Contributions of a Venus Swing-by Maneuver in Earth-Mars Transfers

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Introduction

Our Goal:

To investigate the effect of Jupiter gravitational field in Earth-Mars transfers with a Venus Swing-by

Motivation:

To get trajectories for exploration and colonization of Mars with distinct profiles aiming different purposes

Challenge:

interplanetary transfer design involves many-body effects, primaries orbit geometry, elevated cost, suitable time window for departure and return, transfer time, & others

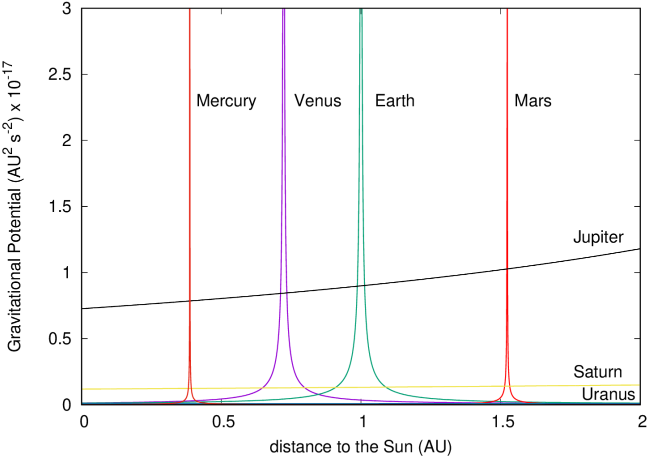
Our Approach:

To build both Direct Earth-Mars transfers and Earth-Mars transfers with a Venus Flyby in the context of the Sun-Jupiter System of the PCR3BP.

Introduction

Why to consider the Sun-Jupiter system in Earth-Mars transfers?

Inspecting the gravitational potentional in the interplanetary region



Inspired by Ren, Masdemont, Gomez, Fantino, CNSNS **17** (2012) 844.

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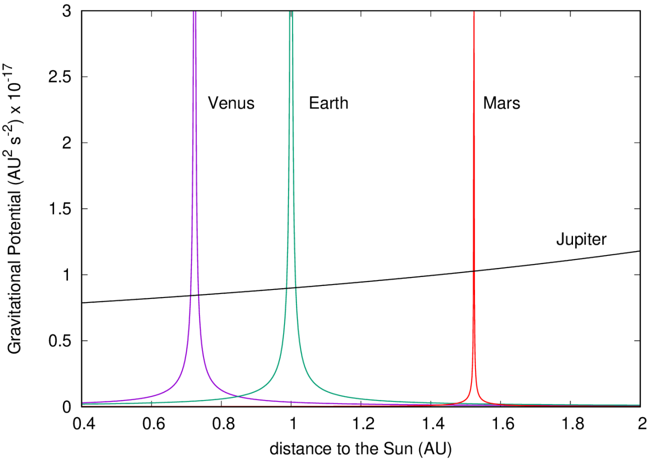

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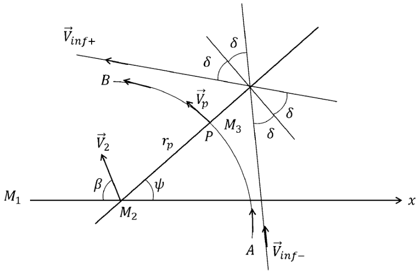
Earth Mars transfer with a Flyby Maneuver by Venus



Variation of SC velocity wrt the Sun:

$$\Delta\vec{V} \equiv \vec{V}_o - \vec{V}_i,$$

$$\Delta V = |\Delta\vec{V}| = 2V_{inf}\sin\delta$$

with V_{inf} defined wrt Venus

$$|\vec{V}_{inf+}| = |\vec{V}_{inf-}| = V_{inf}.$$

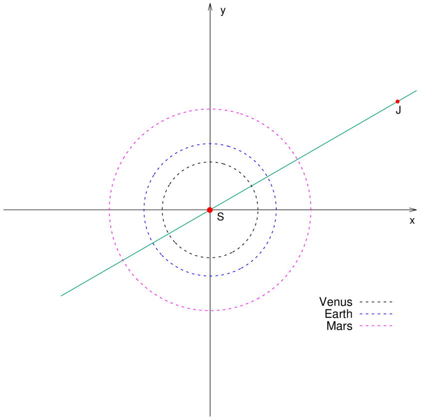
$$\sin\delta = \frac{1}{1 + \frac{r_p V_{inf}}{\mu_{venus}}}$$

Periapsis altitude r_p as control parameter

Besides the opportunity to observe Venus, the flyby maneuver also is exploited to change the velocity of the spacecraft w.r.t the Sun at the input and output of the SOI of Venus.

