Pulsed Plasma Thruster Study for CubeSats

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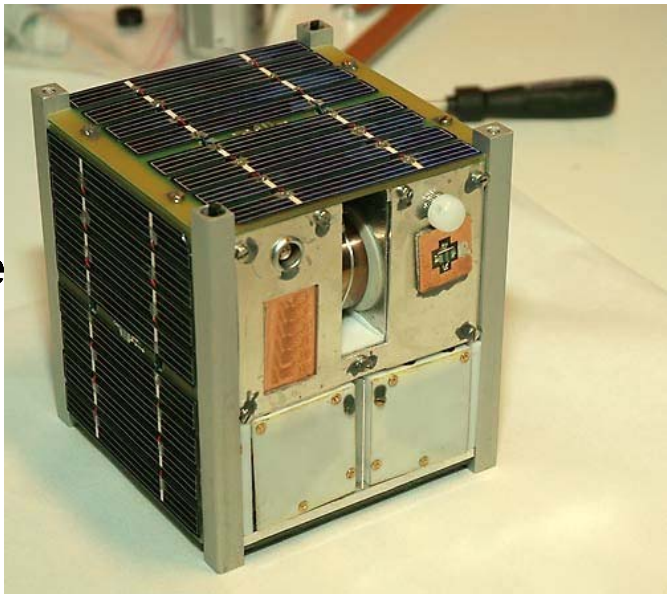
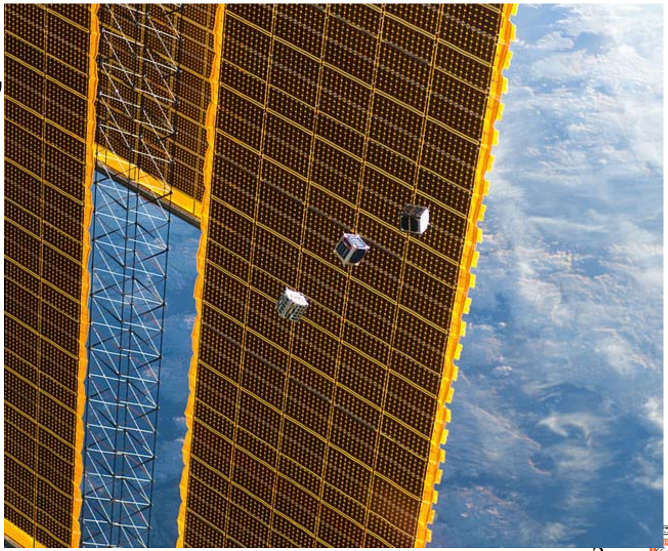
CubeSats?

- CubeSats are standardized spacecraft buses 10 x 10 x 10 cm in size and 1 kg in mass.
- Multiple cube buses (up to 3) have been built.
- Power is user supplied, but typically no more than a few Watts per cube using no deployable arrays so far.
- Substantial challenges exist in placing propulsion systems on CubeSats within the mass, size, and power design constraints.
- Some propulsion options have been developed for CubeSats and other microsats, but none have flown on CubeSats to date.
- Existing micro-thrust propulsion systems that are or may be (with some additional development) suitable to CubeSats





CubeSats

Motivation

Several companies have been formed after CubeSats launched from universities

- ✓ USA (CA, MI, NJ, UT, PA)
- ✓ Canada

- ✓ Germany
- ✓ Sweden
- ✓ Denmark
- ✓ **Scotland**

- ✓ Colombia
- ✓ **Puerto Rico?**

Why?

- ✓ **Traditional Satellites cost ~$100 million for construction and ~$50 million for launching costs (~$150 million total)**
- ✓ **CubeSats can cost ~40,000 to develop and ~$10,000 to launch ($50k total)**
- ✓ **Since 2000, 130 CubeSats have been launched, mostly from universities. The military, NASA, and 2 high schools, among others have participated as well**

Why?

- Designed in 1999 between California Polytechnic State University (Cal Poly) and Stanford University

- Objective: provide complete experience of designing, building and launching a satellite for undergraduate education. Acquire experience for industry

- Evaluate the possibilities of the platform

Small Satellites

Classification	Mass Range (kg)
Minisatellites	100-500
Microsatellites	10-100
Nanosatellites	1-10
Picosatellites	0.1-1
Femtosatelites	<0.1

Propulsion?

Low Earth Orbit (LEO)

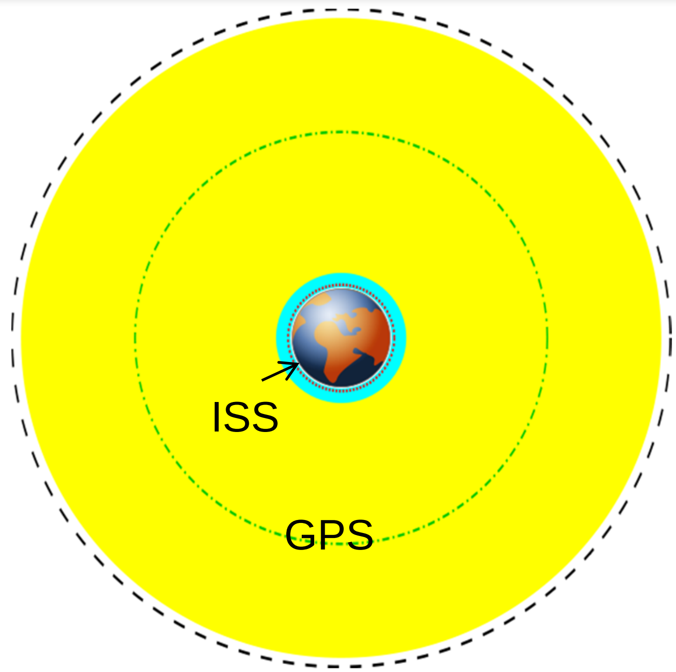
- ✓ 0-1200 km (air drag!)

