Space Radiation Effects on Electronics:
*Simple Concepts and New Challenges*

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Outline

- The Space Radiation Environment
- The Effects on Electronics
- The Environment in Action
- NASA Approaches to Commercial Electronics
  - The Mission Mix
  - Flight Projects
  - Proactive Research
- Final Thoughts
  - Atomic Interactions
    - Direct Ionization
    - Interaction with Nucleus
  - Indirect Ionization
  - Nucleus is Displaced

Space Radiation Effects on Electronics presented by Kenneth A. LaBel at 2004 UPOS Fall Meeting, Boston, MA, Nov 26, 2004
The Space Radiation Environment

Space Environments and Related Effects

- Plasma
- Particle radiation
- Neutral gas particles
- Ultraviolet & X-ray
- Micrometeoroids & orbital debris

- Charging
  - Ionizing & Non-Ionizing Dose

- Single Event Effects
  - Drag
  - Surface Erosion
  - Impacts

- Torques
  - Orbital decay

- Degradation
  - Data corruption
  - Noise on images
  - System shutdowns
  - Circuit damage

- Degradation of structural integrity
  - Structural damage
  - Decompression

Space Radiation Effects on Electronics presented by Kenneth A. Luebo at SPIE Fall Meeting, Boston, MA – Nov 29, 2004
Space Radiation Environment

Sunspot Cycle: An Indicator of the Solar Cycle

Sunspot Numbers

Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum
Solar Particle Events

- Cyclical (Solar Max, Solar Min)
  - 11-year AVERAGE (9 to 13)
  - Solar Max is more active time period
- Two types of events
  - Gradual (Coronal Mass Ejections - CMEs)
    - Proton rich
  - Impulsive (Solar Flares)
    - Heavy ion rich
- Abundances Dependent on Radial Distance from Sun
- Particles are Partially ionized
  - Greater Ability to Penetrate Magnetosphere than GCRs

Solar Proton Event - October 1989

Proton Fluxes - 99% Worst Case Event
Free-Space Particles: Galactic Cosmic Rays (GCRs) or Heavy Ions

- Definition
  - A GCR ion is a charged particle (H, He, Fe, etc)
  - Typically found in free space (galactic cosmic rays or GCRs)
    - Energies range from MeV to GeV for particles of concern for SEE
    - Origin is unknown
  - Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).

Trapped Particles in the Earth’s Magnetic Field: Proton & Electron Intensities

AP-8 Model

AE-8 Model

A dip in the Earth's dipole moment causes an asymmetry in the picture above: the South Atlantic Anomaly (SAA)
SAA and Trapped Protons: 
Effects of the Asymmetry in the Proton Belts on 
SRAM Upset Rate at Varying Altitudes on CRUX/APEX

Solar Cycle Effects: 
Modulator and Source

- Solar Maximum
  - Trapped Proton Levels Lower, Electrons Higher
  - GCR Levels Lower
  - Neutron Levels in the Atmosphere Are Lower
  - Solar Events More Frequent & Greater Intensity
  - Magnetic Storms More Frequent — Can Increase Particle Levels in Belts

- Solar Minimum
  - Trapped Protons Higher, Electrons Lower
  - GCR Levels Higher
  - Neutron Levels in the Atmosphere Are Higher
  - Solar Events Are Rare

Light bulb shaped CBE
courtesy of SOHO/ASCOD C3 Instrument
The Effects

DNA double helix
Pre and Post Irradiation
Biological effects are a key concern for lunar and Mars missions

Radiation Effects and Spacecraft

- Critical areas for design in the natural space radiation environment
  - Long-term effects
    - Total ionizing dose (TID)
    - Displacement damage
  - Transient or single particle effects (Single event effects or SEE)
    - Soft or hard errors
- Mission requirements and philosophies vary to ensure mission performance
  - What works for a shuttle mission may not apply to a deep-space mission

An Active Pixel Sensor (APS) Imager under irradiation with heavy ions at Texas A&M University Cyclotron
**Total Ionizing Dose (TID)**

- Cumulative long term ionizing damage due to protons & electrons
- **Effects**
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- **Unit of interest is krad(material)**
- Can partially mitigate with shielding
  - Low energy protons
  - Electrons
- **Typical ground testing performed with Co-60 or X-ray sources**

