Low Thrust Trajectory Design and Optimization:

Case Study Of A Lunar CubeSat Mission

Dr. Ravishankar Mathur

6th International Conference on Astrodynamics Tools and Techniques (ICATT)
14-17 March 2016

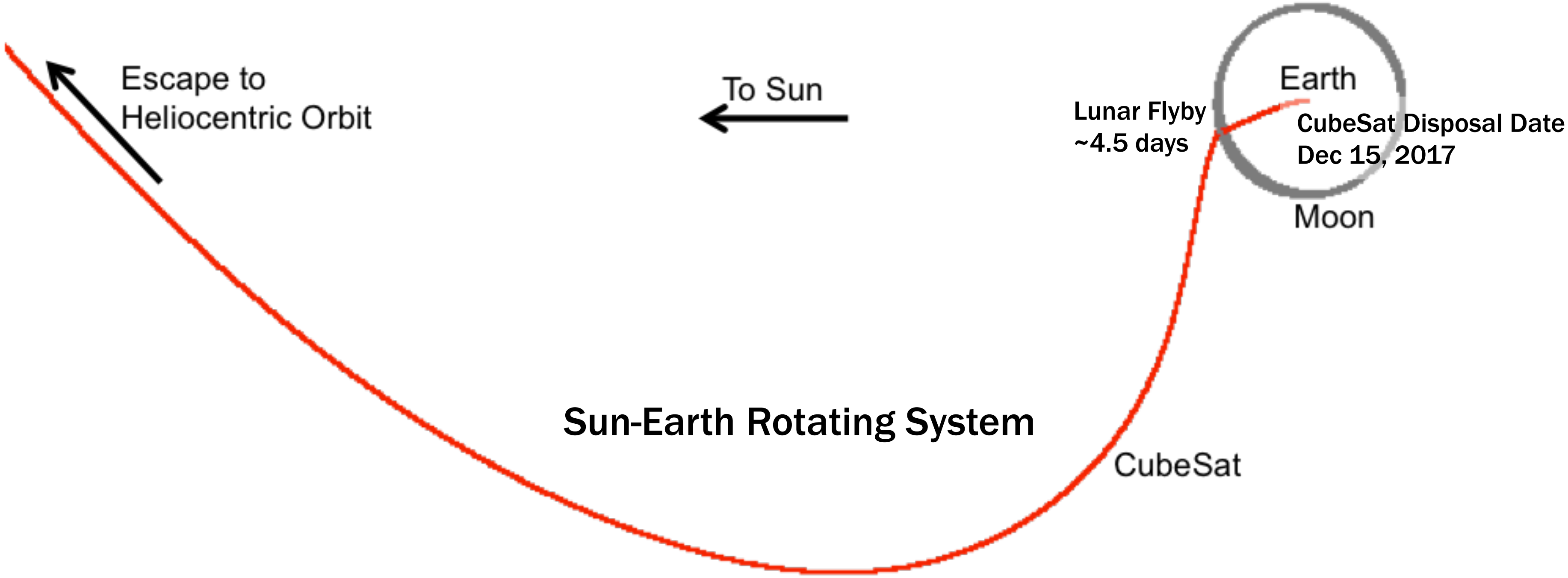
Emergent Space Technologies, Inc.
6411 Ivy Lane, Suite 303 • Greenbelt MD, 20770 • - 301 345-1535 • FAX - 301 345-1553
http://www.emergentspace.com

Introduction: CubeQuest Challenge

- A NASA Centennial Challenge, initiated Nov 2014
- Winning 6U CubeSats are offered a launch on the 2018 Exploration Mission 1 (EM-1) as secondary payload
- CubeSat disposal trajectory performs lunar flyby, gains enough energy to escape Earth-Moon system
- 2 possible design goals, associated prize purse
  - Lunar Derby: max transmitted data from lunar orbit
  - Deep-Space Derby: max transmitted data from 4M km
- EM-1 safety requirements dictate no volatile propulsion for CubeSats: low-thrust propulsion used

