MULASSIS - Monte Carlo Radiation Shielding Simulation for Space Applications Made Easy

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Abstract-- **This paper describes the MULASSIS 1D radiation analysis tool, which is based on the Geant4 Monte Carlo radiation transport toolkit. MULASSIS permits simulation of a wide range of particle physics in almost any shielding material, including treatment of ionization and nuclear interactions of energetic protons, electromagnetic cascades for electrons and photons, and low-energy neutron transport, with the tracking of all secondary particles that are produced by interactions. The implementation of Geant4 physics in a 1D (spherical or planar) shielding application simplifies the input requirements, and because of this, the tool can be operated through a series of web pages from the ESA SPENVIS web-site. Outputs of MULASSIS include particle fluence at boundary layers, total ionizing dose to layers, non-ionizing energy loss at boundary layers and pulse height energy deposition spectra.**

I. INTRODUCTION

THE simulation of shielding against the space radiation environment can be very complex due to the variety of interaction processes that lead both to the attenuation of the incident particles, and the production of secondary radiation. Deterministic solutions to the Boltzmann transport equation have previously been employed due to their efficiency for simplified geometry situations, but there has been growing use of Monte Carlo-based solutions due to their wider applicability for general 3D geometries and the availability of low-cost but powerful personal computers. Today's generation of such codes include GEANT3, FLUKA, HERMES-KFA, IRTS and LAHET, (now LCS), which bring together a variety of other codes in order to address a wide range of particle species and interaction processes, from ultra-relativistic nuclear interactions to electromagnetic processes

and low-energy neutron transport. Geant4 is the latest generation of such codes [1],[2], and has been designed from the outset as an integrated toolkit to provide comprehensive, fully three-dimensional simulation, as well as a flexible software environment allowing the user to tailor the simulation to the diverse needs of space applications. However, Geant4, as with other tools of this type, is yet to find greater use as a practical tool for the spacecraft engineering community rather than the space radiation effects community. Two key drawbacks are:

1. The user-interface: ideally the UI should be intuitive with minimal user-input requirements, but still allowing general radiation analysis. For Geant4, the user is required to write user-specific application code (in C++) which utilizes the classes in the Geant4 toolkit - this entails a significant learning curve.
2. Accessibility/installation: this should be straightforward particularly for the engineer who wishes to perform an initial evaluation of the software on his/her desktop computer.

To achieve these two objectives, QinetiQ, BIRA and ESA have developed the Multi-Layered Shielding Simulation Software (MULASSIS) tool, which utilizes the Geant4 radiation transport toolkit to simulate particle transport in 1D planar or spherical shields. The tool can be used to determine particle attenuation, radiation ionizing dose and non-ionizing dose, and pulse-height energy deposition as a function of material shielding. For users who have a local installation of Geant4, MULASSIS can be downloaded [3], compiled with the toolkit, and executed on the user's local computer system (*i.e.* the tool can be operated in interactive mode). However, in order to better meet the second of the requirements identified above, MULASSIS has also been made available through the SPENVIS web-site [4], so that the user can control the Monte Carlo simulation remotely using a web-browser.

The remainder of this paper discusses the facilities offered by MULASSIS in the context of the SPENVIS web-based user interface, and some of the applications and results for which the tool has been applied.

