On-Orbit CubeSat Performance Validation of a Multi-Mode Micropropulsion System

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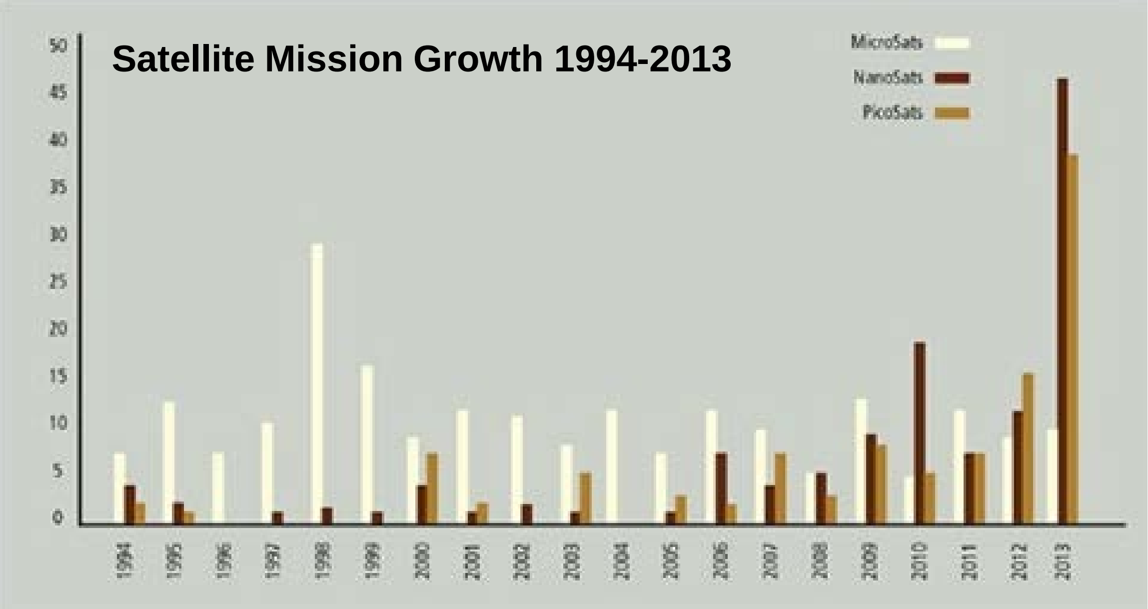
Mission Context

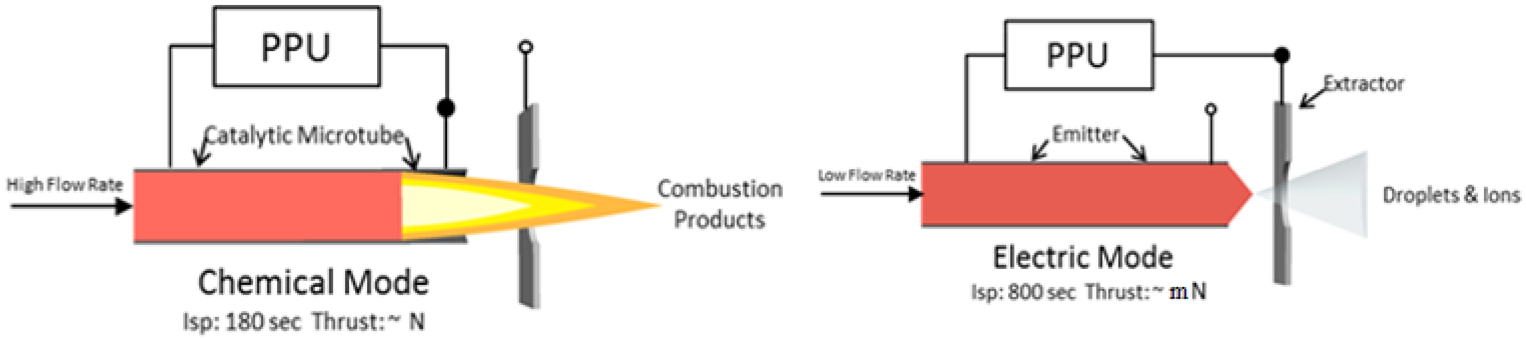
- CubeSat missions have grown exponentially, becoming the most popular form of small satellite



Gustafson, Charles L., and Siegfried W. Janson. "Think Big, Fly Small." The Aerospace Corporation. *Crosslink Magazine*, 1 Sept. 2014. Web. 07 Feb. 2017.

