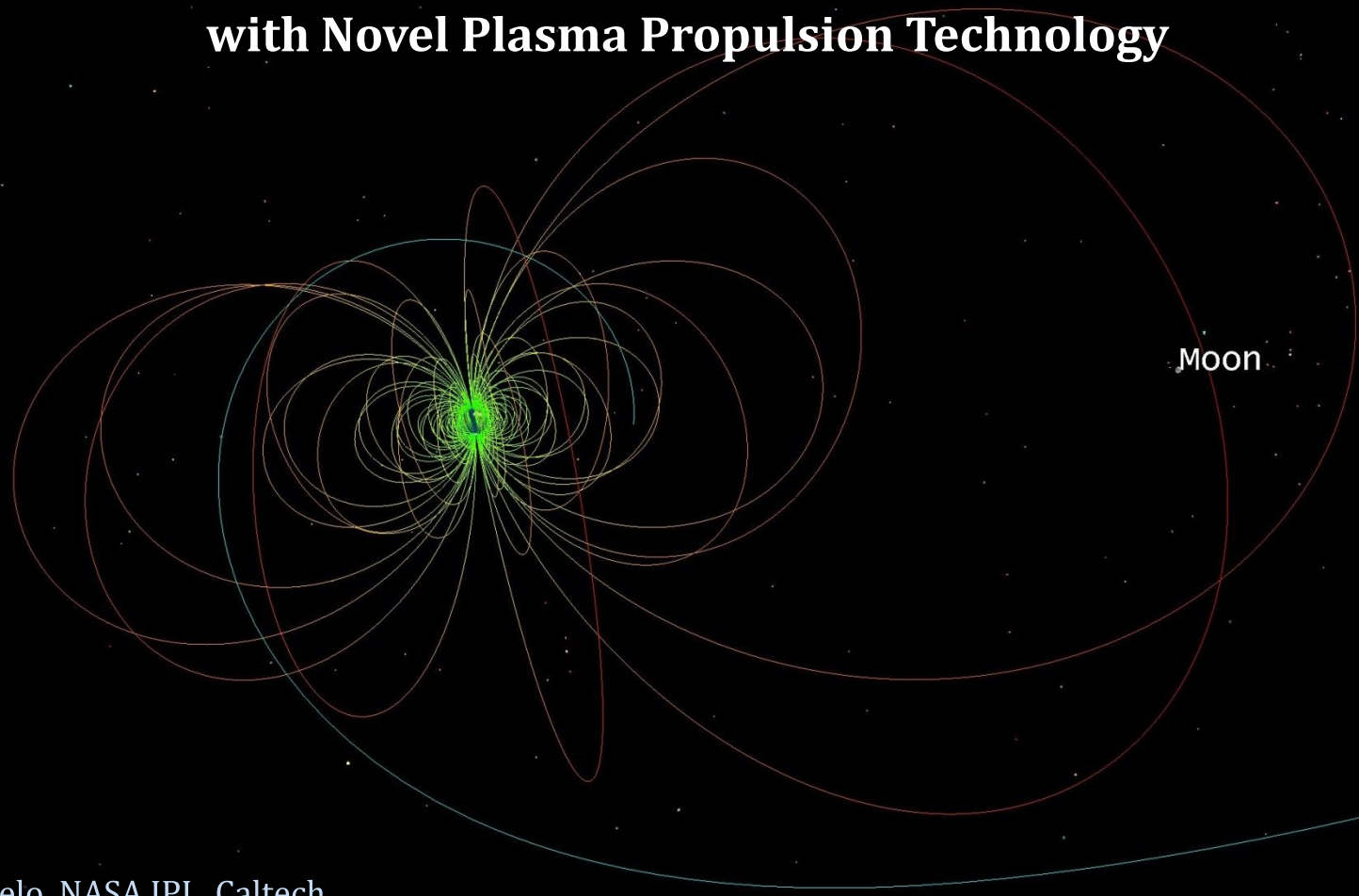
BravoSat:

Optimizing the Delta-V Capability of a CubeSat Mission with Novel Plasma Propulsion Technology



Sara Spangelo, NASA JPL, Caltech
Benjamin Longmier, University of Michigan
Interplanetary Small Satellite Conference, June 2013

How Far Can CubeSats Go (alone)?

- CubeSats have been designed for LEO
  - Is this a fundamental limitation of size/ mass/ cost? ***No!***
- Introducing BravoSat: CubeSat designed to escape Earth Orbit
- Enabling factors:
  1. Miniaturized thruster technology with high ΔV capabilities
  2. Heritage/ experience getting/ operating in LEO
  3. Intelligent use of mass/ volume/ energy!

Photo Credit: RAX and NSF Websites

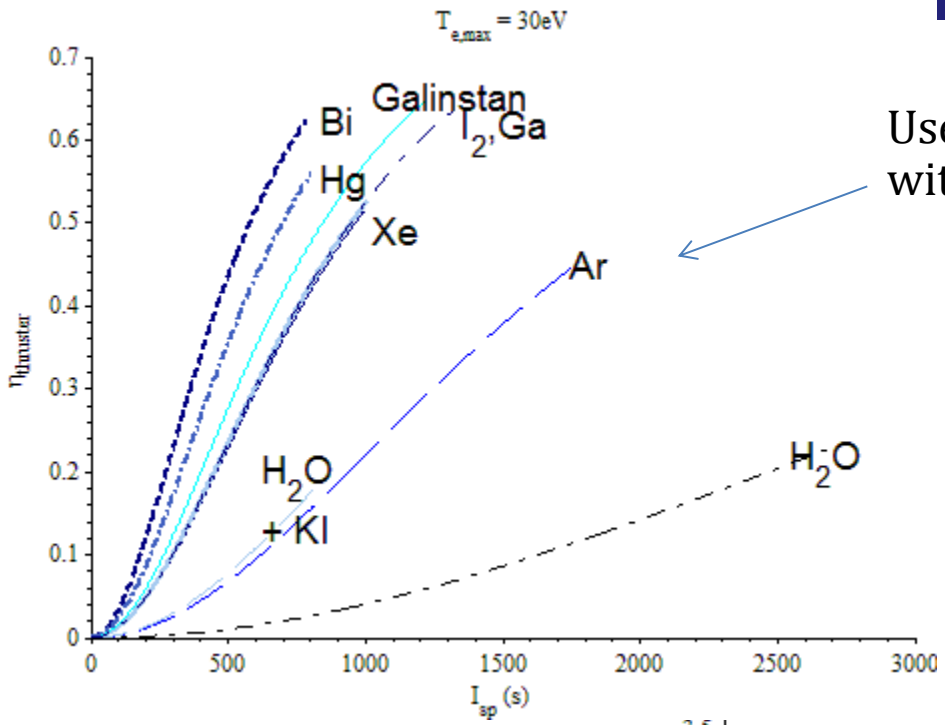
CAT: Large ΔV Engine Capability

- CAT = CubeSat Ambipolar Thruster
- High-density plasma source to study plasma expansion in free space
- Used to develop high ΔV propulsion systems for small spacecraft

