6th International Conference on Astrodynamics Tools and Technique (ICATT)

INDIRECT PLANETARY CAPTURE VIA PERIODIC ORBIT ABOUT LIBRATION POINTS

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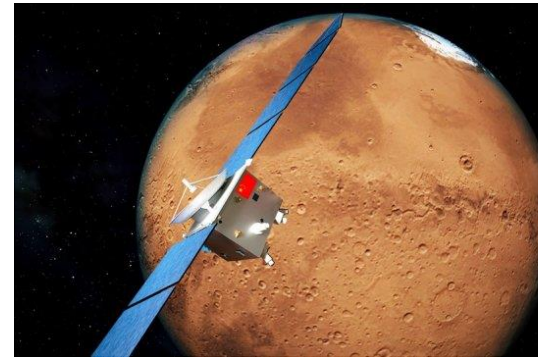
I. Introduction



Planetary Capture

- A key process in planet exploration mission

Interplanetary Trajectory → Planetary Capture → Mission Orbits

- Plays an important role in the trajectory design

Capture Trajectory Design →

- Fuel Consumption
- Flight System Design
- Interplanetary Trajectory Design
- Midcourse Correction

I. Introduction

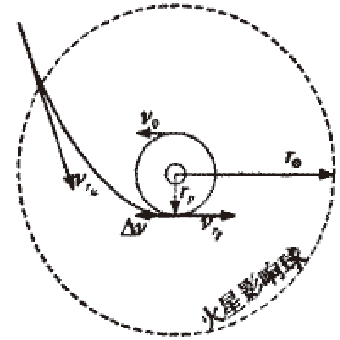
Current Capture Strategy

- Direct Capture

  Single impulsive maneuver at periapsis

  Easy to design

  $r_p \uparrow$, $v_\infty \uparrow$ → $\Delta v \uparrow$



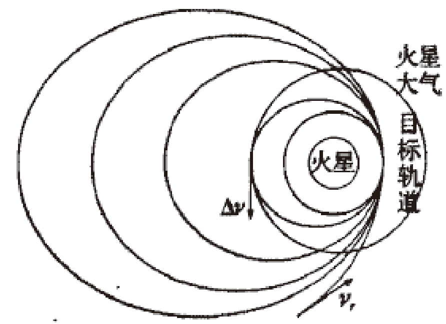
- Aerocapture

  Take advantage of the aerodynamic force to reduce the velocity

  Fuel Saving

  Precise guidance and control

  Protection for high heat rate and overload



- Ballistic Capture

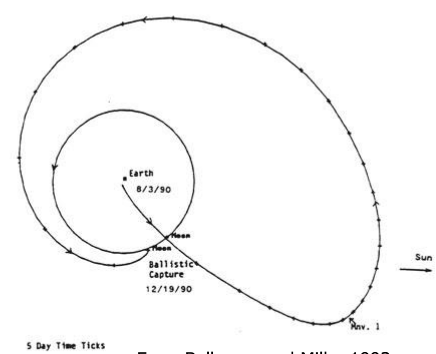
  Exploits the gravitational force of planets to capture a spacecraft

  Low energy Capture

  Multi capture opportunities

  Long transfer time

  Fall when v_∞ is high



From Belbruno and Miller 1993

I. Introduction

Circular Restricted Three body Problem (CRTBP)

- Libration(Lagrange) Points
- Periodic orbits
- Stable/Unstable Manifolds

$$\begin{cases} \ddot{x}-2\dot{y}=x-\dfrac{(1-\mu)(x+\mu)}{r_s^3}-\dfrac{\mu(x-1+\mu)}{r_m^3} \\ \ddot{y}+2\dot{x}=y-\dfrac{(1-\mu)y}{r_s^3}-\dfrac{\mu y}{r_m^3} \\ \ddot{z}=-\dfrac{(1-\mu)z}{r_s^3}-\dfrac{\mu z}{r_m^3} \end{cases}$$

Space observation

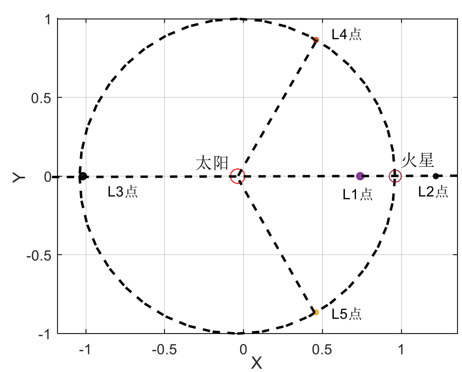
Low energy transfer

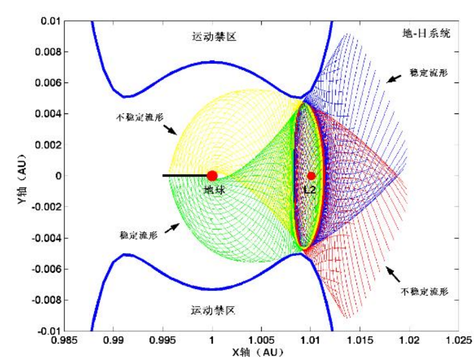
Communication relay

Capture to periodic orbit

Nakamiya and Scheeres (2008,2010)
Wang (2014)