**Displacement Damage (DD)**

- Cumulative long term non-ionizing damage due to protons, electrons, and neutrons
- **Effects**
  - Production of defects which result in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, MOS, linear bipolar devices
- **Unit of interest is particle fluence for each energy mapped to test energy**
  - Non-ionizing energy loss (NIEL) is one means of discussion
- **Shielding has some effect - depends on location of device**
  - Requires significant electron and some proton range
- **Typical ground testing performed with protons or neutrons**
Single Event Effects (SEEs)

- An SEE is caused by a single charged particle as it passes through a semiconductor material
  - Heavy ions
    - Direct ionization
  - Protons for sensitive devices
    - Nuclear reactions for standard devices
- Effects on electronics
  - If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- Severity of effect is dependent on
  - type of effect
  - system criticality
- Typical ground testing performed at:
  - Cyclotron or accelerator

Radiation Effects on Electronics and the Space Environment

- Three portions of the natural space environment contribute to the radiation hazard
  - Solar particles
    - Protons and heavier ions
      - SEE, TID, DD
  - Free-space particles
    - GCR
      - For earth-orbiting craft, the earth’s magnetic field provides some protection for GCR
      - SEE
  - Trapped particles (in the belts)
    - Protons and electrons including the South Atlantic Anomaly (SAA)
      - SEE (Protons)
      - DD, TID (Protons, Electrons)
The Environment in Action

"There's a little black spot on the sun today"

Recent Solar Events – A Few Notes and Implications

- In Oct-Nov of this year, a series of X-class (X-45I) solar events took place
  - High particle fluxes were noted
  - Many spacecraft performed saftng maneuvers
  - Many systems experienced higher than normal (but correctable) data error rates
  - Several spacecraft had anomalies causing spacecraft safing
  - Increased noise seen in many instruments
  - Drag and heating issues noted
  - Instrument FAILURES occurred
  - Two known spacecraft FAILURES occurred

- Power grid systems affected, communication systems affected...
SOHO LASCO C2 of the Solar Event

Solar Event Effect - Solar Array Degradation on CLUSTER Spacecraft

Many other spacecraft to noted degradation as well.
### Science Spacecraft Anomalies During Recent Solar Events

<table>
<thead>
<tr>
<th>Type of Event</th>
<th>Spacecraft/Instrument</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous Processor Resets</td>
<td>RHESSI</td>
<td>3 events; all recoverable</td>
</tr>
<tr>
<td></td>
<td>CLUSTER</td>
<td>Seen on some of 4 spacecraft; recoverable</td>
</tr>
<tr>
<td></td>
<td>ChpSAT</td>
<td>S/C tumbled and required ground command to</td>
</tr>
<tr>
<td>High Bit Error Rates</td>
<td>GOES 9, 10</td>
<td>Correct</td>
</tr>
<tr>
<td>Magnetic Torques Disabled</td>
<td>GOES 9, 10, 12</td>
<td></td>
</tr>
<tr>
<td>Star Tracker Errors</td>
<td>MER</td>
<td>Excessive event counts</td>
</tr>
<tr>
<td></td>
<td>MAP</td>
<td>Star Tracker Reset occurred</td>
</tr>
<tr>
<td>Read Errors</td>
<td>Stardust</td>
<td>Entered safe mode; recovered</td>
</tr>
<tr>
<td>Failure?</td>
<td>Midstar-2</td>
<td></td>
</tr>
<tr>
<td>Memory Errors</td>
<td>GEMINI</td>
<td>18 errors on 1995</td>
</tr>
<tr>
<td></td>
<td>Many</td>
<td>Increase in cumulative error noted on solid-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>state recording noted in many spacecraft</td>
</tr>
</tbody>
</table>

