Space Travel on a Shoestring: CubeSat Beyond LEO

Massimiliano Vasile, Willem van der Weg, Marilena Di Carlo

Department of Mechanical and Aerospace Engineering
University of Strathclyde, Glasgow

5th Interplanetary CubeSat Workshop, Oxford, 24-25 May 2016

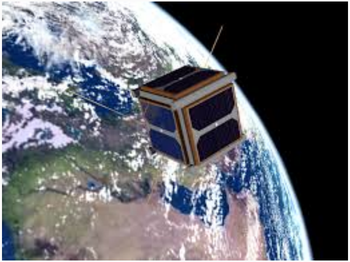
INTRODUCTION

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

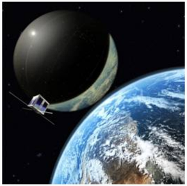


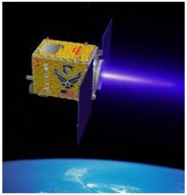
Low Cost Access to Space

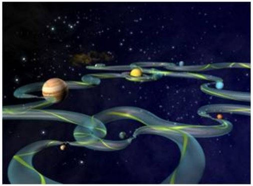
- Increasing interest in **nano** and **pico spacecraft**
- Low cost fabrication does not imply low cost transportation
- Launch as **auxiliary payload** on planned missions:
  - Standard injection orbit (**Geosynchronous Transfer Orbit, GTO**)
  - **No date selection**

- New low-cost transfer solutions are required:

Can we go beyond LEO with CubeSats?







TRANSFER TO THE MOON

Objectives and Assumptions

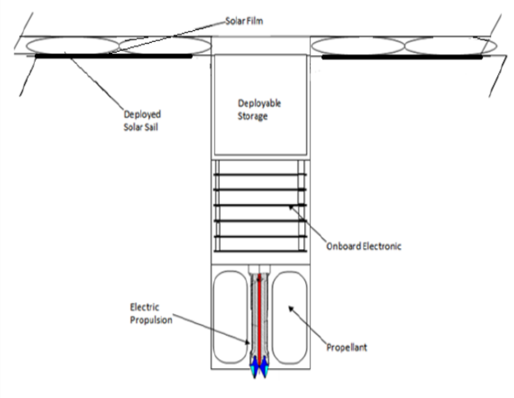
- Achieve spacecraft capture around the Moon with a **transfer time of about 3 years**
- S/C: hybrid propulsion system combining **electric engine** and **solar sail**
- Release in standard **GTO**
- Spacecraft parameters:

	High Performance S/C	Low Cost S/C
Specific impulse [s]	4500	4500
Thrust level [mN]	10	1.6
Wet mass [kg]	4	4
Area to Mass Ratio [m^2/kg]	2, 4, 6	0.5, 1

Conceptual Design

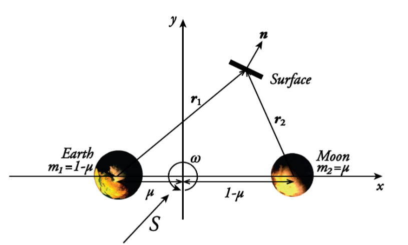
3U cube satellite:

- **service module** (communications, power, attitude control, data handling)
- **propulsion module** (electric engine)
- **deployable storage module** (storage of solar sail with integrated solar cells)



System Model

- Modified version of the **Circular Restricted 3-Body Problem (CR3BP)** including **solar radiation pressure acceleration**, $\mathbf{a}_{SRP}$:



$$\frac{d^2\mathbf{r}}{dt^2} + 2\boldsymbol{\omega} \times \frac{d\mathbf{r}}{dt} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) = \mathbf{a}_{SRP} - \nabla V(\mathbf{r})$$

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

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

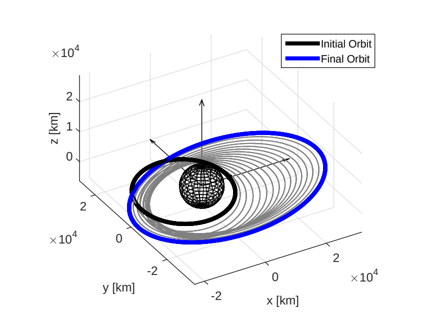
$$\beta = \arctan\left(\frac{3\tan\alpha}{4} + \frac{\sqrt{9\tan^2\alpha + 8}}{4}\right), \qquad \alpha = \arccos\left(\mathbf{e}_v \cdot \mathbf{S}\right) - \frac{\pi}{2}$$