- In spite of this rapid growth, development of propulsion systems for small satellites has lagged behind

One Possibility: Multi-Mode Thruster

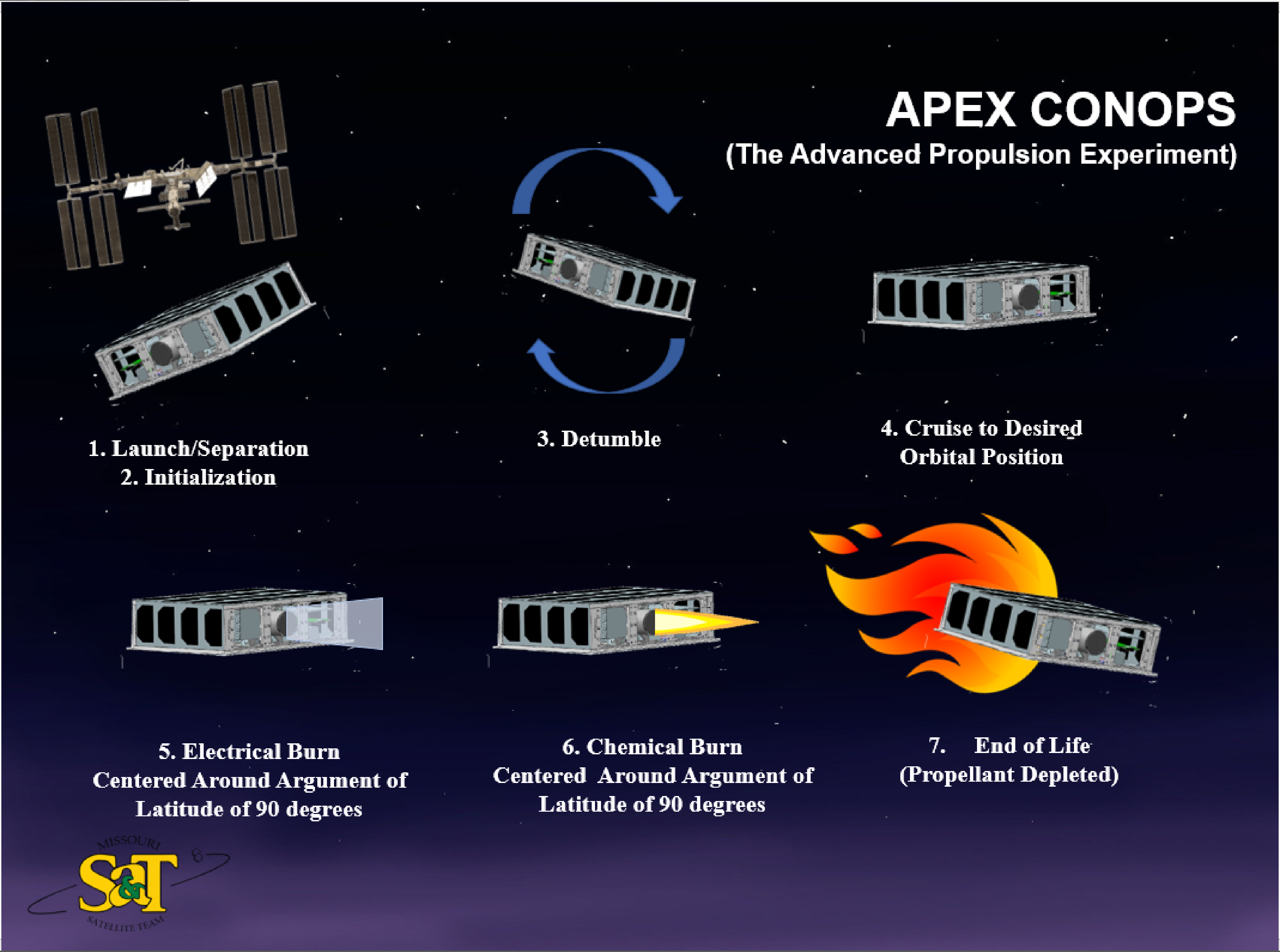


- Multi-Mode SmallSat Propulsion Mission: a technology demonstration of a single propulsion thruster operable in…

  -catalytic chemical mode

  -electrospray electric mode

  …using the same propellant!
- Can be integrated into a CubeSat form factor


APEX CONOPS
(The Advanced Propulsion Experiment)
1. Launch/Separation
2. Initialization
3. Detumble
4. Cruise to Desired Orbital Position
5. Electrical Burn Centered Around Argument of Latitude of 90 degrees
6. Chemical Burn Centered Around Argument of Latitude of 90 degrees
7. End of Life (Propellant Depleted)
MISSOURI S&T SATELLITE TEAM

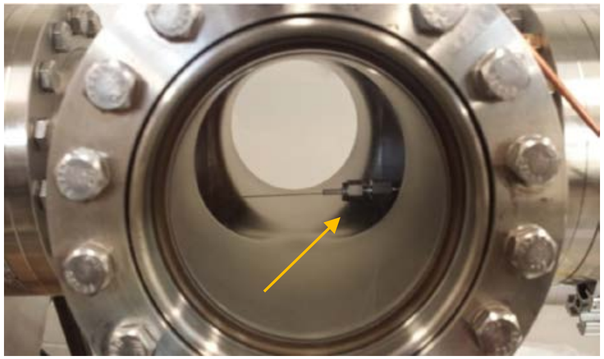
Payload Description

• Utilizes Non-toxic, Green Ionic Liquid Propellant
- Can extract ions
- Energetic and capable of exothermically decomposing