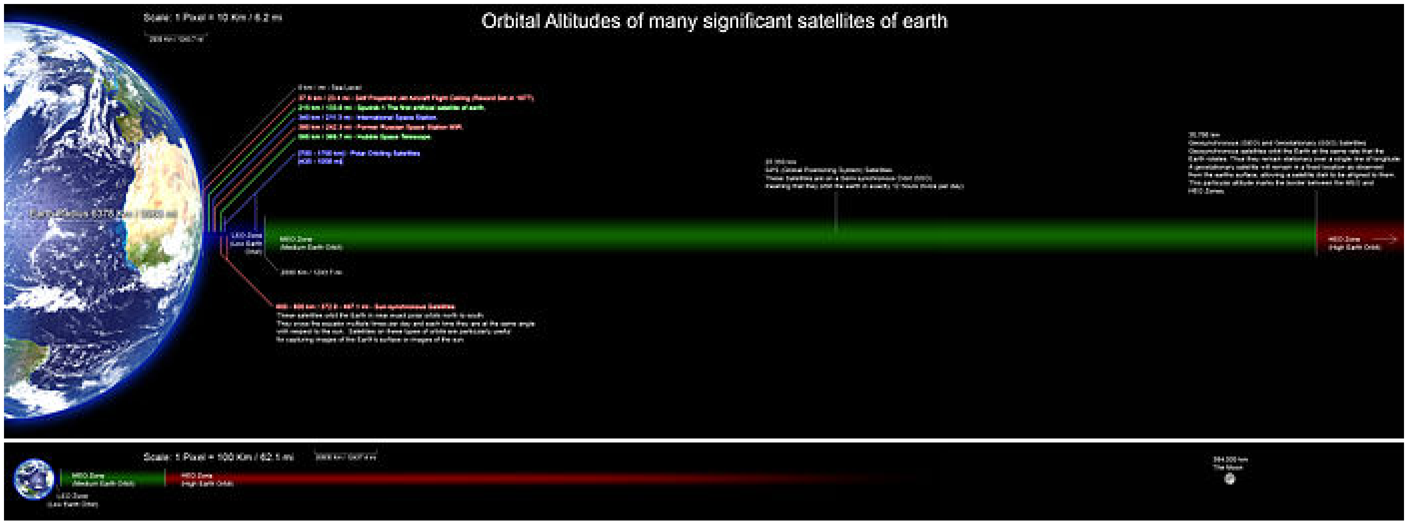
Medium Earth Orbit (MEO)

- ✓ 2000-35,786 km

High Earth Orbit (HEO)

- ✓ >35,786 km





Propulsion

Why diff. orbits?

$$\mathbf{F}_c = \mathbf{F}_g$$

$$m\mathbf{a}_c = m\mathbf{g} \begin{cases} |\mathbf{a}_c| = \omega^2 r \\ |\mathbf{g}| = \dfrac{GM}{r^2} \end{cases}$$

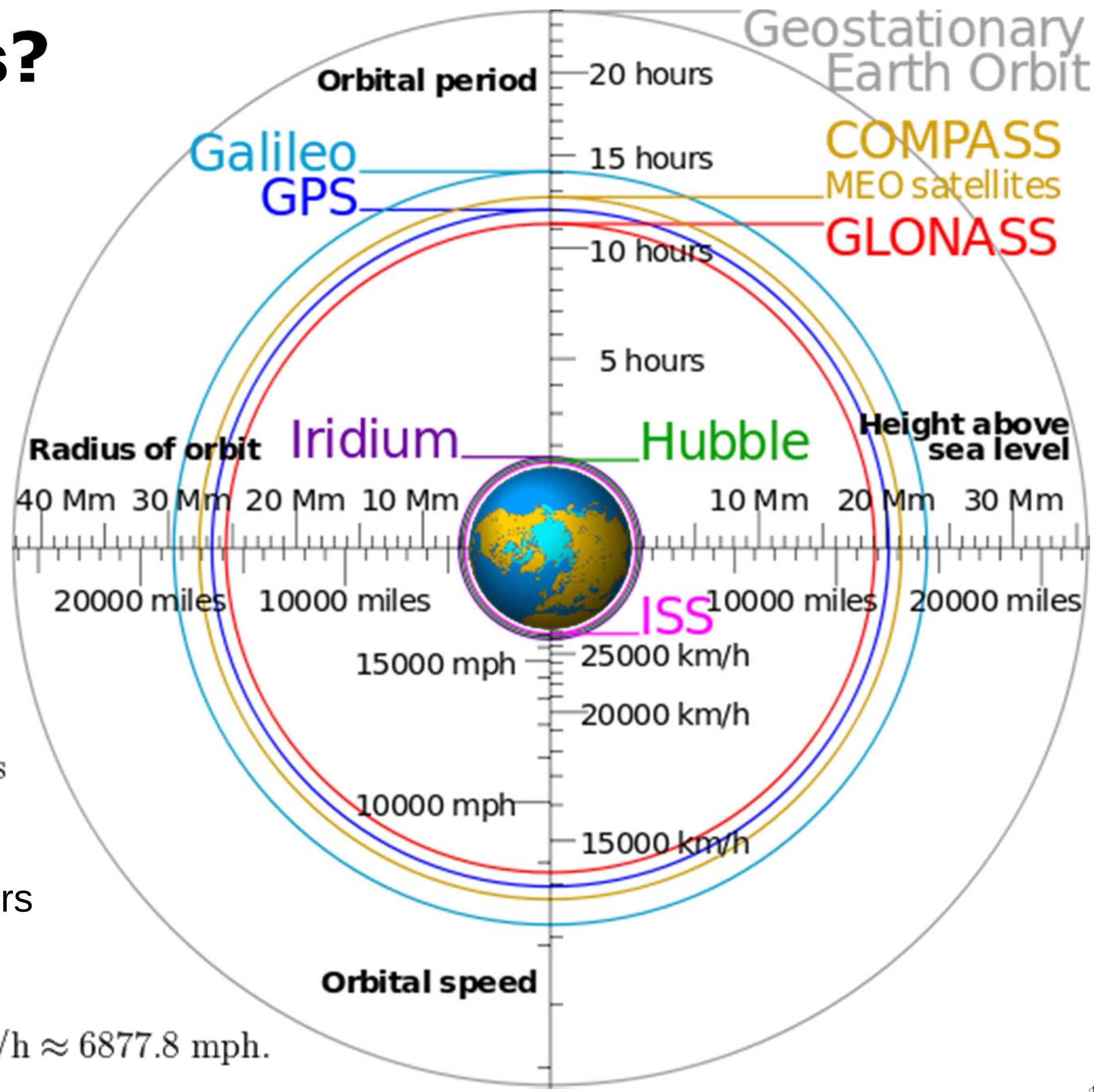
$$r^3 = \frac{GM}{\omega^2} \rightarrow r = \sqrt[3]{\frac{GM}{\omega^2}}$$

