ISTITUTO NAZIONALE DI FISICA NUCLEARE
Sezione di Genova

INFN/AE-2000/??
12 September 2000

SPACE APPLICATIONS OF THE GEANT4 SIMULATION TOOLKIT

E. Daly[1], H. Evans[1], F. Lei[2], F. Longo[3], S. Magni[4],
R. Nartallo[1], P. Nieminen[1], M.G. Pia[5,6], P.R. Truscott[2]
[1) *ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwjik, The Netherlands*
[2) *DERA, Farnborough, The United Kingdom*
[3) *INFN, Sezione di Ferrara and University of Ferrara, I-44100 Ferrara, Italy*
[4) *INFN, Sezione di Milano, I-20133 Milano, Italy*
[5) *INFN, Sezione di Genova, I-16146 Genova, Italy*
[6) *CERN, CH-1211 Geneva 23, Switzerland*

Abstract

The space radiation environment is highly variable and dynamic. With the increasing number and complexity of space missions, the detailed analysis of the effects of that environment often requires the use of advanced Monte Carlo radiation transport tools. In this presentation, various space-oriented developments and applications based on the Geant4 particle transport toolkit are described.

To be published in the
Proceedings of Monte Carlo 2000, International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications,
23-26 October 2000, Lisbon, Portugal

Published by **SIS-Pubblicazioni**
Laboratori Nazionali di Frascati

1 Introduction

There are various undesirable effects the space radiation environment can induce in spacecraft and their instrumentation. These include total dose effects and single event effects phenomena in electronic components, material degradation, and biological effects in astronauts. On the other hand, for a variety of scientific missions the radiation ”background” in sensitive detectors, in addition to the actual signal to be measured, is an important factor to be considered. With the increasing number of complex space missions and their instrumentation, the detailed and accurate analysis of the space radiation effects increasingly requires the use of Monte Carlo radiation transport tools.

Geant4 [1] is a new-generation, Object-Oriented particle transport toolkit that allows full and fast 3D simulation in a user-defined geometry. Due to its versatility, the toolkit has found use in various diverse fields, including high-energy physics, medical and biological applications [2], and nuclear physics. The wide selection of physics processes and the modular, Object-Oriented implementation of Geant4 also make it an ideal platform for space applications, including cosmic ray and astrophysics.

In this presentation, we summarise a number of space applications and developments utilising Geant4. A number of future activities are also presented.

2 Simulation of Radiation Effects on X-ray Telescopes

It has been found that protons of energies in the range of hundreds of keV to a few MeV can scatter at low angles through the mirror shells of space-based X-ray astronomy missions. These protons, because of their low energy can produce a high non-ionising dose in unshielded CCDs and are therefore a potential threat. This is the most likely cause of the degradation in the charge transfer efficiency reported to have occurred in the CCDs of the ACIS instrument on NASA’s Chandra X-ray observatory [3].

An extensive analysis of this process both on Chandra and on ESA’s XMM-Newton observatory was carried out utilising Geant4 [4]. The mirror systems of both spacecraft were modelled in 3D, with some supporting analysis of the scattering off the mirror surface performed in 2D. The Geant4 model of XMM mirrors, consisting of more than 1000 individual elements, is shown in Fig.1. From the right, this shows three baffles, the set of nested mirror shells and the reflection gratings. It was not necessary to model the spacecraft telescope tube that closes the optical axis between the gratings and the detectors 7 m away. The source of the incident protons was placed just outside the telescope baffle structure, covering it in its entirety. The energy range of incident protons simulated was from 100 keV to 1.5 MeV. Protons reaching the focal plane at the other end of the telescope, where the two separate XMM detectors EPIC and RGS reside, were registered.

Based on this analysis, it was concluded that as long as protective measures (i.e. detector shield closure) are adopted to protect the XMM EPIC instrument during passages through the Earth's radiation belts, no damage is expected to occur to its CCDs. The CCDs on the RGS instruments, for which no protective measures can be taken, are on the other hand not expected to be significantly affected by radiation damage. The analysis has shown, however, that low-energy protons both in the radiation belts and in the interplanetary medium need to be taken into account in the design and simulations of future in-orbit X-ray observatories.