Planetary Capture

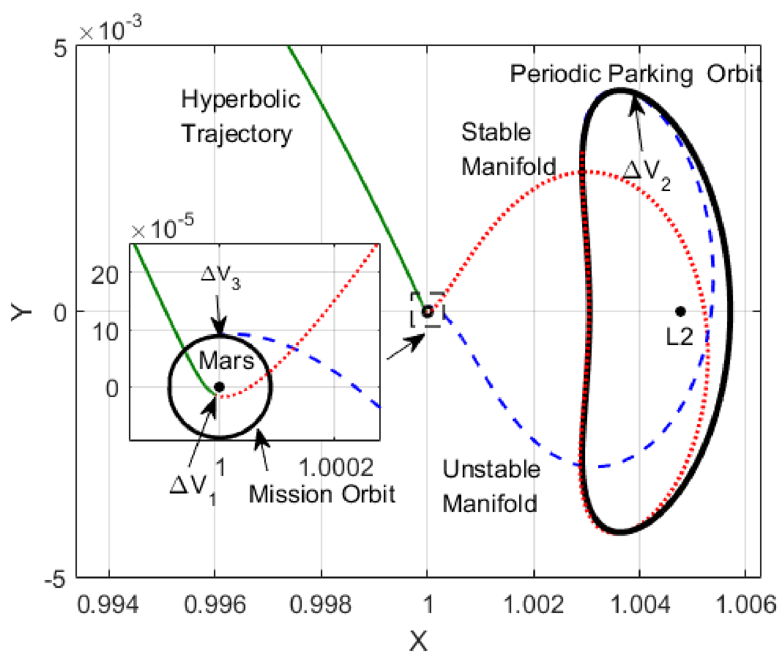


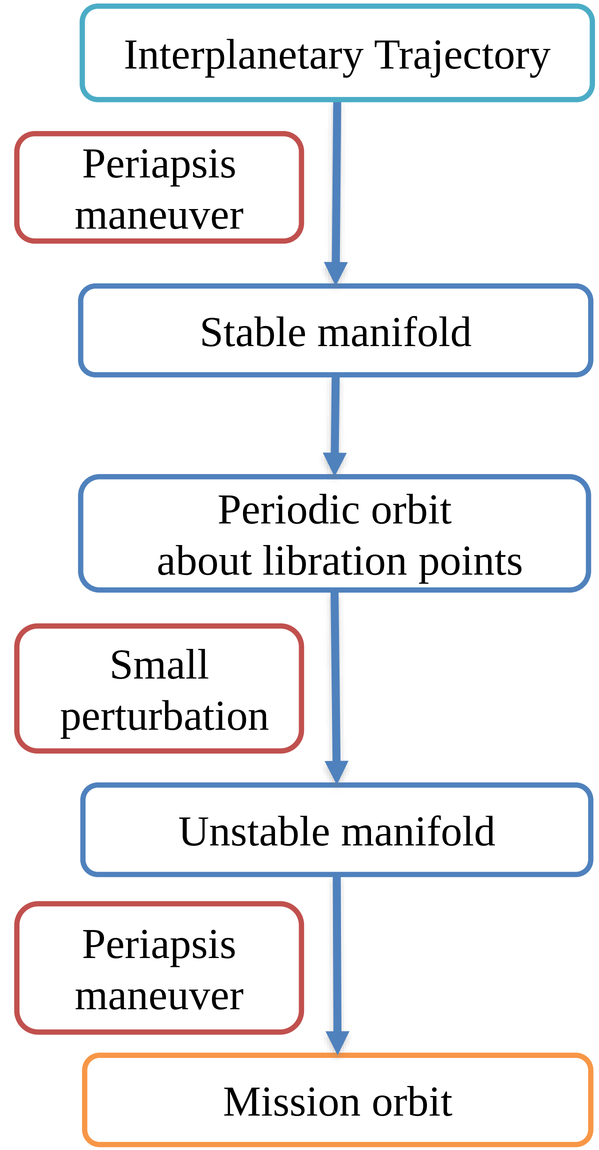


II. Concept of Indirect Planetary Capture

Concept

- Use periodic orbit as a park orbit
- Connect with interplanetary trajectory by stable manifolds
- Connect with mission orbit by unstable manifolds





II. Concept of Indirect Planetary Capture

Process

- Three impulsive maneuver

First periapsis maneuver

$$\Delta v_1 \propto v_\infty$$

Perturbation to generate unstable manifolds

Δv_2 Initial guess and correction

Second Periapsis maneuver

$$\Delta v_3 \propto a, e$$

Process

- Three impulsive maneuver

First periapsis maneuver

Perturbation to generate unstable manifolds

Second Periapsis maneuver

II. Concept of Indirect Planetary Capture

Maneuver

- Three impulsive maneuver

  First periapsis maneuver

  $$\Delta v_1 \propto v_\infty$$

  Perturbation to generate unstable manifolds

  Δv_2 Initial guess and correction

  Second Periapsis maneuver

  $$\Delta v_3 \propto a, e$$

Design

- Construct the periodic parking orbit
- Generate proper unstable manifolds
  same periapsis distance as mission orbit
- Generate proper stable manifolds
  for interplanetary design and midcourse correction

III. Orbit Selection for Periodic Orbit

Orbit Selection

- Two criteria
  - Energy constrain

    First maneuver Δv_1 as low as possible

$$\Delta v_1 = v_{ex} - v_{ps} \approx v_{ex} - v_{es} = \sqrt{v_\infty^2 + \frac{2\mu}{r_{ps}}} - \sqrt{\frac{2\mu}{r_{ps}}} \qquad v_{es} = \sqrt{\frac{2\mu}{r_{ps}}}$$

$$\frac{\partial \Delta v_1}{\partial r_{ps}} = -\frac{1}{\sqrt{v_\infty^2 + \frac{2\mu}{r_p}}}\frac{\mu}{r_p^2} + \sqrt{\frac{\mu}{2r_p^3}} = \frac{\sqrt{v_\infty^2 + \frac{2\mu}{r_p}} - \sqrt{\frac{2\mu}{r_p}}}{\sqrt{v_\infty^2 + \frac{2\mu}{r_p}}} \cdot \sqrt{\frac{\mu}{2r_p^3}} \Rightarrow \frac{\partial \Delta v}{\partial r_{ps}} > 0, \forall v_\infty > 0$$

Periapsis of stable manifolds should close to the surface of Mars

  - State constrain

    The periapsis distance of natural unstable manifolds should close to that of mission orbits

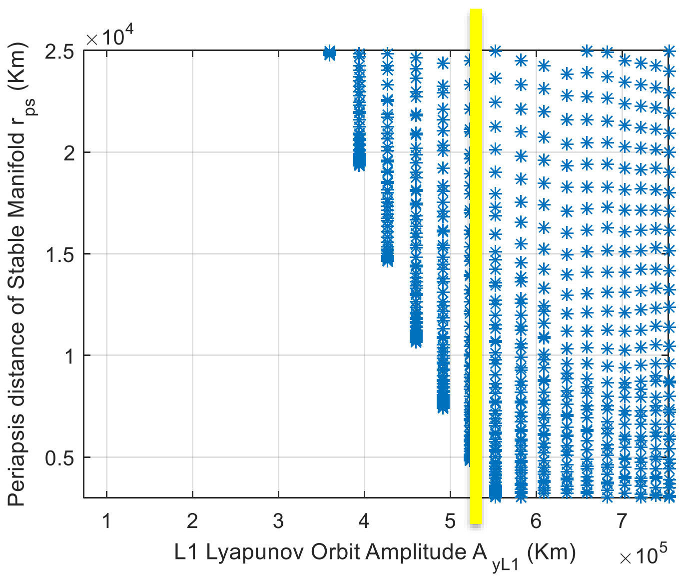
III. Orbit Selection for Periodic Orbit

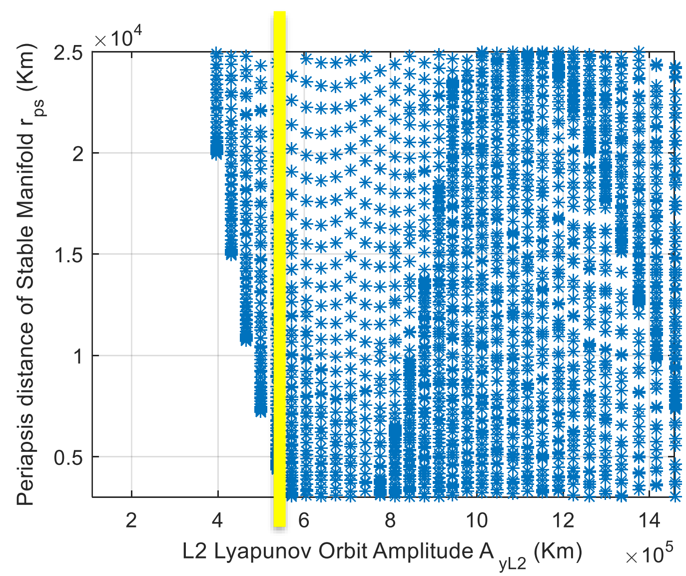
Sun-Mars System

Planar Orbits

- Planar Lyapunov orbit
  - L1 orbit from $A_y = 7.3\times10^4 km$ to $A_y = 7.5\times10^5 km$
  - L2 orbit from $A_y = 1.0\times10^5 km$ to $A_y = 1.5\times10^6 km$