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II. Description of MULASSIS

In the web-based version of the MULASSIS tool, the user is presented with a series web-pages that allows her to define the geometry and materials used, the source particle energy and angular distribution, the physics models and particle cut-offs applied, and the analysis requirements. The geometry definition web-page (Fig. 1) allows control over the type of geometry (planar or spherical), the number of layers of which the shield comprises, the thickness of each layer, and material composition.   MULASSIS includes a set of pre-defined materials, which can be extended by the user (Fig. 1) by defining the chemical (and if required, isotopic) composition, and mass density of the material. The user is also able to identify the visualization attributes of each layer used in the graphical output file, as well as whether particle tracks are shown. Graphics file output formats for the geometry can be either Encapsulated PostScript or virtual-reality (VRML) file.
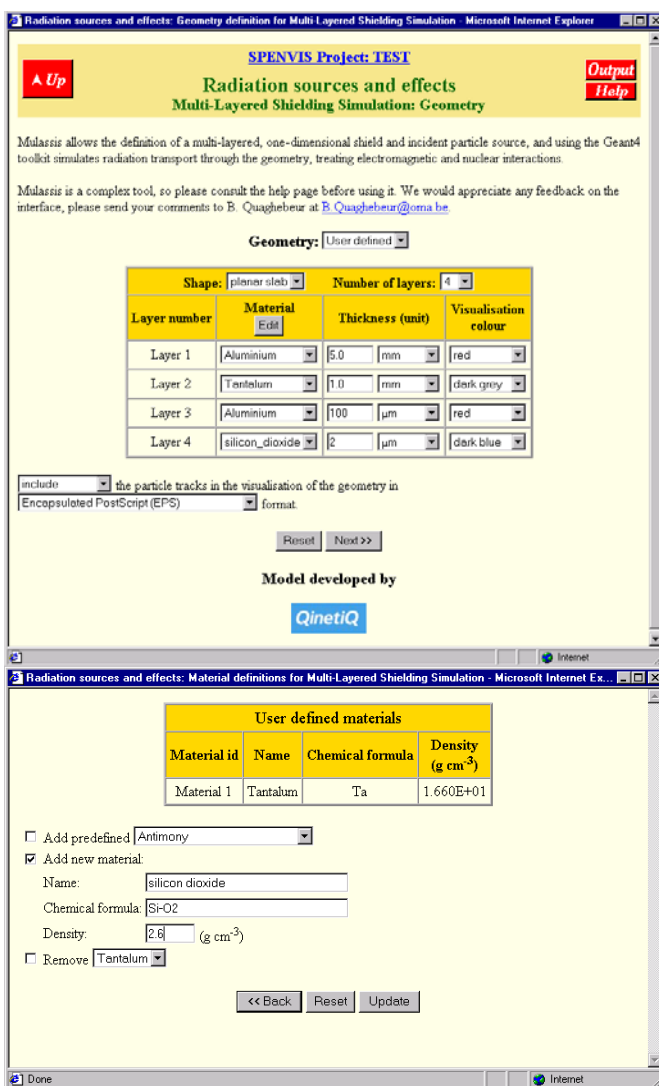

Fig. 1. SPENVIS/MULASSIS Web-pages for geometry (top) and material (bottom) definition.

In the next web-page presented (see Fig. 2), the user is able to specify the source particle type (protons, neutrons, electrons, γ-rays, α-particles or ions) and energy spectrum as one of the following:

1. mono-energetic;
2. linear-function, or power-law function, or exponential function based on parameters provided by the user, together with a specified energy range;
3. cubic-spline or piece-wise linear, power-law, or exponential fit to trapped particle spectra generated by previous tools in the SPENVIS suite;

The angular distribution can be isotropic (varying with $\sin\theta$ only) or cosine-law (proportional to $\sin\theta\cos\theta$) with, if necessary, angular restrictions on the θ angle, e.g. if the user wished to consider particles arriving at a planar shield with θ from 0° to 45°. For a normally incident beam of particles, the user may select either isotropic or cosine-law, and restrict both the upper- and lower-limits for θ to 0°.
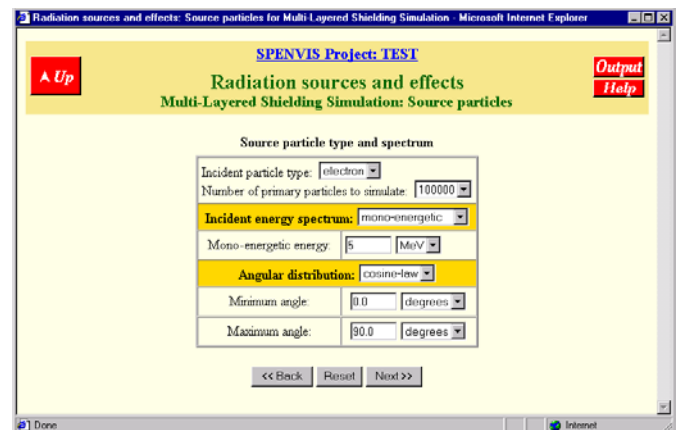

Fig. 2. SPENVIS/MULASSIS Web-pages for source particle definition.