Assumptions of our preliminary analysis

1. Planets in coplanar circular orbits
2. Dynamics of the SC defined by Sun-Jupiter grav.potential
3. Gravitational effects of Earth and Mars compensate each other
4. Dynamics of the interplanetary flight given by R3BP

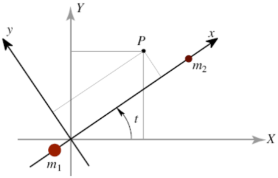


Three reference frames:

1. Heliocentric inertial frame
   Initial conditions
2. Barycentric rotating frame
   Interplanetary Flight
3. Inertial frame centered at Venus
   Inside the Sphere of Influence of Venus

The Restricted Three-body Problem: *Planar Version*

- 2 D.O.F. Hamiltonian system
- Particle P_3 of negligible mass moving under the gravitational influence of P_1 and P_2 of masses m_1 and m_2.
- The primaries describe circular coplanar orbits around the barycenter of P_1-P_2 and are fixed in the synodic reference frame (which rotates w.r.t. an inertial frame).
- Distance between the primaries, the sum of their masses and their angular velocity around the barycenter are normalized to one.
- $\mu = m_2/(m_1+m_2)$, $m_1 \geqslant m_2$ is the only parameter.



Equations of Motion:

$$\ddot{x} - 2\dot{y} = \Omega_x, \quad \ddot{y} + 2\dot{x} = \Omega_y,$$

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

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

Integral of motion: $J(x,y,\dot{x},\dot{y}) = 2\Omega(x,y) - (\dot{x}^2+\dot{y}^2) = C,$

3D manifold $\mathcal{M}(\mu, C) = \{(x,y,\dot{x},\dot{y}) \in \mathbb{R}^4 | J(x,y,\dot{x},\dot{y}) = const.\}$

Equilibrium points

Hill regions:

- Projection of $\mathcal{M}$ onto configuration space
- Areas accessible to trajectories for each C
- Bounded by the Zero Velocity Surfaces

Symmetries:

- $(x, y, \dot{x}, \dot{y}, t) \leftrightarrow (x, -y, -\dot{x}, \dot{y}, -t)$
- $(x, y, \dot{x}, \dot{y}, t) \leftrightarrow (x, y, \dot{x}, \dot{y}, t)$

Collinear points: $L_{1,2,3}$, on the x-axis

- center-saddle
- 2D central manifold: horizontal Lyapunov orbits, invariant tori, other periodic orbits, chaotic regions.

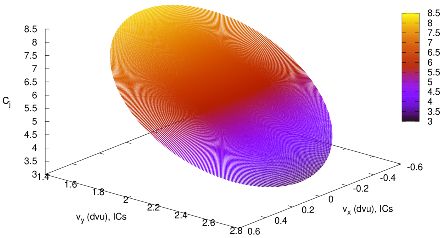
Triangular points: $L_{4,5}$, at $x = \mu - \frac{1}{2}, y = \mp\frac{\sqrt{3}}{2}$

- Nonlinear stability (on a ball of small μ-dependent radius around $L_{4,5}$) for $\mu \in (0, \mu_1)\backslash\{\mu_2, \mu_3\}$, $\mu_1 = \frac{(9-\sqrt{69})}{18}$, $\mu_2 = \frac{(45-\sqrt{1833})}{90}$, $\mu_3 = \frac{(15-\sqrt{213})}{30}$, except a set of initial conditions of small Lebesgue measure for fixed μ.

