Using FLUKA to Calculate Spacecraft Event Environments: A Practical Approach

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SPACE ENVIRONMENT EFFECTS
| Spacecraft Contamination | Space Plasma | Ionsizing Radiation | Solar UV/Solar X-rays | Atomic Oxygen | Thermal Vacuum |

Safety • Reliability • Mission Success

BOEING

NASA

ES4

ENGINEERING NASA
- The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process
  - Role of the mission and spacecraft specific single event effects (SEE) environment
  - Role of nuclear reaction and transport processes in determining the spacecraft SEE environment
    - Natural vs. induced SEE environments ± nuclear reaction in shielding mass and avionics components
  - Why FLUKA (FLUktuierende KAskade)?
- Comparing in-flight single event upset rates with rates calculated using FLUKA LET spectra
  - Low-Earth Orbit (LEO)
    - Space Shuttle and International Space Station (ISS)
    - Calculated vs. observed single event rates
    - LET spectra as a function of shielding mass
  - Geosynchronous and Interplanetary orbits
    - Cassini, SOHO, Mercury Messenger, ETS-V, Thyraya
    - Calculated vs. observed single event rates
    - LET spectra as a function of shielding mass
- Calculating SEE environments and rates with FLUKA
  - Calculating LET Spectra
  - Calculating SEE rates
  - LET spectrum and SEE rate characteristics
    - Shielding mass effects
    - Contribution of various CR elements to the expected SEU rates
    - The effects of high Z elements in microelectronic devices
- Discussion, Summary and Conclusions
The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

Step 1 - Mission Specific SEE Environment Specification

Step 2 - Microelectronic device SEE Characterization

Step 3 - Calculate (estimate) expected in-flight device SEE rates

Step 4 - Is the expected SEE rate acceptable in light of system safety and reliability requirements?

How do we know all this works (method validation)?

Why the interest in FLUKA?
The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

- **Step 1- Mission Specific SEE Environment Specification**
  - **Natural SEE Environment**
    - Galactic Cosmic Ray (GCR) and Trapped Radiation environment definitions from the U.S. Naval Research Laboratory CREME 96 web page, (https://creme96.nrl.navy.mil/) (for solar minimum)
  - **Spacecraft Specific Induced SEE Environment**
    - Results when the natural SEE environment is processed by:
      1) spacecraft structural, consumable, and shielding materials
      2) avionics device materials
    - Calculated using a nuclear reaction and transport model ± FLUKA in this case
    - The result is a differential, $f(\text{LET})$, or integral $F(\text{LET})$ probability distribution function providing the particle flux as a function of particle LET - isotropic to first approximation
    - LET units are in (MeV cm$^2$)/mg (Si)

- **Step 2 - Microelectronic device SEE Characterization**
  - **Device (chip) level heavy ion and/or proton testing**
    - Cross section for single events vs. charged particle Linear Energy Transfer (LET) in the target device at one of several accelerator facilities
The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

- Step 3 - Calculate (estimate) expected (in-flight) device single event rates using:
  - 1) Differential form of the SEE environment definition, $f[\text{LET}]$, solar minimum
    - $f[\text{LET}]$ is isotropic (ICRU definition)
    - Scale the simulation particle flux/fluence to on-orbit flux/fluence
  - 2) The integral form of the device directional cross section
WHY FLUKA?

- Microelectronics are evolving beyond the limits of established single event test and verification methods
  - The size of microcircuit elements continue to shrink
  - Microcircuit element packing density and VLSI circuit complexity continue to increase
  - High atomic number elements like Ni, Cu, W and Hf are introduced over a range of size scales introducing nuclear reaction issues
  - Many of the assumptions underlying affordable versions of the established test methods (JEDEC EIA/JESD57 and/or ASTM F1192 -00(2006)) and associated SEE rate models are increasingly unreliable or not applicable
    - (Johnston, 1998), (Shaneyfelt, Schwank, Dodd, Felix, 2008), (Lacoe, 2008), (Schrimpf, Warren, Ball, Weller, Reed, Fleetwood, Massengill, Mendenhall, Rashkeev, Pantelides, Alles, 2008), (Muntenau, Autran, 2008), (Fulkerson, Nelson, Carlson, 2006), (Reed, Kinnison, Pickel, Buchner, Marshall, Kniffin, LaBel, 2003)

- Increasing community interest in Monte Carlo nuclear reaction and transport codes to understand and evaluate SEE processes in modern microelectronic devices
  - Spacecraft and planetary/lunar/asteroid shielding mass effects
  - Energy/charge deposition
  - Nuclear reactions in or near microcircuit elements
  - Multi-node charge collection
  - Simulation of heavy ion testing
  - Multiple bit upset analysis
  - Simulation of low energy and high energy proton testing
    - (Warren, Sierawski, Reed, Weller, Carmichael, Lesea, Mendenhall, Dodd, Schrimpf, Massengill, Hoang, Wan, De Jong, Padovani, Fabula, 2007) (Skutnik, Lajoie, 2006)
Three basic processes
- **Energy loss (dE/dx) by ionization of material along the particle track**
  - Direct ionization effects ± linear energy transfer (LET)
- **High energy collision (inelastic) with spacecraft materials nuclei**
  - Nuclear reactions initiate secondary particle showers
  - Proton and neutron SEE effects are often the result of direct nuclear reactions
    - reactions in or near the device sensitive volume
  - Further collisions of secondary particles with spacecraft nuclei leading to expansion and propagation of the secondary particle shower
  - Secondary particles can produce direct ionization and more nuclear reactions
    - Recoil nuclei have short range but high LET
- **Collisions with material nuclei produce displacement damage**
  - Higher atomic number spacecraft target nuclei produce more secondary particles
  - Density of spacecraft materials >> density of air

