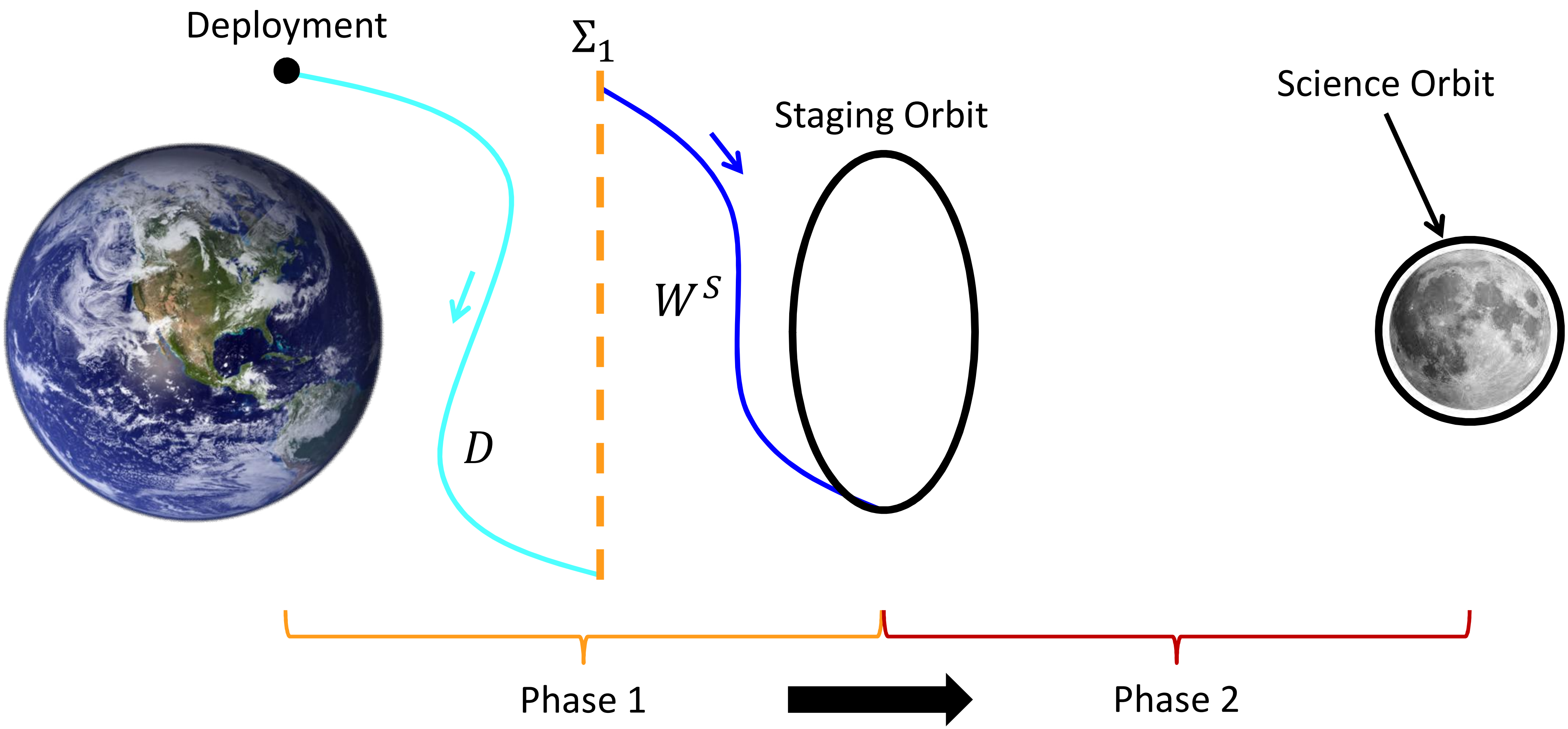
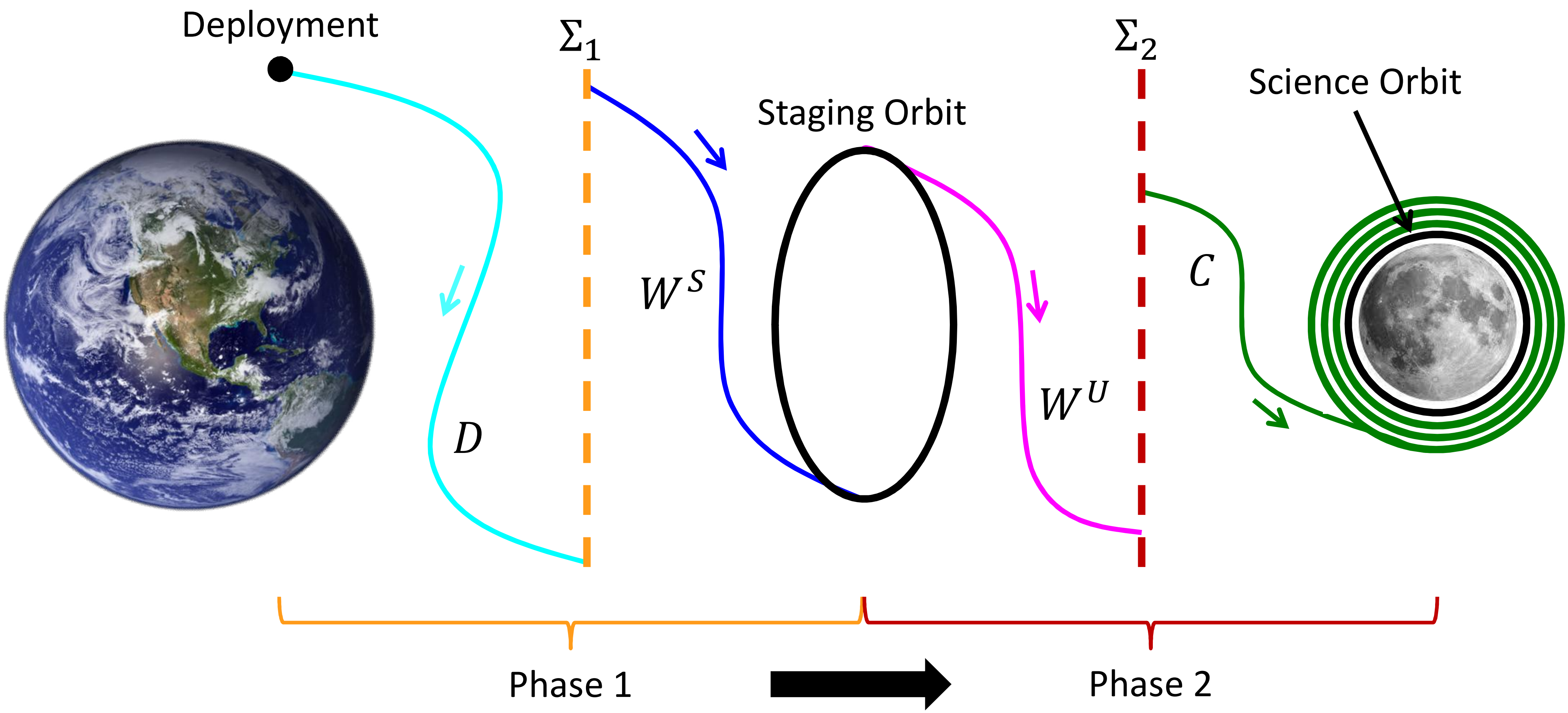
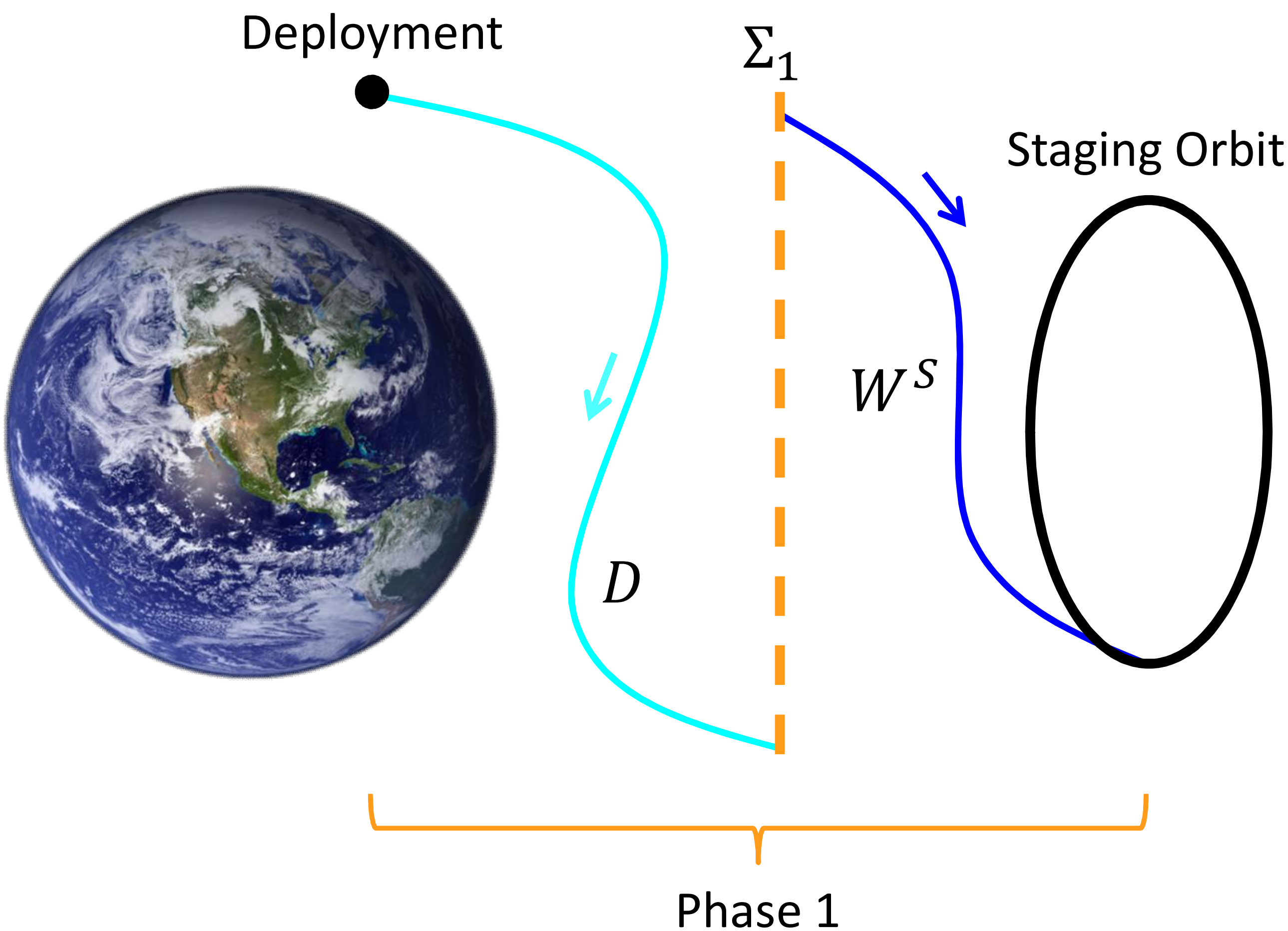
Deployment
Science Orbit


Deployment
Staging Orbit
Science Orbit
Phase 1
Phase 2

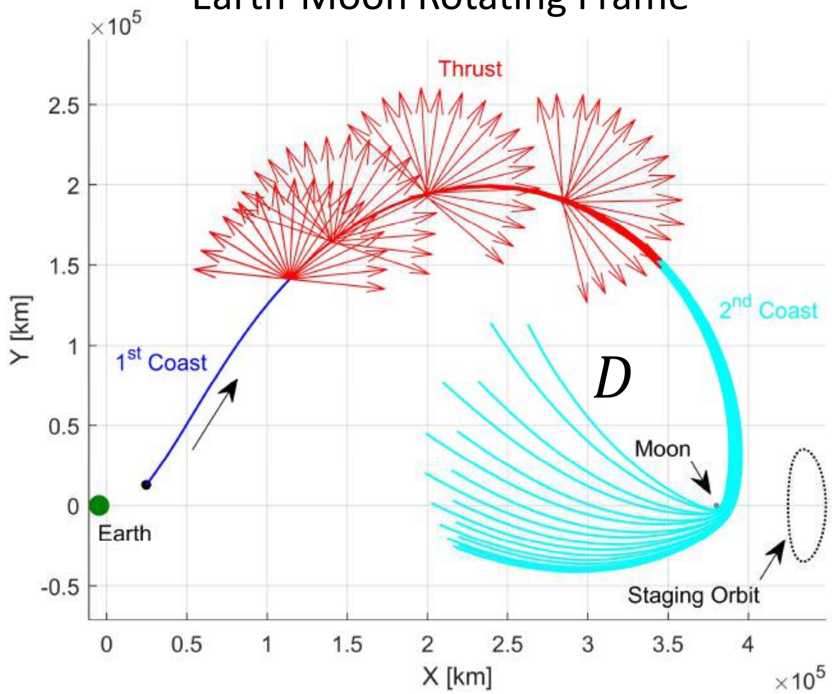

Deployment
Σ_1
Staging Orbit
Science Orbit
W^S
D
Phase 1
Phase 2


Deployment
Σ_1
Σ_2
Science Orbit
Staging Orbit
W^S
W^U
C
D
Phase 1
Phase 2


Deployment
Σ_1
Staging Orbit
W^s
D
Phase 1

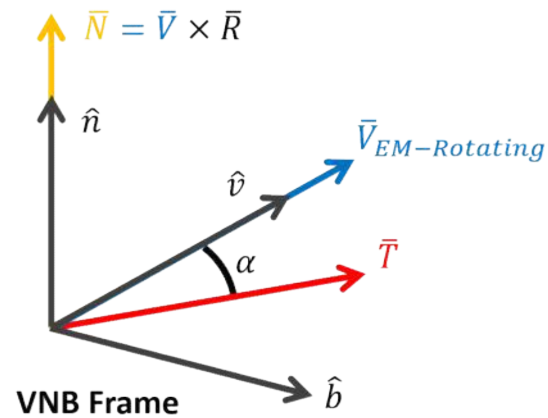
Design Framework – Phase 1: Forward

Earth-Moon Rotating Frame



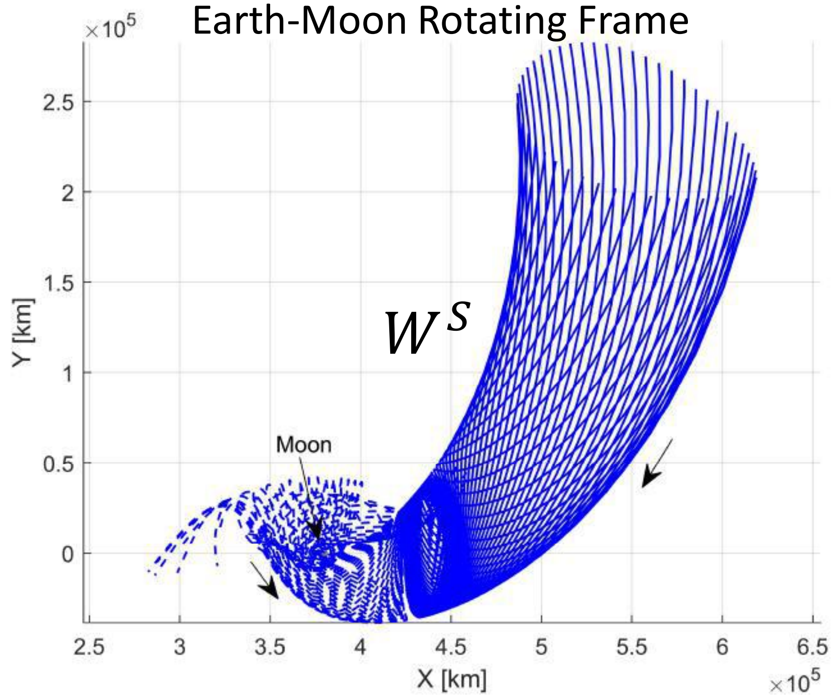
<u>Propagation from Deployment:</u>

- Coast arc, Thrust arc, Coast arc
- Vary α to generate range of post-flyby behaviors