24 hours orbit (23.928 hours)

$$\omega \approx \frac{2\pi \text{ rad}}{86\,164 \text{ s}} \approx 7.2921 \times 10^{-5} \text{ rad/s}$$

Orbital radius of 42,164 kilometers
or altitude of 35,786 kilometers

$$v = \omega r \approx 3.0746 \text{ km/s} \approx 11068 \text{ km/h} \approx 6877.8 \text{ mph}.$$



Propulsion for CubeSats

- At LEO there is atmospheric drag

$$F_{drag} = \frac{1}{2} C_d A_{sat} \rho v^2$$

- Orbits at 600-700 km have atmospheric drag ~0.15 μN

- Orbits at 300 km have atmospheric drag ~23 μN

- Altitude control is required (ISS and others need it too)

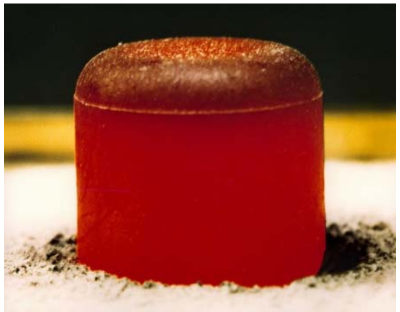
Propulsion Metrics

- **Thrust is defined as the force generated by an engine or rocket**
- **For rockets $F_{thrust} = c_e * dm$;   dm=fuel mass flowrate**
- **Specific Impulse measures the efficiency of a rocket engine (not a physical quantity).**
- **It is effectively equal to the thrust divided by the amount of fuel used per unit time.**
- **It is measured by a quantity called**

  $I_{sp} = c_e / g$

Nuclear Propulsion

Nuclear reactors

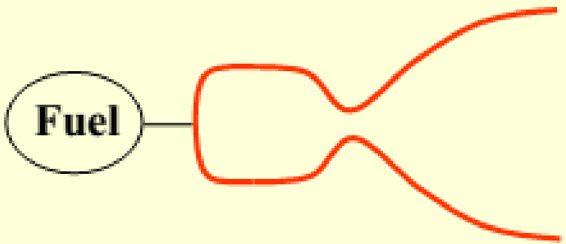


- Soviet RORSAT (33 satellites)
- American SNAP-10A
- Radioactive contamination issues

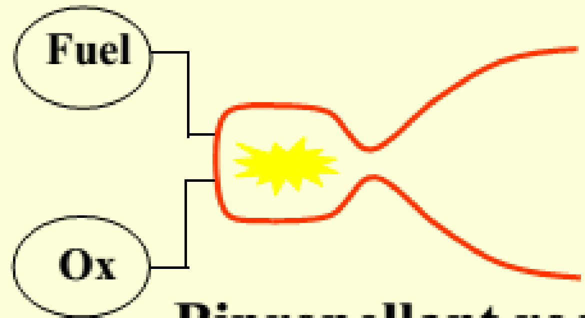
Radioisotope Thermoelectric Generator (RTG)

- Convert heat from decaying radioactive material into electrical energy by thermocouples arrays (Seebeck effect)
- Voyager, Galileo, Cassini, New Horizons, Curiosity Rover (150-300 Watts electrical)
- Use Pu-238 (limited world availability)

