Radiation Hardness Assurance (RHA) for Space Systems

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SGT/NASA-GSFC
The radiation environment outside and inside a spacecraft

Total dose effects in MOS devices

A review Single Event Effects (SEE) charge collection processes

Hazard

Parts response to the hazard

Spacecraft Radiation Hardness Assurance

This talk will present a NASA approach of Radiation Hardness Assurance for space systems
RHA Outline

• Introduction
• Define the mission radiation environment
• Bound the part response
• Define the function/subsystem/system response
• Management of RHA
• Conclusion
RHA Outline

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RHA Definition

- 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 environment.

- Deals with mission/system/subsystems requirements, environmental definitions, part selection, part testing, shielding, and radiation tolerant design.

Radiation Hardness Assurance goes beyond the piece part level.
Project Requirements Flow-Down

Level 1
- Level-1 Requirements Document
  - Mission objectives
  - Orbit
  - Mission duration
  - Schedule and cost

Level 2
- Mission Requirements Document
  - Identifies subsystem impacted
  - Defines verification level

Level 3
- Subsystem Specifications
  - Performance requirement
  - Electrical and mechanical interface requirement

Level 4
- Var Emittance Coatings
- Solar Array Li-Ion Battery
- Magnetometer
- Sun Sensor
- Nutation Damp.
- X-ponder
- Antenna
- Pressure Transducer
- Thruster Cntl. Elec.
- uThruster
- Power/FSW
- Diag. S/W
- Diag. Perf. S/W
- Propellant Tank
- Propellant Line
- Fill & Drain Valve
- Release Mech Actuators
- Deployment Latch Pinpuller
- Autonomous Ground S/W
RHA Overview

MISSION/SYSTEM REQUIREMENTS

SYSTEM AND CIRCUIT DESIGN

RADIATION ENVIRONMENT DEFINITION

RADIATION LEVELS WITHIN THE SPACECRAFT

PARTS AND MATERIALS RADIATION SENSITIVITY

ANALYSIS OF THE CIRCUITS, COMPONENTS, SUBSYSTEMS AND SYSTEM RESPONSE TO THE RADIATION ENVIRONMENT
RHA Outline

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• Management of RHA
• Conclusion
Sources of Radiation to Consider

Galactic Cosmic Rays

Solar Particles

Trapped Particles

After Nikkei Science, Inc. of Japan, by K. Endo
Trapped Radiation Belt Models: NASA AP8, AE8

- Conversion of spatial coordinates to geomagnetic B/L coordinates
- Use of AP8/AE8 tabulated spectra
Trapped Radiation Belt Models: NASA AP8, AE8

• 2 extreme cases of solar modulation
• static models that represent omnidirectional average fluxes over 6 months period of time
• B/L coordinates shall be calculated with the geomagnetic models used at the epoch of the generation of AP8/AE8 models
• At low altitude (<1000km), AP8 underestimates the actual fluxes
  – TIROS

Despite their inaccuracies AE8 and AP8 are still the standard models for engineering analysis

Available at: http://www.spervis.oma.be/spervis/

Solar protons, comparison of JPL91 and ESP model

Confidence level=90%

After Xapsos IEEE TNS, vol 47-3, 2001
Solar Particle Event and Galactic Cosmic Ray (GCR), Individual Event Model: CREME 96

• Provides GCR fluxes for elements from Z=1 to 92 for solar minimum and solar maximum conditions in an energy range from 0.1 to 1E5 MeV/u.

• Provides SPE fluxes for elements from Z=1 to 92 for the worst week, worst day and peak 5 minutes.

Available at: http://crsp3.nrl.navy.mil/creme96/
Effects Induced by the Space Radiation Environment

- Cumulative Effects
  - Induced by electrons and protons
    - Total dose effects
    - Displacement Damage

- Single Event Effects (SEE)
  - Induced by heavy ions and protons
    - Potentially destructive
      - Single Event Latchup (SEL)
      - Single Event Burnout (SEB)
      - Single Event Gate Rupture (SEGR)
    - Non destructive
      - Single Event Upset (SEU)
      - Single Event Transient (SET)
      - Single Event Functional Interrupt (SEFI)
      - Multiple Event Upset (MEU)
      - Multiple Bit Upset (MBU)
      - ...