**Minimum and Median Shielding Mass**
- **Inside ISS - US Lab**
  - Minimum = 10 g/cm² Al
  - Median = 40 g/cm² Al
- **(DUWK)NDWPRVSKHUH-DW≠≠≠≠≠≠NP≠≠DOWLWXGH≠≠**
  - Minimum = 56 g/cm² air
  - Median = 84 g/cm² air
WHY FLUKA? - Demonstrated successful applications include:

- Cosmic ray physics
- Neutrino physics
- $\text{FFHOHUDWRU}^\text{GHVLJQ}$
Spacecraft SEU rate calculations and comparison with in-flight rates

Success Metric Ratio = In-Flight SEU Rate/Predicted SEU Rate

Success Criteria = 0.1 < (In-Flight Rate/Predicted Rate) < 10

This section presents results only ± details of calculation methods, approximations used, and results will be treated in the section 3.
Weekly SEU Sum

- Weekly SEU Sum
- Counter Resets
- Data Dropouts
- Large SPEs
- Linear (Weekly SEU Sum)

SEU Events

Time (Fractional Year)
ISS & Shuttle Success Metric Plot for 2 different spacecraft, 4 different parts, 3 different shielding mass environments

Y axis ± upset rate prediction method

X axis ± Success Metric Ratio = In-Flight Rate/Predicted Rate

1) FLUKA and FOM meet the success criteria or are very close in all cases
2) FLUKA results for the median shielding mass in the spherical target and the simple shielding mass in the slab target are in agreement

See Appendix 2: Tables 1-5 for case specific details
Fluka calculation methods predict shielding mass effects on SEU rate accurately for the standard ISS MDM DRAM but not as accurately for the Enhanced MDM DRAM.

Shielding mass effects: ISS FLUKA spherical target calculation

Y axis - ISS MDM DRAM, upsets per week per MDM

X axis - Median shielding mass in grams/cm²

Shielding mass Rate Ratio = (10 g/cm² Rate) / (40 g/cm² Rate)

<table>
<thead>
<tr>
<th>Device</th>
<th>Rate Ratio - Flight</th>
<th>Rate Ratio ± FLUKA Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI (1M x 4)</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>TMS44400</td>
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<td></td>
</tr>
<tr>
<td>TI (4M x 4)</td>
<td>0.9</td>
<td>1.8</td>
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<tr>
<td>TI SMK416400</td>
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<td></td>
</tr>
</tbody>
</table>
GEO/Interplanetary Success Metric Plot for 5 different spacecraft, 6 different parts and shielding mass environments

Mercury Messenger
Right Circular Cylinder (RCC) Target, T/W=1

*Appendix 2: Tables 6 and 7*
**Mercury messenger shielding mass and tungsten over layer effects:**

**Y axis** - Mercury Messenger SRAM upsets per bit day, RCC, T/W=1

For Mercury Messenger SRAM, a FLUKA rate calculation, using an approximate sensitive volume geometry, predicts a very different SEU rate dependence on shielding mass when the 1 micron Tungsten over-layer is present above the Si detector shell

**X axis** ± g/cm² Al median shielding mass (spherical target, cosine and solid angle corrections)
Calculating SEE Environments and rates with FLUKA:

Calculating LET Spectra

Calculating SEE rates

LET spectrum and SEE rate characteristics
FLUKA—Comprehensive basic physics with experimental validation

- FLUKA is a multipurpose Monte Carlo energetic particle interaction and transport code
  - Monte Carlo code (more than 500,000 lines of Fortran Code)
  - Theory driven/experimentally benchmarked ± well tested physics based microscopic models (not semi-empirical look-up tables)
    - Nucleus-nucleus collisions and secondary particle production included explicitly
  - Benchmarked/verified extensively with high energy accelerator data
    - not yet benchmarked for spacecraft SEE/TID/DD processes of interest
    - FLUKA 2006.3b only partly successful (MRQW 2007)
  - FLUKA is not a tool kit ± the physical models are fully integrated
  - Full development of hadronic (secondary particle) showers
  - Complex user generated target geometries and target materials are possible

- Basic References
  - FLUKA version ± Fluka2008.3b results reported here
    - FLUKA results reported at MRQW 2007 generated with an earlier version of FLUKA
  - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
  - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
  - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
  - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
  - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
    - FLUKA results reported at MRQW 2007 generated with an earlier version of FLUKA
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    - "FLUKA: a multi-pDUcW FOspoWUoQVARFWsF, GH 3errari, )D
“System Requirements”

