

Development of a Spacecraft Radiation Shielding and Effects Toolkit based on Geant4

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Abstract

The need to assess the effects of radiation on spacecraft is becoming increasingly important due to the increased sensitivity of microelectronics and sensors and the reduced availability of radiation hard alternatives. Monte Carlo simulation offers the ability to model in detail the physics of space radiation. Geant4 is a new-generation toolkit for Monte Carlo simulation, intended primarily for the high-energy physics community, but with potentially wider applications including space. Unlike other codes which attempt to treat the wide range of processes by interfacing existing MC models, Geant4 has been developed to provide, in a single tool, comprehensive treatment of the physical processes for a wide range of particles and energies. The European Space Agency as part of the Geant4 international collaboration is supporting the development of this code with the objective of making it the basis of a general space radiation shielding and effects tool (SPARSET). Such a code potentially provides an extremely powerful tool for predicting radiation-induced effects, optimising the design of future spacecraft and their payloads, and for the analysis of data returned by radiation instruments flown in space.

keywords Geant4, space radiation, radiation transport, Monte Carlo

1. Introduction

Spacecraft are required to operate in a severe radiation environment that can temporarily upset, or induce gradual or catastrophic failure of the platform and its payload. For typical missions the sources of radiation that are of concern include high-energy protons (~1 MeV – 100's MeV) and electrons (~1 keV – several MeV) trapped in the Earth's magnetic field, solar flare particles (with energies up to 100 MeV/nuc) and highly-energetic cosmic-ray nuclei (~1 MeV/nuc – 100's GeV/nuc). The nuclear and electromagnetic interactions of these particles can give rise to secondary radiation which, as in the case of cosmic rays, can have higher particle fluxes and greater effect than the primaries.

Since spacecraft can be required to operate for many years without physical repair, the need to ensure that they are designed in a manner that cost-effectively meets the demands of the environment necessitates accurate knowledge of the environment and its potential effects. Indeed this requirement is becoming increasingly demanding due to:

- The reduced availability of radiation-hard alternatives in the post Cold War era;
- The desire to utilise new technologies that promise increased performance, but have little or no flight history.

- The use of smaller feature sizes in microelectronics, which has led to some improvements in radiation tolerance, but increased sensitivity to single event effects (in which single particles can induce temporary or catastrophic device failure).

Monte Carlo radiation transport codes have been developed by the nuclear, medical and high-energy physics (HEP) communities to permit detailed simulation of the interactions of energetic particles. The last decade has seen an increasing emphasis on program suites that allow comprehensive treatment of the full range of physical processes. Such codes include GEANT3, FLUKA, LAHET (now LCS), HERMES-KFA and DERA's Integrated Radiation Transport Suite, which bring together a variety of other transport codes. Geant4 is the latest generation of such codes, and has been designed from the outset as an integrated toolkit to provide comprehensive, fully three-dimensional treatment of the wide range of physical processes in HEP^{1,2}. As such, it is also highly applicable to the study of space radiation effects. The European Space Agency (ESA) is participating in the programme of Geant4 development with the objective of making this software the basis of a general space radiation shielding and effects tool (SPARSET).

2. Summary of Geant4 features

Geant4 is the result of a collaboration of approximately 100 scientist from over 40 institutes worldwide. The code was first made available publicly in December 1998, and has been recently enhanced and updated with release Geant4 1.0 in December 1999. An object-oriented approach has been adopted in design and (C++) implementation, giving rise to a highly modularised code, whose operation is more intuitive than transport codes written in procedural languages, and which is easier to enhance through class inheritance.

Table 1: High Energy Physical Process Models in Geant4¹

Category	Type	Models	Space Appl.
Hadron-nucleon or hadron nuclear	Param.	Parameterized (GHEISHA equiv.)	CR nuclei, sol. particles, trp. protons including secondaries
	Theory	Parton-string (>5GeV), kinetic (40MeV-10GeV), QMD models, precompound (2-100 MeV),	
	Data	Low-energy neutron (thermal-20MeV)	
Nuclear de-excitation	Theory	Evaporation (A>16), Fermi breakup (A≤16), fission, photo-evaporation (+ENSDF data) (A≥65), multifragmentation	
Electromagnetic	Theory	ionisation & multiple scattering of all charged particles, δ-ray prod., bremsstrahlung, annihilation, PE effect, Compton, pair-prod. (originally electrons >10keV, photons >1keV – see §3.2)	Mostly trp. elec. + secondaries from hadron interactions

The toolkit comprises all new code, but does or will include versions of physics models from codes such as HETC and GHEISHA that have been re-engineered in C++. Table 1, which summarises the high-energy particle transport models implemented in Geant4, highlights the range of particles and physics which can be simulated by the code. The last column identifies the relevance of these models to the analysis of space radiation effects. As an alternative to applying the standard physical processes, Geant4 features a “fast simulation” mode that allows the response of a volume to be parameterised based on data from empirical sources or previous simulation.

Geant4 includes excellent tools for visualising geometries (essential for geometry debugging) and facilities to import geometry descriptions from a CAD tool via the STEP interface (ISO 10303 Standard for the Exchange of Product model data). The latter feature is particularly valuable since it introduces the possibility of transferring detailed satellite or sub-system designs to Geant4 without the need for laborious data translation.