Periapsis distance of stable manifolds



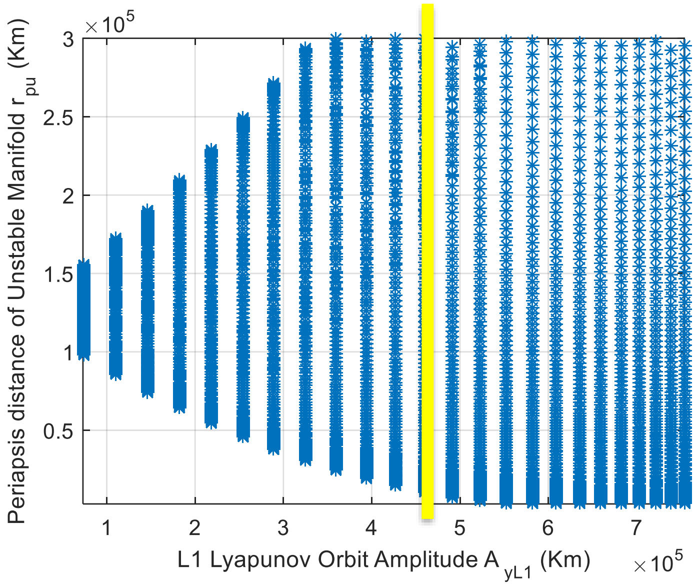


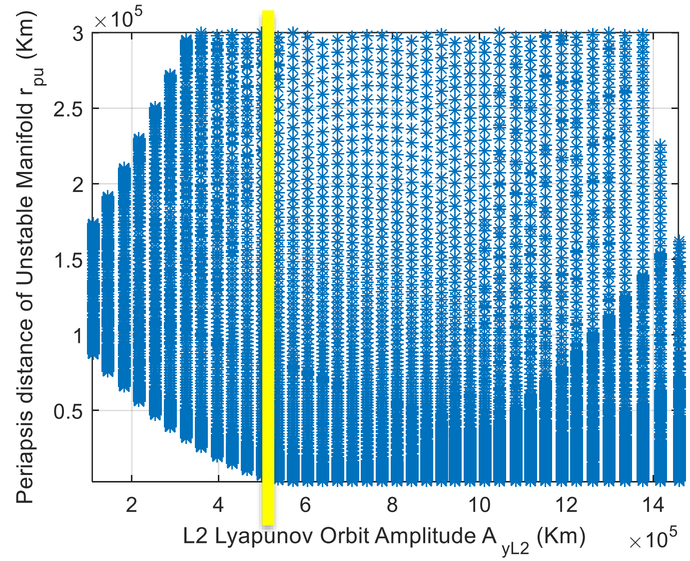
Critical amplitude A_{yc} $A_{yc} = 5.5\times10^5 km$ $A_{yc} = 5.7\times10^5 km$

III. Orbit Selection for Periodic Orbit

Planar Orbits

Periapsis distance of unstable manifolds from $3589km$ to $300000km$





Candidate parking orbits

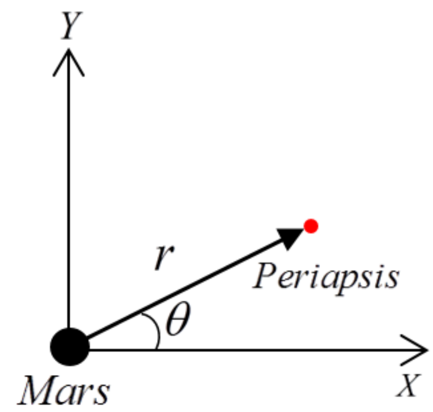
L1 orbit from $A_y = 5.5 \times 10^5 km$ L2 orbit from $A_y = 5.7 \times 10^5 km$