Design Framework – Phase 1: Backward

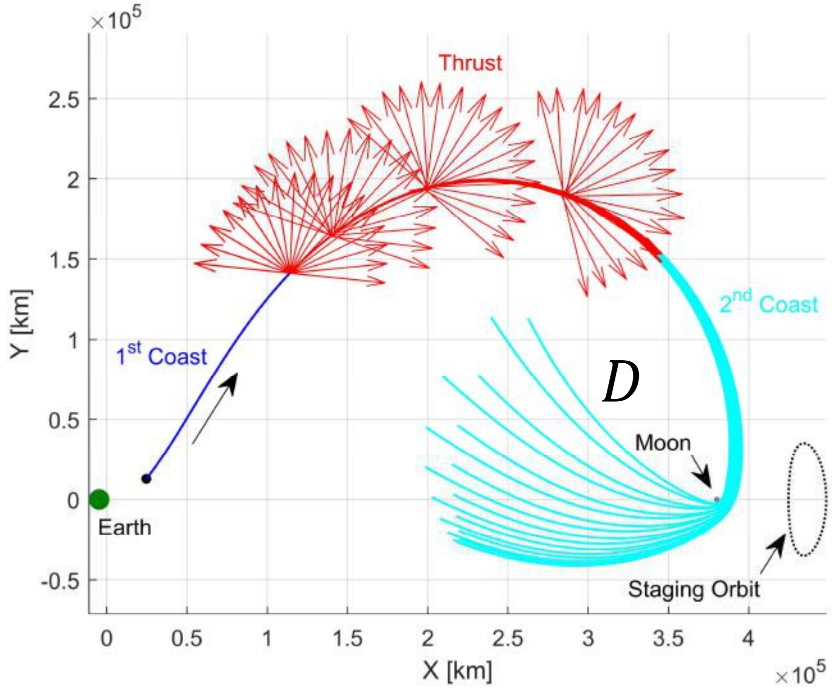
Earth-Moon Rotating Frame



Propagation Along Staging Orbit Stable Manifold

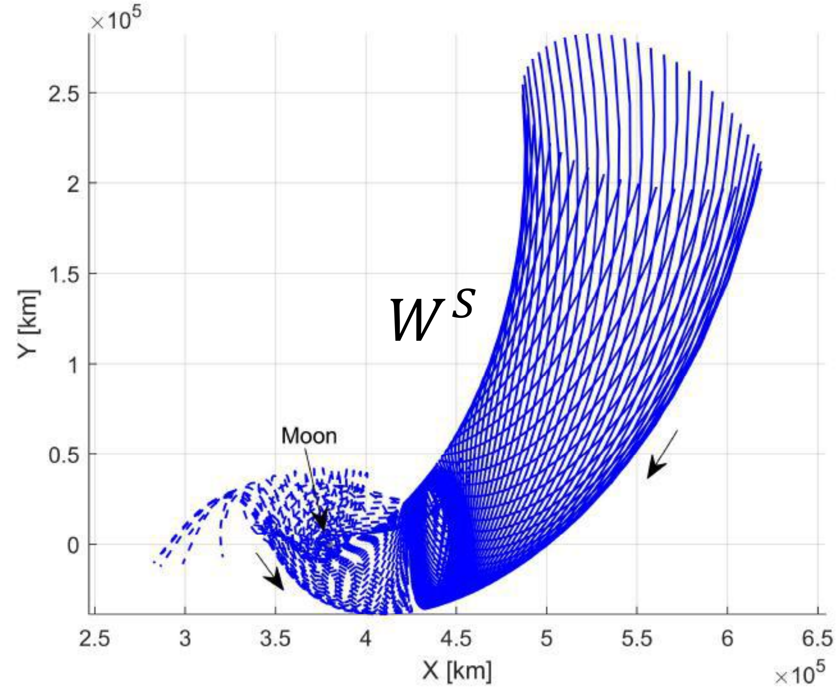
Design Framework – Phase 1: Mapping

Forward Propagation



Σ_1

Backward Propagation

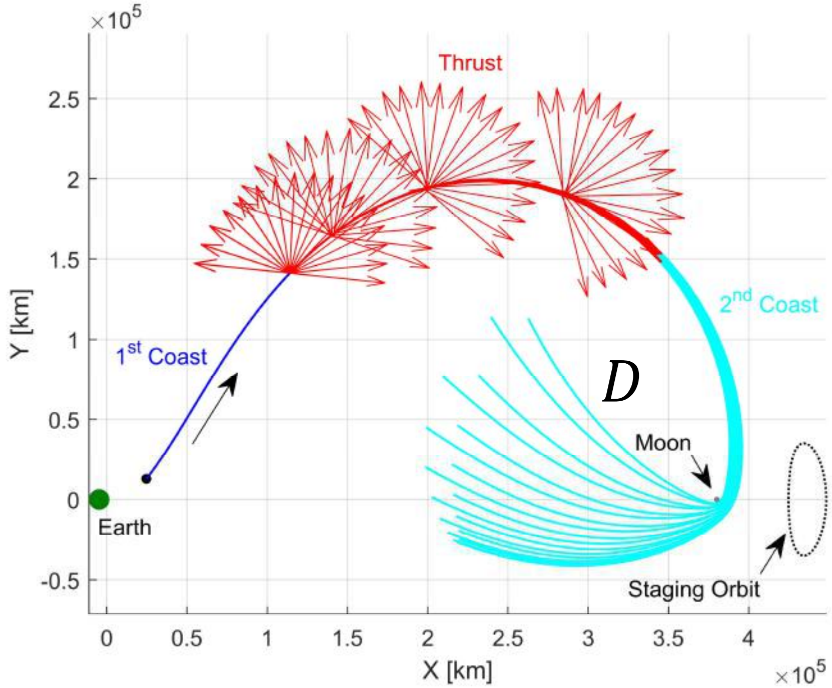


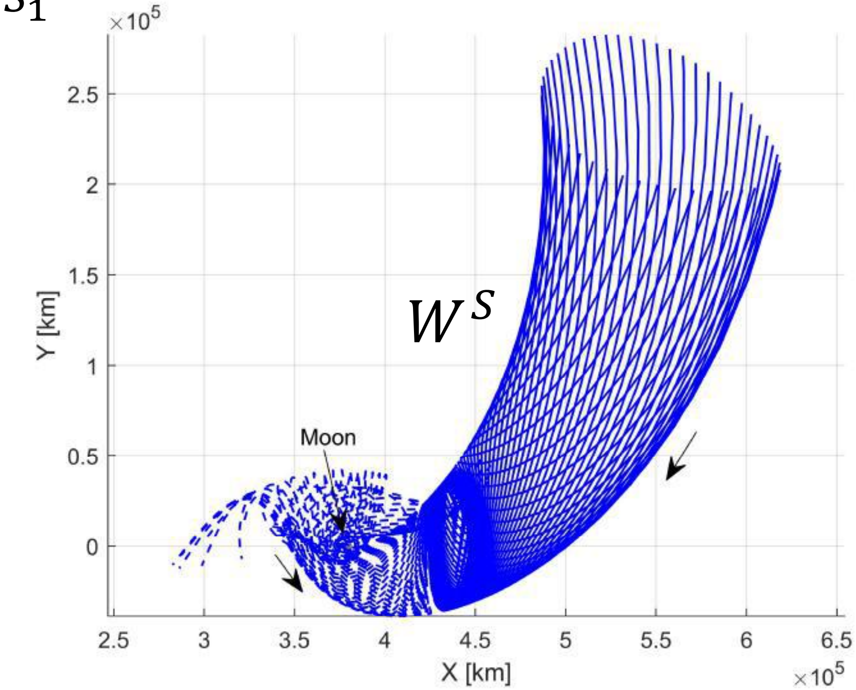
Design Framework – Phase 1: Mapping

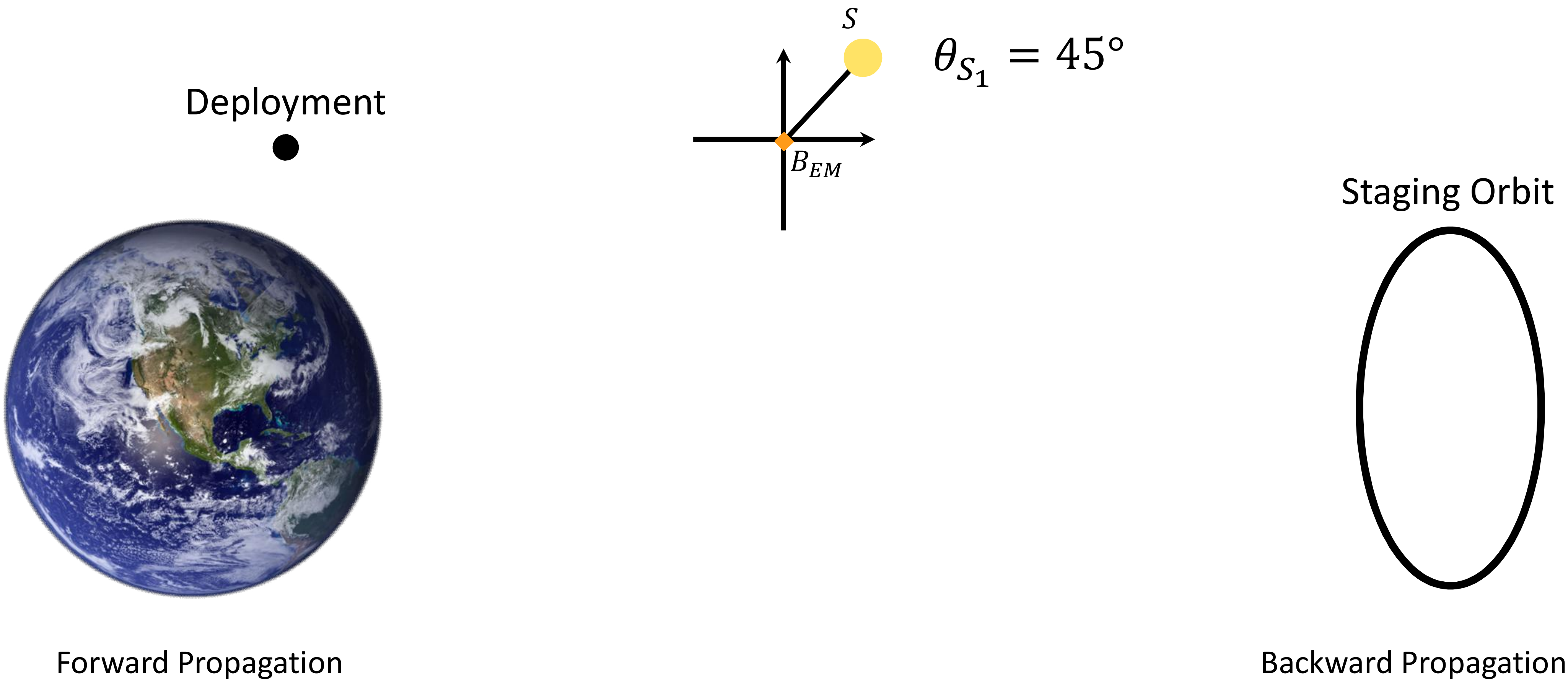
Forward Propagation

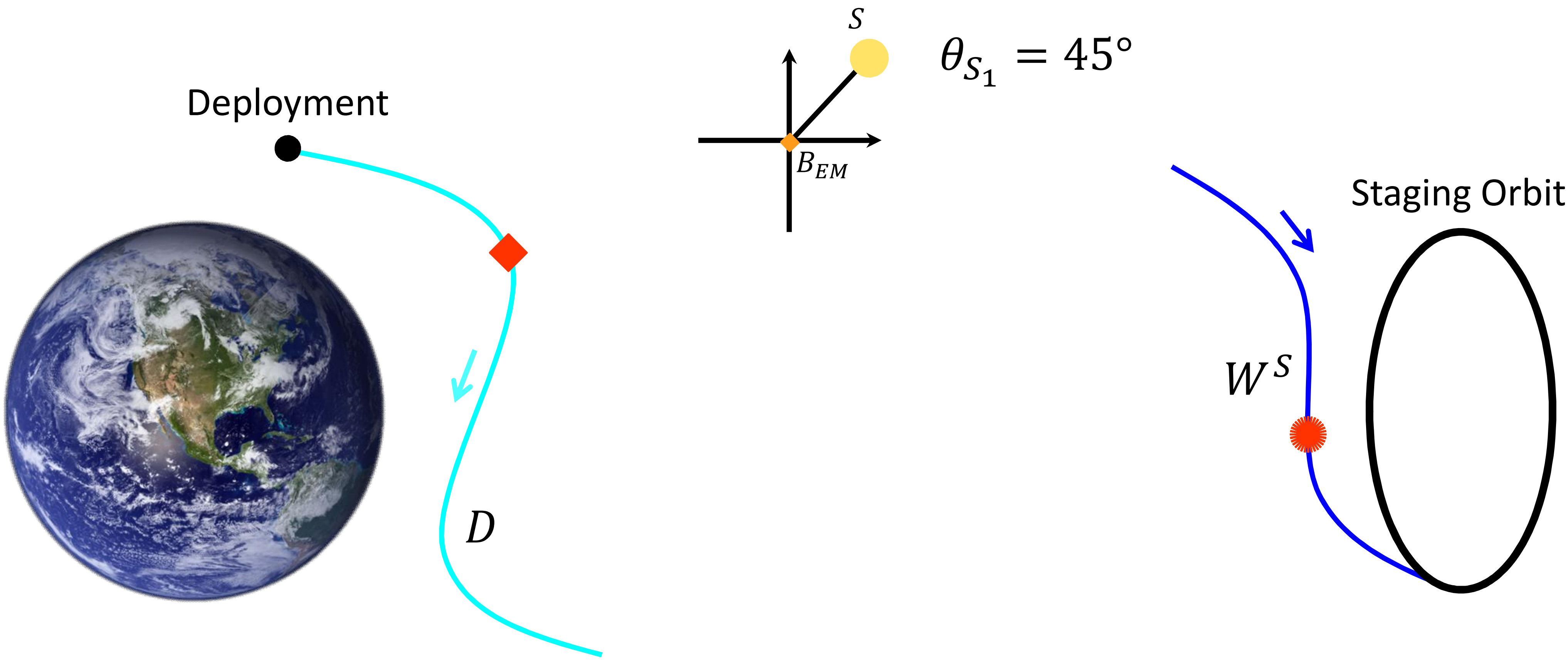
$\Sigma_1 = \theta_{S_1}$

Backward Propagation

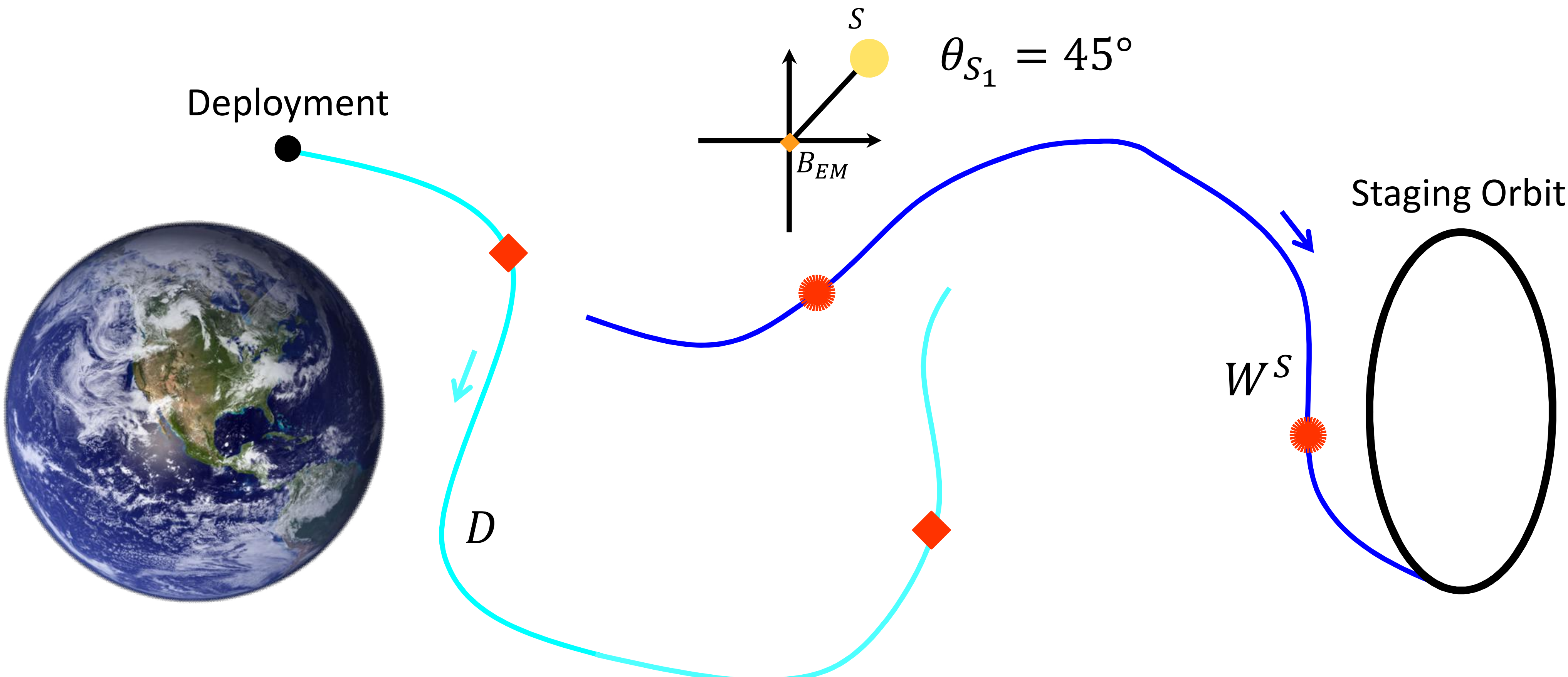




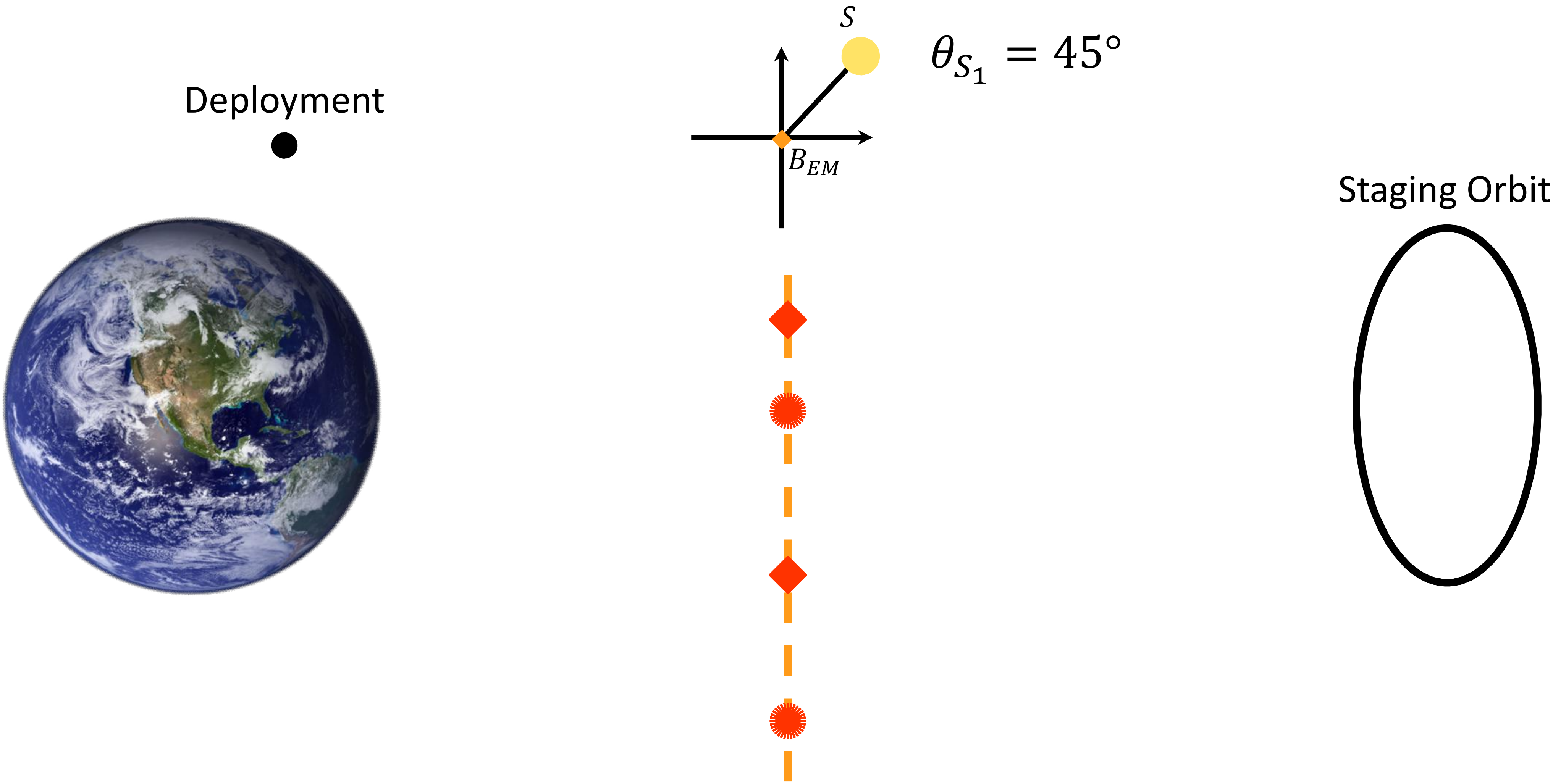

Deployment
S
$\theta_{S_1} = 45°$
B_{EM}
Staging Orbit
Forward Propagation
Backward Propagation



S
$\theta_{S_1} = 45°$
Deployment
B_{EM}
Staging Orbit
W^S
D

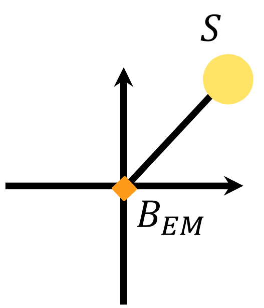


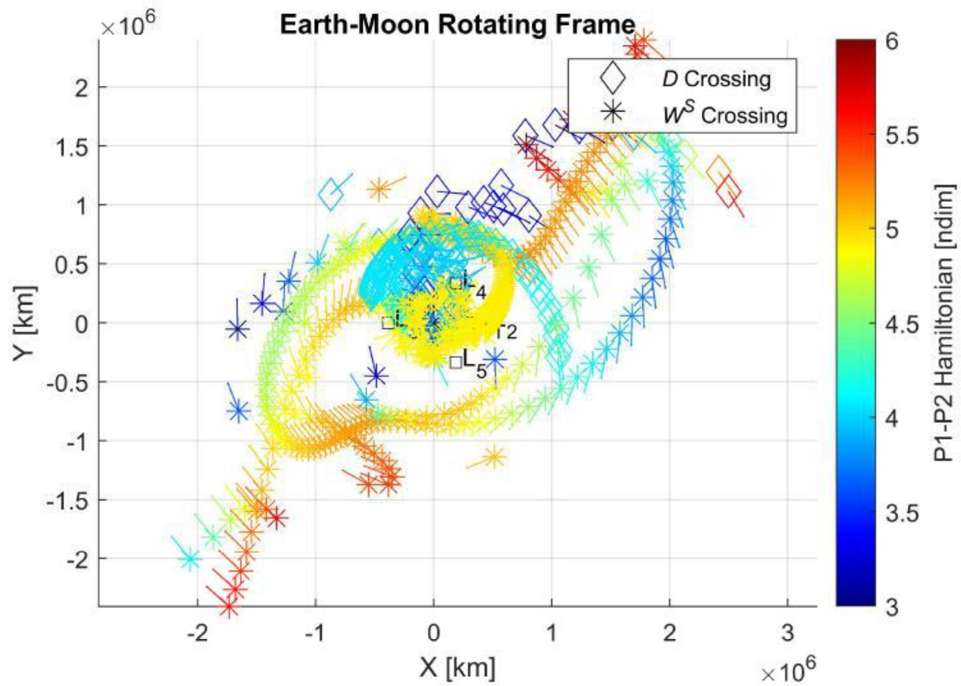
Deployment
S
$\theta_{S_1} = 45°$
B_{EM}
Staging Orbit
W^S
D


