SLAC-PUB-12966
November 2007

GEANT4 APPLICATIONS IN SPACE

MAKOTO ASAI
Stanford Linear Accelerator Center, Stanford University
Menlo Park, California 94025, U.S.A.

Use of Geant4 is rapidly expanding in space application domain. I try to overview three major application areas of Geant4 in space, which are apparatus simulation for pre-launch design and post-launch analysis, planetary scale simulation for radiation spectra and surface and sub-surface explorations, and micro-dosimetry simulation for single event study and radiation-hardening of semiconductor devices. Recently, not only the mission-dependent applications but also various multi-purpose or common tools built on top of Geant4 are also widely available. I overview some of such tools as well. The Geant4 Collaboration identifies that the space applications are now one of the major driving forces of the further developments and refinements of Geant4 toolkit. Highlights of such developments are introduced.

1. Apparatus simulation

Apparatus simulation is essential for both pre-launch design studies and post-launch analyses. Geant4 [1,2] is widely and commonly used for various current and future science missions including XMM-Newton [3], GLAST [4], LISA and LISA Pathfinder [5], RHESSI [6], ACE [7], JWST [8], INTEGRAL [9], Bepi Colombo [10], Messenger [11], Herschel [12], Cassini and Huygens [13], Astro-E2 [14], ConeXpress [15], SELENE [16], SWIFT [17] and modules of ISS (International Space Station) including Columbus [18], AMS [19] and MAXI [20]. In the following sections, I will overview how Geant4 is used for some of these missions.

1.1. *GLAST LAT*

GLAST[4] is to be launched in early 2008 and measure the direction, energy and arrival time of celestial gamma rays. The LAT (Large Area Telescope) instrument measures gamma rays in the energy range from about 20 MeV to greater than 300 GeV. In addition, the GBM (Gamma-ray Burst Monitor) instrument provides correlative observations of transient events in the energy range between 20 KeV and 20 MeV. GEANT4 was adopted since 1999 for the test beam simulations and the balloon flights [21].

Invited talk presented at 10th ICATPP Conference On Astroparticle, Particle, Space Physics, Detectors And Medical Physics Applications, 8-12 Oct 2007, Como, Italy

Work supported by US Department of Energy contract DE-AC02-76SF00515

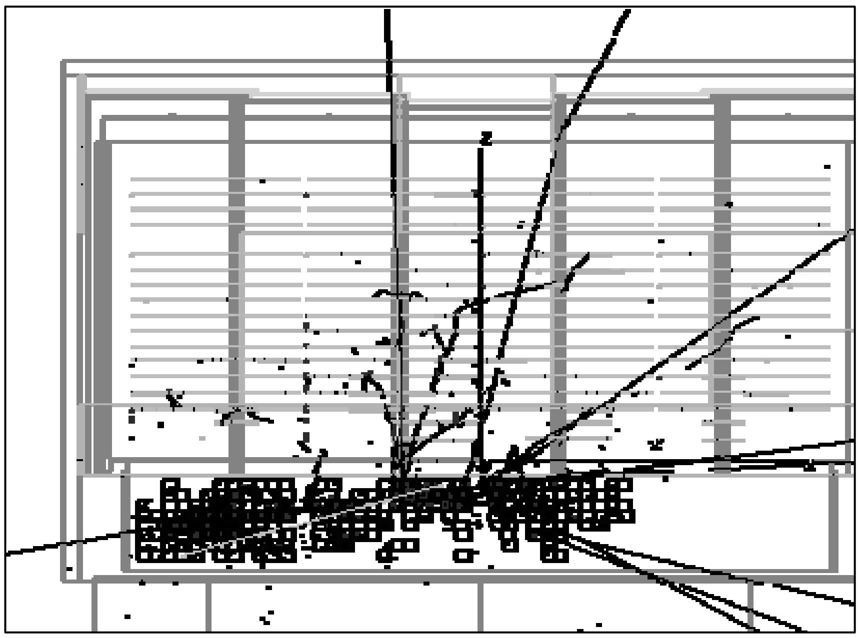

Figure 1. Simulated background hadronic event in GLAST LAT[4]. Courtesy of F. DeBois (SLAC) and F. Longo (INFN/Trieste).