Five Parameters:

- At Earth departure: (4)
  - angle α_{SJ}
    (btw. Sun-Jupiter axis & x-axis of HIRF)
  - angle θ
    (Earth cir. orbit around the Sun,)
  - Δv_E and ξ.
    (magnitude & phase of vel. increment)
- At Venus Swingby: (1)
  - r_p, (due to maneuvers of negligible costs)
    (the altitude of the periapsis wrt Venus)

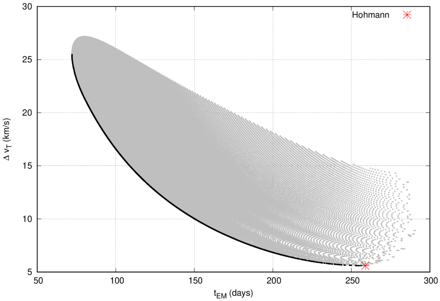
Initial Conditions for $\alpha_{SJ} = \theta = 0$:



Direct Earth-Mars transfers

16 equispaced values of $\alpha_{SJ} = (n_\alpha - 1)\,\pi/8$ for $\theta = 0$

$\Delta v_T \times t_{EM}$



Gray dots: all solutions
Black dots: Δv_T optimal solutions

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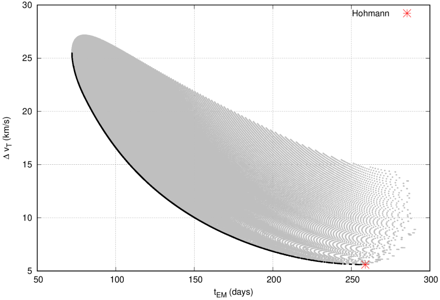

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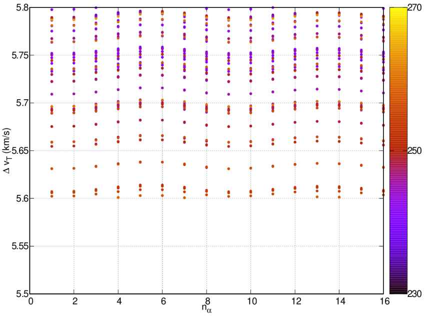
$\Delta v_T \times n_\alpha$



Color code: t_{EM}

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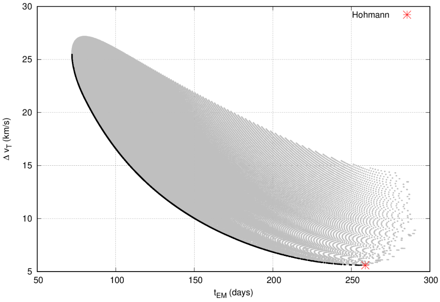

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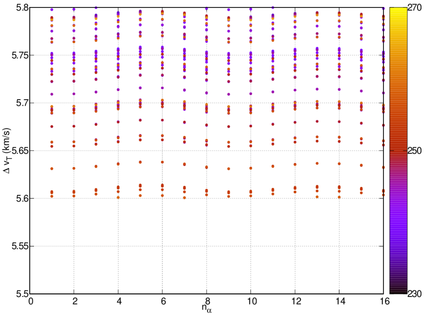

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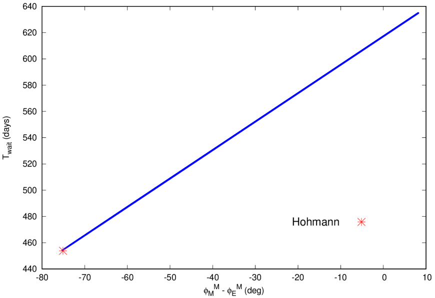
Very tiny effect of Jupiter!!

