Radiation Environment Effects on Spacecraft

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To be presented by Raymond L. Ladbury at the NASA Ames Research Center Radiation Meeting, Mountain View, CA, November 6, 2017.
Outline

• Diversity of Space Radiation Environments: Space is not a Place
  • Low Earth, Low Inclination orbits of Earth
  • Polar and Geostationary
  • Interplanetary
  • Other planets and Beyond

• Radiation Threats
  • Degradation Mechanisms
  • Spacecraft Charging
  • Single-Event Effects

• Radiation Hardness Assurance (RHA)
  • Testing
  • Mitigation
Space Is Not A Place: Many Different Space Radiation Environments

• Radiation Effects
  • Cumulative Effects
    • Materials/surface degradation, Total Ionizing and Displacement Damage Dose (TID and DDD)
    • Prompt effects—Single-Event Effects (SEE), Transient Radiation Effects on Electronics (Sadly, we can’t ignore this anymore)

• Relevant environment for any particular radiation effect depends on many factors:
  • Position in space
    • Proximity to Sun
    • Longitude and latitude near planet with magnetic field
    • Altitude above a planet (geometric and magnetic shielding)
    • Proximity to (cough, cough) manmade sources
  • Time
    • Solar Maximum vs. Solar Minimum
    • Solar Weather, Wind and Events
  • Material/Shielding around susceptible element
  • Material Properties (thermal + electrical conductivity, optical properties, …)

• These many radiation environments tell us: Space is not a place

Sources of Radiation
• Galactic Cosmic Rays—present in all space environments; planetary magnetic fields provide shielding in some orbits
• Charged particles trapped by planetary magnetic fields
• Solar Particle Events—sporadic large increases in particle fluxes due to Solar Coronal Mass Ejections, flares, etc.
• Space Plasma environment (including atomic oxygen) important for surface degradation in some orbits

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Where Is Space Radiation And Where Does It Come From?

- Galactic Cosmic Rays (GCR)—VERY high energy, All Z
  - Small flux means main concern is SEE, even hard devices

- Solar Particle Event (SPE)—Moderate energy, Z variable
  - Intermittent high flux—SEE, TID, DDD all concerns

- Trapped radiation belts—mainly protons and electrons
  - High, variable flux; protons—TID, DDD, SEE; e⁻—TID, DDD, charging (electrostatic discharge (ESD))

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Effects of Space Radiation

**Solar Panels**
Degraded power from TID/DDD
ESD from surface charging

**Avionics**
DDD/TID degradation/failure
SEE/ESD malfunction/failure

**Power Electronics**
DDD/TID degradation/failure
Destructive SEE failure

**Contamination**
Materials degraded by TID/DDD, atomic O, charging
contaminate optics, etc.

**Guidance and Navigation**
Station-keeping/pointing errors from SEE
Star tracker false stars (SEE) and noisy pixels (DDD)

**Communications**
Bit flips/lost data due to SEE/ESD

**Thermal from TID/plasma**
Darkening of surfaces
Materials degradation

**Optics**
Darkening of optics from TID
Detector degradation from DDD

**Surface/Materials**
Degradation due to plasma, atomic oxygen, TID, charging

**Payload**
Loss of data, availability, total loss due to SEE, ESD
Degradation, eventual failure due to TID, DDD

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SEE and ESD—Relative Risks and Rates

### Attribution of Anomalies

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Number of Forms</th>
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<tbody>
<tr>
<td>ESD - Internal Charging</td>
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<tr>
<td>ESD - Surface Charging</td>
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<tr>
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<td>Surface Charging</td>
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<tr>
<td><strong>Total ESD &amp; Charging</strong></td>
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<tr>
<td>SEU - Cosmic Ray</td>
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<tr>
<td>SEU - Solar Particle Event</td>
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<tr>
<td>SEU - South Atlantic Anomaly</td>
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<tr>
<td>SEU - Uncategorized</td>
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<td><strong>Total SEU</strong></td>
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<td>Total Radiation Dose</td>
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<tr>
<td>Materials Damage</td>
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<td>South Atlantic Anomaly</td>
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<tr>
<td><strong>Total Radiation Damage</strong></td>
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<td>Magnetic Field Variability</td>
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<td>Plasma Effects</td>
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<td>Atmospheric Drag</td>
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<tr>
<td>Energetic Electrons</td>
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<td><strong>Other</strong></td>
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<tr>
<td><strong>Total Miscellaneous</strong></td>
<td><strong>36</strong></td>
</tr>
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</table>

Adapted from *Space Radiation Environment – A Short Course, NSREC 2016, Paul O’Brien and Joe Mazur*

Key: CRRES—Combined Release and Radiation Effects Satellite; MEP—Microelectronics Package Space Experiment; SEU—Single-Event Upset; VTCW—vehicle time code word

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Radiation Effect Characteristics: Single-Event Effects

Characteristics and sources of error determine RHA approach, testing protocols and effective mitigations

- Radiation tests potentially destructive, so must be done on sample representative of flight parts
  - SEE usually vary little part to part or lot to lot
  - Not always true, especially for destructive SEE
- Poisson process
  - Just as likely for first ion as for the last
  - All SEE are independent of all others
  - Process is Poisson per unit ion, not per unit time
- Vulnerability depends on application conditions
  - Voltages, temperature, state of operation...
  - Parts only vulnerable when biased
- Relevant environments include
  - Galactic Cosmic Rays
  - Trapped protons
  - Solar-Event protons and heavy ions
- “Representative”=same process and mask set
- Poisson process implies: even low-rate modes can occur any time in the mission
  - High fluence, high-LET heavy-ion test for worst-case application conditions important to ensure detection
  - Heavy ions are not only far more ionizing than proton recoils, they allow test conditions to be selected—both to encompass worst case and to assess SEE mode dependence
- Mitigation strategies
  - Threat avoidance by using parts not susceptible to SEE modes of concern or avoiding application conditions where susceptibility manifests
  - Redundancy—independence of each SEE means redundancy is an effective mitigation strategy
    - Pay in currency of the realm—bits for bits, function for function (hot spares), system for system
    - Poisson per ion means vulnerability depends on environment
    - For hot spares—primary and redundant unit rates increase with environment; not so for cold spares
    - Cold spares more effective for increased survivability
Radiation Effect Characteristics: Cumulative Effects