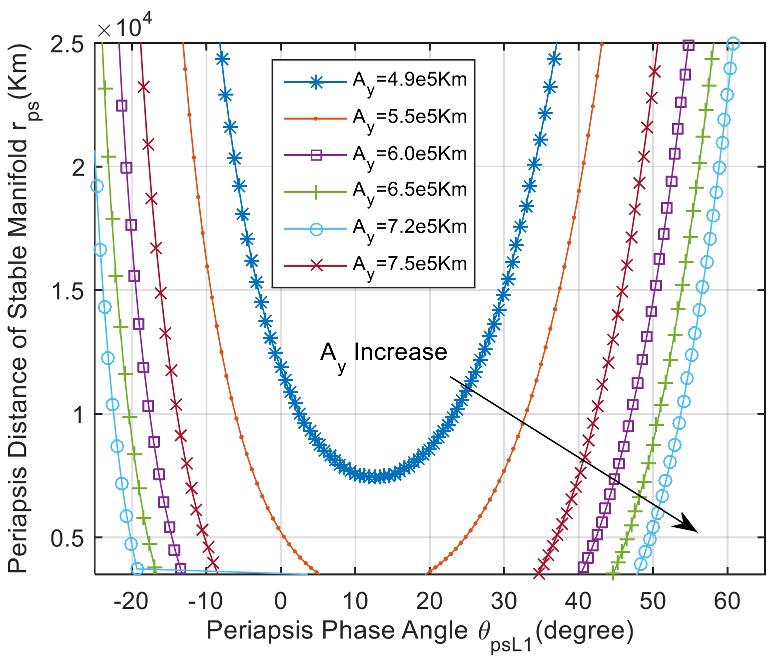
III. Orbit Selection for Periodic Orbit

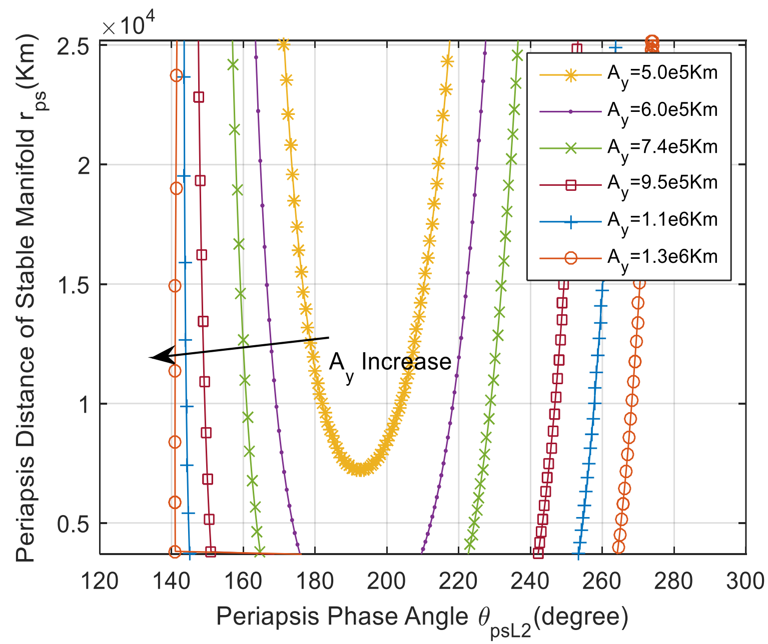
Planar Orbits

- **Periapsis State**

Periapsis phase angle θ







L1: $\theta_0 = 10^\circ$ → $-20^\circ \sim 50^\circ$

L2: $\theta_0 = 190^\circ$ → $140^\circ \sim 260^\circ$

III. Orbit Selection for Periodic Orbit

Sun-Mars System

Spatial Orbits

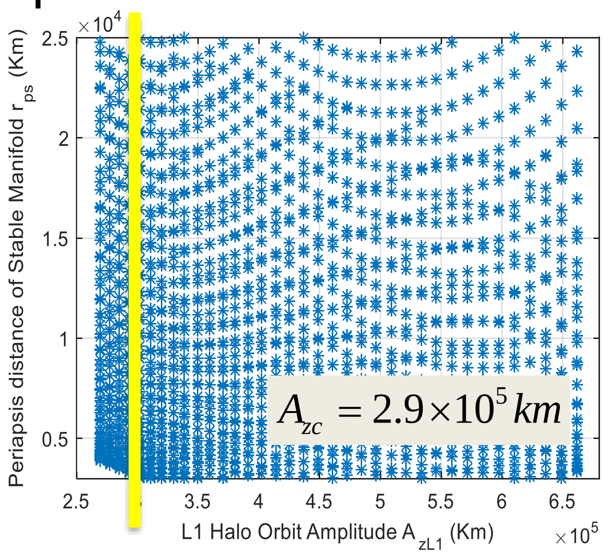
- Vertical Lyapunov orbit

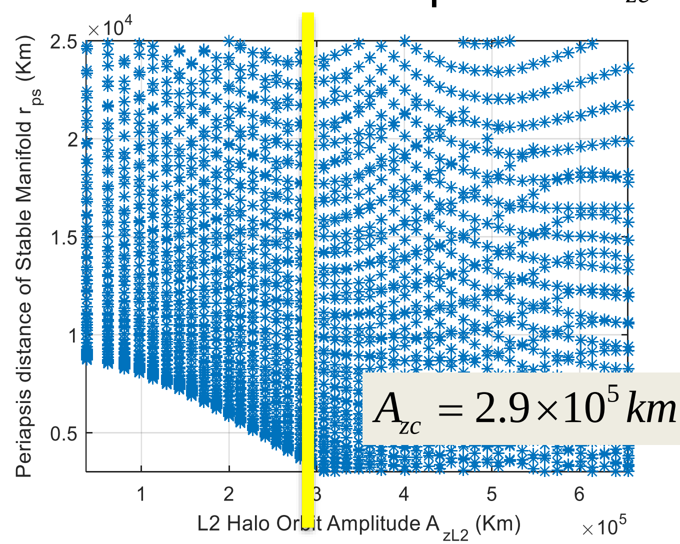
  Large periapsis distance Infeasible

- Halo orbit
  - L1 orbit from $A_z = 2.7\times10^4 km$ to $A_z = 6.6\times10^4 km$
  - L2 orbit from $A_z = 3.7\times10^4 km$ to $A_z = 6.5\times10^5 km$

