Operational Considerations for CubeSats Beyond Low Earth Orbit

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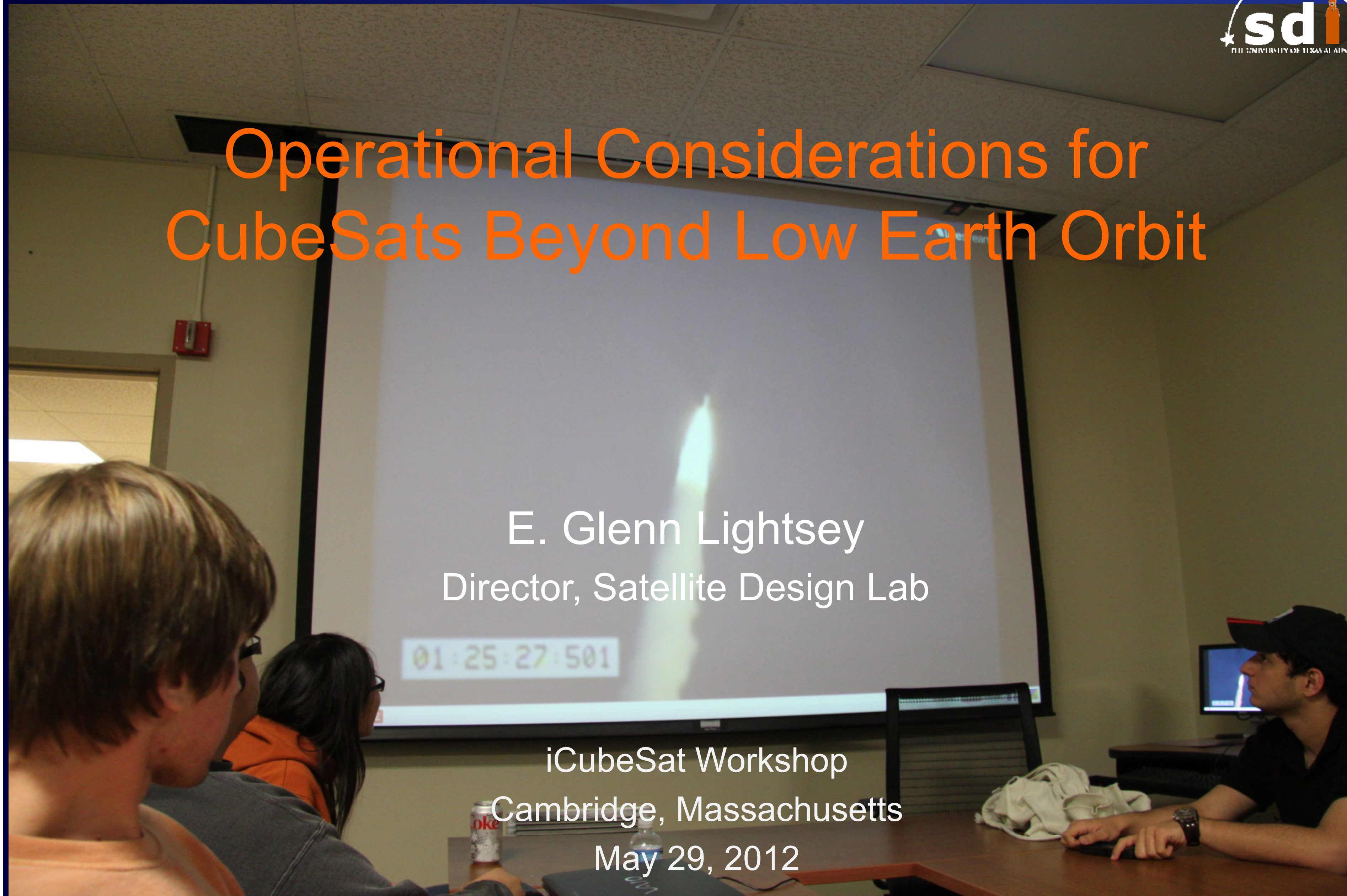


Image: *UT-Austin Satellite Design Lab*

Why We Care About This Topic

- Potential Role for CubeSats Beyond Low Earth Orbit

- CubeSats can provide lower cost, easier access to space
- Opens space exploration to a wider range of participants
- Increased missions allow more opportunities for innovation
- Academic CubeSats (University and K12) encourage STEM career choices

- Raise public awareness and interest in space exploration

Image: *NASA*, CubeSat: *UT-Austin Satellite Design Lab*

- The interplanetary environment has different considerations from LEO which affect mission success
- To design interplanetary CubeSat missions, we must be aware of the environment and take these factors into account

Design Challenges for Interplanetary Spacecraft

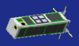
- Radiation
- Lifetime
- Navigation and Control
- Communications
- Power
- Temperature

- Question:

Are CubeSats viable as lower cost alternatives, or as value-added mission enhancers to larger interplanetary space missions?