- Run Times on the JSC/ES4 blade server
  - For a given CR spectrum and shielding mass or target configuration:
    - We run each cosmic ray element as a single job
    - Using a blade server we can submit all 24 to 27 jobs at once and they will execute in parallel
      - We have 3 dual quad core “blades” dedicated to FLUKA runs
      - Each “core” is equivalent to an independent processor for practical purposes
      - So, we have 24 processors available and can run up to 24 jobs in parallel
      - All the runs (24 to 27 batch jobs submitted in parallel) generally complete within one week of submission (see chart 18)
    - For a fixed number of primary particles, run time increases dramatically with particle atomic number
  - Without the parallel processing capabilities of a blade server, execution times are too long to be of any practical use in most cases
    - Unless only one CR or Trapped particle species is of interest

- JSC/ES4 blade server specification:
  - Blade Hardware - HP ProLiant BL460c G1 x64
    - 2 Quad-Core Intel Xeon 2.6 GHz processors with 32 GB RAM and 146 GB storage
  - OS - RedHat ES5 version 5.2
    - Batch job queue management - MCS Portable Batch System
    - Fortran G77 compiler
Calculating Spacecraft SEE Environments with FLUKA

- Use generic slab or concentric shell "spacecraft" geometries with layers of silicon (or other) "scoring" detectors between layers of aluminum (or other) shielding mass.
  - Simple, well defined shielding mass distribution and median shielding mass for each detector shell in each geometry.
  - For the slab target geometry FLUKA simply fires particles into the center of the slab at normal incidence.
  - For the concentric shell target, FLUKA fires randomly directed particles, selected from the spacecraft natural SEE environment, into the spherical shell structure from the outside (an ICRU isotropic flux).

- FLUKA utilities randomly samples natural GCR and Trapped particle spectra to specify particle, particle kinetic energy, and particle direction.
  - For each particle, FLUKA calculates through the target structure along the particle track:
    - Energy loss (LET) of primary particles.
    - Nuclear reactions and reaction products (secondary particle showers).
    - Energy loss (LET) and further nuclear reactions of secondary particles.

- A FLUKA utility generates the final product, i.e. the LET spectrum entering each Si detector shell which includes all contributions to LET from both primary particles and secondary particles formed in shielding.
  - FLUKA also calculates nuclear reactions and recoil products interior to the Si layer but efficient methods for scoring those contributions to the detector shell LET spectrum are still in development at this time.
  - FLUKA reports both forward and backward going particles with respect to the primary beam direction ± only forward going are reported here.
Calculating Spacecraft SEE Environments with FLUKA

- As employed here, FLUKA calculates an estimate of the LET spectrum internal to a microelectronic device die material located internal to spacecraft shielding mass
  - Device or system SEE rates are then calculated using:
    - the FLUKA detector shell LET spectrum
    - device SEE characterization data
    - directional cross section models
  - We do not calculate SEE rates during the FLUKA calculation based on specific sensitive volumes imbedded in the Si detector shells at this time

- The usual assumption is made
  - Energy deposition and charge production in the target is proportional to the product of ion LET and ion track length and LET is assumed constant

- Detailed treatment of nucleus-nucleus collisions in spacecraft SEE transport calculations with comprehensive treatment of all secondary particles
- As employed here, FLUKA calculates an estimate of the LET spectrum internal to a microelectronic device die material located internal to a spacecraft
  - Nuclear reactions internal to the detector shell are counted but the contributions of the nuclear reaction products to the detector shell LET spectra are not at this time

- We compare the FLUKA SEE rate with the in-flight SEE rate for the applicable spacecraft median shielding mass
  - Success Criteria - As a minimum, the on-orbit SEE rate calculation method should provide SEE rate estimates accurate to within a factor of 10 at one standard deviation when compared to available in-flight data

\[ 0.1 < \frac{\text{In-Flight Rate}}{\text{Predicted Rate}} < 10 \]

Success Metric Ratio = \( \frac{\text{In-Flight Rate}}{\text{Predicted Rate}} \)
**FLUKA Al Slab Target**

*10 micron silicon detector layers*

**Particle Beam**

Distance from slab target surface to Si detector layer in cm.

*X axis - distance from center of cylindrical AL slab target in cm*

(The actual slab target diameter used was 100 cm)

*Y axis - distance form top surface of slab to Si detector slab in cm*
FLUKA Concentric Al Sphere Target in Cross Section
100 micron Si detector shells, polar coordinates

Radial distance of Si detector shell from the center of the sphere.

The volume of the sphere at radii smaller than 5000 cm is treated as a perfect particle absorber in all FLUKA runs.
**FLUKA 2008.3b Calculation Details**

- **Number and identity of GCR primary particles**
  - P, He, C, O, Mg, Si, Fe, and Zn only, no higher Z elements
  - Number of primaries particles for FLUKA runs are always greater than the expected CREME-96 weekly fluence (#/cm² week) to assure adequate and physically realistic statistics

<table>
<thead>
<tr>
<th>Element</th>
<th>H trapped</th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>O</th>
<th>Mg</th>
<th>Si</th>
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<td>ISS orbit</td>
<td>2.5 x 10⁷</td>
<td>3.5 x 10⁵</td>
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<tr>
<td>Interplanetary</td>
<td>0.0</td>
<td>2.82 x 10⁶</td>
<td>2.7 x 10⁵</td>
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<td>7.1 x 10³</td>
<td>1.4 x 10³</td>
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<td>FLUKA primaries</td>
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<tr>
<td>ISS orbit</td>
<td>9 x 10⁷</td>
<td>9 x 10⁵</td>
<td>9 x 10⁵</td>
<td>6.8 x 10⁵</td>
<td>4.5 x 10⁵</td>
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<td>6.8 x 10⁵</td>
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<td>4.5 x 10⁵</td>
<td>2.3 x 10⁵</td>
<td>9 x 10⁴</td>
<td></td>
</tr>
</tbody>
</table>