CubeSat Disposal Trajectory

- CubeSat disposed onto lunar-flyby trajectory
- Escapes Earth-Moon system → heliocentric trajectory
- Use low thrust to enter into lunar orbit



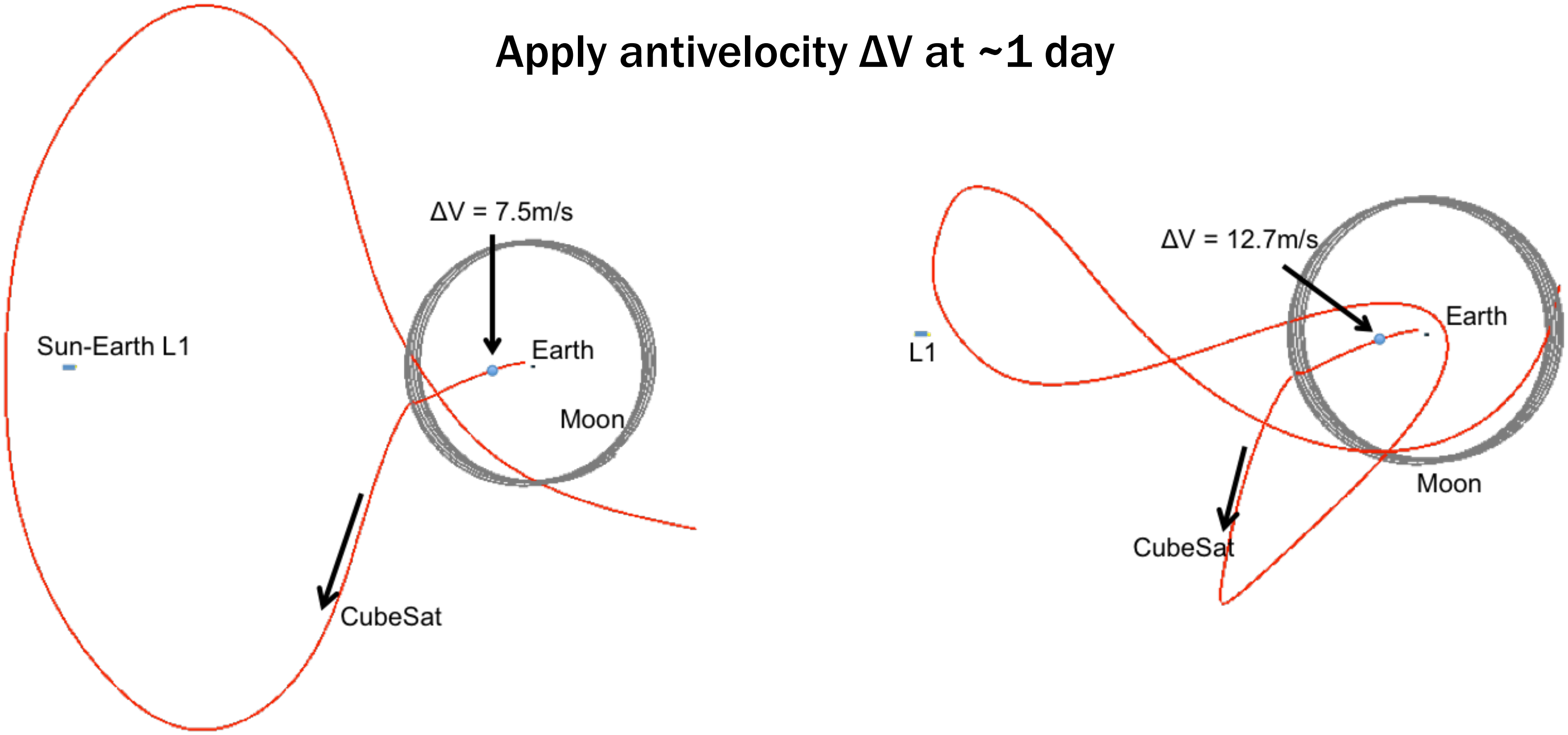
Lunar Flyby ~4.5 days

CubeSat Disposal Date Dec 15, 2017

Sun-Earth Rotating System

Earth-Moon-Sun System