Periapsis distance of stable manifolds

Critical amplitude A_{zc}

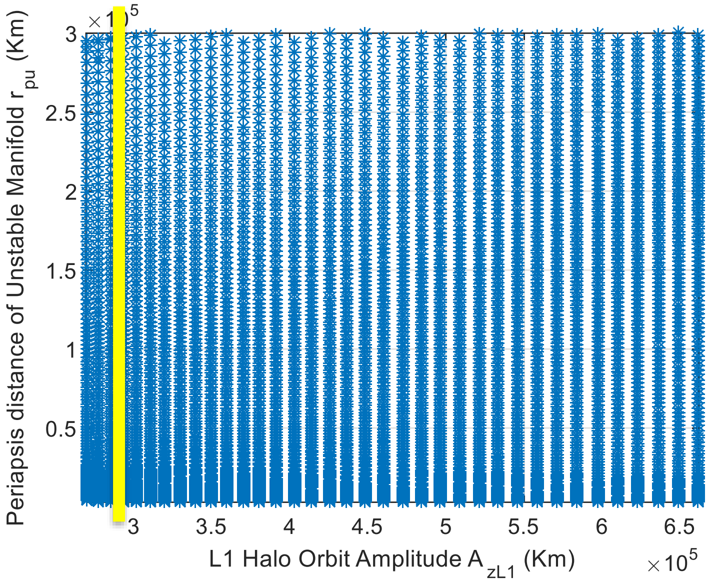


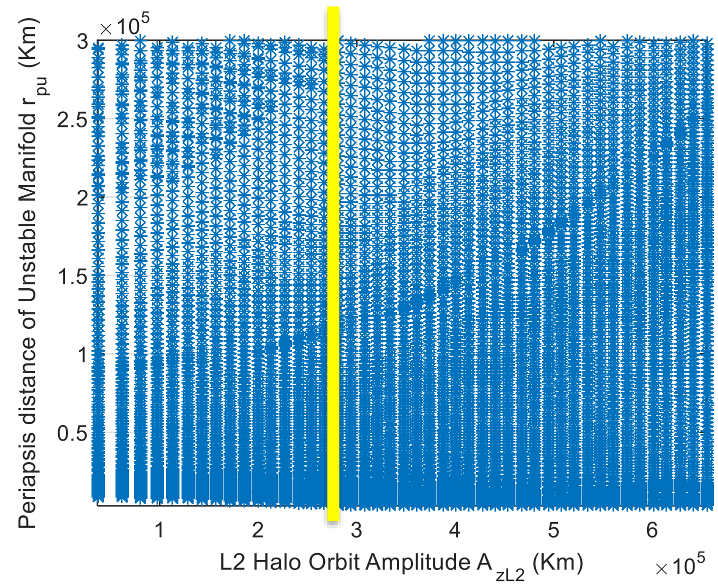


III. Orbit Selection for Periodic Orbit

Halo Orbits

Periapsis distance of unstable manifolds from $3589km$ to $300000km$





Candidate parking orbits

L1 orbit from $A_z = 2.9\times10^5 km$ to $A_z = 6.6\times10^5 km$

L2 orbit from $A_z = 2.9\times10^5 km$ to $A_z = 6.5\times10^5 km$

III. Orbit Selection for Periodic Orbit

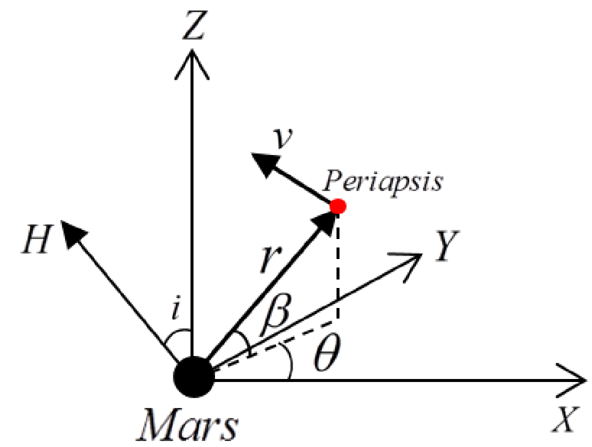
Halo Orbits

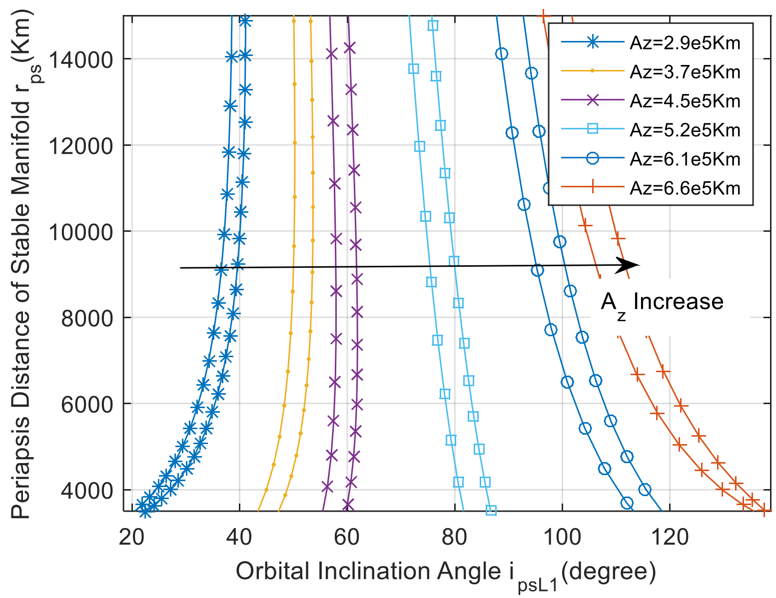
- **Periapsis State**

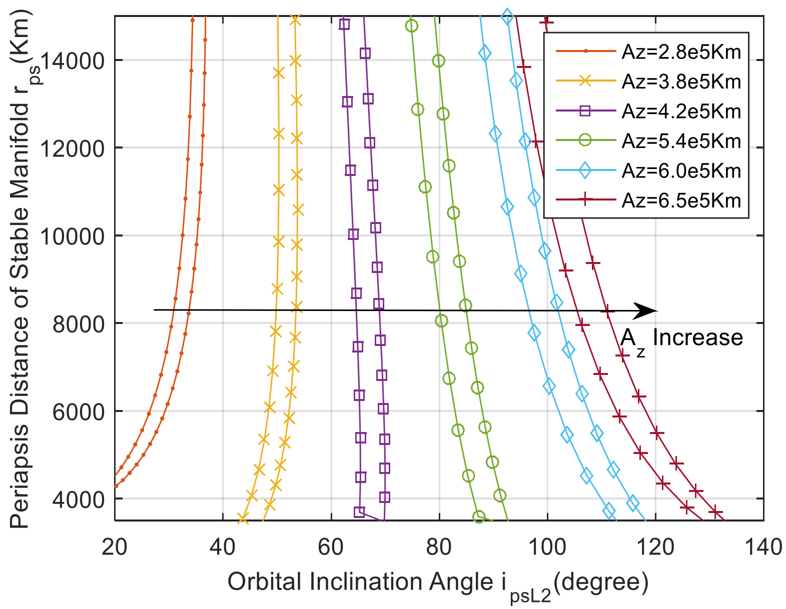
Orbital Inclination i

Periapsis phase angle θ

Periapsis Spatial angle β







L1: $i = 20^\circ$ → $i = 140^\circ$

L2: $i = 20^\circ$ → $i = 130^\circ$

III. Orbit Selection for Periodic Orbit

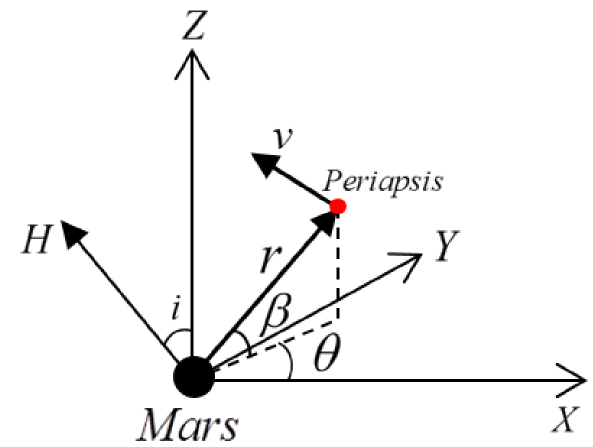
Halo Orbits

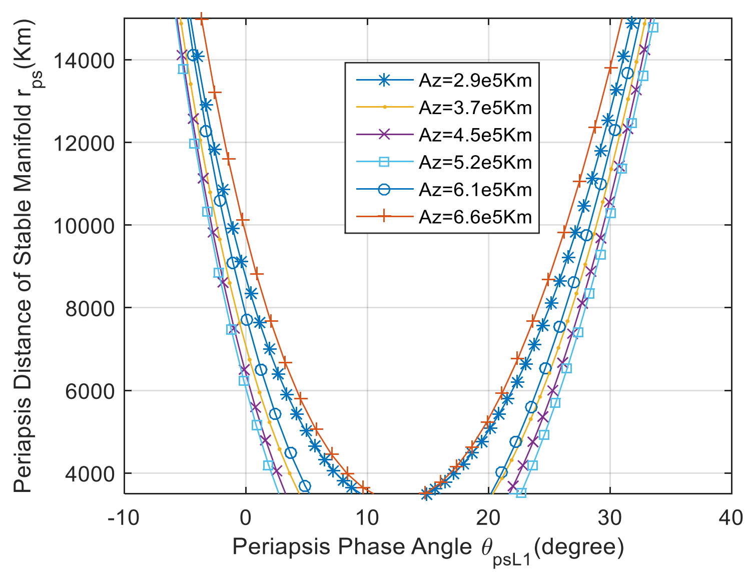
- **Periapsis State**

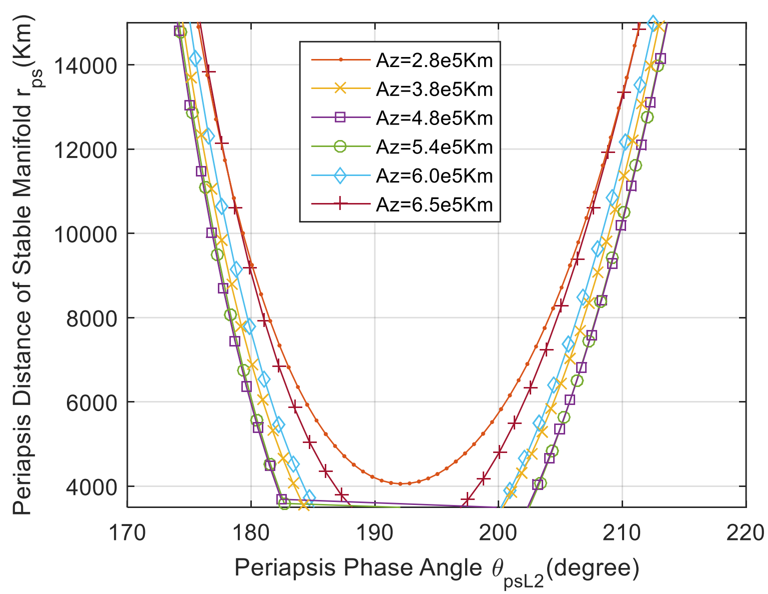
Orbital Inclination i

Periapsis phase angle θ

Periapsis Spatial angle β







L1: $\theta = 10^\circ$ → $5 \sim 20^\circ$

L2: $\theta = 190^\circ$ → $182^\circ \sim 202^\circ$

III. Orbit Selection for Periodic Orbit

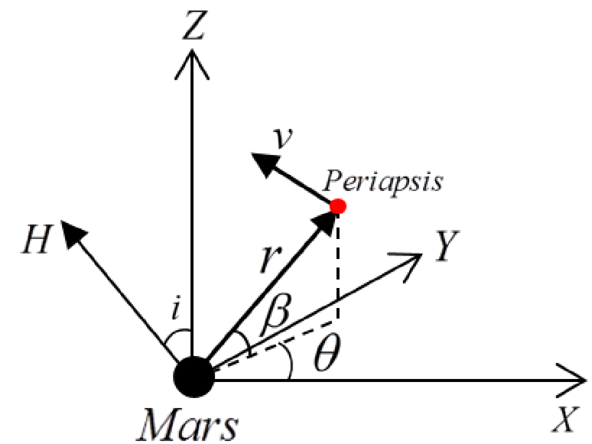
Halo Orbits

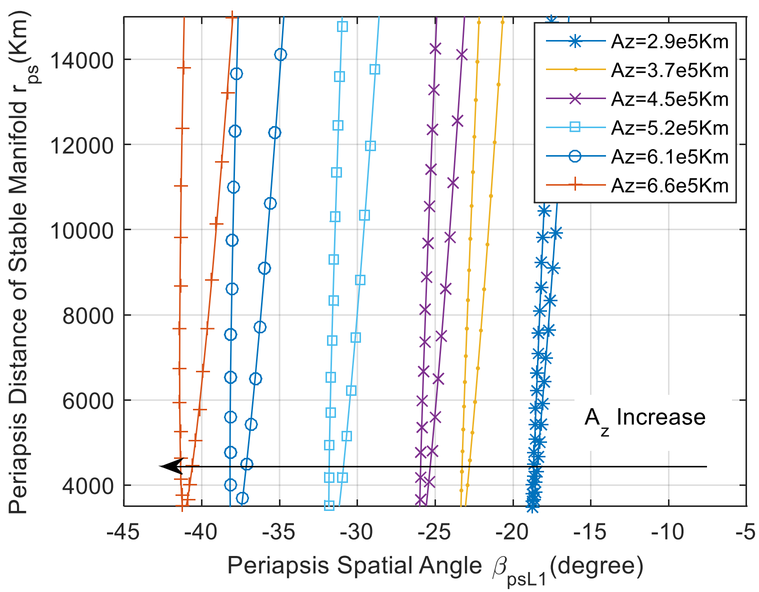
- **Periapsis State**