3 Simulations of Gamma Ray Space Missions

The gamma ray missions GLAST [5] and AGILE [6] are sensitive in similar energy bands, between 30 MeV and around 100 GeV. The main physics process involved is γ conversion. Both of the instruments are essentially made of a converter material and a number of Si tracking detectors. In the energy range in question it is essential to establish the contribution from the cosmic ray-induced background, that can be several orders of magnitude higher than the 'real' astronomical γ ray fluxes.

Several attempts are underway to evaluate this background, with the current activity concentrating on modelling small prototypes of the two instruments in Geant4 (see Fig.2), using both the Low-Energy extension of Geant4 [7] and the General Source Particle Module developed by ESA [8] (see below). The usefulness of Geant4 for AGILE is motivated also by the presence of an on-board X-ray instrument, sensitive in a totally different energy band between 10 and 40 keV, where the Low-Energy extension could be particularly interesting.

4 Mineralogical X-Ray Surveys of Asteroids and Moons

Most solid bodies in the solar system do not contain a substantial atmosphere. Thus they are effectively exposed to the ambient space radiation environment. This consists to a large degree of electromagnetic radiation (particularly X-rays and UV) from the Sun, but also include charged solar particles, Jovian electrons and cosmic rays originating from outside the Solar System. These radiations interact with the surface materials of the target body, the reflection and emission spectra being characteristic of the composition of the surface.

By observing the Sun at soft X-ray wavelengths ($\sim$0.1-10 keV) and simultaneously the X-ray spectra from the illuminated body it is possible to determine the surface geology of the body. There is currently activity in the ESA Space Science Department to develop a standard X-ray survey instrument for mapping this way most of the bodies of the Solar System that retain no atmosphere. Such hardware needs to be combined with a solid predictive capability for the expected emission spectra from the various target bodies.

Geant4 low-energy electromagnetic physics extensions down to 250 eV allow for such a capability. Example simulations for a representative composition of basalt [9] have been perfomed for a range of solar conditions. The results of this analysis for a major X-ray flare spectrum are shown in Fig. 3 and 4. Although the input data of the spectrum is limited above 1 keV, it can be seen that the major K-shell emissions are clearly visible in the simulation. Further Geant4 simulation work with other spectra and charged particles is foreseen in the near future.

5 Space-Specific Modules in Geant4

As a member of the world-wide Geant4 Collaboration, ESA has sponsored [8] the development of a number of space-specific software modules in Geant4, tailored to the demands of the European space radiation community. The main features of these modules are briefly summarised below.

5.1 Low-Energy Electromagnetic Processes Extension

The low-energy cutoff of electromagnetic physics in the earlier Geant3 code was 10 keV, and many other electron-photon transport codes have their cutoff at 1 keV. In Geant4 this lower limit has been extended to allow the physical processes of electrons and photons to be modelled as low as 250 eV. This feature enables studies of the characteristic X-ray line emissions down to Carbon, and has been applied e.g. in the simulation work for geological surveys of asteroids and moons (see above). Wide use in medical, biological and fundamental physics applications have also been found, and low-energy extensions with protons, ions and antiprotons have also been completed [2] [7] [10].

5.2 Sector Shielding Analysis Tool (SSAT)

This tool performs a ray-tracing analysis of a user-defined geometrical configuration to yield the distribution of shielding material and thickness as viewed from a given point within the configuration. The fictious *geantino* particle is used for the purpose. This approach is highly useful for calculating the absorbed radiation dose and for finding optimal shielding geometries.

5.3 Front-End for CAD Software

This module uses the STEP AP-203 protocol to provide an interface to standard computer-aided design tools which facilitates the transfer of instrument engineering designs to Geant4 simulations and vice versa. In addition to geometrical data, materials information may also be included.

5.4 General Source Particle Module (GSPM)

This module allows the user to apply various simulation scenarios assuming unidirectional or omnidirectional incidence of particles with a defined energy spectrum instead of a monoenergetic source. This gives a more realistic analysis of the effects of the radiation environment encountered in many space applications.