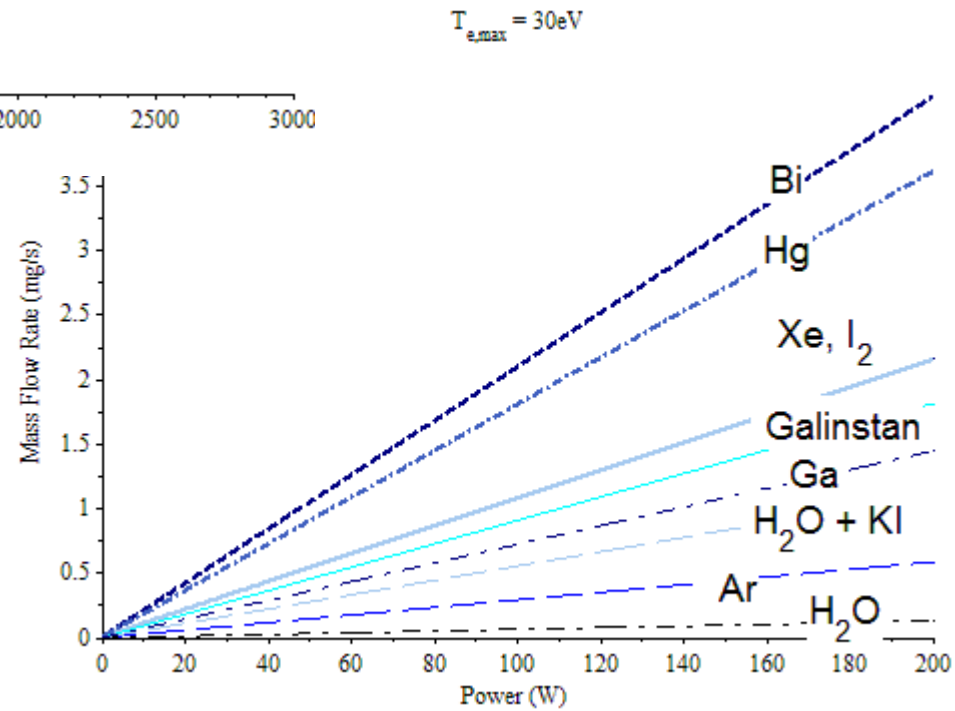
Design of a 5 kg 3U CubeSat with CAT engine performing initial testing in Low Earth Orbit.

Photo Credit: Prof. Longmier's Lab?

CAT: Large ΔV Engine Specifications



Used to select operating point with highest efficiency



Linear relationship:

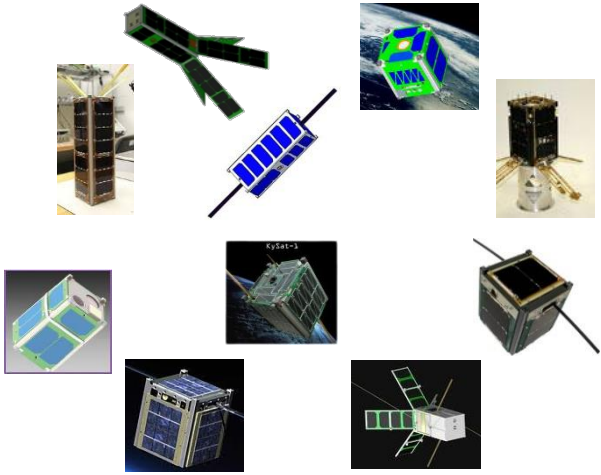
Mass flow ∝ power

Is the Sky the Limit? Dream vs. Reality

Goal (dream)

- Maximize altitude increase on a 3U CubSat- Can you escape Earth?

  [Not exactly same as increasing Δ V]