Image: *NASA*

Example: Integrated Mars Science Laboratory *Curiosity* with EDL system weighs more than 3000 kg.

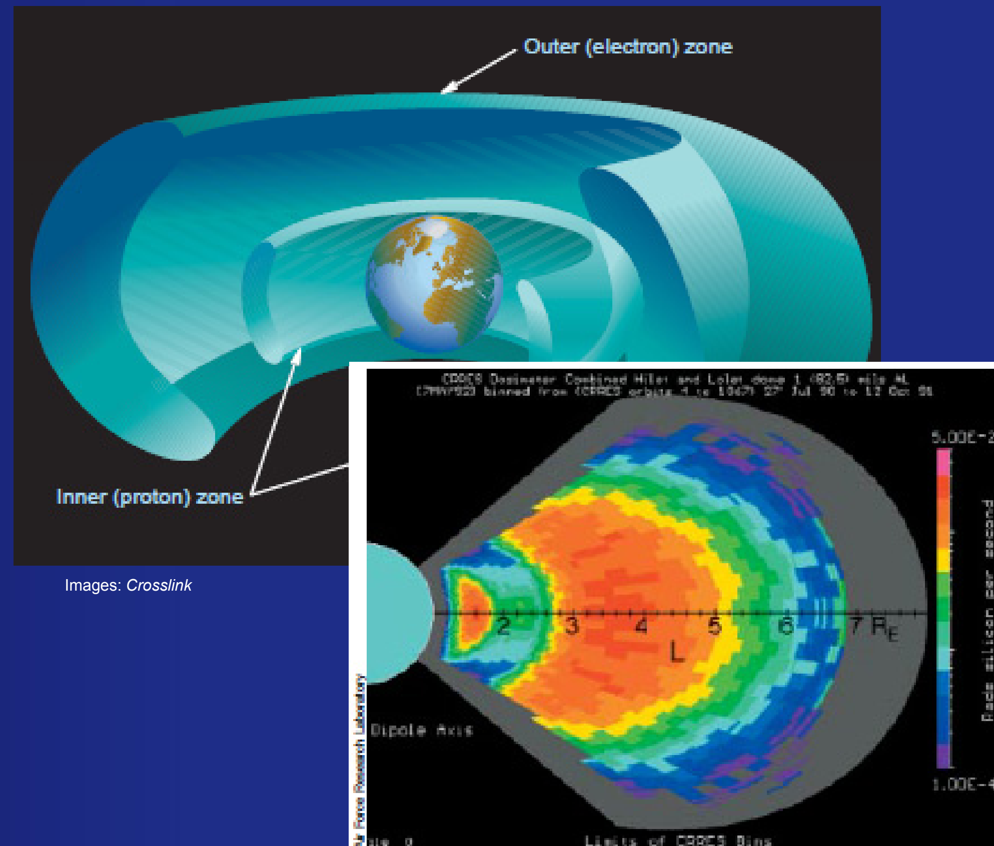


(CubeSat drawn to scale)

One 3U CubeSat weighs less than 5 kg.

The Space Radiation Environment

- Characterized by duration and energy of radiation exposure
- Determined by solar and cosmic forcing interaction with magnetic fields
- Planetary magnetic fields provide both protection from energetic particles (e.g., LEO) and concentrated regions of these particles
- Interplanetary space is dominated by the solar wind, which is not as intense, but always present
- Cosmic rays can cause single event effects at any time and location



Images: *Crosslink*

Example: Earth's van Allen belts trap charged particles and provide locally intense radiation
Inner Proton Belt: h ~ 2,500 – 5,000 km
Outer Electron Belt: h ~ 12,000 – 22,000 km

Planetary Magnetic Fields

Object	Equatorial Field Strength (Gauss)	Relative Field Strength at Equator
Mercury	0.003	0.011*
Venus	0	0
Earth	0.307	1
Moon	0	0
Mars	0	0
Jupiter	4.54	14.8
Saturn	0.233	0.76
Uranus	0.234	0.76
Neptune	0.144	0.47

