Radiation Hardness Assurance (RHA) for Space Systems

Stephen Buchner, NASA/GSFC
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RHA Outline

- Introduction
- Programmatic aspects of RHA
- RHA Procedure
  - Establish Mission requirements
  - Define and evaluate radiation hazard
  - Select parts
  - Evaluate circuit response to hazard
    - Search for data or perform a test
  - Categorize the parts
    - TID/DD
    - SEE
- Conclusion
What is RHA?

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment.

- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, and mission/system/subsystems requirements.

Radiation Hardness Assurance deals not only with the piece part. It includes system, subsystem, box and board levels.

Radiation Environment in Space

1. Solar Wind
   - Solar Cycle
   - Solar Flares
   - Coronal Mass Ejections

2. Van Allen Belts
   - Proton Belts
   - Electron Belts

3. Cosmic Rays
   - Galactic Origins
Solar Dynamic Observatory

- Contains three telescopes to study the sun
  - Each telescope takes a picture of sun with CCD camera
  - No data processing or storage on board
  - Downlink at 150 Mbps.
  - Data storage on earth will require 250 DVDs a day

- Geosynchronous Orbit
  - Exposed to electron belt, solar particles (mostly protons) and galactic cosmic rays

- Launch date is November 2008 for a 5-year Mission
  - Spans maximum of solar activity
    - High solar wind
    - Numerous solar particle events (Coronal Mass Ejections and solar flares)
    - Reduced Galactic Cosmic Ray (GCR) flux
Possible Radiation Effects

- **Cumulative**
  - Total Ionizing Dose (TID = 60 Mrad(Si) – free field)
  - Displacement Damage (DD = Particle Fluence)

- **Transient**
  - Non-Destructive (LET_{th} > 36 MeV.cm^2/mg)
    - Single Event Upset (SEU),
    - Single Event Transient (SET),
    - Single Event Functional Interrupt (SEFI).
  - Destructive (LET_{th} > 80 MeV.cm^2/mg)
    - Single Event Latchup (SEL)
    - Single Event Burnout (SEB)
    - Single Event Gate Rupture (SEGR)

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Hardness Assurance (Overview)

1. Determine radiation environment (external and internal to spacecraft)
2. Select parts
3. Determine radiation sensitivity from existing data or by testing
4. Compare failure level with system requirements

Mission Requirements

Define and Evaluate the Radiation Hazard

Evaluate Circuit Response to Hazard

Categorize the Parts According to RDM

- Hardness Non-Critical
- Hardness Critical
- Unacceptable

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SDO Requirements

System Level Requirements......
1. 5-year Mission
2. Launch date is 2008
3. Must be operational 95% of the time.
4. Data integrity must be 99.99% valid.
5. Data downlink at a rate of 150 MBPS in Geosynchronous Orbit.
6. Total Mass and Mass Distribution of Spacecraft

Flow down to Part Level Requirements

- Survive:
  - 5 years with total dose of 60 Mrad(Si).
  - Most failures occur near beginning, except for radiation
  - Spacecraft mass distribution determines radiation level of parts

- SEE rates based on budgeted down time that includes:
  - Safe-hold,
  - Eclipses,
  - Instrument calibration,
  - Antenna handover,
  - Momentum shedding,
  - RADIATION

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System Hierarchy

Example – SDRAM Buffer

Temporary buffer to store data from all three telescopes prior to down-linking.

- **System Requirement:**
  - Data downlink at 150 Mbps
  - 99.99% valid during 95% up time.

- **SDRAM Requirement**
  - SDRAM suffers from SEFIs due to ion strikes to control circuitry.
  - Mitigate SEFIs by rewriting registers frequently.
  - At temperatures above 42 C, SDRAM stops working.
  - Determined it was due to a timing issue.
  - New mitigation involves triple-voting three SDRAMs.
RHA Challenges

- **Small number of systems, sometimes one, with no redundancy**
  - Requirement for high probability of survival
  - Often no qualification model
- **Electronic parts**
  - Many part types, small buys of each part type
    - No leverage with manufacturers
  - Use of Commercial Off-The-Shelf (COTS) parts
    - No configuration control
    - Obsolescence
    - Little radiation data in databases
    - Frequently only available in plastic