- Other: spacecraft charging*
  * outside the scope of this short course
## Radiation Environment Within the Spacecraft

Quantification of the Different Effects

<table>
<thead>
<tr>
<th>Observed Effect</th>
<th>Parameter used for quantification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Dose Effects</td>
<td>Total Ionizing Dose (TID)</td>
</tr>
</tbody>
</table>
| Displacement Damage              | Displacement Damage Dose (DDD) based on Non Ionizing Energy Loss (NIEL)*  
|                                  | or                               
|                                  | NIEL equivalent fluence for a selected proton energy*                    |
|                                  | or                               
|                                  | Damage equivalent fluence for a selected electron or proton energy         |
| Single Event Effects (SEE)       | Heavy ion Linear Energy Transfer (LET) spectra                            |
|                                  | and                             
|                                  | proton energy spectra           |

* May not be valid for III-V materials
TID, Computer Methods for Particle Transport

After Daly, ESA report 1989
TID Top Level Requirement:
Dose-Depth Curve

Total dose at the center of Solid Aluminum Sphere
ST5: 200-35790 km, 0 degree inclination, three months

Total Dose (rad-Si)

Aluminum shield thickness (mils)
For Electron Dominated Orbits, Sector Analysis/Ray Trace Can Significantly Underestimate or Overestimate the Dose Levels

**GEOSTATIONARY ORBIT**

![Graph showing dose levels for different packages.](image)

- **TO39**: Monte Carlo: 16.7 krad(Si), Ray Trace: 21.5 krad(Si)
- **CQFP**: Monte Carlo: 11.9 krad(Si), Ray Trace: 11.6 krad(Si)
- **TSOP**: Monte Carlo: 24 krad(Si), Ray Trace: 18.6 krad(Si)
- **RadPack™**: Monte Carlo: 2.3 krad(Si), Ray Trace: 3.4 krad(Si)

**Equivalent shielding provided by the Spacecraft:**
~ 350 to 450 mils

*After R. Mangeret, ASTRIUM report, 2001*
For Proton Dominated Orbits, Sector Analysis Gives a Good Estimation of the Dose Levels

LEO ORBIT (820 km/90 degrees)

After R. Mangeret, ASTRIUM report, 2001
Example

External dimensions: 50x30 cm
Weight: 25 Kg

Courtesy of NASA New Millenium Program (NMP)
Spacecraft Structure

- Honeycomb Solar Array Panels
  - 8 Panels
  - ~0.175mils
  - Outside
    30 mils Coverglass
    10mils Carbon Graphite
    125mils Core
    10mils Carbon Graphite
    Inside

- Sheet Metal Side Wall serves as closeout
  - 32mils Sheet Al 6061

- Honeycomb Sandwich Decks
  - ½” core (Composite), 0.015” Facesheets (Al)
  - Equivalent ~30mils Al
Detail - Transponder

- Component Cavity #3
  - Baseband Processor
  - Oscillator Board
  - Transmit Chain
  - Receive Chain

Cover = 40mils Al

Outer Shell = 60mils Al

- Component Cavity #1
  - C-Band Synthesizer

Internal Webs = 40mils Al

- Component Cavity #2
  - L-Band & S-Band Synthesizer
  - Analog Daughter Card
ST5 - Total Mission Dose on Electronic Parts

200-35790km, 0 degree inclination, 3 months

An accurate spacecraft model will increase the accuracy of dose requirements

Top Level Requirement
For Displacement Damage, an Equivalent Fluence or a Displacement Damage Dose (DDD) is Defined Based on NIEL
Heavy Ion Environment is Defined for a Conservative Value of Shielding

Integral LET Spectra at 1 AU (Z=1-92) for Interplanetary orbit
100 mils Aluminum Shielding, CREME96
The Proton SEE Environment is Defined for a Conservative Value of Shielding. Orbit Average and Maximum Fluxes are Defined

Trapped Proton Integral Fluxes, behind 100 mils of Aluminum shielding
ST5: 200-35790 km 0 degree inclination, Solar maximum
RHA Outline

• Overview
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• **Bound the part response**
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Parts and Material Potential Sensitivities

- **Materials**
  - Total Dose Effects
  - Displacement Damage

- **CMOS electronic parts**
  - Total Dose Effects
  - SEE

- **Bipolar electronic parts**
  - Total Dose Effects
  - Displacement Damage
  - SEE

- **Optoelectronic parts**
  - Displacement Damage
  - Total Dose Effects
  - SEE

- **Solar cells**
  - Displacement Damage
  - Total Dose Effects (cover glass)
Laboratory Radiation Testing Conditions are Significantly Different from the Actual in Flight Exposure to the Radiation Environment