The user is able to choose which physics models are applied in the simulation. Two electromagnetic models are available based on the standard EM physics model in Geant4 (which can treat processes down to approximately a few keV) or the low-energy EM physics model (which currently has a lower limit of 250eV for photons and electrons, and <1keV for protons and other ions). The latter model also treats atomic fluorescence and Auger electron production.

The nuclear interactions of hadrons can also be treated. For the current version of MULASSIS, this uses Geant4's parameterized models for interactions above the pion-production threshold, or a pre-equilibrium model at lower energies. For interactions of thermal to 20MeV neutrons, a model based on evaluated neutron cross-sections (e.g. from ENDF/B V1.0, V1.1, and V1.5, JEF 2.2, JENDL 3.1 and 3.2, CENDL 2.2) can also be used. Depending upon the type of study being performed, leptons and γ-rays produced by hadron-nuclear interactions, either through pion production of photonuclear de-excitation, may not be relevant to the user, and therefore the option exists to switch-off tracking of particles produced by these processes.

It is often valuable to be able to change the particle cut-offs applied in the simulation, so that particles which have insufficient range to affect the result are discarded. Geant4

will track *all* particles produced until they interact, leave the geometry, or have insufficient range to exit the current volume that the particle is in. However, the user can change the *minimum energies with which new particles are produced* as a function of particle and material type - this is achieved by altering the "range-cutoff" lengths (see table in Fig. 3).

Fig. 3. SPENVIS/MULASSIS Web-pages for physics processes and particle range-cutoff applied.

The final input web-page (Fig. 4) allows the user to control the type of data output by the simulation. These can include:

1. The omni-directional or planar fluence[1] at the front-surface, back-surface or any intervening boundary between layers, as a function of particle type, energy and angle. The energy- and angular-binning scheme can also be controlled by the user.
2. The non-ionizing energy loss in silicon can also be estimated based on the fluence data and the NIEL coefficient-set, the latter selected by the user. Currently NIEL coefficients from JPL (for protons only) or the CERN ROSE study (for protons, neutrons, electrons and pions) may be selected [5].
3. The ionizing energy deposition in any of the layers can be accumulated in the simulation and output in units of energy (*e.g.* MeV) or dose.
4. The MULASSIS simulation can also be used to estimate the pulse-height energy deposition spectra in any of the layers, which may be valuable, for example, in estimating the spectra of events in a planar detector. Again, the user has full control over the energy-binning scheme used in the output.

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[1] The planar fluence is based purely on the number of boundary-crossing events and is applicable to, for example, estimating the count rate in planar detectors,. The omni-directional fluence includes a modification to the weight of the boundary-crossing particle according to the cosine of the angle of incidence, and is applicable to the determination of dose using stopping powers and NIEL dose.

As well as graphics files for displaying the user geometry cross-section and particle tracks, numerical output is provided in a formatted Report File and Comma Separated Values (CSV) format (the latter being most suitable for input to standard data visualization packages).

Fig. 4. SPENVIS/MULASSIS Web-pages for definition of analysis parameters.

III. GEANT4 SIMULATION FRAMEWORK AND PHYSICS

Geant4 is a software toolkit for the comprehensive simulation of energetic particles in 3D geometries [1],[2]. It is the result of the collaboration of approximately 100 scientists from over 40 institutes world-wide. The code was first made available publicly in December 1998, and the version used in SPENVIS/MULASSIS is Geant4 v4.1 (which was available at the 5th December 2002 release of SPENVIS/MULASSIS).

The toolkit currently comprises approximately one million lines of source code written in C++ describing 2000 classes, and continues to evolve in order to meet the needs of its growing user community. Indeed the rigorous object-oriented design of the software with a clear hierarchical structure and unidirectional flow of dependencies provides a clear and intuitive understanding of the system, and easy extension of the software through class inheritance.

