13th Summer Space School
"FUTURE SPACE TECHNOLOGIES AND EXPERIMENTS IN SPACE"
19 JUNE TO 1 JULY 2017

On small spacecraft to other planets of the Solar system

Prof. Mikhail Ovchinnikov
Keldysh Institute of Applied Mathematics
ovchinni@keldysh.ru

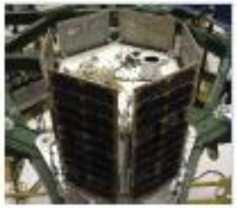
Dr. Maksim Shirobokov
Keldysh Institute of Applied Mathematics

History and milestones of activity

Institute of Applied Mathematics was established in 1953 to lead in the National Programs:

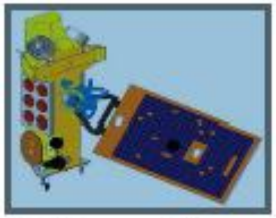
- nuclear energy utilization (for defense goal, nuclear bomb simulation)
- exploration in space (for defense goal, dynamics of missiles)
- development and application of computer science technology (to achieve two goals above)

Partners's missions

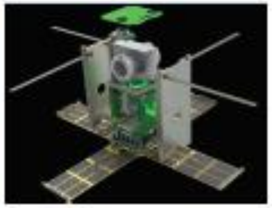


The first Russian private microsatellite TabletSat-Aurora (launched in 2014), active attitude control system, 26 kg (credit Sputnix Ltd)

The Russian microsatellite Chibis-M (launched in 2012), active attitude control system, 43 kg кг (credit SRI of RAS)

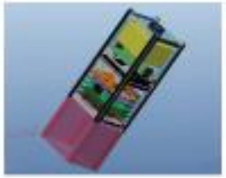


The Taiwanese satellite Formosat-7 (13), active attitude control system, 250 kg(credit NSPO)



The American nanosatellite CXBN-2, active attitude control system, 2.5 kg (credit Morehead State University)

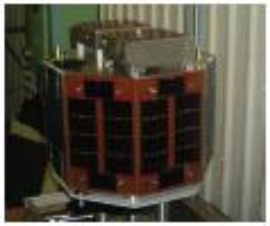
The German picosatellite (cubesat) BeeSat-3 (launched in 2013), passive attitude control system with hysteresis plate, 1 kg (credit TUB)



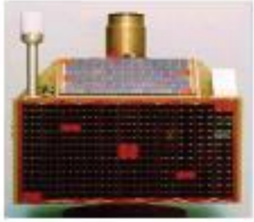
The Russian nanosatelliteSamSat-QB50,aerodynamical attitude control system with hysteresis rods, 2 kg(creditSamara State Aerospace University)

The first Russian nanosatellite TNS-0 №1 (launched in 2005), passive magnetic attitude control system, 4.5 kg (credit JSC "Russian Space Systems")

The Russian nanosatellite TNS-1, active magnetic attitude control system, self-rotation stabilization, 10 kg (credit JSC "Russian Space Systems")

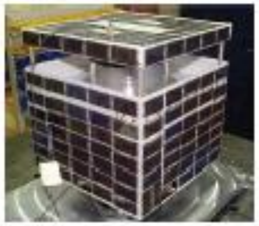


The Italian microsatellite UniSat-4 (launched in 2004), passive magnetic attitude control system, 12 kg (creditUniversity of Rome "La Sapienza")



The Pakistani microsatellite BADR-B (launched in 2001), semiactive gravitational attitude control system, 70 kg (credit SUPARCO)

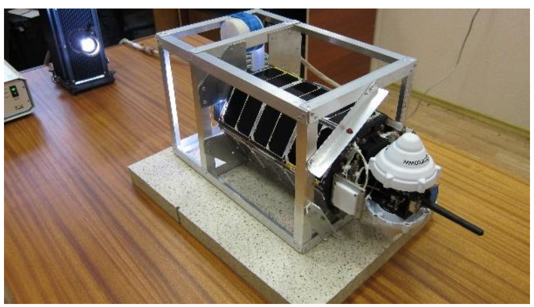
The Russian nanosatellite REFLECTOR (launched in 2001), passive gravity gradient attitude control system, 7 kg (credit Institute of Precision Instrument Engineering)



The Swedish nanosatellite Munin, (launched in 2000), passive magnetic attitude control system, 6 kg (credit IRF)

2017th year missions

- 3U CXBN-2 (PI Morehead State University, KY) deployed on 9th of May from ISS



- Nanosat TNS-0 #2 (PI JSC “Russian Space Systems”) delivered to ISS on 16th of June

- 2U SamSat-QB50 (PI SSAU) expected to launch late 2017

Nowadays tendencies in smallsat utilisation

- Wide implementation in near-Earth missions (remote sensing, communication, space research, technology demonstration and education). This is a main stream for the nearest years…
- Two rills extract from main stream:
  - Formation Flying in variations (trailing, cluster, swarm)
  - Interplanetary missions

Formation Flying Dynamics in KIAM

- M. Koptev, Y. Mashtakov, M. Ovchinnikov, S. Shestakov, Novel approach to construction and maintenance of **tetrahedral formation**, Proceedings of the 9th International Workshop on Satellite Constellations and Formation Flying, 19-21 June, 2017, Boulder, Colorado.
- R. Dosaev, S. Tkachev ,Two spherical satellite relative motion control in formation flying via **variable surface reflectivity**, Keldysh Institute Preprints, 2016, № 107, 28 p.
- M.Ovchinnikov, S. Trofimov, Optimal **Multiple-Impulse** Solution to Circular Orbit Phasing Problem // Journal of Guidance, Control, and Dynamics, July 2016, Vol. 39, No. 7, Pages 1675-1678
- M.Kushniruk, D.Ivanov, Collision Avoidance Algorithms for Satellite Formation Flying by Using **Aerodynamic Drag**, Keldysh Institute Preprints, 2015, № 99, 30 p.
- S. Shestakov, D. Ivanov, M. Ovchinnikov. Formation Flying **Momentum Exchange** Control by Separate Mass// Journal of Guidance, Control, and Dynamics, May 2015, Vol.38. No 8, Pages 1534-1543

Lab facility for FF dynamics and movement control simulation

Motion Model Of Mock-up With Flexible Booms

- Consider the linearized motion model of the mock-up with two equal flexible booms
- Take into account only one mode for each boom - q_a and q_p
- The angular and flexible motion equations:

$$J\dot{\omega} + S_\omega \ddot{q}_a + S_\omega \ddot{q}_p = T_s,$$

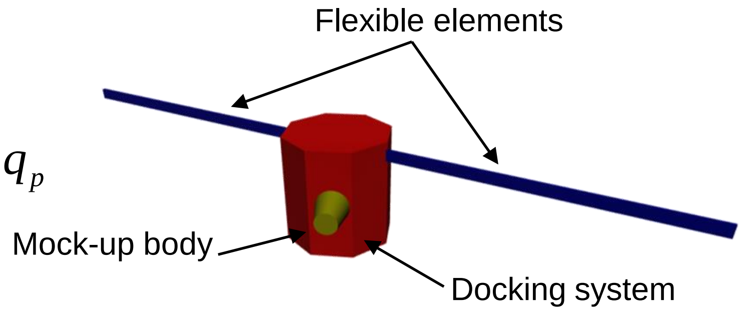
$$S_\omega \dot{\omega} + \left(1 - \frac{1}{m}A^2\right)\ddot{q}_a - \frac{1}{m}A^2\ddot{q}_p = \mathbf{A}^T\frac{\mathbf{F}_O}{m} - \Omega q_a,$$

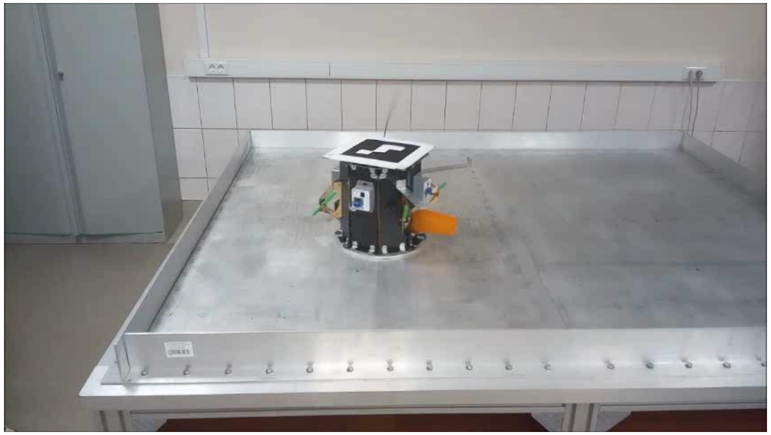
$$S_\omega \dot{\omega} - \frac{1}{m}A^2\ddot{q}_a + \left(1 - \frac{1}{m}A^2\right)\ddot{q}_p = -\mathbf{A}^T\frac{\mathbf{F}_O}{m} - \Omega q_p.$$

- Mock-up body center of mass position

$$\mathbf{r}_s = \mathbf{r} + \frac{1}{m}\mathbf{A}\left(q_p - q_a\right)$$

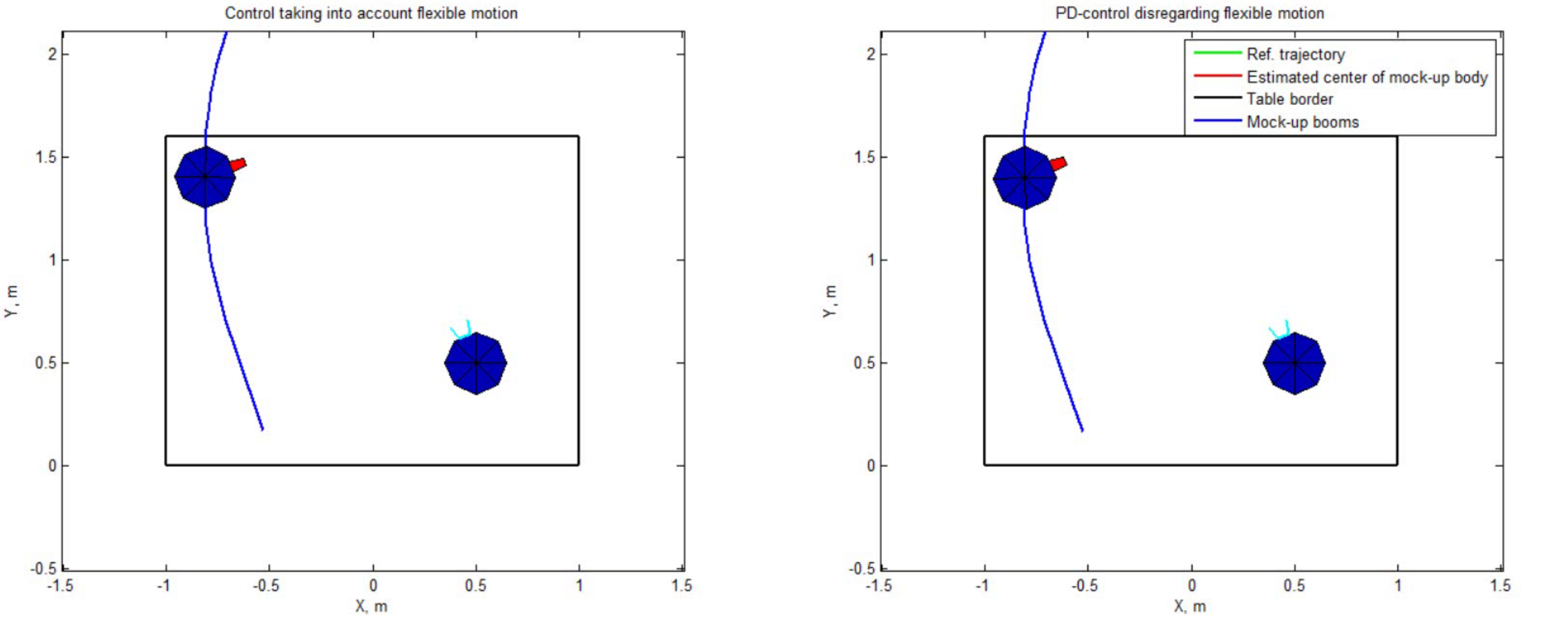
- The parameters of the model are identificated by using Least Square Method



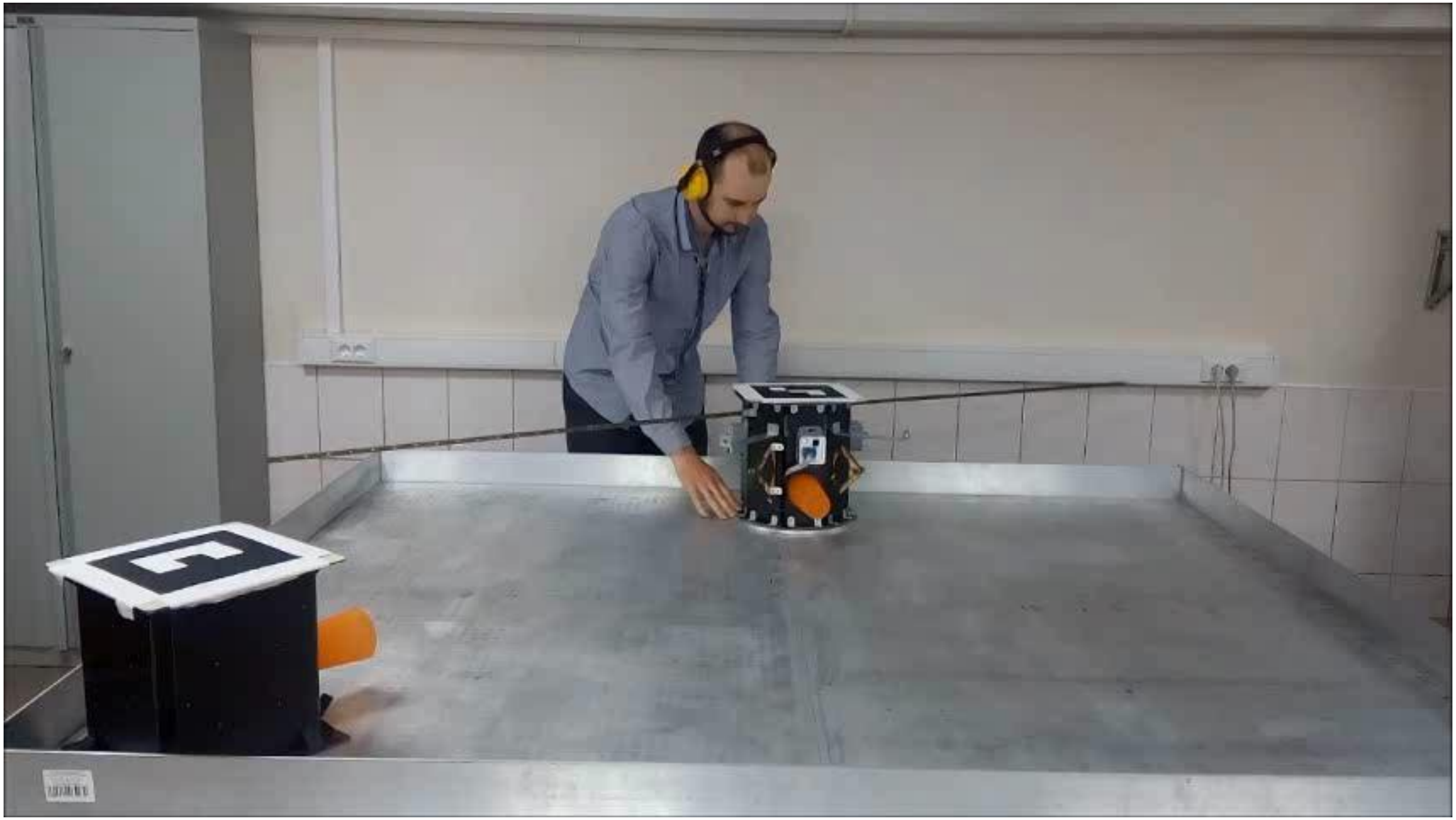


Vibrational modes

Control Algorithms Comparison



Experiments



Interplanetary missions

Contents

State-of-the-art methods of astrodynamics

- Increase capabilities of scientific missions
- Make missions feasible
- Facilitate the trajectory design
- Help to perform a preliminary mission analysis more efficiently
- Provide mathematical insight into the problem of trajectory design optimization