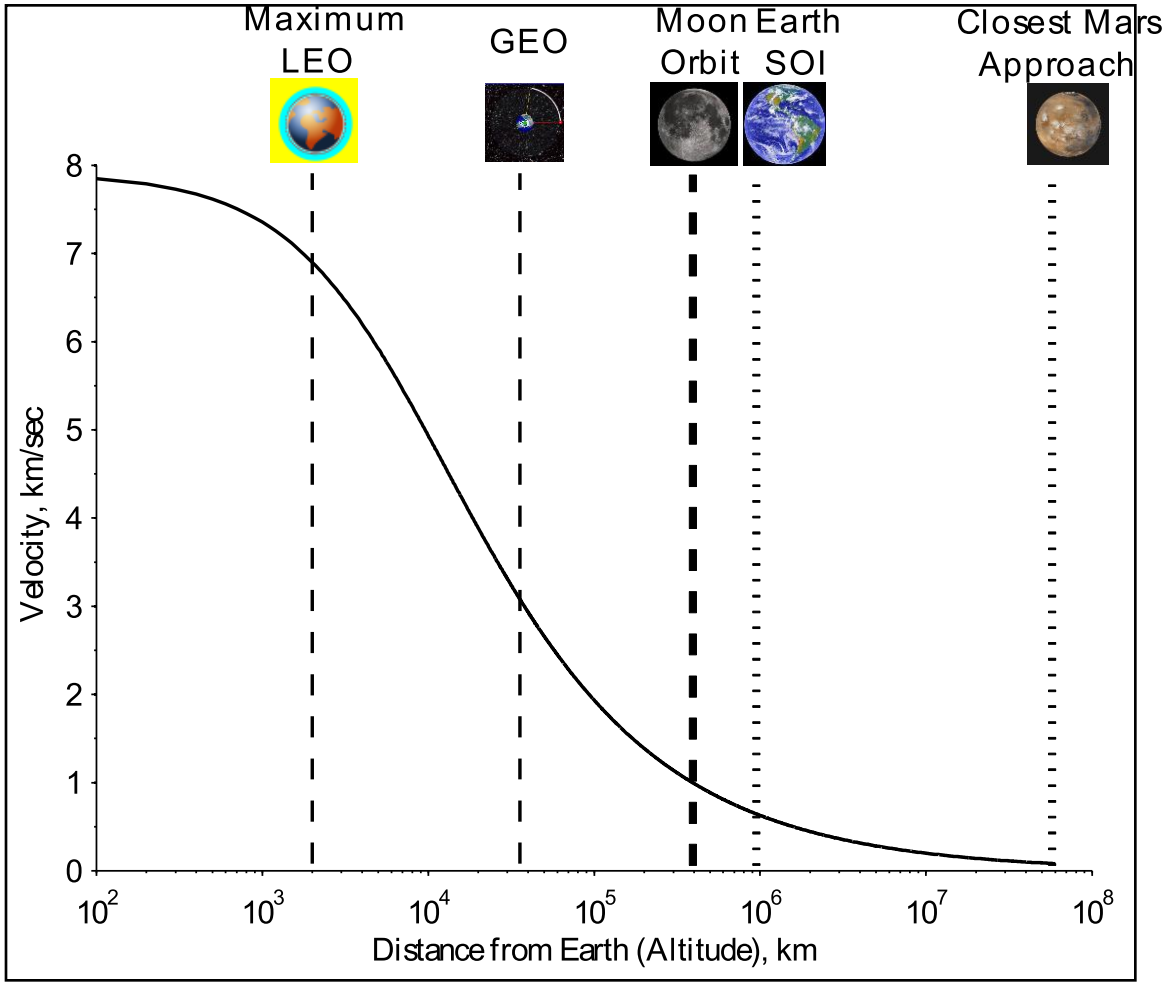


Constraints (reality)

- Maximum power (thrust) from CAT
- Initial orbital configuration
- CubeSat or small satellite:
  - Physical (mass/ volume)
  - Availability to collect/ store energy
  - Maximum instantaneous power

Image Credit: CubeSat Team Websites

How Much ΔV Is Needed?



Circular orbits

$V^2 = (\mu/r)$

V = orbital velocity

μ = constant

$(398600\ {}^{km^3}/_{sec^2})$

r = orbital radius

Starting in LEO, escaping Earth's Sphere of Influence (SOI): ΔV~ 7km/sec

Image Credit: Google Images

How Much Mass Is Needed?

Work through Rocket Equation for I_2 fuel and CAT

Parameter	Symbol	Input/ Equation	Value	Units
Specific Impulse	I_{sp}	Input	1010	sec
Exhaust Velocity	V_{exh}	$V_{exh} = I_{sp} \cdot g$	10100	km/sec
Dry Spacecraft Mass	m_s	Input	2.5	kg
Propellant Mass	m_p	Input	2.5	kg
Initial Mass	m_i	$m_i = m_s + m_p$	5	kg
Final Mass	m_f	$m_f = m_s$	2.5	kg
Delta V Capability	ΔV	$\Delta V = V_{exh} \ln\left({m_i}/{m_f}\right)$	7.01	km/sec

Rocket Equation

We can escape Earth's Sphere of Influence (ΔV~ 7km/sec) with ~2.5 kg of fuel!

g: gravity constant ~= 10 m/sec^2

How Much Mass Is Needed?

Let's take a look at different fuels and destinations

Parameter	Units	Destination				
		Maximum LEO	GEO	Mean Moon	Earth's SOI	Closest Mars Approach
Distance from Earth	km	2,000	35,700	384,000	925,000	56,000,000
ΔV	km/ sec	0.6	4.4	6.5	6.9	7.4
I_2 Fuel	kg	0.3	1.8	2.4	2.5	2.6
Ga Fuel	kg	0.2	1.4	1.9	2.0	2.1
H_20 Fuel	kg	0.1	0.8	1.1	1.1	1.2

LEO: Low Earth Orbit, GEO: Geostationary Earth Orbit, SOI: Sphere of Influence

We may be able to escape with even less fuel!

How Much Time Is Needed?

Let's take a look at different fuels and destinations

Assuming operate continuously at 10 Watts

Parameter	Units	Destination				
		Maximum LEO	GEO	Mean Moon	Earth's SOI	Closest Mars Approach
Distance from Earth	km	2,000	35,700	384,000	925,000	56,000,000
ΔV	km/ sec	0.6	4.4	6.5	6.9	7.4
I_2 Fuel	days	32	194	259	269	284
Ga Fuel	days	36	226	308	321	341
H_20 Fuel	days	202	1,369	1,933	2,026	2,171

We can escape Earth's Sphere of Influence in < 1 year!

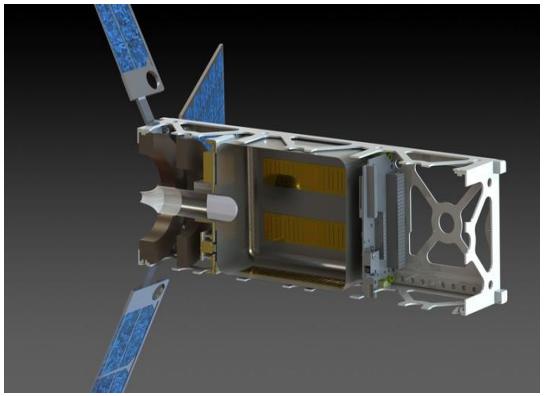
Note time is proportional to power because mass flow rate is linear with power!

LEO: Low Earth Orbit, GEO: Geostationary Earth Orbit, SOI: Sphere of Influence

Is this Really Feasible for a CubeSat???

Let's Review the Major Constraints:

1. Mass/ Volume
   - → CAT Engine is <.5U, <.5 kg
   - → Fuel ~2.5 kg required (~.5 U)



The CAT engine with the power system, propellant tank, solar panels, and CubeSat structure

2. Instantaneous Power
   - → Thruster can operate up to 100W, supportable by CubeSat bus

3. Energy and Time
   - → Trade between power * time (thruster is on) and available energy
   - → Constraint on mission duration!

Summary: None of these constraints are show-stoppers for a CubeSat!