Ground testing conditions
- Single particle sources
- Monoenergetic spectrum
- Individual environment effects
- Unidirectional environment
- Accelerated particle rates

Actual conditions
- Mixed particle species
- Combined environment effects
- Omnidirectional environment
- Broad energy spectrum
- Actual particle rates

temperature and bias conditions are also different

After LaBel & Stassinopoulos
Data Search and Definition of Data Usability Flow

After K LaBel, IEEE TNS vol 45-6, 1998
Sources of Radiation Data

• Available databases:
  – ESA: http://escies.org
  – DTRA ERRIC: http://erric.dasiac.com
  – NRL REDEX: http://redex.nrl.navy.mil

• Other sources of radiation data:
  – Vendors?
Generic TID Testing

- Initial Measurement
- x Krad Irradiation
- Interim Measurement
- Annealing
- Final Measurement

Test standards:
- US MIL-STD-1019.5
- ESA/SCC 22900

Test Guidelines:
- ASTM F1892
TID Characterization - Example

DNL: Differential Non Linearity

Dose Rate = 0.83 rad(Si)/sec

Total Dose (rad(Si))

After J Bings, NAVSEA/CRANE test report, 2001
The laboratory dose rates are significantly higher than the actual space dose rates, testing according to test standards gives conservative estimates of CMOS devices TID sensitivity

After A Holmes Siedle and L Adams, Oxford Un. Press, 1993
The high temperature annealing is very important to check for rebound effect on CMOS devices.

*After J Schwank, IEEE TNS vol 31-6, 1983*
Current Test Standards do not Allow to Bound the TID Response of Linear Bipolar Integrated Circuits

Effect of dose rate

The post irradiation annealing cannot simulate the low dose rate

After T. Carriere, IEEE TNS vol 42-6, 1995
ASTM F1892 ELDRS Flow Diagram

Start → Review data ELDRS?

- Yes: Willing to accept risk?
  - Yes: Default RLAT
    (1) Test at 10 mrad/s, RT; DM = 2
    or (2) Test at 1 rad/s, 100 °C to 50 krad; DM = 3
  - No: Characterization
    (1) Determine max low dose rate enhancement
    (2) Perform elevated temp irradiations and anneals
    (3) Identify RLAT tests

- No: Initial Test
  (1) Baseline: high rate at room temp
  (2) Compare to low rate or ETI at 100 °C, 1 rad/s
  ELDRS?
  - Yes: Perform RLAT
  - No: TM1019 → End

End
The Temperature Environment and the Bias Conditions Also Have a Significant Impact on the TID Response

• Application Conditions: Temperature
  – Space: typical temperature between 0 and 70 °C.
  – Laboratory: ambient temperature.
    • => In general, the laboratory temperature is a worst case in comparison with application temperature

• Application Conditions: Bias
  – Space: dynamic bias or OFF
  – Laboratory: Usually worst-case.
    • => The bias in laboratory is a worst case or equivalent in regard with the application bias
TID Testing - Effect of Bias
FDN361AN

Dose rate < 1 rad(Si)/s

Unbiased parts

Specification limit

Biased parts

Irradiation

168h
25°C annealing

After J Titus, NAVSEA/CRANE report, 2001
TID Testing - Effect of Bias

PM155

After T. Carriere, Astrium report, 1997
Displacement Damage Testing

Initial Measurement

N p/cm² Irradiation

Interim Measurement

After R Reed, IEEE TNS vol 48-6, 2001

CTR: Charge Transfer Ratio (I_{output}/I_{input})
Displacement Damage Testing

• Radiation source: Typically protons, one energy
  – on some devices (e.g. optocouplers), due to inconsistencies between experimental determination of damage factors and NIEL calculations, it is recommended to test the parts at multiple energies.
  – Larger Radiation Design Margins may be appropriate.