Fig. 5. High-energy physical processes in or being developed for Geant4 and their application to space radiation studies.

The toolkit comprises all new code, but includes versions of physics models from codes such as the intranuclear cascade code, INUCL, and the parameterized hadron-nuclear code, GHEISHA, that have been re-engineered in C++. Fig. 5, which summarizes the high-energy particle transport models implemented in or currently being developed for 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. Processes that are based on theory can typically be applied to any material. Those that utilize databases, such as the low-energy neutron transport and photo-evaporation are limited by the availability of data for specific materials. However, the database used for <20 MeV neutron transport has been drawn from many sources to provide a wide range of elastic and inelastic cross-sections (ENDF/B-VI, JEF, JENDL, CENDL, ENSDF (revised as of 15 May 1998), Brond, IRDF-90, MENDL, SAID, MCNP activation data, FENDL). These data include commonly used spacecraft materials. The data used to model discrete photo-evaporation are derived from the Evaluated Nuclear Structure Data File (ENSDF) [6],[7], and is considered the most comprehensive source for information of this type.

The Geant4 electromagnetic physics classes treat electron, positron, photon and muon interactions, as well as the electromagnetic interactions of hadrons and ions. They provide simulation of ionization, multiple scattering, δ-ray production, bremsstrahlung, annihilation, photoelectric effect, Compton and Rayleigh scattering, pair-production synchrotron and transition radiation (Results of comparisons of Geant4 with experimental data are not included here but can be found at [2].)

Fig. 6 omits several other processes or utilities within Geant4 for modeling interactions and tracking of their products:

1. Cerenkov radiation production;
2. Scintillation;
3. Transport of optical photons generated by the above processes (refraction, reflection, absorption and Rayleigh effect);
4. Nuclide production based on evaluated isotope production cross-sections for neutrons and protons up to 100 MeV.

IV. EXAMPLE APPLICATIONS AND RESULTS

MULASSIS may be applied to a wide range of 1D problems, and the following examples are provided to illustrate potential applications.

Fig. 6 shows the MULASSIS-predicted proton, neutron and γ-ray flux at the surface of Mars as a result of galactic cosmic radiation. The atmosphere has been modeled as a series of layers each of different density determined by the atmospheric scale-height. Consideration is also taken of the surface of the planet since the secondary particle flux maximizes beneath the surface.
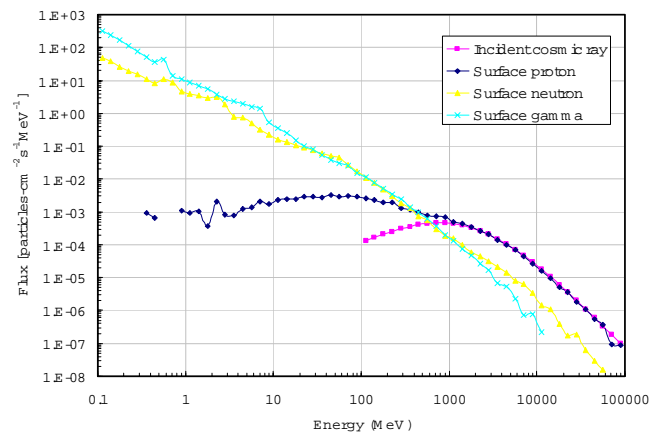

Fig. 6. Differential particle fluxes for protons, neutrons and γ-rays on Mars surface induced to galactic cosmic radiation in the atmosphere and planetary surface.

Fig. 7 shows an example dose-depth curve calculated using MULASSIS with SHIELDOSE2 [8] (also available at the SPENVIS web-site) for trapped protons in a 450km, 62° low Earth-orbit at solar maximum. In both cases, the shield is considered to be finite planar and composed of aluminum, and the particle angular distribution defined as a cosine-law (*i.e.* varying as $sin\theta cos\theta$) to simulate the flux experienced by a planar shield in an isotropic environment. From Fig. 7 it can be seen that the two predictions are in excellent agreement.

