

RADIOPROTECTION FOR INTERPLANETARY MANNED MISSIONS

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ABSTRACT

The study of the dosimetric effects of space radiation on astronauts is an important concern of space missions for the exploration of the Solar System. To protect the crew, shielding must be designed, the environment must be anticipated and monitored and a warning system must be put in place. A Geant4 simulation has been developed for a first quantitative study of existing vehicle concepts and Moon/Mars surface habitat designs, and the radiation exposure of crews therein. We will show the results of the dosimetric analysis of proposed innovative shielding solutions in various geometrical set-ups, complemented with a critical analysis of Geant4 tools currently available for this type of studies. This work represents the first approach in the European AURORA programme to estimate quantitatively a crucial issue in the manned exploration of the Solar System.

Key Words: Astronaut, radioprotection, dose, Geant4

1 INTRODUCTION

The study of the effects of interplanetary space radiation on astronauts is an important concern of space missions for the human exploration of the Solar System, for the danger represented by the radiation hazard to crew. A strategy to protect the astronauts is to study possible shielding solutions to apply in vehicles and planet surface habitats.

A Geant4 simulation, called Geant4 REMSIM simulation, has been developed to perform a first quantitative dosimetric study of existing vehicle concepts and surface habitat designs, and the radiation exposure of crews therein, in a set of candidate shielding configurations, with respect to some radiation exposure hypothesis.

In particular we will show the first results obtained concerning the dosimetric effect of Galactic Cosmic Rays and Solar Particle Events in the astronaut in a set of vehicle and surface habitat models.

The project has been defined in the context of the European AURORA [1] programme, for the robotic and human exploration of the Solar System.

2 THE SPACE RADIATION ENVIRONMENT

Among the radiation environment components, it is widely recognized that the Galactic Cosmic Rays (GCR) and the Solar Particle Events (SPE) can produce harmful effects on the crew [2]. For radioprotection studies it is important to study the effect of GCR ion components with the atomic number $Z < 28$: after this limit the ion flux is very small and the dosimetric effect can be neglected.

In this first iteration of the study, the dosimetric effect of a subset of GCR particles has been analysed; in particular the proton, α particle, carbon, oxygen, silicon and iron ion GCR components have been selected.

Solar Particle Events (SPE) consist in proton, α particles and heavy ions emitted into space from solar flares. In this study the proton and α SPE components have been studied.

A conservative approach has been adopted in the study; GCR and SPE fluxes are given in the worst condition observed.

The GCR fluxes derive from CREME [3] as envelope of the GCR fluxes observed in 1977 and 1975, at 1 AU, during solar minimum activity (worst condition by a radioprotection point of view).

The SPE fluxes follow the model of CREME [3] and result from the envelopes of the SPE fluxes of the events registered in October 1989 and August 1972. The fluxes are given at 1 AU.

The GCR and SPE particle fluxes are provided in the energy range between 1. MeV and 100. GeV.

3 CONCEPTUAL MODELS OF ASTRONAUTS' HABITATS

The vehicle concept under study is the Inflatable Habitation Module, composed by a hard central core and an inflatable exterior shell (Simplified Inflatable Habitat, SIH); this vehicle model represents a new and alternative vehicle design with respect to traditional hard shell habitats [4]. The SIH is a multilayer consisting of:

- MLI: external thermal protection blanket, made of layers of beta cloth and mylar;
- a meteoroid and debris protection, consisting of layers of nextel (bullet proof material) and open cell foam;
- a structure made of kevlar;
- a redundant bladder, consisting of layers of polyethylene, polyacrylate, EVOH, kevlar, nomex;
- shielding.

The materials and thicknesses of the SIH concept are provided by ALENIA SPAZIO.

The shielding should be optimized in terms of material and thickness to limit the astronaut harmful exposure to GCR radiation. The thickness of the shielding should be fixed as compromise between protection from radiation hazard and mechanical engineering constraints.