For GLAST mission, simulation of back ground events is even more important than simulation of signal events. Figure 1 shows a proton incident hadronics event in CsI crystal calorimeter which causes EM particles leak into silicon tracker and fakes as a signal event. They are now processing for 50 billion background events of cosmic proton, neutron and electron and earth albedo backgrounds prior to proceed to simulating one full year signal events.

1.2. *Cassini LEMMS*

LEMMS (Low Energy Magnetospheric Measurement System) is on board of Cassini spacecraft to measure the energy and spatial distribution of energetic particles (electrons and ions separately) in the interplanetary medium and in the magnetosphere of Saturn. LEMMS consists of low energy detector head with collimator, high energy detector head with collimator, and programmable turntable. The measurements of energetic particles are based on the loss of energy in semiconductor detectors. LEMMS has 11 different detectors. These detectors and collimators are modeled in Geant4 and studied as shown in Fig.2 [14].

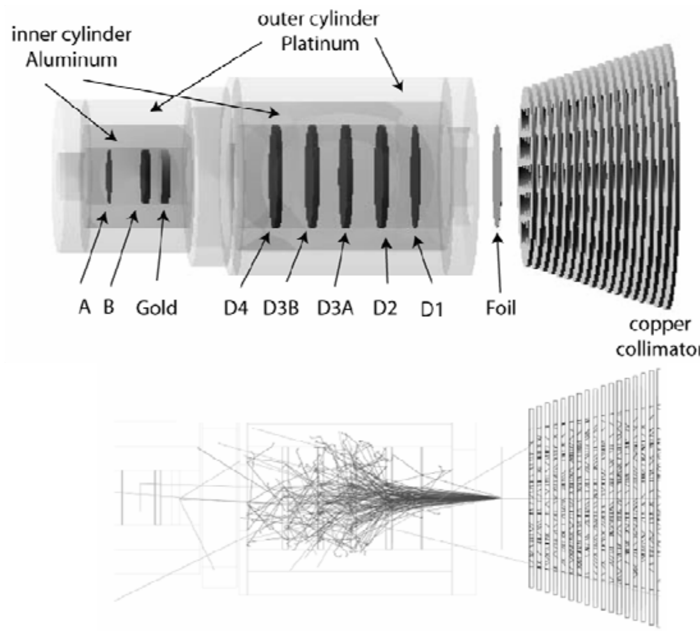

Figure 2. Geant4 geometry model of LEMMS and simulation of 2 MeV electron pencil beam. Courtesy of D.K. Haggerty (JHUAPL).