16 equispaced values of $\alpha_{SJ} = (n_\alpha - 1)\ \pi/8$ for $\theta = 0$

$t_{wait} \times \phi_M^M - \phi_E^M$



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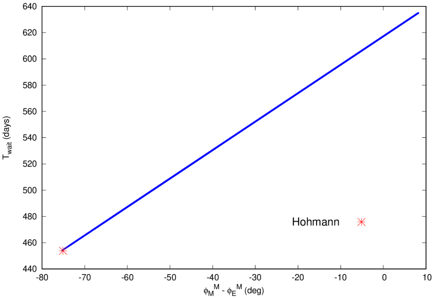

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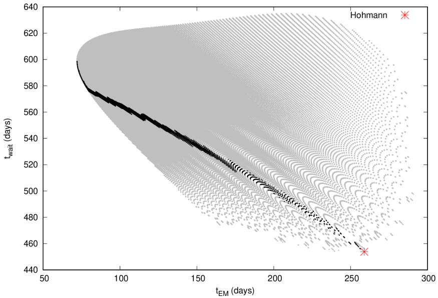

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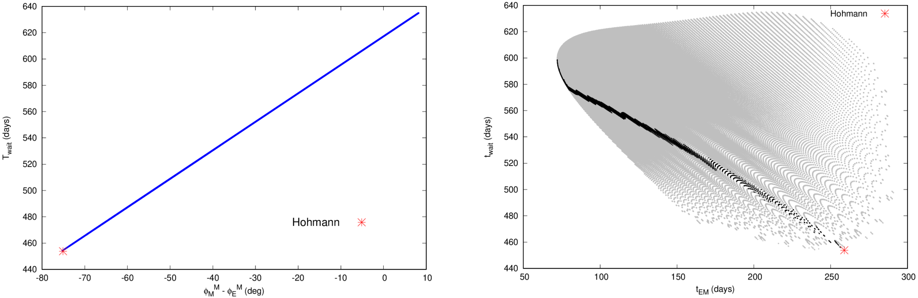
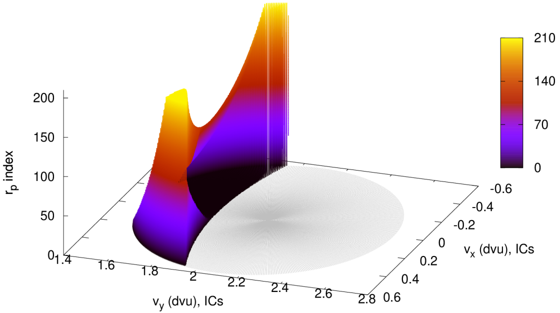


Long waiting time for a Earth return by Hohmann transfer!

Earth-Mars transfers with Venus Flyby

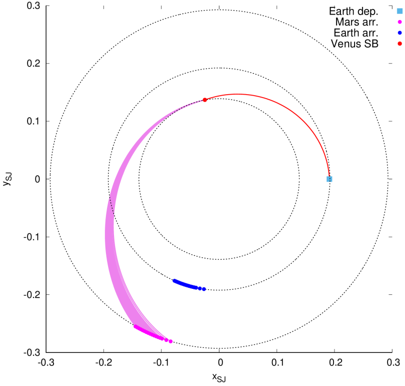
Inspecting Venus flyby process at first (for $\alpha_{SJ} = \theta = 0$)



Venus pericenter altitude $\times$ initial velocities

Inspecting Venus flyby process at first (for $\alpha_{SJ} = \theta = 0$)

Illustration of EM transfers generated by one IC



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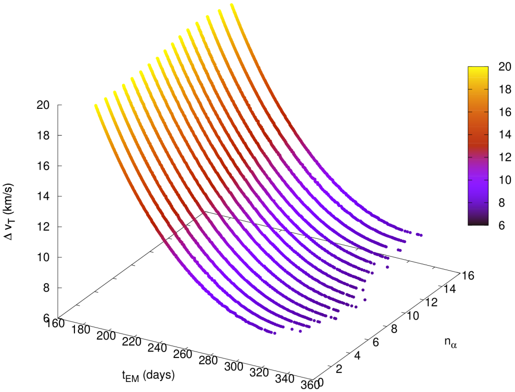
Pareto Optimal Solutions: minimum Δv_T as a function of t_{EM}, for each α_{SJ}



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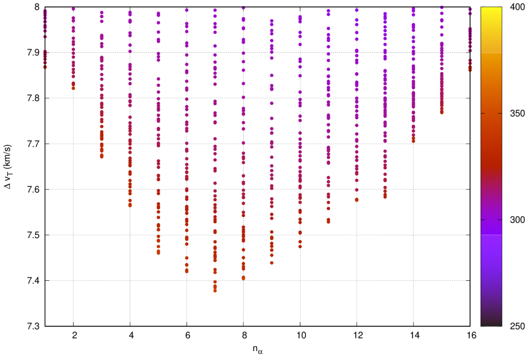
Optimal solutions: minimum Δv_T versus α_{SJ} (i.e., n_α) (colors depicts t_{EM})