The first vehicle concept under study (CONFIGURATION I) corresponds to the analysis of the dosimetric effects of GCR in the SIH concept modeled in figure 1.

The second vehicle concept (CONFIGURATION II) concerns the crew radioprotection from the harmful effects of SPE particles. When a Solar Particle Flare is detected by a warning system set in loco, the crew moves inside the SPE shelter (cylinder with water walls) to limit the exposure to the Solar Particle Events. In this configuration both the GCR and SPE dosimetric effects must be taken into account (figure 1).

The third configuration (CONFIGURATION III) concerns the dosimetric effects of GCR and SPE in astronauts in an example of planet surface habitat set on the Moon, shown in figure 2. The habitat is a cavity underground, covered by a heap of Moon soil, whose scope is to limit the exposure of the crew to the space radiation environment. The model of the Moon surface habitat is provided by ALENIA SPAZIO.

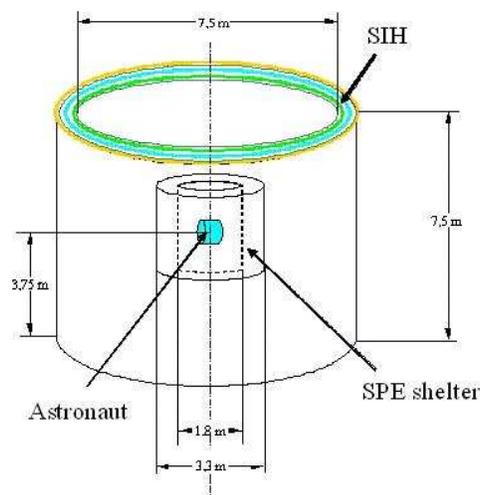


Figure 1: Vehicle concept: model of the SIH and SPE shelter of the Inflatable Habitat Module that should transport the crew in interplanetary space missions.

4 SOFTWARE PROCESS

The adoption of a rigorous software process allows to develop robust and reliable software applications. The software development of the Geant4 application followed an iterative and incremental approach, based on the Unified Software Development Process (USDP) [5]. The Rational Unified Process (RUP) [6], mapped on the ISO 15504 [7] has been adopted as process framework, tailoring the process to the specific characteristics of the project.

The application development passed through all the phases of life-cycle; the User Requirements have been identified and documented, the software architecture has been designed, the code has been implemented and tested [8].

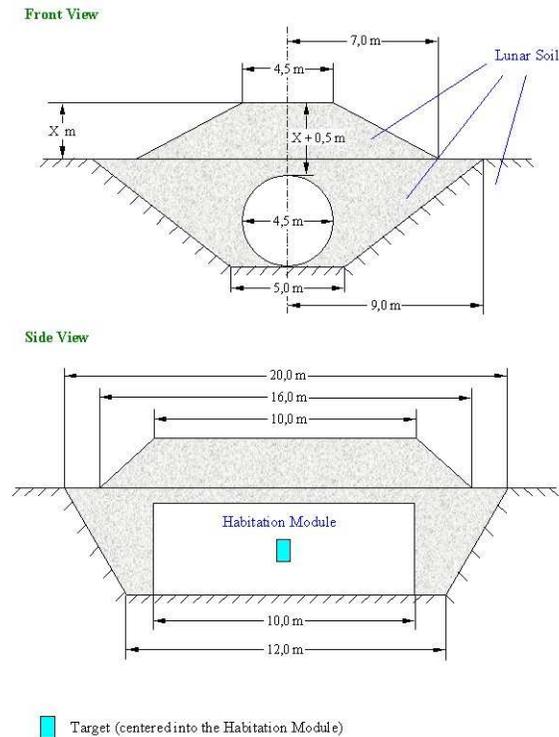


Figure 2: Example of planet surface habitat concept set on the Moon.

5 STRATEGY

Geant4 [9] has been chosen as Simulation Toolkit for its advanced capability addressed to Medical Physics domain [10].