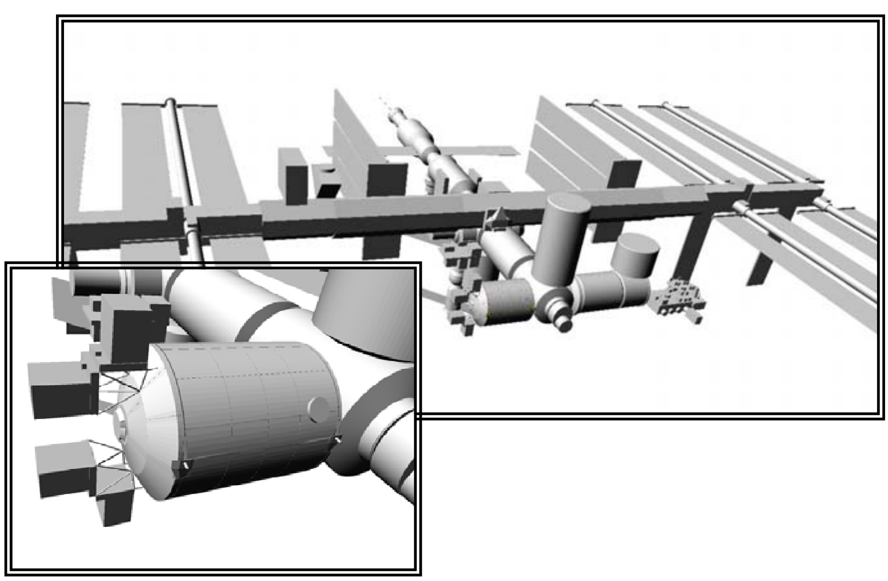

Figure 3. Geant4 geometry model of International Space Station (up) and the Columbus module (left). Courtesy of T. Ersmark (KTH Stockholm).

1.3. *ISS Columbus*

Full geometry model of ISS (International Space Station) and particularly detailed apparatus structure of European Columbus module are built to accurately calculate radiation fluxes and doses to astronauts inside the Columbus module [18]. Incident radiation includes trapped protons, galactic cosmic rays, solar particle events and Earth albedo neutrons.

2. Planetary scale simulation

Planetary scale simulation is essential for both radiation spectra calculation and surface and sub-surface explorations. Full-scale geometrical and magnetosperic structure of a planet is modeled in Geant4 to simulate the trapped solar particles to the Earth [22], Mercury [23], Mars [24] and Jupiter [25]. Geant4 is also used successfully for simulation of even larger scale and in higher energies such as particle accelerations in solar flare [26] and gamma-ray burst [27].

Interactions of solar particles on the (sub-)surface are simulated with Geant4 for mineralogical survey of Mercury for Bepi Colombo mission [28] and for water search of Moon for SELENA mission [29].

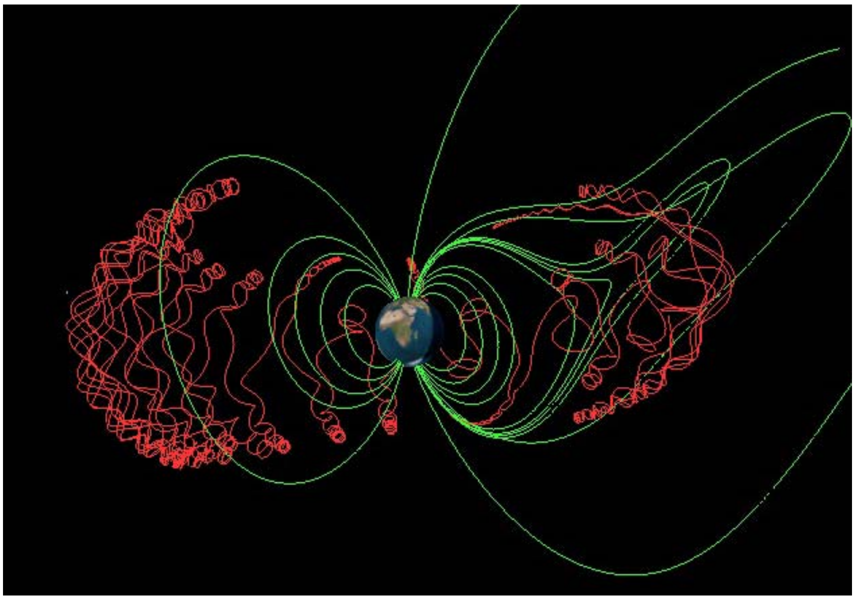

Figure 4. Simulated trajectory of a proton trapped in the Earth magnetosphere. Courtesy of L. Desorgher (U. Bern).

3. Micro-dosimetry simulation

Three sources in natural space environment contribute to various effects on microelectronics. These are solar particles (protons and heavier ions), galactic cosmic rays, and particles trapped in the Earth's radiation belts. Due to these radiations, there are three basic effects that occur when components are exposed, single event effects (SEEs) [30], total ionization dose and charge deposit [31], and displacement damage [32].