Deployment
S
$\theta_{S_1} = 45°$
B_{EM}
Staging Orbit

Design Framework – Phase 1: Mapping

$\theta_{S_1} = 45°$

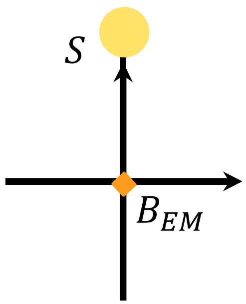


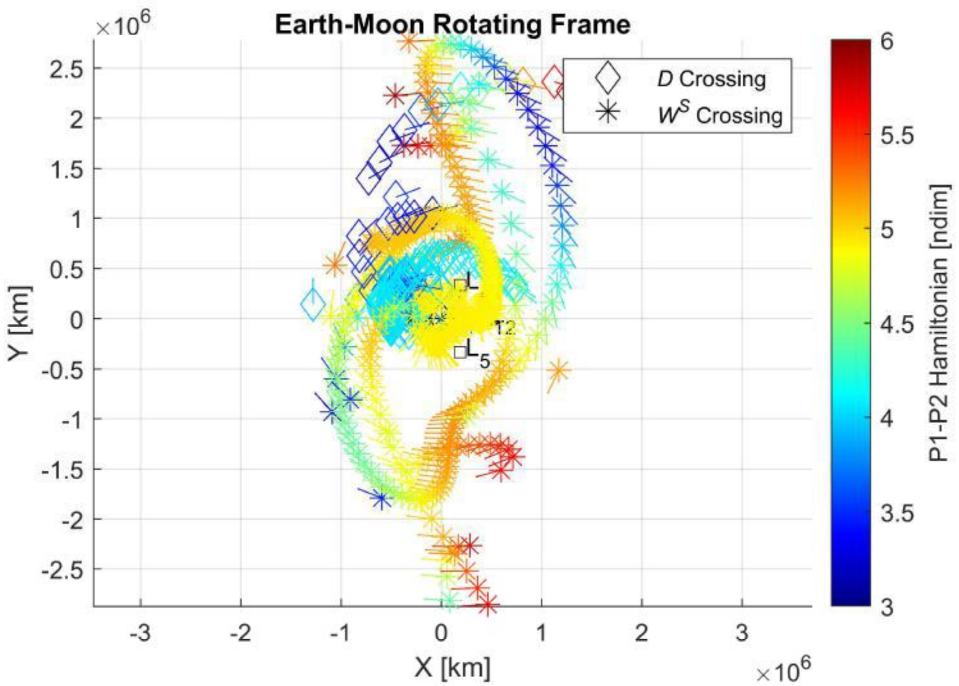


Σ_1

Design Framework – Phase 1: Mapping

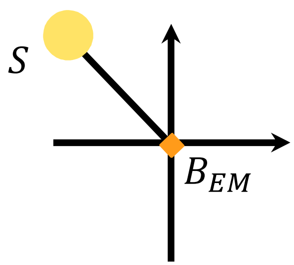
$\theta_{S_1} = 90°$

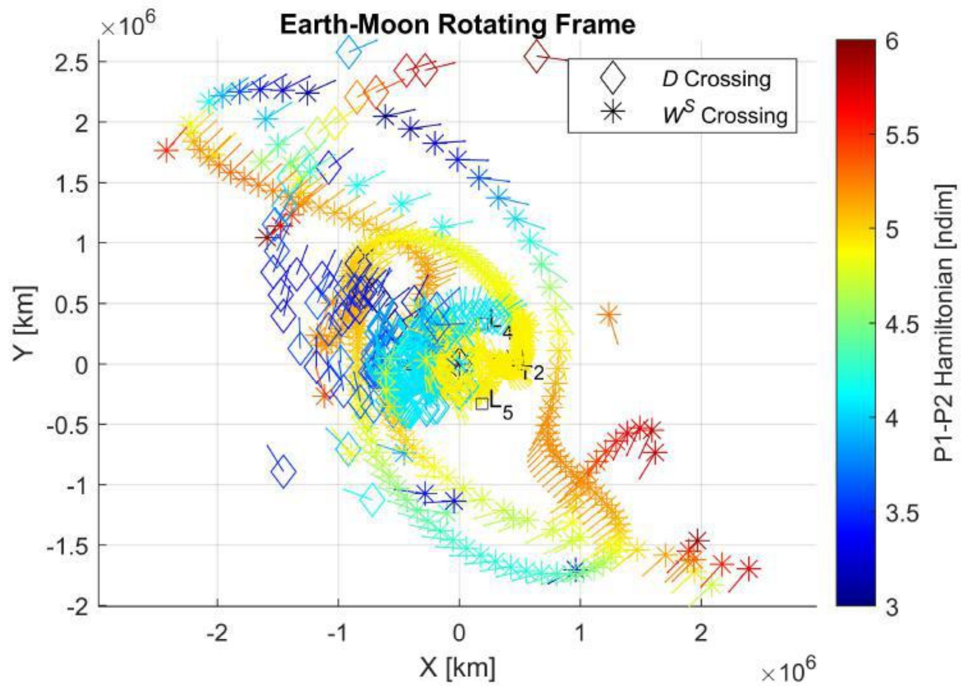




Design Framework – Phase 1: Mapping

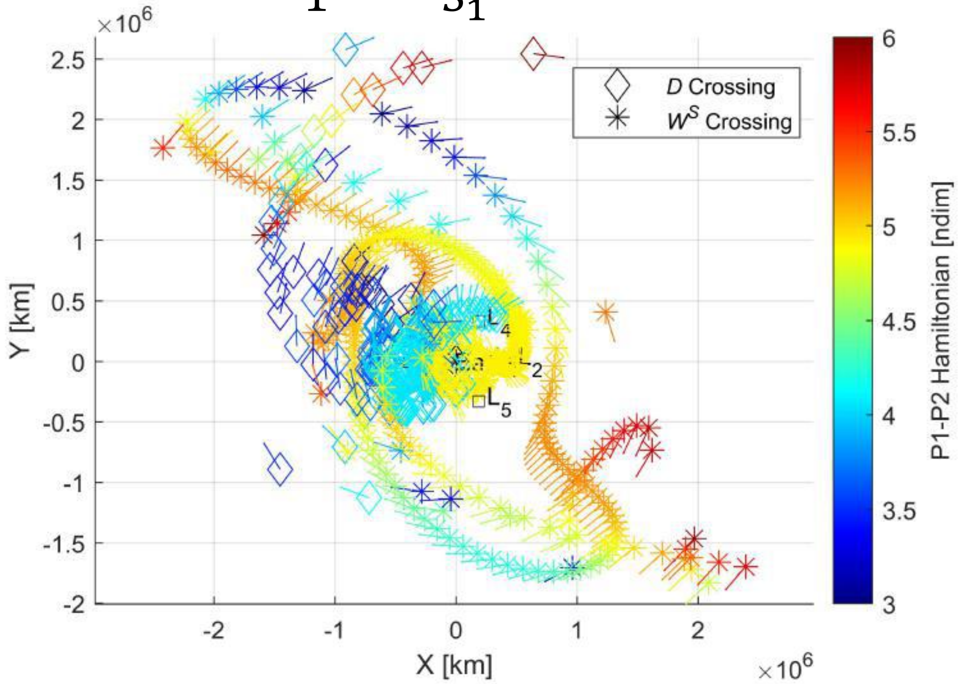
$\theta_{S_1} = 135°$





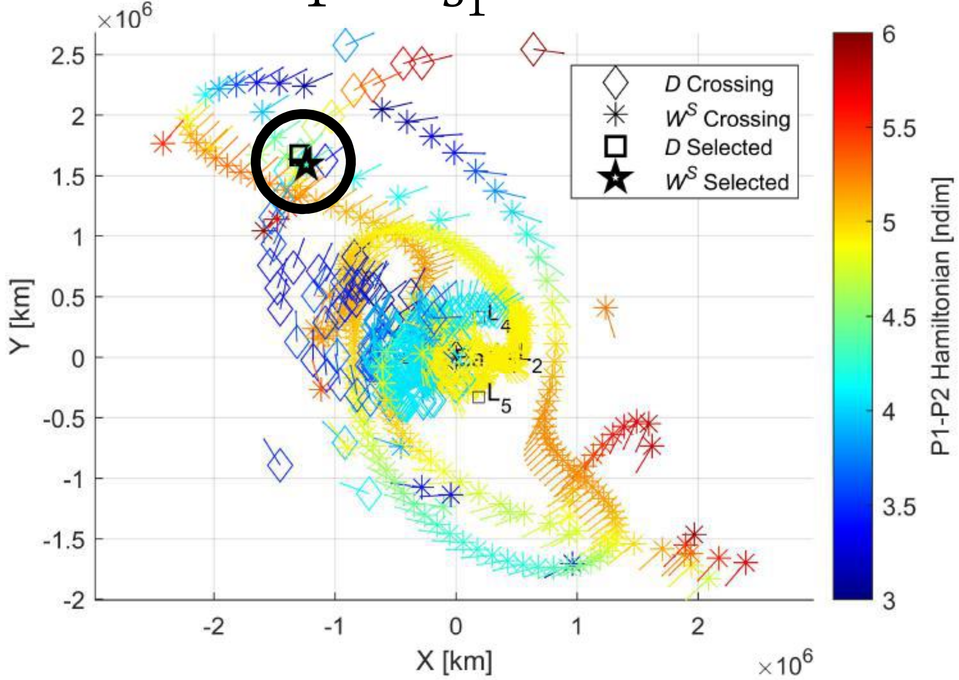
Design Framework – Phase 1: Mapping

$$\Sigma_1 = \theta_{S_1} = 135°$$



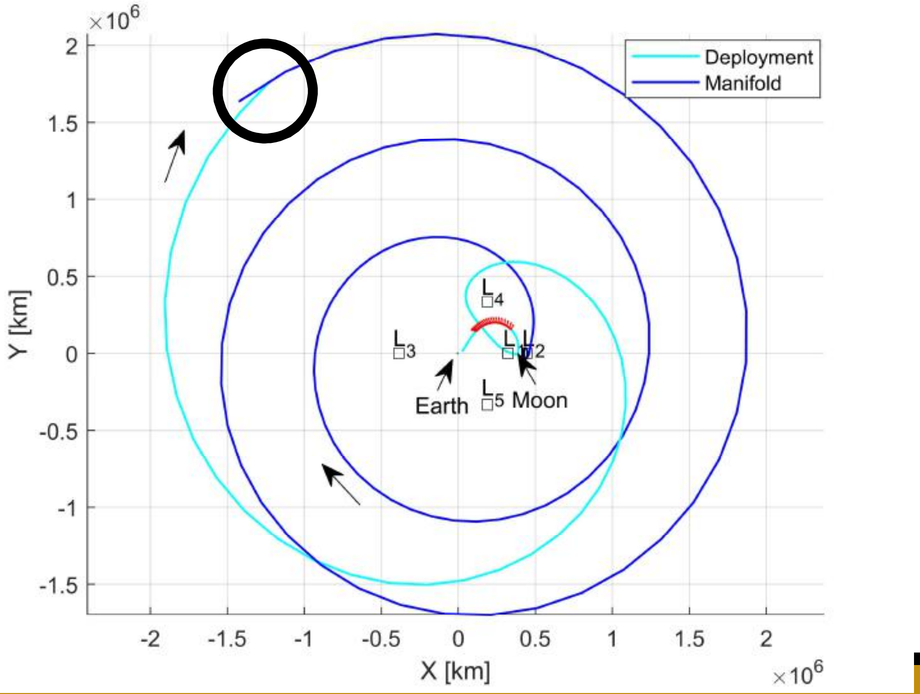
Design Framework – Phase 1: Mapping

$$\Sigma_1 = \theta_{S_1} = 135°$$

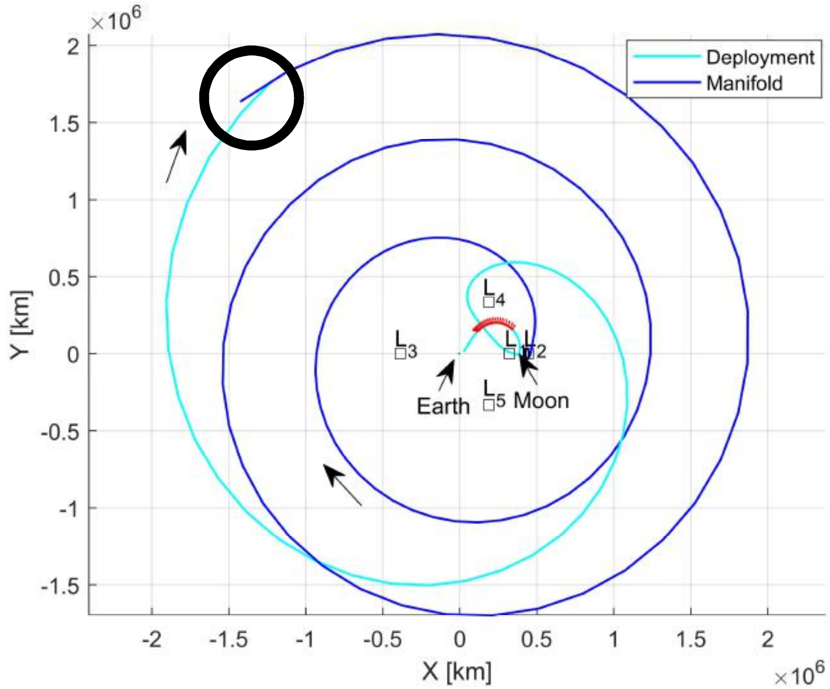


Design Framework – Phase 1: Guess

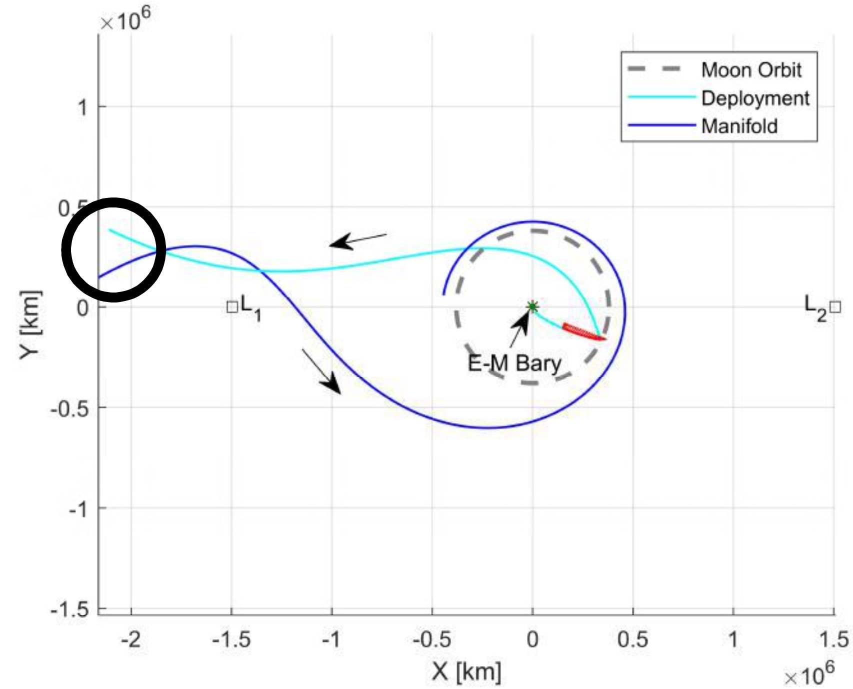
$$\Sigma_1 = \theta_{S_1} = 135°$$



Design Framework – Phase 1: Guess

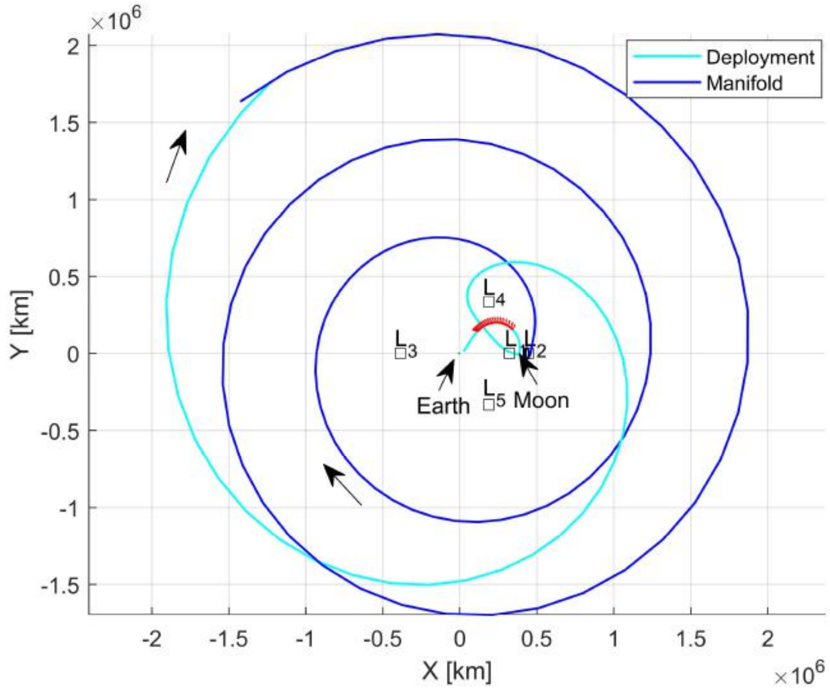


Earth-Moon Rotating Frame

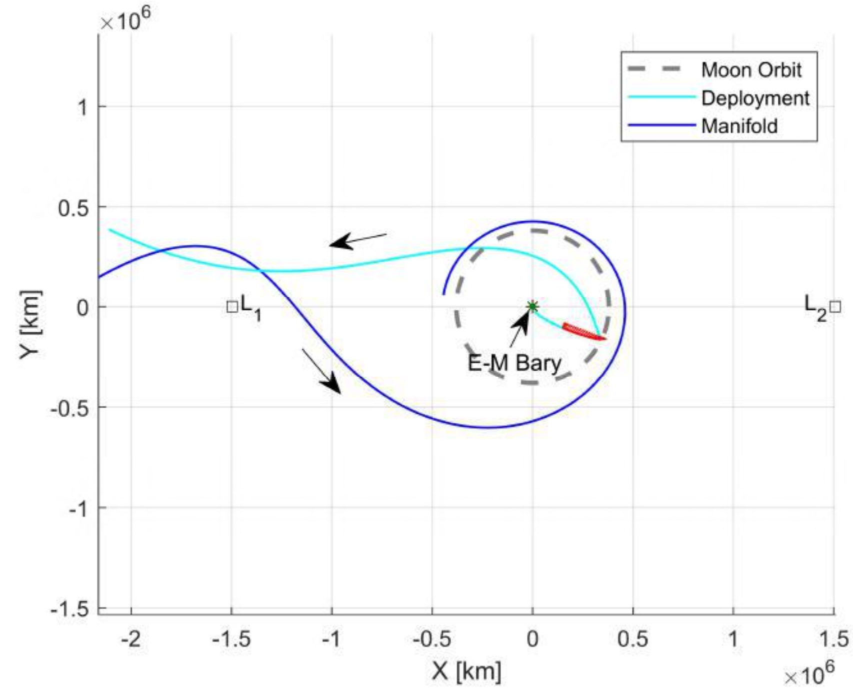


Sun-B_{EM} Rotating Frame

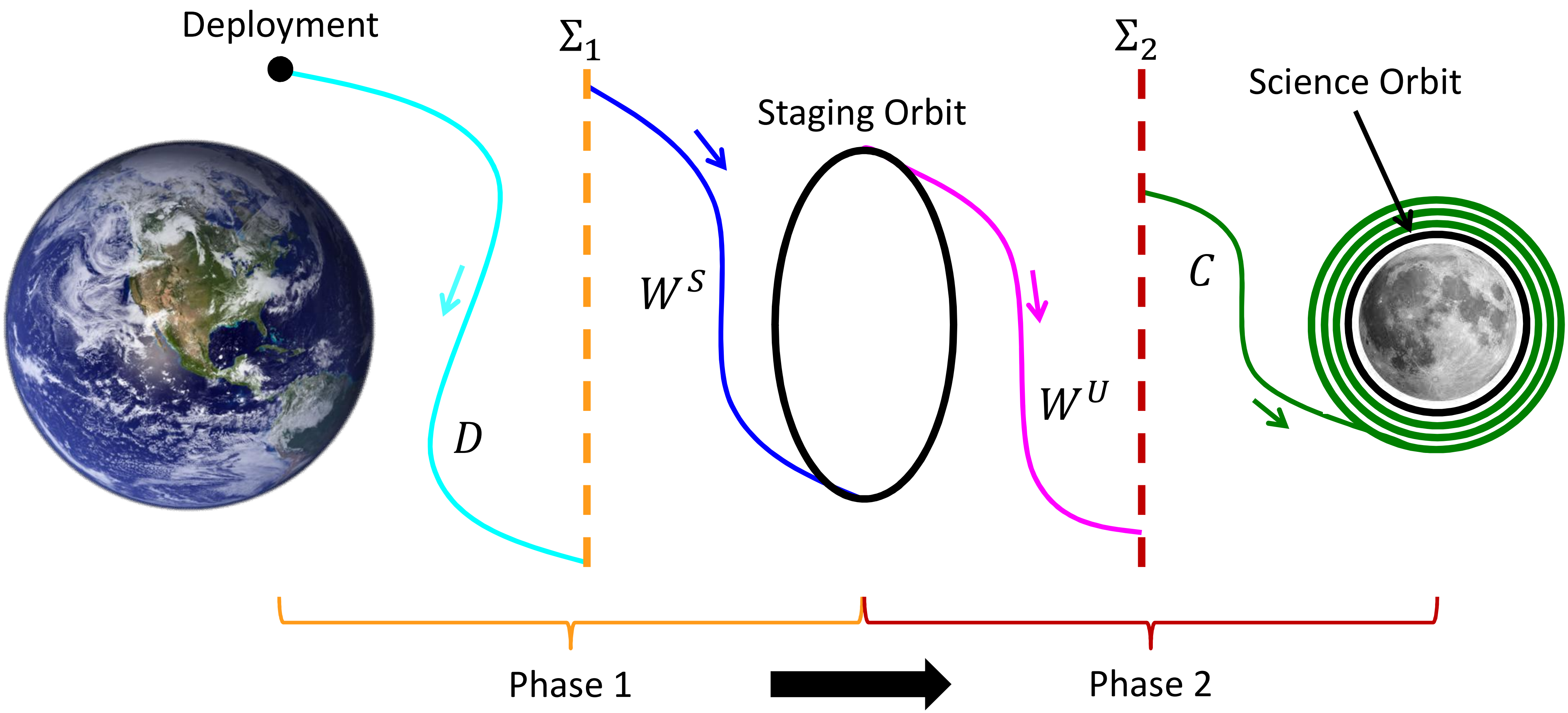
Design Framework – Phase 1: Guess

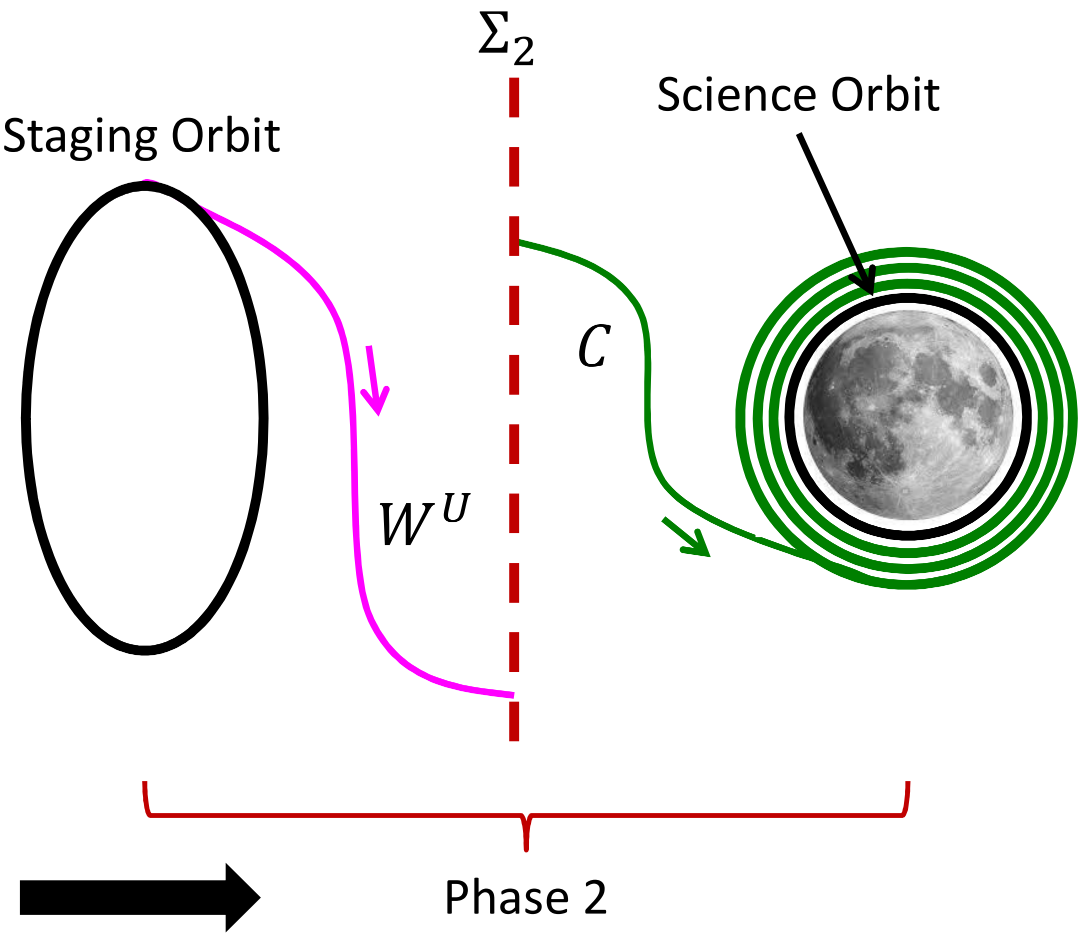


Earth-Moon Rotating Frame



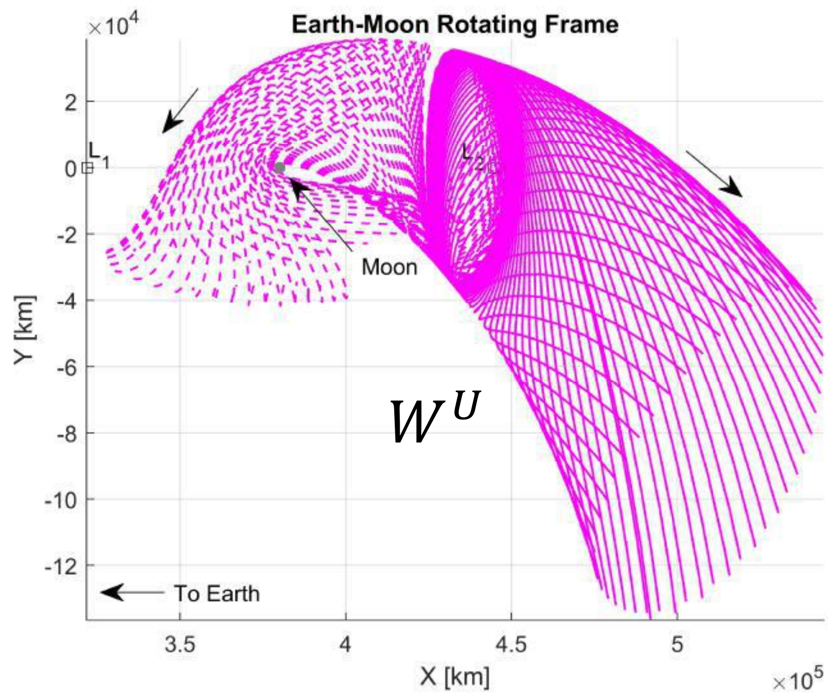
Sun-B_{EM} Rotating Frame


Deployment
Σ_1
Σ_2
Science Orbit
Staging Orbit
W^S
W^U
C
D
Phase 1
Phase 2



Σ_2
Science Orbit