The scope of this iteration of the study is to give a first evaluation of the dosimetric effects of the space radiation environment in vehicle concepts and planet surface habitats of interest, in view of the human exploration of the Solar System, with a dedicated Geant4 simulation.

The GCR and SPE radiation are modeled in the simulation according with the current standard (shown in section II).

Simplified structures of vehicle and surface habitats are modeled in the Geant4 simulation retaining the essential characteristics for the dosimetric study.

In a first phase the dosimetric effects of monochromatic beams of protons, α particles and C-12, O-16, Si-28, Fe-52 ions (GCR selected components) have been studied in the chosen geometrical configurations (CONFIGURATION I, II, III), to point out which components of the GCR and SPE spectra are shielded and do not arrive inside the astronaut habitat, which ones are stopped inside or pass through the astronaut concept, set inside the vehicle or in the planet surface habitat. This study allowed to gain basic information about the effect of a shielding depending on its material and thickness.

In a second phase the GCR and SPE particles have been modeled with the energy spectra derived from the fluxes given by CREME (section II). The dosimetric effect of the radiation has been quantitatively studied in the set of experimental configurations chosen, with proposed

shielding solutions.

For a better understanding of the dependence of the dosimetric results from the physics processes undertaken by particles, in a first moment the dosimetric effect of electromagnetic processes has been studied, then the hadronic physics has been added on top to evaluate the hadronic contribution on the dosimetric results.

Individual simulations have been performed for each GCR and SPE particle component; the result of the simulation, the energy deposit in the astronaut concept, has been elaborated to calculate dose and equivalent dose.

6 GEANT4 REMSIM SIMULATION MODEL

6.1 Simulation components

The Geant4 REMSIM application encompasses components, that have different responsibilities and cooperate to achieve the goals of the application defined in the User Requirement Document.

The primary particle component manages the generation of primary particles, that can be protons, α particles, ions, with a defined energy or following an energy spectrum. At this stage of the study the primary particles are generated from a unique vertex, with a defined direction.

The geometry component has the responsibility of the definition of the experimental set-up in terms of geometry and composition. The vehicle, the surface habitats and the astronaut concepts are defined in this component.

The astronaut concept is the geometrical component where the energy deposit given by primary and secondary particles is collected; it is a water box. The result of the simulation is the energy deposit given by GCR and SPE radiation components with respect to the depth.

The physics component has the responsibility of the activation of the physics processes. It has been modularised in sub-components: each of them controls the activation of processes related to every type of particle involved in the experimental set-up. The user can choose to activate singularly or both electromagnetic and hadronic physics processes.

The user can define interactively the physics processes to activate, the number of events to be generated, the primary particles to generate in terms of particle type and energy, the geometrical configuration.

The simulation is interfaced to the external visualisation tools: OpenGL, DAWN, VRML; DAVID has been used as geometry debugging tool.

The simulation is interfaced to the external analysis tool AIDA 3.2 [11] and its concrete implementation PI 1.2.1 [12].

6.2 Experimental set-ups

Figure 3 shows the experimental set-up modeled in the Geant4 simulation to perform the dosimetric study corresponding to CONFIGURATION I (defined in section III). The incident GCR components impinge on the SIH and on the astronaut concept.

For this first dosimetric study 10. cm and 5. cm thick water or polyethylene layers are added to the SIH concept as shielding solutions.

A second dosimetric study has been performed substituting completely the SIH model with a

layer of aluminum to compare the SIH concept with traditional vehicle designs by a radioprotection point of view.