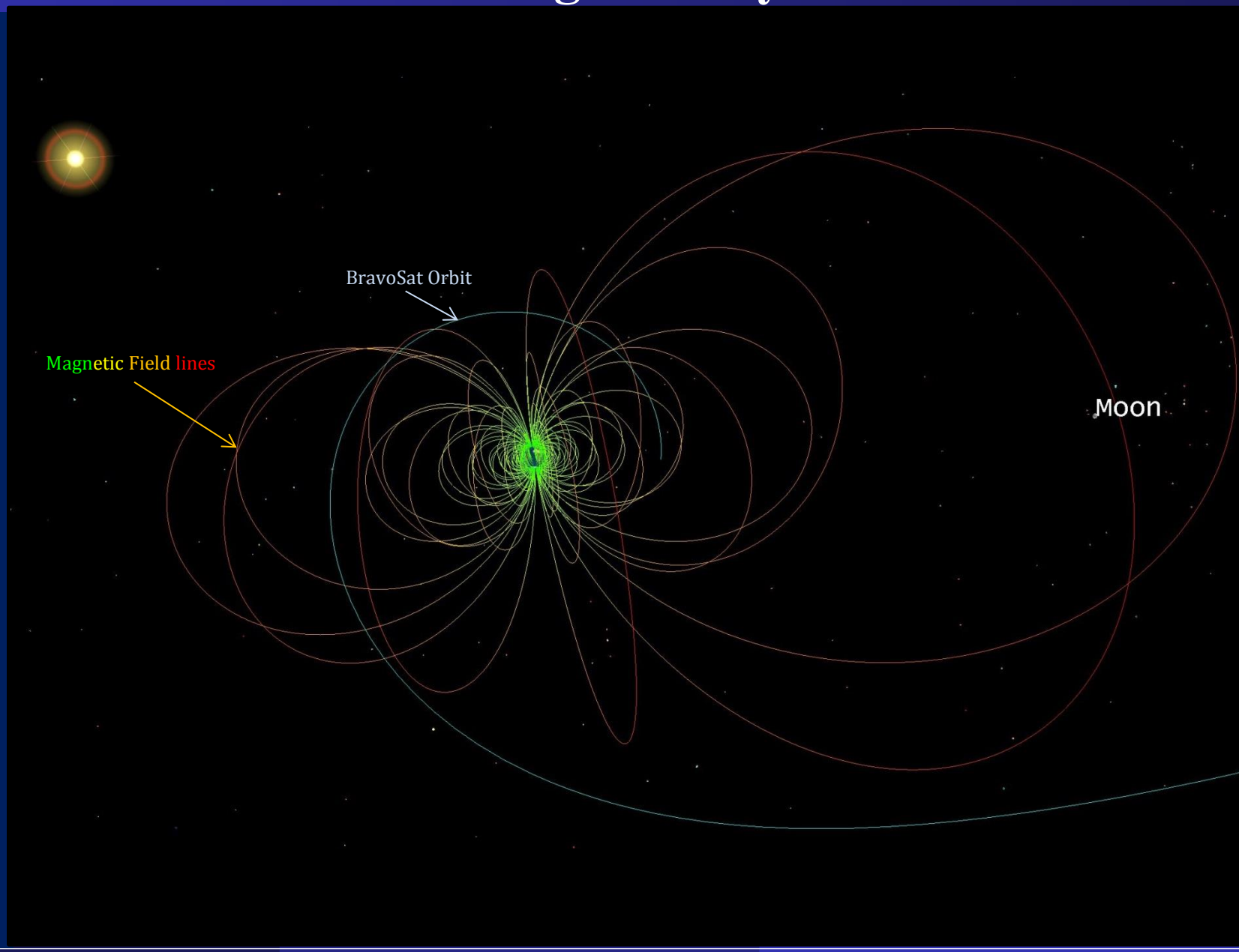
Consider 4 Different Approaches

#	Description	Consider Energy?	Consider Magnetics?	Exploit Perigee?	Challenges
1	Constant thrust along velocity vector	100W: No 10W: Yes	No	No	Need active attitude control
2	Thrust when α[1]$<30^o$	No	Yes	Maybe	Waste energy firing when not aligned
3	Thrust at perigee along velocity vector[2]	Yes	Yes	Yes	Need to start in elliptical orbit Need (fine) active attitude control
4	Phase 1: Thrust when $\alpha<30$ Phase 2: Pulse thrust every 200 minutes	Yes	Yes and No	No	Need active attitude control (phase 2)

[1] α: Angle between the velocity vector and thrust vector (aligned with Earth's magnetic field for passively stabilized spacecraft)

