Trajectories to the Moons (incl. a trajectory for an Enceladus orbiter)

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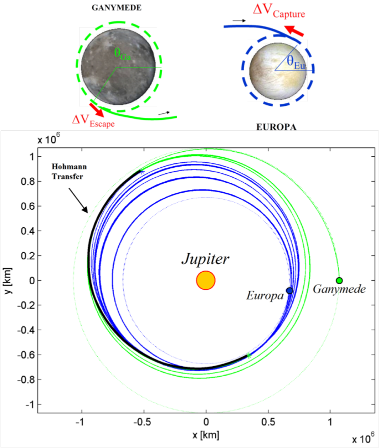
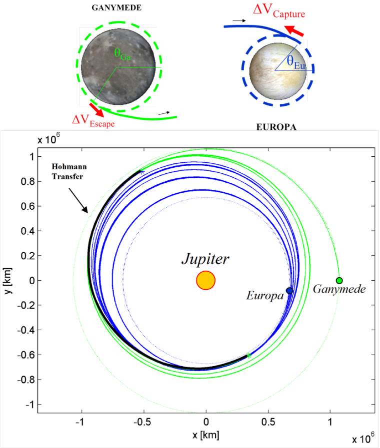
Problem Definition and Motivation

- Trajectories for the exploration of planetary moons (e.g.: Galileo, Cassini)
- Motivation: Orbiters for Missions to the Jupiter Moons; Missions to the Saturn Moons
- Aim: Achieve a low $\Delta V_{capture}$ and or ΔV_{escape} at a moon and a low Time of Flight (ToF)



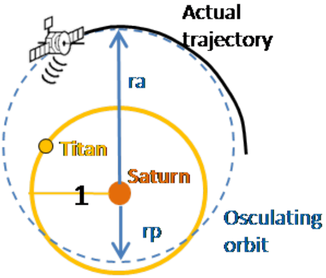
Problem Definition and Motivation

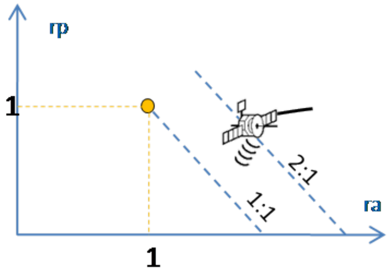
- Trajectories for the exploration of planetary moons (e.g.: Galileo, Cassini)
- Deep space maneuvers ΔV_{DSM}
- Flybys at the same moon and/or at different moons
- Pareto front $\min(ToF, \Delta V_{TOT})$, where $\Delta V_{TOT} = \Delta V_{capture/escape} + \Delta V_{DSM}$
- Models : patched 2-body problems or patched 3-body problems



ra,rp,T

- Assume the s/c is orbiting the major body (Saturn, Jupiter).
- We represent each point of its trajectory in coordinates with the osculating apocenter and pericenter.

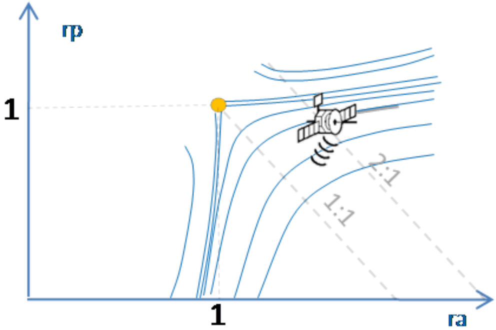




ra,rp,T

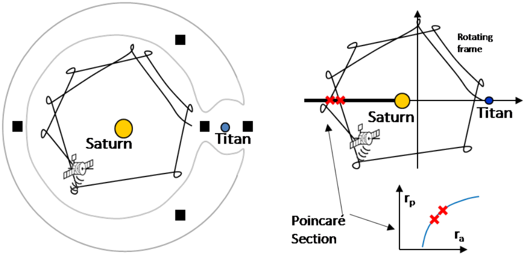
The s/c trajectory is not a keplerian orbit: the perturbation from the nearest and most massive moon changes the osculating pericenter and apocenter. Yet far from the moon, before and after a flyby, the Tisserand parameter remains approximatively constant. Why ? What is the Tisserand parameter?