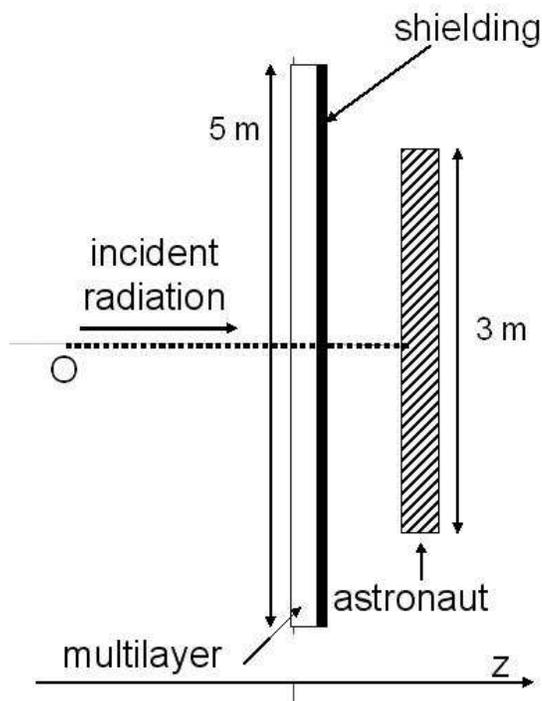


Figure 3: Geant4 model of CONFIGURATION I; multilayer refers to the SIH structure.

The second vehicle concept (figure 4) under investigation corresponds to CONFIGURATION II (defined in section III) and concerns the dosimetric effect of GCR and SPE on the astronaut. GCR and SPE components impinge on the SIH structure complemented with 10. cm water shielding, the SPE shelter and the astronaut.

The third configuration under study is the Moon surface habitat shown in figure 5 and corresponds to CONFIGURATION III (defined in section III). The dosimetric effect of GCR and SPE has been performed with respect to x , height of the roof put on top of the habitat.

6.3 Modeling of the physics processes in the Geant4 REMSIM simulation.

The Geant4 electromagnetic Low Energy package [13], [14], [15], has been chosen to model the electromagnetic processes of photons, electrons, protons, alpha particles, ions. The Geant4 electromagnetic Standard package [9] has been chosen to model the electromagnetic processes of positrons.

Hadronic physics processes have been modeled for protons and α particles as incident particles.

Geant4 offers alternative and complementary hadronic models in the energy range of interest for the Geant4 REMSIM simulation; as a consequence two alternative approaches in the modeling of the inelastic hadronic scattering have been selected to model proton hadronic

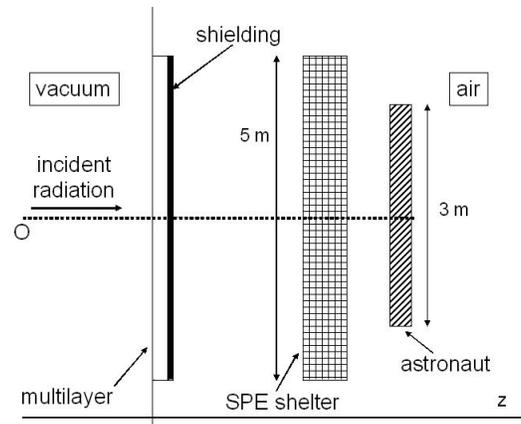


Figure 4: Geant4 model of the SPE shelter experimental configuration (CONFIGURATION II); multilayer refers to the SIH structure.

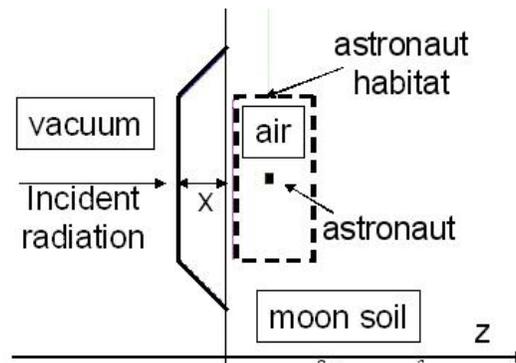


Figure 5: Geant4 model of the Moon surface habitat concept, corresponding to CONFIGURATION III.

interactions to point out the influence of different hadronic models on the dosimetric results.

The two alternative approaches (referred as *Bertini approach* and *Binary approach* in this paper) are described respectively in table I. The α particle hadronic processes both in the *Bertini approach* and in the *Binary approach* are the Geant4 Low Energy Parameterized (LEP) model for energies lower than 100. MeV and the Geant4 Binary Ion model in the energy range between 80. MeV and 10. GeV.

