In-Flight Anomalies and Radiation Performance of NASA Missions -
Selected Lessons Learned

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Outline of Presentation

- Investigative Approach
- An Optocoupler’s Tale
- On the Matter of Small Probabilities
- What’s with the Noise Spikes?
- The Meaning of an Upset in a Fiber Optic Link
- Considerations

Latent damage sites: device did not fail during ground irradiation, but at some time afterward during operation. Could this have been observed in-flight?
Anomaly Resolution –
Root Cause Investigation for Radiation Engineers

• Determine orbital location and time of event
  – Look for the obvious such as solar events or South Atlantic Anomaly (SAA)
• Review electronic parts list for potential sensitive devices
• Review identified device in specific circuit application
  – Factors such as duty cycle, operating speed, voltage levels, and so forth
• Obtain existing SEE, dose, and damage data or gather new data
  – Compare applications between in-circuit and ground data
  – Perform ground testing if needed
• Determine risk probabilities
  – SEE rates, etc
  – Failure potential
• Recommend mitigative action(s) if possible
An Optocoupler’s Tale - Background

- **Optocouplers**
  - Used extensively for the isolation of signals between systems or boxes
  - Translate electrical signals to optical, then back to electrical

- **What radiation-induced failure modes may exist?**
  - Long-term degradation such as current transfer ratio (CTR) – output/input
  - Single particle events
    - Photodiodes, for example, have a history of being used as energetic particle detectors!

![Typical Block Diagram of an Optocoupler](image)
An Optocoupler’s Tale – NASA’s Most Famous Science Spacecraft

- Hubble Space Telescope (HST)
  - Flying for over 18 years
  - Tremendous scientific discoveries (as well as gorgeous images!)
- HST has had several servicing missions (SM)
  - New instruments
  - System upgrades and maintenance
- On the SM2, launched Feb 14th, 1997, two new instruments were installed
  - Multiple anomalies were observed during the on-orbit engineering calibration for these instruments
  - HST’s main radiation concern is SAA
An Optocoupler’s Tale – Resolving the Anomaly

• What steps were needed to determine **ROOT CAUSE** and action?
  – Review of environment during anomalies
    • All events occurred in the SAA
  – Review of parts list
    • Optocoupler highlighted as most likely candidate
  – Review of circuit application
    • SETs simulated showing possible cause
      – SET could trigger a high-voltage portion of the instrument and cause failure
  – Review or gather radiation test data
    • No data existed; accelerator test performed

**Typical Measured Transient During Proton Irradiation**

**63 MeV Proton-Induced Transients on Suspect Device Versus Angular Incidence**
The Optocoupler – Final Analysis

• What steps were needed to determine ROOT CAUSE and action? - continued
  – Determine risk probability (i.e., upset rates)
    • Optocouplers are not just electrical
    • Considerations for tools beyond CREME96 began with this and related work
  – Determine actions to mitigate or reduce risk
    • In-flight hardware is not easily modified ;o(
      – FPGAs improve this ability (but not here)
    • Operational change installed via software update
      – No instrument operation during SAA
      – Critical science was NOT impacted, but some science data loss incurred
On the Matter of Small Probabilities - Background

- **Solid State Recorders (SSRs)**
  - A means for storing science data on-board a spacecraft
  - Use high-density memory ICs for density/power advantages
    - SRAM (early 1990’s)
    - DRAM (mid-1990’s and later)
    - Flash (being considered)
- **DRAMs: What radiation-induced failure modes may exist?**
  - TID
    - Traditional leakage increases, cell failures, etc…
  - SEE
    - Destructive: SEL, stuck bits
    - Upset: bit/multiple bits, block errors, mode errors, SEFI

1 Gb SDRAM circa 2006
Feature size is 90nm
On the SM2, Feb 14\textsuperscript{th}, 1997, a new SSR was installed to increase data storage capacity