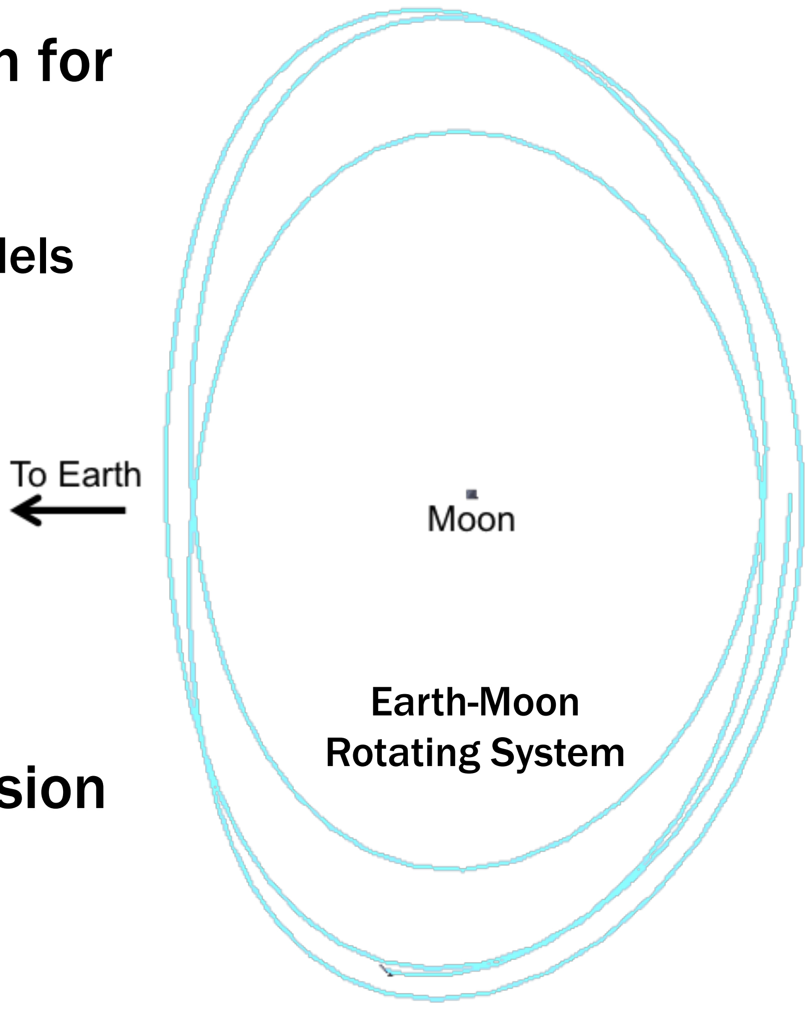
Apply antivelocity ΔV at ~1 day



- Reduce CubeSat’s speed so Moon can “move out of the way”
- Other solution families exist, e.g. with multiple Earth flybys
- Trade-offs between various families of solutions: ΔV, Earth flyby (Van Allen Belts, satellite constellations), tolerance to maneuver failures