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  - Categorize the parts
    - TID/DD
    - SEE
- **Conclusion**
TID Top Level Requirement (SDO)

Dose-Depth Curve for GEO

Behind 200 mils
Al TID (1x)
is 20 krad(Si)

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TID Inside Electronic Boxes

NO MARGIN

3-D Ray Trace Analysis

5 Years in GEO
No Margin Included

Top Level Requirement

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Displacement Damage Dose

200 mils = 5.08 mm

NID = 2E+8 MeV/gm

SEE - Proton Flux vs Energy

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SEE - LET Spectra for GCRs

SEE Requirement

- **Destructive SEE**
  - No destructive SETs for LETs below 80 MeV.cm²/mg.
    - Mitigate (e.g., latchup protection circuit)
    - Replace part if cannot mitigate
      (Sometimes have no other choice but to accept part.)

- **Non-destructive SEE**
  - No non-destructive SEE below 40 MeV.cm²/mg.
    - Mitigate if critical (e.g., majority vote)
    - Replace if cannot mitigate
    - Accept if non-critical (e.g., housekeeping)
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Parts Selection

Initially based on function and performance. Additional factors are:
1. Reliability,
2. Availability,
3. Cost.

High Reliability Parts
- Special process and special design for radiation hardness
- Standard process and special design for radiation hardness
- Standard product with radiation hardness characterized and warranted by the manufacturer

Commercial Parts
- Standard product
- Commercial process designed for radiation hardness

Performance

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  - Categorize the parts
- Analysis at the function/subsystem/system level
  - TID/DD
  - SEE
- Conclusion

Search for Radiation Data

Does radiation data exist?  NO

YES

Has process or foundry changed?  YES

Test recommended but may be waived if risk low  NO

Are data from same wafer lot?  NO

YES

Is test method valid?  NO

YES

Is there sufficient test data?  NO

YES

Perform radiation test

Data is useable!!

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### Sources of Radiation Data

- **In house data from previous projects** (LRO and SDO)
- **Available databases:**
  - ESA: [http://escies.org](http://escies.org)
  - DTRA ERRIC: [http://erric.dasiac.com](http://erric.dasiac.com)
- **Other sources of radiation data:**
  - IEEE NSREC Data Workshop, IEEE Trans. On Nuc. Sci., RADECS proceedings...
  - Vendor data

Stacked devices and hybrids can present a unique challenge for review and test

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### Evaluation of Radiation Data

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Generic Part Number</th>
<th>Function</th>
<th>Manuf.</th>
<th>TID/DO</th>
<th>Source</th>
<th>Destructive SEE</th>
<th>Source</th>
<th>Non-destructive SEE</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>54AC0085-1042</td>
<td>54AC00B3M-0B</td>
<td>Quad-2-Ipul AND gate</td>
<td>National</td>
<td>No radiation data</td>
<td>&gt;100 MeV cm²/mg</td>
<td>Manuf.</td>
<td>&gt;40 MeV cm²/mg</td>
<td>Manuf.</td>
<td>Lot-specific testing needed</td>
<td></td>
</tr>
</tbody>
</table>

Dash indicates not TID rad-hard

Could not find lot-specific data

Meets SDO requirements for SEL

Meets SDO requirements for SETs

Recommendation

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<table>
<thead>
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<th>Manuf.</th>
<th>TID/DD</th>
<th>Source</th>
<th>Source</th>
<th>Source</th>
<th>Non-destructive SEE</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>560DF85470</td>
<td>HS-117RH</td>
<td>Adj. Positive Voltage Regulator</td>
<td>Intemd</td>
<td>300 krad</td>
<td>Manuf. Test report</td>
<td>&gt;87 MeV.cm²/mg</td>
<td>Manuf. Test report</td>
<td>&lt; 15 MeV.cm²/mg</td>
<td>Evaluate SET threat and mitigate if necessary</td>
</tr>
</tbody>
</table>

- "E" indicates rad-hard to 300 krad, but not ELDERS tested, use de-rating factor
- Recommendation
- Meets SDO requirements for destructive SEEs
- Does not meet SDO requirements for SETs

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**Evaluation of Radiation Data**

<table>
<thead>
<tr>
<th>Item #</th>
<th>Part #</th>
<th>Function</th>
<th>Manuf.</th>
<th>TID</th>
<th>Source</th>
<th>Destructive SEEs</th>
<th>Non-destructive SEEs</th>
<th>Comments</th>
<th>Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>RMA-LS1413DM</td>
<td>DC/DC CONV 12VDC</td>
<td>Intemd</td>
<td>50 krad</td>
<td>?</td>
<td>N/A</td>
<td>N/A</td>
<td>MOSFET derated to 50% of rated BVDS to minimize risk of SET</td>
<td>Accepted</td>
</tr>
</tbody>
</table>

- Hybrid
- Source not listed
- No data
- Insufficient de-rating
- ACCEPTED!

