Radiation Transport Tools for Space Applications: A Review

Insoo Jun, Shawn Kang, Robin Evans, and Michael Cherng

Mission Environments Group
Jet Propulsion Laboratory, California Institute of Technology
February 16, 2008

5th Geant4 Space Users’ Workshop
Introduction

• Brief discussion of nuclear transport codes widely used in the space radiation community for shielding and scientific analyses:
  – Overview
  – What it can do
  – What it can not do
  – One or two examples of application
Radiation Environments: Particles that should be considered

- **Electrons**
  - Trapped, solar wind

- **Photons**
  - Bremsstrahlung, Reactor, RTG, RHU

- **Protons**
  - Trapped, Solar Energetic Particle Events, GCR

- **Neutrons**
  - Reactor, RTG, RHU

- **Heavy Ions**
  - GCR, Solar Energetic Particle Events
Primary Use of Radiation Transport Codes

- **Total ionizing dose**
  - Cumulative long term ionizing damage
- **Displacement damage dose**
  - Cumulative long term non-ionizing damage
- **Single event effects**
  - Event caused by a single charged particle (heavy ions and/or protons) traversing the active volume of microelectronic devices
- **Deep charging**
- **Particle detector simulation**
- **Device Simulation**
Radiation Transport Codes that will be Covered in this talk

- CREME96
- TRIM
- Integrated Tiger Series (ITS) 3.0
- NOVICE
- MCNP
- MCNPX
- Geant4
# General Methods

<table>
<thead>
<tr>
<th>Monte Carlo Method</th>
<th>Deterministic Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Does <strong>not</strong> solve explicit transport equation</td>
<td>• Solve transport equation for average particle behavior</td>
</tr>
<tr>
<td>• Obtain answers by simulating individual particles and recording their average behavior</td>
<td></td>
</tr>
<tr>
<td><strong>Pros:</strong></td>
<td><strong>Pros:</strong></td>
</tr>
<tr>
<td>– Can handle complex geometries</td>
<td>– Can obtain results throughout problem geometry in one run</td>
</tr>
<tr>
<td>– Can handle physically accurate cross sections</td>
<td>– Relatively fast even for deep penetration problem</td>
</tr>
<tr>
<td><strong>Cons:</strong></td>
<td><strong>Cons:</strong></td>
</tr>
<tr>
<td>– Slow</td>
<td>– Systematic errors result from discretization of phase space (space, energy, angle)</td>
</tr>
<tr>
<td>– Results are statistical</td>
<td>– Only works for geometries for which transport equations can be solved numerically</td>
</tr>
<tr>
<td>– Not efficient for deep penetration problems and for space applications</td>
<td>– Must use multi-group cross sections, thus results in inherently less accurate results</td>
</tr>
</tbody>
</table>
Monte Carlo Methods

• Forward vs. Adjoint methods
  – Forward: follows particles from source to target
  – Adjoint: follows particles from target to source

• When are forward calculations more efficient?
  – When we require a large number of responses across the problem geometry from a source confined in relatively small volume

• When are adjoint calculations more efficient?
  – When we require responses over the small volume from a source distributed over large volume or surface
Forward vs. Adjoint (1)

We want to compute energy deposition at each slab (different material) from mono-directional particle source.

The forward method is more favorable in this situation because every particles simulated will contribute to the results for all 4 slabs.

If we use the adjoint method, this problem implies we have to run 4 separate runs.
We want to compute energy deposition at the small target region located at the center of the spherical shell shield.

In forward scheme, many of the source particles will not reach the target region and will not contribute to the results.

However, in adjoint scheme, every particle simulated will contribute to the results.
<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Photon</th>
<th>Proton</th>
<th>Neutron</th>
<th>Ion (Z≥2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREME96</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>TRIM</td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>ITS</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOVICE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>MCNP</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>MCNPX</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Up to Z=2</td>
</tr>
<tr>
<td>Geant4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
CREME96: https://creme96.nrl.navy.mil

- Developed by Naval Research Lab (NRL)
- TRANS module
- 1-Dimension for aluminum
- Particles: All particles treated in CREME96 (protons and heavy ions)
- Primary application:
  - Proton energy spectrum or heavy ion LET spectrum for SEE evaluation of microelectronics
- Pros:
  - Easy web-based user interface
  - Simple physics models for energy loss and nuclear fragmentation
- Cons:
  - Limited to aluminum shielding and 1-dimensional
  - Is the physics accurate?
CREME96 LET Spectra for ISS LTMPF for different aluminum shielding thicknesses

GCR Heavy Ion LET Spectra

Integral Flux, (m²-sec-sr⁻¹)

0-mil
100-mil
1000-mil
3000-mil

CREME96 Differential Proton Spectra for different aluminum thicknesses

Differential Flux (m²-sec-sr-MeV⁻¹)