$$T = \frac{2}{r_a + r_p} + 2\sqrt{\frac{2 r_a r_p}{r_a + r_p}}$$



T-P graph and the CR3BP

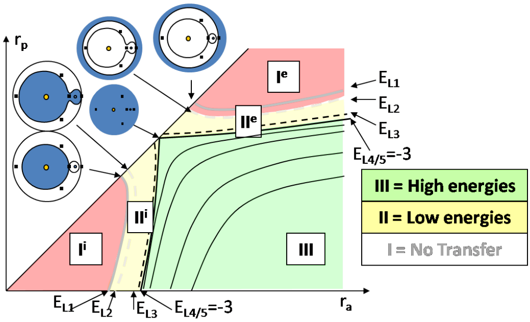
In the circular restricted three-body problem (CR3BP) model, $T \cong J = -E$ when the third body is far from the minor body. If we put a Poincare' section on the negative x axis of the rot. frame, the osculating ra, rp at the crossing will stay on the same Tisserand level set. T-P (Tisserand-Poincare') graph



T-P graph and the CR3BP

We can find Energy regions in the T-P graph. In particular, High Energies and Low Energies.

High Energies →High $\Delta V_{capture}$; Low Energies→Low $\Delta V_{capture}$

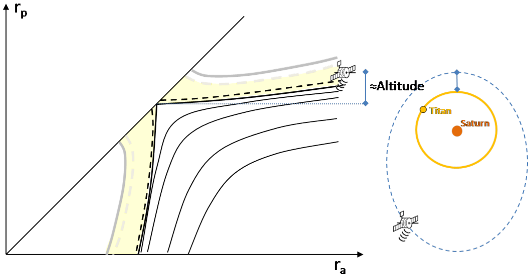


Paradox of the Low Energy Transfers

$\Delta V_{esc/capt}$ depends *mostly* on J = -E
Flybys at the target moon do not change J = -E

→ Flybys at the target moon (with no ΔV_{DSM}) cannot decrease mission costs

In the Low Energy domain, at high *ra* (after Saturn orbit insertion), $rp > 1$. (The closest approach at Titan @ tens of thousands kilometers). PARADOX solution: (high-altitude) flybys brings the spacecraft closer to the Moon, leading to a low-altitude, Low-Energy orbit insertion.

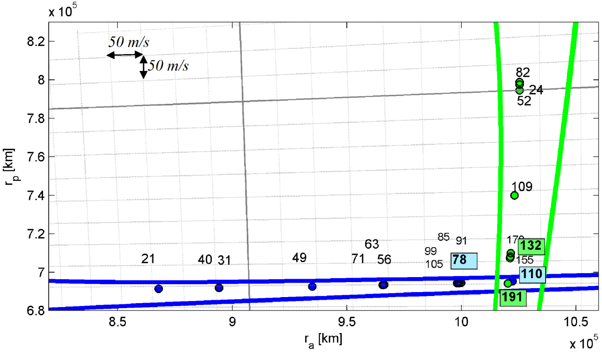


Low Energy Transfers

- Initial altitude too high $\rightarrow$ quasiballistic transfers require several high-altitude flybys to reach the final orbit (Smart1, Multimoon Orbiter, Keplerian Map) $\rightarrow$long ToF.
- Low orbit insertion cost $\rightarrow$ low ΔV_{TOT} (even ballistic transfers to/from Halo orbits).
- ToF can be reduced introducing ΔV_{DSM} to jump between "good" resonances (a 6:5 better then a 17:15). Work in Progress.

Ganymede-Europa

Example: From L1 - Halo orbit around Ganymede, to a L2 - Halo orbit around Europa.