[2] Assume perigee is roughly when α is small

Case 1: Constant Thrust Along Velocity Vector



Case 1: Constant Thrust Along Velocity Vector

VIDEO

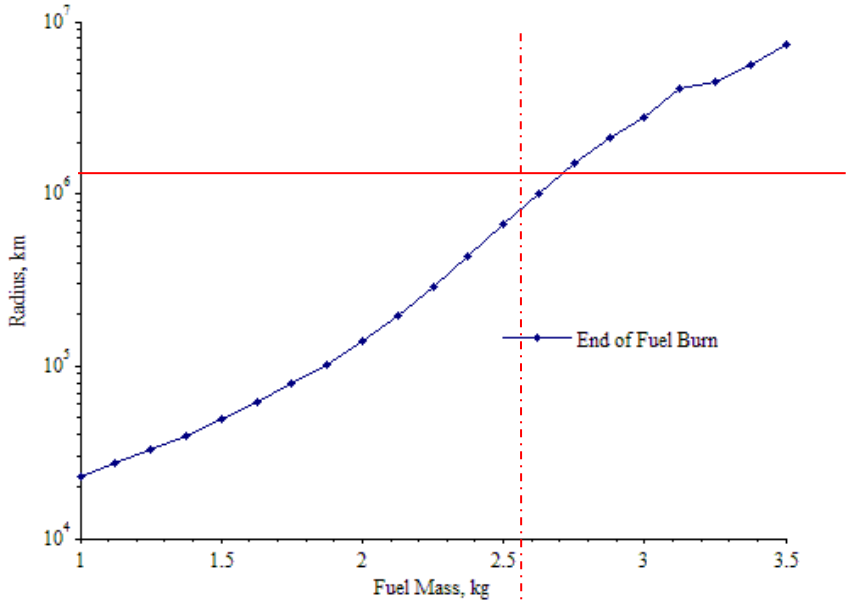
Constant Thrust Along Velocity Vector

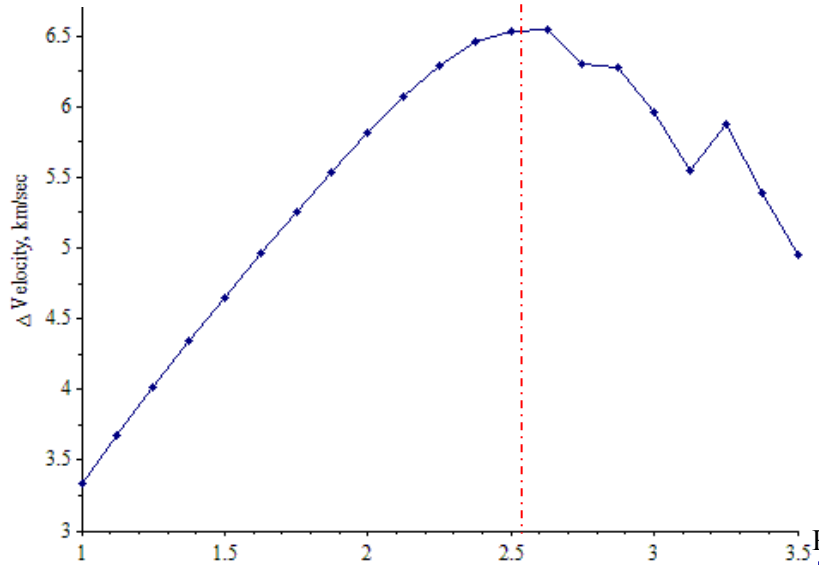
Case	Fuel Type	Fuel Quantity	Power Level	Time until runs out of fuel	Maximum Altitude (5 year scenario)
		kg	W	days	km
1	I_2	2.5	10	269	$168 \cdot 10^6$
2	I_2	2.5	100	27	$317 \cdot 10^6$
3	I_2	2.5	20	134	$12 \cdot 10^6$
4	Gallium	2.5	10	400	$165 \cdot 10^6$
5	Gallium	2.5	100	40	$248 \cdot 10^6$

Might also altitude change in plot for 10W, 100W, I2, Ga cases

How Much Mass do we Need?

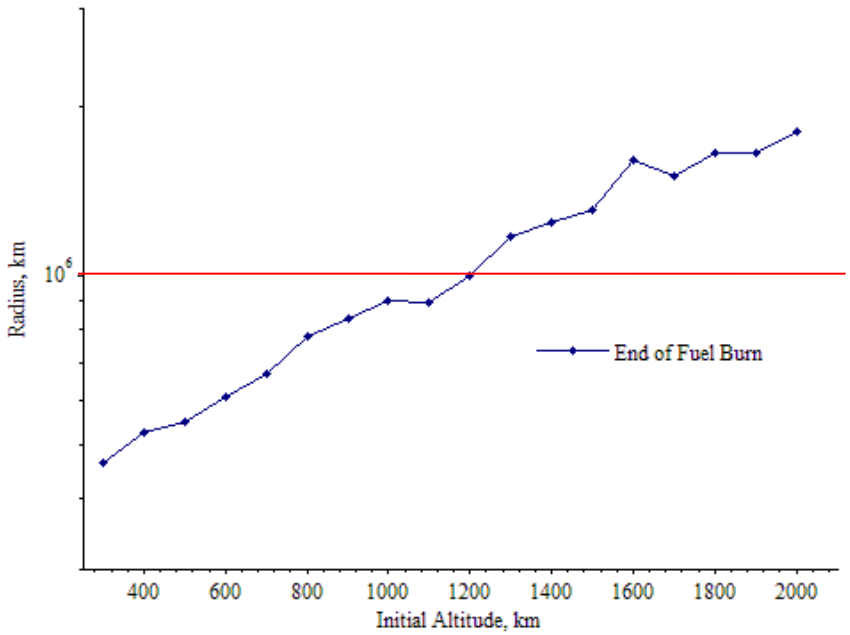
Depends how far you want to go!!!

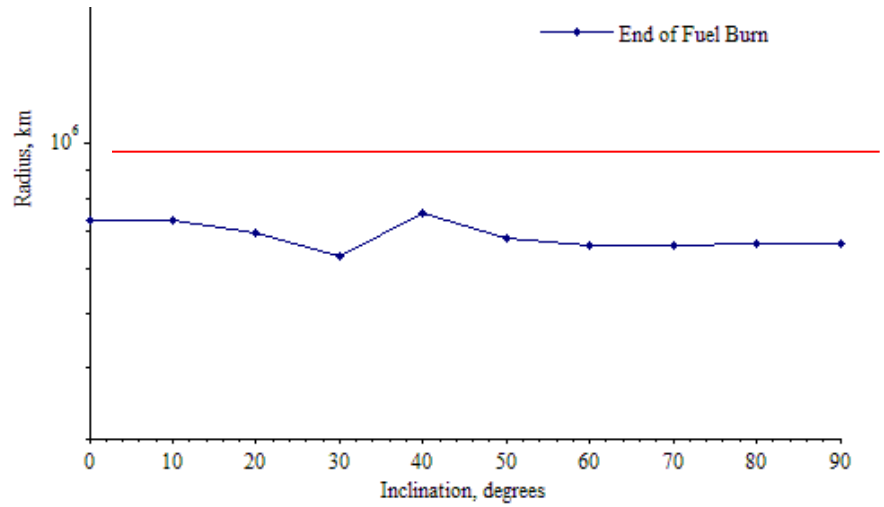




Results are shown when all fuel is used

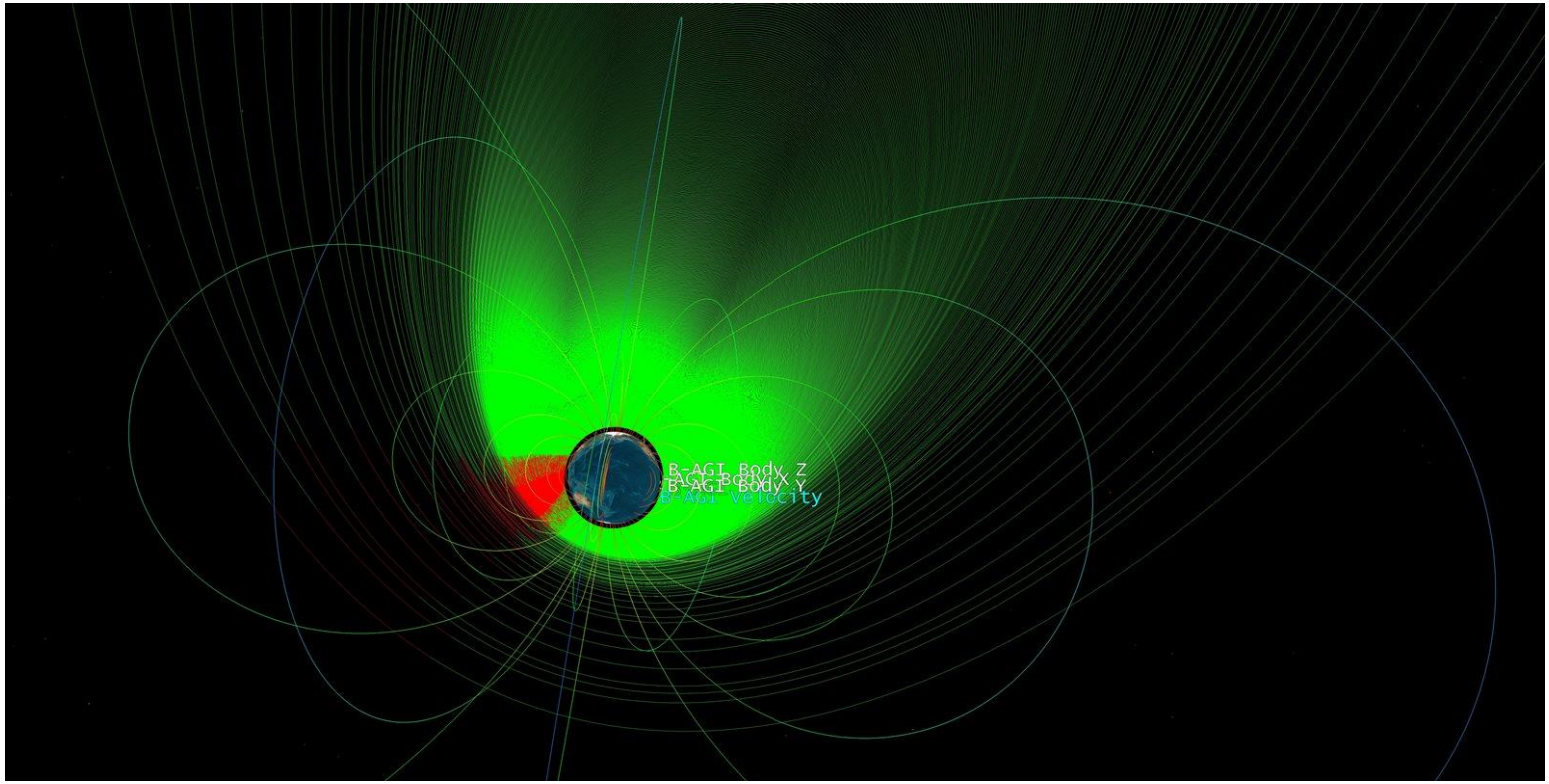
How Important Is Starting Altitude? Inclination?