*significantly greater solar particle flux

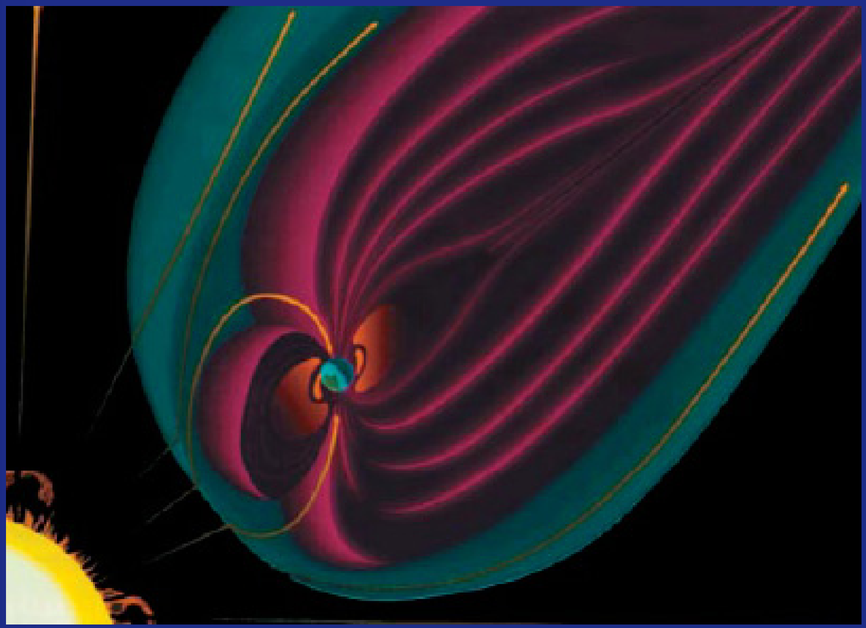
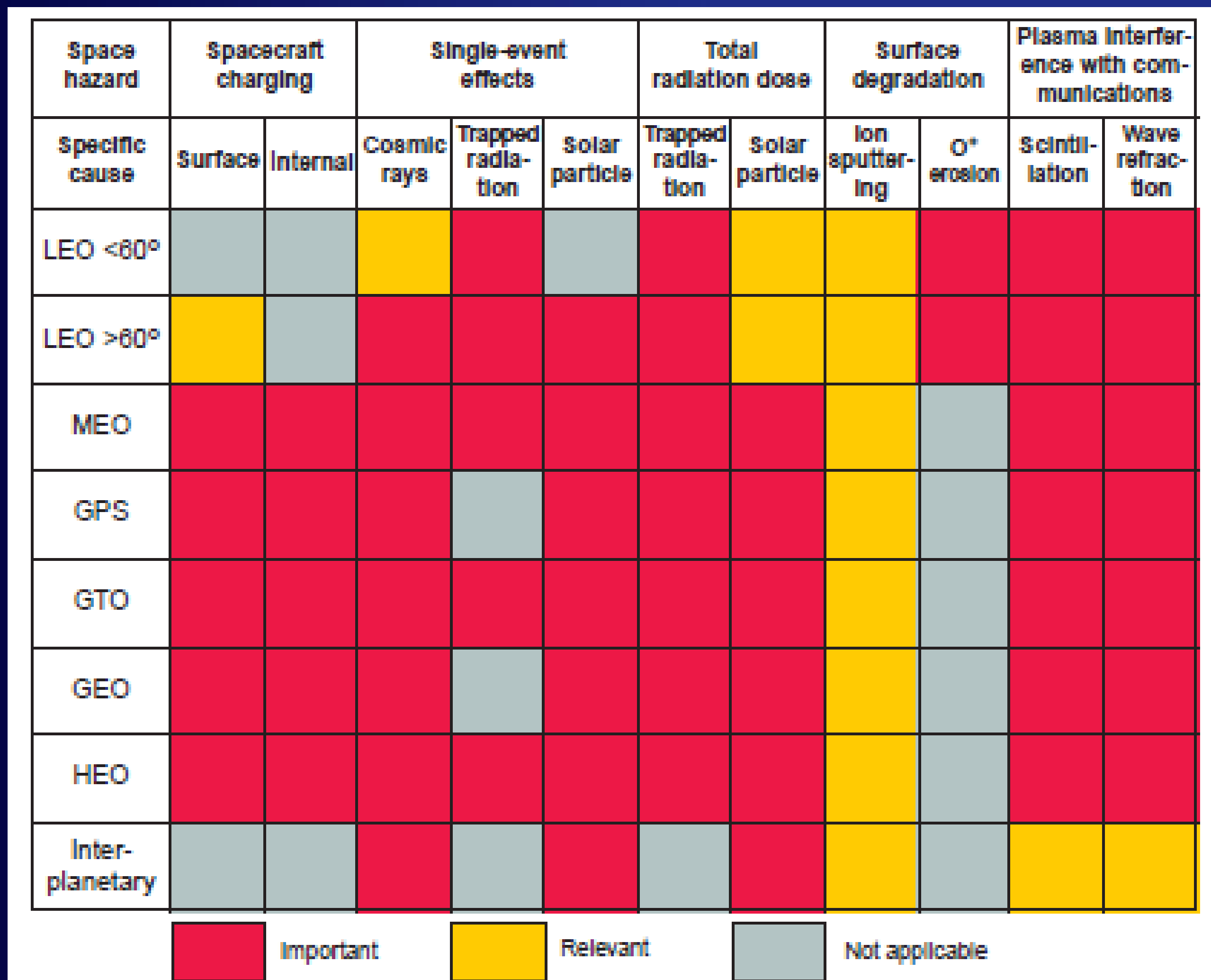


Image: *Crosslink*

Distribution of energetic particles is affected by strength of planetary magnetic field. Stronger fields will hold more energetic particles for longer times, creating more intense radiation environments.