Lunar Arrival: Distant Retrograde Orbit

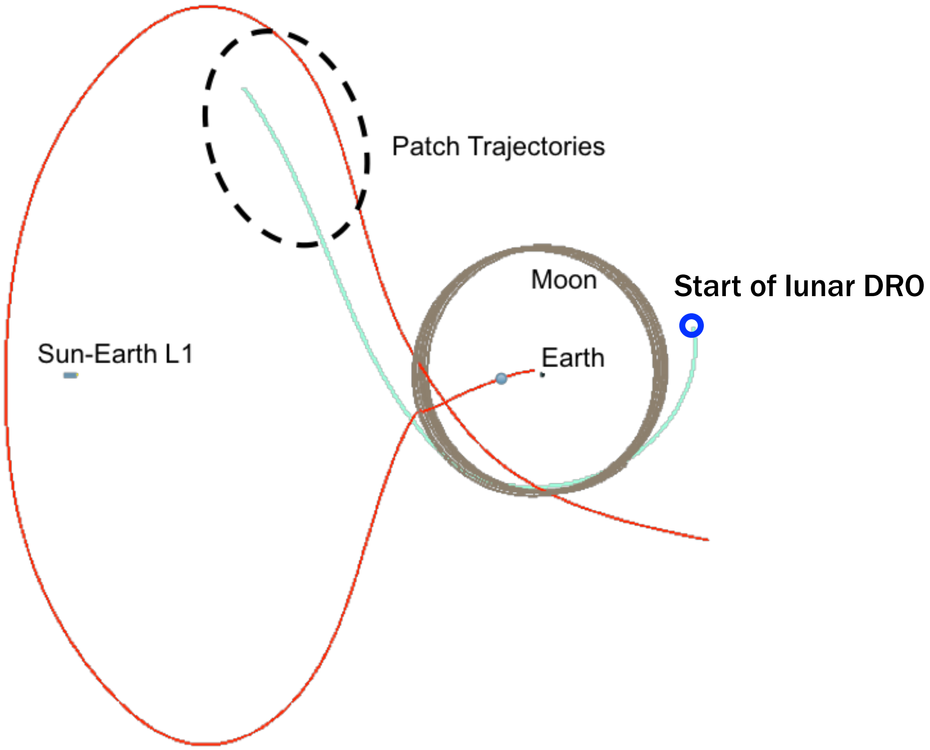
- Shown to remain around Moon for
  - large orbits (> 100,000 km)
  - long times (> 2 months)
  - with Sun, SRP, and ephemeris models



- Useful for loiter before lunar spiral-down maneuvers
- Stay near Moon even if propulsion system fails or underperforms during spiral-down

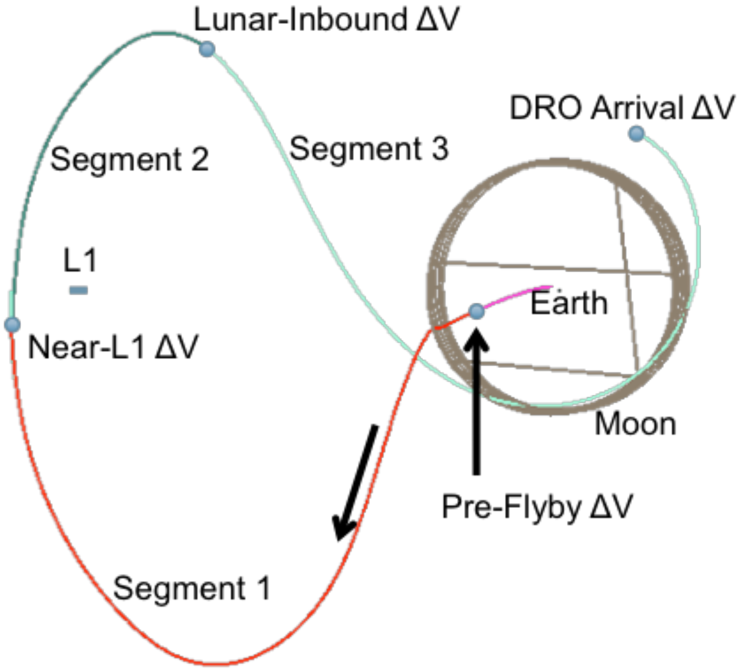
Connecting Trajectories: Impulsive ΔV

- Relatively small impulse from DRO, back-prop
  - ❑ Stable manifold of DRO, arrives from Sun-Earth L1 region
- Good candidate for low-energy transfer to Moon