- **Slab Target** - particles flux at normal incidence - slab 10 meters in diameter
- **Spherical Shell Target**
  - FLUKA isotropic (ICRU) flux utility provides an isotropic flux to the exterior surface of the sphere
  - Inner radius of concentric spherical shell structure = 5,000 cm = 50 meters
- **LET scoring** ± 0.0010 or 0.0100 cm thick Si scoring targets for both slab and concentric spherical shell targets for each shielding mass thickness
  - LET from all particles and interactions to include recoil products from proton and neutron reactions in the Si scoring target
**FLUKA 2008.3b Calculation Details**

- **FLUKA Target Shielding mass for each Si detector layer**
  - From outside to inside in g/cm$^2$ total shielding mass (overlying Al or PE + Si scoring target mass) exterior to each Si scoring detector (SiDet)
  - Spherical shell and slab targets
  - Total areal shielding mass - from outside to inside with respect to the entering particle beam

<table>
<thead>
<tr>
<th>FLUKA Target</th>
<th>SiDet1</th>
<th>SiDet2</th>
<th>SiDet3</th>
<th>SiDet4</th>
<th>SiDet5</th>
<th>SiDet6</th>
<th>SiDet7</th>
<th>SiDet8</th>
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<td>Slab</td>
<td>0.1</td>
<td>0.5</td>
<td>1.0</td>
<td>5.0</td>
<td>10.0</td>
<td>20.0</td>
<td>50.0</td>
<td>100</td>
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<tr>
<td>Sphere (minimum)</td>
<td>0.1</td>
<td>0.5</td>
<td>1.0</td>
<td>5.0</td>
<td>10.0</td>
<td>20.0</td>
<td>50.0</td>
<td>100</td>
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<tr>
<td>Sphere - median (cosine correction only)</td>
<td>0.14</td>
<td>0.70</td>
<td>1.40</td>
<td>6.90</td>
<td>13.7</td>
<td>27.3</td>
<td>68.1</td>
<td>137.2</td>
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<td>Sphere ± median cosine and solid angle corrections</td>
<td>0.15</td>
<td>0.81</td>
<td>1.6</td>
<td>7.9</td>
<td>15.6</td>
<td>31.1</td>
<td>77.5</td>
<td>156.2</td>
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</table>
**FLUKA differential LET spectra – ISS Orbit – SLAB Target**

**Y axis:** on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SLAB target

**X axis:** particle LET in MeV x mg/(cm²) (Si)
FLUKA differential LET spectra – ISS Orbit – SPHERE Target

Y axis: on-orbit particle flux to each Si detector in units of #/cm²/week per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections

X axis: particle LET in MeV x mg/(cm²)
Device Directional Cross Sections

- Problem - isotropic flux on a generally anisotropic target
SEE Rate Calculations

- Generalized Rate Equation
  - Polar angle (θ)
ISS orbit SEU rates for a simple Isotropic Step Function $\sigma$

**SLAB**

- $1 \times 10^5$
- $1 \times 10^6$
- $1 \times 10^7$

**SPHERE**

- $1 \times 10^5$
- $1 \times 10^6$
- $1 \times 10^7$

$X$ axis ± g/cm$^2$ Al median shielding mass
(For the spherical target, cosine and solid angle corrections per page 27)

$Y$ axis - number of step function isotropic target hits per week;
Which energetic nuclei contribute most to the step function SEU rates in LEO?

Full FLUKA LEO particle set

Full FLUKA LEO particle set removing Trapped radiation

Full FLUKA LEO particle set removing Trapped radiation and Fe

X axis $\pm \text{g/cm}^2$ Al shielding mass, spherical target with cosine and view factor corrections per page 27

Y axis - number of step function isotropic target hits per week;
FLUKA differential LET spectra – GEO/Interplanetary – SPHERE Target – Silicon detector shells only

Y axis: on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections

X axis: particle LET in MeV x mg/(cm²) (Si)
FLUKA differential LET spectra – GEO/Interplanetary – SPHERE Target – Silicon detector shells with 1 micron tungsten over-layer

Y axis: on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections

X axis: particle LET in MeV x mg/(cm²)
GEO/Interplanetary SEU rates for a simple Isotropic Step Function $\sigma$

$X$ axis $\pm$ g/cm$^2$ median Al shielding mass, spherical target with cosine and solid angle corrections per page 27

$Y$ axis - number of isotropic target hits per week;
Which Cosmic ray nuclei contribute most to the step function SEU rates?