Radiation Effects in Different Orbits



Source: *Crosslink*

How Radiation Affects Spacecraft Electronics

- A circuit requires a highly ordered system of components to work properly
- Radiation processes increase the entropy of the circuit, causing it not to work as well
- More intense particle fields can also cause spacecraft charging*, degrade surfaces, and damage photodetectors

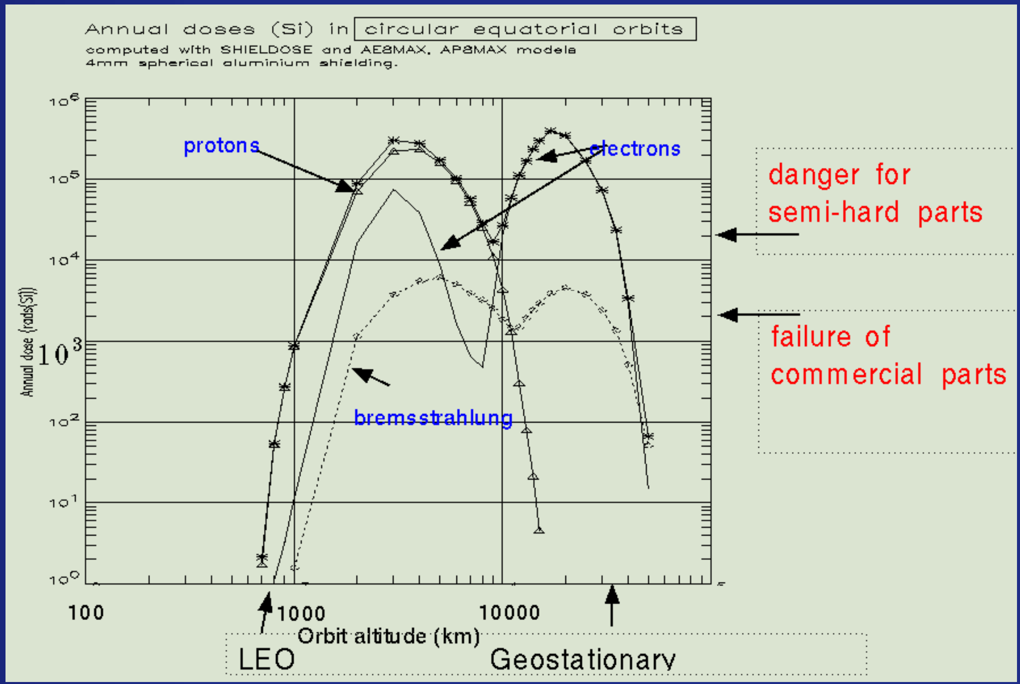
*Leading radiation-related cause of spacecraft failures.

Radiation environment	Shielding feasibility	Typical effects
Total ionizing dose Permanent bit flips Damaged electronics Increased power	Some	–Threshold shifts in CMOS transistors, leading to failure of logic gates –CMOS field-oxide charge trapping, loss of isolation, excessive power-supply currents –Power transistor threshold shifts, loss of on/off control –Gain degradation in bipolar-junction transistors
Neutron or proton flux events Damage to CCDs, Dynamic memories, Surface charging	Some	–Displacement damage effects –Gain degradation in bipolar-junction transistors –Severe degradation of charge-coupled devices, dynamic memory performance –Damage to photodetectors
Single-event phenomena Temporary bit flips Power resettable bit flips "Latchup" Pemanent malfunction "Burnout"	Some	–Single heavy ion causes ionization "track" –Temporary logic scramble –Single bit errors in static memories –Localized latchup in CMOS integrated circuits –Gate rupture of power transistors –Temporary upset of analog devices such as amplifiers –Burnout of diodes, transistors –Discharge of capacitors

Source: *Crosslink*

Are Today's Devices More Susceptible to Radiation?