0-mil
100-mil
1000-mil
3000-mil

February 16, 2008

2008 Geant4, Tokyo, Japan

500 km/51.5 degree
Solar Minimum

Jun-12
TRIM: http://www.srim.org/

- Developed by James Ziegler
- Monte Carlo (Forward)
- 1-Dimension
- Particles: protons and heavy ions
- Primary application area
  - Proton or heavy ion beam simulation
- Pros:
  - Very simple and easy to learn
  - Cover the whole spectrum of heavy ions
- Cons:
  - Limited in 1-dimensional slab geometry
  - Only Coulomb interaction (no nuclear interaction)
100 keV Ion Beams into 1-μm SiO₂

Proton
R=0.9 μm

Alpha
R=0.7 μm

Carbon
R=0.3 μm

February 16, 2008
2008 Geant4, Tokyo, Japan
Jun-14
ITS3.0: http://www-rsicc.ornl.gov/

- Developed by Sandia National Lab. (SNL)
  - The latest version is ITS5.0, which is being distributed upon request.
- Monte Carlo (mostly forward)
- 1-D (TIGER), 2-D (CYLTRAN), and 3-D (ACCEPT)
- Primary application
  - Electron/photon beam experiment simulation
- Particles:
  - Electrons and photons
- Pros:
  - Validated physics models
  - Very easy to use (especially for TIGER)
- Cons:
  - Limited geometry modeling, simulation of space environments
Electron Beam into 2 μm Mylar Film

Charge Deposition Profile

Dose Profile
NOVICE: tj@empc.com

- Monte Carlo (adjoint)
  - Specifically developed for space applications
  - Only adjoint code available for charged particle transport
- 3-Dimension
- Primary application
  - Component level analysis with full spacecraft geometry
- Particles:
  - Electrons, protons, photons, heavy Ions
- Pros:
  - Fast
  - Versatile geometry, relatively easy to use
- Cons:
  - Can not handle neutrons, secondary particles
  - Black box (poor user manual)
MCNP: http://mcnp-green.lanl.gov/index.html

- Developed by Los Alamos National Lab (LANL)
- Monte Carlo (mostly forward)
- 3-Dimensional
- Particles:
  - Neutron, photons, and electrons
- Primary application
  - Neutron/photon transport for RTG and space reactor
- Pros:
  - Extensive history (since the Manhattan Project) and user base
  - Comprehensive physics
  - Versatile geometry and input/output options
- Cons:
  - Relatively difficult to learn
  - Slow for space applications
Mars Science Laboratory
Assessing the present and past habitability of Mars

1 MeV Eq. Neutron Fluence Level for 1-Year Operation

1 Year Fluence
# of 1MeV neutron / cm²

RDF=1

Neutron Displacement Damage, 25 cm grid

Ionizing Dose Level for 1-Year Operation

Rad(Si)/year
RDF=1

Gamma Dose in Silicon, 25 cm grid

Axial distance from the center of the RTG
Radial distance from the center of the RTG

February 16, 2008
2008 Geant4, Tokyo, Japan
Jun-20
Space Reactor with LiH Shield

Gamma Dose

February 16, 2008

2008 Geant4, Tokyo, Japan

Jun-21
MCNPX: http://mcnpx.lanl.gov/

- Developed by Los Alamos National Lab (LANL)
- Monte Carlo (mostly forward), built upon MCNP
- 3-Dimension
- Particles:
  - Neutrons, anti-neutrons, anti-neutrons, photons, electrons, positrons, muons, anti-muons, electron neutrinos, anti-electron neutrinos, protons, anti-protons, positive pions, negative pions, neutral pions, positive kaons, negative kaons, neutral kaons short, neutral kaons long, deuterons, tritons, helium-3’s, and helium-4’s
MCNPX (continues)

• Primary application
  – Proton transport where secondary particle generation is important
  – Detector simulation

• Pros:
  – Charged particle capability (up to Helium)
  – Capability of treating secondary particle generation
  – Extensive high energy physics
  – Versatile geometry and input/output options
  – Visual output

• Cons:
  – Relatively difficult to learn
  – Slow for space applications
Displacement damage energy deposition profile normalized to 1 proton/cm² source strength as a function of aluminum shield thickness for isotropic 1000 MeV protons.

Displacement damage energy deposition profile normalized to 1 proton/cm² source strength as a function of tungsten shield thickness for isotropic 1000 MeV protons.

Ratio of the neutron displacement damage to the total displacement damage for the 1000 MeV proton case as a function of shield thickness.
Galileo Energetic Particle Detector

(LEMMS shown here)
(b) TIGER
- - MCNP4C

Scaled Energy Deposition, \( (\tilde{E} / E_0) D(z) \)

- Experimenta square - Loc
  circle - Naka
- Aluminum ta
  \( T_0 = 1 \text{ MeV}; \ r_0 \)

- Copper target
  \( T_0 = 1 \text{ MeV}; \ r_0 = 0.63 \epsilon \)

- Tantalum target
  \( T_0 = 1 \text{ MeV}; \ r_0 = 0.7664 \text{ g/cm}^2 \)

Experimental data:
- square - Lockwood et al. [18]

