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 $\Delta V_{\text{capture}}$ and or $\Delta V_{\text{escape}}$ 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 $\Delta V_{DSM}$
- 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
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.
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?

\[
T = \frac{2}{r_a + r_p} + 2\sqrt{\frac{2r_a r_p}{(r_a + r_p)^2}}
\]
In the circular restricted three-body problem (CR3BP) model, \( T \approx J = -E \) when the third body is far from the minor body. If we put a Poincaré section on the negative x axis of the rot. frame, the osculating \( r_a, r_p \) at the crossing will stay on the same Tisserand level set. T-P (Tisserand-Poincaré) 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 $\rightarrow$ High $\Delta V_{\text{capture}}$; Low Energies $\rightarrow$ Low $\Delta V_{\text{capture}}$
Paradox of the Low Energy Transfers

ΔV_{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 $\Delta V_{TOT}$ (even ballistic transfers to/from Halo orbits).
- ToF can be reduced introducing $\Delta V_{DSM}$ to jump between “good” resonances (a 6:5 better than a 17:15). Work in Progress.
Ganymede-Europa

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

$$\Delta V_{tot} = \Delta V_{DSM} \approx 50 \text{ m/s}, \text{ 10 months (or 8 months and 100 m/s).}$$

Hohmann transfer $> 2 \text{ km/s!}$
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Low-energy transfers can provide large $\Delta V$ 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 additional $\Delta V$.

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

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

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

$$T = 3 - v_\infty^2$$
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 $\Delta V_{DSM}$ to jump between good resonances.
- Representation on the T-P (Tisserand) graph: $\Delta V_{DSM}$ 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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Tethys

- 1 km/s
- 1.5 km/s
- 2 km/s
Titan-Enceladus

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

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 $\Delta V$, 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 $\Delta V$, in eight months.

Consequences for the EJSM?

▶ Trajectories in the high energy domain have high $\Delta V$, 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?