Single event upset (SEU) is one of SEEs. SEU observations recorded by ISS show clear patterns of temporal and special dependence. SEUs are mainly due to two ionization cases, direct ionization caused by incident particle and indirect ionization caused by secondary particles generated by the interaction of the primary particle. In all cases, charge collected on a sensitive node of electrical circuit causes unwanted change in the information stored in the circuit. Commercial Technology Computer Aided Design (TCAD) [33] tool alone is unable to predict indirect ionization case. Also, classical method with CREME96 [34] does not give satisfactory results [35]. Combining Geant4-based Monte-Carlo Radiative Energy Deposition (MRED) tool with TCAD and SPICE, energy partitioning information simulated by MRED is transferred to TCAD to model the electron-hole transportation, and then whole-circuit response of SEU is calculated by SPICE [36]. Similar approach is taken by other applications [37].

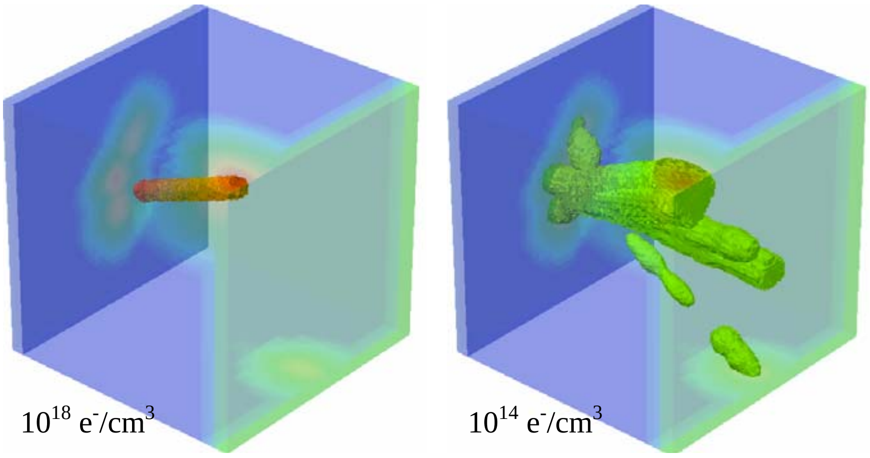

Figure 4. Electron density distribution caused by secondary particles of proton-tungsten interaction simulated by MRED. Courtesy of R. Reed (Vanderbilt Univ.) .

4. General-purpose tools

There are many general / multipurpose tools built on top of Geant4 available for space applications. These include the following tools.

- General Framework
  - GRAS [38]
- Plug-in Physics Model
  - G4LECS [39]
- Sector Shielding Analysis
  - MULASSIS [40]
  - Open Frontier [41]
- Radiation on planets
  - PLANETOCOSMICS [42]
- Dosimetry on semiconductor devices
  - MRED [36]
  - GEMAT [43]
  - FASTRAD [44]

Geant4 offers flexibility and robustness of kernel, powerful capability of geometrical modeling and comprehensive coverage of physics models, which are all essential to these diverse variations of application tools.

5. Recent developments in Geant4 toolkit

The Geant4 Collaboration [45] identifies that the space application domain is now one of the major driving force of the further developments and refinements of Geant4 toolkit. In this section I introduce some of such developments which are driven mainly, if not solely, by the requirements from the space application domain.

5.1. *Tessellated solid*

Tessellated solid is a kind of solid newly supported by Geant4 since 2006. It is a solid consists of arbitrary number of facets. Each facet can be triangular or quadrangular. This solid shape is of particular importance for conversion from CAD system bounded with generic surfaces into an approximate description with facets of defined dimension (Fig. 5).