Chemical Propulsion

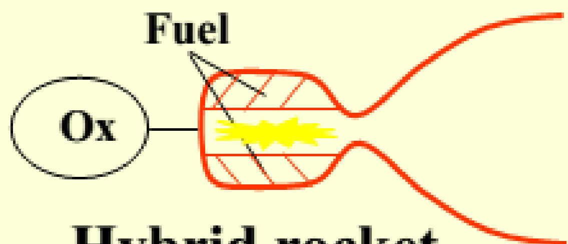


Cold jet

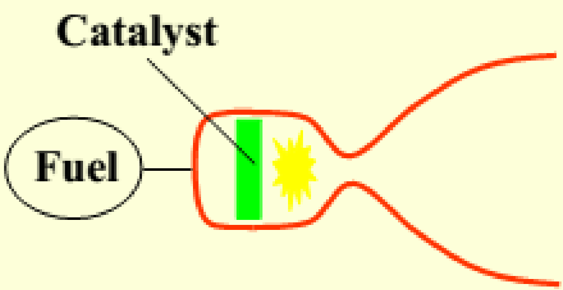


Bipropellant rocket

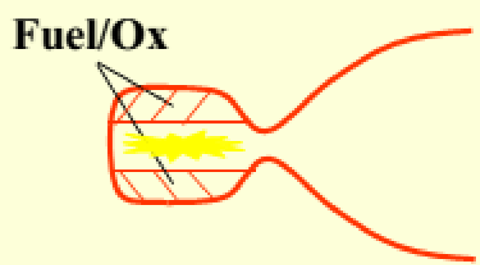
Type	Specific impulse (sec)
Cold gas	50-75
Solid rocket motors	280-300
Liquid monopropellant	150-225
Liquid bipropellant	300-450