### Science Instrument Anomalies During Recent Solar Events

<table>
<thead>
<tr>
<th>Type of Event</th>
<th>Spacecraft/Instrument</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument Failure</td>
<td>GOES-8 XRS</td>
<td>Under investigation as to cause</td>
</tr>
<tr>
<td></td>
<td>Mars Odyssey/Marly</td>
<td>Under investigation as to cause; power</td>
</tr>
<tr>
<td></td>
<td></td>
<td>consumption increase noted; S/C also had</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a safe hold event - memory errors</td>
</tr>
<tr>
<td>Excessive Count Rates</td>
<td>NOAA-17/AMSU-A1</td>
<td>Lost scanner; under investigation</td>
</tr>
<tr>
<td>Upset</td>
<td>ACE, WIND</td>
<td>Plasma observations lost</td>
</tr>
<tr>
<td></td>
<td>GALEX UV</td>
<td>Excess charge - turned off high voltages;</td>
</tr>
<tr>
<td></td>
<td>Detectors</td>
<td>Also Upset noted in instrument</td>
</tr>
<tr>
<td></td>
<td>ACE</td>
<td>Solar Proton Detector saturated</td>
</tr>
<tr>
<td></td>
<td>Integral</td>
<td>Entered Safe mode</td>
</tr>
<tr>
<td></td>
<td>POLAR/TIDE</td>
<td>Instrument reset spontaneously</td>
</tr>
<tr>
<td>Hot Flares</td>
<td>SMM/IRIS</td>
<td>Increase in hot pixels on IR images; Proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heating also noted</td>
</tr>
<tr>
<td>Safe Mode</td>
<td>Many</td>
<td>Many instruments were placed in Safe mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>prior to or during the solar events for</td>
</tr>
<tr>
<td></td>
<td></td>
<td>protection</td>
</tr>
</tbody>
</table>
Selected Other Consequences

- Orbits affected on several spacecraft
- Power system failure
  - Malmo, Sweden
- High Current in power transmission lines
  - Wisconsin and New York
- Communication noise increase
- FAA issued a radiation dose alert for planes flying over 25,000 ft

NASA Approaches to Electronics: Flight Projects and Proactive Research

It doesn’t matter where you go as long as you follow a programmatic assurance approach.
NASA Missions –
A Wide Range of Needs

- NASA typically has over 200 missions in some stage of development
  - Range from balloon and short-duration low-earth investigations to long-life deep space
  - Robotic to Human Presence
- Radiation and reliability needs vary commensurately

Implications of NASA Mix

- Prior to the new Presidential “Moon-Mars” vision
  - >90% of NASA missions required 100 krad(Si) or less for device total ionizing dose (TID) tolerance
    - Single Event Effects (SEEs) were prime driver
      - Sensor hardness also a limiting factor
    - Many missions could accept risk of anomalies as long as recoverable over time
- Implications of the new vision are still TBD for radiation and reliability specifics, however,
  - Nuclear power/propulsion changes radiation issues (TID and displacement damage)
  - Long-duration missions such as permanent stations on the moon require long-life high-reliability infrastructure
    - Human presence requires conservative approaches to reliability
    - Drives stricter radiation tolerance requirements and fault tolerant architectures
NASA Approach to RHA

- With commercial technology sensitivity to SEU increasing and limited radiation hardened offerings, a dual approach to RHA needs to be installed
  - A systems approach at the flight mission level, and
  - Proactive investigation into new technologies

Rockwell/Hawaii 2048x2048
5µm HgCdTe NGST FPA (ARC)

Candidate James Webb Space Telescope (JWST)
IR array preparing for rad tests. The ultra-low noise requirement of JWST is the driver.

A Systematic Approach to Flight Project Radiation Hardness Assurance (RHA)

Size, complexity, and human presence are among the factors in deciding how RHA is to be implemented
Sensible Programmatica for Flight RHA:
A Two-Pronged Approach for Missions

- Assign a lead radiation engineer to each spaceflight project
  - Treat radiation like other engineering disciplines
    - Parts, thermal,...
  - Provides a single point of contact for all radiation issues
    - Environment, parts evaluation, testing,...
- Each program follows a systematic approach to RHA
  - RHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
    - What is the cost of reworking a flight board if a device has RHA issues?

Flight Program Radiation Hardness Assurance (RHA) Flow
Radiation and Systems Engineering: A Rational Approach for Space Systems

- Define the Environment
  - External to the spacecraft
- Evaluate the Environment
  - Internal to the spacecraft
- Define the Requirements
  - Define criticality factors
- Evaluate Design/Components
  - Existing data/Testing/Performance characteristics
- “Engineer” with Designers
  - Parts replacement/Mitigation schemes
- Iterate Process
  - Review parts list based on updated knowledge

Approach to Insertion of New Electronics

IBM CMOS 8SF ASIC
Microelectronics: Categories

- Microelectronics can be split several ways
  - Digital, analog, mixed signal, other
  - Complementary Metal Oxide Semiconductor (CMOS), Bipolar, etc...
  - Function (microprocessor, memory, ...)
- There are only two commercial foundries (where they build devices) in the US dedicated to building radiation hardened digital devices
  - Efforts within DoD to provide alternate means of developing hardened devices
    - Hardened-by-design (HBD)
    - Provides path for custom devices, but not necessarily off-the-shelf devices
  - Commercial devices can have great variance in radiation tolerance from device-to-device and even on multiple samples of same device
    - No guarantees!
- Analog foundry situation is even worse
- New technologies have many unknowns
  - Ultra-high speed, nanotechnologies, microelectromechanical systems (MEMS and the optical versions -- MOEMS), ...