- HST passes through the SAA several times daily
  - Bit upsets tracked fairly well with predicted rate based on ground data (3 samples, one proton energy)
  - \textbf{HOWEVER}, two more complex anomalies were observed
    - Each had \textasciitilde 100 bits in error (block)
    - Block was not corrected by a re-write

- \textit{Project in panic!}

HST SSR utilizes
Irvine Sensors DRAM Modules
Comprised of 16 Mb IBM Luna DRAMs
On the Matter of Small Probabilities– Resolving the Anomaly

- What steps were needed to determine ROOT CAUSE and action?
  - Review of environment during anomaly
    - SAA
  - Review of parts list
    - Memory controller was rad-hard
    - DRAM was not
  - Review of circuit application
    - Circuit application was the same as in ground testing (refresh rate, etc)
  - Review or gather radiation test data
    - Proton data: no observed block errors (sample size = 3 w/ 1x environment fluences)
    - HOWEVER, heavy ion data exhibited these type of events at low LETs
      - Proton events would be expected
      - New test data required for statistics on 1440 device usage
    - With 1440 devices being used for this SSR application
      - Expected event cross-section of ~a few E-13 cm² based on 2 events in 9 months versus (predicted) in-flight proton fluence
On the Matter of Small Probabilities—Final Analysis

- Review or gather radiation test data (cont’d)
  - New test undertaken with protons with 100 die and to higher proton fluence levels
    - 9 events observed with proton fluences ~100x over expected HST expected levels
      - 2 different event signatures noted
        » block (column/row) errors
        » weak columns (suspect data – sometimes good, sometimes bad)

- Determine risk probability (i.e., upset rates)
  - Predicted error rate of 2.2/yr is the same order of magnitude as observed

- Determine actions to mitigate or reduce risk
  - Reset of mode register or power cycle clear the anomaly
    - Circuitry not included to provide reset
    - Power cycle determined to be feasible when needed
      - Data is Reed-Solomon (RS) Encoded
        » Probability of RS failure is low
      - No action taken at that time
What’s With the Noise Spike? - Background

- Linear devices such as analog comparators are
  - Used extensively in instruments, power, data collection, and more
  - Compares the voltage levels between two analog signals
- What radiation-induced failure modes may exist?
  - Long-term degradation is focused on
    - Enhanced low dose rate sensitivity (ELDRS) and displacement damage (in bipolars)
  - Single events
    - Single event transients (SETs) are the prime concern.

Sample SETs induced by heavy ions in a PM/LM139 comparator
What’s With the Noise Spike? – Microwave Anisotropy Probe (MAP)

  - Had phasing orbits prior to insertion in final orbit.
- An anomaly occurred causing a reset of the spacecraft processor on November 5, 2001.
What’s With the Noise Spike? – Resolving the Anomaly

- What steps were needed to determine ROOT CAUSE and action?
  - Review of environment during anomaly
    - Solar event
      - Significant heavy ion component
  - Review of parts list
    - Analog comparator (PM/LM139) identified as likely problem
What’s With the Noise Spike? – Resolving the Anomaly (2)

- Review of circuit application
  - Confirmed that LM/PM139 could be the cause
  - Application had changed since initial parts review pre-launch
- Review or gather radiation test data
  - No documented proton sensitivity
  - Heavy ion sensitivity documented as a function of the application using existing data plus new data gathered

![Circuit Diagram]

Heavy ion data
What’s With the Noise Spike? – Final Analysis

• What steps were needed to determine ROOT CAUSE and action?
  - continued
  – Determine risk probability (i.e., upset rates with heavy ions)
    • Additional shielding analysis performed for particle transport
    • Assumption of sensitive volume thicknesses
  – Determine actions to mitigate or reduce risk
    • Event rates deemed acceptable by project
    • No action taken