Contents

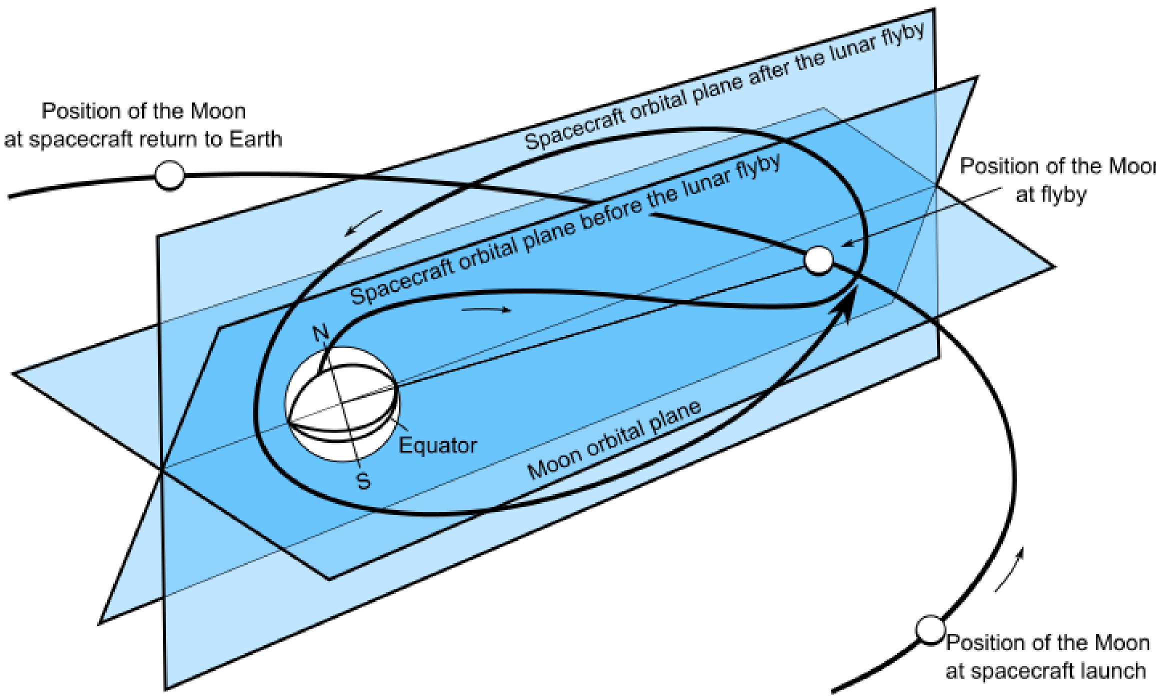
Gravity assist (GA) maneuvers

- The planetary gravitational fields can efficiently accelerate or decelerate the fly-by bodies

- The essence of GA maneuvers: a spacecraft **steals the kinetic energy** from the planet to change its own trajectory in a required way

The Luna-3 mission

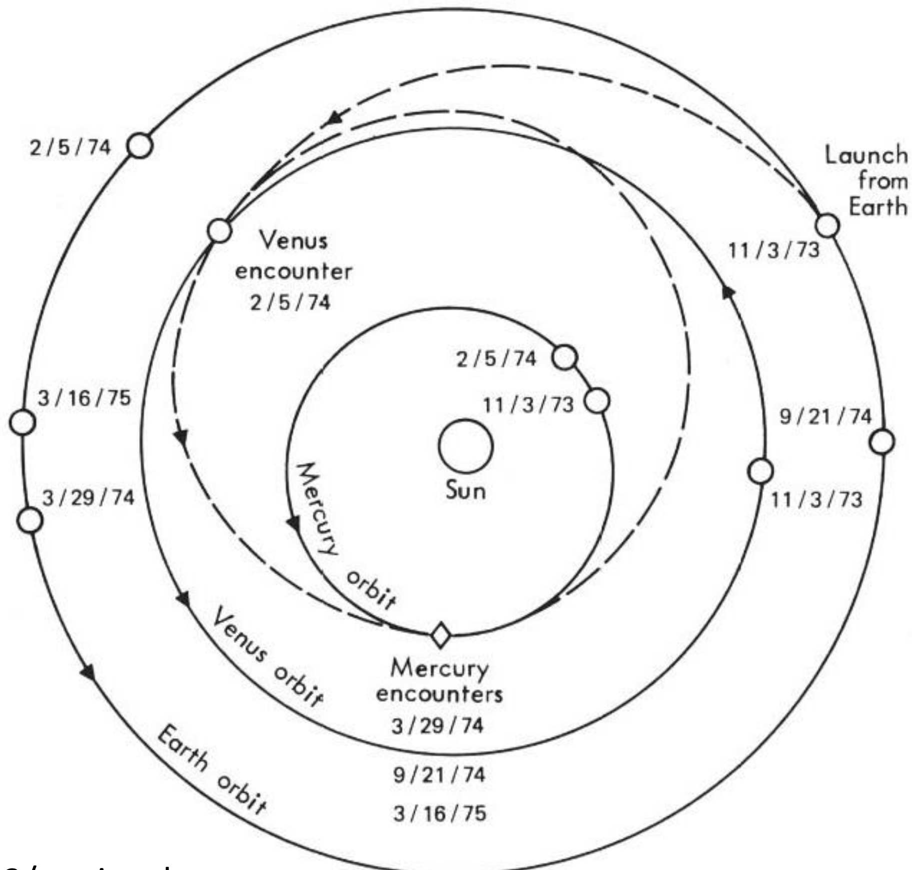
- In 1959, a GA maneuver was first used by the Luna-3 spacecraft in its way to deliver the first photographies of the far side of the Moon



Credit: Hiparick, https://commons.wikimedia.org/wiki/File:Luna3-trajectory-eng.svg

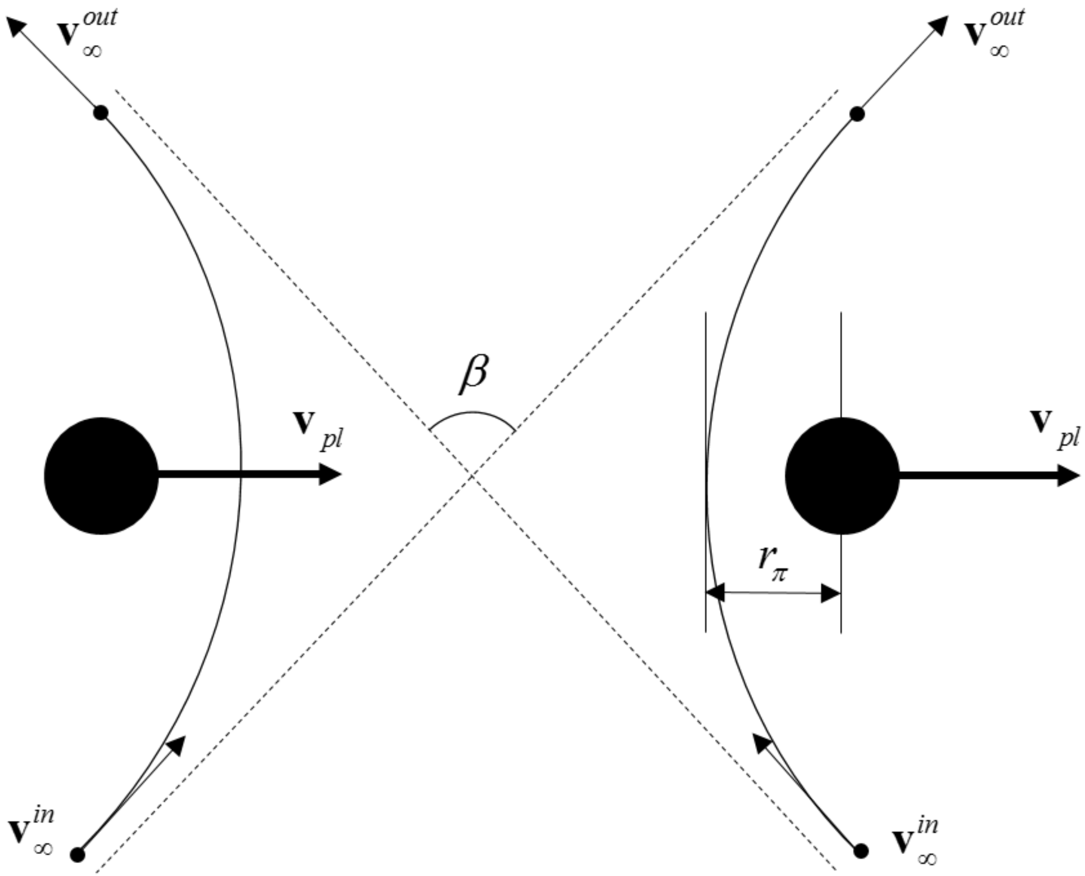
The Mariner 10 mission

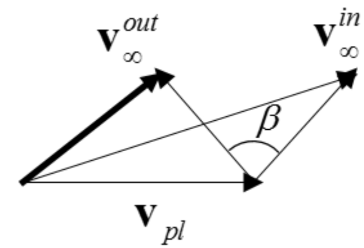
- In 1974, NASA's Mariner 10 perform a GA maneuver using Venus to achieve the Mercury



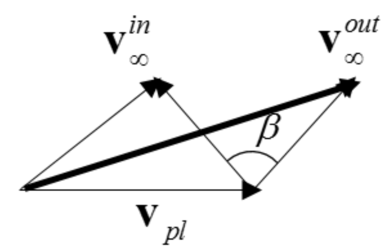
Credit: NASA, http://history.nasa.gov/SP-423/mariner.htm

Geometry of the GA maneuver (sling effect)





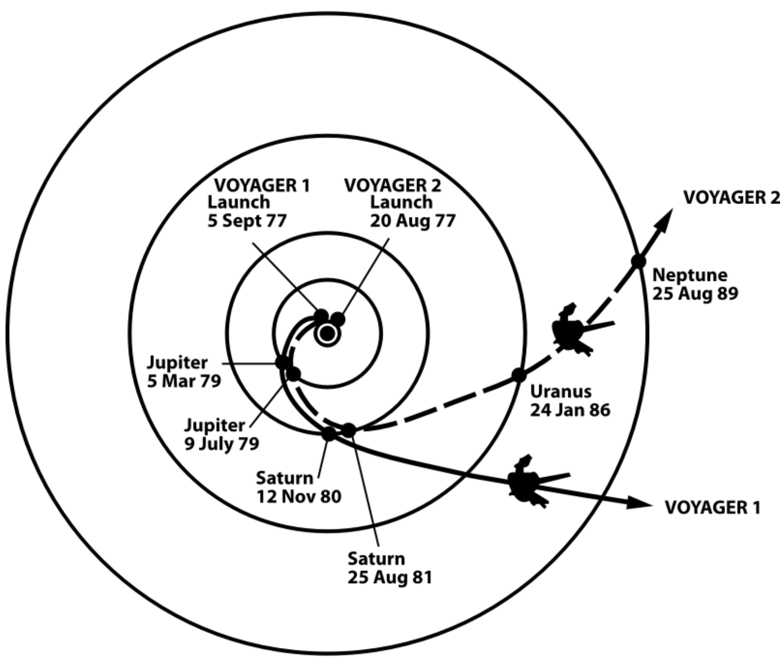
Final heliocentric velocity (bold) for energy-reducing GA maneuver

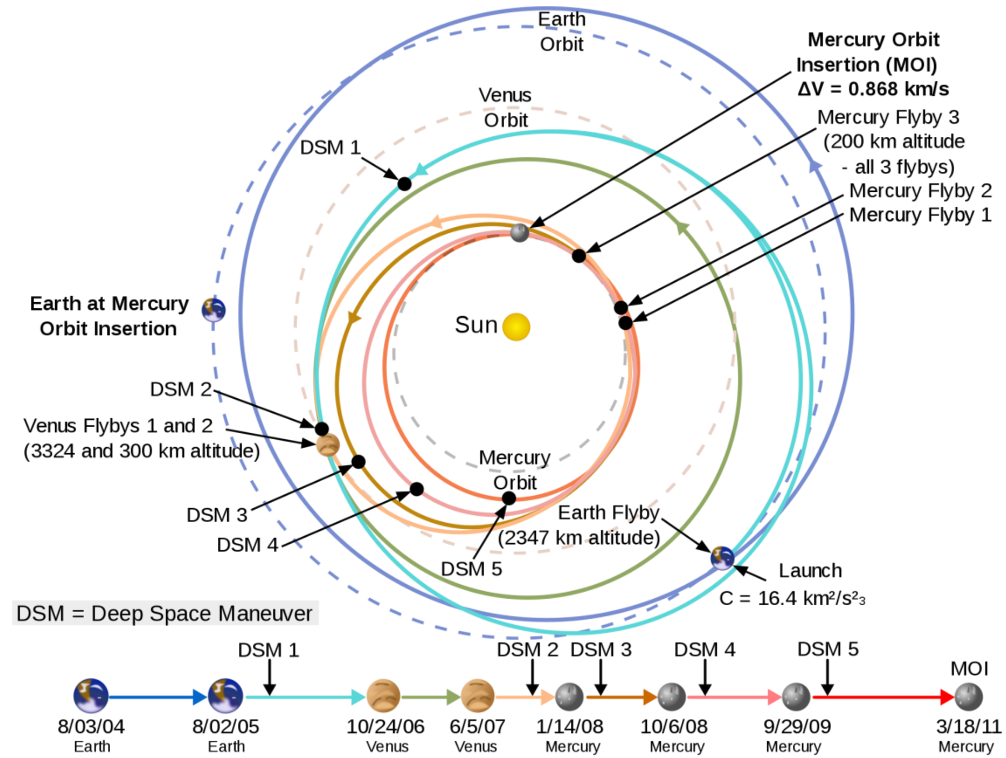


Final heliocentric velocity (bold) for energy-increasing GA maneuver

Multiple GA trajectories

Voyager 1,2 paths





MESSENGER path

McAdams, J.V., et al., "Trajectory Design and Maneuver Strategy for the MESSENGER Mission to Mercury," Journal of Spacecraft and Rockets, 2006, Vol. 43, No. 5, pp. 1054-1064.

Delta-v/TOF tradeoff

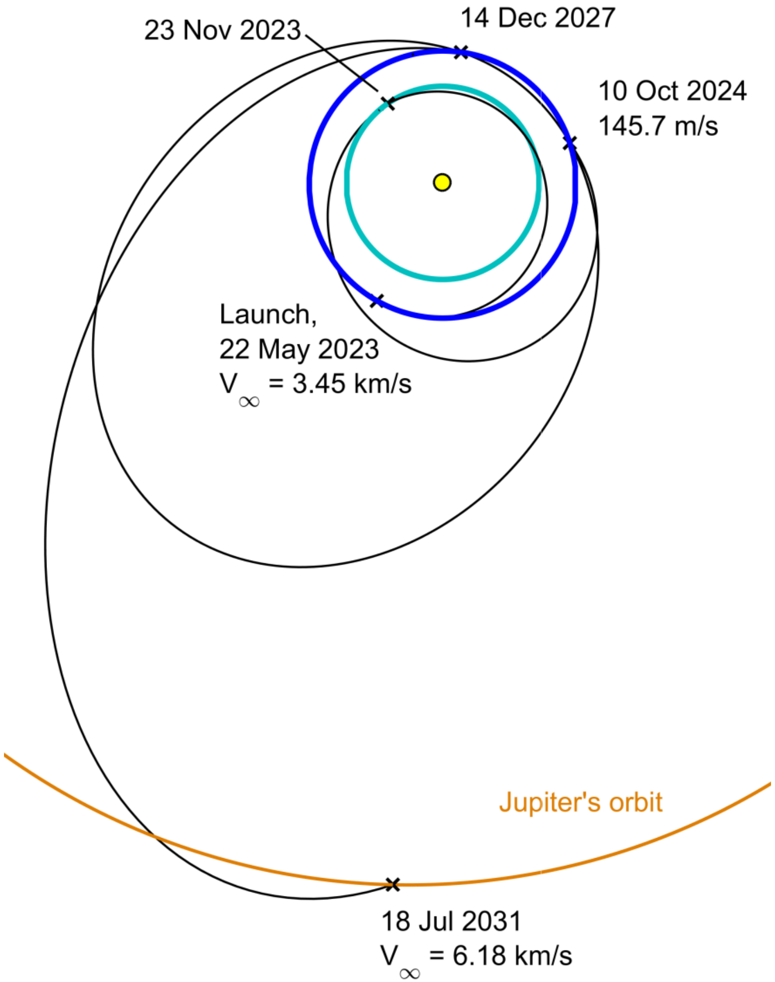
- Powered GA maneuvers (single impulse at pericenter):

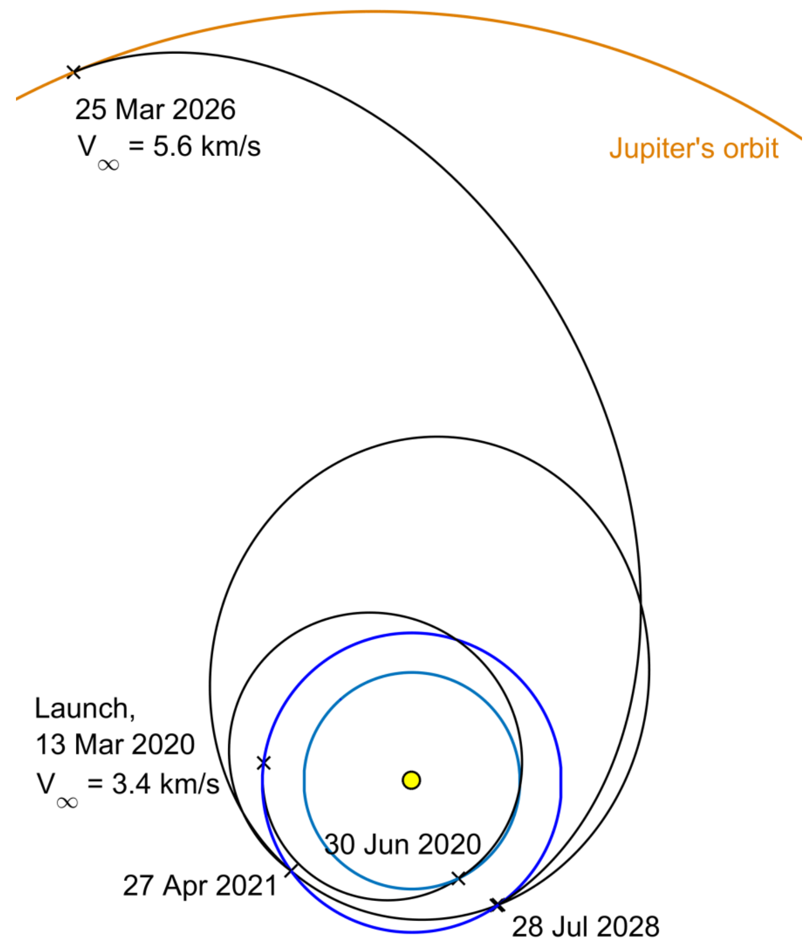
EJ	EVJ	EVEJ	EVEEJ
8.70 km/s	3.8745 km/s	1.6996 km/s	0.1457 km/s
2.75 years	2.4378 years	5.9034 years	8.1571 years