Staging Orbit
C
W^U
Phase 2

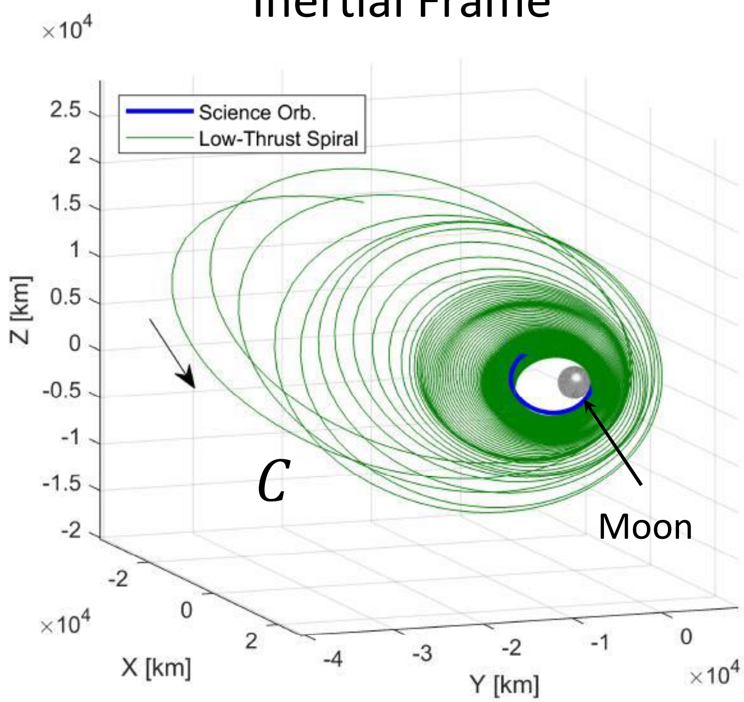
Design Framework – Phase 2: Forward



Propagation Along Staging Orbit Unstable Manifold

Design Framework – Phase 2: Backward

Inertial Frame

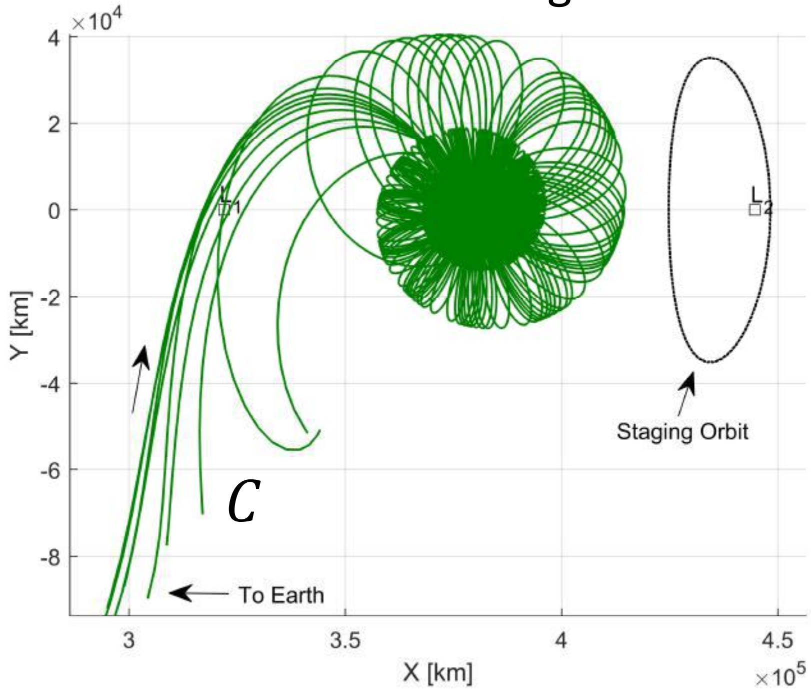


<u>Propagation from Science Orbit:</u>

- Propagated backward from science orbit insertion (SOI)
- Constant anti-velocity thrust at T_{max}

Design Framework – Phase 2: Backward

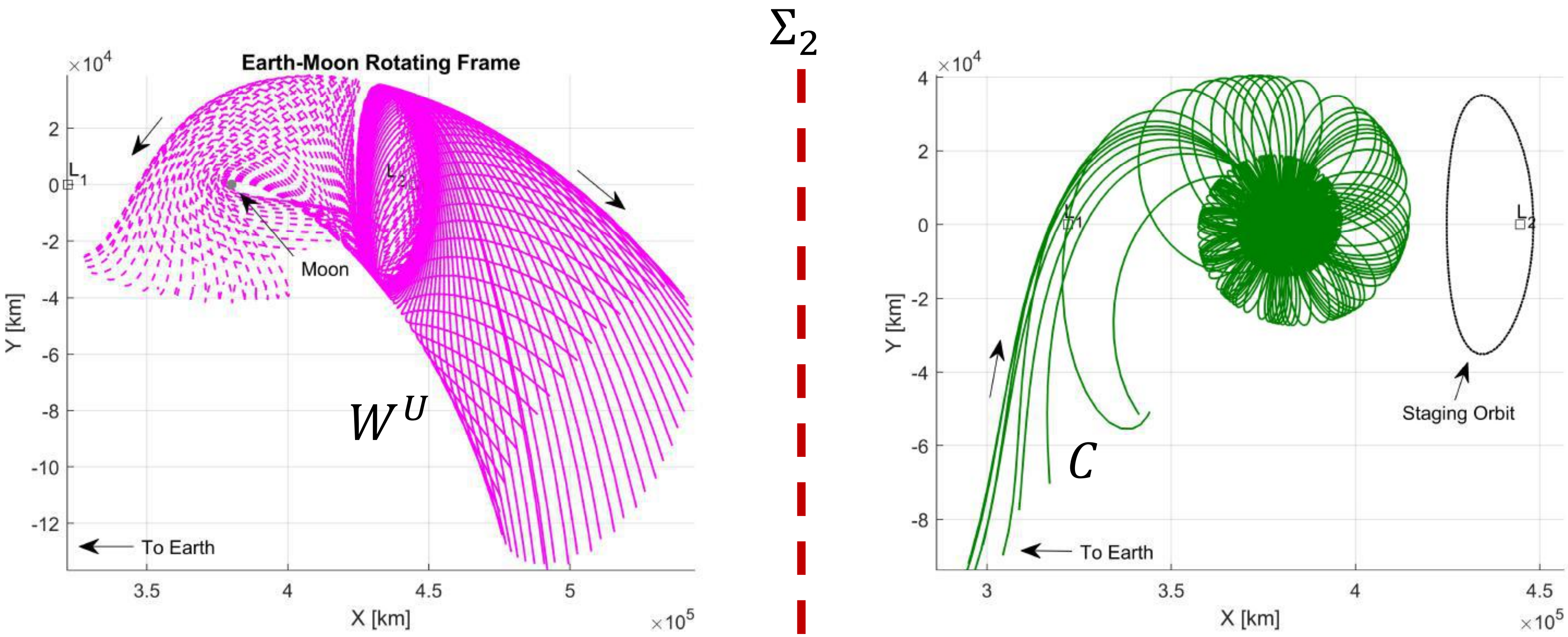
Earth-Moon Rotating Frame



<u>Propagation from Science Orbit:</u>

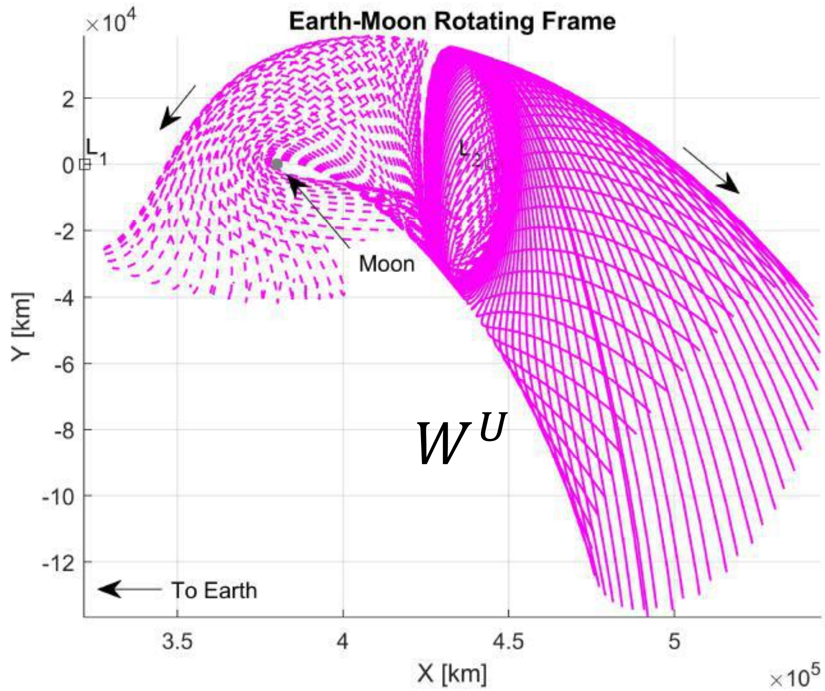
- Propagated backward from science orbit insertion (SOI)
- Constant anti-velocity thrust at T_{max}
- Varying true anomaly at SOI generates a range of capture trajectories

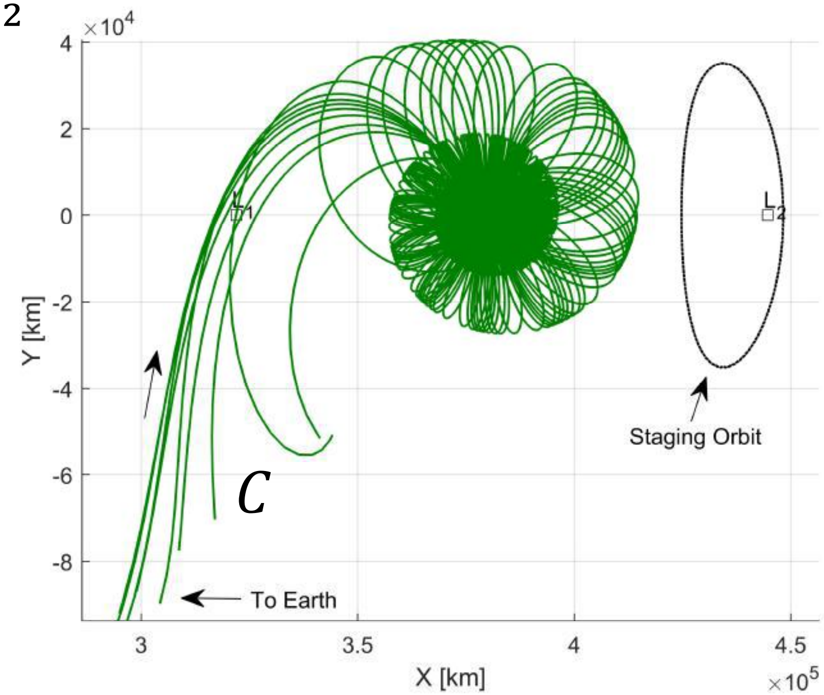
Design Framework – Phase 2: Mapping



Design Framework – Phase 2: Mapping

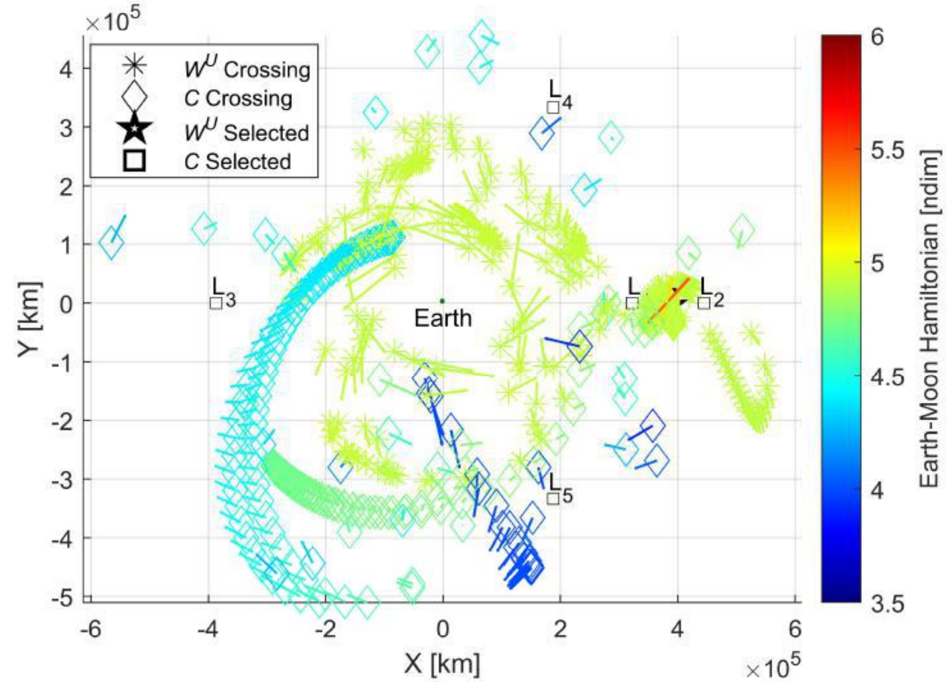
$$\Sigma_2 = \theta_{S_2}$$





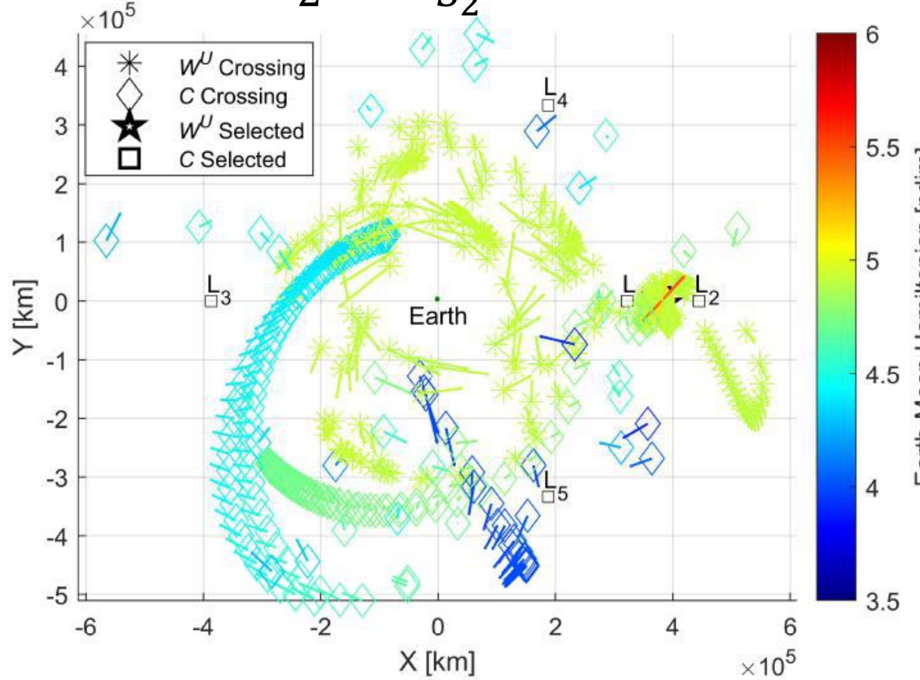
Design Framework – Phase 2: Mapping

$\Sigma_2 = \theta_{S_2}$



Design Framework – Phase 2: Map

$$\Sigma_2 = \theta_{S_2} = 75°$$



Design Framework – Phase 2: Map

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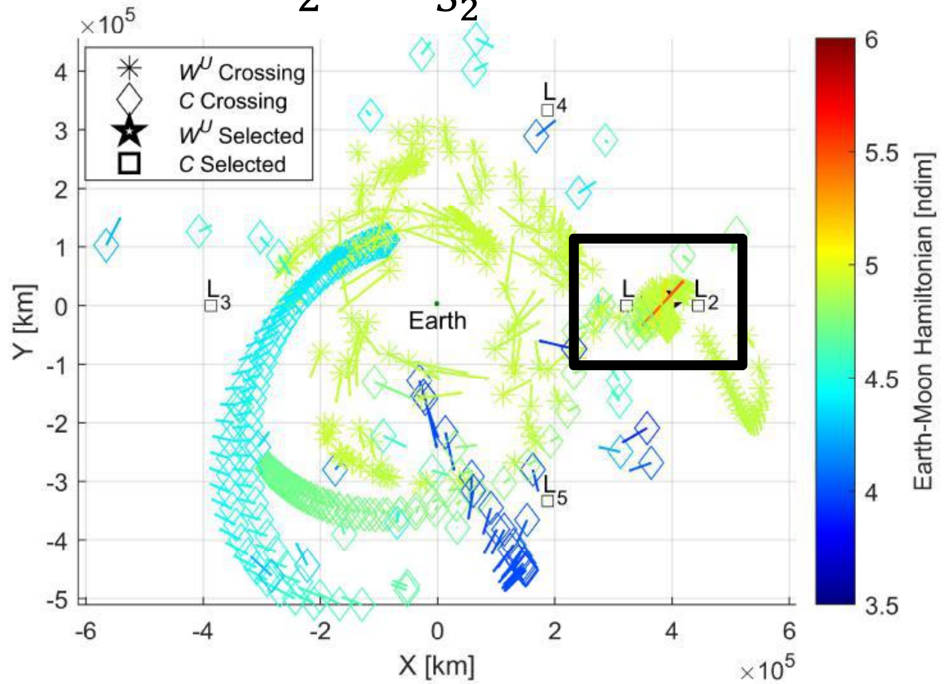
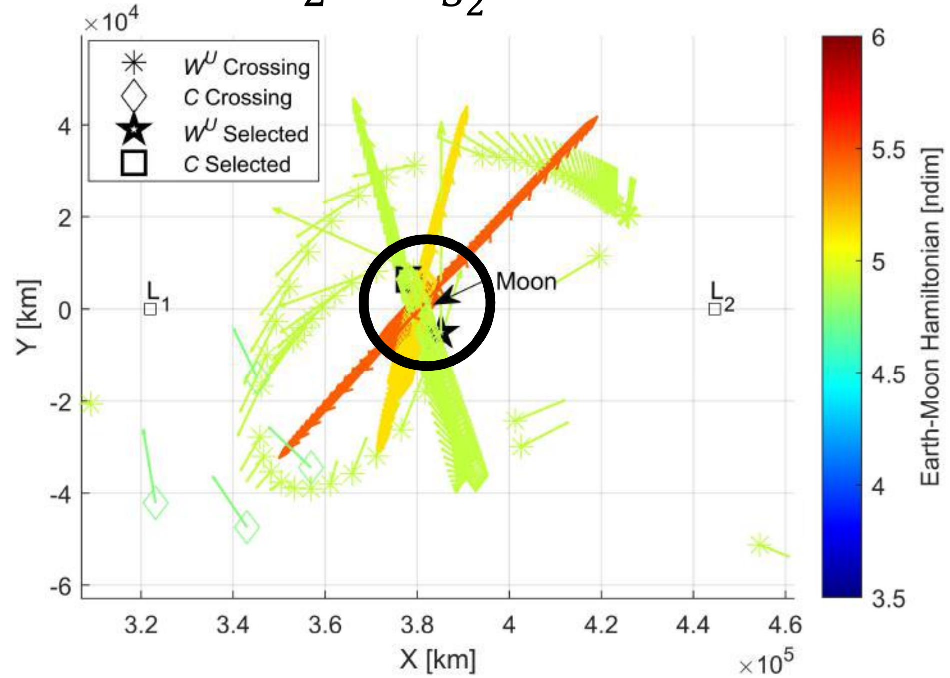
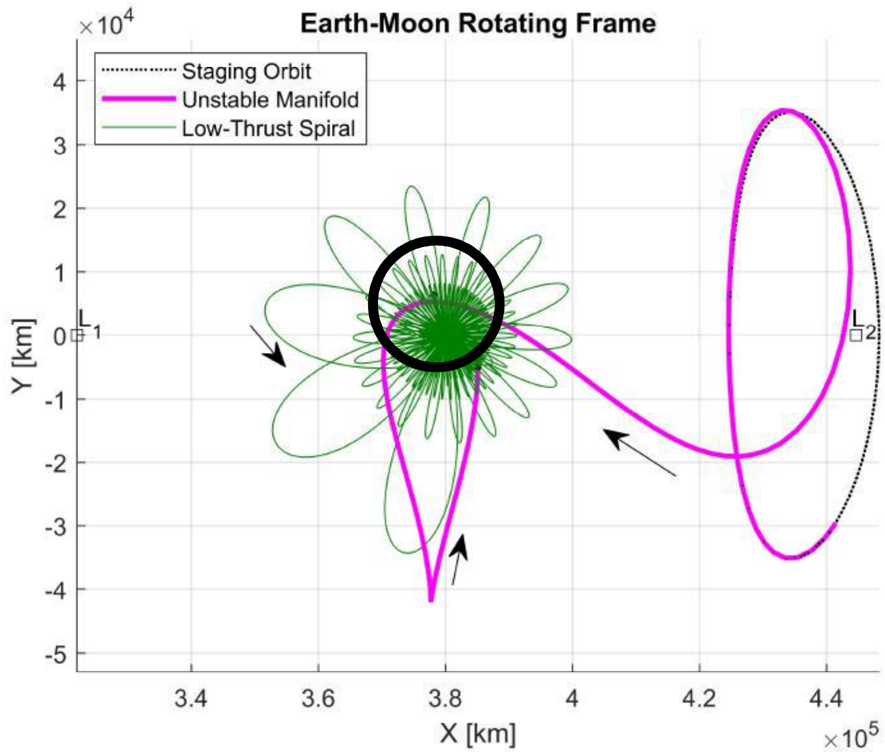