• Multiple Cumulative effects: Total Ionizing Dose, Displacement Damage Dose, Atomic Oxygen and energetic plasma exposure

• Consider TID as most complicated mode
  • Cumulative effect—each krad(Si) absorbed make failure more likely with the next krad(Si)
  • Damage accumulates whether parts biased or not

• TID test potentially destructive, so performed on sample representative of flight parts
  • Part-to-part and lot-to-lot variation often significant

• TID susceptibility often application dependent

• Relevant environments include
  • SPE protons and trapped protons and electrons

• DDD shows less part-to-part, lot-to-lot and application dependence
  • Plasma and Atomic O even less

• “Representative” sample= from flight wafer diffusion lot

• Effect is cumulative w/ or w/o bias applied—so threat avoidance is preferred mitigation; redundancy ineffective
  • Avoid susceptible parts or conditions where more susceptible
  • Shielding reduces dose/plasma/particle flux to acceptable limit
  • Design margin reduces probability of susceptibility as long as susceptibility vs. stress distribution is well behaved

• Susceptibility test needs to encompass WC conditions
  • e.g for TID, dose rate, biases, temperature...

• Part-to-part variation means sample size is important
  • Most general method assumes binomial statistics, but requires large sample sizes (230 parts for Ps=99% w/ CL=90%)
  • Assuming failure vs. dose well behaved reduces sample size, but introduces systematic error if distribution pathological

Key: CL—confidence level; Ps—probability of survival; WC—worst case
Radiation Effect Characteristics: Spacecraft Charging (It’s complicated)

• Two different modes of charging
  • Surface Charging has 2 contributing mechanisms
    • Photoelectric effect depends on illumination of surfaces and yield positive charging
    • Plasma charging depends on low-energy plasma environment and yields negative charging
  • Internal charging caused by high-energy electrons penetrating dielectrics in spacecraft
  • Both modes also depend on how quickly charge bleeds off of charged surface/dielectric (e.g. resistivity of path to ground)

• Charging neither Poisson, nor cumulative
  • Depends on integral of environment on timescales comparable to discharge time

• Testing is complicated
  • Needs to be performed on representative sample
  • Resistivity depends on sample storage conditions
  • Very difficult to test and model differential charging

• “Representative” means same resistive properties
  • e.g. Same material + outgassing in thermal vacuum

• Mitigation approach is threat avoidance
  • Design rules limit resistivity from metal to ground
  • Operational rules associated with eclipse conditions
  • Shielding can decrease high-energy electron fluxes
  • Environmental monitoring of plasma, electron fluxes

• Redundancy unlikely to be effective
  • Primary redundant systems are in same environment
  • Biased and unbiased systems have same risk

• Testing is difficult
  • Sample resistivities (and therefore integration times) may increase with time as system outgasses
  • System geometries important to reflect differential charging—important for determining charging rate
Which Environments are Important?

• Single-Event Effects caused by protons (trapped and SPE) and heavy ions (GCR and SPE)
  • Average environments determine whether mission meets requirements
    • Average trapped proton environment (AP9@50% confidence or AP8)
    • CREME-96 GCR and Average SPE proton and heavy-ion environments
  • Peak environments important to determine if redundancy overwhelmed by WC environment
    • WC trapped proton environment (South Atlantic Anomaly, AP9@>90% Confidence)
    • SPE proton and GCR environments (e.g. CREME-96 Solar Flare or ESP and PSYCHIC @>90% Confidence)
    • GCR environment does fluctuate, but changes are tiny compared to trapped proton and solar particle event changes.

• Cumulative Effects
  • Except for very short missions (<1-2 years), average environments dominate
  • Solar particle events can dominate TID/DDD for short missions, but few devices susceptible at such doses
  • Other effects (plasma and atomic Oxygen)—need model of average conditions throughout mission

• Charging depends on environments averaged over scales of hours to a day or so
  • Ensuring surfaces grounded, limiting high-resistivity dielectrics limits timescales considered
  • SPE and trapped electron fluctuations (e.g. AE9 at high confidence level over several hours)
Space Radiation Environments Pose a Variety of Threats

• Different threats important for different mission environments
  • Charging important mainly where space plasma and energetic electrons present (GEO, Polar, Jupiter…)
  • Cumulative effects most important where ionizing and energetic particle fluxes are high
  • SEE occur in all environments

• Time scales also vary for different threats
  • Charging takes place over several hours of (usually elevated) environment
  • TID/DDD and other cumulative effects develop and worsen over years
    • Often failure preceded by period of gradual degradation
    • SEE can occur at any time during the mission with equal probability (modula the environment)

• Threat characteristics determine appropriate hardness assurance, testing and mitigation options
  • SEE are Poisson processes
    • Need to be detected if susceptibility present
    • Independent of each other, so appropriate redundancy can be an effective mitigation
  • Cumulative effect failure rates increase w/ dose/time
    • Mitigation means threat avoidance (shielding, part substitution, increased design margin…)
  • Spacecraft charging risk accumulates for all systems when environment is elevated
    • Mitigation means threat avoidance (shielding, low-resistivity path to ground…)

• Knowing what risks apply to your mission is key—where and when change risk calculus