Extended Tisserand graph and multiple lunar swing-by design with Sun perturbation

Daniel García Yárnoz, Chit Hong Yam, Stefano Campagnola, Yasuhiro Kawakatsu

6th ICATT. Darmstadt, Germany
Outline

• Intro
• Tisserand-Poincaré graph and extension
• Lunar transfer database
• Application examples
  – EQUULEUS
  – DESTINY
• Conclusions

http://destiny.isas.jaxa.jp/
Background and rationale

• New trends in small missions:
  – Small sats / CubeSats beyond LEO, beyond cislunar space?

• Launch / escape strategies
  – Piggy-back / secondary payloads
  – Spiralling from LEO
  – Limited choice of date and target orbits conditions

• **Moon: single, massive, close to ecliptic, high potential**
  – Pump up/down
  – Phasing
  – Transfers

Earth & Moon from PROCYON 😞
Tisserand-Poincare graph

\[ T_M = \frac{2a_M}{r_a + r_p} + 2 \sqrt{\frac{2r_ar_p}{(r_a + r_p)a_M}} = 3 - v_\infty^2 \approx J \]

(Campagnola & Russell 2009a,b)
Extension with Sun perturbation

- **Analytical approximation (continuous)**
  \[ \Delta a \approx 0 \rightarrow \text{Lines of slope } -1 \]
  \[ \Delta e = 15 \frac{\pi}{2\mu} a^3 e \sqrt{1 - e^2} \sin 2(\omega_p - \theta) \rightarrow \text{quadrants} \]

- **Numerical propagation (dashed)**
  - Similar slope for low vel or low apocentres
  - Greater deviations achievable

- **Issues:** geometry dependant, multiple revs, deviations at \( r_a, v \)
Introducing: The “Mooning” Database

- **Planar CR3BP**
  - Neglect $e_E, e_M, i_M \rightarrow$ planar, pseudo epoch-free transfers
  - Transfers repeat every Moon period
- **Families generated with continuation method**
- **Database stored for quick and easy access**
- **Generation of first guesses for full-model optimisation**
  - “Substitute” Lambert arc calculations
  - Usual methods used in multiple gravity assists can be build on top (branch and pruning, genetic algorithms…)
- **Extend to multiple revolutions + additional families**

(Lantoine & McElrath 2014)
Synodic frame and transfer parameters

- 4 variables define a transfer

Database of transfers stored:

\[ SEM, v_\infty, \Psi v_\infty, t_F, SEM, v_\infty, \Psi v_\infty, r_{2\text{min}} \]

initial  final
“Mooning” Database Structure

- Four types: oo, oi, ii, io
  - Outgoing: $\cos(\Psi_{\infty}) > 0$
  - Incoming: $\cos(\Psi_{\infty}) < 0$
- Families branch off and reconnect (loops, helix)
- Example connections $oi$-$oo$: tangent to Moon orbit

\[ v_{\infty 0} = 1.2 \quad n_{SC} = 1 \quad oi \text{ (continuous)} \quad oo \text{ (dashed)} \]
\[ v_{\infty 0} = 0.8 \quad n_{SC} = 2 \]
Database sub-families examples: $n_M=7$

Planar Lyap / a fam / g fam

$n_{SC}=1$

$n_{SC}=2$

DPO / g’ fam

(Broucke 1968)
Applications

Two opposite problems:

- EQUULEUS: decrease velocity (+phasing)
- DESTINY: increase velocity (+phasing)
Application 1: EQUULEUS

- NASA offering 11-13 Secondary Payload opportunities on SLS EM-1 test launch
- JAXA proposed EQUULEUS to Moon L₂
- 6U CubeSat: study plasmasphere, navigation and control WSB
- Launch “moon-bound”: $v_\infty = 0.8 \text{ km/s}$
- Reduction of velocity to libration orbit

http://www.nasa.gov/content/exploration-mission-1-secondary-payloads
Application 1: EQUULEUS results

- One leg transfers: 25, one with $v_\infty < 0.45$
- Two leg transfers: 468, 24 with $v_\infty < 0.45$
- Branch and pruning can be recursively applied
- Initial guess generation
EQUULEUS selected transfers

- 1 leg oo
- 2 legs $v_\infty < 0.3$
  - $oi\ ii\ (n_{SC}=1)$
  - $oi\ ii\ (n_{SC}=1)$
  - $oo\ ii\ (low\ fb\ height:\ unfeasible?)$
- Tangent transfers: lower velocity
Application 2: DESTINY

• Interplanetary low-thrust traj. to asteroid Phaethon
• Escape from Earth-Moon system at least 1.5 km/s
  – Connect with spiral up with multiple flybys
  – Last swing-by velocity wrt Moon 2.08 km/s
  – SEM-v\textit{inf} feasible pairs (1-3 km/s)

• Database search
DESTINY: Final leg search

- Assume last swing-by velocity < 2 km/s
- SEM-\(v_{\infty}\) pairs intersection with families 0.3-0.6 km/s
- Check rotation \(v_{\infty}\) latitude feasible
- Multiple solutions
DESTINY: transfer options

- Vel: 0.3-0.6 km/s
- Diverse shapes
- Multiple options
- Recursively backwards…
Conclusions and future work

- Small missions will benefit of trajectory design with one/multiple lunar swing-bys
- T-P graph allows estimation of reachable regions
- Database of trajectories built $\rightarrow$ easy generation of initial guesses
- Application examples
- Ongoing / future work:
  - Extension of database
  - Regularized eq. of motion
  - Pseudo-arclength continuation
  - Include $\pi$ transfers (3D)
Kawakatsu Lab - 川勝研究室
http://kawakatsu.isas.jaxa.jp/
Daniel.Garcia@ac.jaxa.jp