- Unpowered GA maneuvers augmented with deep space maneuvers

EVJ	EVEJ	EVEEJ
9.5265 km/s	2.97 km/s	0.089 km/s
2.303 years	5.0513 years	6.03 years

Transfers to Jupiter, EVEEJ





Delta-V: 145.7 m/s
TOF: 8.157 years

Delta-V: 89 m/s
TOF: 6.03 years

Contents

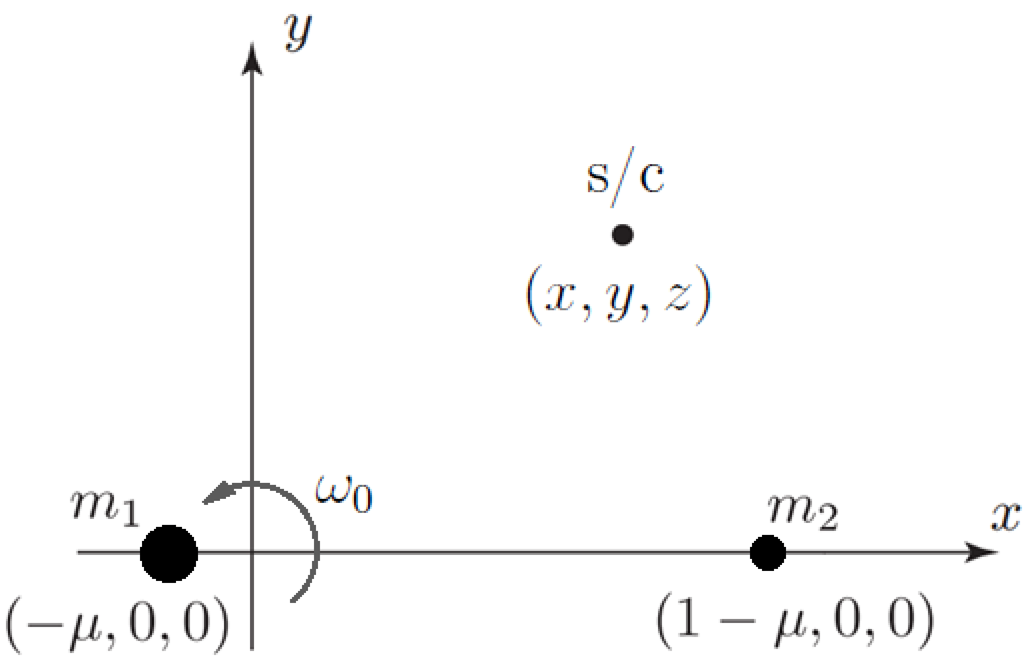
- Introduction
- Gravity assists maneuvers
- **Invariant manifolds of the libration point orbits**
- Weak stability boundary
- Resonant encounters
- Summary

Circular restricted three-body problem

The circular restricted three-body problem (CR3BP) assumes that

- a spacecraft of negligible mass moves under the gravitational influence of two masses m_1 and m_2
- the masses m_1 and m_2 move around their barycenter in circular orbits

Reference frame



Mass parameter

$$\mu = m_2 / (m_1 + m_2)$$

Non-dimensional units:

$$m_1 = 1 - \mu \qquad x_{m1} = -\mu$$

$$m_2 = \mu \qquad x_{m2} = 1 - \mu$$

$$\omega_0 = 1$$

The Sun-(Earth+Moon) system $\mu = 3.03939 \cdot 10^{-6}$

The Earth-Moon system $\mu = 1.21506 \cdot 10^{-2}$

Equations of motion of the CR3BP

In the rotating frame

$$\ddot{x} - 2\dot{y} = U_x, \quad \ddot{y} + 2\dot{x} = U_y, \quad \ddot{z} = U_z$$

where

$$U(x, y, z) = \frac{x^2 + y^2}{2} + \frac{1-\mu}{r_1} + \frac{\mu}{r_2},$$

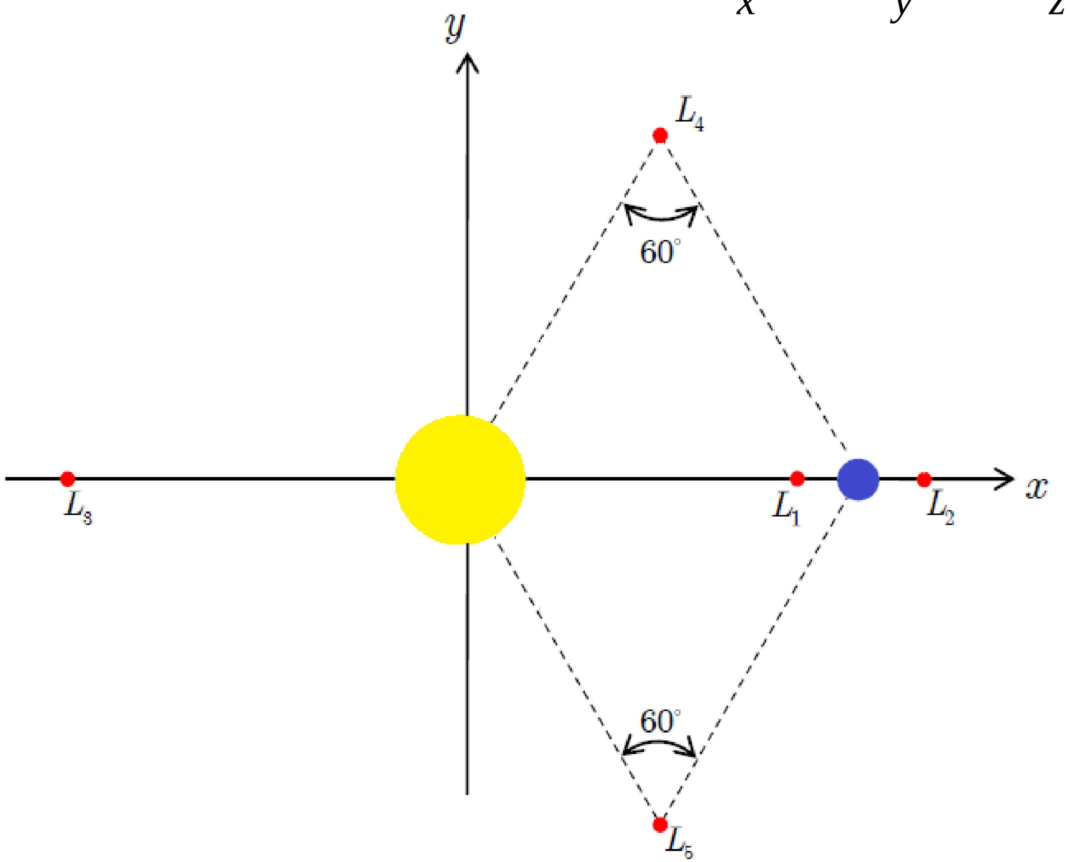
is the so called effective potential; U_x, U_y, and U_z are the partial derivatives of U with respect to the position variables. The distances between the spacecraft and the primaries equal

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2} \qquad r_2 = \sqrt{(x-1+\mu)^2 + y^2 + z^2}$$

Libration points

Equilibrium (libration) points can be found from the equations

$$U_x = U_y = U_z = 0$$



	Sun-Earth	Earth-Moon
x_{L1}	0.989987	0.836914
x_{L2}	1.010074	1.155682
x_{L3}	−1.000001	−1.005062
x_{L4}	$1/2$	$\sqrt{3}/2$
x_{L5}	$1/2$	$-\sqrt{3}/2$

The linearized equations of motion

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) \qquad \mathbf{f}(\mathbf{x}) = (\dot{x}, \dot{y}, \dot{z}, 2\dot{y} + U_x, -2\dot{x} + U_y, U_z)^T$$

$$\delta\mathbf{x} = \mathbf{x} - \mathbf{x}_L$$

$$\delta\dot{\mathbf{x}} = \mathbf{A}\delta\mathbf{x}, \;\; \mathbf{A} = \left(\frac{\partial \mathbf{f}}{\partial \mathbf{x}}\right)_{\mathbf{x}=\mathbf{x}_L} = \begin{pmatrix} \mathbf{O}_{3\times3} & \mathbf{I}_{3\times3} \\ U_{\mathbf{rr}} & -2\mathbf{\Omega}_{3\times3} \end{pmatrix}_{\mathbf{x}=\mathbf{x}_L}$$

$$\lambda_{1,2} = \pm\sqrt{(\bar{\mu} - 2 + \sqrt{9\bar{\mu}^2 - 8\bar{\mu}})/2} \qquad \lambda_1 = -\lambda_2 = \lambda > 0$$

$$\lambda_{3,4} = \pm i\sqrt{(2 - \bar{\mu} + \sqrt{9\bar{\mu}^2 - 8\bar{\mu}})/2} \qquad \lambda_3 = -\lambda_4 = i\omega_p$$

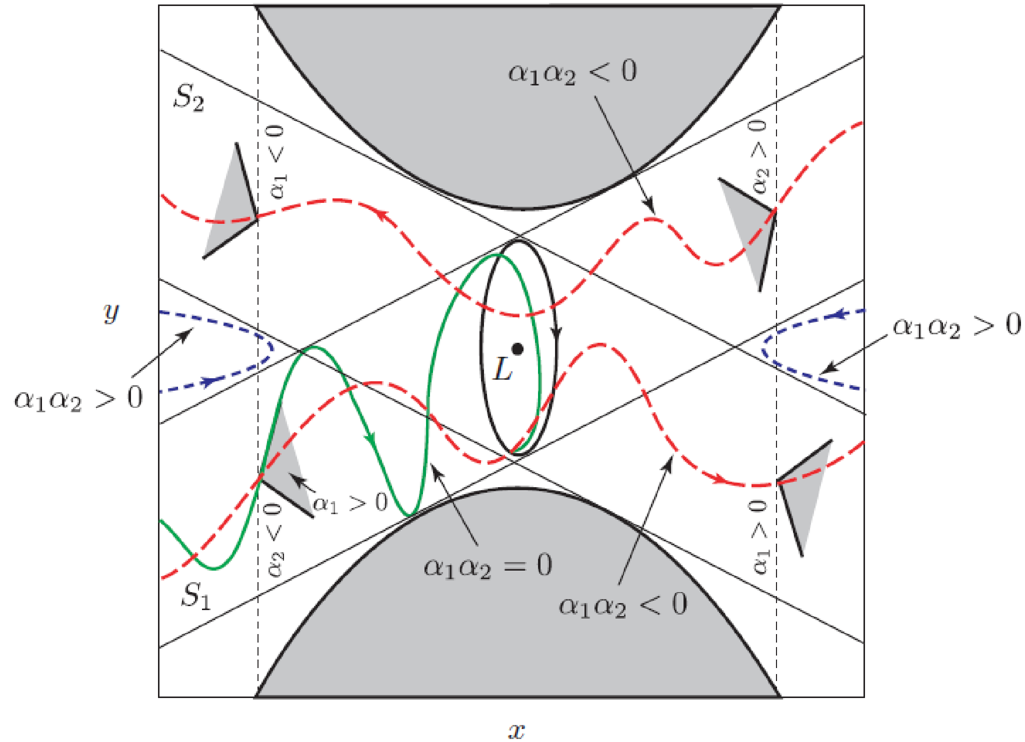
$$\lambda_{5,6} = \pm i\sqrt{\bar{\mu}} \qquad \lambda_5 = -\lambda_6 = i\omega_v$$

Solutions to the linearized equations

$$\delta \mathbf{x} = \alpha_1 e^{\lambda t}\mathbf{u}_1 + \alpha_2 e^{-\lambda t}\mathbf{u}_2 + 2\mathrm{Re}\left(\beta_1 e^{i\omega_p t}\mathbf{w}_1 + \beta_2 e^{i\omega_v t}\mathbf{w}_2\right)$$

Classification of orbits:

$\alpha_1 = \alpha_2 = 0$	Periodic orbits
$\alpha_1\alpha_2 = 0$	Asymptotic orbits
$\alpha_1\alpha_2 < 0$	Transit orbits
$\alpha_1\alpha_2 > 0$	Nontransit orbits



Koon, W.S. et al., "Dynamical Systems, the Three-Body Problem and Space Mission Design", Springer, 2001

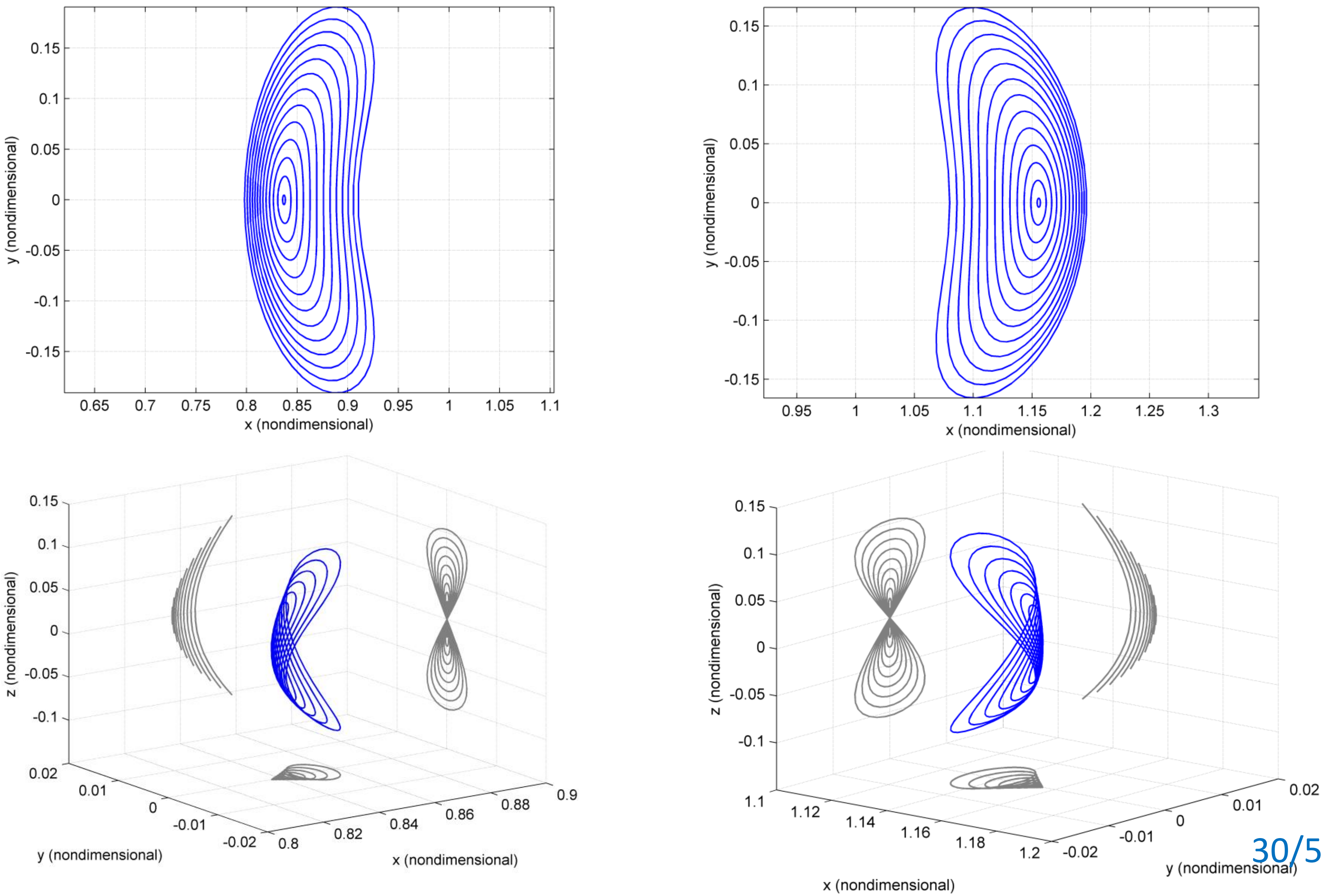
Lyapunov's and Moser's results

- **Lyapunov Center Theorem (LCT)**: periodic libration point orbits exist in the nonlinear dynamics of the CR3BP