5.5 Radioactive Decay Module (RDM)

Traditionally, Monte Carlo transport codes only consider the prompt component of an atomic or nuclear reaction. This module introduces a delayed component, which can be a significant contributor to undesirable instrument background radiation experienced in certain types of mission (e.g. gamma ray observatories, such as ESA's INTEGRAL), particularly during and after passage through the radiation belts. The decay branching ratios are based on data from the Evaluated Nuclear Structure Data File (ENSDF). Decays can be performed over multiple nuclide generations. The RDM includes biasing techniques to increase the sampling of events within the user-chosen observations times. Furthermore, other variance reduction techniques such as splitting are included to increase the sampling of the nuclear decay scheme.

6 Discussion and Future Developments

Geant4 has proven to be a powerful tool for modelling the interactions between spacecraft and their radiation environments. A number of future developments utilising Geant4 capabilities are currently planned. An activity will be started at ESA later this year to implement further space-specific software modules in Geant4, with the emphasis on electronic components and circuits. In 2001, a project will be started to transfer the old Geant 3.21 simulation models of the ESA Standard Radiation Environment Monitor (SREM) [11] to Geant4. A Phase-A study on the ESA Charged Particle Telescope (CPT) has also addressed simulation requirements, and concluded that Geant4 is the preferred tool for design and optimisation of this instrument when eventually constructed.

Recently, a program has been initiated to ultimately enable the simulation of the interactions of radiation with biological systems at the cellular and DNA level [12]. This project, coordinated by ESA and INFN, will in its first phase concentrate on a rigorous collection of user requirements, and has generated wide interest in the European space, medical, and biological communities. Geant4 has been chosen as a platform for this work. The current Geant4-DNA Collaboration consists of some 25 experts in astrophysics, nuclear physics, microbiology, genetics and Object-Oriented software design, and is an excellent example of a multidisciplinary approach to a demanding software development project.

References

[1] http://wwwinfo.cern.ch/asd/geant4/geant4.html

[2] S. Chauvie et al., Medical Applications of the Geant4 Simulation Toolkit, Proceedings of Monte Carlo 2000, International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, 23-26 October 2000, Lisbon, Portugal

[3] http://www1.msfc.nasa.gov/NEWSROOM/news/status/chandrastatus/chandrastatus49.html

[4] R. Nartallo et al., Modelling the Interaction of the Radiation Environment with the XMM-Newton and Chandra X-Ray Telescopes and its Effects on the On-board CCD Detectors, in the Space Radiation Environment Workshop and Workshop on Radiation Monitoring for the International Space Station, Farnborough, U.K., November 1–25, 1999

[5] http://glast.gsfc.nasa.gov, http://glast.stanford.edu

[6] http://www.ifctr.mi.cnr.it/ Agile

[7] M.G. Pia et al., Geant4 Electromagnetic Physics, Proceedings of Monte Carlo 2000, International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, 23-26 October 2000, Lisbon, Portugal

[8] http://www.space.dera.gov.uk/space_env/geant_mn.html

[9] P.R. Truscott et al.:, Basalt X-Ray Fluorescence Study, Technical Note to ESA, DERA/CIS/CIS2/7/36/4/1/3, November 1999