- Developed by CERN
- Monte Carlo (forward)
- 3-Dimension
- Particles:
  - All particles relevant to space environment
- Primary application
  - Detector simulation
  - SEU simulation with TCAD
- Pros:
  - Charged particle capability including heavy ions
  - Capability of secondary particle transport
  - Extensive high energy physics
  - Versatile geometry and input/output options
  - Visual output
  - Extensive, and growing, space user-base:
- Cons:
  - Very difficult to learn
  - Slow for space applications
  - No error bar of results
Application of the RADSAFE Concept

Vanderbilt University
R.A. Reed, R.A. Weller, R.D. Schrimpf, L.W. Massengill,

NASA/GSFC
K.A. LaBel

SLAC
M. Asai, D.H. Wright, T. Koi
Single Event Effects

Two Ionization Cases:

- **Incident particle generates electron-hole (e-h) pairs**
  
  ![Direct](image)

- **Secondary particles add to generated e-h pairs**
  
  ![Indirect](image)

Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

- Single Event Upset
- Single Event Latchup
- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interrupt
- Single Event …

*P. J. McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course*
Single Event Effects

Two Ionization Cases:

- **Direct**
  - Incident particle generates electron-hole (e-h) pairs

- **Indirect**
  - Secondary particles add to generated e-h pairs

SEE modeling challenges we are currently addressing with RADSAFE:

- **Detailed device and circuit response**
  - Technology Computer Aided Design (TCAD) + Geant4 + spice
  - Commercial tools unable to predict indirect ionization case

- **On-orbit rate prediction**
  - Approximation methods
  - Failure of models when applied to emerging technology

*P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course*
Classical Model Does Not Predict Low LET Upsets

\[ \text{Cross Section (cm}^2\text{bit)} \]

\[ \begin{align*}
\text{LET (MeV cm}^2\text{mg)} & \quad \text{Classical Model Does Not Predict Low LET Upsets} \\
0 & \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70 \quad 80 \quad 90 \quad 100
\end{align*} \]

\[ \int \text{Omnidirectional LET Flux} \]

\[ \text{SV} \]

\[ \approx \]

\[ \text{CRITICAL ENERGY DEPOSITION (ED)} \]

\[ \text{\textit{n-Orbit Rate}} = \]
The RADSAFE System: Current Focus

MRED - Monte Carlo Radiative Energy Deposition tool
- Developed at Vanderbilt University
- Based on Geant4
- Run time selectable physics list
- Python interface
- Highly Flexible output

February 16, 2008

2008 Geant4, Tokyo, Japan
Example: SEUs in SRAMS
Ion Tracks

$10^{18} \text{ e}^-/\text{cm}^3$  $10^{14} \text{ e}^-/\text{cm}^3$
TCAD simulation of radiation event
TCAD simulation of radiation event
TCAD simulation of radiation event

February 16, 2008 2008 Geant4, Tokyo, Japan Jun-37
Classical Model Does Not Predict Low LET Upsets

Cross Section (cm^2/bit) vs LET (MeV*cm^2/mg)

- Simulation
- Experiment

February 16, 2008
2008 Geant4, Tokyo, Japan
Conclusion

• Careful code selection for specific situation is required for correct answer.
  – Some of the codes may be easy to learn and run, but may need correct interpretation of output.

• My personal view of what we need to do in the future:
  – To develop an adjoint Monte Carlo code (independent of NOVICE)
  – To improve heavy ion capability
  – To expand to lower (< 1 keV) energy

• Radiation transport codes not covered today:
  – EGS4, CEPXS, HZETRN, PENELLOPE, FLUKA, MARS, …..
## Summary

<table>
<thead>
<tr>
<th>Program</th>
<th>Application</th>
<th>Primary Application</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREME96</td>
<td>1-D</td>
<td>Single Event Effects</td>
<td>Proton and all heavy ions</td>
</tr>
<tr>
<td>TRIM</td>
<td>1-D</td>
<td>Beam Simulation for dose and damage profile</td>
<td>Proton and all heavy ions (Coulomb only)</td>
</tr>
<tr>
<td>ITS</td>
<td>3-D</td>
<td>Beam simulation for dose and charging profile (TIGER)</td>
<td>Electron and photon</td>
</tr>
<tr>
<td>NOVICE</td>
<td>3-D</td>
<td>Component level analysis with complex spacecraft geometry</td>
<td>Electron, photons, and heavy ions</td>
</tr>
<tr>
<td>MCNP</td>
<td>3-D</td>
<td>RTG and space reactor simulation</td>
<td>Neutron, photon, and electron</td>
</tr>
<tr>
<td>MCNPX</td>
<td>3-D</td>
<td>Secondary particle simulation, science instrument simulation</td>
<td>Neutron, photon, electron, and helium</td>
</tr>
<tr>
<td>Geant4</td>
<td>3-D</td>
<td>Secondary particle simulation, science instrument simulation, device simulation</td>
<td>All particles relevant to space environment</td>
</tr>
</tbody>
</table>