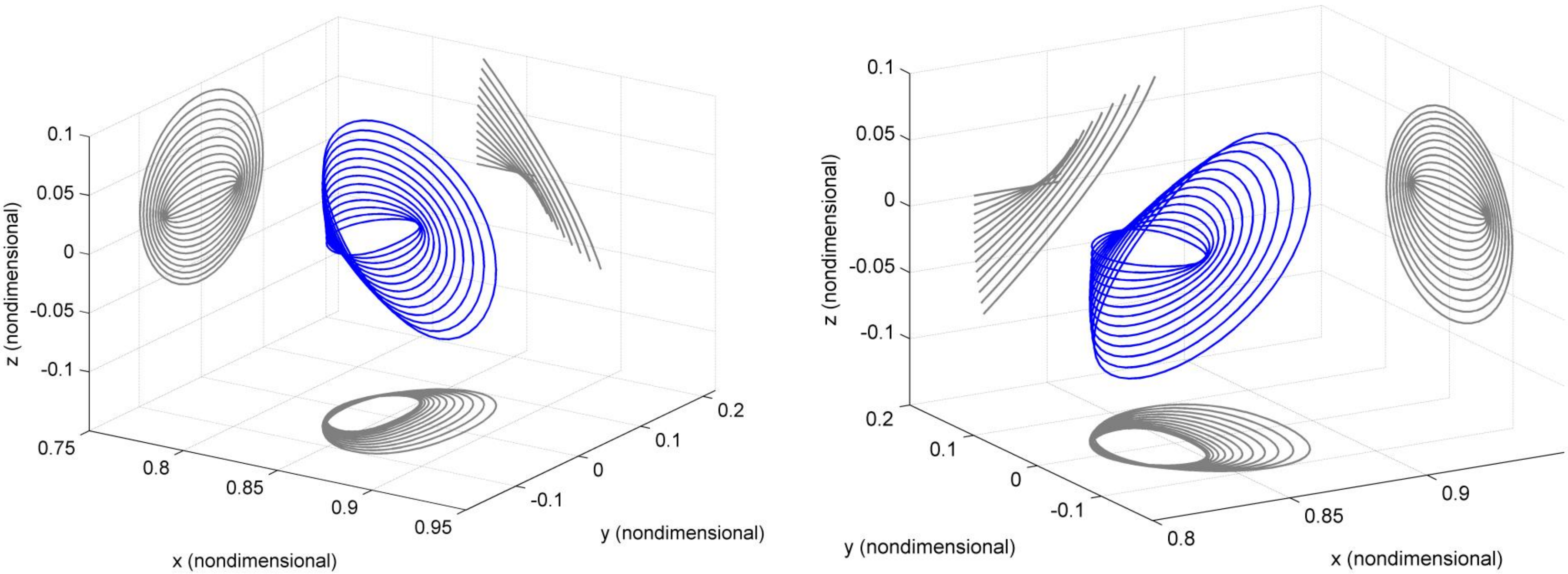
- **Moser's generalization of LCT**: four-parameter families of trajectories exist around libration points in the CR3BP

Qualitative behaviour of the dynamics remains the same in the CR3BP model

Planar and vertical Lyapunov orbits in the EM system



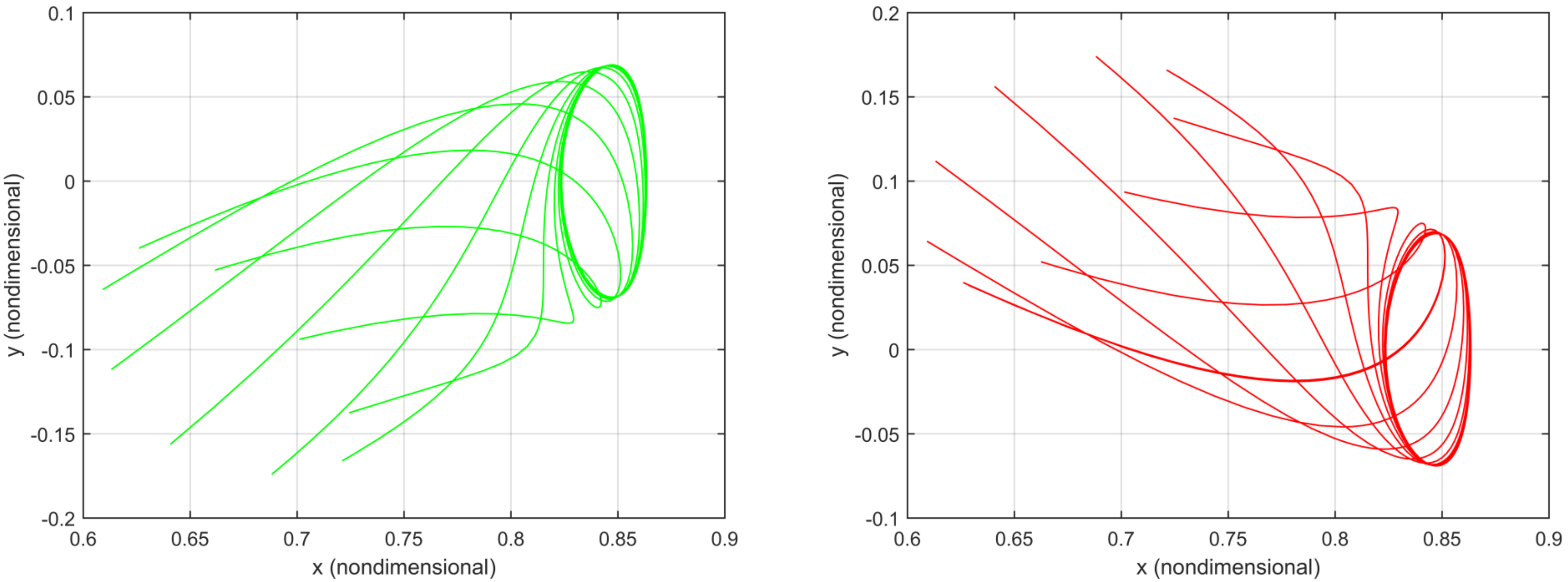
Northern and southern halo orbits around EM L1



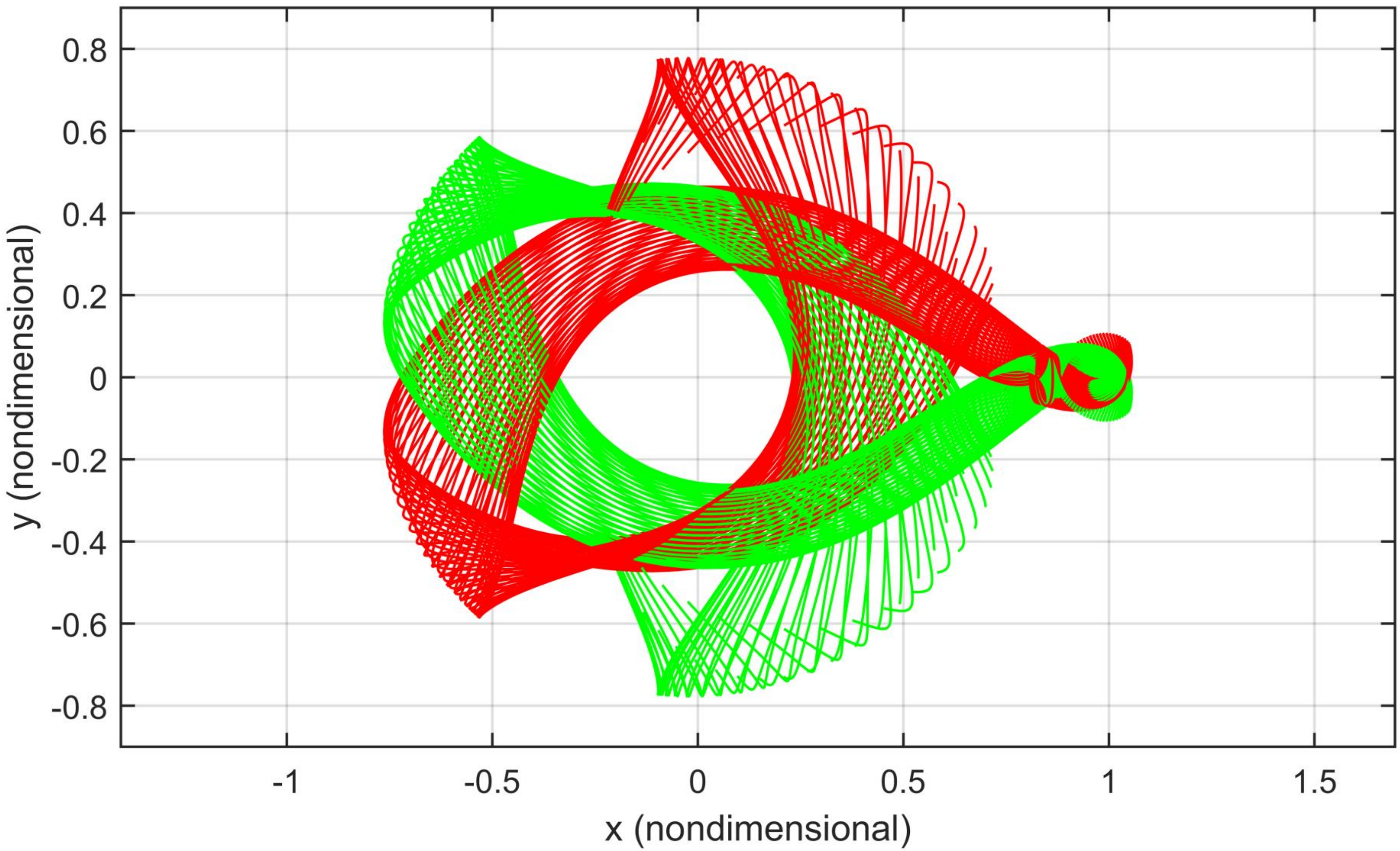
A lot of other periodic orbits exist in CR3BP:

Doedel, E. J. et al., "Elemental Periodic Orbits Associated with the Libration Points in the Circular Restricted 3-Body Problem," International Journal of Bifurcation and Chaos, 2007, Vol. 17, Is. 8, pp. 2625–2677

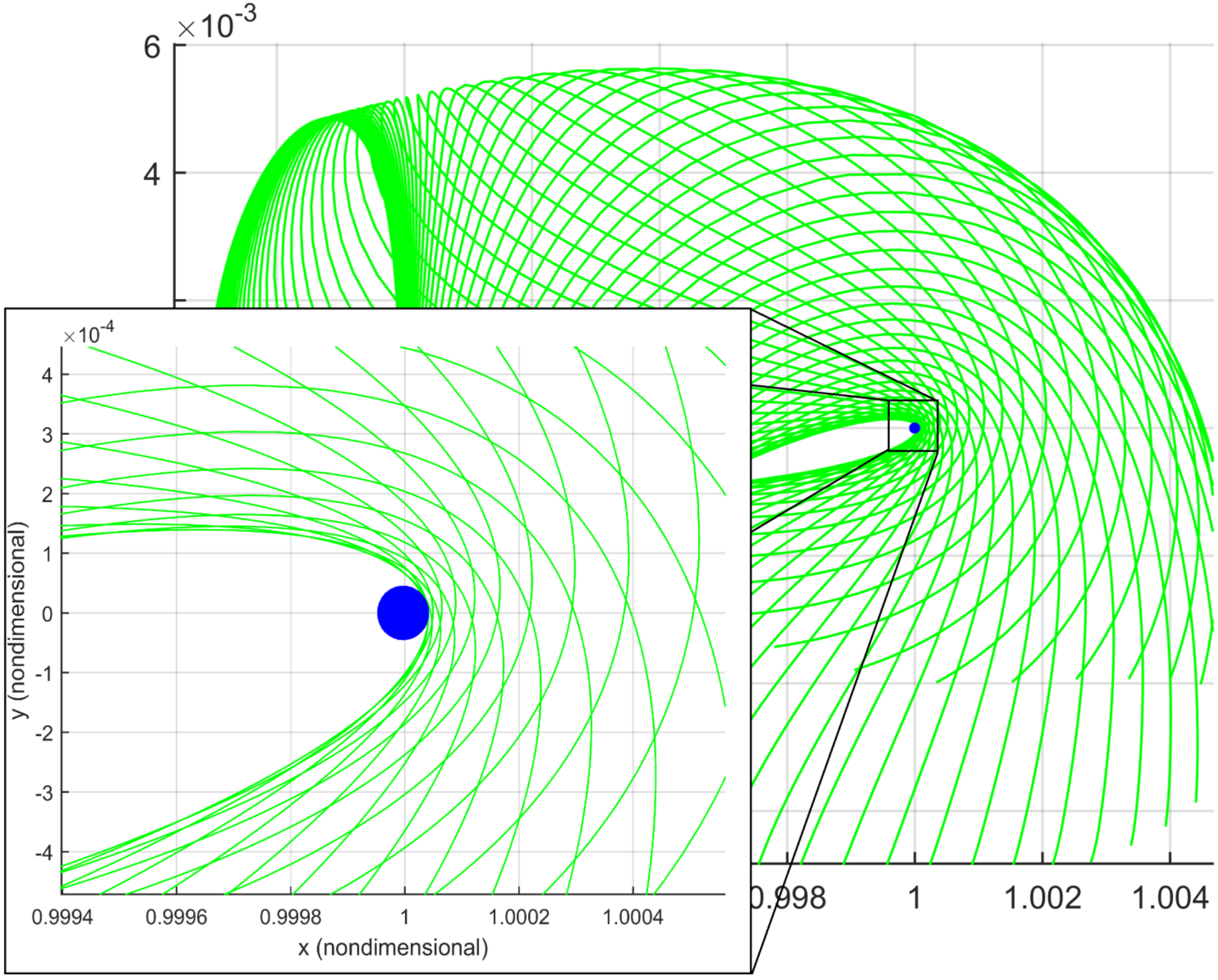
Stable (green) and unstable (red) manifolds near an EM L1 halo orbit