Hybrid rocket



Monopropellant rocket

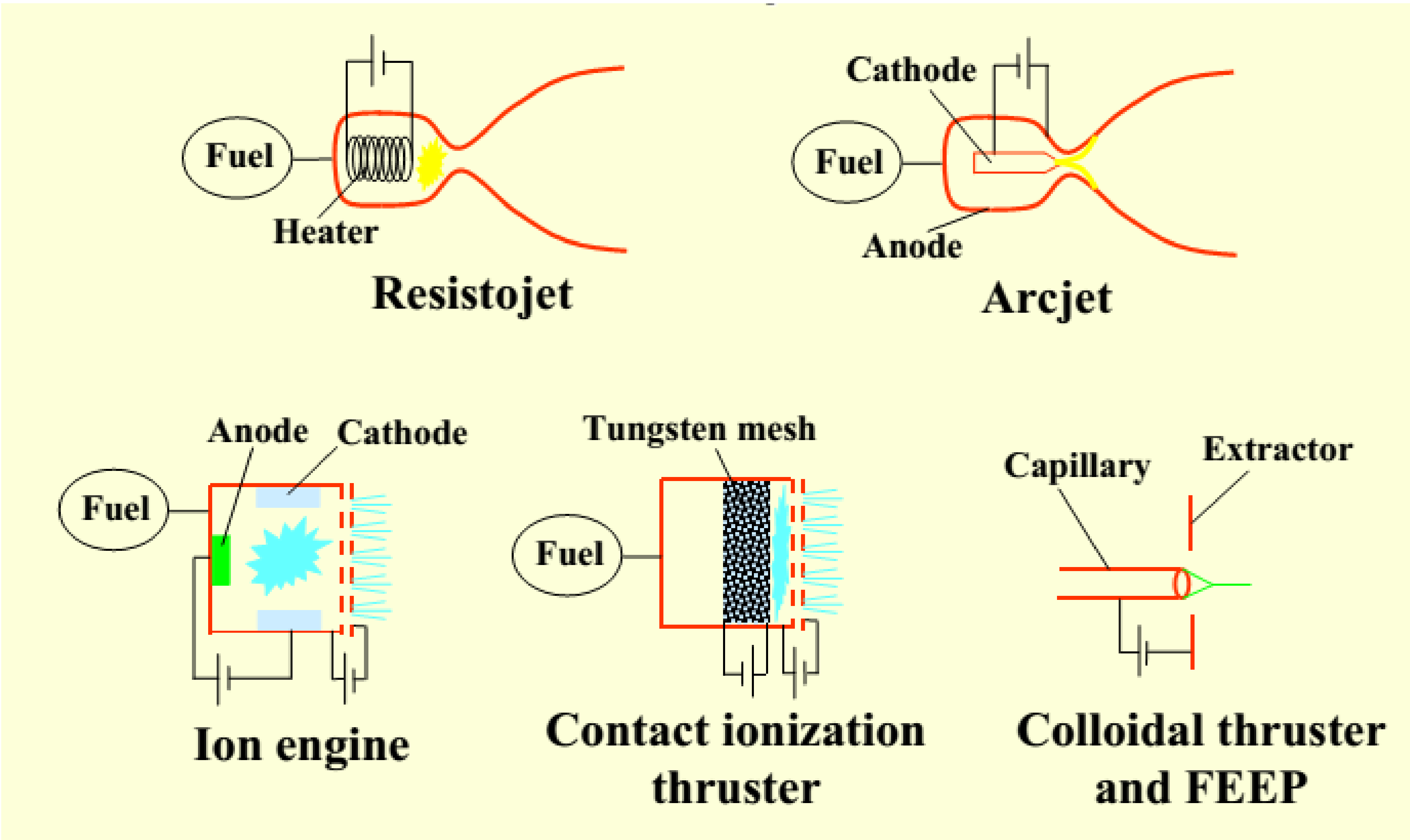


Solid rocket motor

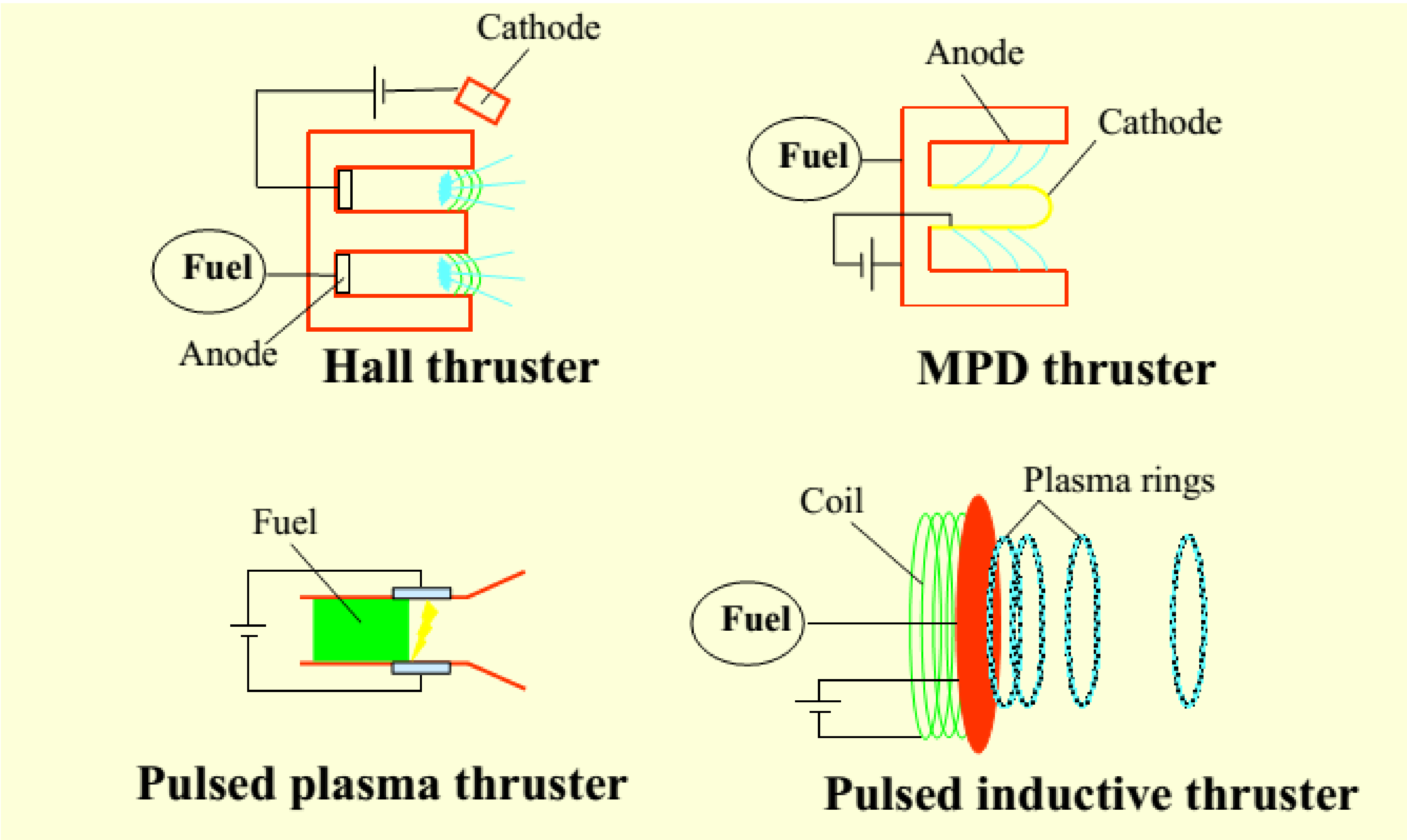
Types of Electric Propulsion

- ***Electrothermal***
  - Uses electricity to heat a neutral gas *examples*: arcjet
- ***Electrostatic***
  - Uses a static electric field to accelerate a plasma. Static magnetic field are sometimes used to help confine the plasma, but they are not used for acceleration. *examples*: gridded ion thruster
- ***Electromagnetic***
  - Uses electric and magnetic fields to accelerate a plasma. *examples*: Hall thruster, pulsed plasma thruster

Electric Propulsion



Electric Propulsion (cont)



Propellants - Fuels

Gas

- ✓ Reservoir tanks, feeding systems, valves
- ✓ Low energy density per volume

Liquid

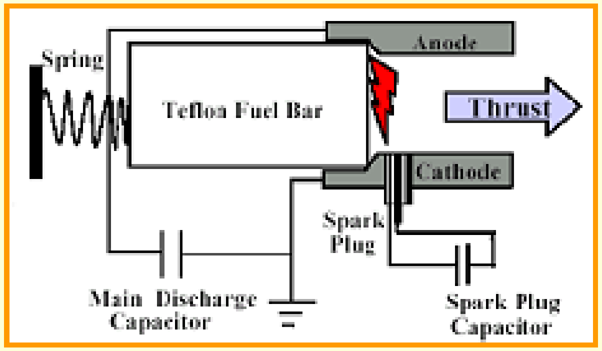
- ✓ Tanks, pump systems, valves
- ✓ Medium energy density per volume