Fig. 8 compares the MULASSIS and SHIELDOSE2 predictions for the ionizing dose due to trapped electrons and bremsstrahlung in geostationary orbit at solar maximum. Once again the two predictions for finite aluminum shields show good consistency, although due to the importance of the bremsstrahlung contribution of thicknesses ≥3mm, and the lower probability of the X-rays interacting with the thin (1-20 μm) silicon layer, there are larger statistical errors in the MULASSIS results at these depths.
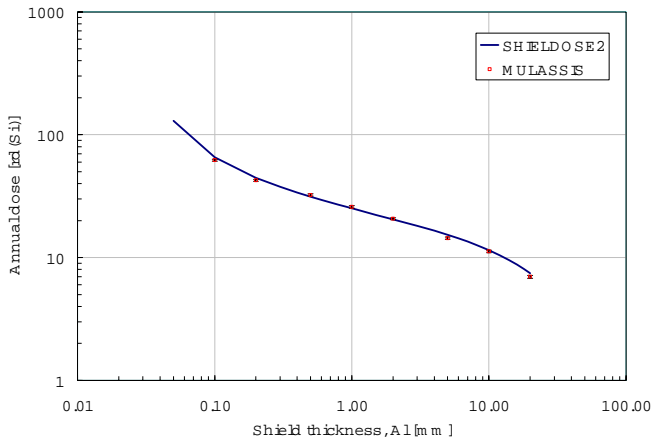

Fig. 7. Ionizing dose-depth curve for trapped protons in 450km, 62° orbit (solar maximum) predicted by SHIELDOSE2 and MULASSIS.
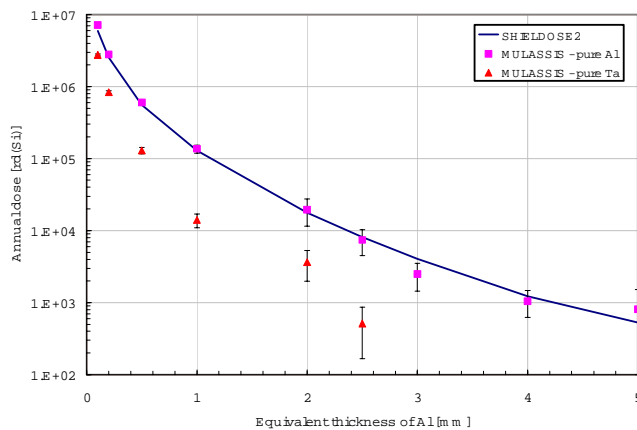

Fig. 8. Ionizing dose-depth curve for trapped electrons/bremsstrahlung in geostationary orbit (solar maximum) predicted by SHIELDOSE2 and MULASSIS. The MULASSIS results are for pure aluminum and pure tantalum shields, and the data-points for the latter are plotted for the equivalent thickness in aluminum to provide the same areal mass in g/cm^2.

Fig. 8 also includes MULASSIS results for pure tantalum shields with the same areal mass as the aluminum shields (the effects on dose from varying shield material cannot be quantified using the conventional SHIELDOSE2 model). These results highlight the benefit of using higher-Z materials (due to the increased multiple scattering of electrons) for this radiation source and orbit. In some cases, it can be beneficial to use a combination of low- *and* high-Z materials to form a graded shield against electrons – the low-Z layer usually as the first layer encountered by the radiation to slow the electrons but minimize the production of bremsstrahlung. Fig. 9 shows the annual dose for the same geostationary orbit due to trapped electrons/bremsstrahlung for different shield