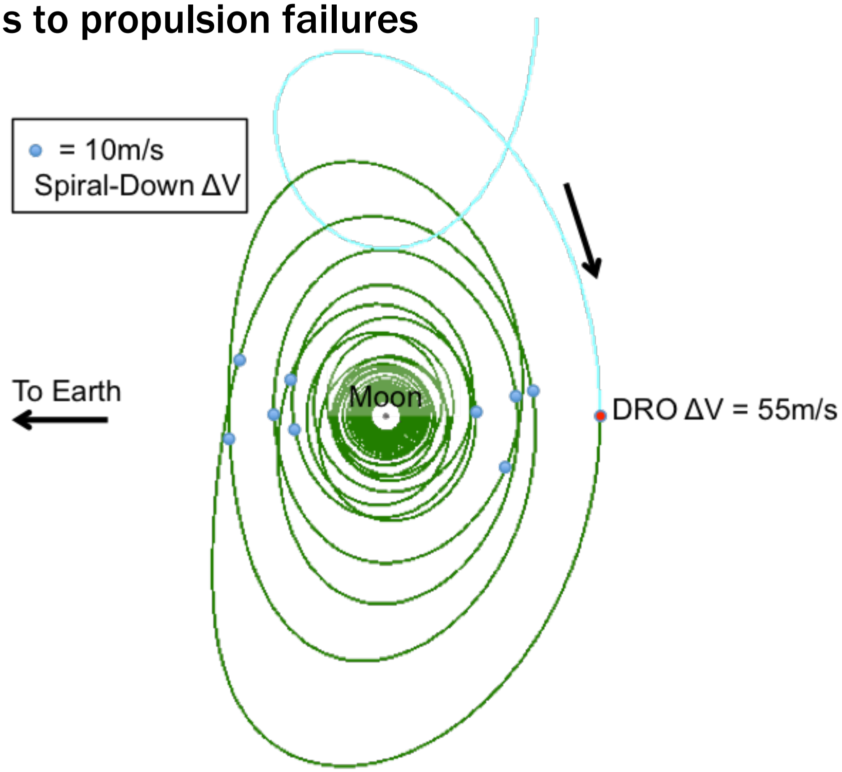
Connecting Trajectories: Impulsive ΔV

- Insert trajectory arc to connect Earth-departure and lunar-arrival trajectories
- Optimize ΔV components to match patch-point position
- Lunar-inbound ΔV computed to match lunar-arrival velocity
- DRO-arrival ΔV fixed to match DRO insertion requirements



Spiral-Down: Impulsive ΔV

- Target orbit: radius < 10,000 km , altitude > 200 km
- Strategy: coast to periapse → ΔV = 10 m/s antivelocity
- Total Cost = 500 m/s … expensive, but very safe
    - Intermediate (post-impulse) orbits still stay around Moon for weeks, allowing time for corrections to propulsion failures