Stable (green) and unstable (red) invariant manifolds



Transfer to Sun-Earth L1 along the stable manifold

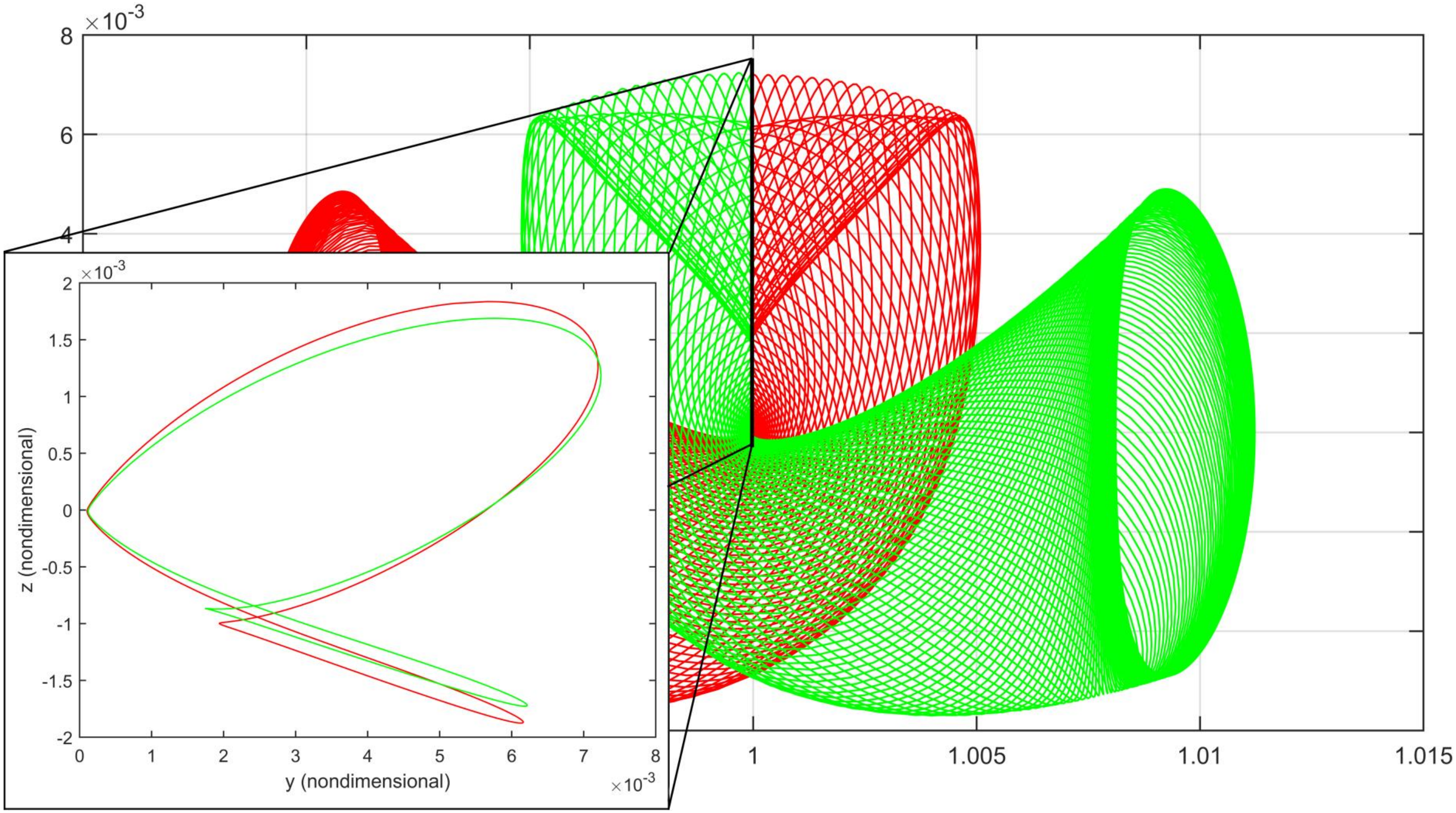


ΔV = 3.0-3.2 km/s

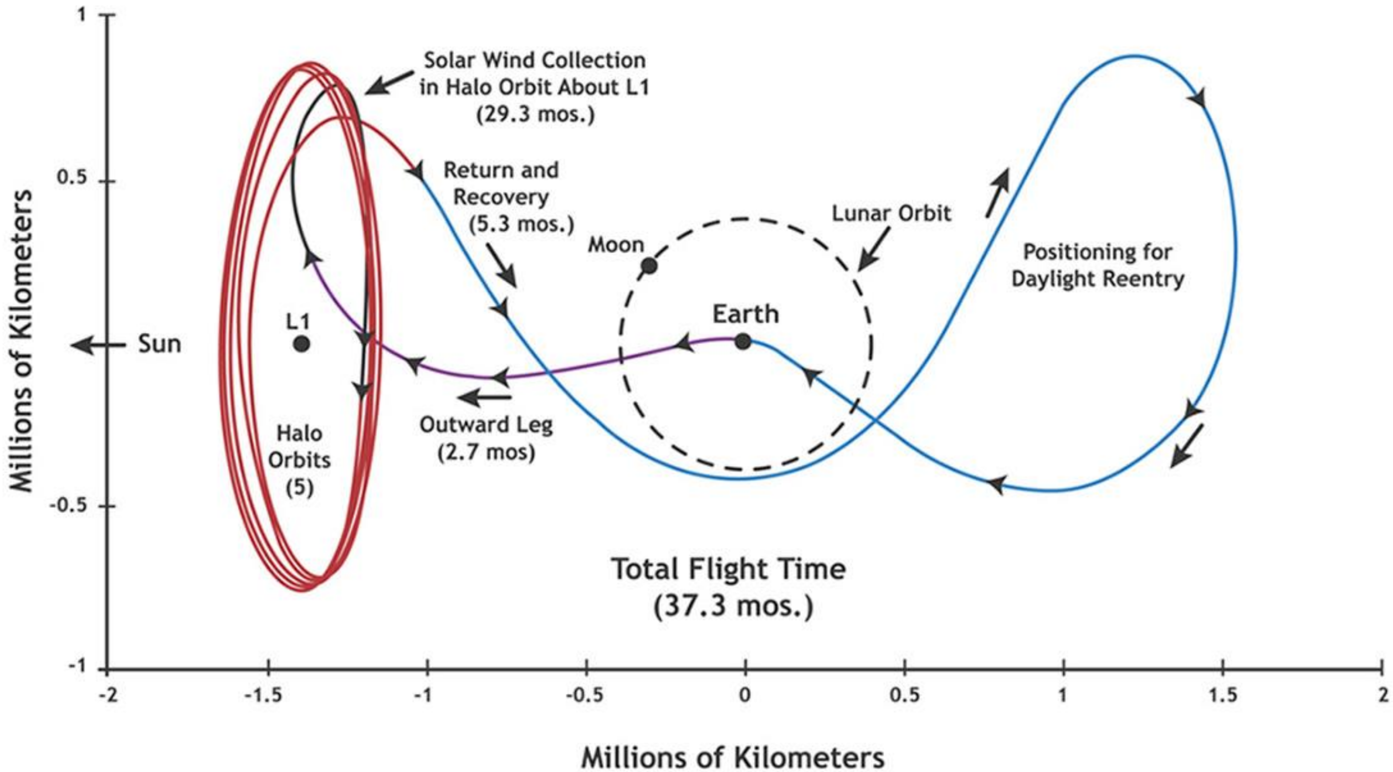
TOF = 80-90 days

Single-impulse transfers are possible for L1 halo orbits with Az ≥ 300,000 km

Transfers between L1 and L2 halo orbits



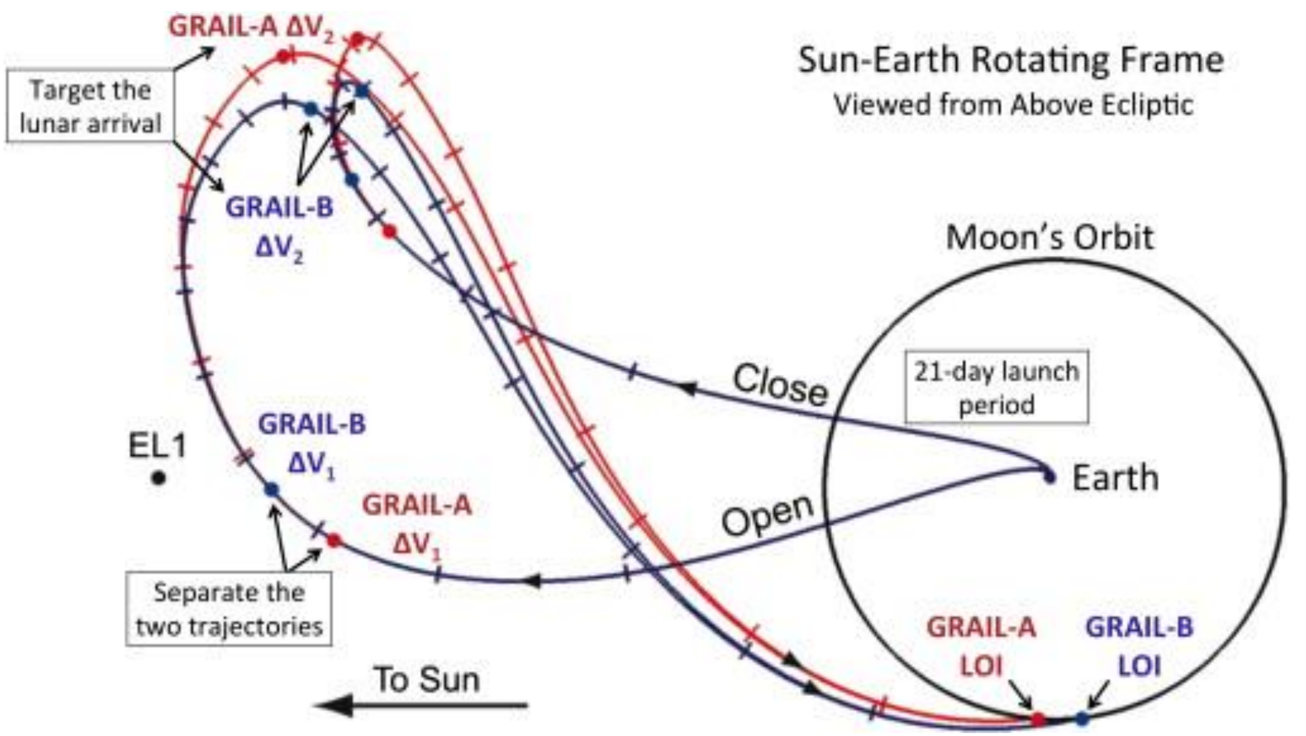
The Genesis trajectory



- LOI: 6-36 m/s
- SK: 9 m/s/year
- s/c mass: 636 kg
- Az = 450,000 km

Credit: NASA, http://genesismission.jpl.nasa.gov/gm2/mission/history.htm

The GRAIL trajectory



Advantages over the direct transfers to the Moon:

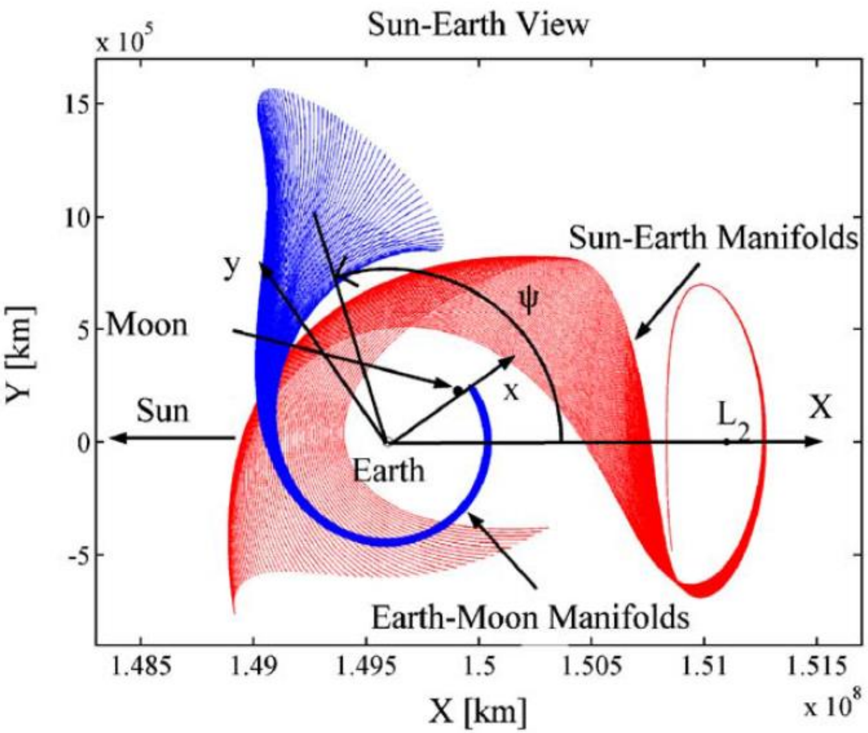
1) Lower LOI delta-v;
2) Low delta-v cost for LOI separation;
3) Longer launch period (at least 21 days)
4) Longer flight time

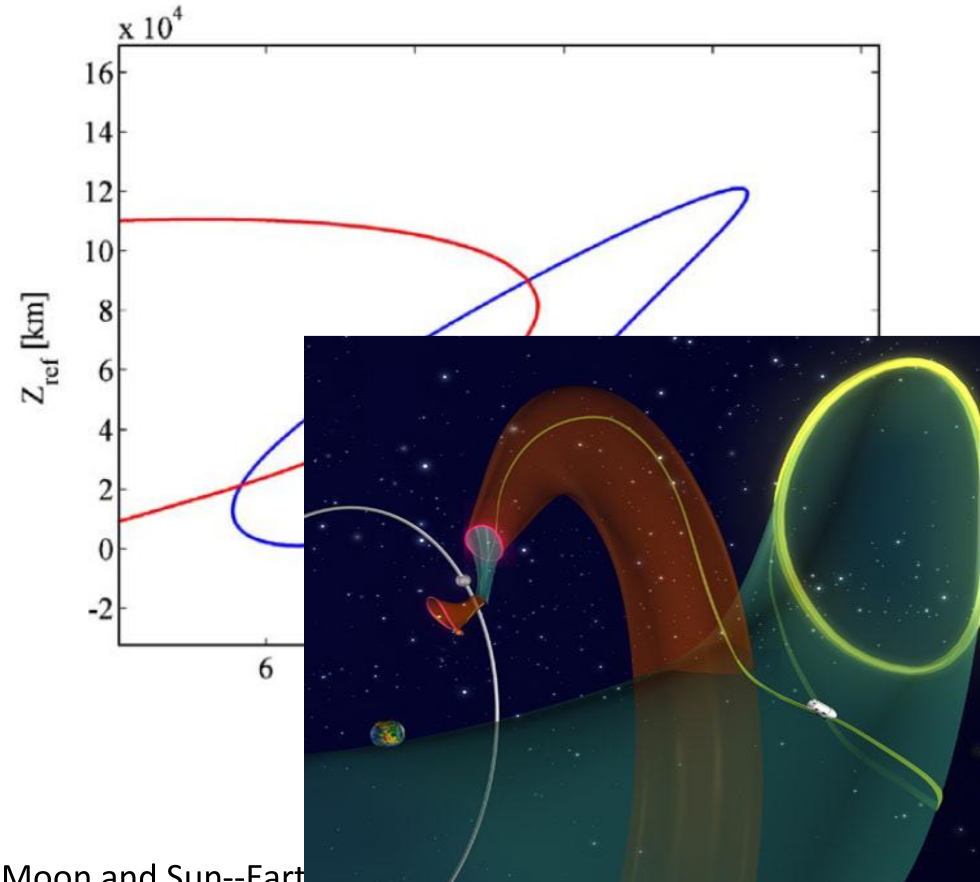
- Launch period: 8 Sep 2011 – 19 Oct 2011
- TOF to the Moon: 3—4 month
- Lunar orbit insertion (LOI): 190 m/s

Parker, J.S., Anderson R.L., "Targeting Low-Energy Transfers to Low Lunar Orbit," Acta Astronautica, 2013, Vol. 84, pp. 1-14.

M.-K. Chung, et al., "Trans-Lunar Cruise Trajectory Design of GRAIL (Gravity Recovery and Interior Laboratory) Mission," AIAA/AAS Astrodynamics Specialist Conference, 2010, Paper AIAA 2010-8384

Transfers between the Sun-Earth and the Earth-Moon systems





Howell, K.C., Kakoi, M., "Transfers Between the Earth--Moon and Sun--Eart
Manifolds and Transit Orbits," Acta Astronautica, 2006, , Vol. 59, Is. 1, pp. 367--380.

Credit: Ken Murphy, http://www.outofthecradle.net/archives/2010/03/my-new-space-hero/

Best SE/EM halo orbit combinations, the ephemeris model

Earth–Moon Az (km)	Sun–Earth Az (km)	ΔV (m/s)
16,000	111,000	0
18,000	142,000	0
19,000	140,000	0
22,000	126,000	0
24,000	130,000	0
26,000	131,000	0
28,000	155,000	0
30,000	157,000	0

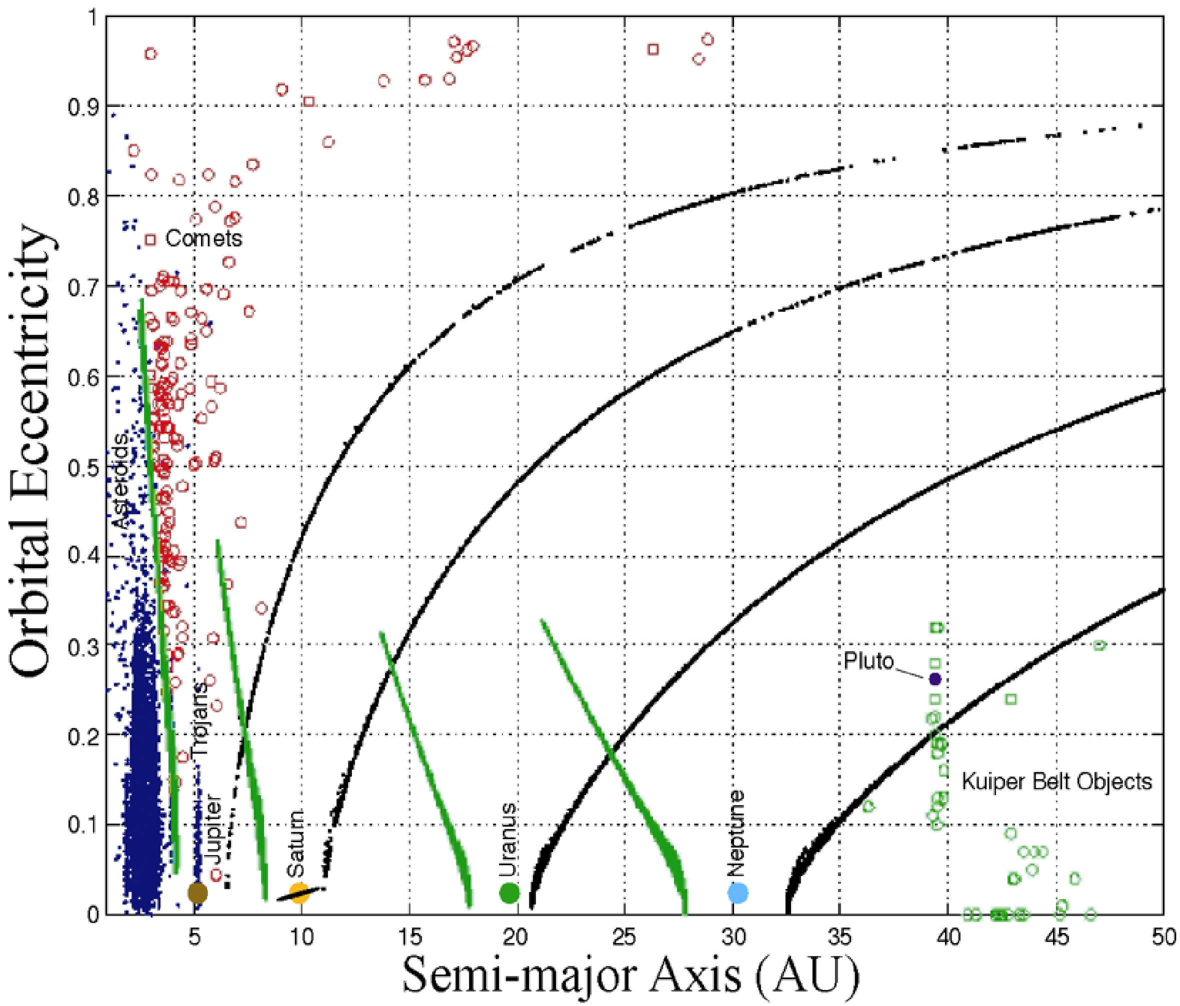
Howell, K.C. and Kakoi, M., "Transfers Between the Earth--Moon and Sun--Earth Systems Using Manifolds and Transit Orbits," Acta Astronautica, 2006, Vol. 59, Is. 1, pp. 367--380.