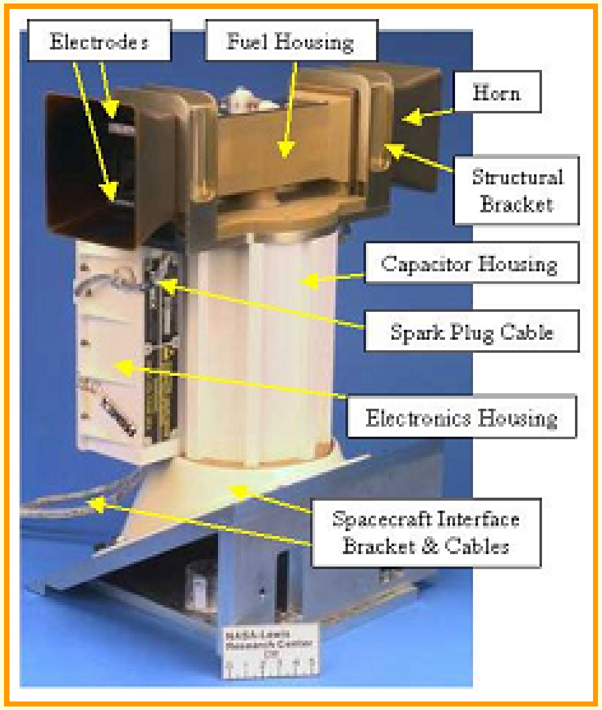
Solid

- ✓ Storage, feeding system
- ✓ High energy density per volume

Pulsed Plasma Thrusters

- Bar of Teflon is pressed against a shoulder by a spring; a capacitor is discharged through a spark plug between two electrodes. The discharge oblates and partially ionizes a small amount of Teflon and accelerates it to high exhaust velocities.
- Thrust is produced by a combination of accelerated ions and thermal acceleration non-ionized vapor
- Advantages:
  - simple, self-contained system (propellant, PPU, feed system), no tanks, valves, etc
  - precise impulse control in the μN sec range; no moving parts (eliminates jitter associated with reaction wheels)
- Disadvantages:
  - low thrust (unacceptable for certain missions)
  - low efficiency (due to polydispersity)

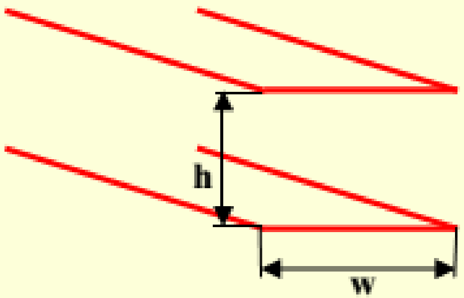




Pulsed Plasma Thrusters (cont.)

- Magnetic field [Tesla] generated between two plates can be estimated as follows, where $\mu_0 = 4\pi \times 10^{-7}$ and *I* [A] is the discharge current):

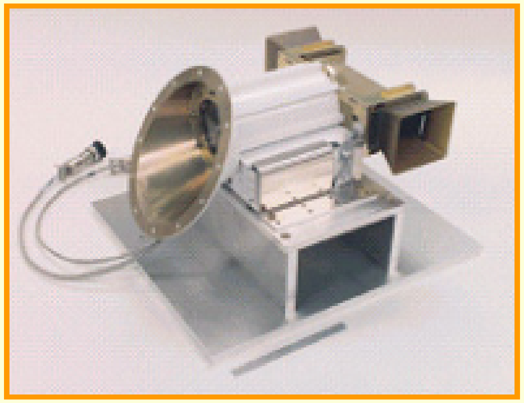
$$B = \frac{\mu_0 I}{w}$$



- Thrust (due to electromagnetic acceleration only) is given by:

$$T = p_M A \approx \frac{B^2}{2\mu_0}(wh) = \frac{\mu_0 I^2}{2}\left(\frac{h}{w}\right)$$

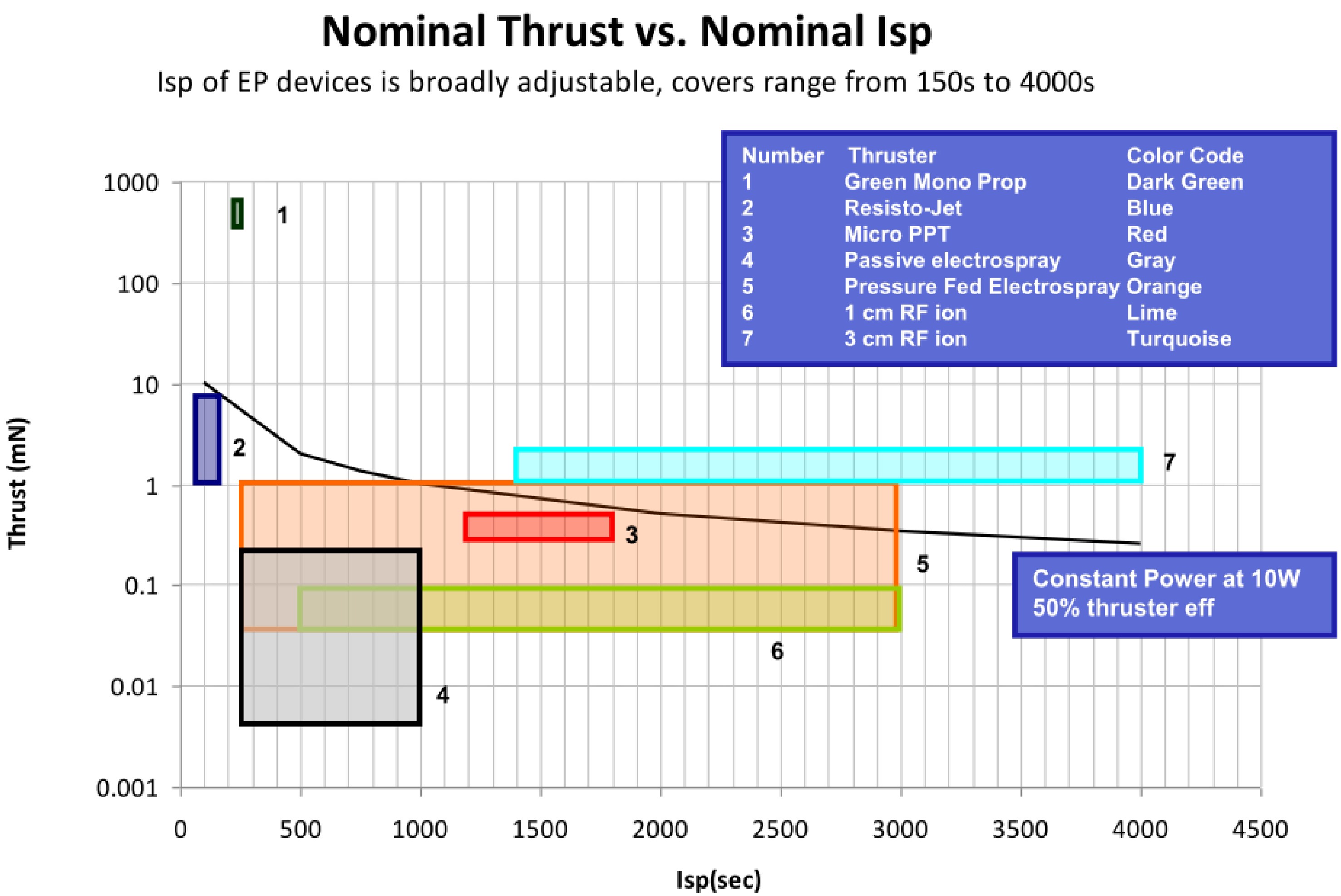
- Thrust efficiency is very low due to thermal energy wasted to ablate propellant at the surface
- Ablated propellant is thermally accelerated and does not contribute significantly to thrust