- **Full FLUKA Free Space GCR set**
- **Removing Free Space GCR Fe**
- **Removing Free Space GCR Fe, He, P**

**X axis** ± g/cm² median Al shielding mass, spherical target with cosine and solid angle corrections per page 27

**Y axis** - number of isotropic target hits per week;

The answer depends on the step function threshold and the shielding mass.
Discussion Summary and Conclusions

- The FLUKA LET spectra in combination with heavy ion test data successfully predicts on-orbit SEE rates for several different CMOS SRAM, DRAM, and SDRAM components
  - Success criteria 1 ± The FLUKA predicted rate is within a factor of 10 of the in-flight rate in many cases using approximate treatments of the directional cross section
  -成功 criteria 2 - Shielding mass effectiveness may still be overestimated in some cases; accurate for the standard ISS MDM CMOS DRAM
  - Compares favorably with the well documented Figure of Merit method for those cases where the Figure of Merit is applicable
  - Predicts an increase in SEU rates produced by inclusion of a high Z element (W) in micro-device structure, all else being equal
  - Predicts important effects of the shielding mass on the SEU rate increase produced by a high Z element (W) in the micro-device architecture

- So what happened between MRQW 2007 and MRQW 2009?
  - FLUKA 2006.3b vs. FLUKA 2008.3b
  - 7KH8$/FRQVRUWLXP/XSGDWHG WKH 86(FXWLOLWWR SURYL) more accurate/complete reporting of high LET particles (personal communication, Professor L. S. Pinsky, Physics Department, University of Houston, FLUKA consortium)
Discussion Summary and Conclusions

- The FLUKA nuclear transport and reaction code can be developed into a practical tool for calculation of spacecraft and planetary surface asset SEE and TID environments
  - Nuclear reactions and secondary particle shower effects can be estimated with acceptable accuracy both in-flight and in test
    - More detailed electronic device and/or spacecraft geometries than are reported here are possible using standard FLUKA geometry utilities
    - Spacecraft structure and shielding mass
    - Effects of high Z elements in microelectronic structure as reported previously (Schrimpf, Warren, Ball, Weller, Reed, Fleetwood, Massengill, Mendenhall, Rashkeev, Pantelides, Alles, 2008), (Warren, Sierawski, Reed, Weller, Carmichael, Lesea, Mendenhall, Dodd, Schrimpf, Massengill, Hoang, Wan, De Jong, Padovani, Fabula, 2007)
  - Median shielding mass in a generic slab or concentric sphere target geometry are at least approximately applicable to more complex spacecraft shapes
    - Need the spacecraft shielding mass distribution function applicable to the microelectronic system of interest
  - SEE environment effects can be calculated for a wide range of spacecraft and microelectronic materials with complete nuclear physics
    - Evaluate benefits of low Z shielding mass can be evaluated relative to aluminum
    - Evaluate effects of high Z elements as constituents of microelectronic devices
- The principal limitation on the accuracy of the FLUKA based method reported here are found in the limited accuracy and incomplete character of affordable heavy ion test data
  - To support accurate rate estimates with any calculation method, the aspect ratio of the sensitive volume(s) and the
Appendices
Appendix 1: FLUKA based in-flight SEE rate calculation details
FLUKA Physics Overview

- Heavy ion interactions models
  - $E > 5$ GeV/n
    - Dual Parton Model, DPMJET-III
  - $0.1$ GeV/n < $E < 5$ GeV/n
    - Relativistic Quantum Molecular Dynamics, RQMD 2.4
  - $E < 0.1$ GeV/n
    - Boltzmann Master Equation (BME) Theory
    - BME code ± not utilized in this study

- Hadron - Nucleus Interactions
  - Resonance production and decay below a few GeV energy
  - Dual Parton model above a few GeV energy
    - The PEANUT model includes a detailed Generalized Intra-Nuclear Cascade (GINC) and a pre-equilibrium stage
    - Gribov- Glauber multiple collision model included in a less sophisticated GINC

- Transport of charged particles in matter
  - Bethe-Bloch theory
    - Shell and other low energy corrections,
    - Density effects according to Sternheimer
    - Restricted fluctuations (Landau fluctuations)
    - Delta ray production and transport optional
**Typical FLUKA Input (run) Physics Card Choices**

With the PRECISION default we request the following nuclear physics model

1) **Dual Parton Model Jet (DPMJET)**
   with Relativistic Quantum Molecular Dynamics (RQMD)

2) **Evaporation, Coalescence, and Electromagnetic Dissociation**
   are enabled

3) **The Peanut model is activated at all energies**

**TITLE**
CREME 96 GCR Spectrum

**DEFAULTS**
<table>
<thead>
<tr>
<th>Beam</th>
<th>-100.0</th>
</tr>
</thead>
</table>

**BEAMPOS**
| 0.0 | 0.0 | 5037.2 |

**HI-PROPE**
| 26.0 | 56.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**EVENTYPE**
| 2.0 |

**DPMJET**
| 0.0 | 0.0 | 0.0 |

**PHYSICS**
| 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**PHYSICS**
| 1.0 |

**PHYSICS**
| 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**PHYSICS**
| 1000. | 1000. | 1000. | 1000. | 1000. | 1000. | 1000. | PEATHRES |
SEE Rate Calculations

- **Isotropic Target**,  
  (Edmonds, Barnes and Scheick, 2000)
SEE Rate Calculations

Right Circular Cylinder (RCC) Target

- Barak, Akkerman, 2005
- Akkerman, Barak, 2002
- Barak, 2001
- Barak, Reed, LaBell, 1999

Note that we use the average (first moment) cord length for a given
Appendix 2: Spacecraft, Device Data, EDAC Protocols, and Shielding Mass Distribution Functions
ISS DRAM and SDRAM Characteristics