- Rewritable flash devices (e.g., FPGA's) are generally softer than programmable read-only devices
- More dense placement of components creates shorter paths for leakage and interference
- BUT, smaller, thinner components are less susceptible to build up effects such as total ionizing dose
- COTS parts are generally not designed for radiation tolerance
- "Typical" COTS parts will provide ~5-10 krad Si total dose lifetime, ~6-24 months in LEO
- Can expect similar performance to LEO in interplanetary space

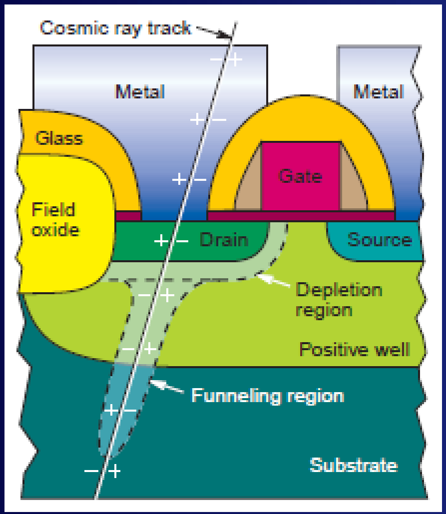


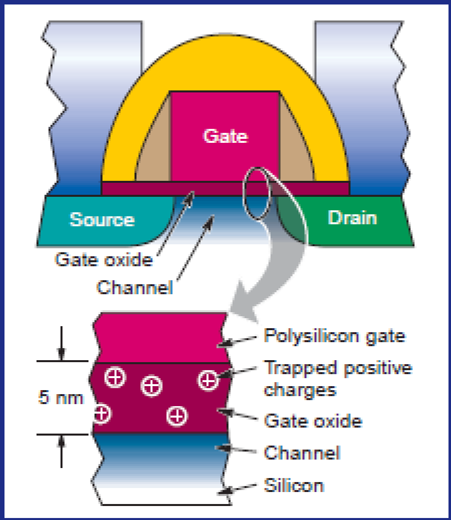
Source: *Space Environment Analysis, Experience and Trends*

- Operation in radiation belts, or longer duration missions (e.g. GEO, interplanetary) may require radiation-hardened components

Radiation Environment Mitigation Methods

- Single Event Effects
  - Use radiation tolerant components
  - Memory Scrubbing
  - Triple Module Redundancy
  - Selective Functional Redundancy
  - Operational planning for SEE tolerance
- Total Dose Lifetime
  - Use radiation tolerant components
  - Selective Shielding of Sensitive Parts
  - Selective Hardware redundancy





Images: *Crosslink*

Attitude Determination and Control

- CubeSat COTS Integrated ADC solutions exist, but most are intended for LEO
- Sensor and actuator selection is reduced for interplanetary missions

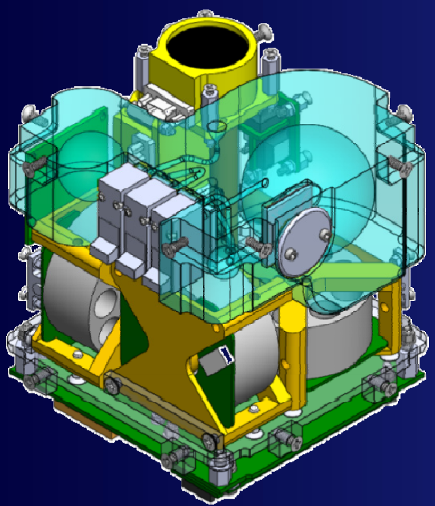


Image: *UT-Austin Satellite Design Lab*

Example: Integrated 1U 3-axis ADC with thruster

External Sensors	Estimated Accuracy (degrees)	Comment
Sun Sensor	0.1	available
Star Camera	0.01	in development
Horizon Detector	varies	used near objects
Deep Space Network	1	requires NASA support
Earth Sensor	0.1	Earth orbit
Magnetometer	1	LEO
GPS	1	LEO

Actuators	Estimated Accuracy (degrees)	Comment
Reaction Wheels	0.01	available
Impulsive Thruster	0.01	in development
Solar sails	1	in development
Torque Rods	1	LEO

Navigation Beyond LEO

- Traditional methods with Deep Space Network probably not an option for CubeSats
- GPS possible in Earth orbit, but not beyond
- Interplanetary navigation needs during cruise are usually modest
- Near planetary objects, horizon imaging provides relative navigation
- Autonomous navigation algorithms need further development