### The Digital Logic Trends

- Standard CMOS
  - Feature sizes are scaling (shrinking) to sub-0.1 micron sizes
    - Faster devices, lower operating voltages
      - Reduced electrical margins within devices
  - New dielectrics are being used
  - Thickness of gate oxide is being diminished
  - Implications (general)
    - Improved TID tolerance
      - DD not an issue (except possibly at nuclear levels)
    - Improved SEL tolerance
    - Increased SEU sensitivity
      - Technology speed increase drives this issue (SEIs in logic propagate)
    - Unknown effect of other technology changes
    - Increased use of silicon-on-insulator (SOI) substrates

Higher speed digital operation can defeat Radiation Hardening techniques after Benedetto, 2004

Effects of protons in SOI with varied angular direction of the particle; Blue line represents expected response with "standard" CMOS devices, after Reed 2002
The New Challenge: Changes in CMOS Technology and Design

- Not scaled as aggressively
  (need higher voltages to get analog range)
  - Efforts to improve electrical performance have reduced reliability and signal margins within the device
  - Increased sensitivity to
    - SETs (noise propagation that can be invasive to operations)
      - The higher the resolution or speed, the worse this becomes
    - TID and DD
      - Commercial device failure noted as low as 1 fad(Si)
        - Even short duration missions would have concerns without test data

Laser SEU tests on a LM124 Op Amp.
Note the variety of transients generated depending on particle arrival point and circuit application.
Efforts to “Harden” Commercial Microelectronics

- With limited radiation hardened by process (RHBP) foundries available, many organizations are seeking alternate approaches:
  - Radiation-hardened by design (RHBD) – using non-invasive circuit techniques to utilize commercial foundries to build hardened circuits, and
  - Radiation-tolerant system architectures – building a system that can detect and recover from errors with some loss of operating time or data.

New Technologies – Sample Issues

- Ultra-high speed
  - Devices that may be relatively tolerant at low-speed (<100 MHz) have vastly increased SEU sensitivity at high-speeds (>1 GHz)
    - Speed can defeat HBD methods
    - New technologies don’t fit old models

- Sensors
  - Noise, damage, etc. can limit device performance (such as an imager) and lifetime
    - Small effort at DoD to provide hardened solutions

- MEMS
  - Combined effects of electrical, optical, and mechanical degradation

- Nanotechnologies
  - A great unknown for radiation effects and protection
Insertion of New Technologies –
A Mission Perspective

• NASA mission timeframes rarely allow for a technology development path
  - For a 2008 launch, for example, technology freeze dates are likely 2005 or earlier
    • Technology must be moderately mature when a mission is being developed
      - There may be time to qualify a device, but there may not be time to develop/validate a new technology solution!
  • Risk versus performance reward for using less mature or commercial off-the-shelf (COTS) technologies

• Technology development and evaluation programs need to be in place prior to mission design
  - Strategic planning

Insertion of New Technologies
An Approach

• Develop knowledge-base of existing technology information
• Determine reliability/radiation gaps
• Performance ground-based tests
  - May be sufficient to “qualify” for a specific mission, but not generically for all
• Develop technology-specific models/test protocols
  - Performance Predictions
• Validate models with flight data
  - Requires in-situ environment monitoring
Radiation Test Issues - Fidelity

The Physics Models of Space Radiation – Environment to Target

- Predictive model of the external space radiation environment that impinges on the spacecraft
- Predictive model of the interaction of that environment with the spacecraft

- This is the induced or internal environment that impinges on electrical, mechanical, or biological systems
- May need to consider spacecraft transport and local material transport separately
- Predictive model for the effects of the interactions of the induced environment with semiconductor, material, or biological systems (the target)
Gaps for New Technologies