Design Framework – Phase 2: Map

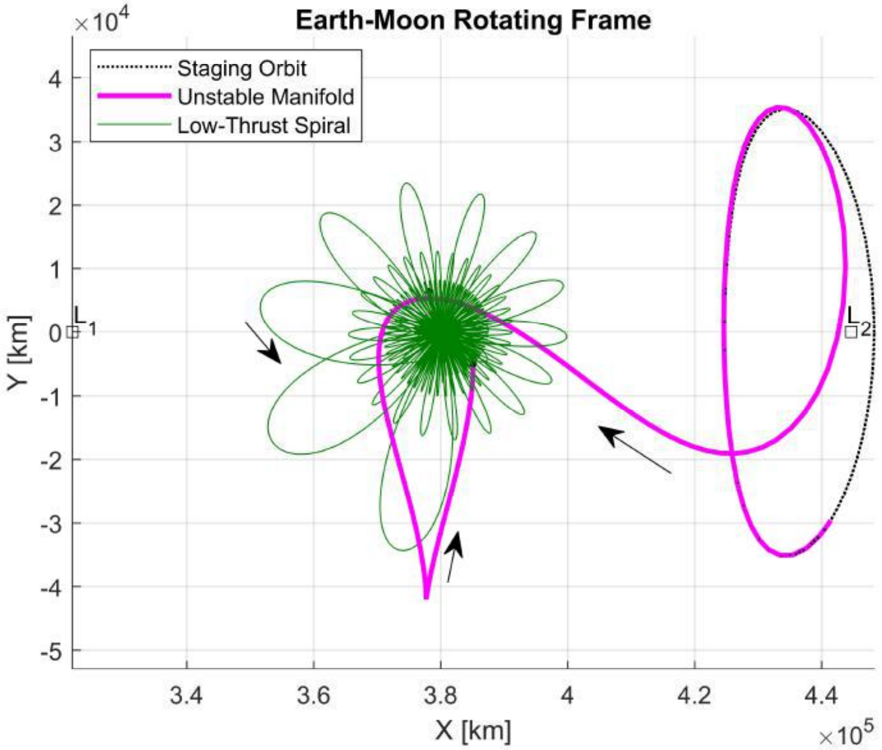
$$\Sigma_2 = \theta_{S_2} = 75°$$

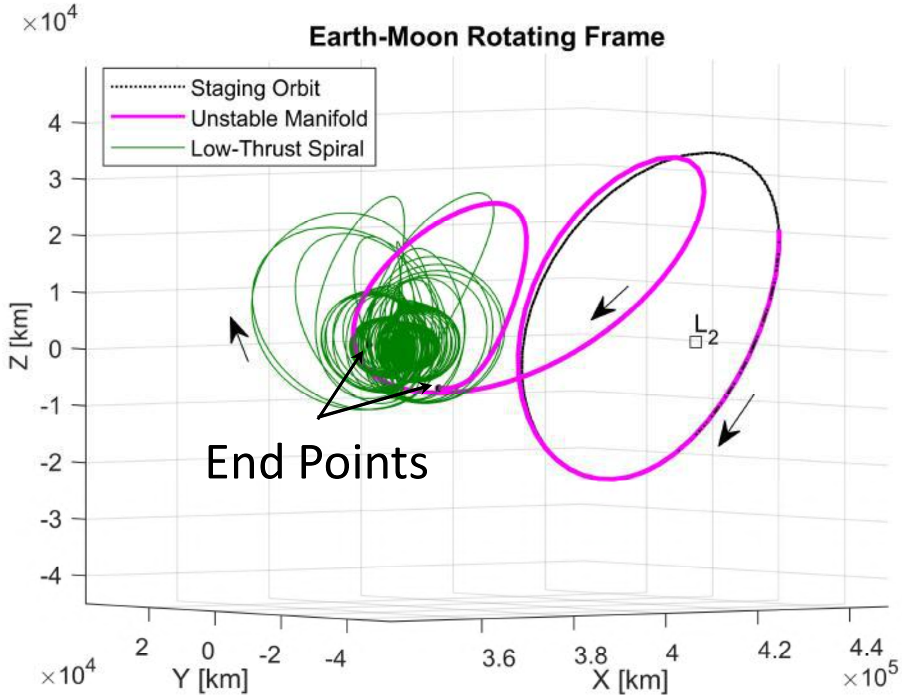


Design Framework – Phase 2: Guess



Design Framework – Phase 2: Guess





Outline

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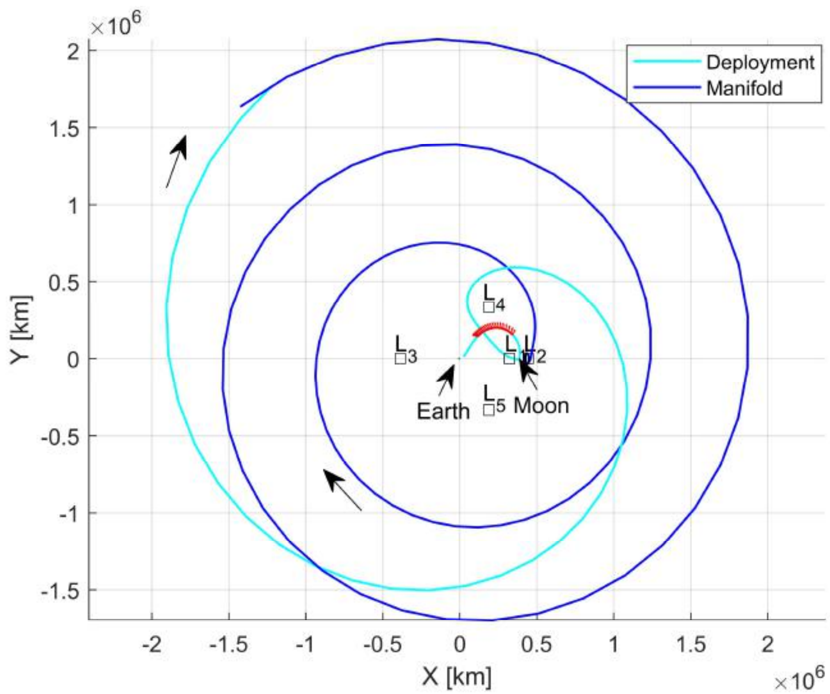
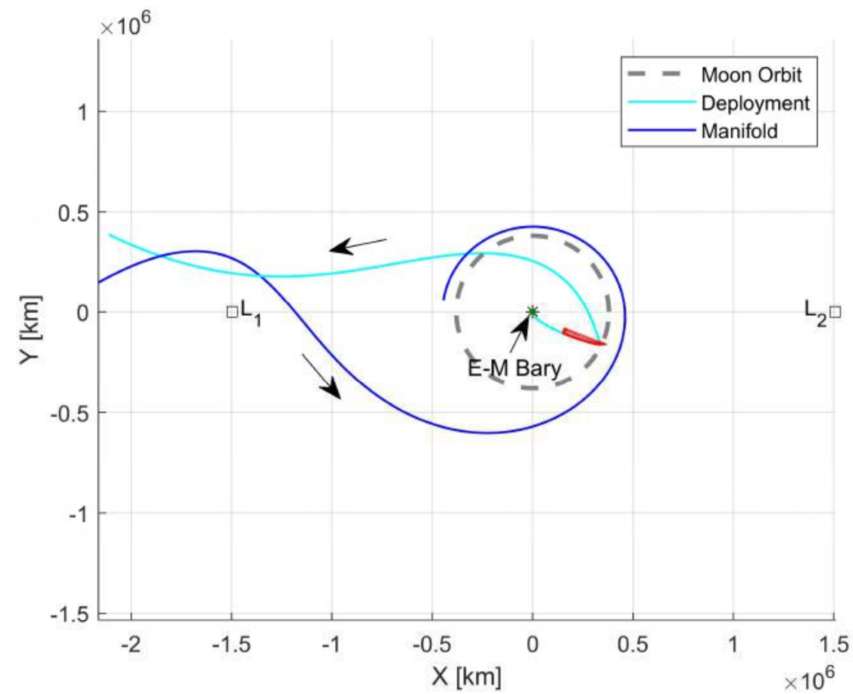
IV. Concluding Remarks

Sample Trajectory Design – Phase 1: Guess

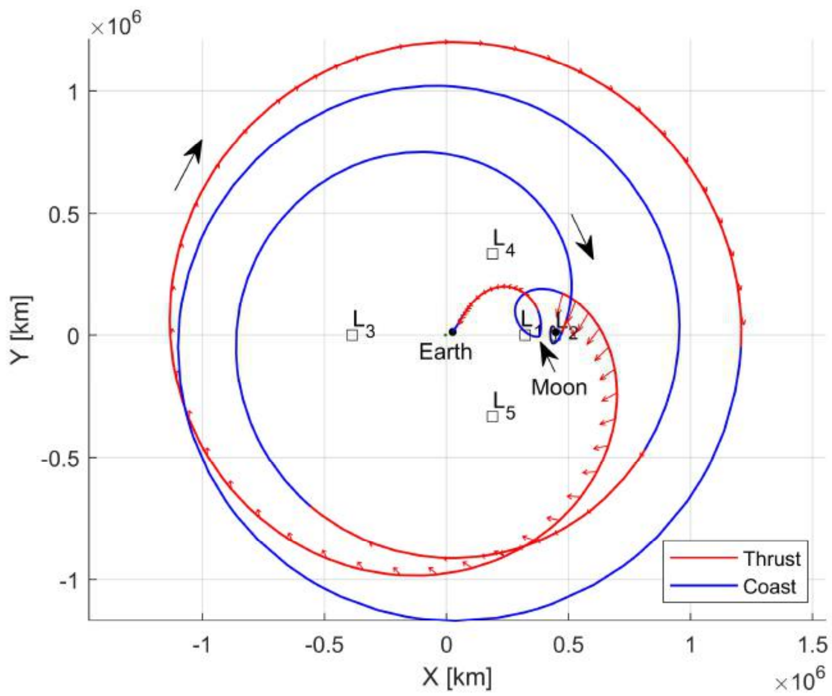


Earth-Moon Rotating Frame

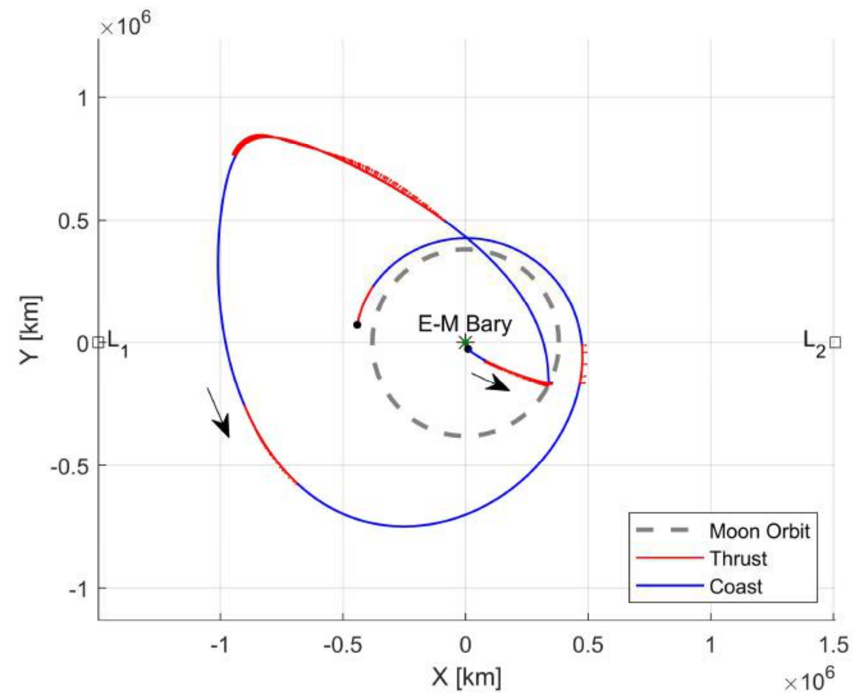


Sun-B_{EM} Rotating Frame

Sample Trajectory Design – Phase 1: Result



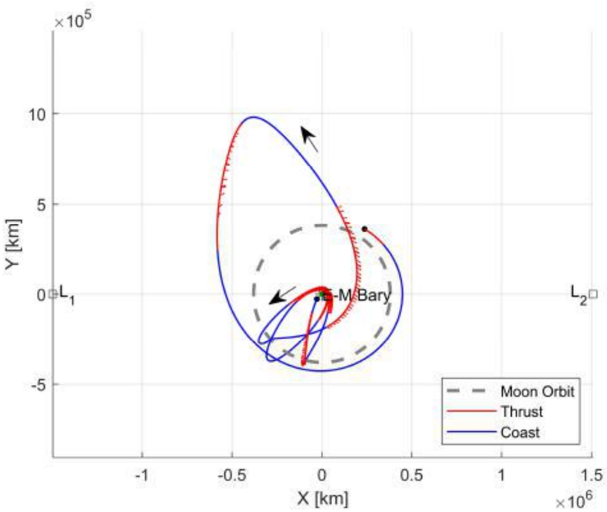
Earth-Moon Rotating Frame



Sun-B_{EM} Rotating Frame

Sample Trajectory Design – Phase 1: Result

October 2018



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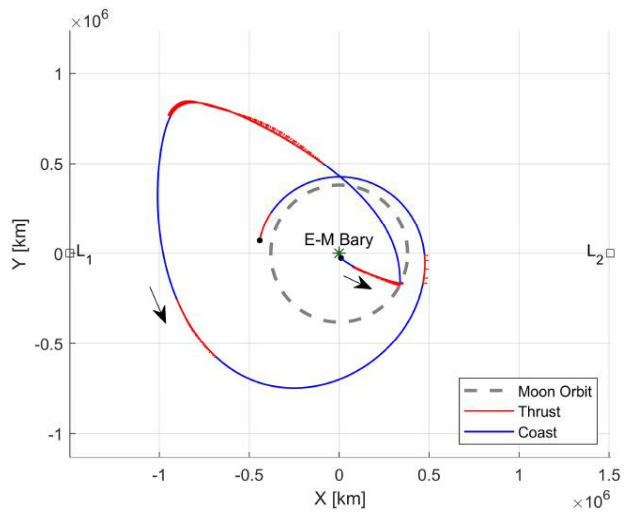

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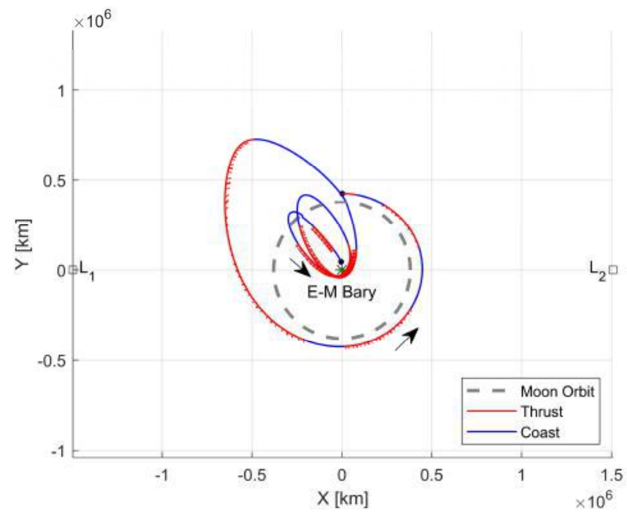
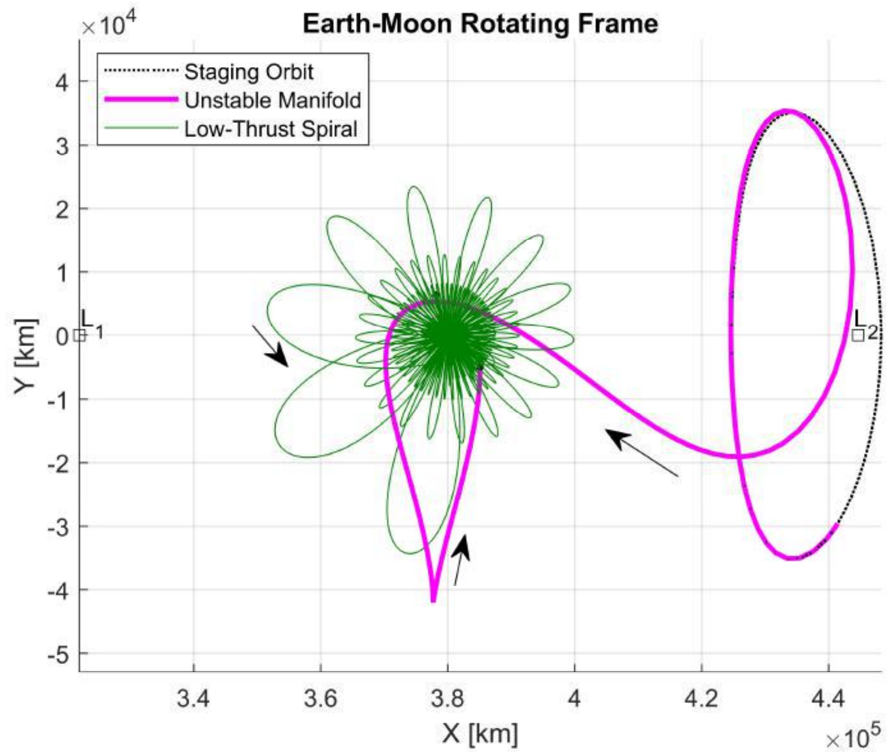
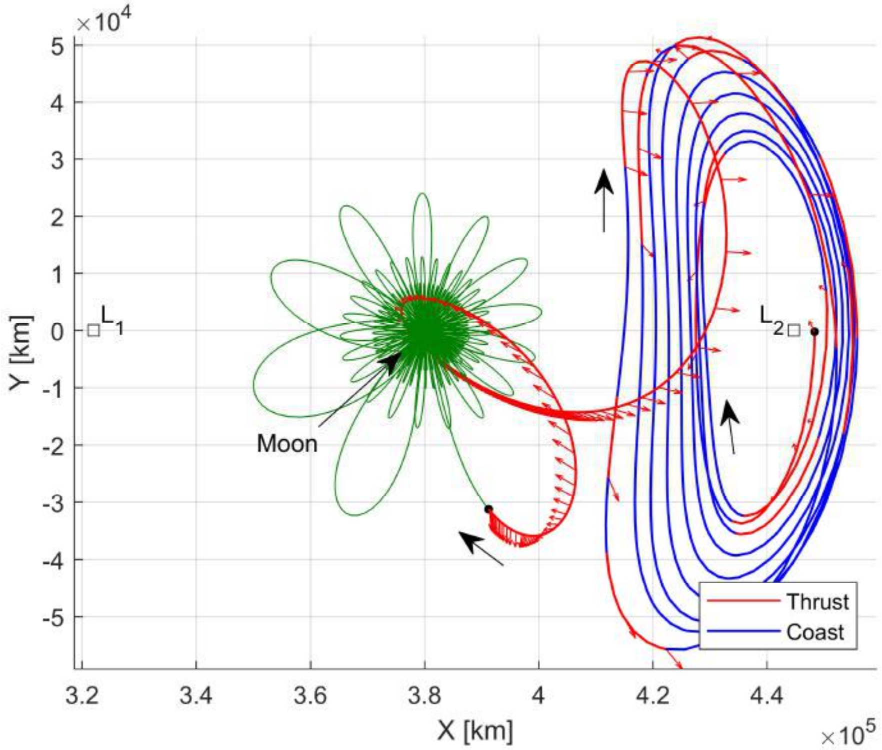