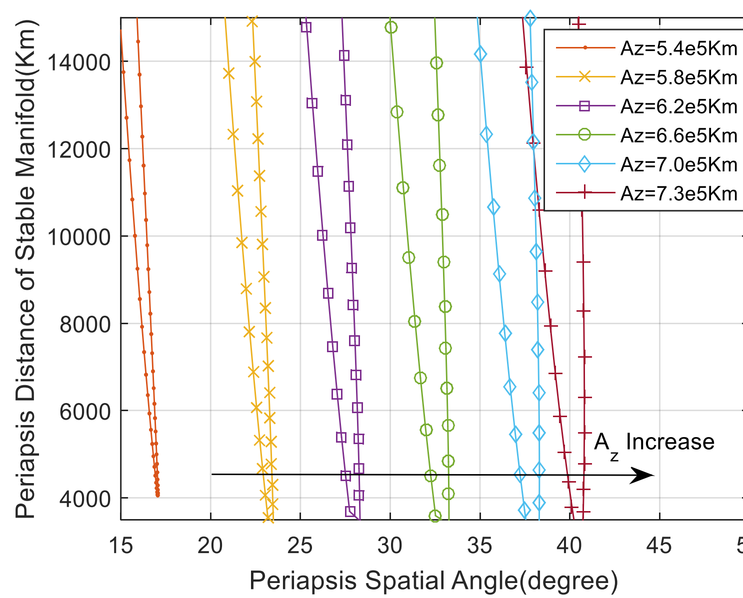
Orbital Inclination i

Periapsis phase angle θ

Periapsis Spatial angle β







L1: $|\beta| = 19^\circ$ → $|\beta| = 41^\circ$

L2: $|\beta| = 17^\circ$ → $|\beta| = 40^\circ$

IV. Simulation and Comparisons

- Direct capture

$$\Delta v_d = \sqrt{v_\infty^2 + \frac{2\mu}{r_p}} - \sqrt{\frac{(1+e)\mu}{r_p}}$$

$$r_p = a(1-e)$$

- Indirect capture

First impulsive maneuver

$$\Delta v_1 = \sqrt{v_\infty^2 + \frac{2\mu}{r_{ps}}} - v_{ps}$$

$$r_{ps} \approx 3589km$$

Third impulsive maneuver

$$\Delta v_3 = v_{pu} - \sqrt{\frac{(1+e)\mu}{r_p}}$$

$$\Delta v = \Delta v_1 + \Delta v_2 + \Delta v_3$$

Perturbation velocity

$$\Delta v_2 \propto 1m/s$$

Capture Time

$$T = T_s + T_p + T_u$$

T_s Stable manifold transfer time

T_p Parking time

T_u Unstable manifold transfer time

IV. Simulation and Comparisons

- Mission Orbit I

    200km circular orbit

- Parking orbit

    L2 planar Lyapunov orbit $A_y = 5.7 \times 10^5 km$

v_∞ (km/s)	Direct Capture Δv_d (km/s)	Indirect capture		$\Delta v_d - \Delta v$ (km/s)
		Δv (km/s)	T (day)	
1.88	1.780	1.779	775.37	0.001
2.09	1.859	1.858		0.001
3.39	2.492	2.487		0.005

Low orbit capture:

➢ Cost the same velocity as direct capture

Provides a chance to explore the space environment in the vicinity of Mars and Lagrange points without extra velocity increment