Case 2: Strategy Using Passive Stabilization

Short, high-powered (100W) impulses… and no need to actively control attitude !



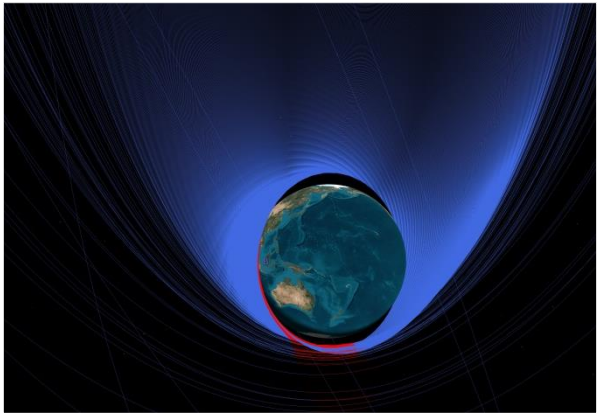
Thrust only when angle between engine vector (body-fixed) and velocity vector < 30°.

Challenges: Once orbit grows, need to thrust for a long time… may not be feasible!

Case 3: Exploiting Perigee to Escape Earth!

Strategy:

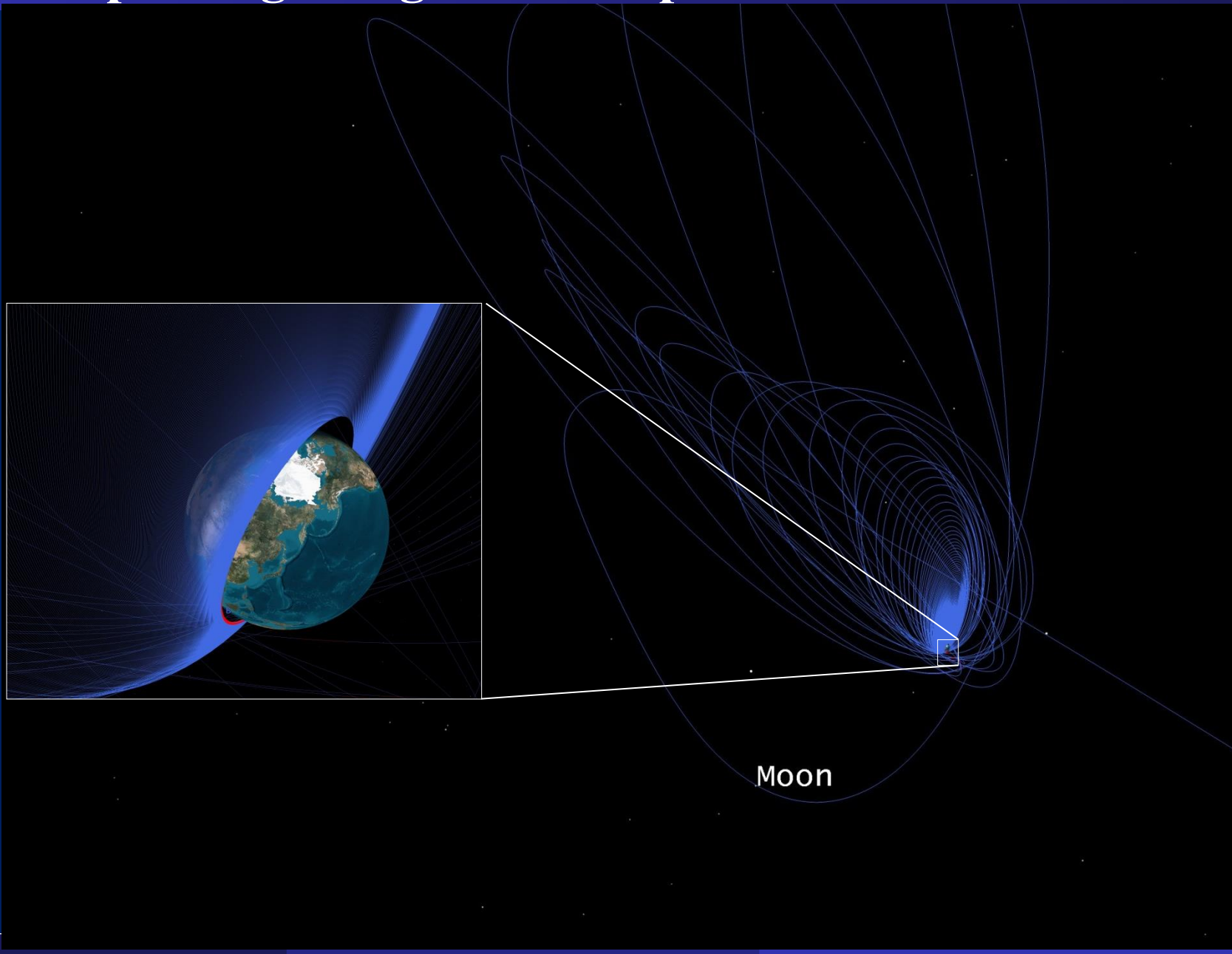
1. Start in elliptical orbit (assume 500km x 1500km)
2. Thrust at perigee (100W, 10mins)
3. If altitude gets low, also thrust at apogee
4. Continue until escape Earth orbit, or run out of fuel/time