Sun-B_{EM} Rotating Frame

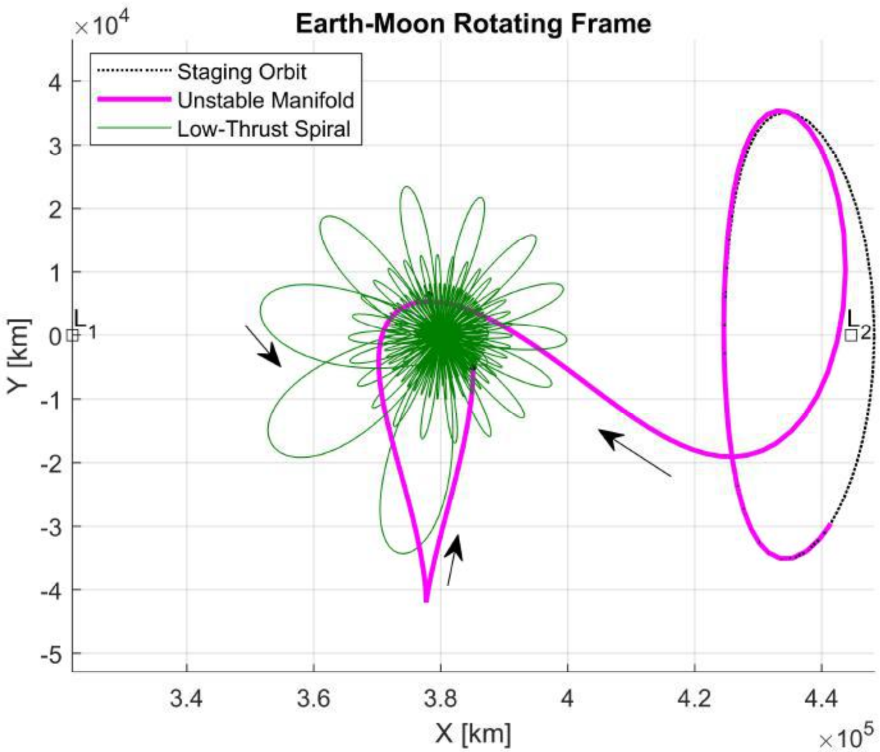
Sample Trajectory Design – Phase 2: Guess

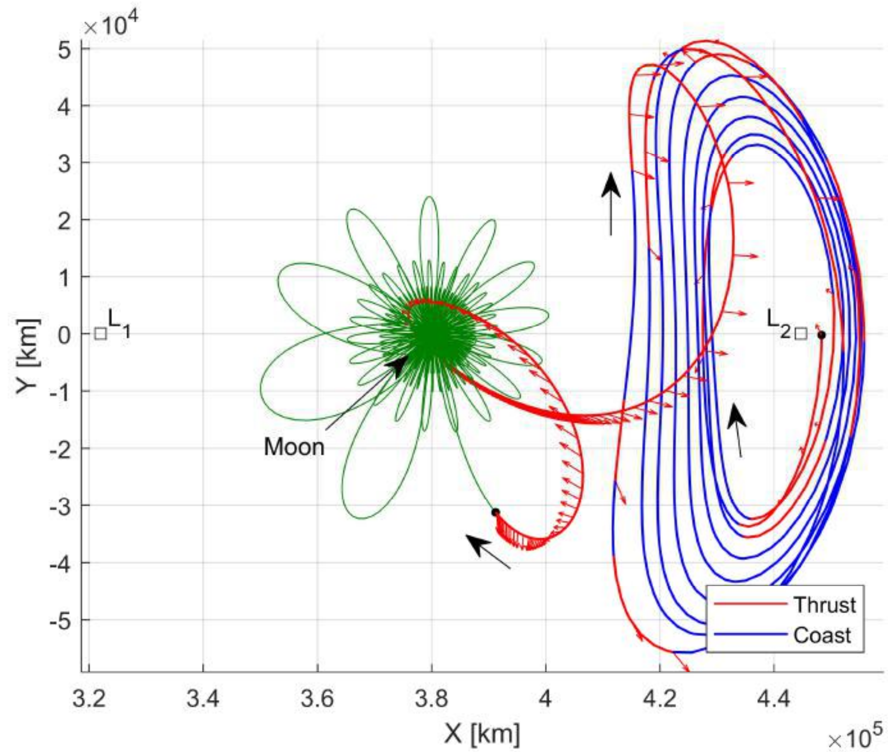


Sample Trajectory Design – Phase 2: Result

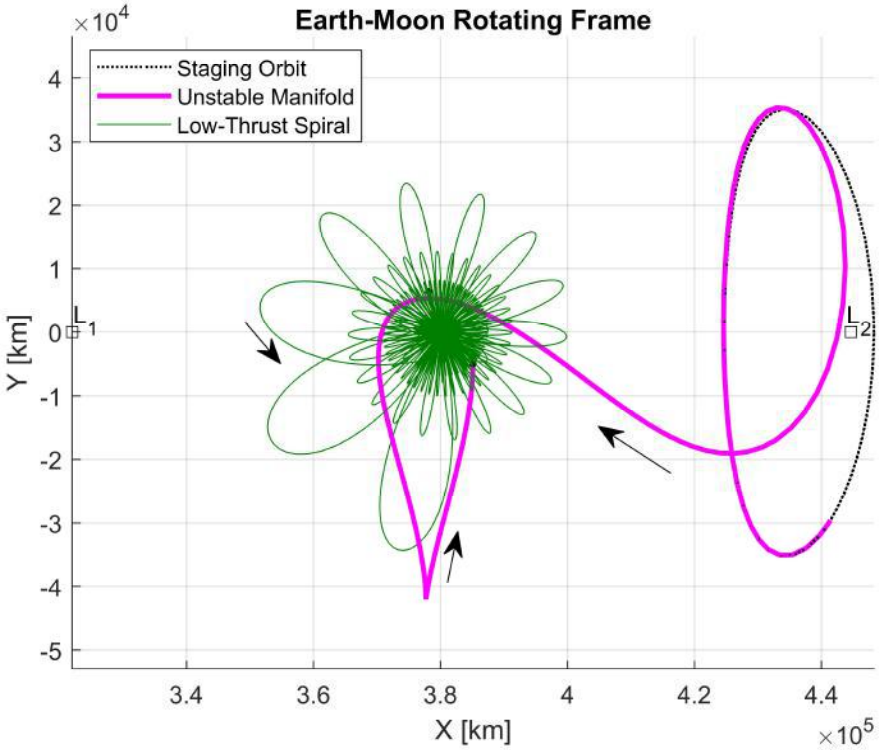


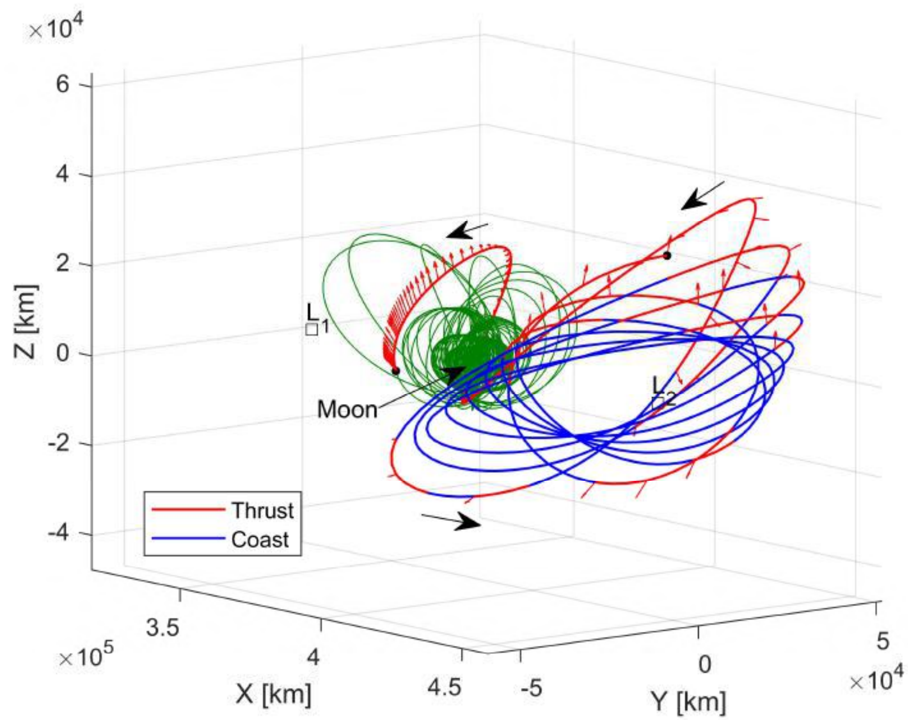
Sample Trajectory Design – Phase 2: Result





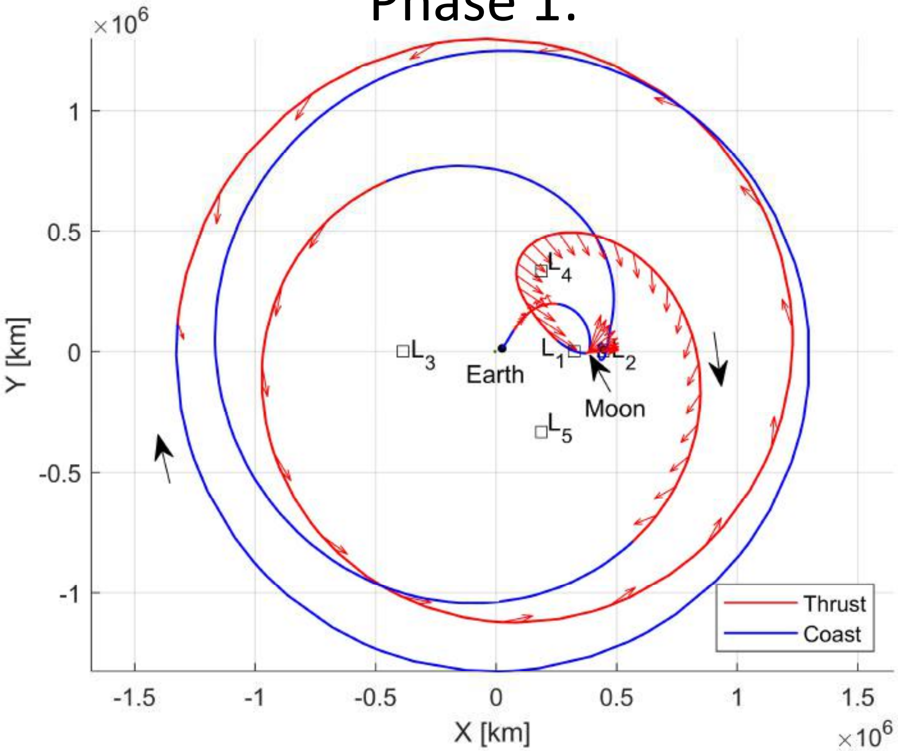
Sample Trajectory Design – Phase 2: Result



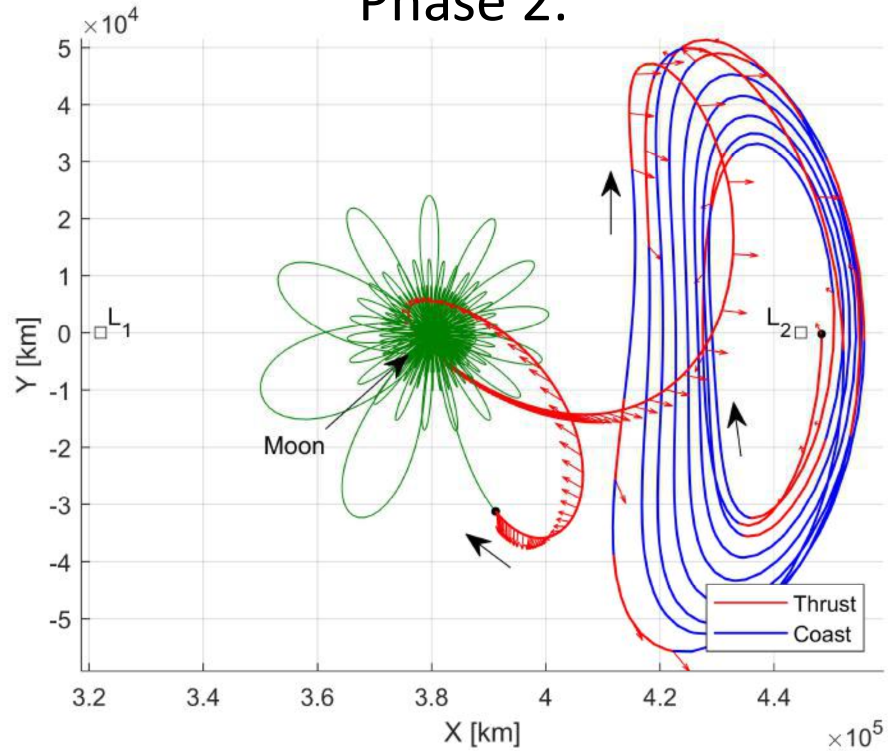


Sample Trajectory Design – Final Result

Phase 1:



Phase 2:



Sample Trajectory Design – Final Result

- Can combine different Phase 1 and 2 results to yield different end-to-end solutions
- The following are options for end-to-end Lunar IceCube transfers in the BCR4BP:

Deployment Date	Phase 1		Phasing Time	Phase 2		Total		Final Mass
	Δm [kg]	TOF [days]	TOF	Δm [kg]	TOF [days]	Δm [kg]	TOF [days]	
Oct. 2018	0.11	109.82	7.72	0.5	228.77	0.61	346.31	13.39
Jun. 2020	0.21	139.90	0.89	0.86	229.01	1.06	369.80	12.94
Nov. 2020	0.10	117.39	10.24	0.76	232.55	0.86	360.18	13.14

Outline

I. Background

II. Trajectory Design Framework

III. Sample Trajectory Design

IV. Concluding Remarks

Concluding Remarks

- Key Elements of Design Framework:
  - Bicircular Restricted Four-Body Problem (BCR4BP)
  - Staging Orbit
  - Direct Collocation
- Together key elements offer a *robust* and *adaptable* approach for Lunar IceCube mission design
  - Numerous transfer configurations
  - Flexible with changes in launch date

Acknowledgements

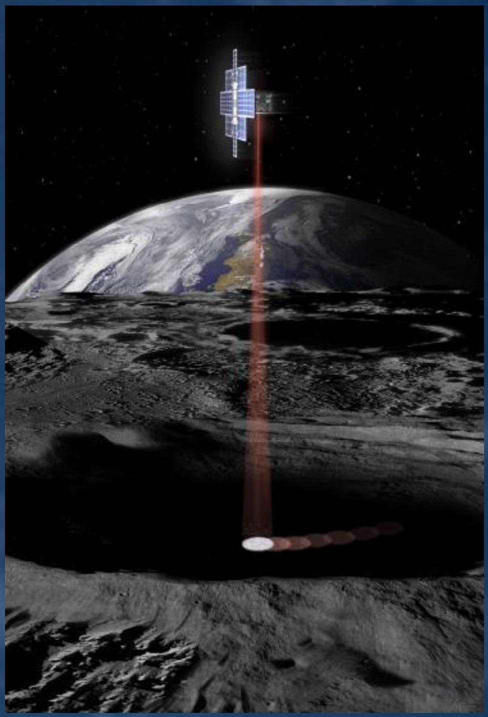
- Members of the Multibody Dynamics Research Group
- Navigation and Mission Design Branch at NASA Goddard Space Flight Center
- This work was supported by a NASA Space Technology Research Fellowship

Questions?

Backup Slides

Image Credits: nasa.gov

CubeSat Deployment

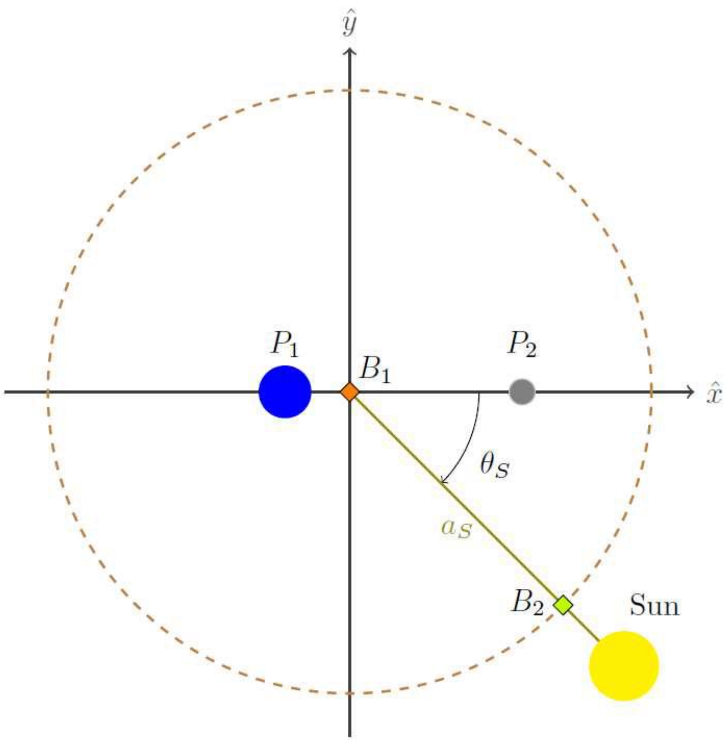


Lunar Flashlight

NEA Scout

Lunar IceCube

Background – Dynamical Model: BCR4BP

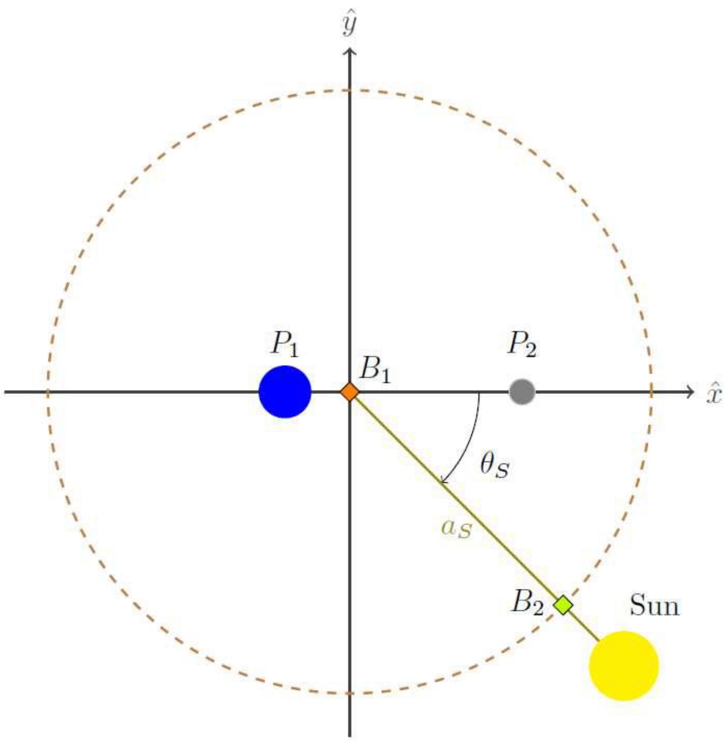


Bicircular Restricted Four-Body Problem (BCR4BP):

- Assumptions
  - Earth and Moon (E-M) in circular orbits about barycenter, B_1
  - Sun and B_1 (S-B_1) in circular orbits about barycenter, B_2
  - E-M orbits are coplanar with but not affected by S-B_1 orbits
- Time Dependency
  - Sun angle, θ_S, is epoch
  - Model is periodic
- Energy
  - Ballistic energy in the E-M rotating frame is defined:

$$H = 2\Psi - (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - \sigma$$

Background – Dynamical Model: BCR4BP



<u>Bicircular Restricted Four-Body Problem (BCR4BP):</u>

- Pseudo-Potential:

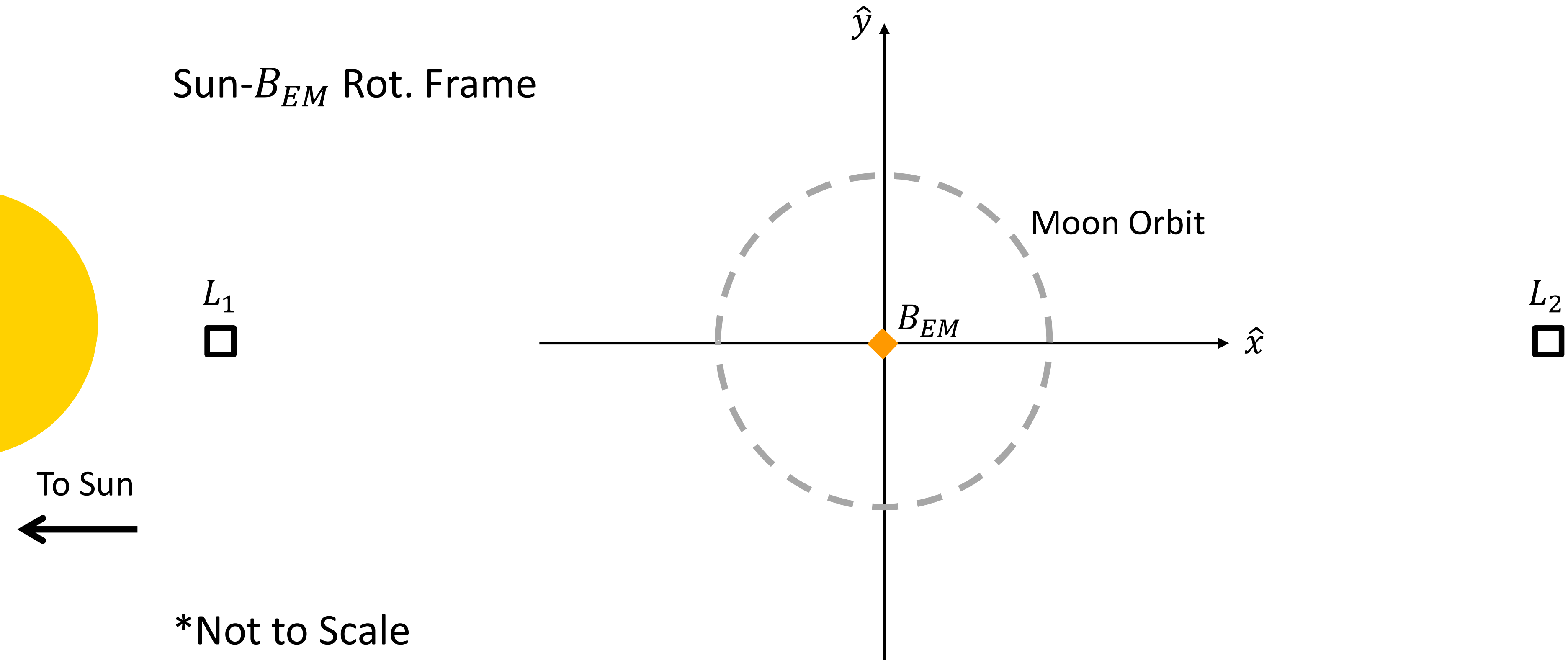
$$\Psi = \frac{1-\mu}{r_{13}} + \frac{\mu}{r_{23}} + \frac{1}{2}(x^2 + y^2) + \frac{m_S}{r_{S3}} - \frac{m_S}{a_S^3}(x_S x + y_S y + z_S z)$$