$\Delta V_{tot} = \Delta V_{DSM} \approx 50$ m/s, 10 months (or 8 months and 100 m/s).
Hohmann transfer $>$ 2 km/s!

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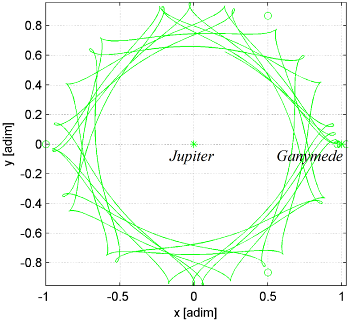

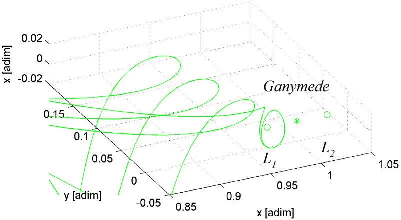

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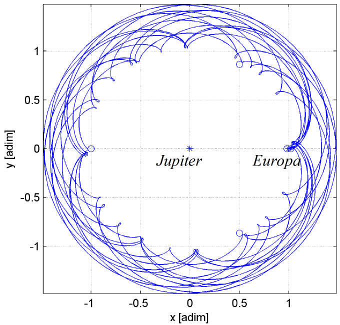

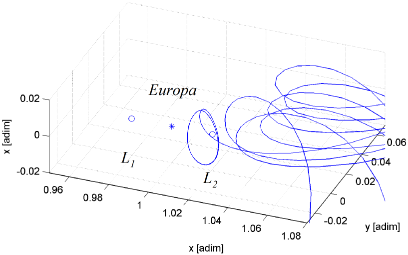

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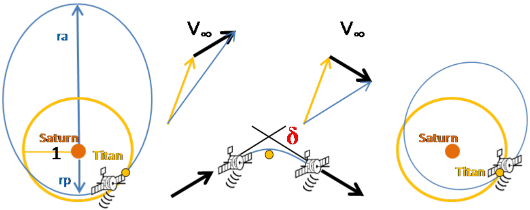
T-P graph and the patched 2BP (High Energy)

- Low-energy transfers can provide large ΔV savings for the orbit insertion.
- Other part of the missions can have flybys at the moon without orbit insertion (Cassini, Galileo).
- Then it is more efficient to navigate the spacecraft in the High-Energy regime, where low-altitude flybys provide a larger controllability and shorter ToF with no additionalΔV.
- Design is also simpler because in this domain we can use *linked conics* , and the solutions to the 2 Body Problem (2BP).
- The special case: Enceladus Orbiter. Very small moons: Rhea, next largest moon, has 2% of Titan's mass. Enceladus radius is only 250 km, $GM = 7$ and its orbit is at 4 Saturn Radii.

T-P graph and the patched 2BP (High Energy)



In the linked conic model, trajectories are made of conics linked by flybys or maneuvers. Flybys only occurr if $rp < 1, ra > 1$, and change the relative velocity v_∞ by

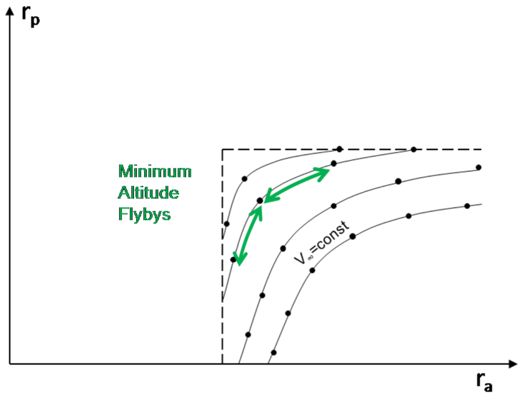
$$\delta = \arcsin\left(\frac{\mu_M}{\mu_M + v_\infty^2(r_M + h)}\right)$$

Before and after a flyby: $|v_\infty| = const$. In fact it can be proved that:

$$T = 3 - v_\infty^2$$

T-P graph and the patched 2BP (High Energy)

The *Tisserand graph* is a graphical method used in orbital mechanics to study flyby trajectories in the linked conic model. Here we introduce a $ra - rp$ representation.