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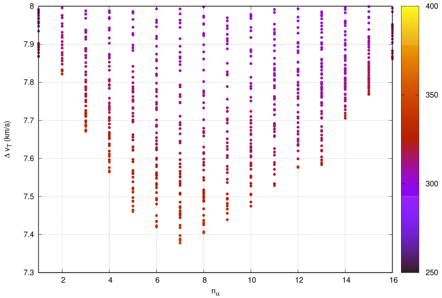

Δv_T	α_{SJ}
7.378 km/s	$3\pi/4$ $(n_\alpha = 7)$
7.868 km/s	0 $(n_\alpha = 1)$

A variation of 0.490 km/s.

A save of 6.2% is possible

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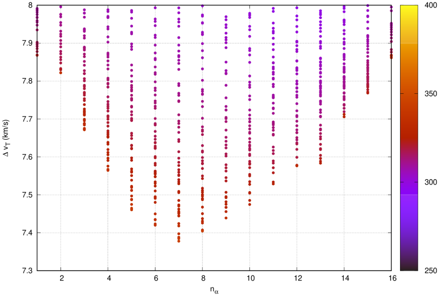

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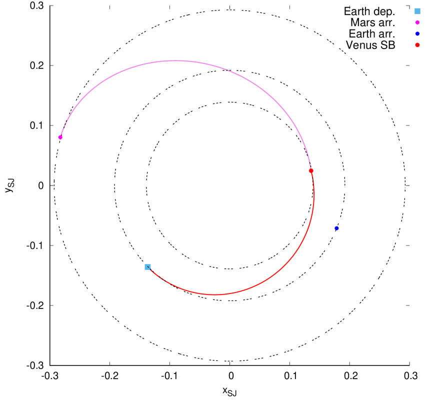
Jupiter grav. field plays an important role for transfers with Venus flyby

Optimal transfer $(\alpha_{SJ} = 3\pi/4)$



Sun-Jupiter Rotating Frame

$t_{EV} = 132$ days

$t_{EM} = 343$ days

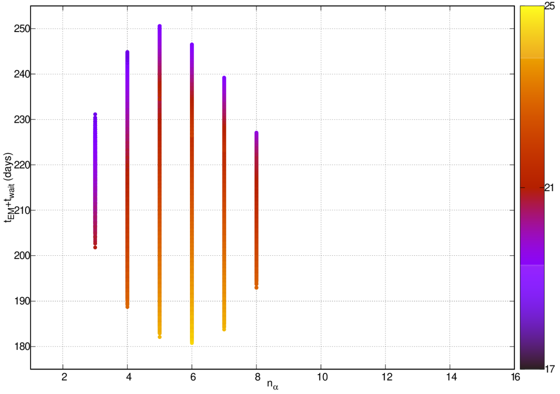
$\Delta v_E = 2.60 km/s$

$\Delta v_M = 4.478 km/s$

Swing-by $\Delta v = 4.83 km/s$

$t_{wait} = 594$ days

Non-optimal solutions with low waiting time: from 0 to 24 days with higher cost (color depicts Δv_T)



Conclusions and Future Works

- Earth-Mars transfers with Venus swingby were obtained and *the role played by Jupiter* investigated.
- Possible applications:
  - the judicious choice of the relative phase of Earth and Jupiter at the departure can lead to a significant fuel save.

    For the simplified model we employed and before a full optimization procedure, we found a save of 6.2 %.
  - combination of α_{SJ} and r_p may leads to solutions with short waiting time for low cost Earth return.

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- Further work:Inclusion of a multi-objective optimization strategy to allow the inclusion of more realistic geatures to the dynamical model, such as, the 3D orbits of Mars and Earth.

Besides that, an impulsive thrust must be included at different points in the swing-by by Venus aiming to decrease the value of Δv_M or even to enable future purposes after Mars passage.

Thanks for your attention!

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