The overlapping energy ranges of the definition of the complementary hadronic models allow the smooth blending of different hadronic models.

7 VALIDATION OF THE SIMULATION

To verify the correct activation of Geant4 physics in the simulation, tests concerning the electromagnetic processes of protons and α particles have been performed to verify the consistency of the application results with respect to protocol data used in medical physics (ICRU

Table I: Geant4 hadronic models activated in the *Bertini approach* and in the *Binary approach* for protons as incident particles. In the following LEP refers to the Geant4 Low Energy Parameterized model, QGSP is the Geant4 Quark Gluon String model.

<i>Bertini approach</i>	<i>Binary approach</i>
Bertini Cascade up to 3.2 GeV	Binary Cascade up to 10. GeV
LEP $2.5\text{GeV} < E < 25.\text{GeV}$	LEP $8.\text{GeV} < E < 25.\text{GeV}$
QGSP $20.\text{GeV} < E < 100.\text{TeV}$	QGSP $20.\text{GeV} < E < 100.\text{TeV}$

Report 49 [16]). The tests are included in the Geant4 electromagnetic physics validation activity [17].

8 RESULTS

This section illustrates the dosimetric results obtained in the vehicle concept and in the Moon surface habitats with the Geant4 REMSIM simulation.

8.1 Vehicle concept: SIH

The dosimetric effect of the Galactic Cosmic Rays in CONFIGURATION I has been studied, complementing the SIH concept with the following shielding options:

- no shielding,
- 5. cm and 10. cm polyethylene layer,
- 5. cm and 10. cm water layer.

Figure 6 shows the energy deposit in the astronaut with respect to the depth for the GCR proton component, for 100K events, modeling only the electromagnetic physics processes.

Figure 7 reports the total equivalent dose* in the astronaut concept, summing the effect of all the GCR components, in the SIH configuration, in different shielding options. The equivalent dose has been calculated also in the case in which the SIH concept and the shielding are substituted by a layer of aluminum, usually used in traditional space vehicles. From the results it is possible to infer that thicker shielding layers limit the exposure of the astronaut to GCR. The hadronic contribution has a relevant dosimetric effect in the calculation of energy deposit in the astronaut. Polyethylene and water have an equivalent shielding behavior.

*The quality factors are derived from the Particle Data Book [18].

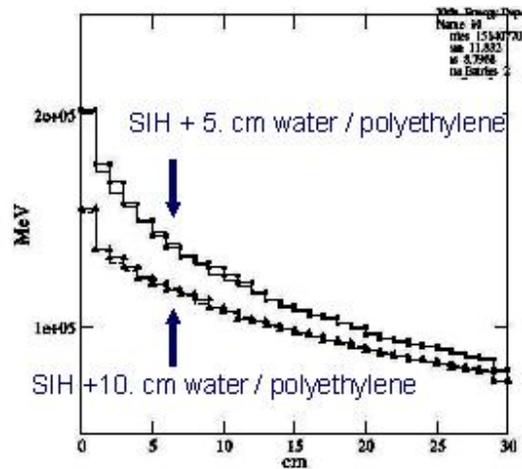


Figure 6: Energy deposit in the astronaut concept resulting from GCR protons, incident on the experimental set-up referred as CONFIGURATION I, shown in figure 3, in different shielding configurations (indicated by the arrow in the figure); the energy deposit is calculated with respect to the depth in the astronaut concept.