- ISS standard multiplexer de-multiplexer (std-MDM) input-output control unit (IOCU) board
  - Texas Instruments (TI) (1M x 4) 4 Mbit CMOS DRAM TMS44400
  - 3.3554 x 10^7 bits in each std-MDM
  - EPIC Process
  - 0.9 micron device scale
  - 5 V

- ISS enhanced MDM DRAM (enh-MDM) IOCU board
  - TI (4Mx4) CMOS DRAM TI SMJ416400
  - 1.342 x 10^8 bits in each enh-MDM
  - 5V

- ISS High Rate Communications Outage Recorder Samsung KM44S32030T-GL CMOS SDRAM 128 Mbit (Rev. A, 34M/4)
  - ISS High Rate Communications Outage Recorder (HCOR)
  - 2.115 x 10^{11} bits SDRAM in one HCOR (constant since launch+ losses made up from reserves)
  - 0.35 micron process/device scale
  - 3.3 V
ISS DRAM and SDRAM Weibull Parameters

STD MDM DRAM cross section vs LET

\[ \text{lostd} := 0.99 \quad \text{ostdsat} := 3.00 \times 10^{-7} \quad \text{wstd} := 7.7 \quad \text{zstd} := 1.3 \]

\[ \alpha_{\text{stdMDM}}(\ell) := \gamma - \exp \left( -\left( \frac{\ell - \text{lostd}}{\text{wstd}} \right)^{\frac{\text{zstd}}{} \right) \]

ENH (Enhanced) MDM rates - SMJ416400

\[ \text{loenh} := 0.42 \quad \text{oenhsat} := 1.10 \times 10^{-8} \quad \text{wenh} := 0.8 \quad \text{zenh} := 1.7 \]

\[ \alpha_{\text{enhMDM}}(\ell) := \gamma - \exp \left( -\left( \frac{\ell - \text{loenh}}{\text{wenh}} \right)^{\frac{\text{zenh}}{}} \right) \]

---

STD MDM DRAM (TMS44100DM-80) characterization - Harboe Sorensen, Muller, Daly, Nickson, Schmitt, Rombeck 1991)

ENH MDM DRAM characterization - Brown, R., IBM Manassas Test Report 2/23/93, and Falguere, Duzellier, Ecoffet, Tsourilo, 2000

---

Heavy ion data for Samsung 128Mbit (Rev. A, 34M/4) SDRAM: average values from Henson, MacDonald, and Stapor, NSREC Workshop 1999 - Samsung KM4432030T-G Fig. 6, static tests

HCOR SDRAM upper bound cross section vs LET

\[ \text{losdram1} := 13 \quad \text{osatsdram1} := 5.859 \times 10^{-8} \quad \text{wsdram1} := 30 \quad \text{zsdram1} := 1 \]

\[ \alpha_{\text{HCORhigh}}(\ell) := \gamma - \exp \left( -\left( \frac{\ell - \text{losdram1}}{\text{wsdram1}} \right)^{\frac{\text{zsdram1}}{}} \right) \]

HCOR SDRAM lower bound cross section vs LET

\[ \text{losdram2} := 14 \quad \text{osatsdram2} := 1.563 \times 10^{-8} \quad \text{wsdram2} := 30 \quad \text{zsdram2} := 1 \]

\[ \alpha_{\text{HCORlow}}(\ell) := \gamma - \exp \left( -\left( \frac{\ell - \text{losdram2}}{\text{wsdram2}} \right)^{\frac{\text{zsdram2}}{}} \right) \]

Heavy ion data for Samsung 128Mbit (Rev. A, 34M/4) SDRAM: values from SEAKER report - SDRL number MD005, SDS Number SS-EE-008, transmittal number 00-HCOR-086, PDC Number FM27257,

HCOR rates -HCOR SDRAM cross section vs LET (SEAKR - low k ions, normal incidence only except for one 40.5 degree angle and one 30.2 degree angle) - Boeing Dr. Tiku Rao-Sahib, and Aerospace Corp. Dr. Rocky Koga; U.C. Berkeley Cyclotron facility August 2, 2000.

\[ \text{losdram3} := 1.95 \quad \text{osatsdram3} := 1.863 \times 10^{-9} \quad \text{wsdram3} := 30 \quad \text{zsdram3} := 1.9 \]

\[ \alpha_{\text{HCOR3}(\ell)} := \gamma - \exp \left( -\left( \frac{\ell - \text{losdram3}}{\text{wsdram3}} \right)^{\frac{\text{zsdram3}}{}} \right) \]
ISS: Memory device information and Error Detection and Correction (EDAC) Protocols

- **Standard MDM Memory Information (MDM-4, MDM-10, MDM-16)**
  - Part Number = TMS44400; Part Type = 1Mx4 DRAM
  - Manufacturer = Texas Instrument (TI)
  - Device count (per MDM) = 8
  - Total Bits (per MDM) = 33,554,432
  - Memory Scrub Rate = memory initiated every 8 usec, 8.2 seconds total to scrub entire DRAM memory

- **Enhanced MDM Memory Information**
  - Part Number = SMJ416400; Part Type = 4Mx4 DRAM
  - Manufacturer = Texas Instrument (TI)
  - Device count (per MDM) = 8
  - Total Bits (per MDM) = 134,217,728
  - Memory Scrub Rate = initiated every tbd usec, 28.6 seconds total to scrub entire DRAM memory