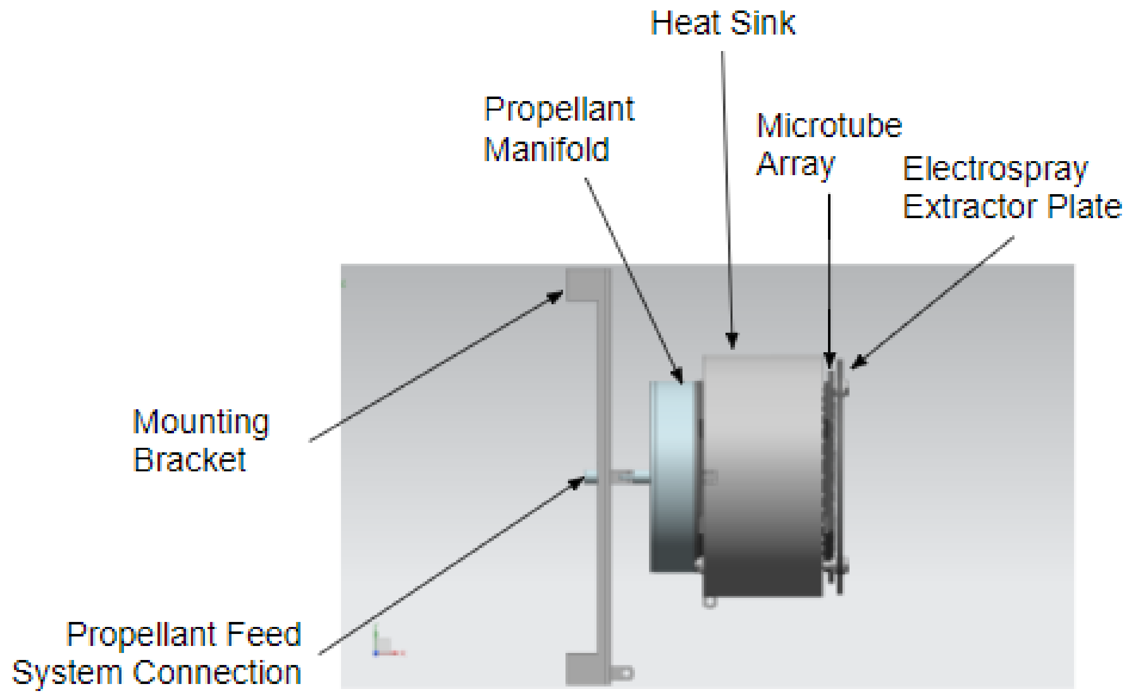
• Chemical Mode
- Propellant fed to thruster at high flow rate
- Combination of applied heat and catalytic microtube ignite propellant

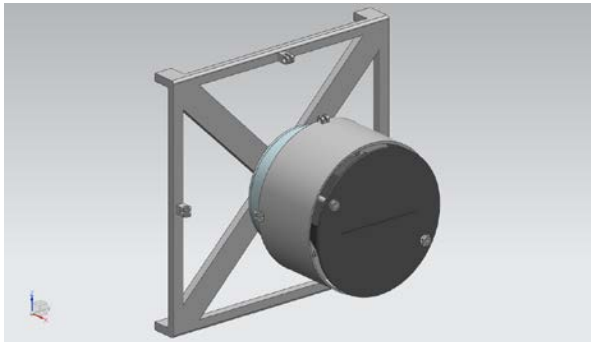
• Electric Mode
- Propellant fed to thruster at low flow rate
- Voltage potential applied between emitter and extractor to release ions from propellant

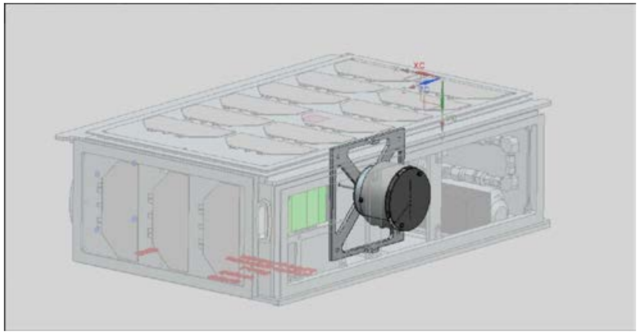
Preliminary testing of chemical mode with a single emitter in vacuum chamber



Payload Description







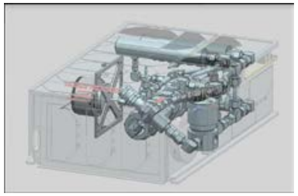
Challenges

- Mass and Volume Constraints: 6U
- Power Constraints: Electric mode requires 3400 V in a compact circuit
- Communication: Pointing constraints
- Propulsion hardware
- Accuracy of GNC hardware
- Capabilities of thruster itself
- Thruster Validation

  -Thruster data downlinked for comparison with ground testing

  -Thrust measured using orbit/attitude changes

Validation Through Propulsion Engineering Data



- **Pressure**
  - Feed system pressure will be measured by pressure transducers in the feed system
  - Provides values just before the propellant storage system and thruster
  - Expected value: 200 psi

- **Temperature**
  - Thermal sensor on the propellant storage system will provide a reference temperature to compare with readings from thermocouples in the thruster itself
  - Expected combustion temperature: 1900 K (1627 degrees Celsius)