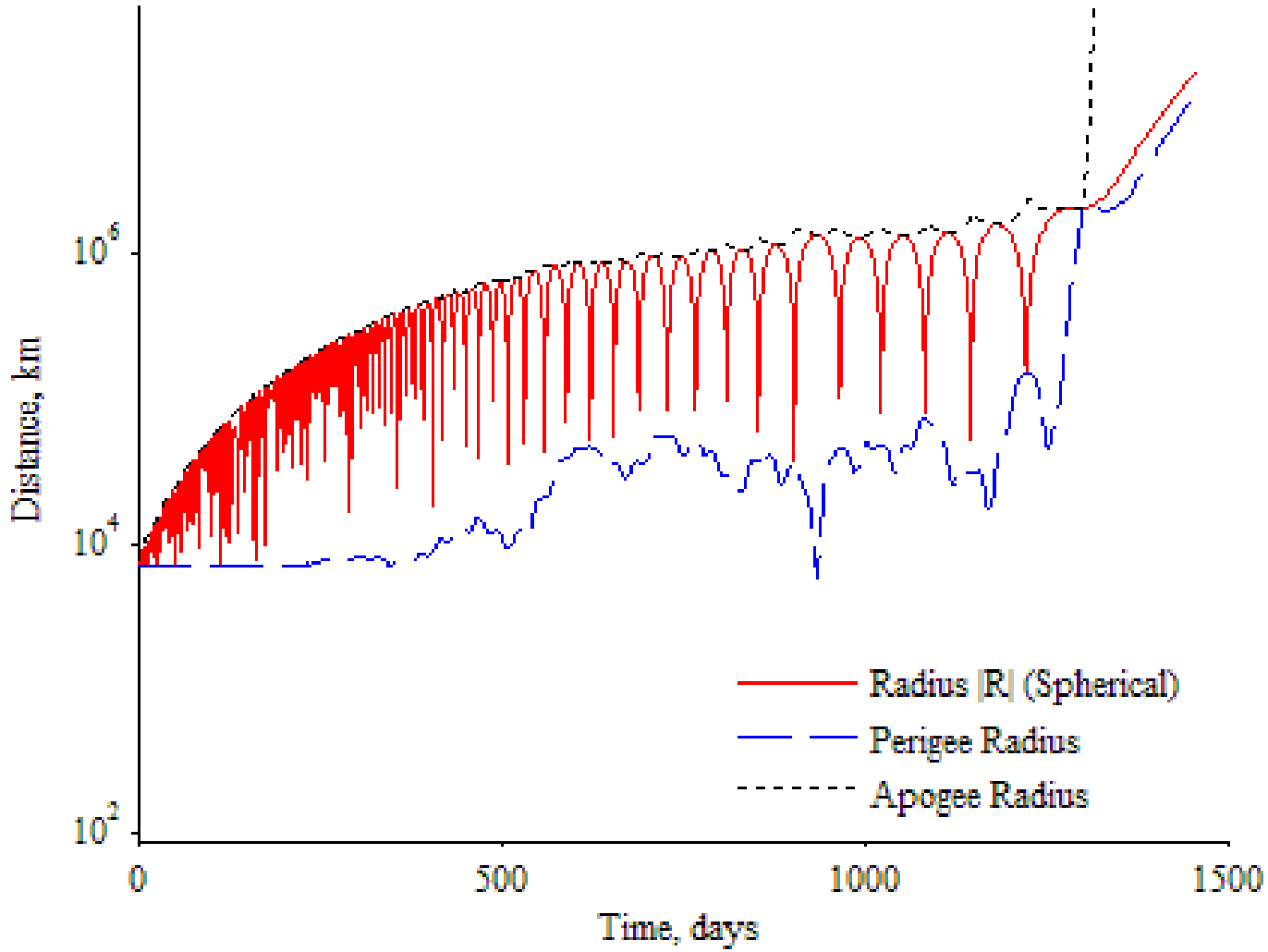
Rationale:

- Exploit passive magnetic stabilization
  - Thrust at perigee, where thrust vector ~parallel to velocity vector
- Energetically possible (thrust once per orbit for 10 mins)

Case 3: Exploiting Perigee to Escape Earth!