- Equations of Motion:

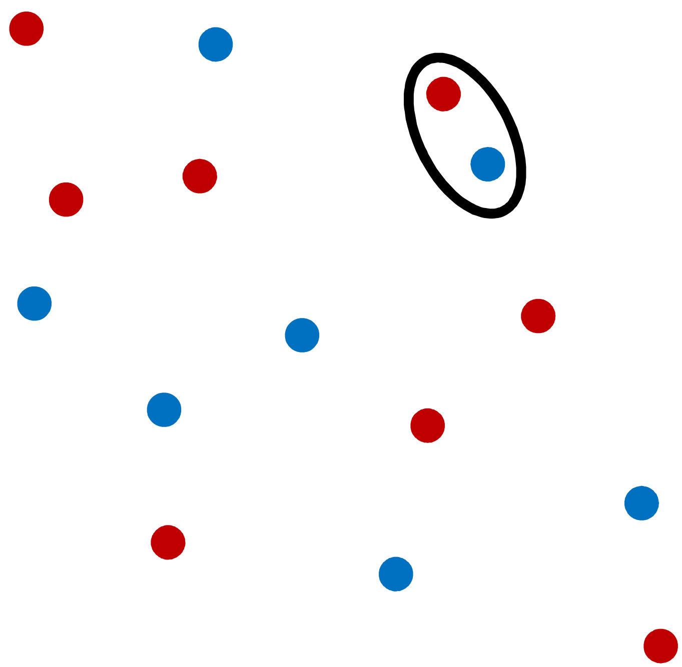
$$\ddot{x} = 2\dot{y} + \frac{\partial \Psi}{\partial x} + \frac{T_x}{m} \qquad \ddot{y} = -2\dot{x} + \frac{\partial \Psi}{\partial y} + \frac{T_y}{m}$$

$$\ddot{z} = \frac{\partial \Psi}{\partial z} + \frac{T_z}{m} \qquad \dot{m} = \frac{T}{v_e}$$

Background – Dynamical Model: BCR4BP



Background – Nearest Neighbor Search

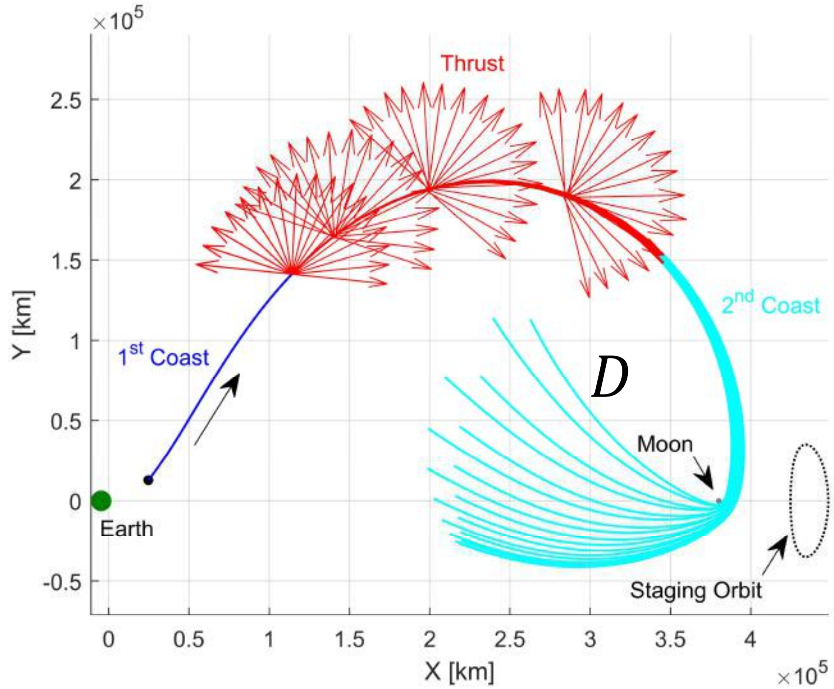


- Data Set P
- Data Set Q

Standardized Euclidean Distance:

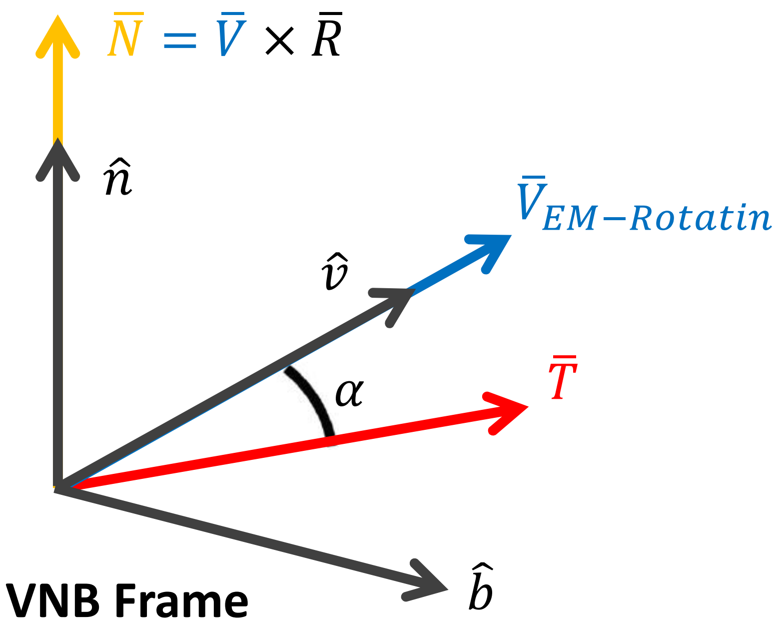
$$\frac{1}{s}\sqrt{\bar{p}_i^2 - \bar{q}_j^2}$$

Design Framework – Phase 1: Forward



Deployment

Design Framework – Phase 1: Forward



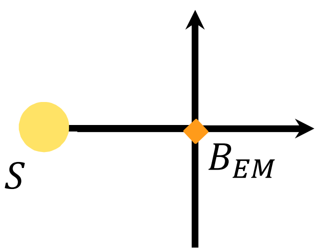
<u>Propagation from Deployment:</u>

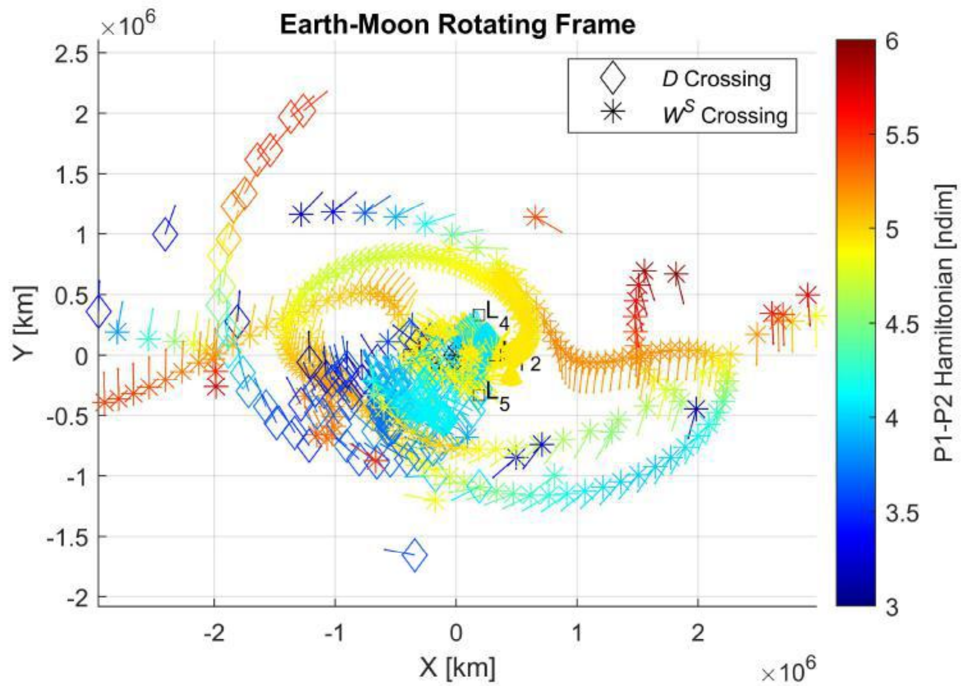
1. Coast arc
2. Thrust arc
3. Coast arc

- Thrust direction defined by constant angle, α, in the velocity-normal-binormal frame.
- Varying α generates a range of post-flyby behaviors.