- **Voltage**
  - Thruster extractor voltage will be measured by voltage dividers on the digital circuit board at a rate of 1 Hz during electric mode burns
  - Expected value: 3.4 kV

Validating Thruster Performance with Measured Orbit Changes

- Direct thrust measurement with IMU
- Measuring attitude change
- Measuring orbit change
  - Altitude changing maneuver
  - Inclination changing maneuver
  - RAAN changing maneuver

Restrictions: Limited quantity propellant (75 cm^3)

Inertial Measurement Unit Acceleration

- IMU accuracy of 5 mG (0.049 m/s^2)

  - Largest thrust detectable: 0.43 N (for a satellite mass of 8.6 kg)

- Chemical Mode

  - ~1 newton thrust

  - Acceleration ***can*** be measured

- Electric Mode

  - ~0.00025 newton thrust

  - Acceleration undetectable

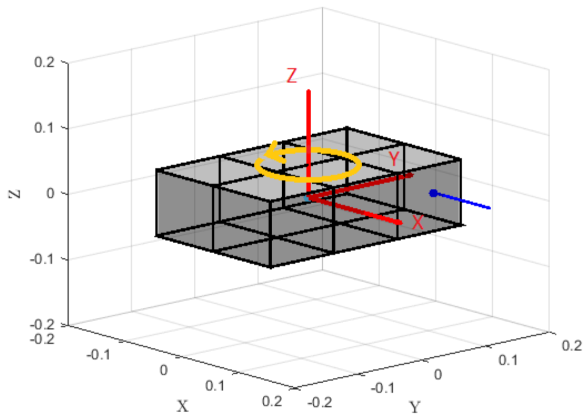
Attitude Change Results

Minimum IMU detectability: 0.21 deg/s with factor of safety = 2

Positioning Thruster to Generate Maximum Torque:

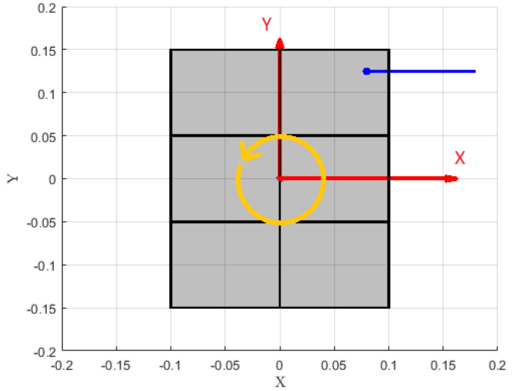
Chemical:

- Burn Time = 1.14 sec or longer
- Change = 0.21 deg/sec



Electric:

- Burn Time = 1.06 hours or longer
- Change = 0.21 deg/sec

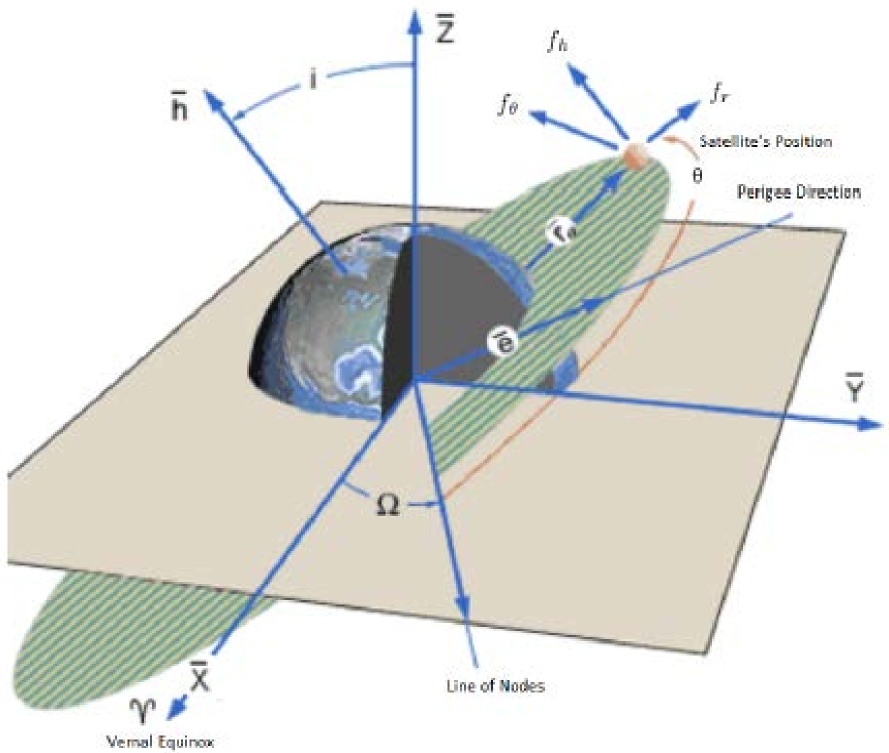


Orbit Changing Maneuver

- Key question: What orbital element gives best “bang-for-the-buck” measurability?

