Space Travel on a Shoestring: CubeSat Beyond LEO

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INTRODUCTION
EXPLORING SPACE: AN EXPENSIVE BUSINESS

- Standard exploration mission cost: £ 100-2000 M
- Cassini: $ 3.4 billion total program cost

New type of spacecraft:
- Small, light and simple
- COTS and spare parts
- No dedicated launch
- No dedicated ground infrastructure
- Ingenious low-cost solutions
Low Cost Access to Space

- Increasing interest in **nano** and **pico spacecraft**
- Low cost fabrication does not imply low cost transportation
- Launch as **auxiliary payload** on planned missions:
  - Standard injection orbit (**Geosynchronous Transfer Orbit, GTO**)  
  - No date selection

- New low-cost transfer solutions are required:

  **Can we go beyond LEO with CubeSats?**
TRANSFER TO THE MOON
Objectives and Assumptions

- Achieve spacecraft capture around the Moon with a transfer time of about 3 years
- S/C: hybrid propulsion system combining electric engine and solar sail
- Release in standard GTO
- Spacecraft parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Performance S/C</th>
<th>Low Cost S/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific impulse [s]</td>
<td>4500</td>
<td>4500</td>
</tr>
<tr>
<td>Thrust level [mN]</td>
<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td>Wet mass [kg]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Area to Mass Ratio [m²/kg]</td>
<td>2, 4, 6</td>
<td>0.5, 1</td>
</tr>
</tbody>
</table>
3U cube satellite:
- **service module** (communications, power, attitude control, data handling)
- **propulsion module** (electric engine)
- **deployable storage module** (storage of solar sail with integrated solar cells)
- Modified version of the **Circular Restricted 3-Body Problem (CR3BP)** including **solar radiation pressure acceleration**, $a_{SRP}$:

\[
\frac{d^2 r}{dt^2} + 2\omega \times \frac{dr}{dt} + \omega \times (\omega \times r) = a_{SRP} - \nabla V(r)
\]

\[
V = - \left( \frac{1 - \mu}{r_1} + \frac{\mu}{r_2} \right)
\]

- Control of the reflecting surface: **maximisation of the increase of energy** of the spacecraft

\[
\beta = \arctan \left( \frac{3 \tan \alpha}{4} + \sqrt{\frac{9 \tan^2 \alpha + 8}{4}} \right), \quad \alpha = \arccos (e_v \cdot S) - \frac{\pi}{2}
\]
CAMELOT: Computational Analytic Multi-fidElity Low-thrust Optimisation Toolbox

Analytical propagator based on analytical formulas for the perturbed Keplerian motion (first order expansion in the perturbing acceleration):

- low-thrust acceleration
- J2, J3, J4, J5 harmonic of the Earth’s gravity field
- atmospheric drag perturbation
- solar radiation pressure (eclipses)
- Sun and Moon perturbations
Transfer Design

1. Spacecraft into planar **halo orbit** at the Earth-Moon L1 libration point
2. Backward propagation **from halo to Earth** along stable manifold
   - *coasting phase* (**reflective surface** is pointed such that the energy of the spacecraft is increased from Earth to halo)
   - *manoeuvres* to connect the initial Earth orbit and the state obtained from coasting backwards from the halo
3. Forward propagation **from halo to the Moon**
   - *reflective surface* and maneuvers used to reduce energy for capture
**Initial Earth Orbit**

- **Release in GTO** for both high performance and low cost S/C
- Initial orbit:
  - High performance S/C: GTO
  - Low cost S/C: **continuous low-thrust propulsion** to increase perigee to GEO radius
- From GTO or GEO perigee orbit: **apogee and perigee raising manoeuvres** to hop onto a stable invariant manifold leading to L1

Low cost S/C continuous low-thrust propulsion:

- ToF = 54 days
- $\Delta V = 1.9 \text{ km/s}$
- $m_{\text{fuel}} = 0.17 \text{ kg}$
TRANSFER TO THE MOON: RESULTS
Different manifold lines on the manifold tubes are used to attempt connection between halo and Earth GTO

- $\Delta V$ costs:

<table>
<thead>
<tr>
<th>Transfer Time [years]</th>
<th>Area to Mass Ratio $[m^2/kg]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>0.5</td>
<td>1,244</td>
</tr>
<tr>
<td>1</td>
<td>1,105</td>
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<tr>
<td>1.5</td>
<td>1,034</td>
</tr>
<tr>
<td>2</td>
<td>984</td>
</tr>
<tr>
<td>1.5</td>
<td>913</td>
</tr>
<tr>
<td>3</td>
<td>936</td>
</tr>
</tbody>
</table>
- Different manifold lines on the manifold tubes are used to attempt connection between halo and enlarged GTO
- $\Delta V$ costs:

- Total cost: $\Delta V +$ cost for continuous low-thrust propulsion to reach enlarged GTO ($\Delta V = 1.9 \text{ km/s}$)
Low Cost Spacecraft Transfer

- 72 manoeuvres
- $\Delta V = (0.351 + 1.9) \text{ km/s} = 2.24 \text{ km/s}$
- Total transfer time: 701 days
- Coasting period where reflective sail is used: 1 year
- Cost for capture: 20 m/s
What are the best conditions near the L1 libration point for longer duration orbit about the Moon?

- **3-years propagation** from:
  \[ x = [X_{L1} \ y \ 0 \ \dot{x} \ 0 \ 0]^T \]
  for different values of \( y \) and \( \dot{x} \)

- **Orbit ‘stability’**:
  \[ X_{L1} < x < X_{L2} \]
  \[ \sqrt{x_{\text{Moon}}^2 + y_{\text{Moon}}^2} > R_{\text{Moon}} \]
Lunar Orbit Longevity

Event causing the orbit propagation to halt (left) and orbit lifetime in non-dimensional time unit (right):
TRAJECTORY DESIGN FOR OTHER CUBESAT MISSIONS
CubeSat Trajectory Design

Small satellites propulsion technology:

- cold gas
- simple electric engine (arcjet, resistojet)
- solar sail

Low-thrust trajectory design for CubeSat:

- CAMELOT (Computational Analytic Multi-fidElity Low-thrust Optimisation Toolbox)
- Quick assessment and optimisation of low-thrust orbital transfers
- Trajectory design exploiting natural dynamics for limited-resource spacecraft
CubeSat Trajectory Design

Small spacecraft orbital transfers:
- GTO-GEO transfer
- Orbit raising from LEO
- De-orbiting at end-of-life

Exploitation of natural dynamics:
- Variation of right ascension: J2
- Eccentricity variation: J3, J4, J5, SRP
CONCLUSIONS
Conclusions

- Transfer to the Moon through L1 halo orbit
- High area-to-mass ratio hybrid propulsion spacecraft (electric engine, solar sail)
- Control of the reflective surface to increase or decrease spacecraft energy
- Transfer to the Moon realised in less than 3 years

We can go beyond LEO with CubeSats.
Thank you for your attention.