Transfers between other three-body systems

- The invariant manifolds associated with libration point orbits of the Sun-Earth system do not intersect manifolds of any other Sun-Planet system
- Transfers can be assisted with high/low-thrust arcs or by using solar sails*
- However, the manifolds of the gas giants' and the ice giants' systems do intersect

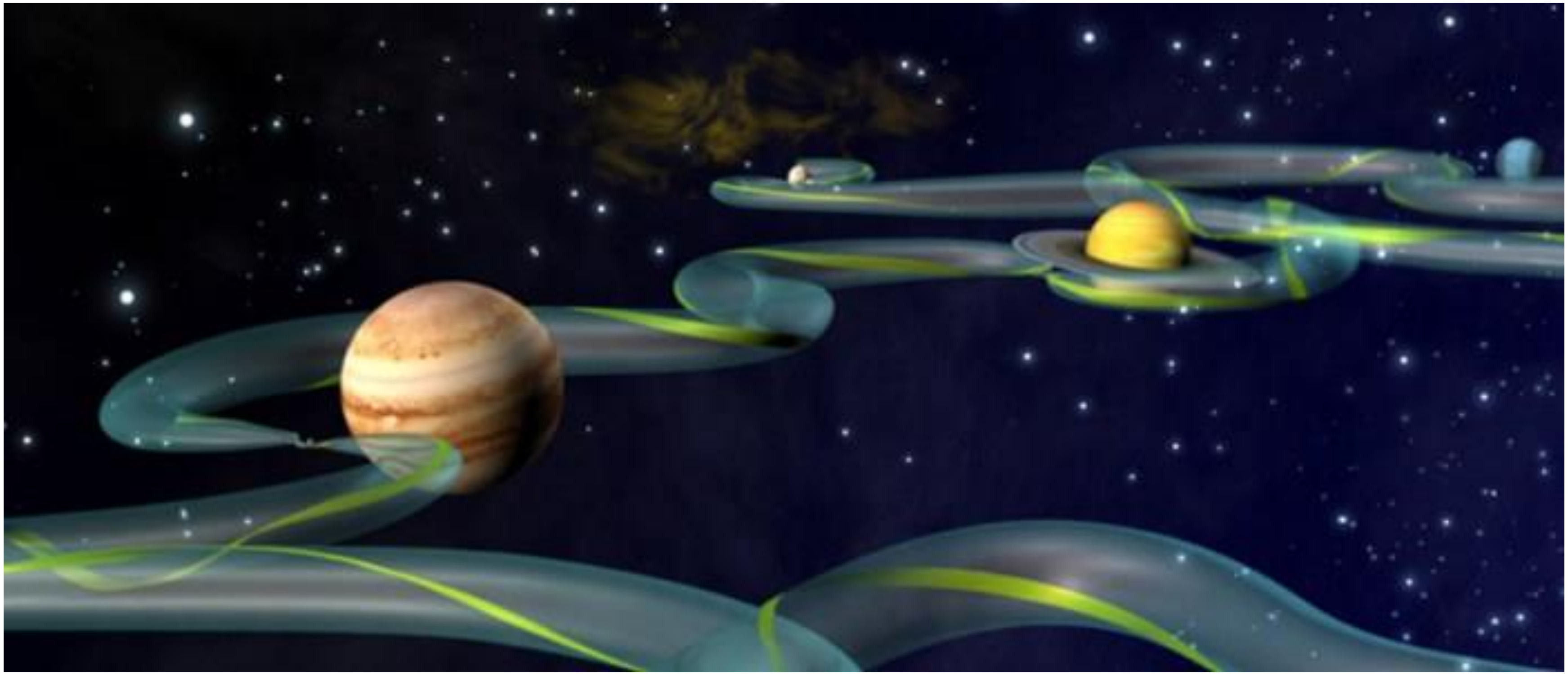
*J. Heiligers, M. Giorgio, and C.R. McInnes, "Optimal solar sail transfers between Halo orbits of different Sun-planet systems," Advances in Space Research, 2015, Vol. 55, Is. 5, pp. 1405--1421.

Interplanetary superhighway



M.W. Lo, “The Interplanetary Superhighway and the Origins Program,” IEEE Aerospace Conference, March 2002, Big Sky, MT, USA.

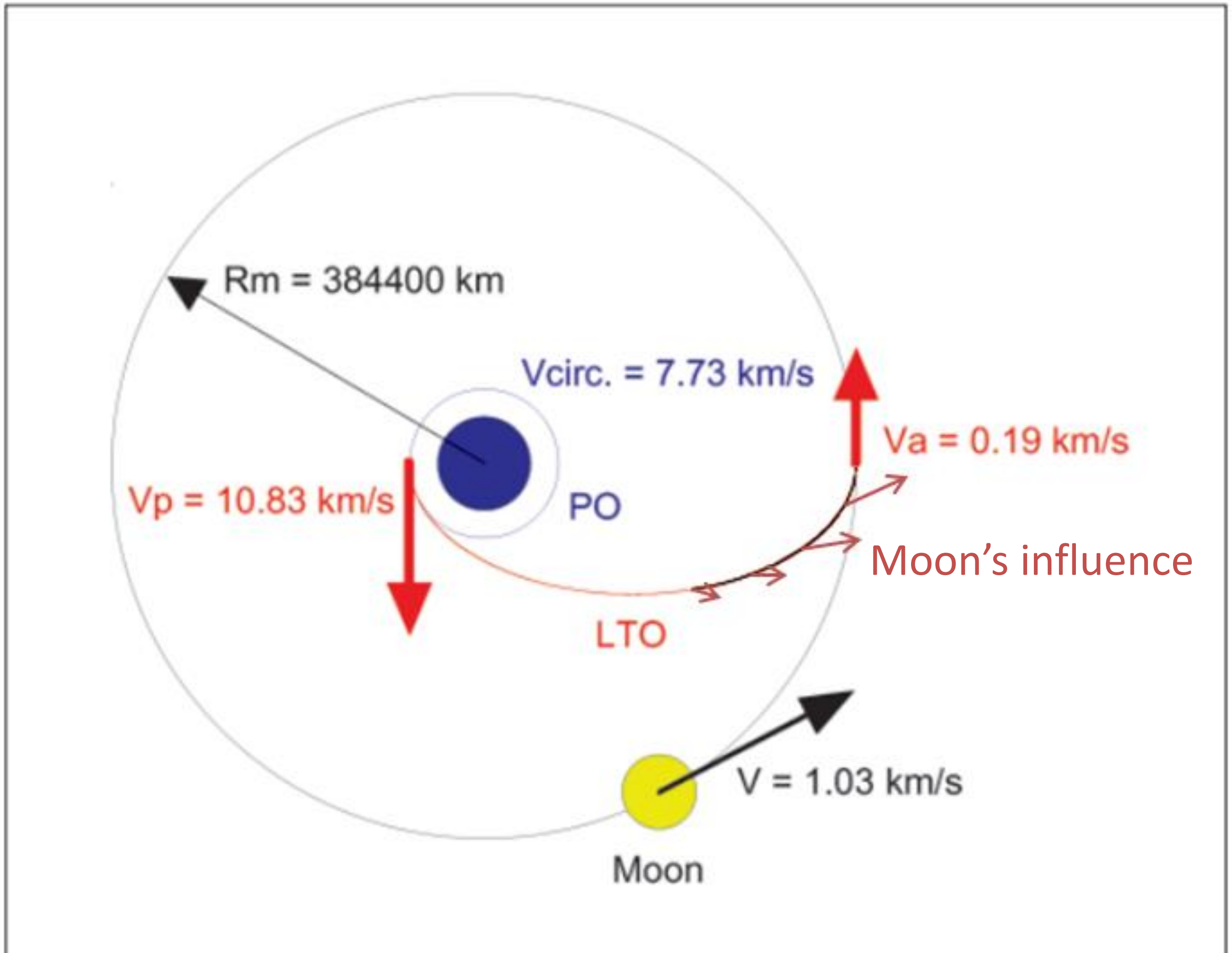
Interplanetary superhighway



Credit: NASA, http://www.jpl.nasa.gov/releases/2002/release_2002_147.html

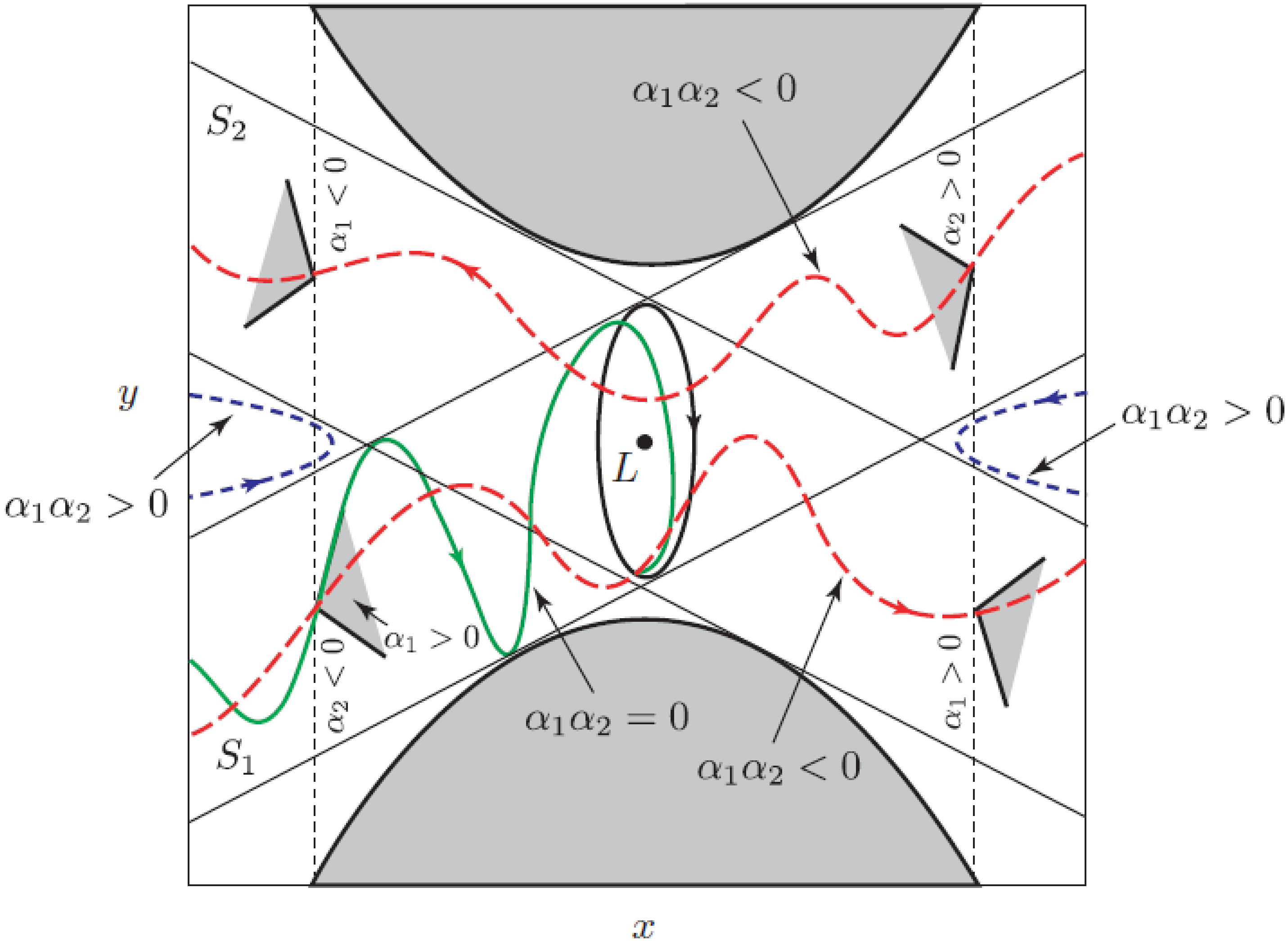
Contents

Hohman transfer to the Moon



Biesbroek R., Janin G., "Ways to the Moon?" ESA bulletin, 2000, Vol. 103, pp. 92-99.

The flow in the equilibrium region of position space



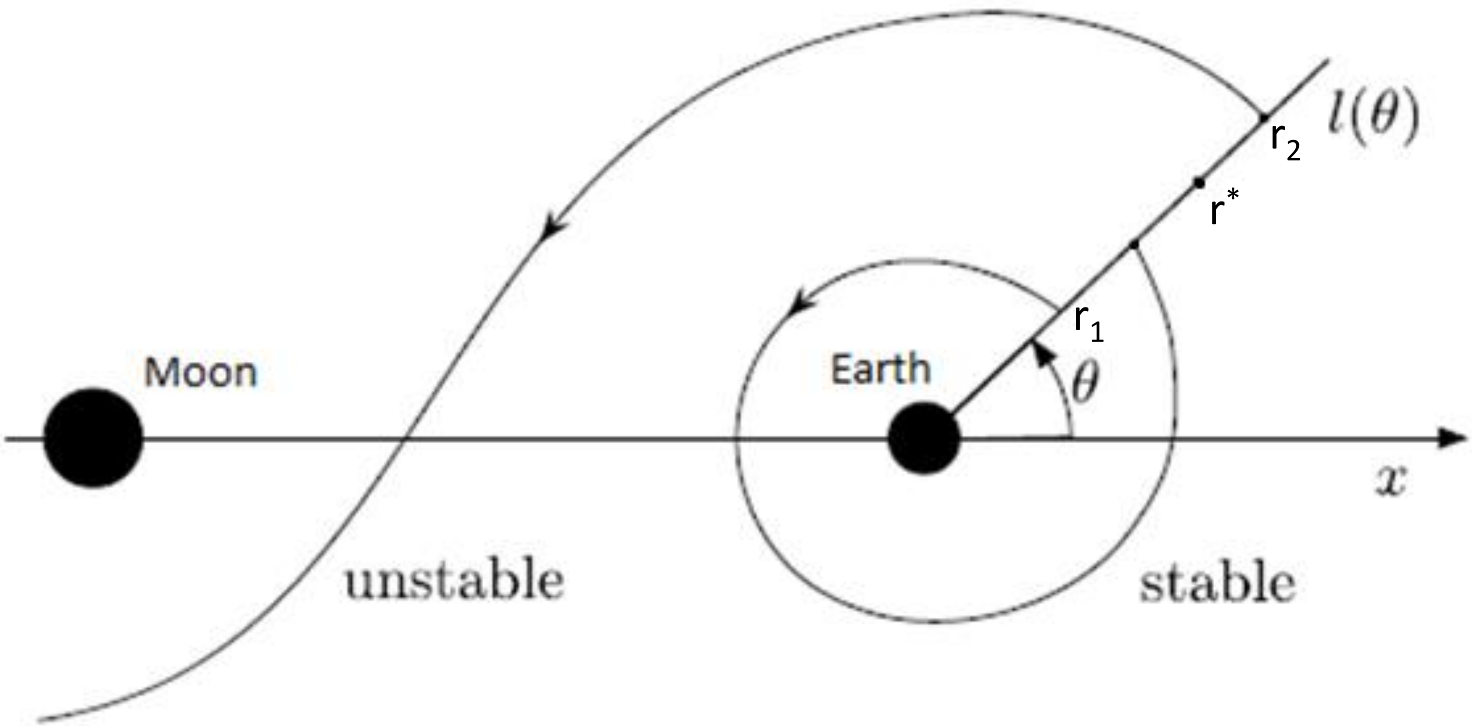
Conley, C.C., "Low Energy Transit Orbits in the Restricted Three-Body Problems", SIAM Journal on Applied Mathematics, 1968, Vol. 16, No. 4, pp. 732—746

Weak stability boundary (WSB)

E. Belbruno have generalized the notion of the sphere of influence:

- WSB is a surface in phase space
- WSB concept is based on behavior of trajectories rather than on relation between gravitational forces
- WSB is the boundary between the stable and unstable motion