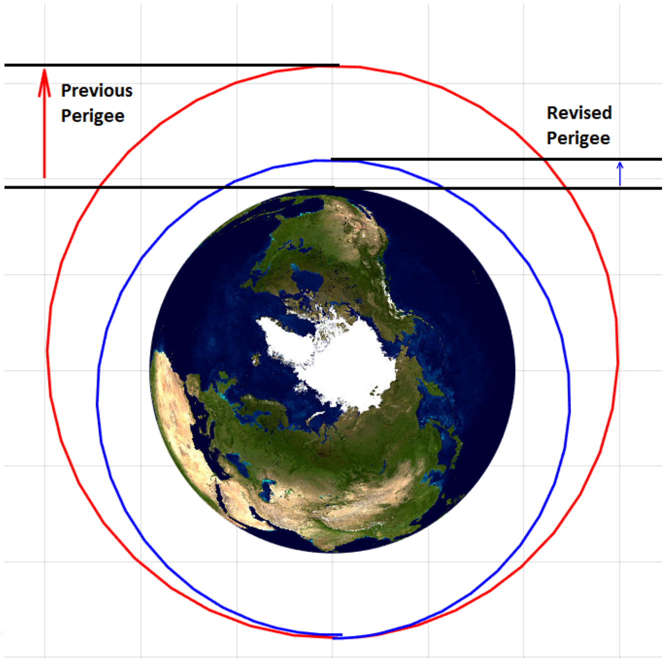
Initial Conditions:

a (km)	e	i	Ω	ω	r (km)
6753.14	0	45°	45°	90°	6753.14

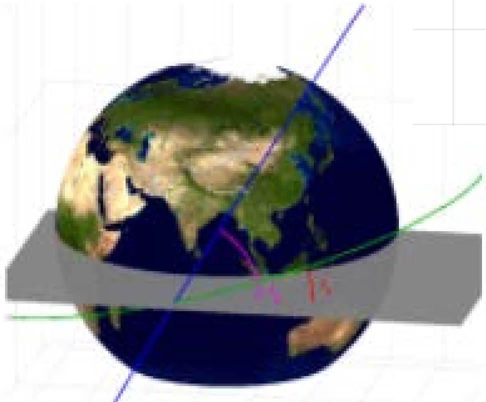


Altitude, Inclination, & RAAN Change

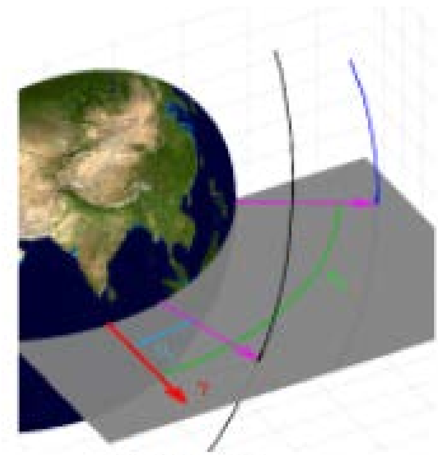
- Inclination: centered about ascending/descending nodes
- RAAN: centered about argument of latitude θ = ± 90°



Periapsis Altitude Change Diagram



Inclination Change Diagram



RAAN Change Diagram

Element Sensitivity Analysis

Maneuver Type	Mode	Burn Length (sec)	Change
Periapsis Altitude	Chemical	5	2.014 km
	Electric	1000	0.106 km
Inclination	Chemical	5	0.00434°
	Electric	1000	0.00021°
RAAN	Chemical	5	0.00613°
	Electric	1000	0.00030°

- RAAN is the clear "winner"
- Now how do we measure the RAAN change and use that to quantify thruster performance?

Quantifying Thruster Performance

- Orbit determination algorithms used to determine orbital elements (RAAN change) using GPS data/measurements
- Attitude determination and control used to maintain thrust normal to orbit plane
- By integrating the Gauss Variational Equations (with constant thrust/mass) the thrust can be determined analytically

Gauss Variational Equations

$$\dot{h} = r f_\theta$$

$$\dot{e} = \frac{r}{h}\left[\sin\theta(1 + e\cos\theta)f_r + (e + 2\cos\theta + e\cos^2\theta)f_\theta\right]$$

$$\dot{i} = \frac{r f_h}{h}\cos\theta$$

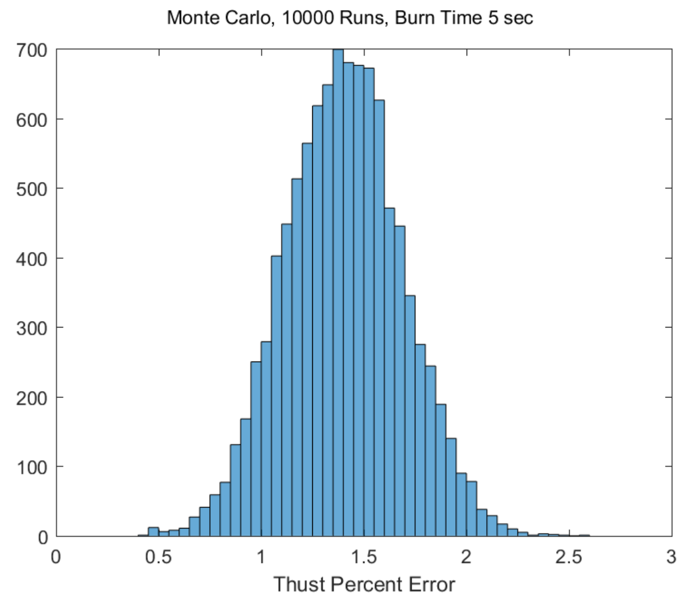
$$\dot{\Omega} = \frac{r f_h \sin\theta}{h\sin i}$$