[10] http://www.ge.infn.it/geant4/lowE/

[11] http://pc1582.psi.ch:80/SREM/

[12] http://www.ge.infn.it/geant4/dna/

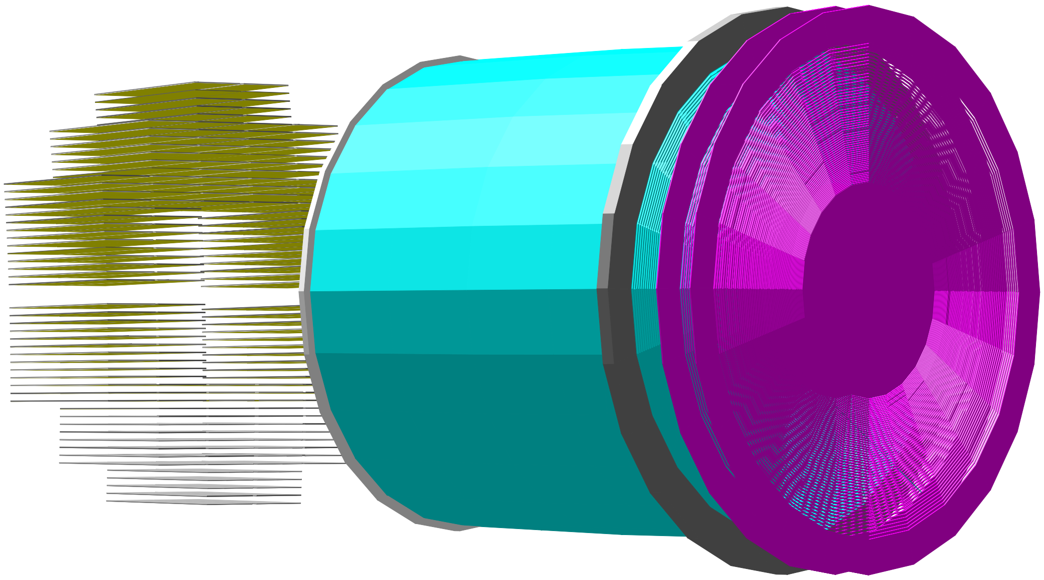

Figure 1: XMM geometric model used in Geant4 simulations

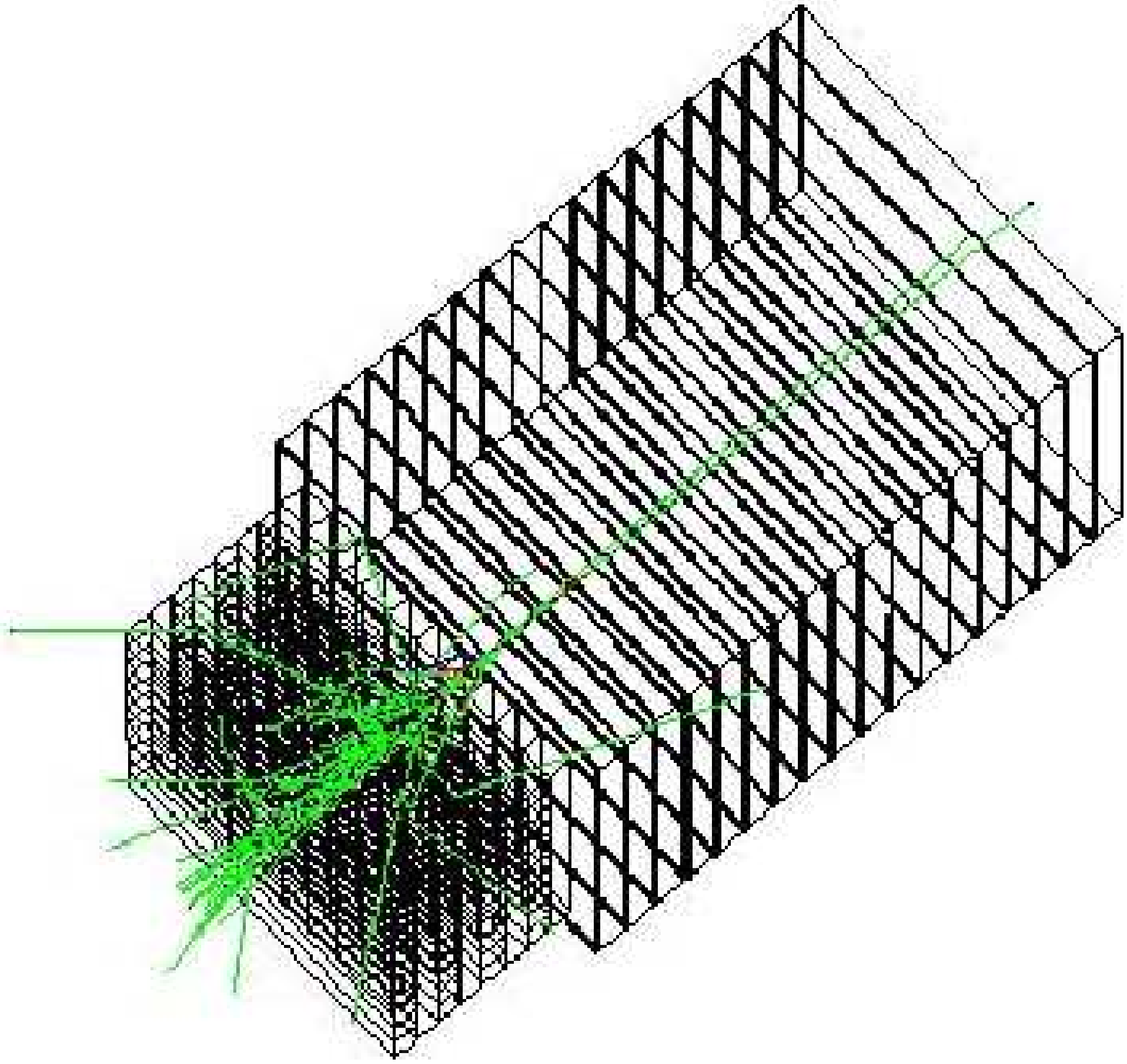