Stable and unstable motion



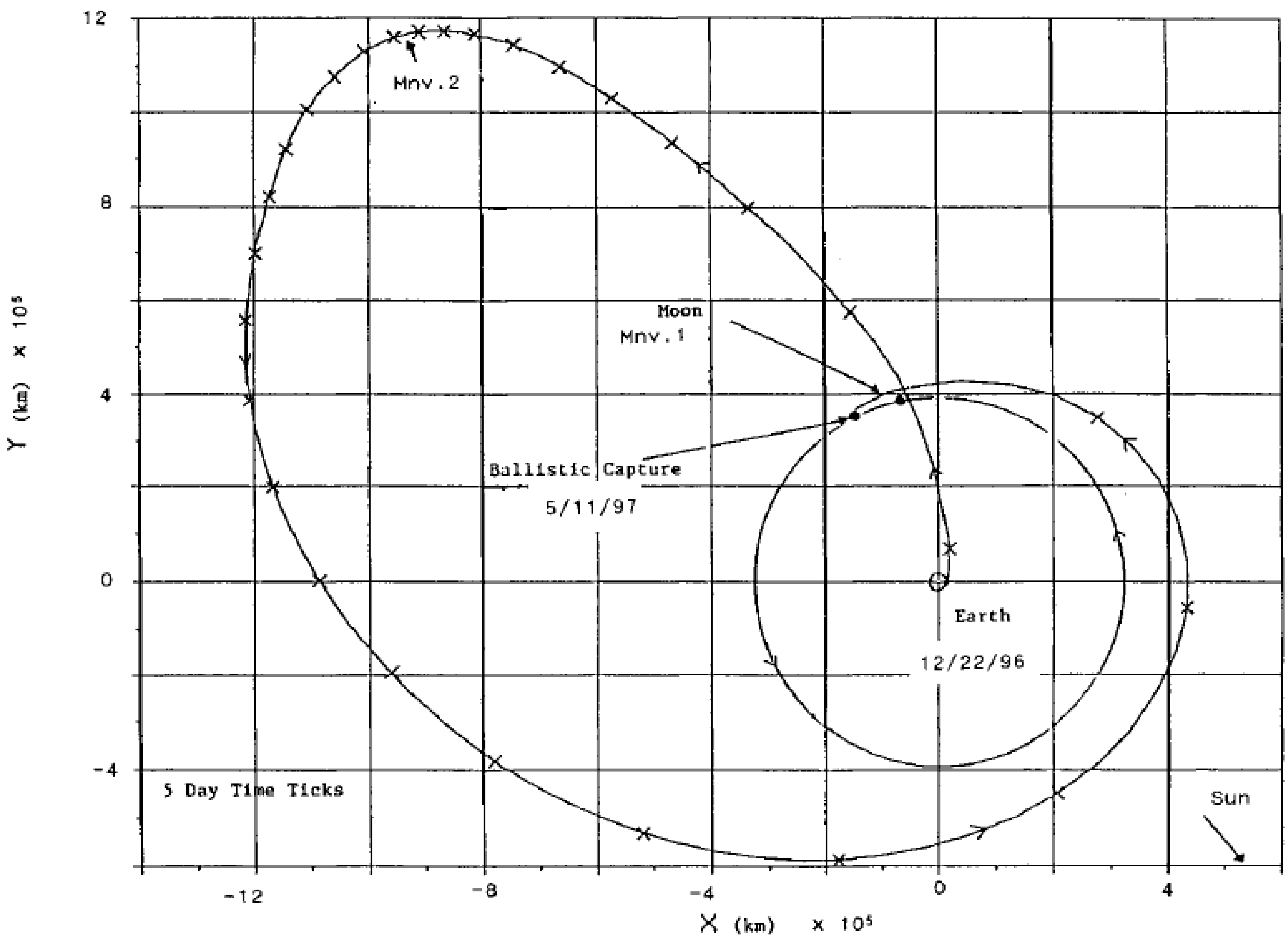
$$W = \{(\mathbf{r}, \mathbf{v}) : \mathbf{r} \in l(\theta),\ e \in [0,1),\ \theta \in [0, 2\pi]\}$$

Transfer design to the Moon

- Fix the position near the Moon
- Find a near-Moon orbit such that the s/c is in the WSB w.r.t. the Moon
- Propagate the trajectory backward in time until the WSB w.r.t. the Earth (near SE L1)
- Fix the position near the Earth and find an impulse that deliver the s/c through the Moon's gravity assist to the required point near SE L1
- Eliminate the velocity discontinuity by an impulse
- Optimize the transfer by varying the initial and final times of flight and the near-Moon orbit

Belbruno, E. A., Miller, J.K., ``Sun-perturbed Earth-to-Moon Transfers with Ballistic Capture", Journal of Guidance, Control, and Dynamics, 1993, Vol. 16, Is. 4, pp. 770—775.

The Hiten trajectory



Belbruno, E. A., Miller, J.K., ``Sun-perturbed Earth-to-Moon Transfers with Ballistic Capture”, Journal of Guidance, Control, and Dynamics, 1993, Vol. 16, Is. 4, pp. 770—775.

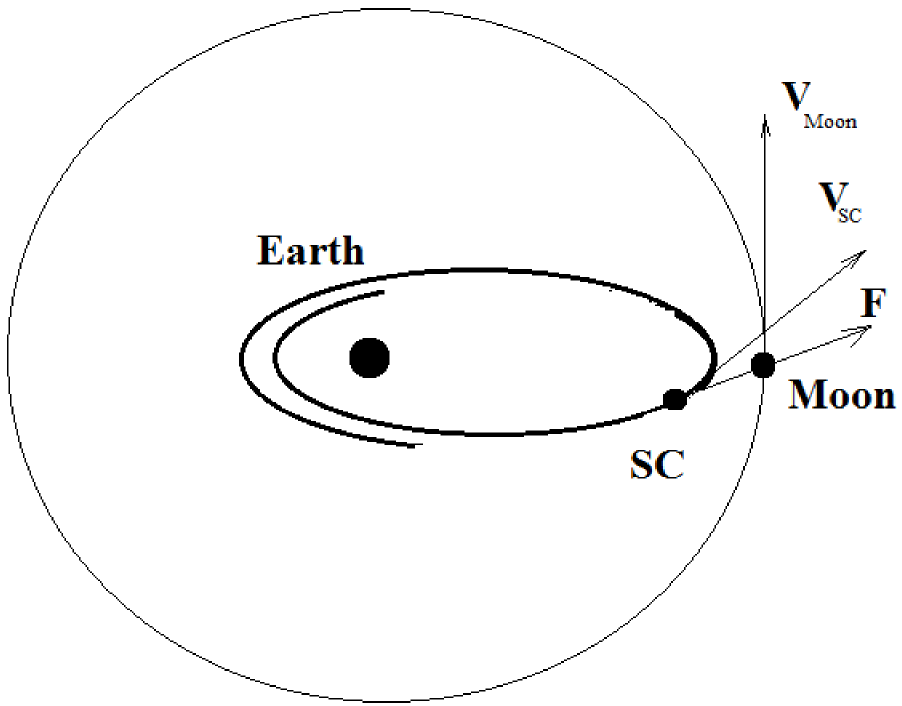
Contents

GA maneuvers outside the sphere of influence (SOI)

- Previously (classical way):
  - Patched conic approximation
  - GA maneuvers inside the SOI

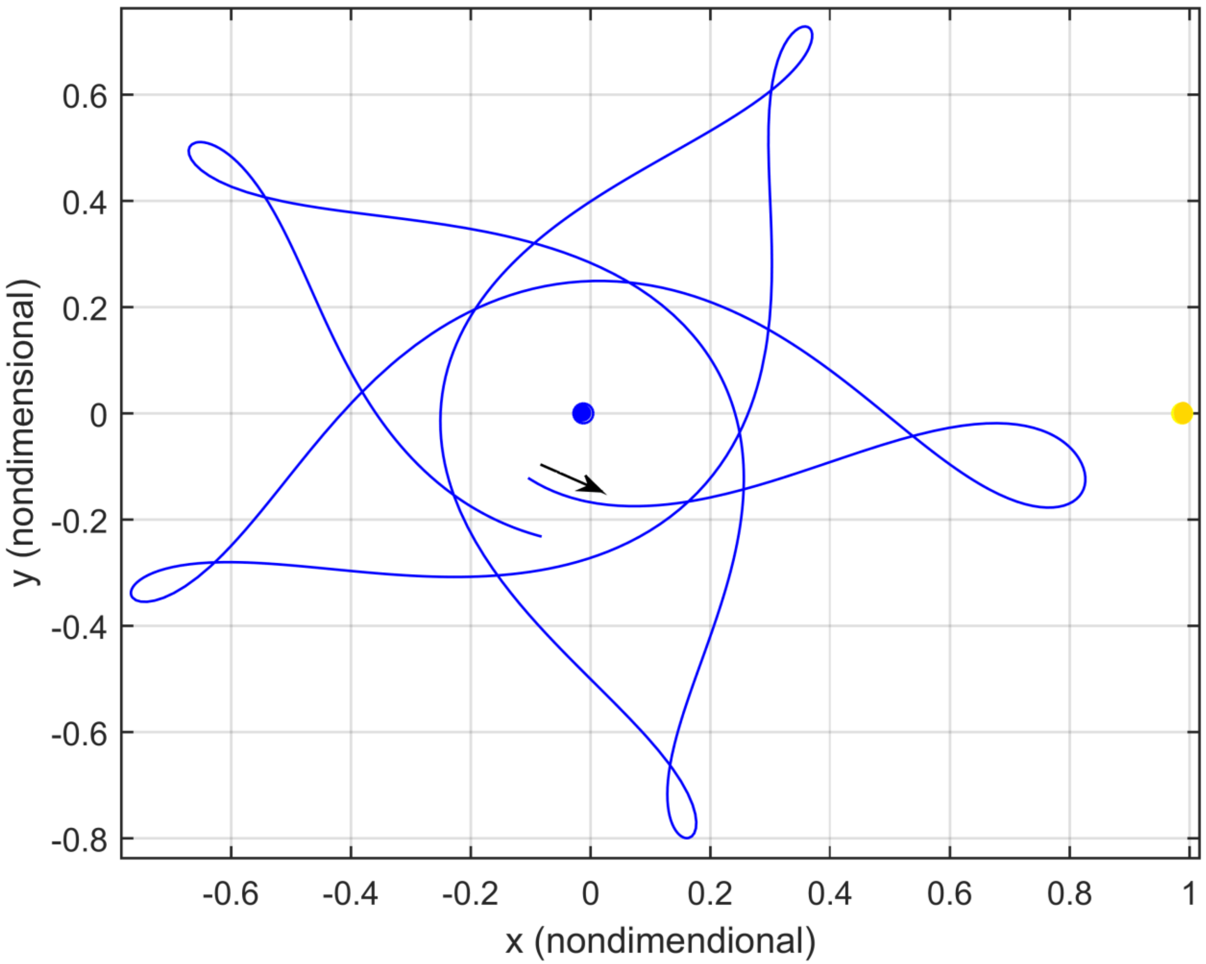
- Now:
  - Restricted three-body problem
  - GA maneuvers outside the SOI (high-altitude fly-bys)

Idea of resonant encounters



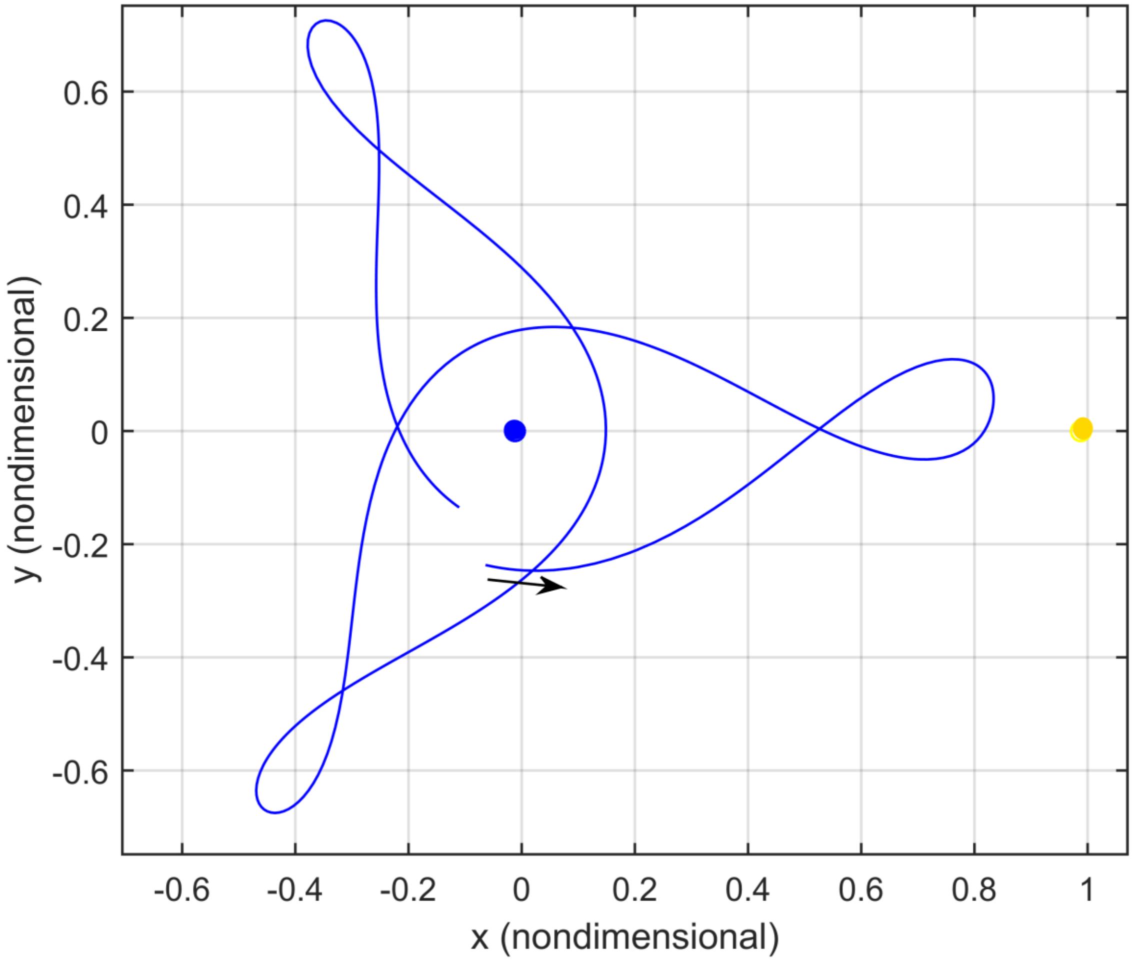
Perigee raising by using the high-altitude fly-by