$$\dot{\omega} = \frac{r}{he}\left[-\cos\theta(1 + e\cos\theta)f_r + \sin\theta(2 + e\cos\theta)f_\theta\right] - \frac{r f_h \sin\theta\cos i}{h\sin i}$$

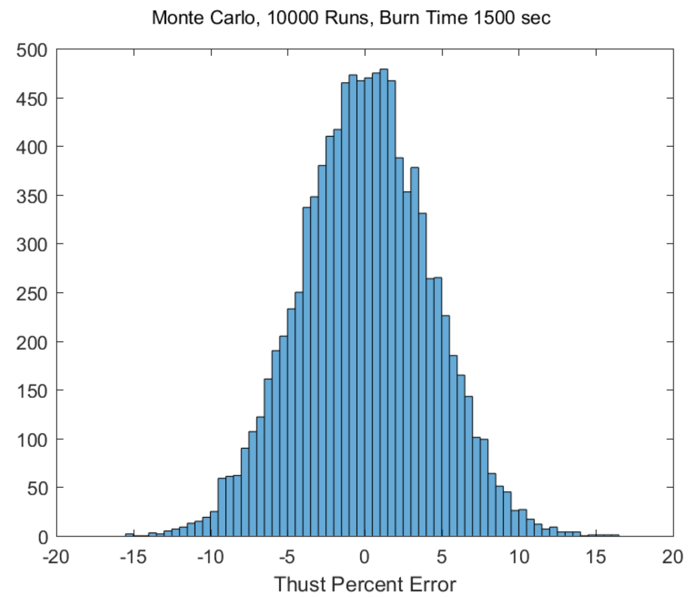
$$\dot{\theta} = \frac{h}{r^2} - \frac{r f_h \sin\theta\cos i}{h\sin i}$$

Thruster Performance Cont.

- Considering the accuracy of GPS data we are confident in being able to determine the thrust within 10% of the true value



Chemical Mode (1 N thrust)



Electric Mode (0.25 mN thrust)

Ω noise: σ = 12.72 μ-degrees

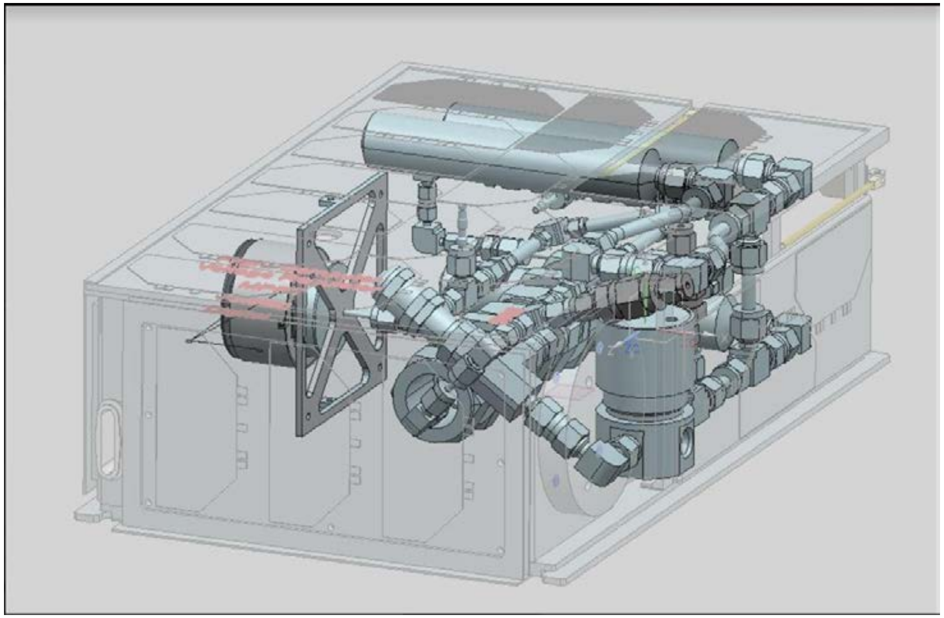
Final Remarks

- Thruster qualitatively validated with downlinked engineering data
- Thruster quantitatively validated using change in RAAN
- Considering also corroborating with change in inclination and IMU/accelerometer
- Considering expanding our paper, after receiving reviewer feedback, to apply to more general CubeSat missions