compositions with a total areal mass 0.27g/cm^2 (*i.e.* the equivalent of 1mm of aluminum). It has been found that placing 10%-80% (by mass) of aluminum in front of the tantalum layer does not reduce the dose to below that for a pure tantalum shield 0.27g/cm^2 thick. However, placing some aluminum *after* the tantalum layer, may be beneficial compared with the pure Ta result (although the statistical errors for this data-point, based on 100,000 primary electron simulations, are of the order to the difference observed). In this case the low-Z material acts as a shield against photoelectrons generated in the rear of the tantalum, which would otherwise give rise to dose-enhancement in the silicon. (Obviously, in real applications with microelectronics, the device packaging performs the function of the low-Z layer.)
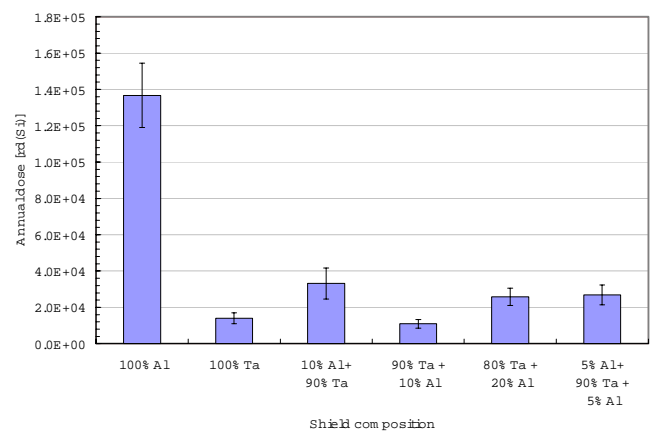

Fig. 9. MULASSIS prediction of variation in GEO annual dose (from trapped electrons/bremsstrahlung) as a result of changing the composition of the shield but maintaining a shield mass of 0.27g/cm^2. "10%Al + 90%Ta" denotes a shield comprising 10% by mass of aluminum in the first layer followed by 90% by mass tantalum as a second layer.
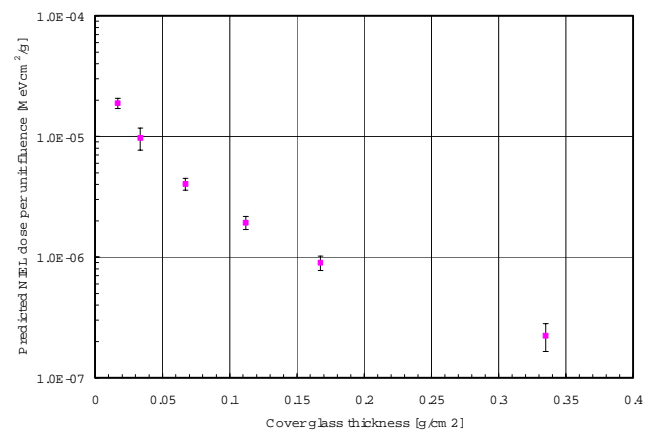

Fig. 10. Predicted NIEL dose in silicon per unit fluence for trapped electrons in geostationary orbit. The dose is given as a function of cover-glass shielding thickness.

As a final example in Fig. 10, MULASSIS has been used to predict the NIEL dose in silicon as a function of cover-glass thickness. The radiation source is again the trapped electron environment at geostationary altitude, and the ordinate is in

units of dose per unit planar electron fluence incident upon the glass in a cosine-law angular distribution.

The above are just a few examples of how MULASSIS could be employed for simple shielding calculations, but where greater detail is required in the physics simulation than offered by other tools. In the case of these examples, treatment included secondary particle production from nuclear interactions of the GCR protons (in the results of Fig. 6), and the simulation of coupled electron-photon transport when calculating the GEO trapped electron ionizing and non-ionizing doses (Figs. 7 to 10).

V. FUTURE DEVELOPMENTS

The current version of MULASSIS at SPENVIS is based on Geant4 v4.1. It is intended that this will be upgraded in the near future to v5.2 (or later) allowing use of improved hadron-nuclear interaction models and consideration of ion-nuclear interactions.

VI. SUMMARY

MULASSIS is a 1D radiation shielding simulation tool based on the Monte Carlo radiation transport code, Geant4. This tool has been in operation at the BIRA SPENVIS web-site since December 2002, and as such permits the space radiation community, as well as spacecraft designers, easy web-available access to a detailed radiation model for use as a practical engineering tool. In addition, an important benefit of this Geant4-based tool is that, as more accurate models become available within Geant4, MULASSIS can be updated to take advantage of these improvements.

VII. ACKNOWLEDGMENT

VIII. REFERENCES

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