• Bias conditions
  – In general, less effect than for TID, in most cases parts are unbiased during irradiation.
SEE Testing

Test standards:

• JESD57 (heavy ions only)
• ESA/SCC 25100 (heavy ions and protons)

Test guidelines:

• ASTM F1192-90 (heavy ions only)

Cross section = number of observed SEE/particle fluence

• Particle fluence in #/cm²
• Cross section in cm² (or cm²/bit)
Heavy Ions Cross Section Curves, Example

KM44V16104BS-50, 64Mbit DRAM from SAMSUNG
SEU bit errors

Cross section saturates

LET threshold:
- highest LET at which no event is observed after $10^7$ ions/cm$^2$

After C Poivey, ESA parts conference 2000
Proton Cross Section Curves, Example

Austin/Motorola 512K8 SRAM
SEU bit errors

Cross Section (cm²/bit)

Proton Energy (MeV)

After C Poivey, NSREC 1998 data workshop
SEE Testing - Radiation Sources

• Heavy ion accelerator
  – low energy, short penetration range compared to space heavy ions
    • parts are usually delidded for testing.
    • Tests performed under vacuum in most cases.

• Proton accelerators
  – space energy range available on accelerators
    • irradiation performed in Air.
    • parts generally do not need to be delidded.
    • A larger number of particles per test run is often needed for the tests (>10^{10} p/cm^2 compared to 10^7/cm^2 for heavy ions). The dose deposited may be significant.
SEE Testing

• Application conditions: temperature
  – Space: typical temperature between 0 and 70 °C.
  – SEE testing: ambient temperature.
    => In general, high temperature is a worst case for SEE testing

• Application conditions: bias
  – Space: dynamic bias
  – SEE testing: usually worst case, but not always
    => High supply voltage is a worst case for Single Event Latchup (SEL). Low supply voltage is a worst case for Single Event Upset (SEU).
    => The test frequency and the test patterns have a significant impact on the test results.
Effect of Test Pattern - Example

XPC603

After F Bezerra, RADECS 1997 data workshop
RHA Outline

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TID / DD - Analysis flow

- TID/DD Environment Definition
  - Shielding Analysis
    - TID/DD Requirement
      - Radiation Design Margin
  - Part TID/DD Sensitivity
- Radiation
- Design Worst Case Analysis
  - Requirements Satisfied?
    - Yes: Design Validated
    - No:Go back to TID/DD Environment Definition

Temperature
Aging
Design Margin Breakpoint (DMBP)

DM < 1-2 < DM < 10 < DM < 100 < DM

- Unacceptable
- Hardness Critical-HCC1
- Hardness Critical-HCC2
- Hardness Non-Critical

• Radiation Lot Testing

Qualitative approach recommended for systems with moderate requirements

*After MIL-HDBK814*
Part Categorization Criteria (PCC)

Log normal distribution law

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

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

\( s \) = standard deviation of sample data

DM < 1-2 < DM < PCC < DM

Unacceptable

Hardness Critical

Hardness Non-Critical

After MIL HDBK-814
One-Sided Tolerance Limits, $K_{TL}$, for 90% Confidence

After R Pease, Rad Phys Chem 43, 1994
PCC - Example of Application

RDM = 2
Ps = 99%
C = 90%
K_{TL} = 3.5
PCC = 1.44

Rspec = 30 krad
One sided tolerance limit 42 krad
Design dose = 60 krad

Radiation degradation for WCA = 10 mV

After T. Carriere, Astrium test report, 1997
## SEE - Analysis Requirement

<table>
<thead>
<tr>
<th>SEE LET threshold</th>
<th>Analysis Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100 MeVcm$^2$/mg</td>
<td>SEE risk negligible, no further analysis needed</td>
</tr>
<tr>
<td>$15 \text{ MeVcm}^2/\text{mg} &lt; \text{LET}_{\text{threshold}} &lt; 100 \text{ MeVcm}^2/\text{mg}$</td>
<td>SEE risk, heavy ion induced SEE rates to be analyzed</td>
</tr>
<tr>
<td>LET$_{\text{threshold}} &lt; 15 \text{ MeVcm}^2/\text{mg}$</td>
<td>SEE risk high, heavy ion and proton induced SEE rates to be analyzed</td>
</tr>
</tbody>
</table>
Heavy Ion SEE Rate Calculation
Integral RPP Method

Integral LET Spectra at 1 AU (Z=1.92) for Interplanetary orbit
100 mils Aluminum Shielding, CREME 96

KM44V16104B S-50, 64Mbit DRAM from SAMSUNG

# SEU / ion/cm²

# ions / cm² / s

Sensitive volume (SV) geometry

X_{sat}

SEU rate / s
Comparative Upsets Rates Geosynchronous GCR Solar Minimum Environment, CREME 96

Uncertainties in SEE predictions are significant

After E. Petersen, NSREC 1997 short course
Proton SEE Rate Calculation

Trapped Proton Integral Fluxes, behind 100 mls of Aluminium shielding STs: 200-35/90 km 0 degree inclination, Solar maximum