Acknowledgments

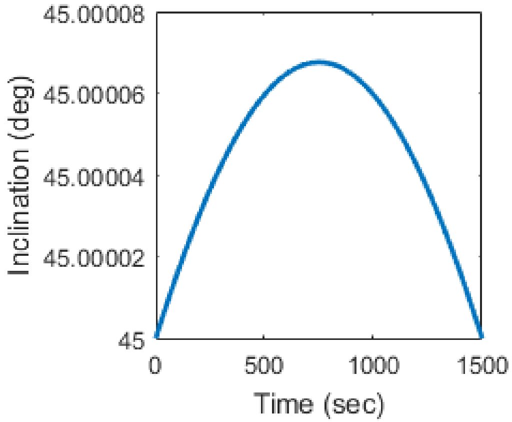
- Dr. Henry Pernicka: Missouri S&T professor, advisor for Missouri S&T satellite research team
- Dr. Joshua Rovey, Dr. Steven Berg : Missouri S&T Aerospace Plasma Lab
- Alex Mundahl, Mitchell Wainwright: Missouri S&T Aerospace Plasma Lab

Questions?



Backup Slides

Solving for Thrust



$$\dot{\Omega} = \frac{r f_h}{h \sin(i)} \sin(\theta)$$

Assuming circular orbit ($r = const$ and $\dot{\theta} = n = \left(\mu/_{a^3}\right)^{1/2}$)

$$\int_{\Omega_i}^{\Omega_f} d\Omega = \int_0^t \frac{r f_h}{h \sin(i)} \sin(\theta)\ dt = \frac{r f_h}{h \sin(i)} \int_0^t \sin(\theta)\ dt$$

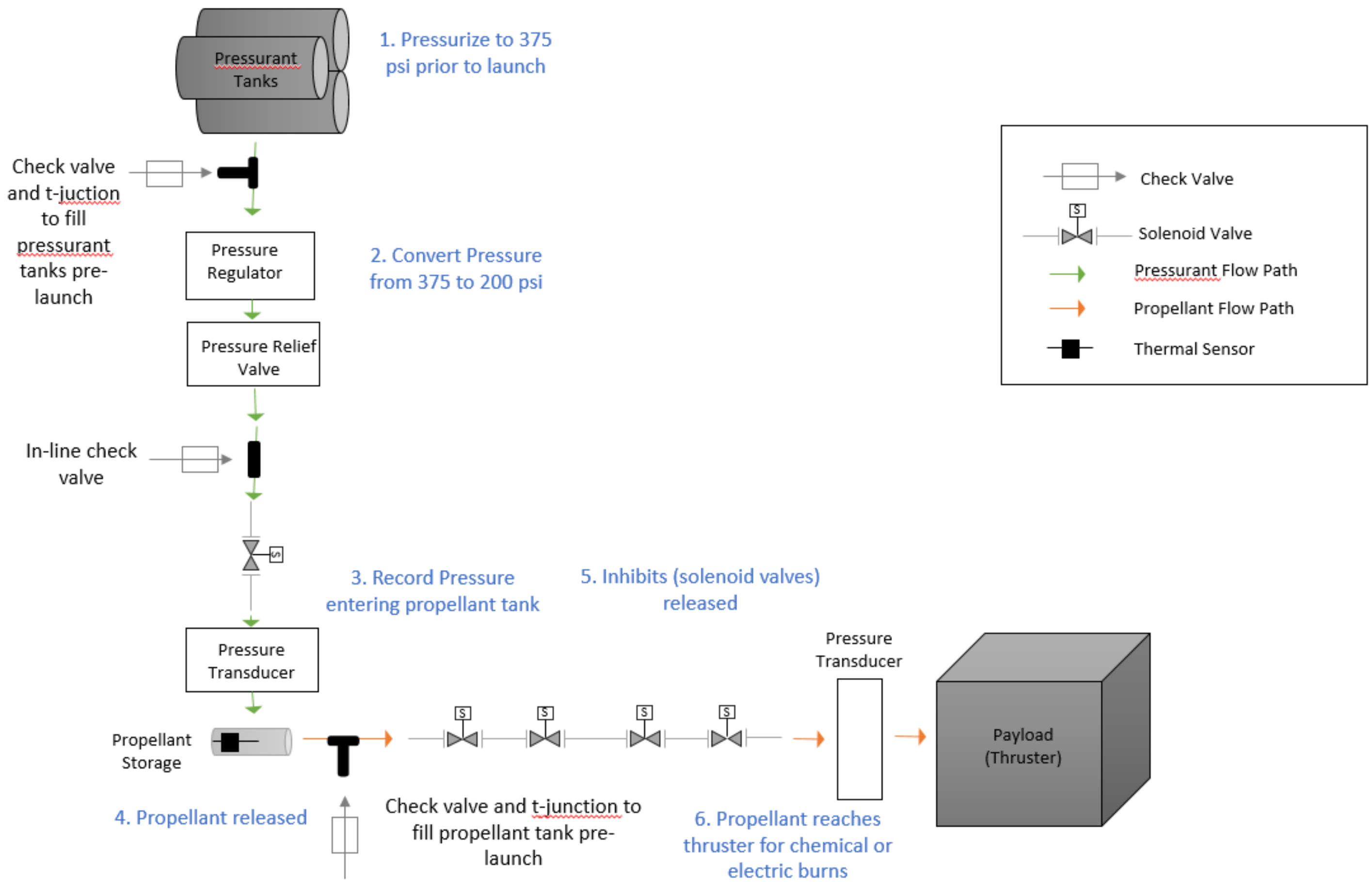
Where $i \approx const$ so $\sin(i) = const$ resulting in

$$\Delta\Omega = \frac{r f_h}{h \sin(i)\, n} \left[\cos(\theta_i) - \cos(\theta_f)\right]$$

