Operational Considerations for CubeSats Beyond Low Earth Orbit

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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

- 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

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

**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

Example: Earth’s van Allen belts trap charged particles and provide locally intense radiation
Inner Proton Belt: $h \sim 2,500 – 5,000$ km
Outer Electron Belt: $h \sim 12,000 – 22,000$ km
Planetary Magnetic Fields

<table>
<thead>
<tr>
<th>Object</th>
<th>Equatorial Field Strength (Gauss)</th>
<th>Relative Field Strength at Equator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.003</td>
<td>0.011*</td>
</tr>
<tr>
<td>Venus</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Earth</td>
<td>0.307</td>
<td>1</td>
</tr>
<tr>
<td>Moon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mars</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>4.54</td>
<td>14.8</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.233</td>
<td>0.76</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.234</td>
<td>0.76</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.144</td>
<td>0.47</td>
</tr>
</tbody>
</table>

*significantly greater solar particle flux

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

<table>
<thead>
<tr>
<th>Space hazard</th>
<th>Spacecraft charging</th>
<th>Single-event effects</th>
<th>Total radiation dose</th>
<th>Surface degradation</th>
<th>Plasma interference with communications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific cause</td>
<td>Surface Internal Cosmic rays Trapped radiation Solar particle Trapped radiation Solar particle Ion sputtering O+ erosion Scintillation Wave refraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO &lt;80°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO &gt;80°</td>
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<td></td>
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<td></td>
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<tr>
<td>MEO</td>
<td></td>
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<tr>
<td>GPS</td>
<td></td>
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<tr>
<td>GTO</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HEO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interplanetary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Radiation environment</th>
<th>Shielding feasibility</th>
<th>Typical effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ionizing dose</td>
<td>Some</td>
<td>-Threshold shifts in CMOS transistors, leading to failure of logic gates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-CMOS field-oxide charge trapping, loss of isolation, excessive power-supply currents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Power transistor threshold shifts, loss of on/off control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Gain degradation in bipolar-junction transistors</td>
</tr>
<tr>
<td>Neutron or proton flux events</td>
<td>Some</td>
<td>-Displacement damage effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Gain degradation in bipolar-junction transistors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Severe degradation of charge-coupled devices, dynamic memory performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Damage to photodetectors</td>
</tr>
<tr>
<td>Single-event phenomena</td>
<td>Some</td>
<td>-Single heavy ion causes ionization “track”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Temporary logic scramble</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Single bit errors in static memories</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Localized latchup in CMOS integrated circuits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Gate rupture of power transistors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Temporary upset of analog devices such as amplifiers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Burnout of diodes, transistors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Discharge of capacitors</td>
</tr>
</tbody>
</table>

Permanent bit flips
Damaged electronics
Increased power

Temporary bit flips
Power resettable bit flips
“Latchup”
Permanent malfunction
“Burnout”

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

- 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
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

<table>
<thead>
<tr>
<th>External Sensors</th>
<th>Estimated Accuracy (degrees)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Sensor</td>
<td>0.1</td>
<td>available</td>
</tr>
<tr>
<td>Star Camera</td>
<td>0.01</td>
<td>in development</td>
</tr>
<tr>
<td>Horizon Detector</td>
<td>varies</td>
<td>used near objects</td>
</tr>
<tr>
<td>Deep Space Network</td>
<td>1</td>
<td>requires NASA support</td>
</tr>
<tr>
<td>Earth Sensor</td>
<td>0.1</td>
<td>Earth orbit</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>1</td>
<td>LEO</td>
</tr>
<tr>
<td>GPS</td>
<td>1</td>
<td>LEO</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actuators</th>
<th>Estimated Accuracy (degrees)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Wheels</td>
<td>0.01</td>
<td>available</td>
</tr>
<tr>
<td>Impulsive Thruster</td>
<td>0.01</td>
<td>in development</td>
</tr>
<tr>
<td>Solar sails</td>
<td>1</td>
<td>in development</td>
</tr>
<tr>
<td>Torque Rods</td>
<td>1</td>
<td>LEO</td>
</tr>
</tbody>
</table>

Example: Integrated 1U 3-axis ADC with thruster

Image: UT-Austin Satellite Design Lab
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

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

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
CubeSat Thruster Performance Testing

R236fa propellant
- Relatively Low Pressure at 60°C
- Inert Gas
- Measured >15 m/s delta-v, 65 s Isp

Conducted Several Tests at Vacuum
- Outgassing / Leakage Tests
- Operational Tests
- Thrust Quantification Tests

\[ \text{delta-v} = 12.61 e^{0.0073 \times \text{temp}} \]

90 g of 236fa propellant, 4 kg satellite

Images: UT-Austin Satellite Design Lab

Thrust Vacuum Test

Thruster Impulse Determination Test

The University of Texas at Austin
Satellite Design Lab
Operational Considerations Beyond Low Earth Orbit
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

- 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

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:

• For questions relating to the UT-Austin Satellite Design Lab:
  – Glenn Lightsey, email: lightsey@mail.utexas.edu
  – http://lightsey.ae.utexas.edu

Thank You