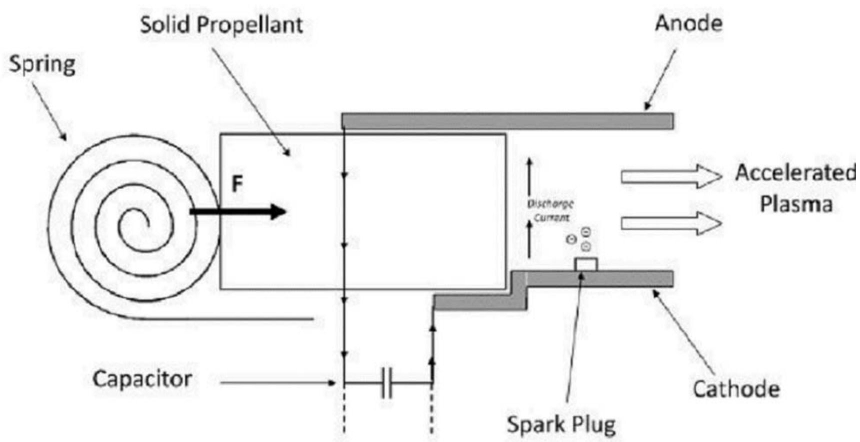
PRS 101
Aerojet

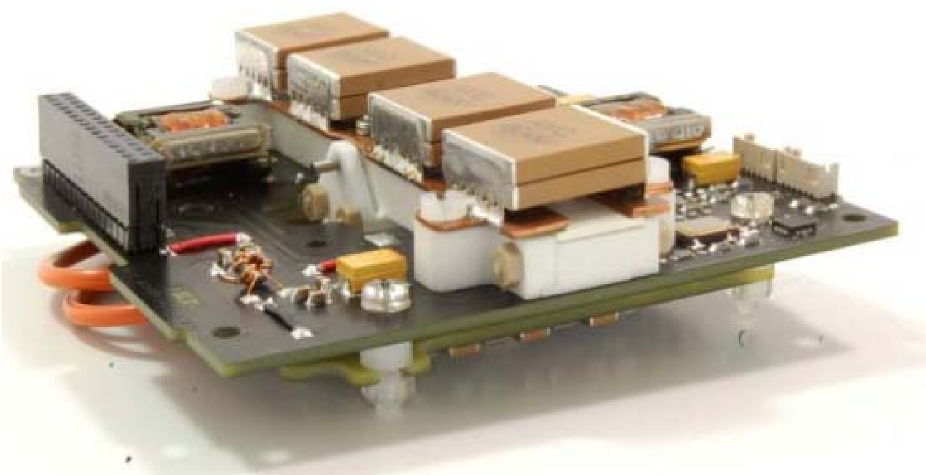
Engine	Supplier	Maximum Thrust (mN)	Specific Impulse (sec)	Mass (kg)	Max. Impulse (N sec)	Min. Impulse (μN sec)	Effici-ency (%)	Input Power (W)	Flight status
PRS 101	Aerojet	1.40	1,150	5.0	1.5×10^4	100	9.8	100	EO-1, MightySAT
LES 8/9	Aerojet	0.60	1,075	7.3	7.3×10^3	300	7.0	50	LES
NOVA	Aerojet	0.34	300	6.4	2.2×10^3	378	3.0	20	NOVA