Δr_π = 34,000 km

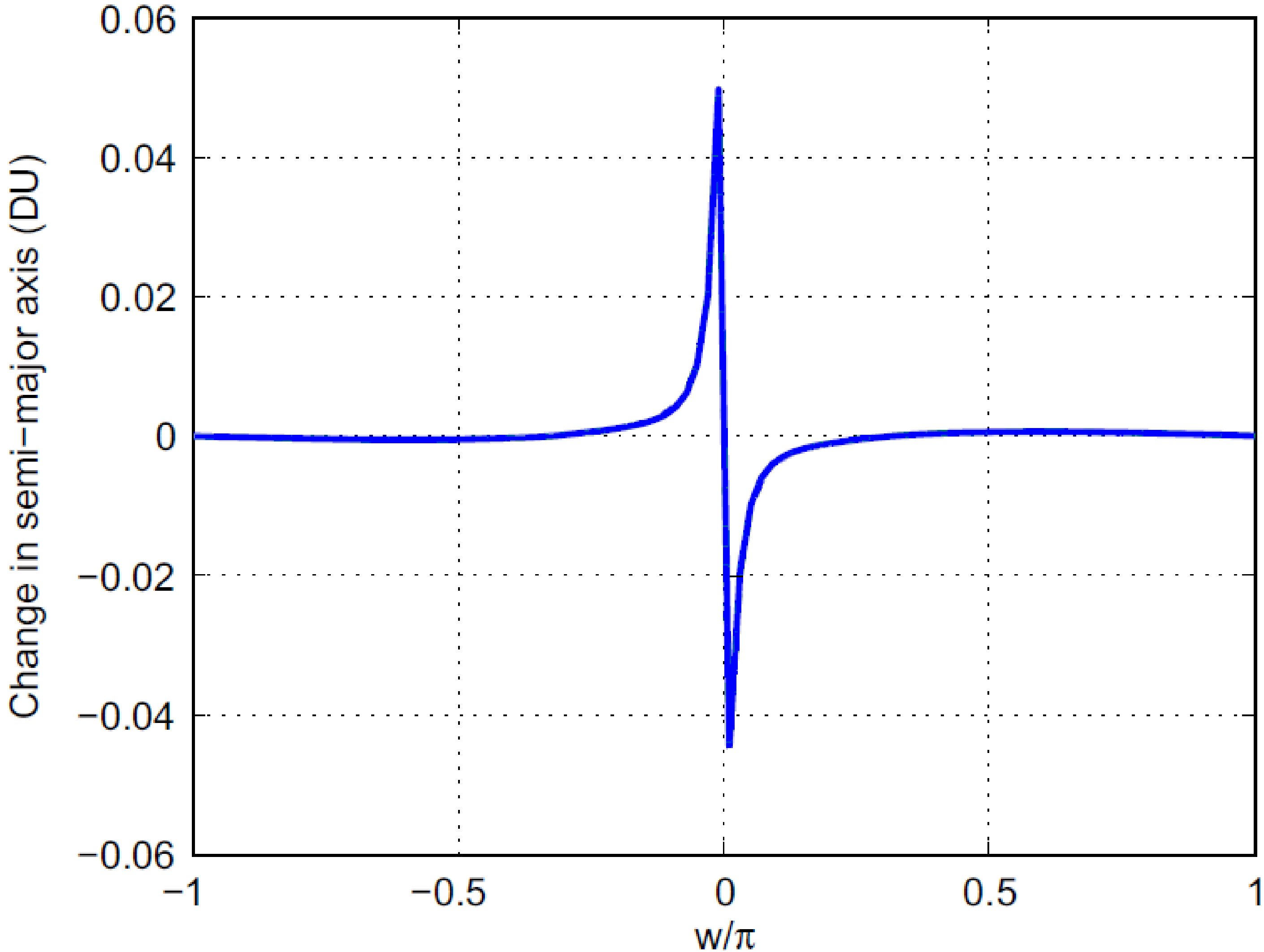


Perigee lowering by using the high-altitude fly-by

$\Delta r_\pi = -\ 29{,}000$ km

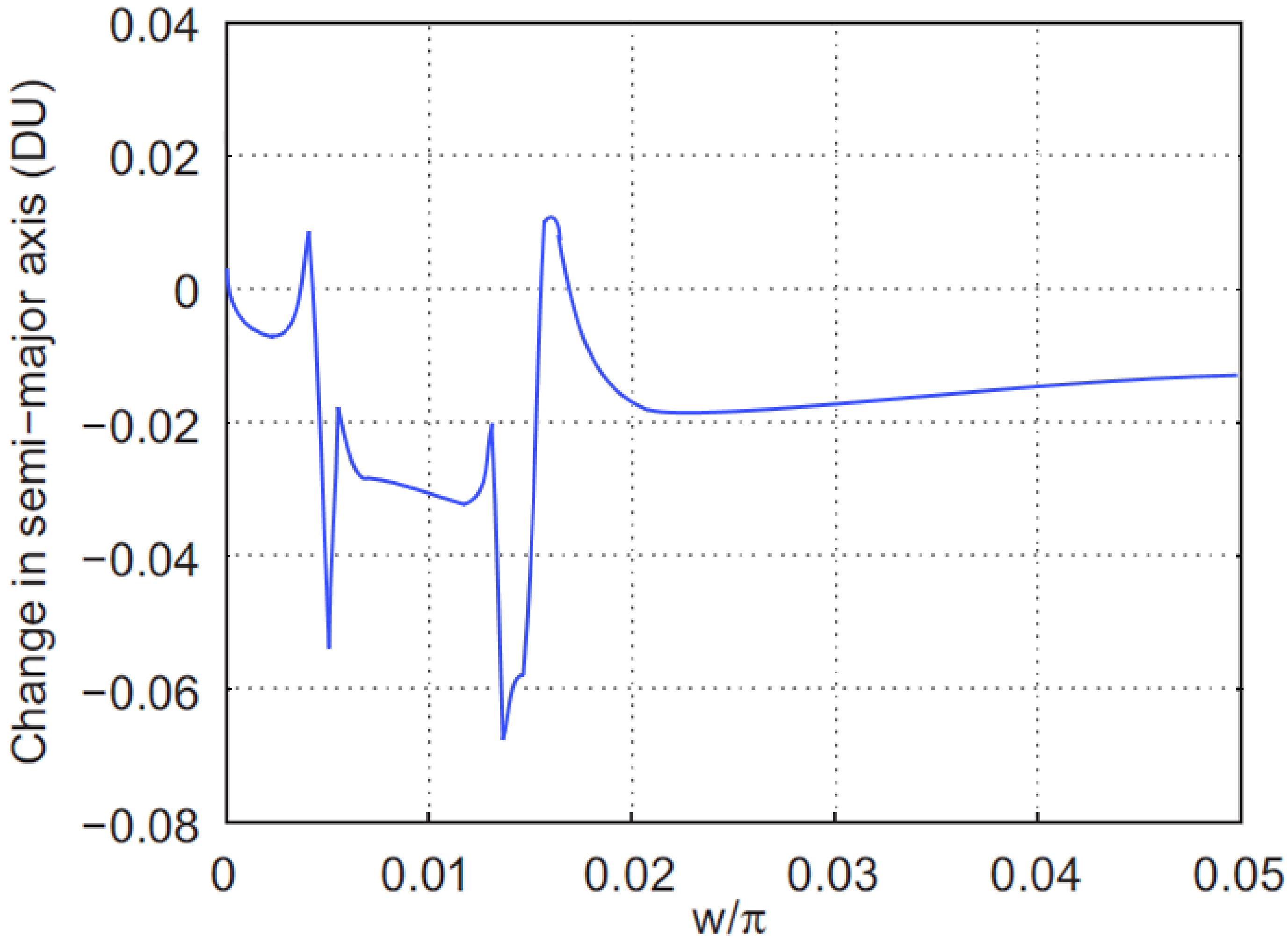


Impact of encounter on semi-major axis, one revolution



Lantoine, G., et al., "Optimization of Low-Energy Resonant Hopping Transfers Between Planetary Moons," Acta Astronautica, 2011, Vol. 68, Is. 7, pp. 1361--1378.

Impact of encounters on semi-major axis, 14 revolutions



Lantoine, G., et al., "Optimization of Low-Energy Resonant Hopping Transfers Between Planetary Moons," Acta Astronautica, 2011, Vol. 68, Is. 7, pp. 1361--1378.

Resonant encounters

- The l:m resonance:

$$l \cdot T = m \cdot 2\pi$$

- Encounter that occur in the l:m resonance orbit repeats after m periods of the Moon
- Hopping between resonances ensures <u>regular</u> energy growth/reduction

Example: transfer to a halo orbit around EM L1

$\varphi = 0.2$

$\Delta v_0 = 0.78 \text{ m/s}$

$5:2 \rightarrow 3:1$

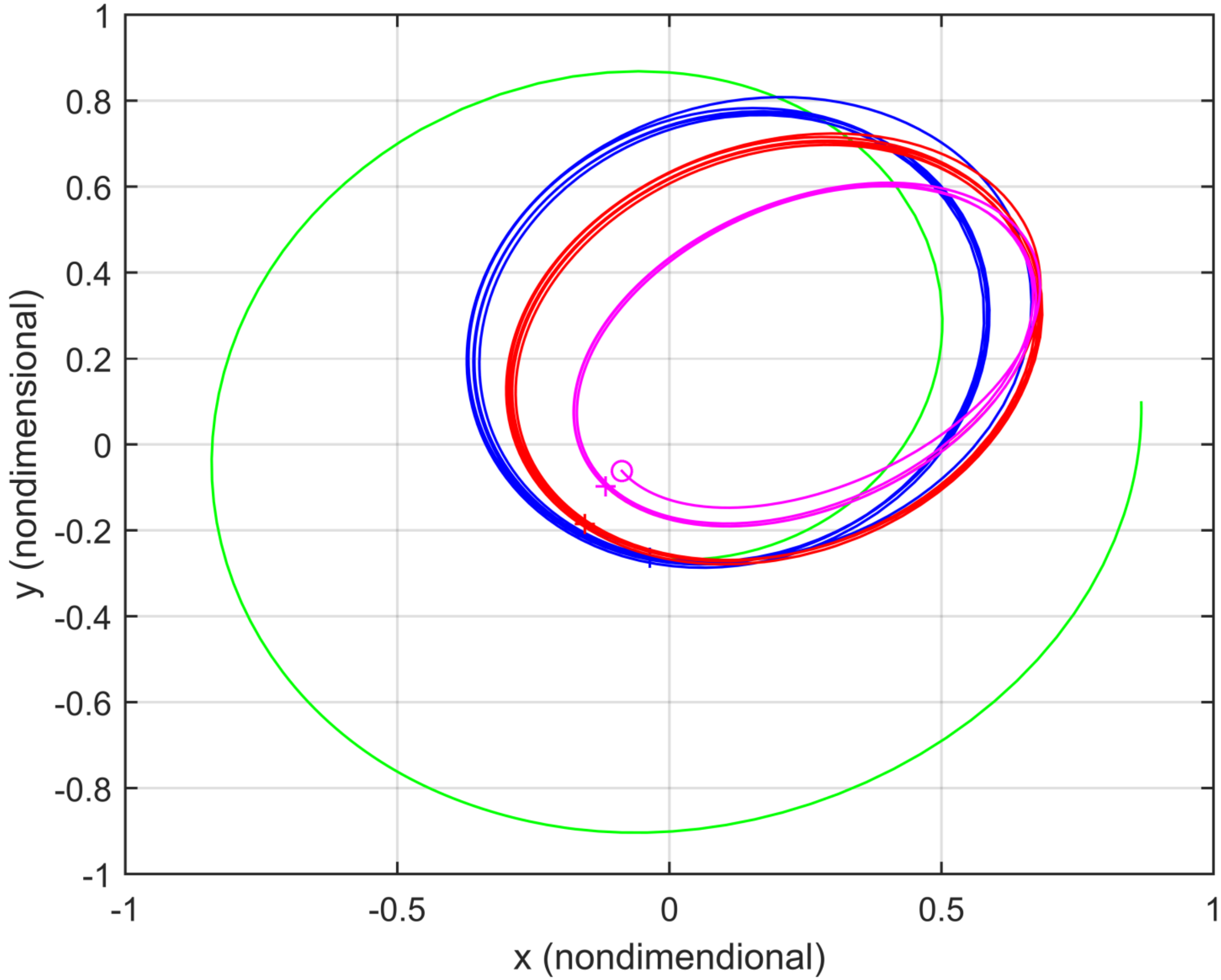
$\Delta v_1 = 47.5 \text{ m/s}$

$\Delta v_2 = 0 \text{ m/s}$

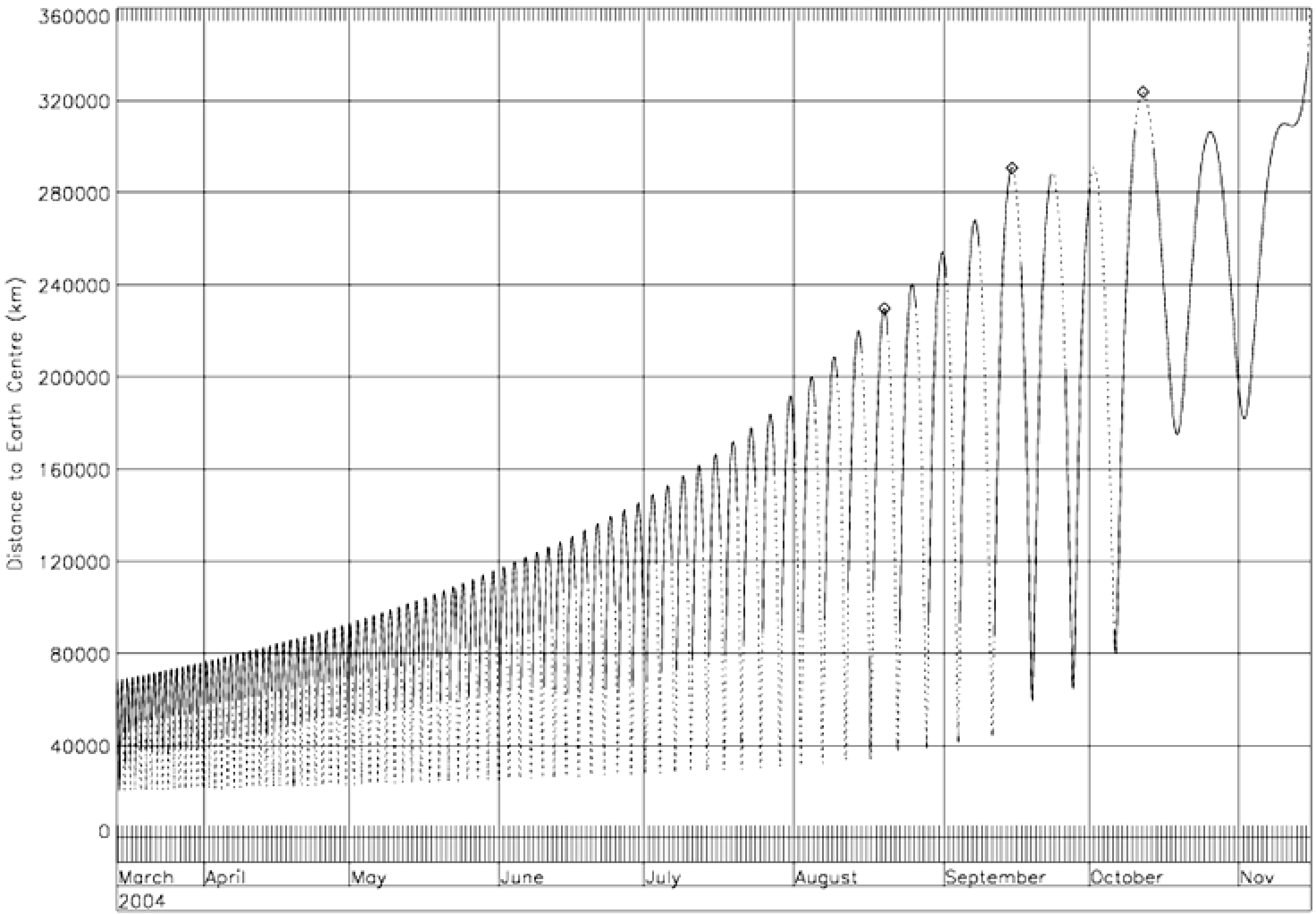
$r_\pi = 41,127 \text{ km}$

$r_\alpha = 300,600 \text{ km}$

$\text{TOF} = 163.4 \text{ days}$

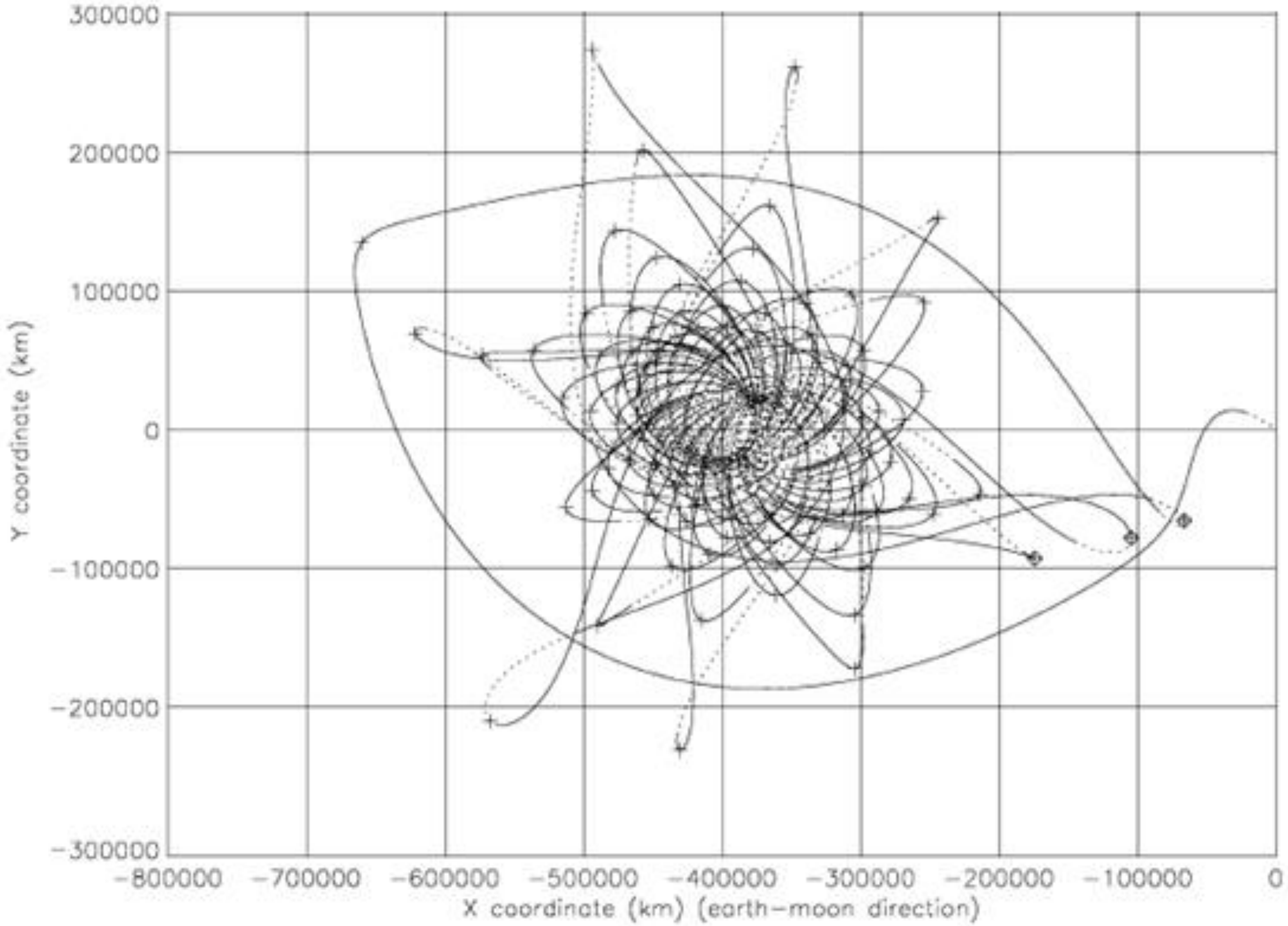


SMART-1 hopping



J. Schoenmaekers, ``Post-launch Optimisation of the SMART-1 Low-thrust Trajectory to the Moon,'' 18th International Symposium on Space Flight Dynamics, October 2004, Munich, Germany.

SMART-1 trajectory, capture by the Moon



J. Schoenmaekers, ``Post-launch Optimisation of the SMART-1 Low-thrust Trajectory to the Moon,'' 18th International Symposium on Space Flight Dynamics, October 2004, Munich, Germany.

Contents

- Introduction
- Gravity assists maneuvers
- Invariant manifolds of the libration point orbits
- Weak stability boundary
- Resonant encounters
- **Summary**

Summary

- GA maneuvers exploit the orbital energy of the planets, save fuel, and increase the mass of payload needed for scientific observations

- Invariant manifolds associated with LPOs form a vast transport network in the solar system (the “Interplanetary Superhighway”) and lead to cheap interplanetary transfers between different two-body systems

- The notion of weak stability boundary formalizes the thinnest border between the near-Earth orbits and the Earth-to-Moon trajectories facilitating the trajectory design

- Resonant encounters are a natural energy-increasing tool on the way to the Moon

Thank you for your attention!