3. Space-specific software development for Geant4

3.1. CAD front-end tool (MGA)

Since the use of professional CAD tools is commonplace in the aerospace industry, the availability of STEP interface in Geant4 is particularly advantageous. However, the protocol within ISO 10303 (AP203) does not allow assignment within the STEP file of Monte Carlo-related materials information with geometry bodies. The Materials and Geometry Association (MGA) tool is a Java-based utility that has been developed to obviate the need for the user to write Geant4 code to perform this function. MGA provides a graphical user-interface (GUI) that allows the user to draw upon material definitions from an existing database of common spacecraft materials, or to define new materials in terms of elemental or nuclear composition. As well as physical properties, visualisation attributes may also be assigned to the materials. The association between volumes in the STEP file can be performed manually through the MGA graphical environment, or automatically if the CAD engineer uses pre-defined meta-data information in the PRODUCT records of the STEP file. Once this association is complete, Geant4 can read both the MGA interface file and the STEP file to obtain a complete description of the geometry.

3.2. Low-energy electromagnetic transport

One of ESA's requirements identified for a general space radiation analysis tool was the simulation of induced low-energy X-ray fluorescence from the surfaces of asteroids and moons. However, the low-energy limit of the electromagnetic processes in Geant4 had previously been too high for this application, and a programme of software enhancement was undertaken to reduce this to 250 eV (corresponding to the K-shell of carbon). To achieve this, the new processes (for low-energy Compton, Rayleigh, photo-electric effect, bremsstrahlung, ionisation and fluorescence) utilise data parameterisations to evaluated data sets from Lawrence Livermore (EPDL97, EEDL, and EADL)³. To extend the physics for low-energy hadron and ion ionisation, parameterisations to particle range and stopping power data from Ziegler⁴ and ICRU⁵ have been used, permitting accurate tracking down to 1 keV for protons.

3.3. Treatment of radioactive decay

Long-term radioactivity produced by nuclear interactions represents an important contributor to background levels in space-borne γ -ray and X-ray instruments, as the ionisation events that result often occur outside the time-scales of any veto pulse. A Radioactive Decay Module is therefore being developed as part of the ESA sponsored activity to treat the emissions of α , β^\pm , ν and $\bar{\nu}$ particles, as well as the γ - and X-rays associated with α , β^\pm , electron capture and isomeric transition decays. The decay branching ratios are based on data from the Evaluated Nuclear Structure Data File (ENSDF)⁶, which is also used by Geant4's photo-evaporation routines to correctly sample discrete γ -ray transitions. Decays can be performed over multiple nuclide generations, where appropriate using recursive formulae to determine the probability of decay for radioactive descendants⁷.

Simulations of non-equilibrium systems are often required to generate results relating to specific time-windows of observation, and it is possible that the half-lives of the radionuclides may be such that analogue Monte Carlo sampling produces only a few events in these periods. To avoid wasting computation time simulating events that will not contribute to the observation, the RDM includes biasing techniques to increase the sampling of events within the observations times. Furthermore, other variance reduction techniques such as splitting are included to increase the sampling of the nuclear decay scheme.

3.4. General Source Particle Module

Whilst the default particle generator within Geant4 is suitable for studies in accelerator physics, the potential complexity of the primary particle distributions within the space environment necessitates a more sophisticated sampling algorithm. The General Source Particle Module (GSPM) allows the user to utilise standard energy, angular and spatial distributions:

- Spectrum: linear, exponential, power-law, blackbody, or piece-wise fits to data.
- Angular distribution: unidirectional, isotropic, cosine-law or arbitrary (user defined).
- Spatial sampling: on simple 2D or 3D surfaces such as discs, spheres, and boxes.

As with radioactive decay, the GSPM includes methods to bias the sampling distribution. This feature permits, for example, more particles to be sampled closer to the area of the spacecraft where greater sensitivity to radiation effects is expected.

3.5. Sector Shielding Analysis Tool

It is often possible to obtain a first-order estimate of the radiation dose received within a spacecraft as a function of location using shield distribution data for that location in conjunction with particle range and stopping power information. A common spacecraft engineering tool ESABASE⁸ uses such an approach, but imposes significant restrictions on the degree of control of the sampling process that determines shield distributions. The Sector Shielding Analysis Tool can provide this shield distribution information using the particle tracking facilities in Geant4. The tool analyses the material boundaries for rays emanating from a user-defined point to determine the amount of material in units of g/cm², cm or radiation lengths. The user is able define the limits of the solid angle analysed (using spherical polar co-ordinates) and define sub-divisions in this solid angle, in which shielding can be randomly sampled so that its directional dependence can be quantified in terms \mathbf{q} and \mathbf{f} . Analysis output can be provided as a function of material, or for overall thickness irrespective of media type. "Error" information associated with the shielding distribution is also provided to identify whether sufficient sampling of the geometry has been performed.

4. Summary

Geant4 is a new-generation toolkit for Monte Carlo HEP simulation that offers a comprehensive environment to specify three-dimensional geometries, perform particle tracking, and model a wide range of physical interaction processes. Its object-oriented design allows relatively straightforward extension of the code (*e.g.* adding new physical processes) through class inheritance. ESA, as a member of the Geant4 collaboration, has been sponsoring the development of a number of software modules of relevance to the space, as well as the wider radiation physics community. Ultimately, Geant4 will form the foundation of a general spacecraft radiation shielding and effects tool, to assist in the design and optimisation of spacecraft and their operation.

References

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