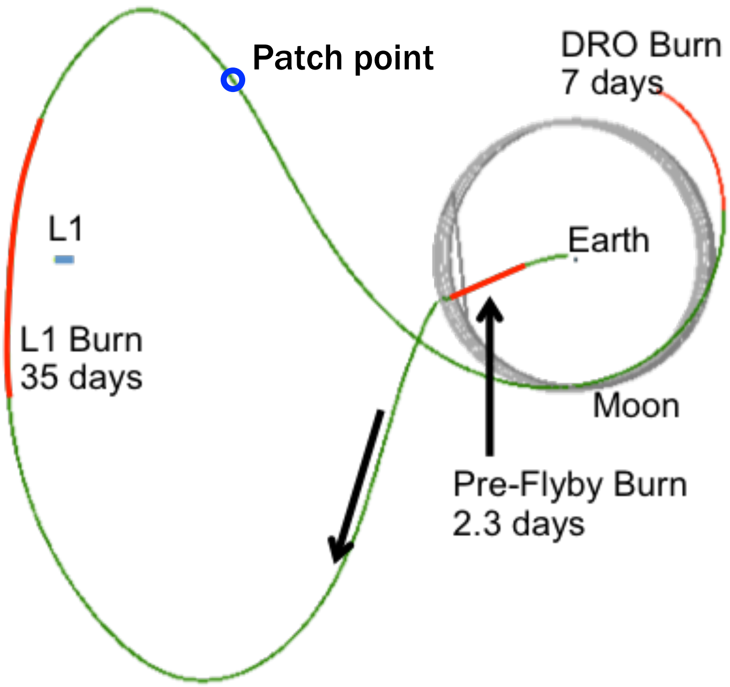


Impulsive to Finite Burn Conversion

- GMAT Spacecraft parameters
  - Mass m = 14 kg
  - Thrust T = 1 mN –> 1/10th weight of notebook paper sheet!
  - SRP Area A = 1 m^2
  - SRP $C_r = 1.7$
- GMAT Simulation parameters
  - Sun, Earth, Moon point-mass ephemeris models
  - SRP included
  - Near Earth: EGM-96 100x100
  - Near Moon: LP-165 100x100
- ΔV → Finite Burn with force-momentum relation
  - $\Delta t = m\ |\Delta V|\ /\ T$ (centered about $t_{nominal}$)
  - $\mathbf{u} = \Delta V\ /\ |\Delta V|$

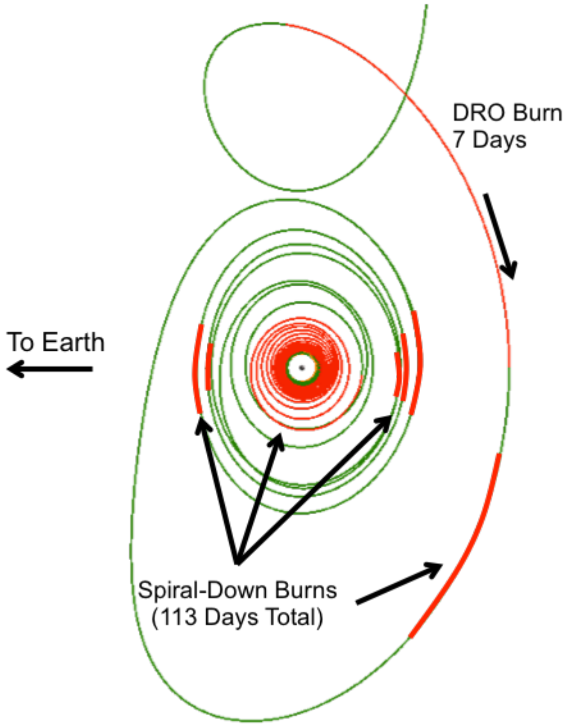
Impulsive to Finite-Burn Conversion

- Optimize using GMAT with VF13AD plug-in
- 7 variables: Δt_1 α_1 β_1 t_2 Δt_2 α_2 β_2 (burn times & directions)
- 6 constraints: match position & velocity at patch point
- Cost: $\Delta t_1 + \Delta t_2$ → Many local minima!



Finite-Burn Spiral Down

- Thrust to maintain vertical x-axis crossing
  - Utilize symmetry property of CR3BP
- Safe orbit that stays near Moon if thrusters fail



Finite-Burn Trajectory Cost

Burn Name	Duration [days]	$\lvert\Delta V\rvert$ [m/s]
Pre-Flyby	2.3	14
L1	35.0	216
DRO	7.0	43
Spiral-Down (combined)	113.4	700
Total Burn Duration	**157.7**	**973 m/s**
Total Mission Duration	**322.5 (<11mo)**	**–**

- CubeSat Disposal: Dec 15, 2017
- Lunar Orbit Arrival: Nov 3, 2018
- 6-week buffer before end of CubeQuest competition
  - ❑ Allows time for on-orbit CubeQuest data transfer challenge → Most amount of data transferred on-orbit

Conclusions & Future Work

- A feasible, fault-tolerant, partially-optimized Earth-Moon transfer trajectory was presented
- The first burn is critical: failed burn → no lunar orbit
  - ☐ Alternately, could aim for Deep-Space Derby at 4M km
- Fault-tolerance achieved in exchange for time
  - ☐ Split up long near-L1 burn to allow for intermediate tracking
  - ☐ Use DRO at lunar arrival before spiral-down burns
- Free lunar-arrival parameters to improve ΔV & time
  - ☐ DRO size, arrival burn duration and direction
  - ☐ Possible because target lunar orbit is not prescribed
- Compute comprehensive ΔV budget
  - ☐ Thrust, pointing, SRP errors
  - ☐ Launch window analysis

Thank you for your attention!