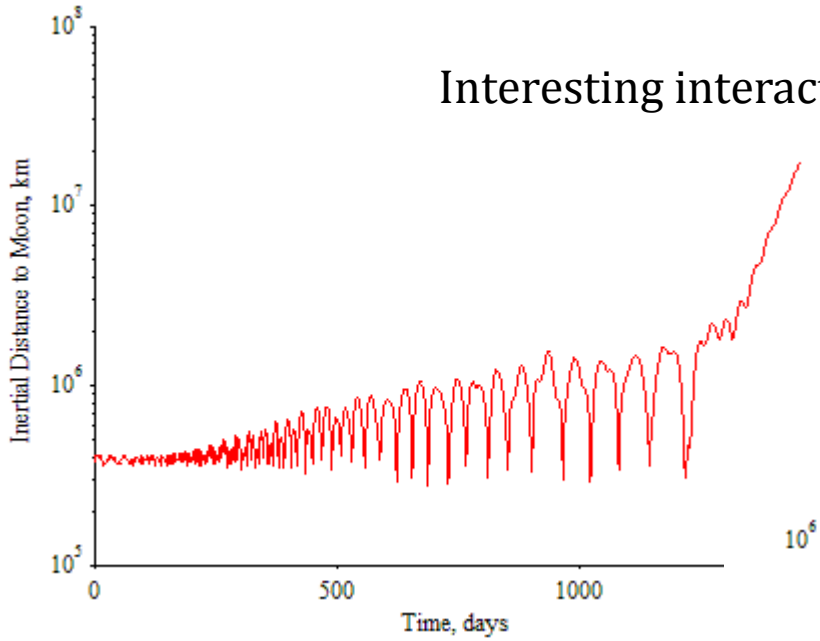
Stuff



Note results are sampled once a day

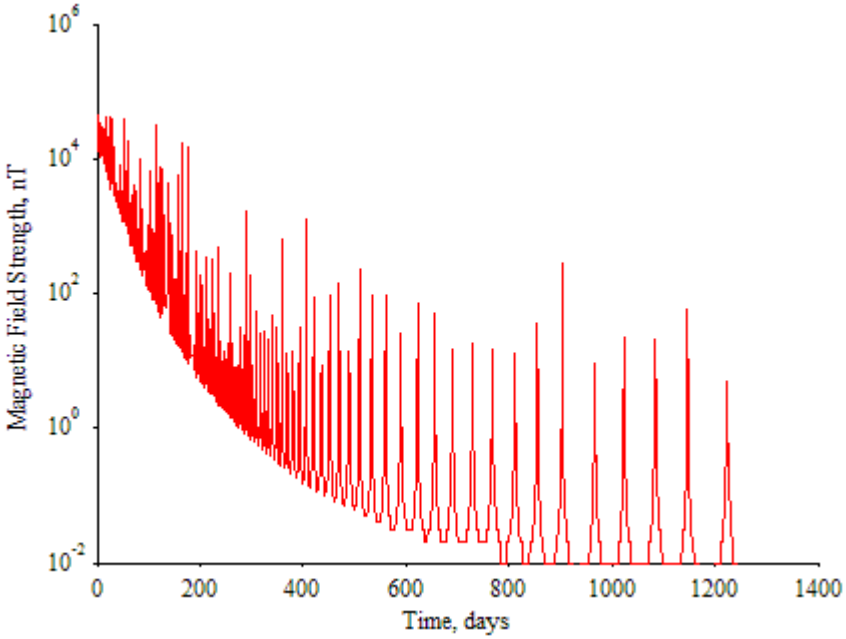
Case 3: Exploiting Perigee to Escape Earth!

Interesting interactions with the Moon!



Magnetic field still high at perigee

(passive stabilization)



Note results are sampled once a day

Case 4: Multi-Staged Approach

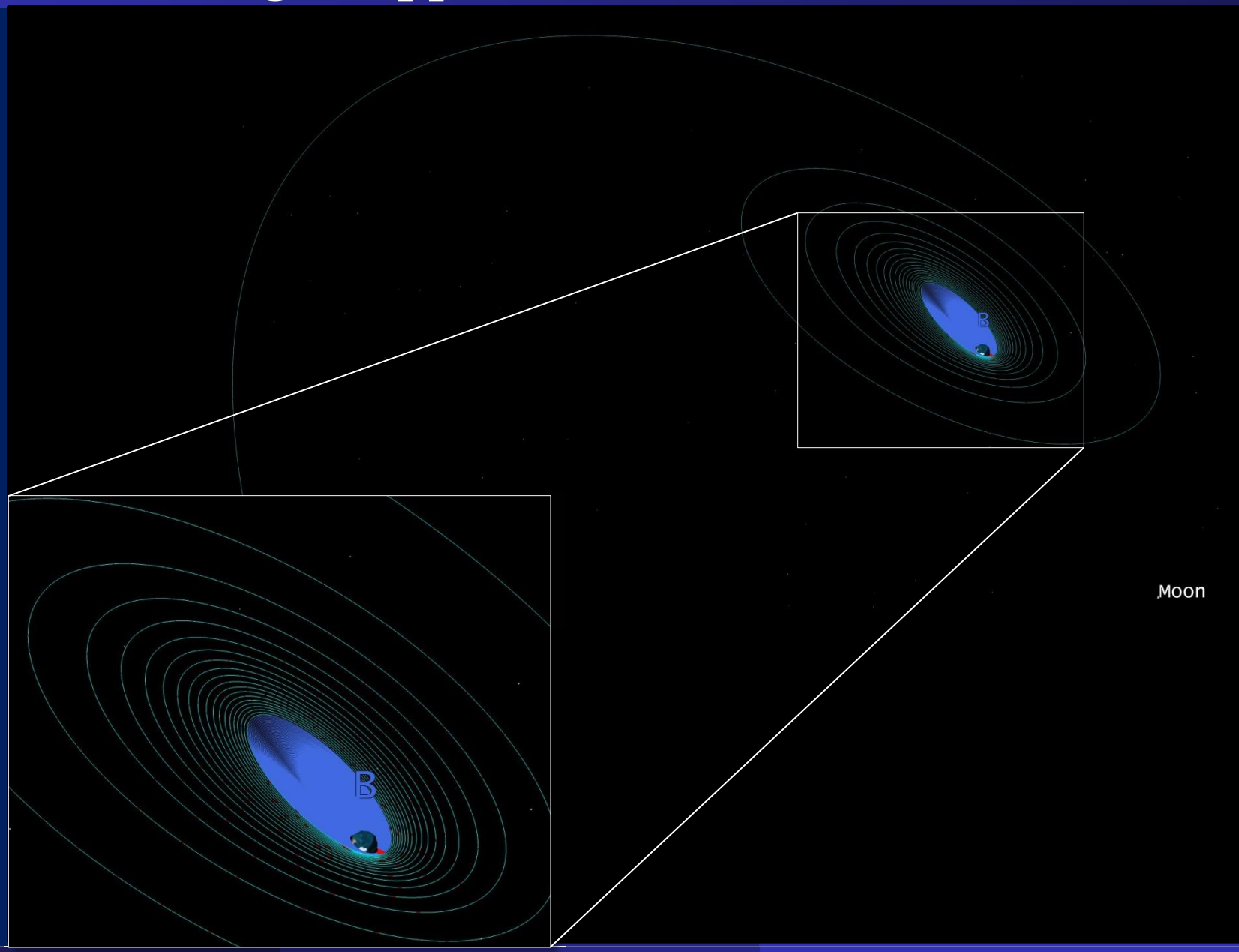
Strategy:

1. Phase 1: Thrust for 10 minutes when aligned (passive magnetically)
2. Phase 2: Thrust for 10 minutes every 200 minutes

Rationale:

- Exploit passive magnetic stabilization in Phase 1
  - Thrust at perigee, where thrust vector ~parallel to velocity vector
- Energetically possible in both phases (thrust <10 minutes at a time)

Case 4: Multi-Staged Approach



Conclusions/ Future Work

Conclusions

- Demonstrated capability for CubeSat to escape Earth orbit!
- Explored 4 different strategies (considering realistic constraints)

Future Design Considerations

- Battery charge cycles- How many can we tolerate?
- Thermal issues- Design thruster to manage?
- Radiation- Mission Duraiton, passing through South Atlantic Anomaly
- Improved Earth-escape trajectories

Acknowledgements

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Questions?