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Radiation Test

- **Determine types of tests needed**
  - TID (gamma rays),
  - DD (neutrons or protons),
  - SEE (protons or heavy ions).
- **Define appropriate test levels**
  - Sample size,
  - Particle type,
  - Fluence and flux,
  - Dose and dose rate.
- **Operate part as in application, i.e., bias, frequency, software, etc.**
  - *Not always possible*

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Total Dose Test (Co$^{60}$)

- **Dose Rate**
  - Linear Bipolars: ELDRS dose rate of 0.01 rad(Si)/s
  - CMOS: High dose rate of 50 to 300 rad(Si)/s
- **Total Dose**
  - At least 2X of expected mission dose for part
  - 100 krad(Si) better so can use data for other missions
- **Bias**
  - ELDRS both biased and unbiased
  - CMOS - bias to $V_{dd}$ and $V_{ss}$, inputs grounded, outputs floating
- **Temperature**
  - Room temperature (or application temperature), annealing step
- **Minimum Number of Parts**
  - 10 with 2 for controls,
  - Quad parts - must test all four.

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Single Event Test

- **Protons or Heavy Ions**
  - Determines which accelerator to use
- **Air or Vacuum**
  - For high-speed prefer air.
- **Flux**
  - Low enough to prevent “pile-up” of transients
- **Fluence**
  - Determined by statistics:
    - For SEUs minimum of 100 upsets or 1x10^7 particles/cm²
    - For SEL minimum of 1x10^7 particles/cm²
- **Angle**
  - Normal to grazing, depending on application
- **Temperature**
  - Room temperature for SEU, 100 C for SEL.
- **Bias**
  - $V_{cc}$ +10% for SEL
- **Number of parts**
  - Depends on cost of parts, availability of parts, availability of beam time (Minimum of 3)

SEE Test Results

- Fit data with Weibull curve.
  \[ \sigma = \sigma_{sat} \cdot (1 - \exp(-x \cdot \text{LET(th)})/W)^p \]
- Extract fitting parameters:
  - LET(th)
  - Width (W)
  - Shape (S)
  - \( \sigma_{sat} \)
- Use fitting parameters in CREME96 or SPENVIS to calculate SEE rate.
- Compare calculated rate with mission requirements

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Radiation Test Issues - Fidelity

How accurate is the ground test in predicting space performance? Example, how does aging affect dose degradation?

Example of Unexpected Results

- **Solid State Power Controller (SSPC) from DDC (RP-21005DO-601P)**
  - DDC replaced FET from Signetics with non rad-hard FET from IR.
  - Heavy-ion testing at Texas A&M revealed the presence of SETs causing the SSPC to switch off.
  - Pulsed laser testing revealed that the ASIC was sensitive to SETs, and that large SETs caused the SSPC to switch off.
  - Replaced DDC SSPC with Micropac SSPC
  - Previous SEE testing of ASIC at Brookhaven revealed no SETs.

Problem was range of ions at BNL

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Measurement Statistics

- Probability of survival
- Confidence level

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**Radiation Design Margin**

- Definition of RDM (for TID):

\[
RDM = \frac{\text{Mean failure level}}{\text{Maximum TID for mission}}
\]

---

**TID Design Margin Breakpoints**

<table>
<thead>
<tr>
<th>RDM &lt; 2</th>
<th>&lt; RDM &lt; 10</th>
<th>RDM &lt; 100</th>
<th>RDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unacceptable</td>
<td>Hardness Critical-HCC1</td>
<td>Hardness Critical-HCC2</td>
<td>Hardness Non-Critical</td>
</tr>
<tr>
<td>Do not use</td>
<td>Radiation lot testing recommended</td>
<td>Periodic lot testing recommended</td>
<td>No further action necessary</td>
</tr>
</tbody>
</table>