Design Framework – Phase 1: Mapping

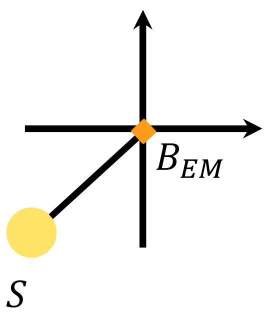
$\theta_{S_1} = 180°$

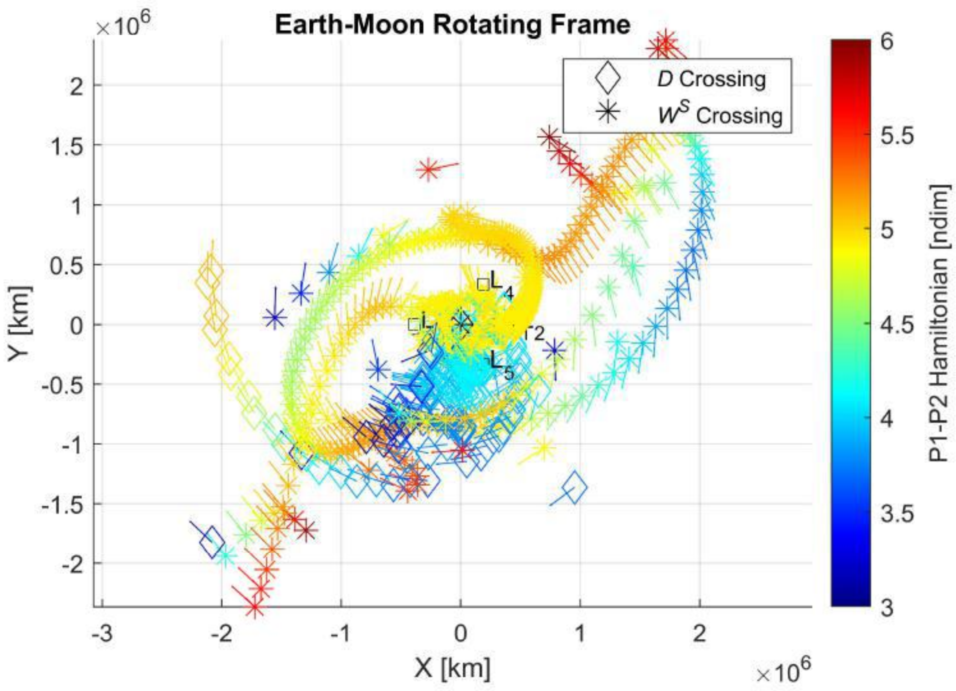




Design Framework – Phase 1: Mapping

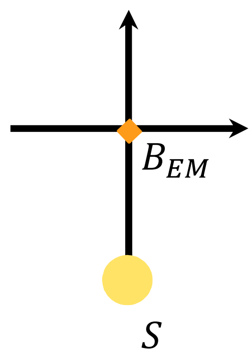
$\theta_{S_1} = 225°$

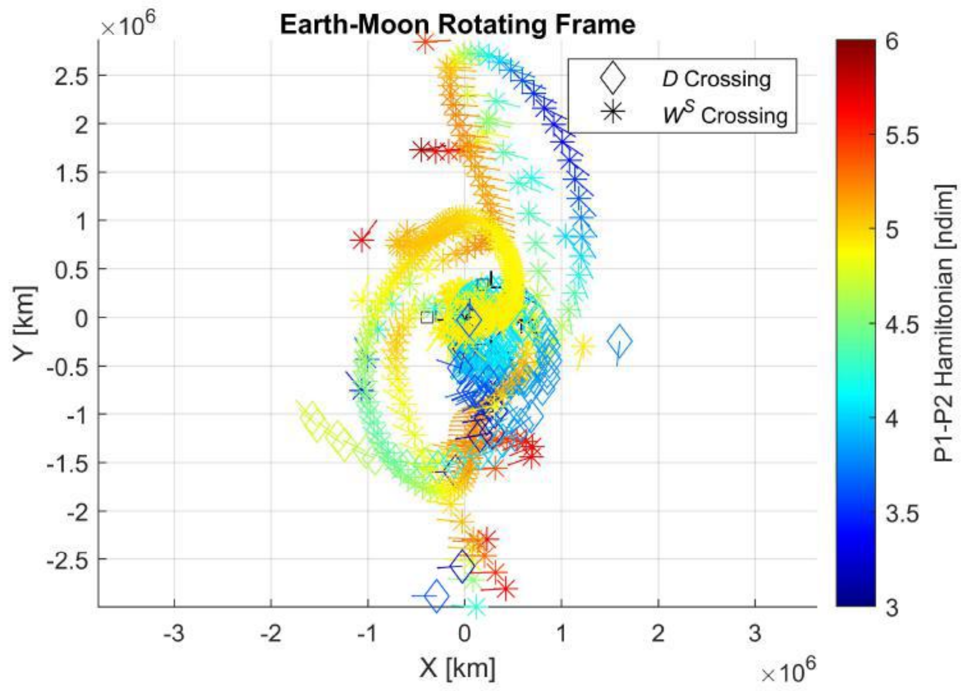




Design Framework – Phase 1: Mapping

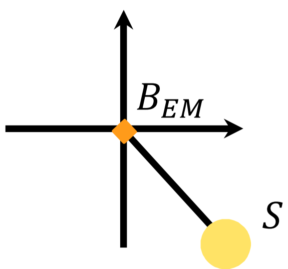
$\theta_{S_1} = 270°$

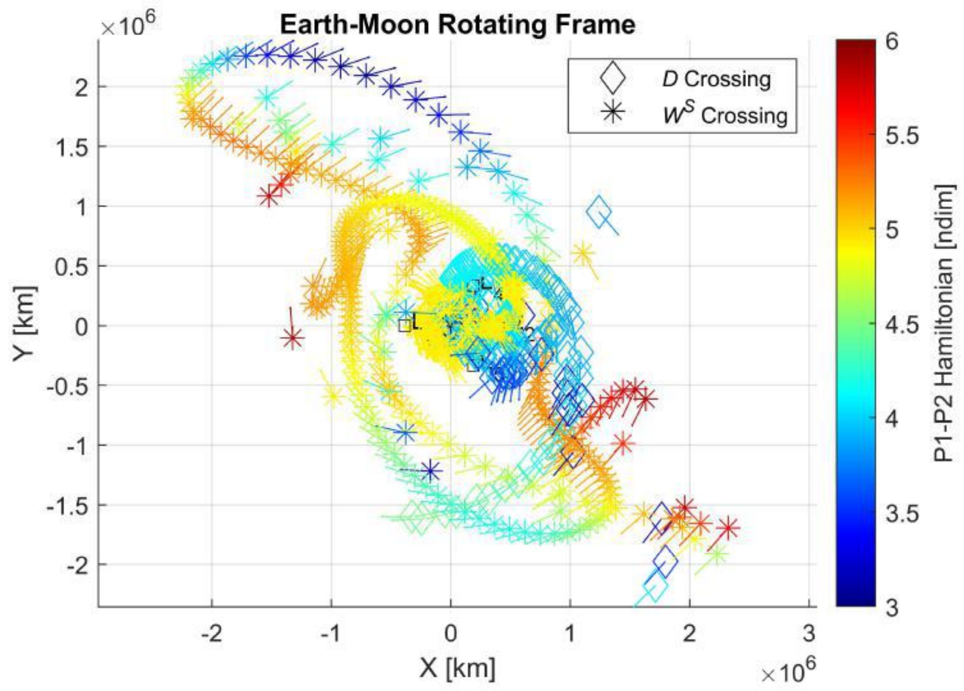




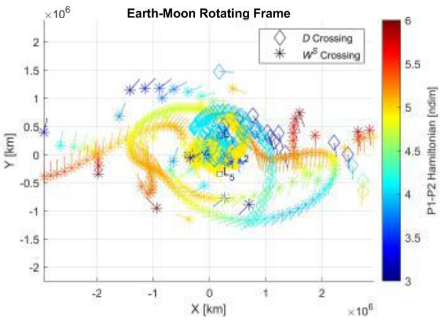
Design Framework – Phase 1: Mapping

$\theta_{S_1} = 315°$

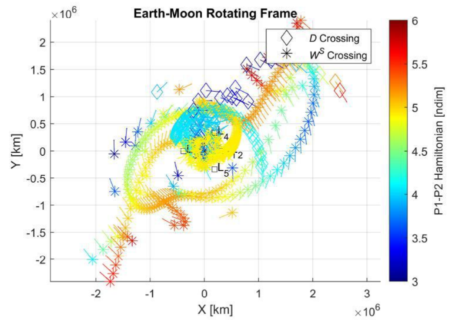




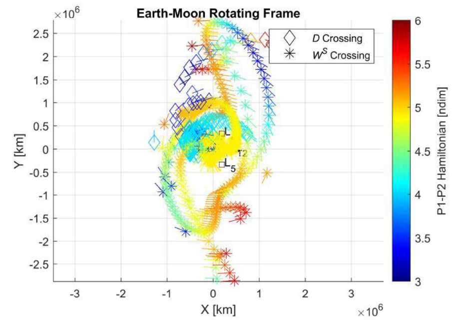
Design Framework – Phase 1: Mapping



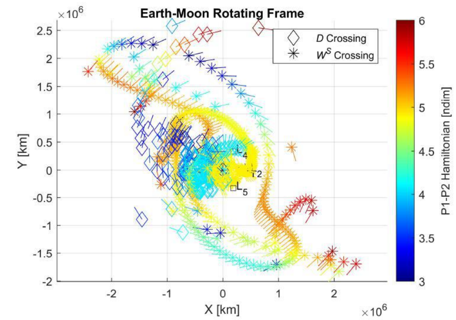
$\theta_{S_1} = 0°$



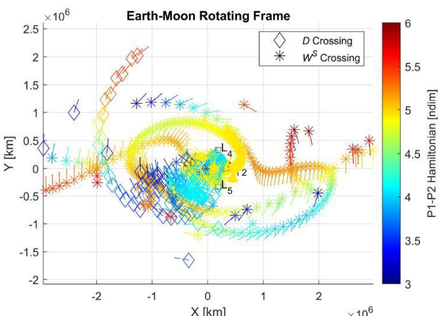
$\theta_{S_1} = 45°$



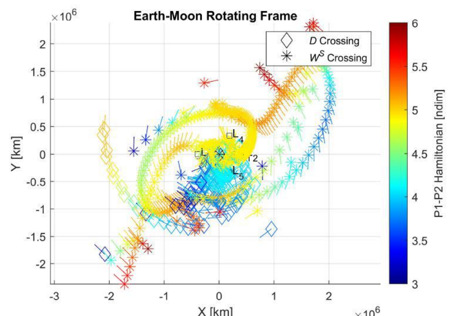
$\theta_{S_1} = 90°$



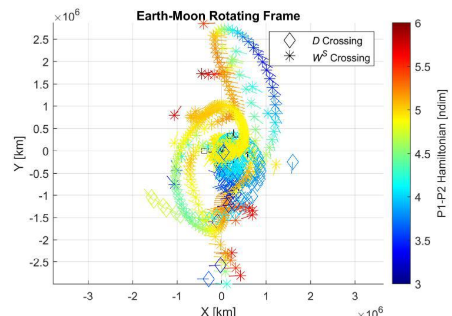
$\theta_{S_1} = 135°$



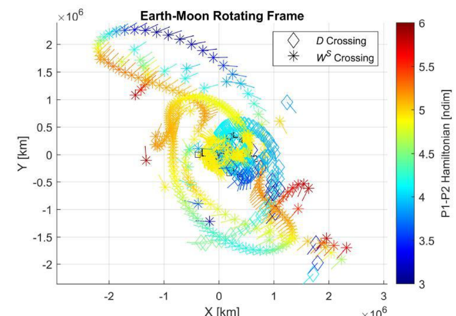
$\theta_{S_1} = 180°$



$\theta_{S_1} = 225°$



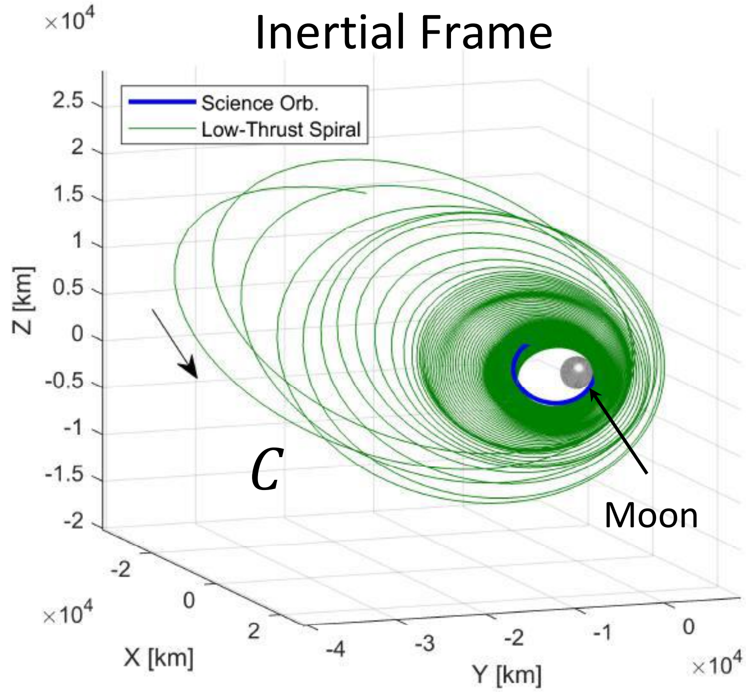
$\theta_{S_1} = 270°$



$\theta_{S_1} = 315°$

Design Framework – Phase 2: Backward

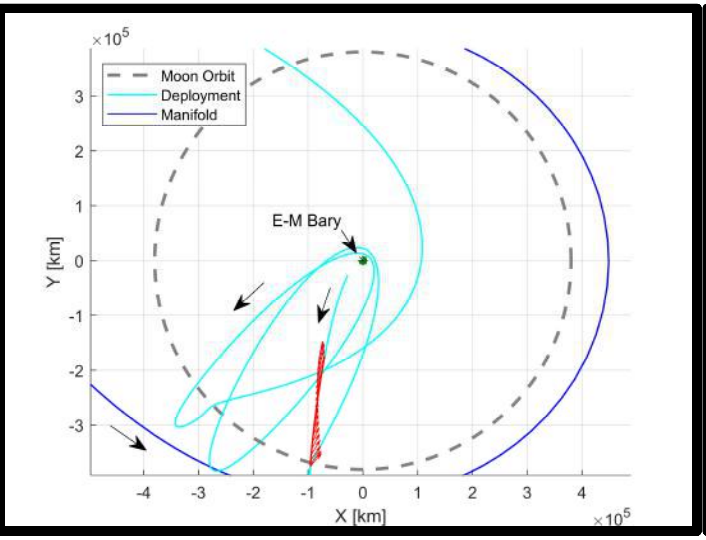
Inertial Frame



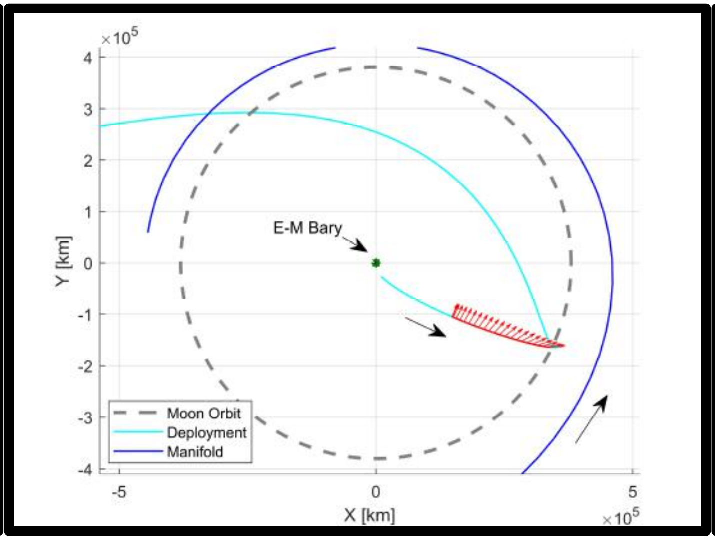
Propagation From Science Orbit

Sample Trajectory Design – Phase 1: Guess

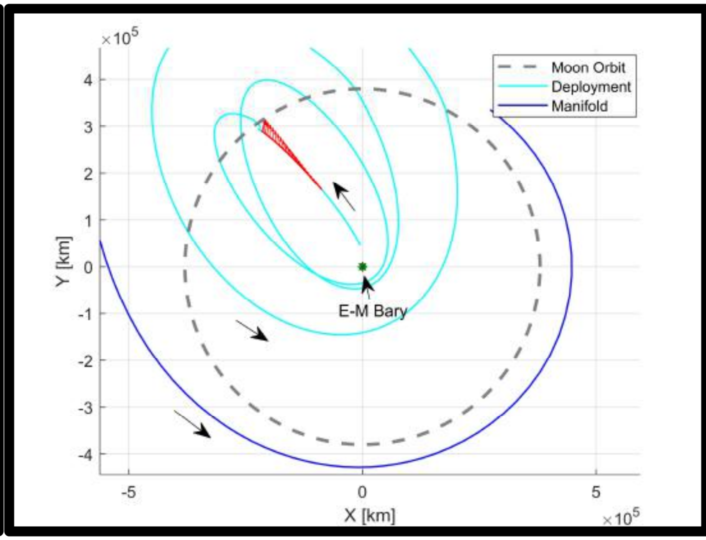
October 2018



June 2020



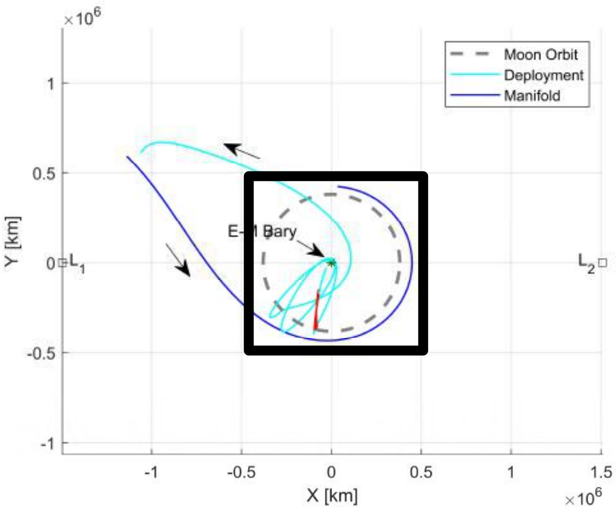
November 2020



Sun-B_1 Rotating Frame

Sample Trajectory Design – Phase 1: Guess

October 2018



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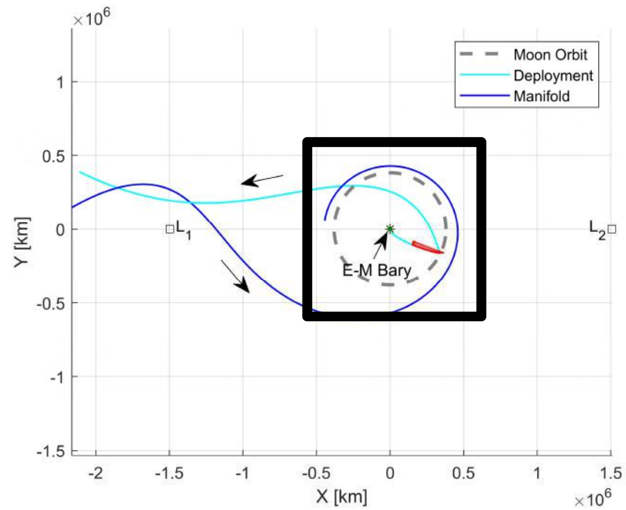
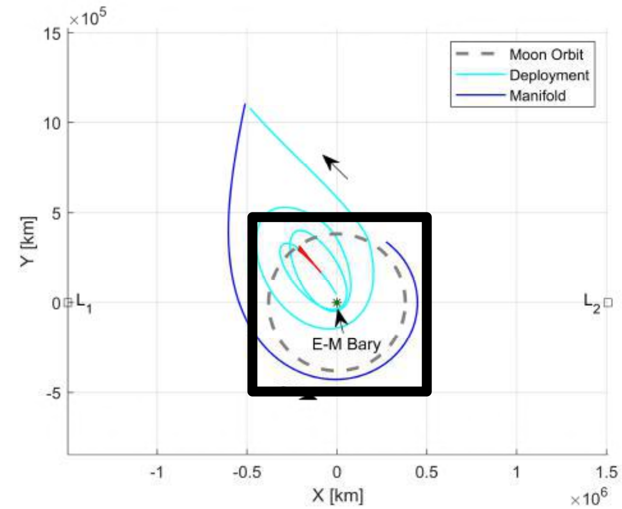
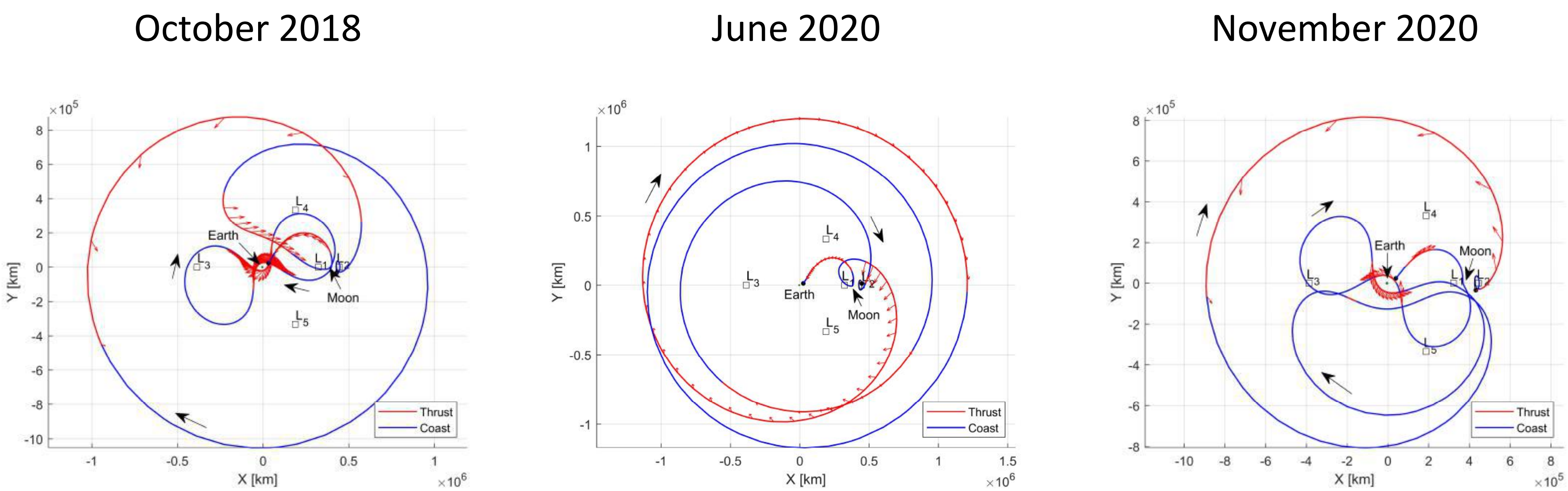


November 2020



Sun-B_1 Rotating Frame

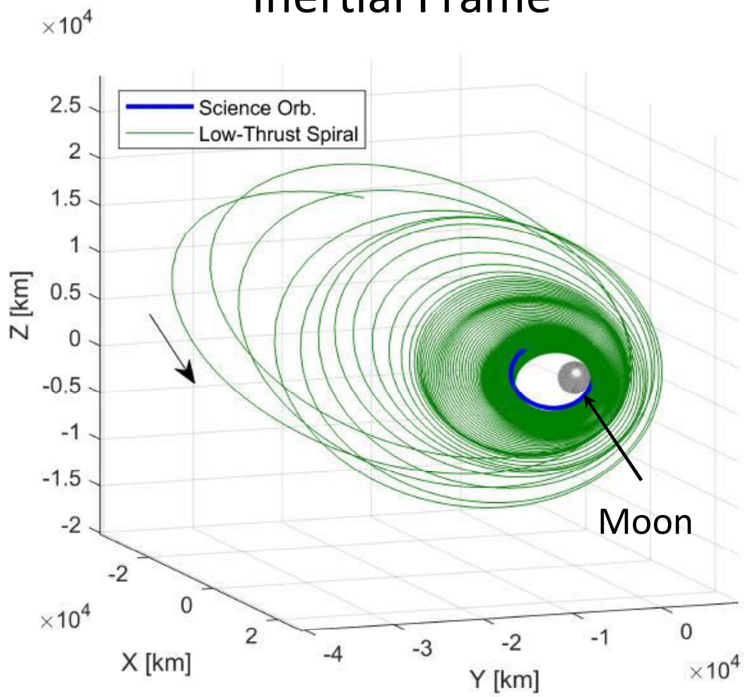
Sample Trajectory Design – Phase 1: Result

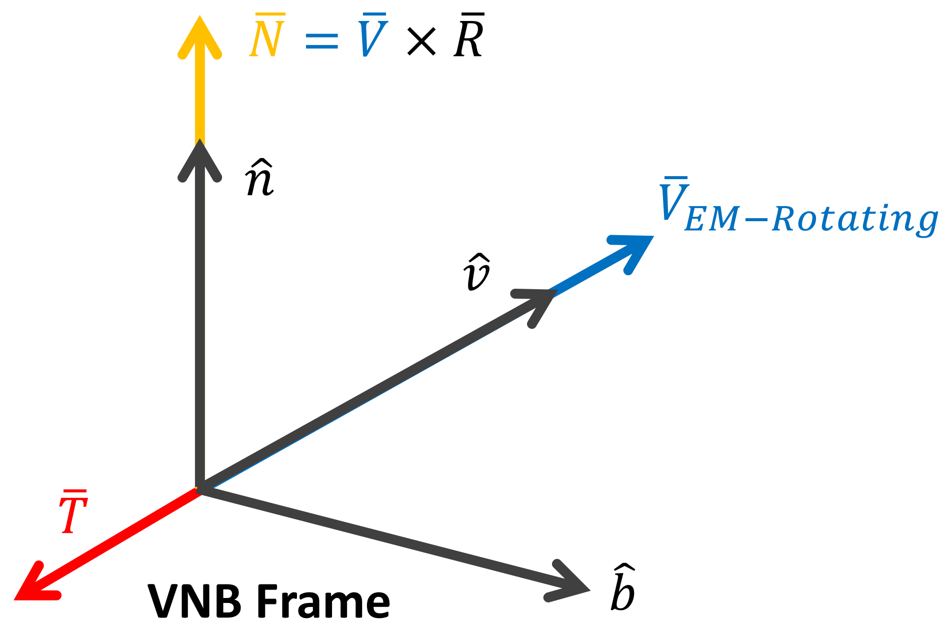


Earth-Moon Rotating Frame

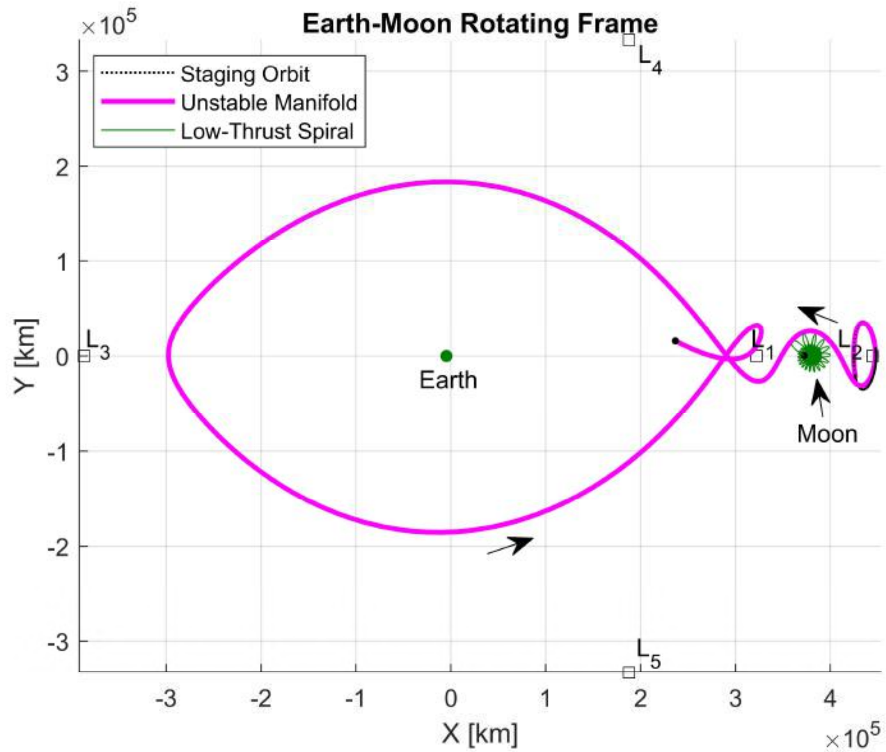
Design Framework – Phase 2: Backward

Inertial Frame

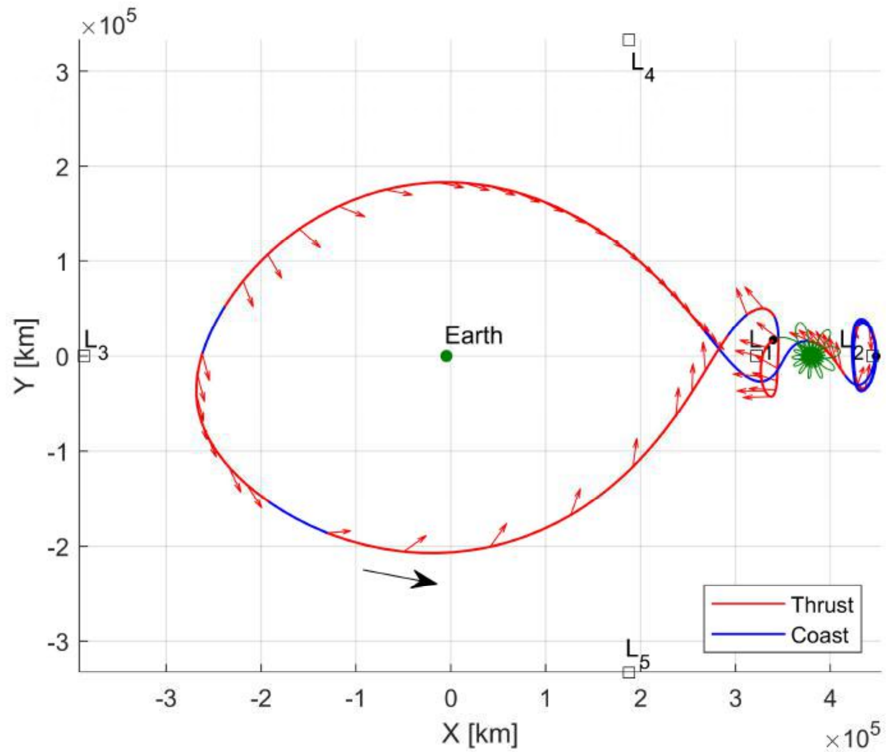




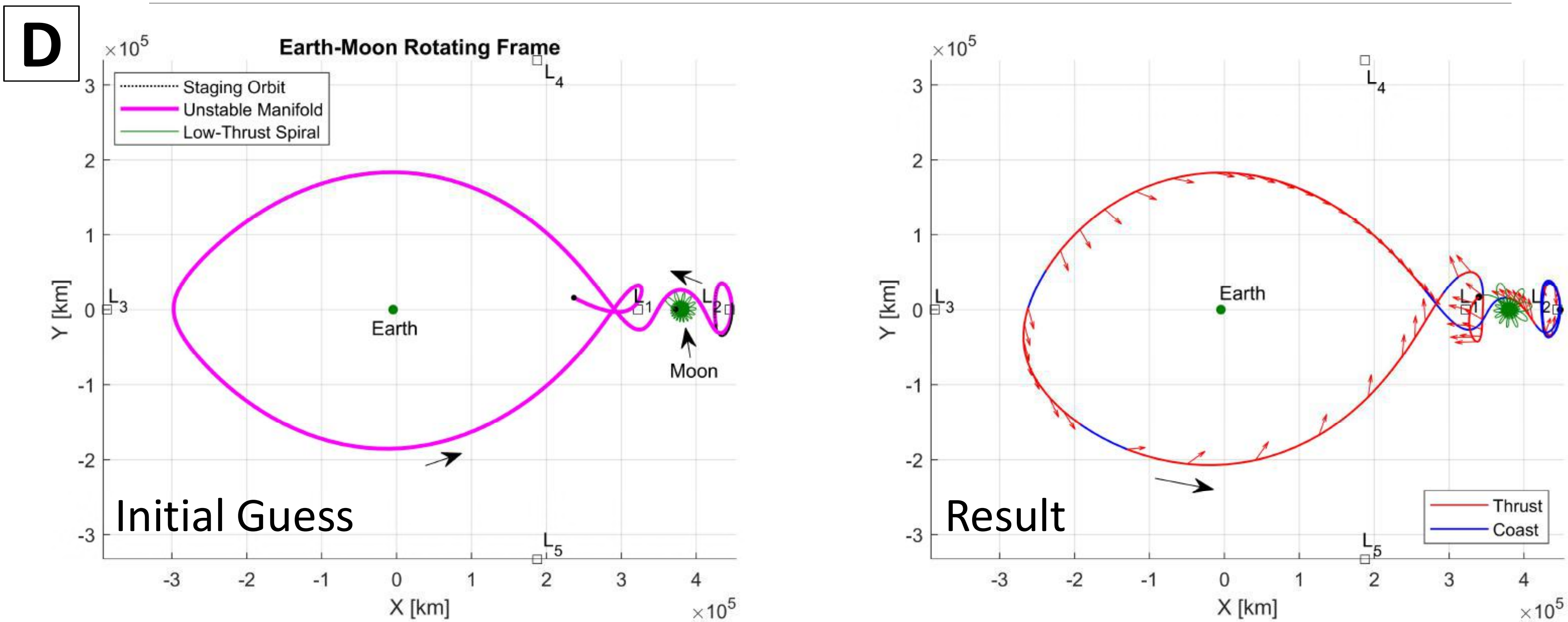
Sample Trajectory Design – Phase 2: Guess



Sample Trajectory Design – Phase 2: Result



Sample Trajectory Design – Phase 2: Result



Sample Trajectory Design – Phase 2: Result