- **HCOR Memory Device Information**
  - Part Number = KM44S32030AT
  - Part Type = 128MB SDRAM
  - Manufacturer = Samsung Memory
  - Array = 140 128Mbit devices (70 stacks of 2 high)
  - Memory Utilization = 211,452 Mbits (this is the amount of scrubbed memory available for users, accounting for spare boards, image RAM, etc.)
  - Scrub Rate = 3.25 usec/row, 7.3 min/board, 96 minutes total to scrub entire memory (assumes minimal errors encountered. One scrub in progress at any given time). It is not possible to generate position data with the HCOR SDRAM error counter data because of the delay (up to 95 minutes) between an SEU event occurring and the EDAC scrub correcting and counting the error. Refresh rate for error counter telemetry is 1Hz prior to January 12, 2005 and 0.1Hz from January 12, 2005 to the present.
ISS Shielding Mass Distribution Functions:
1) Multiplexer/De-multiplexer (MDM) internal vs external
2) High Rate Communication Outage Recorder (HCOR)

MDM DRAM Structural Shielding Distributions.

HCOR SDRAM Structural Shielding Distributions.

Table 1: Std-MDM DRAM and enh-MDM DRAM upset rates are in reasonable agreement with FOM predictions and FLUKA predictions

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of bits Per MDM</th>
<th>Median Shielding Mass</th>
<th>Device FOM</th>
<th>FOM calculated upsets per week per MDM</th>
<th>FLUKA Sphere Target RCC calculated upsets Observed In-Flight Upsets per week</th>
<th>Range of Observed In-Flight Upsets per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI (1M x 4) TMS44400</td>
<td>33.55x10^6</td>
<td>40 g/cm^2</td>
<td>1.93x10^-8</td>
<td>16</td>
<td>17</td>
<td>15 to 18 Regression line</td>
</tr>
<tr>
<td>TI (1M x 4) TMS44400</td>
<td>33.55x10^6</td>
<td>10 g/cm^2</td>
<td>1.93x10^-8</td>
<td>59</td>
<td>21</td>
<td>18 to 22 Regression line</td>
</tr>
<tr>
<td>TI (4M x 4) TI SMK416400</td>
<td>1.342 x 10^8</td>
<td>40 g/cm^2</td>
<td>8.98x10^-9</td>
<td>2</td>
<td>26</td>
<td>3 to 4 Regression line</td>
</tr>
<tr>
<td>TI (4M x 4) TI SMK416400</td>
<td>1.342 x 10^8</td>
<td>10 g/cm^2</td>
<td>8.98x10^-9</td>
<td>9</td>
<td>48</td>
<td>3 Regression line</td>
</tr>
</tbody>
</table>

Range of observed weekly rates from 2007 to 2009 for: 1) two std-MDMs at 40 g/cm^2, 2) six std-MDMs at 10 g/cm^2, 3) two enhanced MDMs at 40 g/cm^2, 4) one enhance MDM at 10g/cm^2

* SV aspect ratio = Sensitive volume aspect ratio = T/W
<table>
<thead>
<tr>
<th>Device Test Data</th>
<th>Number of bits per HCOR</th>
<th>Median Shielding Mass</th>
<th>Device FOM</th>
<th>FOM Calculated Upsets per week</th>
<th>FLUKA Sphere Target RCC calculated upsets per week per MDM (SV aspect ratio)*</th>
<th>Range of Observed In-Flight Upsets per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samsung KM44S32030T-GL (high)</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shuttle Flights</td>
<td>Device</td>
<td>Median shielding Mass</td>
<td>Observation Time</td>
<td>Device FOM</td>
<td>Weibull</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>--------</td>
<td>-----------------------</td>
<td>------------------</td>
<td>------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>STS-39, Inmos 64K</td>
<td>48, 52, 56 x 1 CMOS</td>
<td>34 g/cm²</td>
<td>29 flight</td>
<td>9.5 x 10⁻⁹</td>
<td>1.56 x 10⁻⁵</td>
<td>2.75</td>
</tr>
</tbody>
</table>

[Image of a space shuttle in orbit]
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>System</th>
<th>Device</th>
<th>Observation Period</th>
<th>Median Shielding Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cassini (interplanetary near 1 AU)</strong></td>
<td>Solid state recorder</td>
<td>OKI (4Mx1) DRAM 640/SSR</td>
<td>March 2000</td>
<td>3.4 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(NASA/JPL estimate)</td>
</tr>
<tr>
<td><strong>SOHO (Interplanetary near 1 AU)</strong></td>
<td>Solid state recorder</td>
<td>TI (4Mx1) DRAM SMJ44100</td>
<td>1996 ± 2001</td>
<td>1.0 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(ESA estimate)</td>
</tr>
<tr>
<td><strong>SOHO (Interplanetary near 1 AU)</strong></td>
<td>GOLF instrument</td>
<td>ATMEL CP65656EV-45 32kx8 SRAM</td>
<td>1996 - 2001</td>
<td>1.0 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(ESA estimate)</td>
</tr>
<tr>
<td><strong>Mercury Messenger (Interplanetary near 1 AU)</strong></td>
<td>Solid state recorder</td>
<td>CMOS SRAM (4 M x 1) (ASIC SEE/RAD KDUG365$65$01)</td>
<td>2004 to 2006</td>
<td>1.0 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(NASA estimate)</td>
</tr>
<tr>
<td><strong>ETS-V (GEO)</strong></td>
<td>Technical Data Acquisition Instrument (TEDA)</td>
<td>NEC (64k x 1) CMOS SRAM μ PD44464D-20</td>
<td>1987-1997</td>
<td>5.8 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(JAXA estimate)</td>
</tr>
<tr>
<td><strong>Thuraya (GEO)</strong></td>
<td>Digital Signal Processor (DSP)</td>
<td>0.25 μ SRAM, ASIC, IBM SA-12 Library</td>
<td>2001 - 2007</td>
<td>0.68 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Boeing Satellite Development Center estimate)</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Device</td>
<td>Median Shielding Mass</td>
<td>FOM Calculated Upsets per bit day</td>
<td>FLUKA (RCC or Isotropic (ISO)) Calculated Upsets per bit day (SV aspect ratio)</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------</td>
<td>-----------------------</td>
<td>-----------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Thuraya (GEO)</td>
<td>ASIC DSP 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**GEO/Interplanetary spacecraft device weibull parameters**