Qualitative approach recommended for systems with moderate requirements

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Part Categorization Criteria (PCC)

Log normal distribution law

\[ PCC = \exp(K_{TL}s) \]

\[ K_{TL} = \text{One sided tolerance factor based on sample size } n, \text{ confidence level } C \text{ and probability of survival } P_s \]

\[ s = \text{standard deviation of sample data} \]

\[ DM < 1-2 < DM < PCC < DM \]

Unacceptable \[ \rightarrow \]
Hardness
Critical

Hardness
Non-Critical

After MIL HDBK-814

---

Parts Categorization Criteria

\[ P_s=0.999 \]
\[ C=0.9 \]
\[ N=30 \text{ samples} \]
\[ \text{Gives} \]
\[ K=3.79 \]

\[ PCC=\exp(3.79*0.365) = 3.99 \]
**TID- Example of Application**

<table>
<thead>
<tr>
<th>PM155</th>
<th>Spec. limit</th>
<th>Tolerated limit</th>
<th>Design dose limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDM=2</td>
<td>30 krad</td>
<td>42 krad</td>
<td>60 krad</td>
</tr>
<tr>
<td>P_s=99%</td>
<td>C=90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_P=3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data after Astrium test report, 1997

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**TID Mitigation**

- **Reduce the dose levels**
  - Improve the accuracy of the dose level calculation
  - Change the electronic board, electronic box layout
  - Add shielding
    - Different location on spacecraft
    - Box shielding
    - Spot shielding

- **Increase the failure level**
  - Test in the application conditions
  - Test at low dose rate (CMOS only)
  - Tolerant designs (cold redundancies, etc.)
  - Relax the functional requirements

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TID Mitigation – Spot Shielding

- T039: 0.37 g/cm² Al
- T039: 0.27 g/cm² Ta
- T039: 1.08 g/cm² Al
- T039: 1.08 g/cm² Ta

Total dose - TID orbit - 15 years (krad-Si)

Target #

EADS-Astrium data

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TID Mitigation - Examples

- **TMS320C25 (DSP) Texas Instruments – LEO polar**
  - TID soft: 3 krad(Si) (functional failure)
  - Duty cycle in the application: 10% on
  - TID tolerance with application duty cycle: 10 krad
  The device has operated flawlessly during the mission

- **FPGA 1280 ACTEL - GEO**
  - TID soft: 3 krad functional at high dose rate.
  - TID at 1 rad/h: ~ 14 krad functional, 50 mA power consumption increase (max design value) after 8 krad.
  - Spot shielding with Ta: received dose = 4 krad

EADS-Astrium data

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SEE - Analysis Requirements

- $\text{LET}_{\text{th}} > 80$
  - SEE risk negligible, no further analysis needed

- $80 > \text{LET}_{\text{th}} > 15$
  - SEE risk moderate, heavy-ion induced SEE rates must be analyzed. In many cases SEE can be tolerated. Requires analysis.

- $15 > \text{LET}_{\text{th}}$
  - SEE risk high, heavy ion and proton induced SEE rates to be analyzed. In many cases can tolerate the SEEs

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SEE - Analysis Flow

MISSION REQUIREMENTS

RADIATION ENVIRONMENT PREDICTION

PART SEE SENSITIVITY

SEE CRITICALITY ANALYSIS

SEE RATE PREDICTION

FUNCTIONAL SEE REQUIREMENTS

DECISION TREE ANALYSIS

SEE - Decision Tree

Single Event Effect Severity Assessment

Include effects of error mitigation in design

Is function error-tolerant?

YES

Procure Components so that Predicted Error Rate for Function Meets Requirement

NO

Is function error-vulnerable?

YES

NO

Additional error mitigation useful/cost-effective?

YES

Procure Components so that Predicted Error Rate for Function is < 0

NO

Function is Error-critical

Add additional Mitigation for SEE in Design

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Conclusion

- The RHA approach is based on risk management and not on risk avoidance

- The RHA process is not confined to the part level, but includes
  - Spacecraft layout
  - System/subsystem/circuit design
  - System requirements and system operations

- RHA should be taken into account in the early phases of a program, including the proposal and feasibility analysis phases.

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