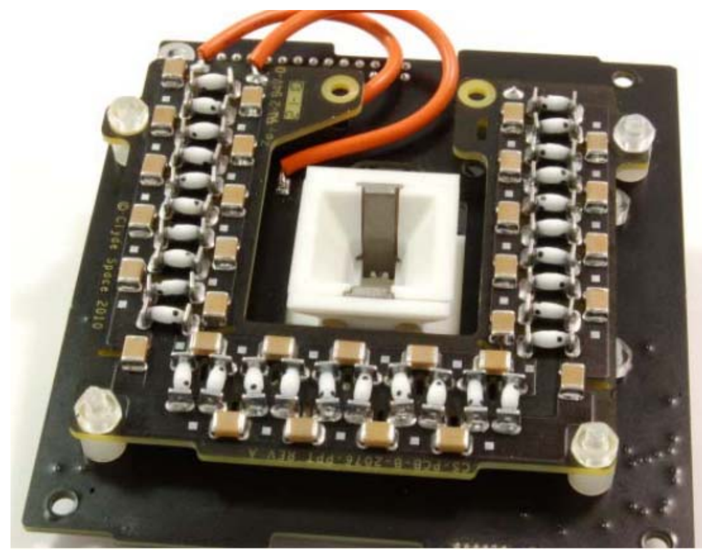
Why Pulsed Plasma Thrusters?



Pulsed Plasma Thrusters



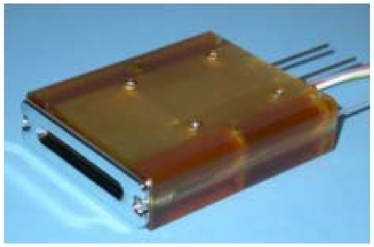




Scotland ~$20k

Commercial Solutions

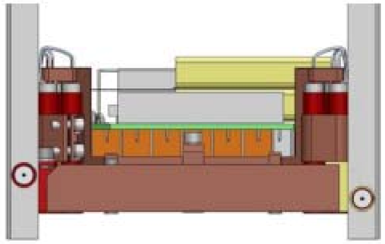
Electrospray Thruster
- ✓ High Efficiency
- ✓ Multi-emitter
- ✓ Low Risk / Technically Mature



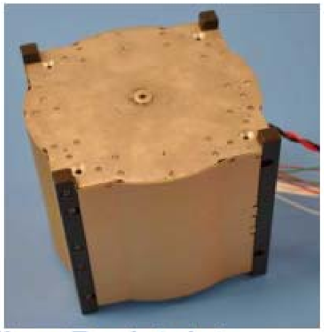
Passive Electrospray Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power
- ✓ High ISP

1 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ >2000s Isp
- ✓ FE Neutralizer is space qualified

3 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ Tested up to 3,000s Isp
- ✓Thermionic Neutralizer is space qualified



Micro Pulsed Plasma Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power
- ✓ Integrated Primary / ACS
- ✓Prior version flying on FalconSat3



Micro Resistojet
- ✓ Simple, ideal for prox-ops
- ✓ Higher thrust (scales with power)
- ✓ Integrated Primary / ACS

Green Monoprop
- ✓ High thrust (high Cubesat acceleration)
- ✓ High density Isp
- ✓Low-toxicity propellant

Applications

Compensation for disturbance torques:

- ✓ Drag, gravity gradient, solar pressure, magnetic forces.....

Attitude control:

- ✓ Communication improvement (antenna pointing)
- ✓ Scientific payload requires control/fine-pointing (spectrometry, camera)
- ✓ Improved power generation (solar panels)

Orbit control:

- ✓ Improved mission autonomy (compensation for errors during orbit insertion, change of orbit, etc.)
- ✓ Broader mission range (formation flying etc.)
- ✓ Higher mission pay-off /success

De-orbiting after EOL (to a certain extent).

De-orbiting ability might become compulsory in the near future!

Means of active propulsion results in a broader mission range for CubeSats
longer missions

Pulsed Plasma Thrusters

- Structural simplicity facilitates miniaturization
- Specific Impulse: 500 – 1000 s
- Low power consumption
- No moving parts (valves etc.)
- Teflon propellant:
  - ✓ unlimited storability
  - ✓ easy handling
  - ✓ non-toxic, non-carcinogenic
  - ✓ no degradation in space
  - ✓ no sensitivity to temperature
  - ✓ cheap
- PPT system is a space proven system

PPTs are the ideal solution for CubeSats

Research Objectives

- **Miniaturization of PPT and PPU to comply with the stringent mass, power, and volume limitations of CubeSats.**
  - Investigation of electrode geometry influences in small scale thrusters
  - Performing tests in a wide range of electrode sizes (down to 3mm width and further)
  - Clarification of the effect of electrode length on performance
  - Investigation into aspect ratio and its relation to impulse bit, thrust to power ratio and thruster efficiency
  - Investigation of alternative electrode designs do improve performance for low energy operation
  - Extensive testing at low energy and identification of regimes which result in propellant carbonization with the aim of eliminating charring at low energy operation
  - Identification of technology suitable for implementation into a µPPT
  - Miniaturized energy storage device

What can a PPT system do?

- Attitude control
- Fine pointing (<1 ° precision)
- Orbit change/insertion
- Spin-up, spin down
- Formation flight
- Deorbiting (within limits)

Conclusions

- **Technology with commercial potential**
- **Altitude control for extended operation**
- **Extend CubeSats lifetime to several years for research and commercial applications ($50k rather than $150M)**
- **Natural 25-year Deorbit (no control) for under 700 km orbits**
- **Deorbit at 300 km is ~1 month**
- **Deorbit at 150 km is a few days**
- **Research just started at Turabo!**

Questions