Rearranging

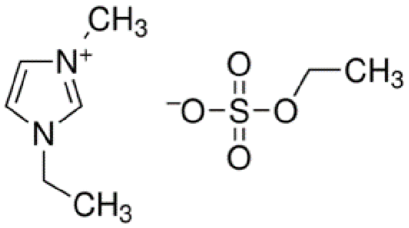
$$f_h = \frac{F}{m} = \frac{\Delta\Omega h \sin(i)\, n}{r\left[\cos(\theta_i) - \cos(\theta_f)\right]}$$

Propellant Feed System

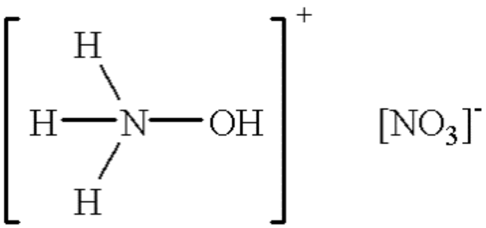


Propellant Composition

- Monopropellant Mixture: 41% Fuel 59% Oxidizer
- Fuel: 1-ethyl-3-methylimidazolium ethyl-sulfate ([Emim][$EtSO_4$])
- Oxidizer: Hydroxylammonium Nitrate (HAN)

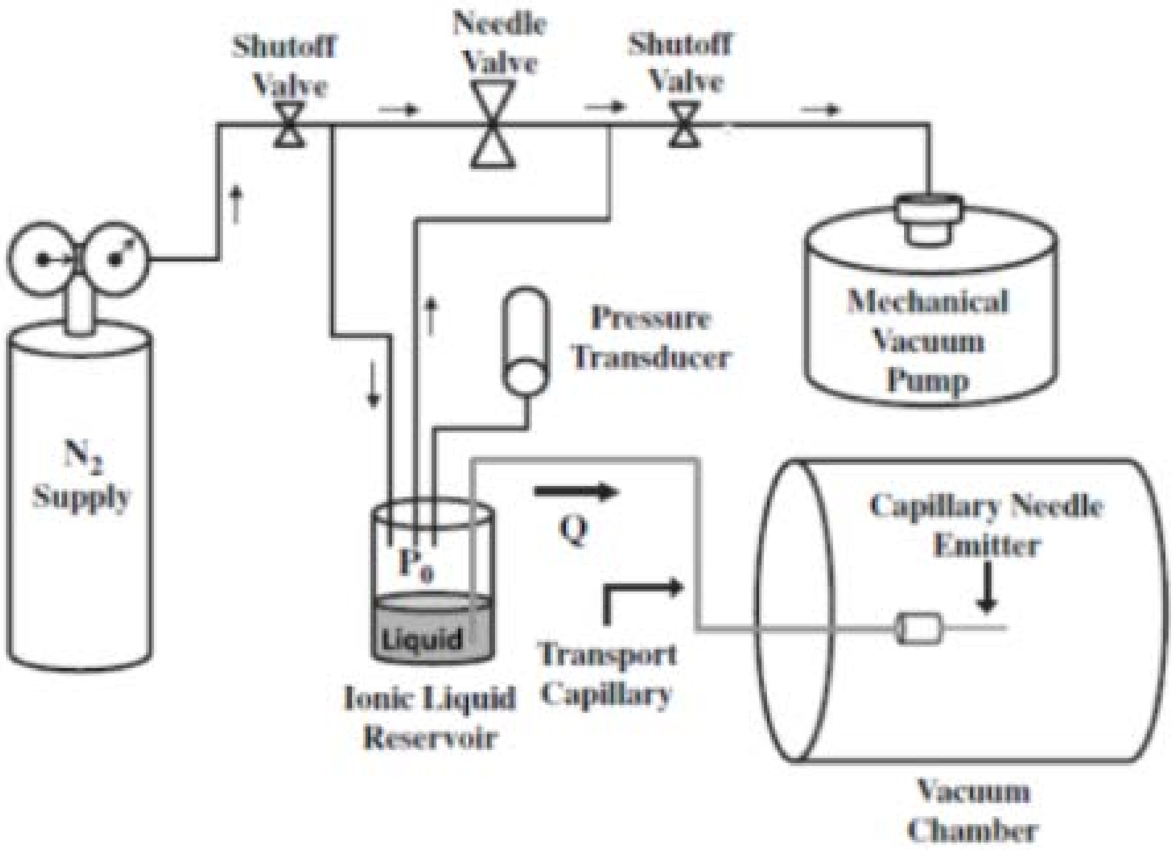


[Emim][$EtSO_4$]



HAN

Electrospray Mode Set Up



Plumbing and Instrumentation Diagram of the Electrospray Apparatus