# SEU / proton / cm²/bit

# protons / cm² / s

SEU rate/ bit s
SEE Criticality Analysis (SEECA) Leads to System Performance

From SEECA document NASA-GSFC radhome web page
http://radhome.gsfc.nasa.gov
SEE - Decision Tree

Single Event Effect Severity Assessment

Include effects of any error mitigation in design

Function is Error-functional

Large number of SEEs can be tolerated

YES

Procure Components so that Predicted Error Rate for Function Meets Requirement

NO

Add additional Mitigation for SEE to Design

Function is Error-vulnerable

Very low number of SEEs can be tolerated

YES

Additional Error Mitigation Useful/Cost-effective

NO

Function is Error-critical

No SEEs permitted

YES

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

From SEECA document NASA-GSFC radhome web page
http://radhome.gsfc.nasa.gov
Example of SEE Analysis

• Function Description
  – Memory module for Command&Data Handling (C&DH) subsystem processor: 8M*40 bits
  – 5 8Mx8 DRAM K4F660812D
  – SEU mitigation: Hamming (32,8) EDAC (correct one error, detect 2) + scrubbing

• Mission environment
  – 200km-35790 km
  – 0 degree inclination
  – 3 months duration

• Exposed to GCR, solar particles and trapped protons

DRAM: Dynamic Random Access Memory
EDAC: Error Detection And Correction
Example of SEE Analysis

• Heavy ion results
  – No SEL
  – No SEFI
  – No block/column error
  – MBU
  – SEU

• GCR Heavy ion induced SEE rate
  – 0.07 SEU/device day
  – $10^{-4}$ MBU/device day

• Proton results
  – No SEL
  – No SEFI
  – No block/column error
  – No MBU
  – SEU

• Trapped Proton induced SEU rates
  – 3 SEU/device day
Example of SEE Analysis

- Function criticality analysis & requirement
  - one uncorrected error may cause the C&DH processor to fail, and then to reset
  - error vulnerable class: < 1 failure/mission is allowed

The failure rate is acceptable for this mission, but a failure could happen the first day of the mission

- Function failure rate for background environment (GCR+trapped protons)
  - MBU ~ 0.04/mission
  - Accumulation of 2 SEU between two consecutive scrubbing of a data word

\[ \text{Rate/s} = \frac{1 - [e^{-\mu} \times (1+\mu)]^N}{t_i} \]

- \( t_i \) = time required to update the total system memory = 240s
- \( \mu \) = mean number of upsets per memory word during \( t_i \) = 5E-9
- \( N \) = total number of system memory word = 8M

Rate/year ~ 4x10^-6/mission

*After JB White, IEEE Trans on Aerospace and Electronics Systems, vol 18-1, 1982*
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Management of RHA

SPACECRAFT DESIGN TEAM

- Project Management
- System
- Electrical
- Command & Data Handling
- Power Systems
- Guidance Navigation & Control
- Flight Software
- Science Instruments
- Ground System & Ops
- Propulsion
- Integration & test
- RF Communication
- Thermal
- Mechanical
- Radiation
- EEE Parts
- Reliability
- Safety
- Quality Assurance
Project Requirements Flow-Down
Radiation Specifications

- Environment specification
  - Particle flux, peak and average, shielded and unshielded
  - Mission dose depth curve
- Radiation Hardness assurance specification
  - Mission top level requirements
  - Required design margins
  - Test requirements
Radiation Hardness Assurance During the Program Life

• During the Proposal/feasability Phase
  – Draft Environment definition
  – Draft Hardness assurance requirement
  – Preliminary studies
• At the Preliminary Design Review (PDR)
  – Final Environment definition
  – Electronic design approach, ..
  – Preliminary spacecraft layout for shielding analysis
  – Preliminary shielding analysis
  – Final Hardness assurance requirement definition
• At the Critical Design Review (CDR)
  – Radiation test results
  – Final shielding analysis
  – Circuit design analysis results
• After CDR
  – Radiation Lot Acceptance tests
• After Launch
  – Failure analysis
RHA Outline

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Conclusion

• The RHA approach on space systems is based on risk management and not on risk avoidance.
• RHA process is not confined to the part level.
  – Spacecraft layout
  – System/subsystem/circuit design
  – System operations
• RHA should be taken into account in the early phases of a program development, including the proposal and feasibility analysis phases.
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