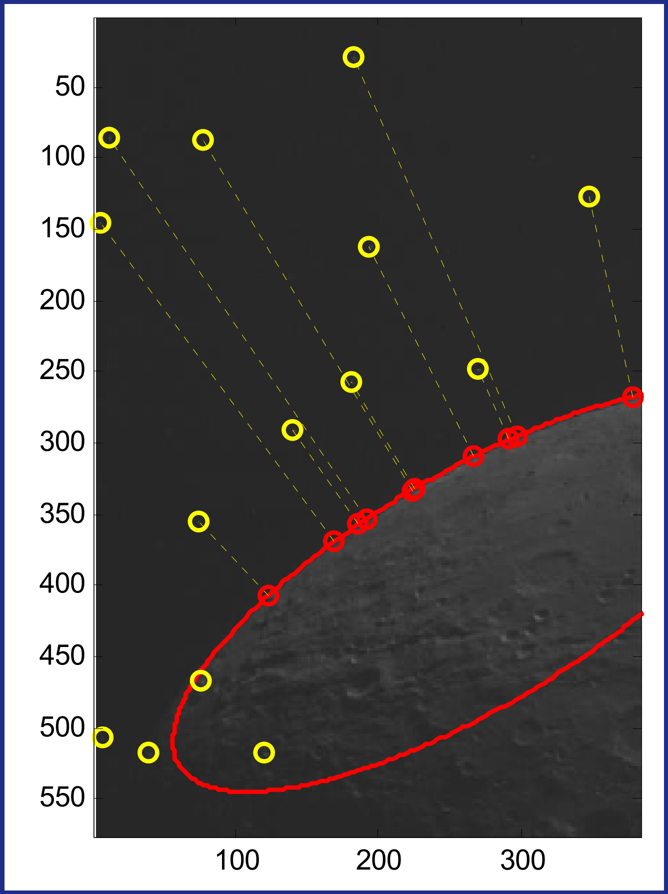


Image: *UT-Austin Satellite Design Lab*

Example star-horizon navigation algorithm (distances in km).

CubeSat Communications Beyond LEO

- Free space path loss makes direct satellite to ground link challenging
- E.g. at Lunar orbit, additional
  -38 dB path loss requires kWs of transmit power to close equivalent of 1W LEO link
- Mitigation methods:
  - Directional antenna
  - Deployable antenna
  - Attitude Control
  - Larger Ground Station
  - Bent Pipe (Mother/Daughter Ship)
  - Stored Data
- For interplanetary missions, consider light-time delays in operations

Image: *NASA*

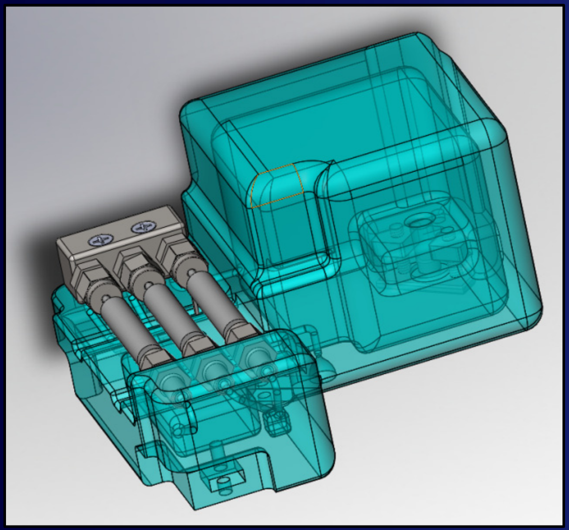
Example: Traditional Interplanetary communications uses NASA's Deep Space Network to compensate for path loss

Maneuverable CubeSat Thruster

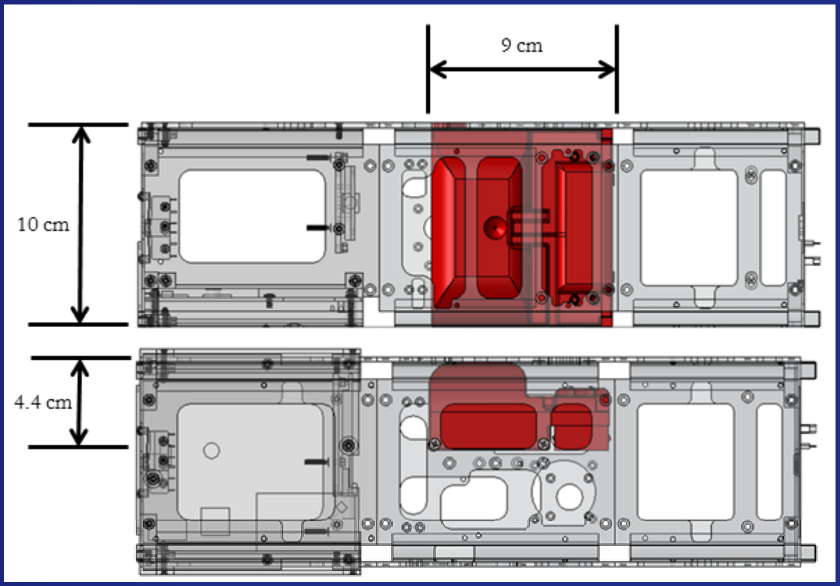
Stereo Lithography Thruster Concept pioneered by The Aerospace Corp. on MEPSI STS-126, 2008

Advantages of Stereo Lithography:

- The only interface is the exchange between thruster and control valves
- All internal plenums and pipes are stereo-lithographed and are essentially leak free
- Built in converging-diverging nozzle
- Production of apparatus is quick and inexpensive allowing for an iterative design