<table>
<thead>
<tr>
<th>Sensitive volume thickness (μm)</th>
<th>GCR SET rate CREME96, solar maximum (event/ comparator-day)</th>
<th>Solar Event CREME96, worst day (event/ comparator-day)</th>
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<tbody>
<tr>
<td>10</td>
<td>1.8E-3</td>
<td>5.1E-1</td>
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<tr>
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<td>60</td>
<td>9.9E-4</td>
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The Meaning of an Upset in a Fiber Optic Link (FOL) - Background

- **FOLs**
  - MIL-STD-1773 implementation (1 MHz) used since the early 1990’s in many NASA systems
  - Transmits electrical data and command signals to/from optical

- **What radiation-induced failure modes may exist?**
  - Similar to optocouplers
  - SEUs imply single or multi-bit errors
    - Photodiodes, have a history of being used as energetic particle detectors.
    - Errors are temporal via photodiode
      - Transients may affect more than one clock cycle
    - High-speed electrical circuits also sensitive
    - Major impact is on data *bit error rate* (BER)

Representative FOL architecture
The Meaning of an Upset in a Fiber Optic Link (FOL)- Background (cont’d)

• Original MIL-STD-1773 transceivers used Si photodiodes
  – Sensitive to direct ionization from protons
    • Implies high bit error rate (BER) for space applications.
    – Angle of incidence, optical power budget, and proton energy effects noted
• This forced the usage of protocol fault-tolerant features to be implemented (message retries).
  – Used successfully in NASA missions
    • BUT reduced effective bus bandwidth by ~50%.
    • For higher data rate systems, this hardening solution may not be applicable.

Ground data illustrating the effect of optical power budget on radiation performance
The Meaning of an Upset in a Fiber Optic Link (FOL)- Making a Better Mousetrap

- Hardening methodologies explored
  - Change of optical wavelength from 850 nm to 1300 nm light showed improved SEU tolerance
    - Reduced volume of photodiode
  - Receiver noise filtering techniques and optical power budgets also help
  - Higher data rate development (20 MHz) – AS1773
    - Flown as an experiment on Microelectronics and Photonics Testbed (MPTB)
      - Boeing DR1773 Transceivers

MPTB DR1773 Test Board
The Meaning of an Upset in a Fiber Optic Link (FOL) – MPTB Performance

- MPTB launched in 1997
  - 6 years of in-flight performance in a highly elliptical orbit (HEO)
- Transceivers were operated in two modes
  - ED mode used a physical contact (PC) polished fiber optic terminal
  - DE mode used a flat polished connector (air gap)

Which do you think would work better?
The Meaning of an Upset in a Fiber Optic Link (FOL) – In-Flight

- Did the hardening effort pay off?

### ED and DE bit error rates by Year

<table>
<thead>
<tr>
<th>Year</th>
<th>ED BER</th>
<th>DE BER</th>
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<tbody>
<tr>
<td>1997</td>
<td>1.738E-12</td>
<td>N/A</td>
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<tr>
<td>1998</td>
<td>4.224E-14</td>
<td>3.787E-11</td>
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<td>1999</td>
<td>3.855E-14</td>
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<td>2000</td>
<td>0</td>
<td>8.501E-11</td>
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<tr>
<td>2001</td>
<td>8.168E-15</td>
<td>N/A</td>
</tr>
<tr>
<td>2002</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

![Graph showing number of upsets over Julian Day of Year](image)


Few errors were noted on the “good” PC
Considerations

• Methodical process for anomaly review takes into account
  – Environment
  – Selected parts
  – Design
  – Existing radiation test data and/or new data
  – Impact (i.e., risk probability)
  – Actions (mitigative or otherwise)

• Notes:
  – Design and parts list reviews are good for flight programs
    • BUT, any changes later in design process need to be reviewed as well
  – Protons aren’t always the cause of anomalies during solar events
    • Solar heavy ions must be taken into account
  – System design and not just device radiation tolerance needs to be taken into account
    • Mechanical issues, for example, can be related (as in the FOL example)
  – Spacecraft charging effects not discussed, but should be considered as well
    • *Can charging in plastic packages be the next SEU?*