Long transfer time

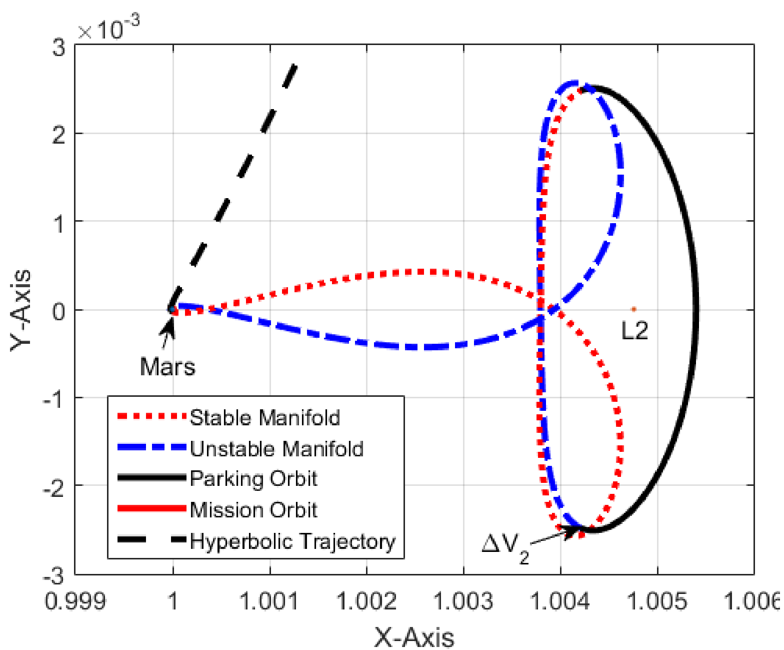
IV. Simulation and Comparisons

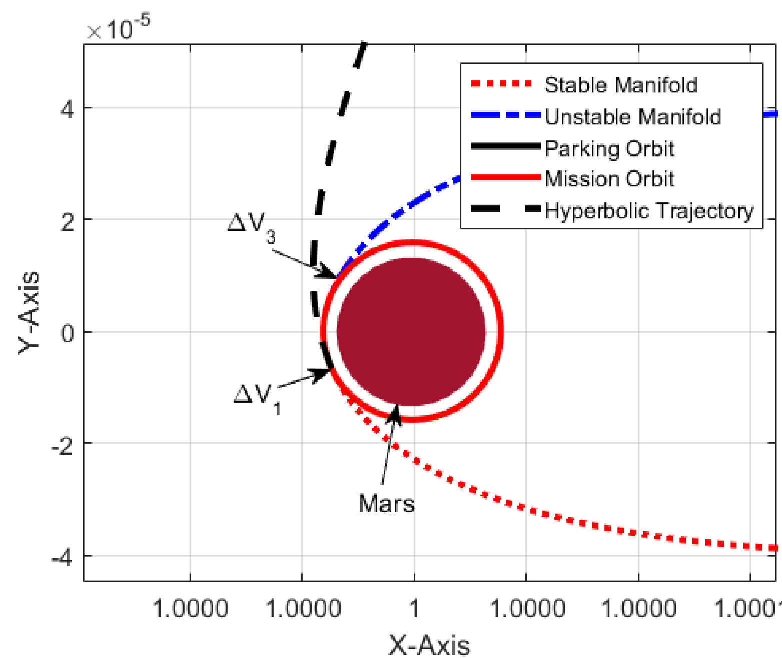
- Mission Orbit I

  200km circular orbit

- Parking orbit

  L2 planar Lyapunov orbit $A_y = 5.7 \times 10^5 km$





IV. Simulation and Comparisons

- Mission Orbit II
  800km*60000km elliptic orbit
- Parking orbit
  L2 Halo orbit $A_z = 4.6 \times 10^5 km$

v_∞ (km/s)	Direct Capture Δv_d (km/s)	Indirect capture		$\Delta v_d - \Delta v$ (km/s)
		Δv (km/s)	T (day)	
1.88	0.518	0.493	696.85	0.025
2.09	0.602	0.572		0.030
3.39	1.272	1.205		0.067

Middle orbit capture:

- As the periapsis of mission orbit increases, the indirect capture requires less velocity than direct capture
- Save more fuel for higher excess velocity v_∞

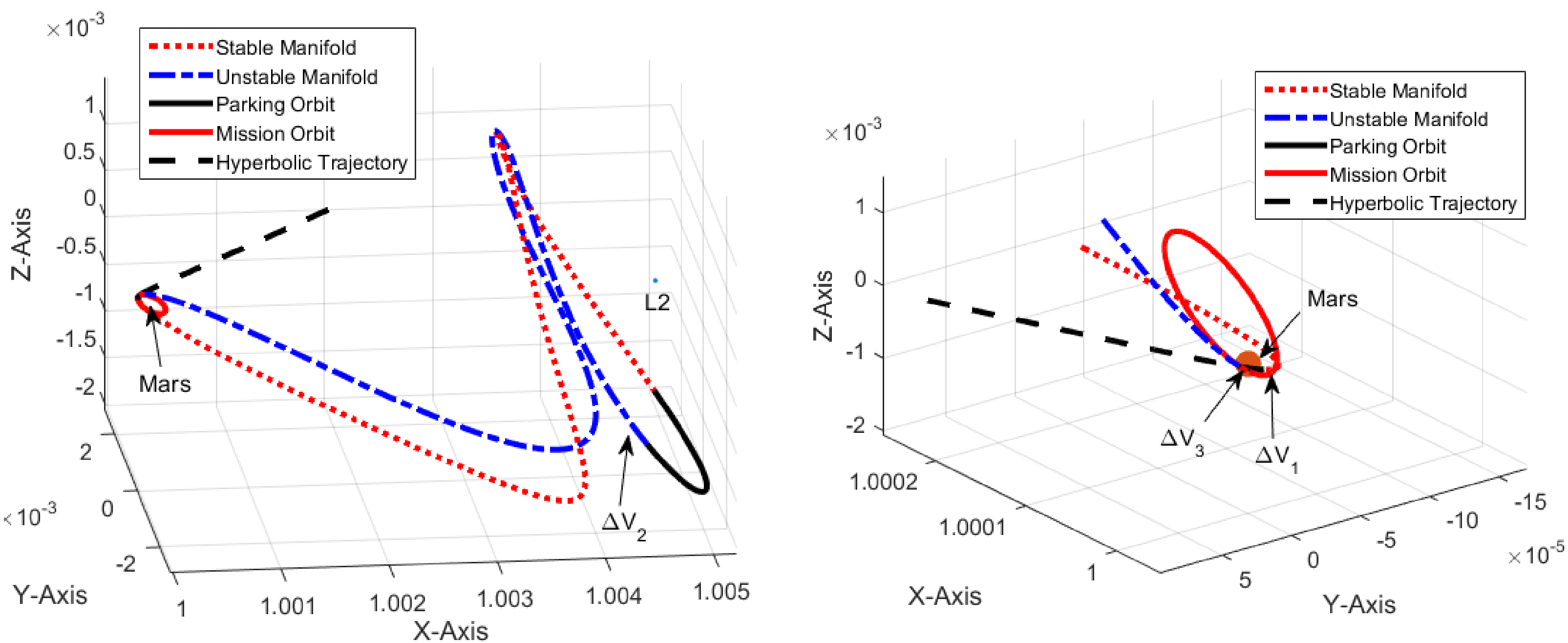
IV. Simulation and Comparisons

- Mission Orbit II

  800km*60000km elliptic orbit

- Parking orbit

  L2 Halo orbit $A_z = 4.6 \times 10^5 km$



IV. Simulation and Comparisons

- Mission Orbit III
  20000km circular orbit
- Parking orbit
  L1 Halo orbit $A_z = 3.4 \times 10^5 km$

v_∞ (km/s)	Direct Capture Δv_d (km/s)	Indirect capture		$\Delta v_d - \Delta v$ (km/s)
		Δv (km/s)	T (day)	
1.88	1.329	0.897	691.03	0.432
2.09	1.481	0.976		0.505
3.39	2.540	1.609		0.931

High orbit capture:
- Save more than 30% velocity
- Keep the same efficiency in high v_∞