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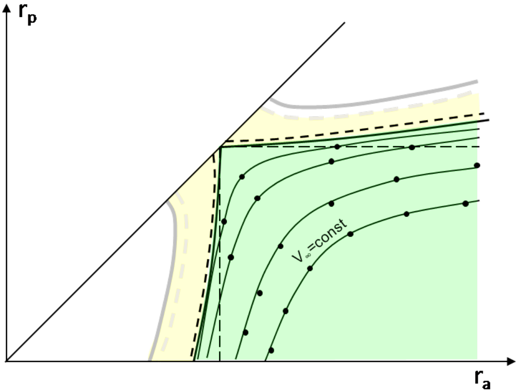
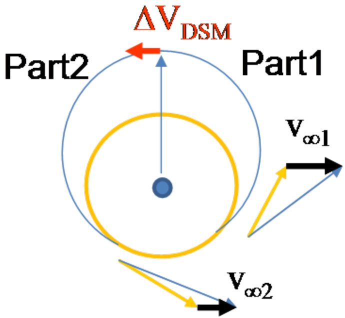


The Tisserand graph is the restriction of the T-P graph to the $ra > 1, rp < 1$ (High Energy) domain!

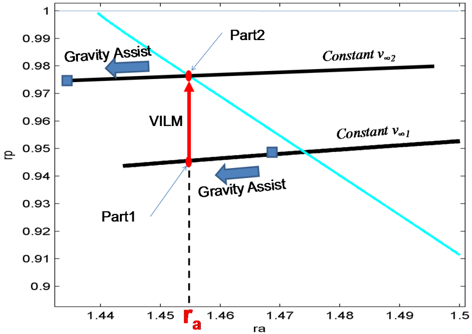
High Energy Transfers

- Reducing the ToF for the Enceladus Orbiter: leveraging the Energies with flybys and ΔV_{DSM} to jump between good resonances.
- Representation on the T-P (Tisserand) graph: ΔV_{DSM} at *ra* (*rp*) are vertical *(horizontal)* shift.
- Solving the phasing using Kepler's equation yields to $f(v_{\infty 1}, v_{\infty 2}, ra) = 0$
- Parameters: spacecraft and moon revolutions, the revolution of the maneuver, the departure/arrival configuration (In-Out)



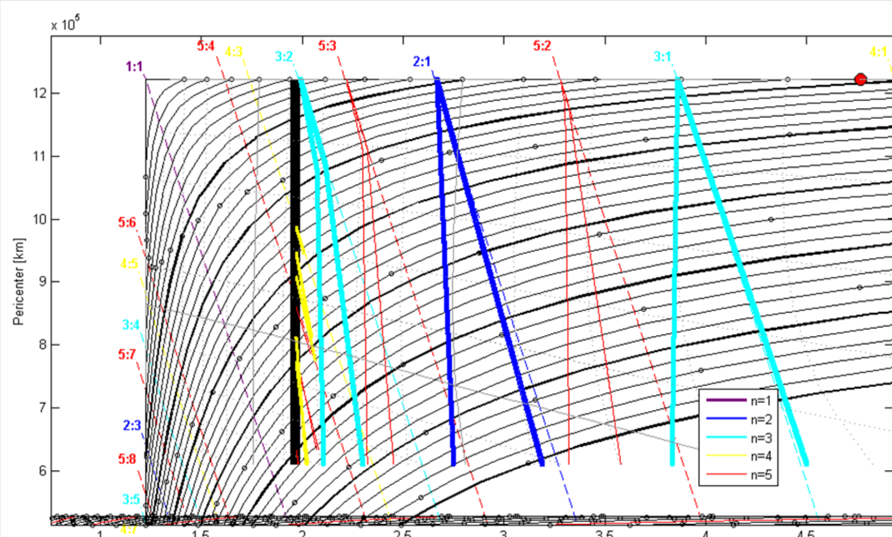
High Energy Transfers

- Starting with a given $v_{\infty 1}$, the solution space is a 1-dim manifold.
- *Actually, $2m + 2m$ 1-dim manifolds for each $n : m$ resonance*
- Solution manifold on the T-P graph; Linear approximation is accurate enough
- Method to compute linear solutions