To import geometrical models from CAD, it is required to convert first the CAD shapes into tessellated surfaces. A way to do this is to save the shapes in the geometrical model as STEP [46] files and convert them using a tool like STViewer [47] to tessellated (faceted surfaces) solids. This strategy allows to import any shape with some degree of approximation; the converted CAD

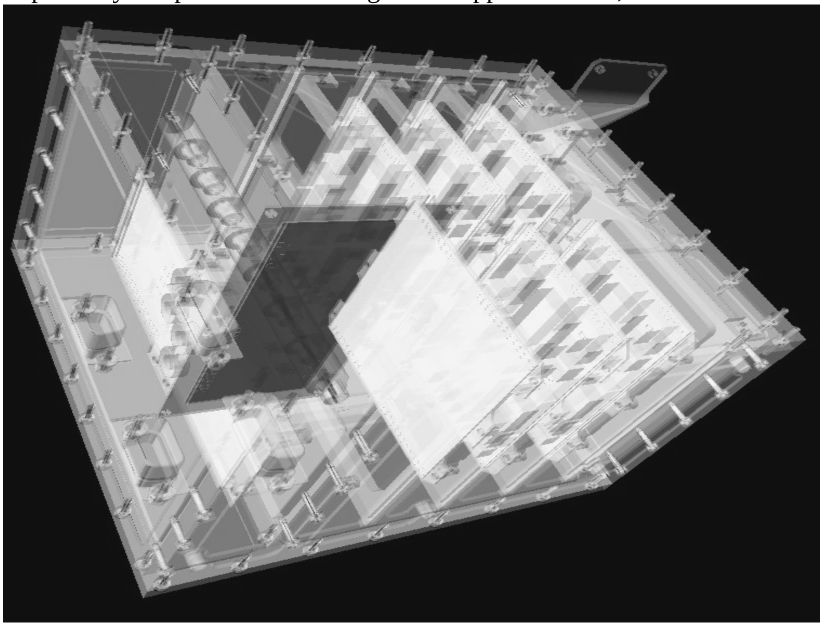

Figure 5. A module geometry imported from CAD into Geant4 tessellated solid. Courtesy of G. Cosmo (CERN)

models can then be imported through GDML (Geometry Description Markup Language) [48] into Geant4 and be represented as tessellated solid shapes.

5.2. *Quantum Molecular Dynamics code*

Radiation in space includes considerable heavy nuclides and they are in particular important for simulating dose and also SEEs. Geant4 currently has Binary Light Ion Cascade model [49] and Wilson Abrasion and Ablation model [50], both of which work mainly for relatively light nucleus [51]. By the end of 2007, Geant4 is releasing its new Quantum Molecular Dynamics (QMD) model [52], which firstly works for most nuclides of up to 300 MeV/n (Fig. 6), and it is foreseen to be extended to several GeV/n.

5.3. *Built-in scoring tools*

For recording detector responses, Geant4 originally offered only the abstract classes with various ready-to-reuse examples. Thus, the user had to implement his/her detector responses. It is a reasonable requirement for a large-scale HEP experiment, but it is a burden for space/medical users who just want to score

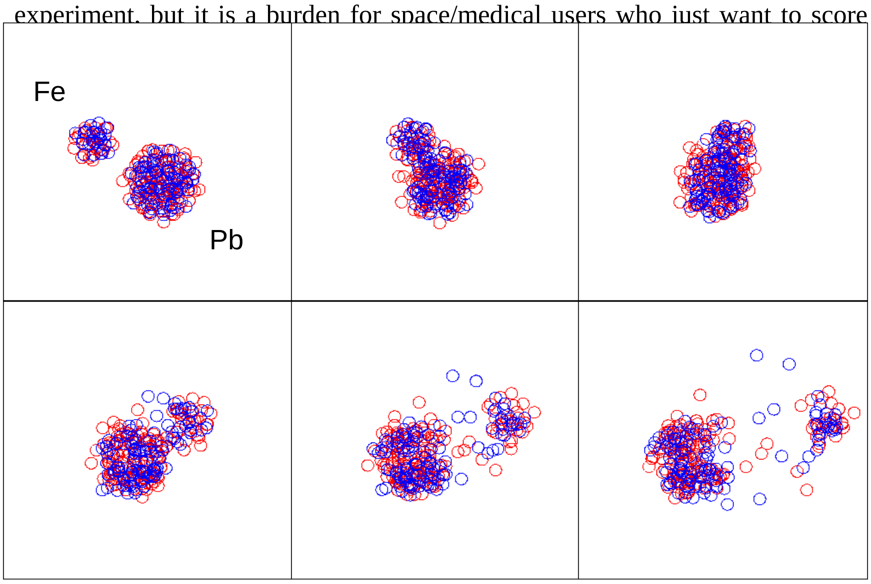

Figure 5. A collision of 290 MeV/n iron onto lead simulated by Geant4 QMD code. Blue circle represents proton and red circle represents neutron. Courtesy of T. Koi (SLAC)