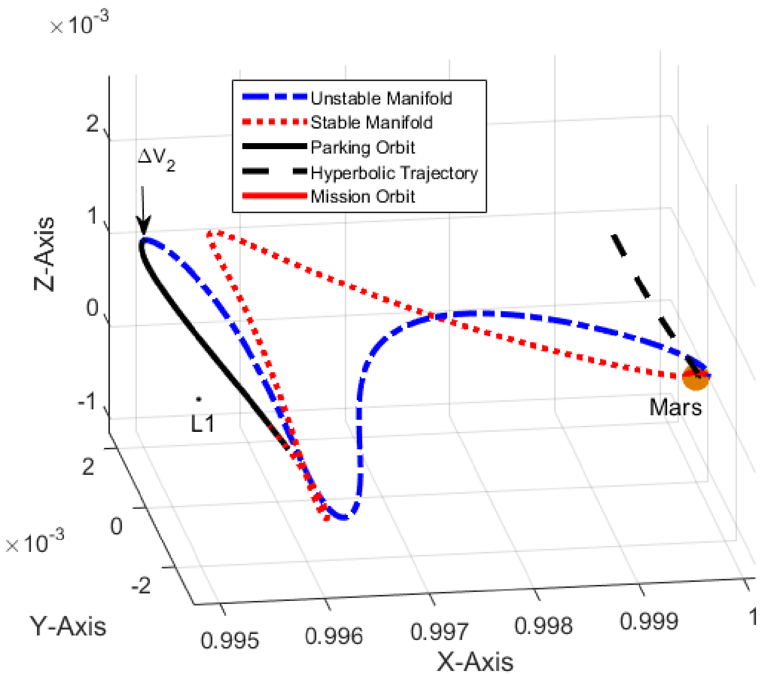
IV. Simulation and Comparisons

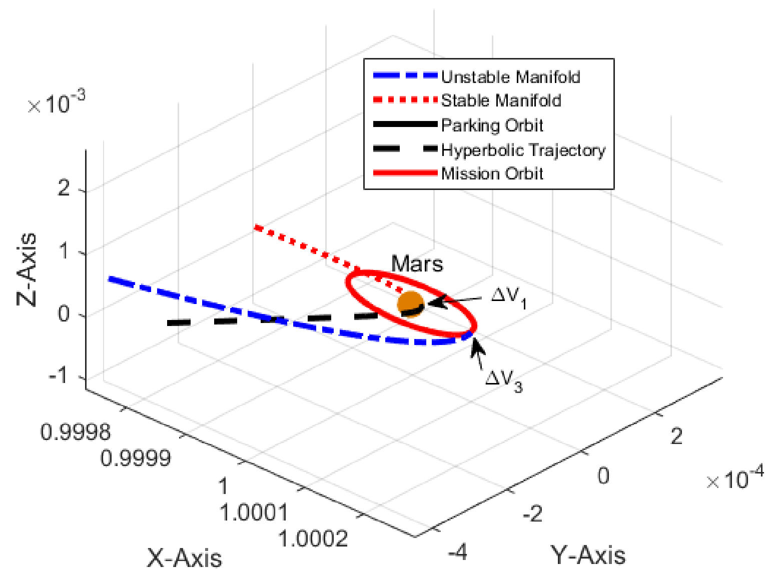
- Mission Orbit III

  20000km circular orbit

- Parking orbit

  L1 Halo orbit $A_z = 3.4\times10^5 km$





IV. Simulation and Comparisons

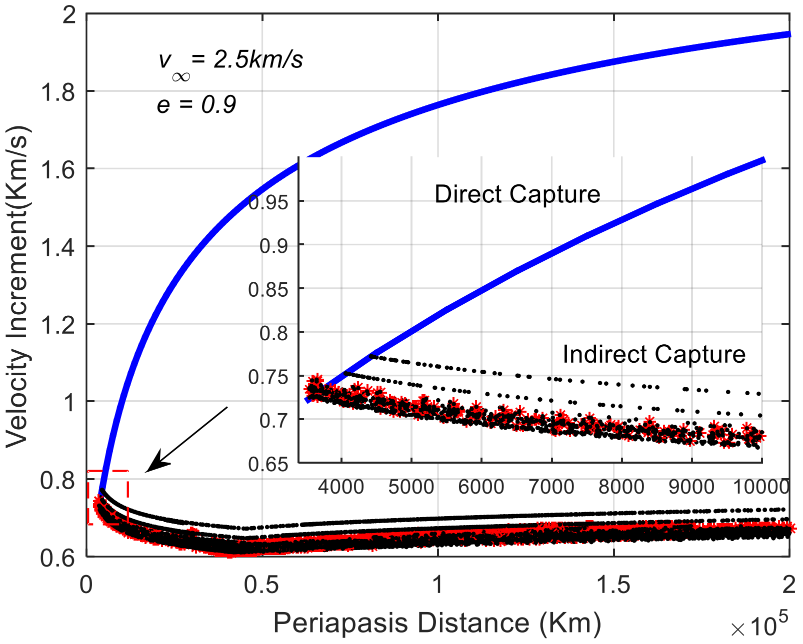
- Mission Orbit IV

  Elliptic orbit $e = 0.9$ with different periapsis distances

- Parking orbit

  L1 Lyapunov orbit

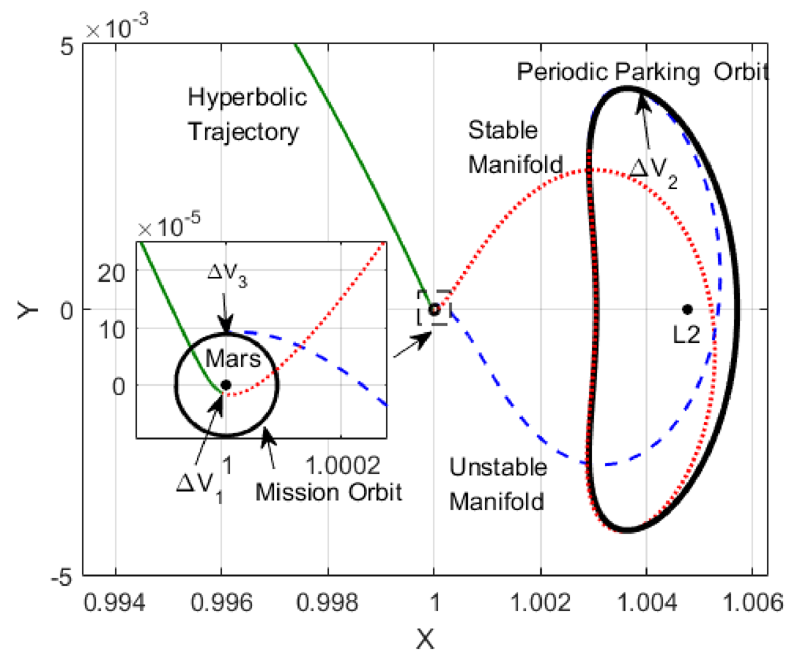
  $v_\infty = 2.5km/s$



➢ Cost is approximately constant regardless of the periapsis distance

V. Conclusion

- Indirect capture could save velocity increment than direct capture at the cost of long transfer time
- Shows better efficiency for high altitude and high v_∞ orbit insertion
- Extra scientific returns
- Increases transfer flexibility
- Reduce gravity loss



Thank you!