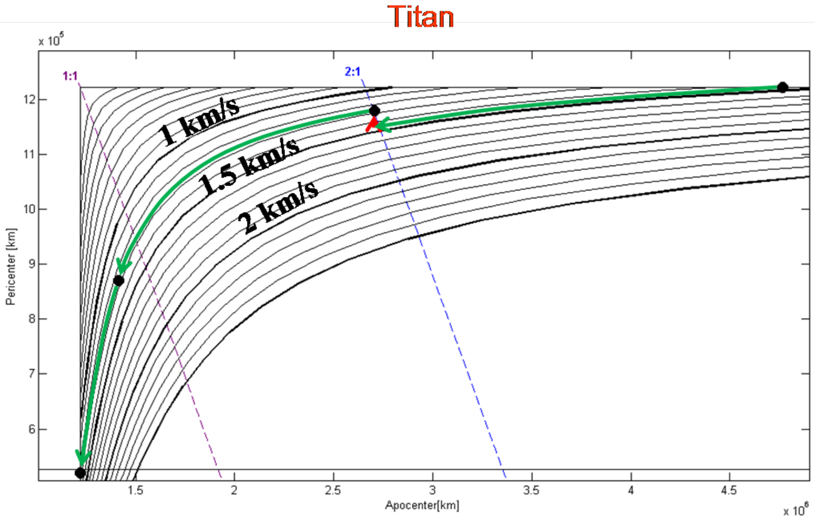
High Energy Transfers

Graphical method shows piecewise linear solutions which are the Pareto-optima of the linear approximations.



Titan-Enceladus

Staring from the first Titan's flyby to Enceladus Orbit Insertion



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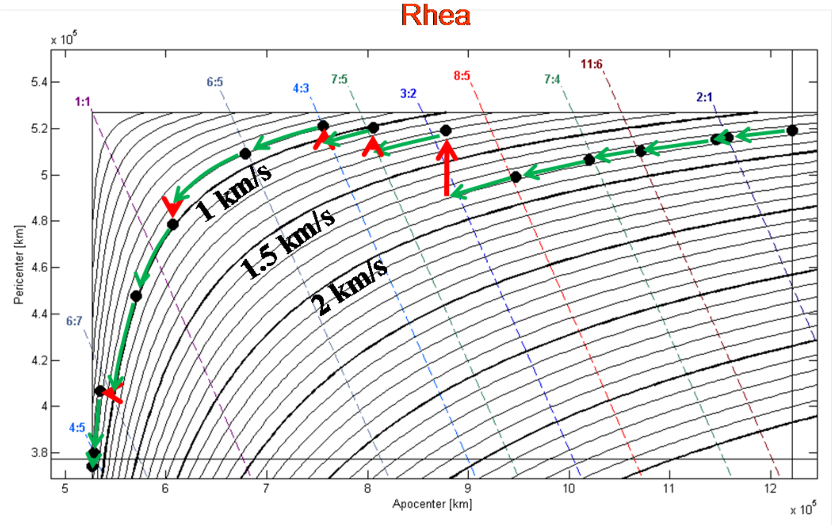