In-House Thruster Module (**Above**)
Thruster Design integrated in 3U CubeSat (**Right**)



Images: *UT-Austin Satellite Design Lab*

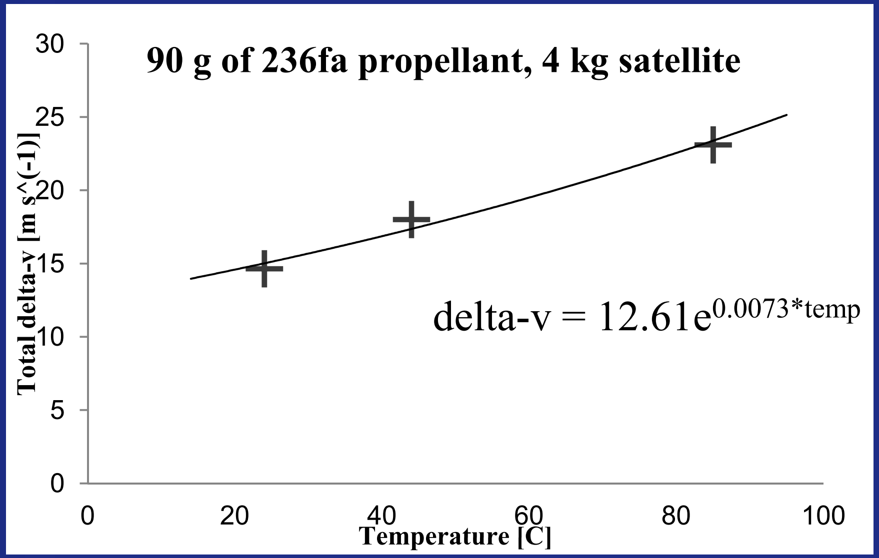
CubeSat Thruster Performance Testing

R236fa propellant

- Relatively Low Pressure at 60C
- Inert Gas
- Measured >15 m/s delta-v, 65 s Isp

Conducted Several Tests at Vacuum

- Outgassing / Leakage Tests
- Operational Tests
- Thrust Quantification Tests



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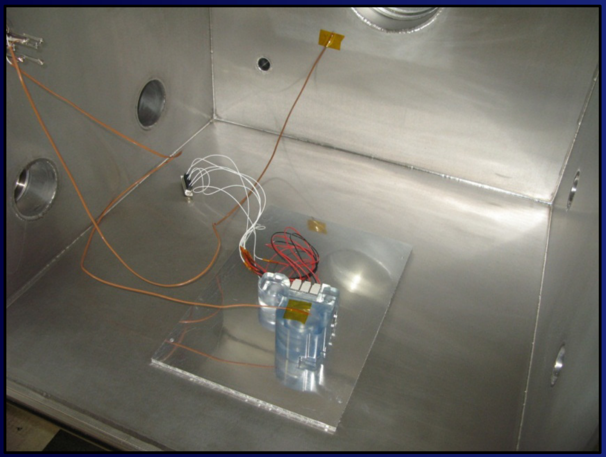
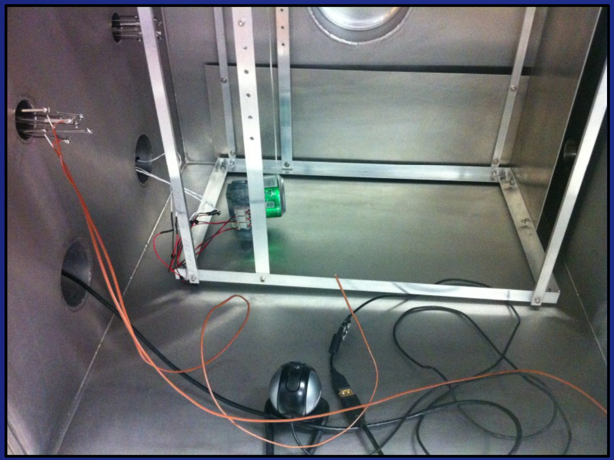