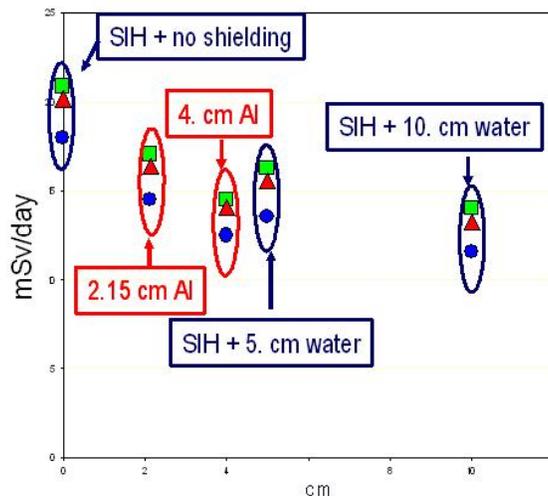


Figure 7: Total equivalent dose in the astronaut concept resulting from GCR beams, incident on the SIH configuration.

8.2 Vehicle concept: SPE shelter

A radioprotection study has been performed in the experimental set-up shown in figure 4, corresponding to CONFIGURATION II, to calculate the dosimetric effect of GCR and SPE inside the SPE shelter.

The total equivalent dose given by GCR in the astronaut concept has been calculated, obtaining the first results summarized in table II from which it can be inferred that the hadronic

physics contribution has a strong impact on the dosimetric results.

Table II: Total equivalent dose given by GCR in CONFIGURATION II.

e.m. contribution	5. mSv/day
e.m. + hadronic contribution - Bertini approach	7.83 mSv/day
e.m. + hadronic contribution - Binary approach	7.5 mSv/day

A first evaluation of the dosimetric impact of the SPE has been evaluated in the same experimental set-up.

8.3 Moon surface habitat concept

The dosimetric effect of GCR and SPE has been calculated in the experimental set-up shown in figure 5, corresponding to CONFIGURATION III, with respect to the thickness x of the Moon soil roof put on top of the surface habitat.

Figure 8 shows the total equivalent dose in the astronaut concept with respect to x ; the equivalent dose decreases with increasing the thickness of the roof. From these first results it is possible to infer that the hadronic contribution cannot be neglected in the radioprotection study. Figure 9 shows the energy deposit given by SPE particles in the Moon surface Habitat in the two

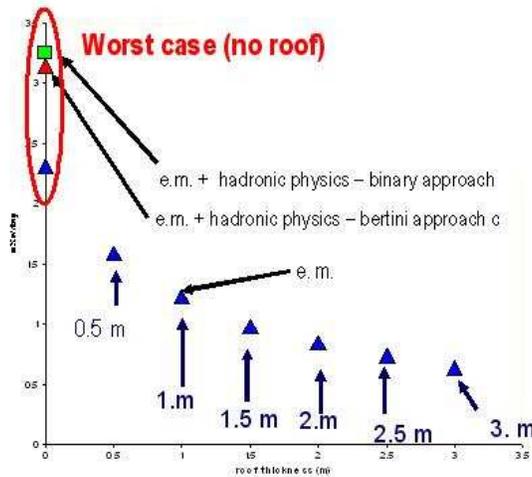


Figure 8: Total equivalent dose in the astronaut concept with respect to the thickness of the moon soil roof, covering the surface habitat as shown in figure 5.

extreme cases: no roof and 3. m thick roof.

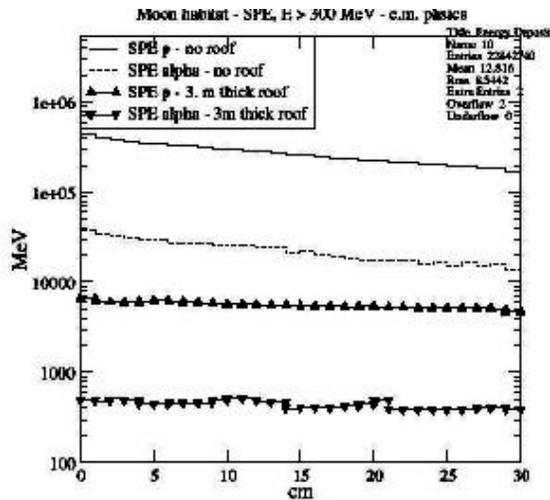


Figure 9: Energy deposit in the astronaut with respect to the depth, produced by SPE protons and α particles in the experimental set-up shown in 5 in the two extreme condition: no roof and 3. m thick roof put on top of the habitat.