Low-Thrust Model

CAMELOT: Computational Analytic Multi-fidElity Low-thrust Optimisation Toolbox

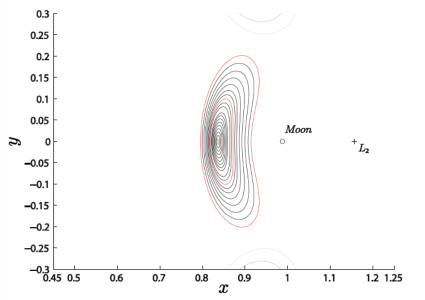
Analytical propagator based on analytical formulas for the perturbed Keplerian motion (first order expansion in the perturbing acceleration):

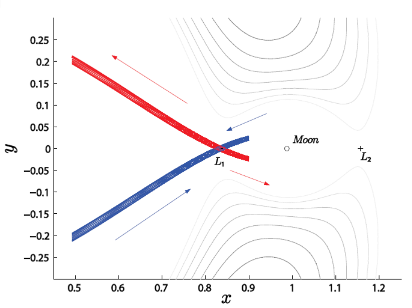
- **low-thrust acceleration**
- J2, J3, J4, J5 harmonic of the Earth's gravity field
- atmospheric drag perturbation
- solar radiation pressure (eclipses)
- Sun and Moon perturbations



Transfer Design

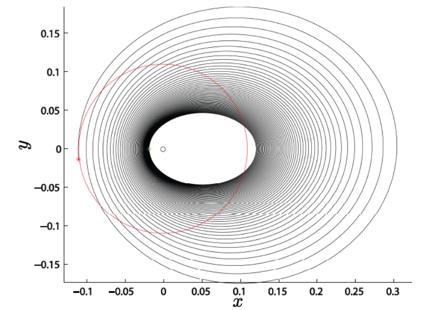
1. Spacecraft into planar **halo orbit** at the Earth-Moon L1 libration point
2. Backward propagation **from halo to Earth** along stable manifold
   - **coasting phase** (**reflective surface** is pointed such that the energy of the spacecraft is increased from Earth to halo)
   - **manoeuvres** to 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



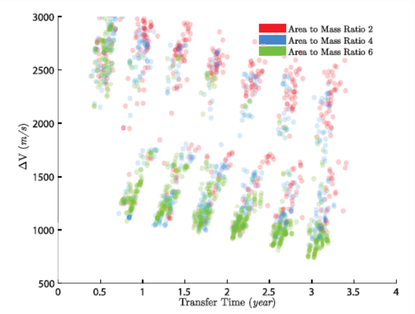
Low cost S/C continuous low-thrust propulsion:

- ToF = 54 days
- ΔV = 1.9 km/s
- m_{fuel} = 0.17 kg

TRANSFER TO THE MOON: RESULTS

High Performance Spacecraft

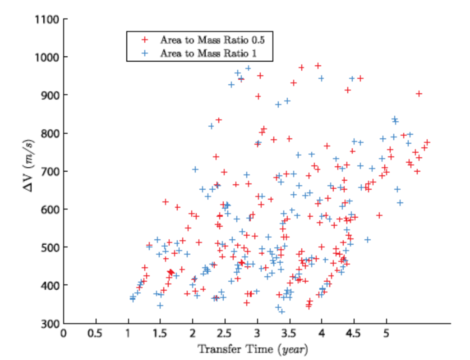
- Different manifold lines on the manifold tubes are used to attempt **connection between halo and Earth GTO**
- ΔV costs:



Transfer Time [years]	Area to Mass Ratio [m^2/kg] 2	4	6
0.5	1,244	1,111	1,081
1	1,105	1,046	1,072
1.5	1,034	997	985
2	984	960	916
1.5	913	883	812
3	936	854	747

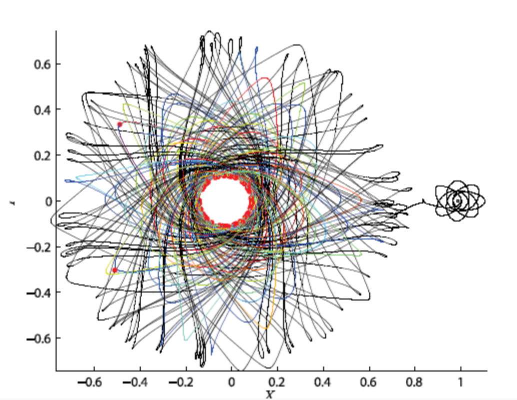
Low Cost Spacecraft

- Different manifold lines on the manifold tubes are used to attempt **connection between halo and enlarged GTO**
- ΔV costs:



- Total cost: ΔV + cost for continuous **low-thrust propulsion to reach enlarged GTO** (ΔV = 1.9 km/s)

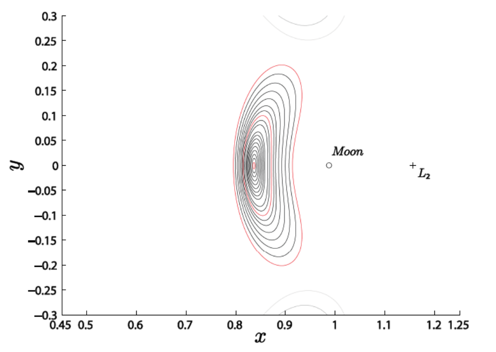
Low Cost Spacecraft Transfer



- 72 manoeuvres
- $\Delta V = (0.351 + 1.9)$ km/s = 2.24 km/s
- Total transfer time: 701 days
- Coasting period where reflective sail is used: 1 year
- Cost for capture: 20 m/s

Lunar Orbit Longevity

What are the best conditions near the L1 libration point for **longer duration orbit about the Moon**?



- **3-years propagation** from:

$$\mathbf{x} = [X_{L1} \quad y \quad 0 \quad \dot{x} \quad 0 \quad 0]^T$$

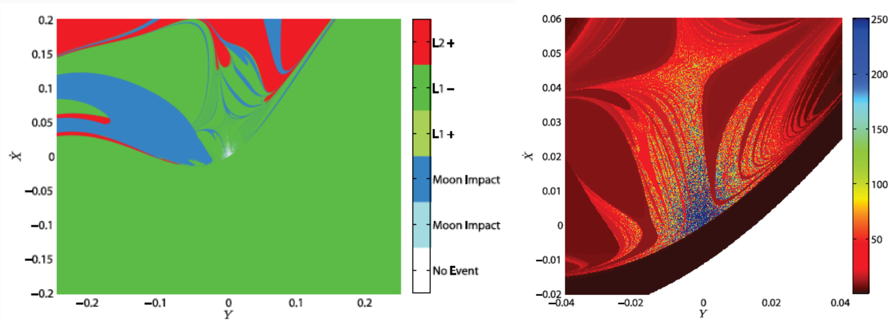
  for different values of y and $\dot{x}$
- **Orbit 'stability'**:

$$x_{L1} < x < x_{L2}$$

$$\sqrt{x_{Moon}^2 + y_{Moon}^2} > R_{Moon}$$

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**

Arcjet thrusters, IRS, Stuttgart.

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

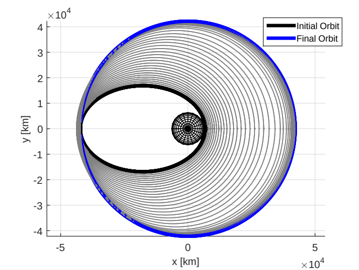
CubeSat Trajectory Design

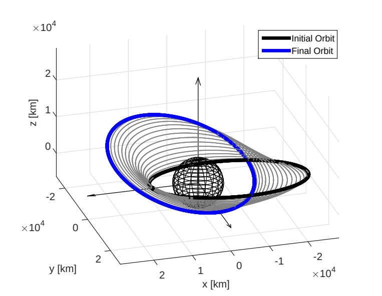
Small spacecraft orbital transfers:

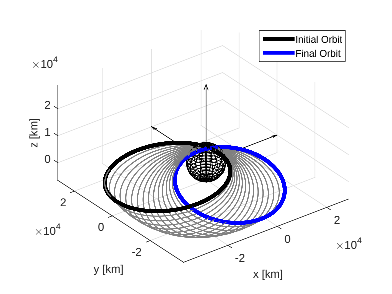
- GTO-GEO transfer
- Orbit raising from LEO
- De-orbiting at end-of-life

Exploitation of natural dynamics:

- Variation of right ascension: J2
- Eccentricity variation: J3, J4, J5, SRP





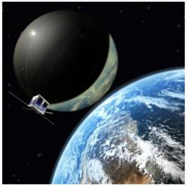


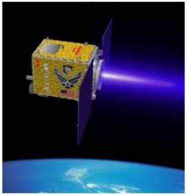
CONCLUSIONS

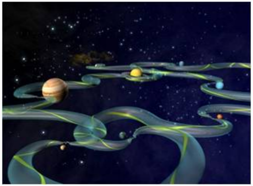
Conclusions

- 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.