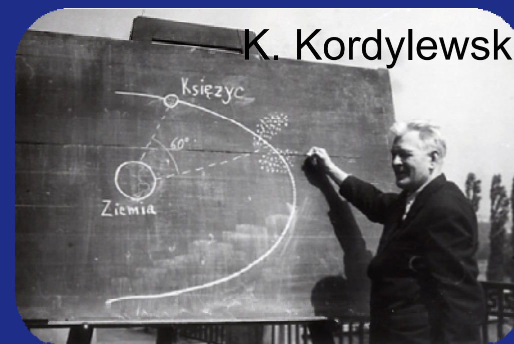
Thruster Vacuum Test

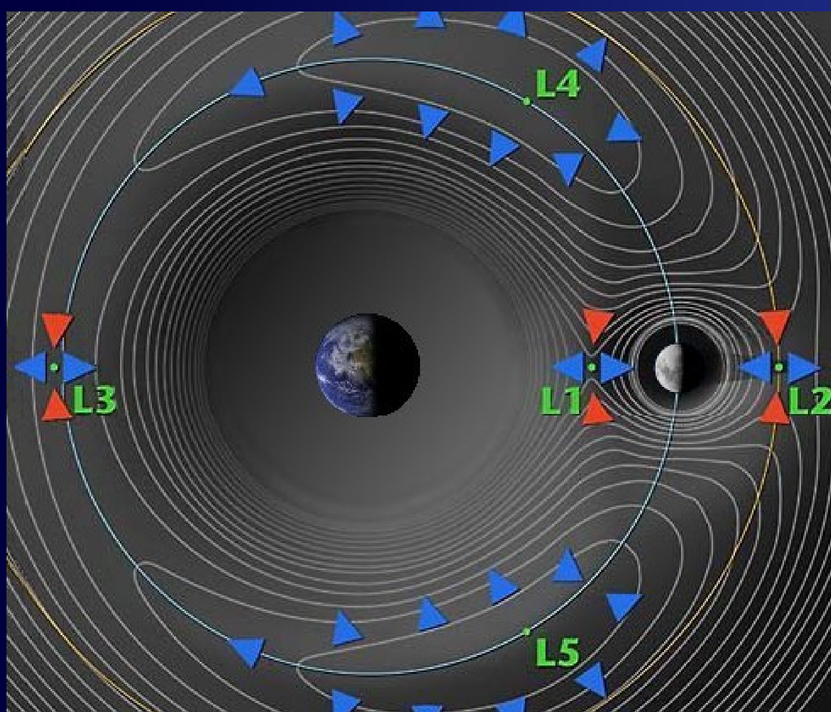


Thruster Impulse Determination Test

Example CubeSat Mission : Kordylewski Cloud Explorer

- Examine Potential Debris Field at Earth-Moon L4, L5 Libration Points
- Scientific Debate over whether Debris actually exists there





- Could we go to the Kordylewski Clouds with a low cost Cubesat-like target of opportunity?
- Could we do a Stardust-like sample return mission with a CubeSat?

Images: *GPL/Wikipedia*

Kordylewski Cloud Mission Concept

Images: *ESA, Univ. Stuttgart, Aerospace Corp., UT Austin Satellite Design Lab*

- CubeSat probe carried as a secondary payload during an Earth-Moon transfer
- Ejected from a SMART-1 type mission for L4/L5 fly-through
- Impulsive cold-gas thruster is able to provide needed delta-v for mission

Conclusion

- Operational Challenges for Interplanetary CubeSat Missions:
  - Radiation
  - Lifetime
  - Navigation and Control
  - Communications
  - Power
  - Temperature

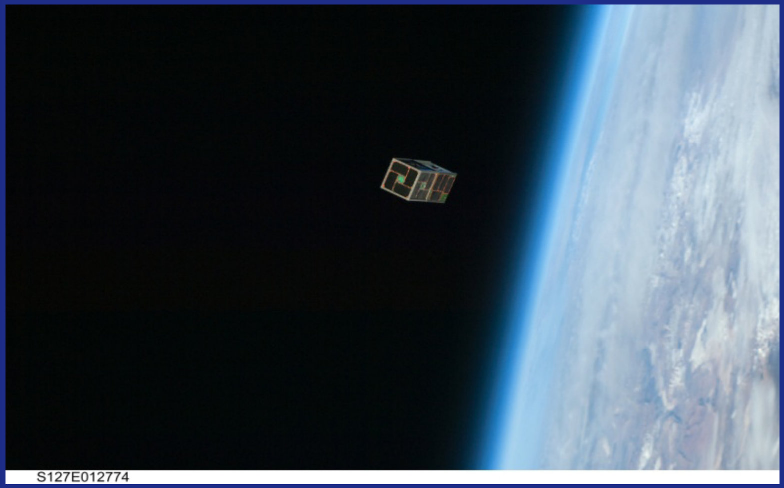


Image: *NASA*

Example: Future Interplanetary CubeSat mission?
(Actual photo of UT-Austin CubeSat deployed in 2009)

- With Careful Design, Many Interesting Mission Types are Possible with CubeSats:
  - Mother/Daughter Missions
  - Sample Return
  - Sensor Swarms
  - Surface Probes

References

- For questions relating to space radiation effects:
  - *Crosslink*, The Aerospace Corp., Vol. 4, No. 2, Summer 2003.
- For questions relating to the UT-Austin Satellite Design Lab:
  - Glenn Lightsey, email: lightsey@mail.utexas.edu
  - http://lightsey.ae.utexas.edu

Thank You