most common quantities such as dose or flux. By the end of 2005, Geant4 released built-in concrete implementation of scorers for common quantities, which include energy, dose and charge deposition, surface flux and current, and number of secondary generation [53]. It is foreseen that all of such scorers will be able to define to arbitrary scoring mesh with simple interactive commands regardless of the geometrical model of actual materials.

6. Conclusions

In 2008, Geant4 will be in 10 years of its public releases. It had been addressing mainly to the requirements from HEP experiments, and Geant4 is nowadays well adapted to most of the current and future HEP experiments as their simulation engine [54]. Use of Geant4 is quite rapidly expanding in space application domain. I gave an overview of such Geant4 applications, in particular for apparatus simulation, planetary scale simulation, micro-dosimetry simulation and general-purpose tools for space missions. I have to note here that my overview is quite incomplete, and much richer list of Geant4 applications in space domain can be found at the Geant4 Space Users home page [55]. Robust and flexible kernel structure, comprehensive coverage of physics models and powerful geometrical modeling capability provided by Geant4 were proven to be suitable for mission critical simulations.

References

1. S. Agostinelli *et al.*, *NIM* A506, 250 (2003)
2. J. Allison *et al.*, *IEEE Trans. Nucl. Sci* 53, 270 (2006)
3. R. Nartallo *et al.*, *IEEE Trans. Nucl. Sci* 48, 1815 (2001)
4. L. Baldini *et al.*, *Nucl. Phys. Proc. Suppl.* 150, 62 (2006).
   N. Omodei *et al.*, *AIP Conf. Proc.* 906, 1 (2007)
   R.M. Kippen *et al.*, *AIP Conf. Proc.* 921, 590 (2007)
5. M. Henrique *et al.*, *Astropart. Phys.* 22, 451 (2005)
   H.M. Araujo, *et al.*, *Class. Quantum Grav.* 20, S311 (2003)
6. C. Wigger *et al.*, *Astrophys. J.* 613, 1088 (2004)
7. D.K. Haggerty *et al.*, Advances in Space Research 32, 423 (2003)
8. G. Santin *et al.*, *IEEE Trans. Nucl. Sci* 52, 2294 (2005)
9. C. Ferguson *et al.*, presentation at 4th INTEGRAL workshop (2000).
10. A. Owens *et al.*, presentation at Round Table on 21st Century Monte Carlo Methods for Space Applications, Noordwijk, 2001
11. D.K. Haggerty, presentation at Conference of Solar and Space Physics and the vision for Space Exploration (2005)
12. C. Bongardo, *et al.*, *Exp. Astro.* 21, 67 (2006)
13. D.K. Haggerty *et al.*, Advances in Space Research 33, 2303 (2004)
14. M. Ozaki *et al.*, *IEEE Trans. Nucl. Sci* 53, 1310 (2006)
15. http://space-env.esa.int/ProjectSupport/ConeXpress/ConeXpress.htm
16. O. Okudaira *et al.*, Proceedings of 9th Conference on Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications, 490 (2005)
17. M. Suzuki *et al.*, *IEEE Nucl. Sci. Symp. Conf. Rec. vol.5*, 3550 (2003)
18. T. Ersmark *et al.*, *IEEE Trans. Nucl. Sci* 51, 1378 (2004)
    T. Ersmark, Ph.D. thesis, ISBN 91-7178-398-9, KTH Stockholm, June 2006
19. M.C. Espirito-Santo *et al.*, *IEEE Trans. Nucl. Sci.* 51, 1373 (2004)
20. H. Tomida *et al.*, *Proc. SPIE vol.*4851, 993 (2003)
21. T.H. Burnett *et al.*, *IEEE Trans. Nucl. Sci* .49, 1898 (2002)
22. L. Desorgher *et al.*, Proceedings of 28th International Cosmic Ray Conference, 4281 (2003)
    F. Lei *et al.*, *IEEE Trans. Nucl. Sci* 51, 3442 (2004)
    M.D. Looper *et al.*, Presentation at 4th Geant4 Space Users' Workshop, (2005)
23. M. Gurtner *et al.*, Advances in Space Research 37, 1759 (2006)
24. A. Keating *et al.*, *IEEE Trans. Nucl. Sci* 52, 2287 (2005)
25. R.F. Elsner *et al.*, Icarus 178, 417 (2005)