9 CONCLUSIONS

A Geant4 simulation has been developed and used to perform a first quantitative dosimetric study of the effects of Galactic Cosmic Rays and Solar Particle Events in vehicle concepts and Moon surface habitats, that have been modeled with simplified geometrical structures, retaining the essential characteristics for the purposes of the dosimetric study.

From this first iteration of the study, it is possible to infer that the Simplified Inflatable Module, new and alternative engineering design with respect to the traditional hard shell Habitat, offers a similar radioprotection behavior from GCR with respect to traditional aluminum structures. In the Simplified Inflatable Module water and polyethylene have an equivalent shielding behavior.

The Geant4 REMSIM simulation shows that a water SPE shelter is a possible solution to limit the exposure of the astronauts to the harmful effects of SPE.

A planet surface habitat built out of local material looks like a possible solution to protect the crew from the GCR and SPE effects.

The dosimetric study performed with the Geant4 REMSIM simulation had a second scope a part from the first dosimetric analysis of shielding solutions in vehicle concepts and planet surface habitats: the exploration of the Geant4 capability addressed to the critical domain of the radioprotection of astronauts. Geant4 has been identified as a valid Simulation Toolkit addressed to this kind of studies, thanks to its flexibility, the wide set of physics models provided for both electromagnetic and hadronic processes, the possibility to describe accurately vehicle and habitat's geometries and their composition.

This work represents the first approach in the European AURORA programme to estimate quantitatively a crucial issue, the radioprotection of astronauts, in the manned exploration of the Solar System.

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11 REFERENCES

1. <http://www.esa.int/SPECIALS/Aurora/>
2. P. Nieminen, "Space Radiation Environment in the context of Interactions of Radiation with Biological Systems at the Cellular and DNA Level", ESA Publications Division, (2000).
3. A.J. Tylka et al., "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code", *IEEE Trans. Nucl. Sci.*, **NS-44**, pp. 2150-2160 (1997).
4. K.J. Kennedy, AIAA 2002-6105, NASA JSC.
5. I. Jacobson et al., "The Unified Software Development Process", Addison-Wesley (1999).
6. P. Kruchten, "The Rational Unified Process: an introduction", Addison-Wesley (2000).
7. ISO/IEC Joint Technical Committee 1 (JTC1), "ISO/IEC DTR 15504 Software Process Assessment".
8. <http://www.ge.infn.it/geant4/space/remsim>
9. S. Agostinelli et al., "Geant4 - a simulation toolkit", *NIM A* 506, pp. 250-303, (2003).
10. L. Beaulieu et al., "Overview of Geant4 Applications in Medical Physics", *Proceeding of IEEE NSS 2003 Conference*, Portland Oregon, October 2003, (2003).
11. G. Barrand et al. "Abstract Interfaces for Data Analysis - Component Architecture for Data Analysis Tools" *Proceedings of CHEP 2001 Conference*, (2001).
12. <http://lcg-pi.web.cern.ch/lcg-pi>
13. S. Giani et al., "Geant4 simulation of energy losses of ions", *INFN preprint INFN/AE-99/21*.
14. S. Giani et al., "Geant4 simulation of energy losses of slow hadrons", *INFN preprint INFN/AE-99/20*.
15. J. Apostolakis et al., "Geant4 low energy electromagnetic models for electrons and photons", *INFN preprint INFN/AE-99/18*.
16. International Commission on Radiation Units and Measurements, "ICRU Report 49, Stopping Powers and Ranges for Protons and Alpha Particles", (1993).
17. K. Amako et al. "Validation of Geant4 Electromagnetic Physics Versus Protocol Data", *Proceeding of IEEE NSS 2004 Conference*, Rome Italy, October 2004, (2004).
18. S. Eidelman et al., "The Review of Particle Physics", *Physics Letters B* 592 1, (2004).