Titan-Enceladus

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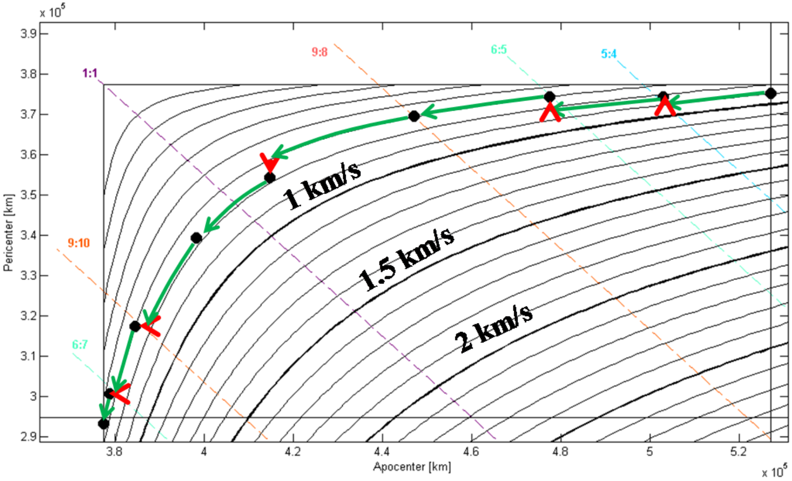
Dione



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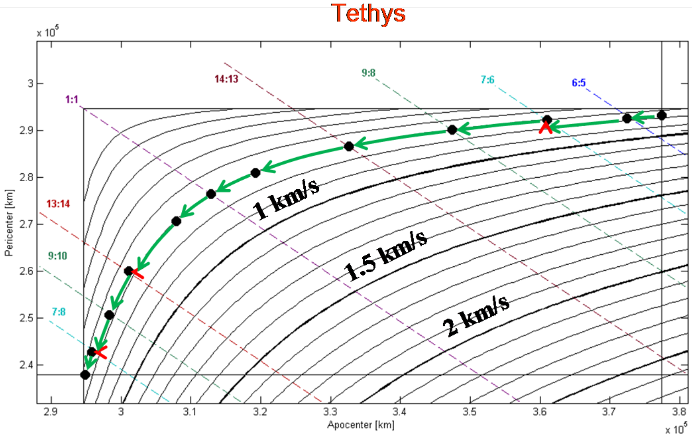

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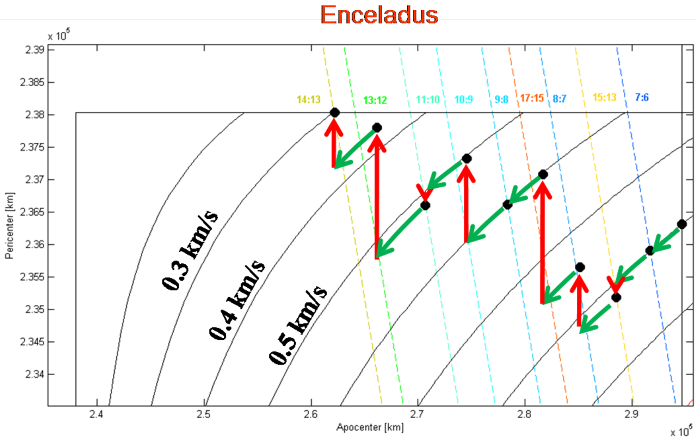

Titan-Enceladus

An Enceladus orbiter mission (alone or jointly with the Titan balloon mission) was considered unfeasible because the transfer from the first Titan's flyby would require 3.5 km/s or > 4 years. We show that with 47 flybys and 0.7 km/s , (including EOI), we arrive at Enceladus in $<$2 years!

Conclusions

- The T-P graph gives insight and a smooth transition between High-energy and a Low-Energy domain.
- Trajectory in the low energy domain have low ΔV, but high ToF because they start at high *altitudes*
- It is possible to transfer a spacecraft from a closed orbit near Europa and Ganymede at almost no ΔV, in eight months. Consequences for the EJSM?
- Trajectories in the high energy domain have high ΔV, but lower ToF. They can be used efficiently in the phases that do not end with an orbit insertion. They *must* be used for small mass moons.
- Leveraging techniques allow to shorter the transfer time- an Enceladus orbiter is now a feasible option. Consequences for TSSM?