- Simple example citing tool limitations
  - CREME96 Tool (standard SEU rate tool)
    - Assumes the sensitive portion of the device (flip-flop) looks like a rectangular parallel-piped (RPP)
    - Data over the last few years has shown the RPP model doesn’t always fit modern technology/circuits
      - Single event transient (SET) issues for higher speeds
      - Diffusion effects noted in SDRAMs (synchronous dynamic random access memories)
      - Non-bulk CMOS test results

![](Proton-induced-angular-effects-in-SOI-device-with-high-aspect-ratio.png)

Expected curve shape
Proton-induced angular effects in SOI device with high aspect ratio

Implications of Space Radiation Technology “Gaps”

- Simplifying assumptions (such as RPP) used in many existing tools are inadequate for new technology performance
  - Use of existing tools for predictive purposes may add large risk factors onto NASA missions (significant under or over prediction of performance)
  - Physics-based models could provide a more accurate solution using physics-modeling codes (GEANT4, MCNPX, etc.)

- Comprehensive tool suite is desired using physics-based codes
  - Requires careful technology characterization and modeling effort
    - Challenge is to make the tool suite realizable (i.e., physics-based codes could take long periods of time to calculate results)
    - Simplifying assumptions and 1st order model development

- New effort is to define the gaps and begin development of a Space Computational Radiation Interaction Performance Tools (SCRIPT) suite
  - Note: CNES and ESA collaboration with GEANT4 is part of the picture (Space User’s Group)

![](Sample-particle-interaction-of-a-100-MeV-proton-in-a-Si-block-using-the-GEANT4-toolkit.png)

Sample particle interaction of a 100 MeV proton in a Si block using the GEANT4 toolkit.

![](Implications-of-space-radiation-technology-Gaps.png)

NASA

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Flight Experiments - Validating Technology and Environment Interactions

- Differences exist between ground-based radiation tests and the actual space environment
  - Energy spectrum
  - Directionality
  - Mixed environment
  - Particle arrival rates (flux or dose)
- Flight experiments and/or monitoring technology performance are required to validate ground-based models and tools
  - In-situ technology AND environment measurements desired

Brief History of Electronics and NASA Flight Radiation Experiments
- Microelectronic and Photonics Testbed (MPTB)
  - Fiber optic data bus, commercial electronics
- Space Technology Research Vehicle - 1st (STRV-1d) - mission failed 12 days after launch
  - Optoelectronics, state-of-the-art digital electronics, pulse-height analyzer (PHA) instrument, dosimetry
- Others
  -チェック HOST, commercial airplanes
  - Engineering data from SAMPEX, TOMDOLLON, SORBER, ITE, TRIMM, ESI, etc.

Flight technology experiments such as ACTS help provide validation for ground-based technology models and concepts.

NASA’s Living With a Star (LWS) Space Environment Testbed (SET) – A Dual Approach to Flight Validation

- Data mining
  - The use of existing flight data to validate or develop improved models and tools
- Examples
  - Linear device performance on Microelectronics and Photonics Testbed (MPTB)
  - Physics-based Solar Array Degradation Tool (SAVANT)
- Flight experiments
  - Focus on correlating technology (semiconductor to material) performance with solar-variant space environment (radiation, UV, etc.)
    - Model/technology validation and not device validation are the goals
  - In-situ environment monitoring allows for ground test protocol/model correlation
  - Multiple flight opportunities
  - Carrier under development

Investigations are selected via NASA Research Announcements (NRAs) or provided under partnering arrangements.
Final Comments and Future Considerations

Technology, Testing, and Flight

- Technology complicates radiation effects
  - Speed, Thermal, Fault Isolation, Packaging: die access, etc
  - SETs are the "new" effect in digital devices
  - Ultra-low noise science instruments
- Future facility issues
  - Beam structure
    - Issue: At-speed testing
  - Microbeam
    - Issue: Isolation of errors/Identification of sensitive junctions
  - High energy heavy ions – Michigan State University (MSU) National Superconducting Cyclotron Labs (NSCL) now open for business
    - Issue: Increased fidelity to space environment
    - Issue: Improved ion penetration (packaging issues)
    - Issue: Thermal (open-air testing possible)
    - Issue: Speed (reduced cabling requirements)
- Nanotechnologies? MEMS?
- A proactive radiation test and modeling program is required to allow successful system RHA

Ion Penetration depth depends on energy