Figure 2: Geant4 model of the basic tracker and calorimeter structures of GLAST mission

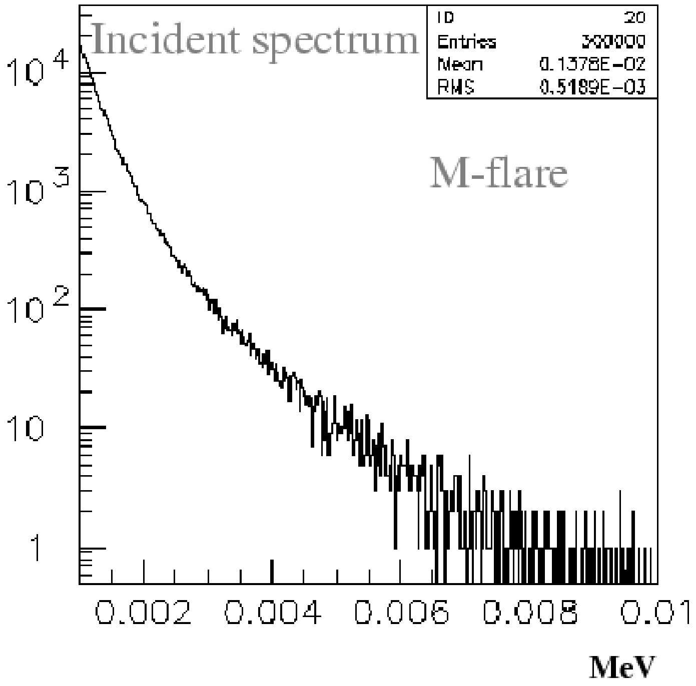

Figure 3: Modelled major solar flare X-ray spectrum.

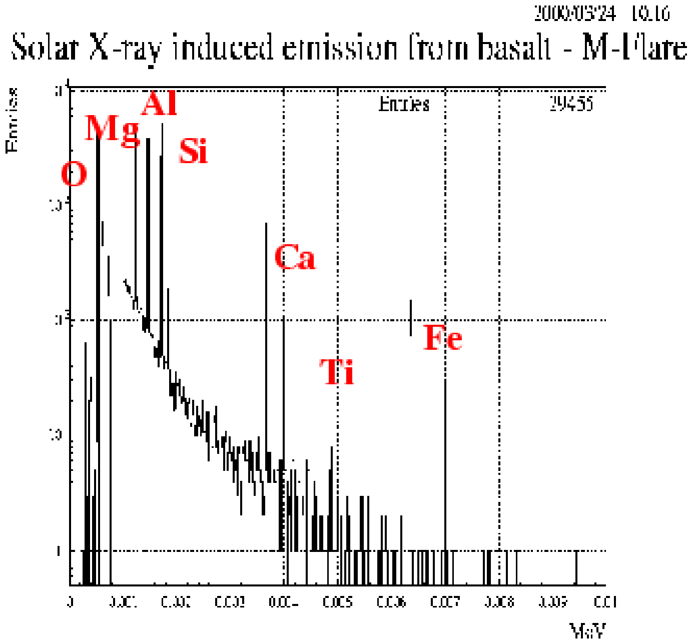

Figure 4: Simulated response from a representative composition of basalt.