Thuraya DSP 0.25 micron CMOS megagate ASIC
cross section v s LET, aspect ratio, T/W = 0.7 Hansen et al 2007

\[ l_{dsp} = 2.7 \quad \sigma_{dsp}\text{sat} = 6.3 \times 10^{-8} \quad w_{dsp} = 20.6 \quad z_{dsp} = 1.2 \]

\[ \sigma_{d}(l) = \sigma_{dsp}\text{sat} \left[ 1 - \exp \left( \frac{l \cdot 0.1 - l_{dsp}}{w_{dsp}} \right)^{z_{dsp}} \right] \]

ETS-V, 64K SRAM NEC µPD4464D-20; 8 devices in ETS-V
SEL masked SEU in ground tests - SV depth 1 micron
aspect ratio = T/W = 0.05, Goka, 1998

\[ \gamma = 0.5 \quad \sigma_{sat \text{ETS}} = 0.24 \frac{64000}{w_{\text{ETS}}} = 15 \quad z_{\text{ETS}} = 2.9 \]

\[ \sigma_{\text{ETS}\text{(l)}} = \sigma_{sat \text{ETS}} \left[ 1 - \exp \left( \frac{l \cdot 0.1 - l_{\text{ETS}}}{w_{\text{ETS}}} \right)^{z_{\text{ETS}}} \right] \]

*Note ± Weibull parameters are either taken directly from references or were produced by nonlinear least squares fitting to heavy ion test data published in the references. The Pearson R correlation coefficients are greater than 0.9 in all cases.*

Mercury Messenger, aspect ratio approximately 1 , Reed et. al. 2007

\[ l_{\text{mm}} = 0.3 \quad \sigma_{sat \text{mm}} = 4 \times 10^{-8} \quad w_{\text{mm}} = 60 \quad z_{\text{mm}} = 6 \]

\[ \sigma_{\text{mm}}(l) = \sigma_{sat \text{mm}} \left[ 1 - \exp \left( \frac{\text{LET}_{\text{mm}} - l_{\text{mm}}}{w_{\text{mm}}} \right)^{z_{\text{mm}}} \right] \]

Cassini Solid State Recorder, isotropic target - Swift 200

\[ \gamma = 0.5 \quad \sigma_{\text{sat \text{ETS}}} = 0.24 \frac{64000}{w_{\text{ETS}}} = 15 \quad z_{\text{ETS}} = 2.9 \]

\[ \sigma_{\text{CS}}(l) = \sigma_{\text{sat \text{CS}}} \left[ 1 - \exp \left( \frac{\text{LET}_{\text{CS}} - \gamma_{\text{CS}}}{w_{\text{CS}}} \right)^{z_{\text{CS}}} \right] \]

SOHO TISMX44100-80 4 M x 1, thickness = 2 microns; Harboe-Sorensen, 2002

\[ \gamma = 0.7 \quad \sigma_{\text{sat \text{ETS}}} = 5 \times 10^{-7} \quad w_{\text{ti}} = 15 \quad z_{\text{ti}} = 2.7 \]

\[ \sigma_{\text{ti}}(l) = \sigma_{\text{sat \text{ETS}}} \left[ 1 - \exp \left( \frac{\text{LET}_{\text{ti}} - \gamma_{\text{ti}}}{w_{\text{ti}}} \right)^{z_{\text{ti}}} \right] \]

SOHO MHS CP65656EV 32K x 8 SRAM; thickness = 2 microns - Harboe-Sorensen, 2002

\[ \gamma = 1.9 \quad \sigma_{\text{sat \text{ETS}}} = 6 \times 10^{-7} \quad w_{\text{cp}} = 17 \quad z_{\text{cp}} = 1.2 \]

\[ \sigma_{\text{cp}}(l) = \sigma_{\text{sat \text{ETS}}} \left[ 1 - \exp \left( \frac{\text{LET}_{\text{cp}} - \gamma_{\text{cp}}}{w_{\text{cp}}} \right)^{z_{\text{cp}}} \right] \]
References


Barak, J., Reed, R. A., LaBel, K. A.; "On the Figure of Merit Model for SEU Rate Calculations," IEEE Transactions on Nuclear Science, 46(6), December 1999, pp 1504-1510.