26. J. Kotoku *et al*, e-Print: arXiv:0708.0057 (2007)
27. K. Murase and S. Nagataki, *Phys. Rev.* D73:063002 (2006)
28. A. Mantero *et al., IEEE Nucl. Sci. Symp. Conf. Rec. vol.3,* 1527 (2003)
29. K. Hayatsu *et al.*, Presentation at 10th Conference on Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications (2007) N. Yamashita *et al.*, Presentation at 10th Conference on Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications (2007)
30. P.E. Dodd *et al., IEEE Trans. Nucl. Sci* 50, 583 (2003)
31. T.R. Oldham and F.B. McLean *et al., IEEE Trans. Nucl. Sci* 50, 483 (2003)
32. J.R. Srouor *et al., IEEE Trans. Nucl. Sci* 50, 653 (2003)
33. http://www.synopsys.com/products/tcad/tcad.html
34. A.J. Tylka *et al., IEEE Trans. Nucl. Sci* 43, 2758 (1996)
35. R.A. Reed *et al., IEEE Trans. Nucl. Sci* 50, 622 (2003)
36. K.M. Warren *et al., IEEE Trans. Nucl. Sci* 53, 2125 (2005)
    A.S. Kobayashi *et al., IEEE Trans. Nucl. Sci* 53, 2189 (2003)
37. I. Jun *et al*, JPL R&TD Annual Report 06-128, Pasadena, CA (2006)
38. G. Santin *et. al., IEEE Trans. Nucl. Sci* 52, 2294 (2005)
39. R.M. Kippen, New Astronomy Reviews 48, 221 (2004)
40. F. Lei *et al., IEEE Trans. Nucl. Sci* 49, 2788 (2002)
41. H. Sdunnus *et al.*, Presentation at 20th European Workshop on Thermal and ECLS Software (2006)
42. http://cosray.unibe.ch/~laurent/planetocosmics/
43. G. Santin *et al.*, Nuclear Physics B – Proceedings Supplements vol.125, 69 (2003)
44. T. Beutier *et al.*, Proceedings of 7th European Conference on Radiation and its Effects on Components and System, 181 (2004)
45. http://cern.ch/geant4/
46. http://www.tc184-sc4.org/SC4_Open/SC4_Standards_Developers_Info/ Files/ STEP_application_handbook_63006.pdf
47. http://www.steptools.com/products/stviewer/
48. R. Chytracek *et al., IEEE Trans. Nucl. Sci* 53, 2892 (2006)
49. G. Folger *et al., Eur. Phys. J.* A21, 407 (2004)
50. P. Truscott *et al.*, Proceedings of Monte Carlo 2005 Topical Meeting ISBN:0-89448-695-0 (2005)
51. T. Koi *et al.*, Proceedings of Monte Carlo 2005 Topical Meeting ISBN: 0-89448-695-0 (2005)
52. J.Z.H. Zhang, ISBN 981-02-3388-4, (1998)
53. T. Aso *et al., IEEE Nucl. Sci. Symp. Conf. Rec. vol.2,* 978 (2005)
54. http://geant4.web.cern.ch/geant4/collaboration/Geant4-Review2007.html
55. http://geant4.esa.int/