Comparative Study Between Monte-Carlo Tools for Space Applications

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***Abstract*—Radiation analyses in the space industry rely more and more on Reverse Monte Carlo radiation transport calculation tools. These tools allow engineers to compute deposited dose and transmitted fluence in complex geometrical models, taking into account particle physical interactions with matter. Despite their widespread use, few studies exist that compare Monte Carlo tools or validate Monte Carlo Reverse results. Both Direct and Reverse Monte Carlo methods are available in FASTRAD, allowing to establish a comparison point between the well validated Forward algorithm and the Reverse one. A comparative study between FASTRAD® (Forward and Reverse), GEANT4 (Forward) and MCNPX was performed on volume detectors. In addition, results obtained with two Reverse Monte Carlo tools, FASTRAD and NOVICE, on point detectors were compared for realistic satellite models and space environment conditions.**

***Index Terms*—Comparative study, Dose calculation, FASTRAD, Forward/Reverse Monte Carlo method**

I. Introduction

IMPROVEMENT of the Monte Carlo calculation algorithm, development of calculation acceleration methods and introduction of more powerful personal computers allow now engineers to use Monte Carlo methods for their radiation analyses. Monte Carlo techniques are the most accurate calculation methods since they simulate the physical interactions between particles and matter. The Reverse Monte Carlo (RMC) method is the most suitable for calculations in the space domain since the Forward Monte Carlo (FMC) method needs a high computing time to ensure particles (tracked from the external source) to reach a very small area (i.e chip die), within a much bigger model like the whole spacecraft.

Some attempts have been made to perform validations of Monte Carlo codes [1][2], however, their lack of extent does not allow to fully validate the RMC approach.

The aim of this study is to compare results obtained with Monte-Carlo tools which are widely used in radiation analyses: FASTRAD® [3], GEANT4 [4], MCNPX [5], and NOVICE [6]. First, the Monte-Carlo tools used for comparison are described. Then, a first part presents the results of the comparative study focusing on the FMC method. In the second part, results of FMC are compared to those of RMC for a variety of materials, using FASTRAD. Finally, results from two RMC tools, FASTRAD and NOVICE are compared using real 3D satellite models and a realistic space environment.

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II. Monte-Carlo Codes presentation

FASTRAD® is a 3D CAD tool, developed by TRAD, dedicated to radiation shielding analysis in space environment. FASTRAD manages 3D geometry models which can be composed of simple shapes, added or modified through the interface, and of tessellated shapes imported from CAD tools using a STEP or IGES format. Total Ionizing Dose (TID), Non-Ionizing Dose (TNID) as well as transmitted particle fluence and internal charging can be calculated.

FASTRAD v3.6 performs FMC and RMC calculations using electrons, photons, and protons as particle sources. Secondary electrons, photons and positrons are managed after the interaction of primaries with matter. The physics of particle-matter interactions is based on GEANT4.

GEANT4 v10 (GEometry ANd Tracking), developed by the CERN, is a toolkit for simulating the passage of particles through matter. Its areas of application include high energy, nuclear, and accelerator physics, as well as studies in medical and space science. The GEANT4 FMC method is widely used and documented and will be considered in this study. Its RMC method is not yet fully usable for complex geometries. Six different particle categories are available: leptons, mesons, baryons, bosons, radioactive, and ions.

MCNPX v2.7 (Monte Carlo N-Particle eXtended), developed by LANL, is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with everything. MCNPX only proposes a FMC method based on the tracking of its original particles (neutrons, photons, electrons, and positrons) and additional ones: leptons, baryons, mesons, and ions.

NOVICE is a commercial code package used primarily for space system analysis, developed by EMPC. It includes algorithms for neutron, photon, electron, proton, and galactic cosmic ray transport in three dimensional geometries. The

NOVICE RMC method was considered for this study.

III. MONTE-CARLO DETECTOR OPTIONS

Different detector types (point or volume) can be defined for a Monte Carlo calculation. Each type gives a different estimation of the deposited dose. The point detector allows the transmitted particle fluence and thus the deposited dose to be determined in a specific location. The deposited dose is obtained from the transmitted fluence by using the LET, Linear Energy Transfer, for the charged particles (electrons and protons) and usually the mass energy-absorption coefficient, μ_{en}/ρ, for photons. The volume detector allows the mean deposited dose and the transmitted fluence to be calculated in the whole volume. Depending on the calculation tools and the user's choice, the fluence may be calculated at the surface or in the whole volume.

The detector type choice is limited by the Monte Carlo method used for the calculation. FMC is designed to perform calculations only for volume detectors. Point detectors may be used but the simulation requires a difficult and risky biasing. As RMC simulations back track the particle trajectories, it is possible to define the starting position as a point, for a point detector, or a random point on the surface of a volume for a volume detector. In either case, the RMC calculation will predict the transmitted fluence reaching the starting point and the resulting deposited dose.

IV. FORWARD MONTE-CARLO STUDY

A calculation comparison campaign was performed between FASTRAD, GEANT4, and MCNPX. Different particle sources were considered: electrons, protons, and secondary photons. The studied materials correspond to commonly used materials in space industry. For photons, an electron beam hitting a Copper target has been simulated and results on the secondary photons have been analyzed.

A. Electron simulation

Electron simulations were carried out using a mono-energetic beam of 5 MeV electrons. A circular beam with a 5.64 mm radius hits 50 successive layers set perpendicularly to the incident particles. For a given material, each layer has the same thickness. The cumulated thickness was defined so as to be larger than the 5 MeV electron range in that material [7]. Fig. 1 displays trajectories of incident electrons and subsequent secondary particles in aluminum layers. Each layer was considered as a volume detector. An incident fluence of 1 electron per square centimeter was taken into account.

Aluminum is the first studied material as it is the most used material in a satellite and the reference material when dealing with space radiation analysis. The total layer thickness was set to 15 mm, corresponding to 50 successive layers of 0.3 mm. This thickness is larger than the mean electron range that is equal to 11.5 mm [7].

Dose depth curves obtained with the three tools are shown in Fig. 2. As it can be seen, the three dose profiles are very similar.

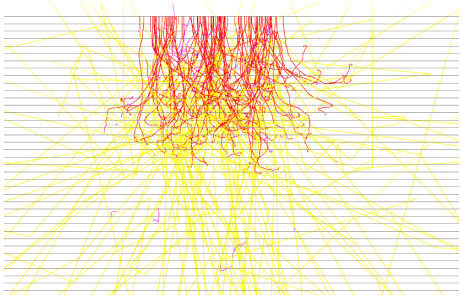

Fig. 1, 5 MeV electron beam incident on successive aluminum layers. Primary electrons are shown in red, secondary electrons are shown in magenta, and secondary photons are shown in yellow.

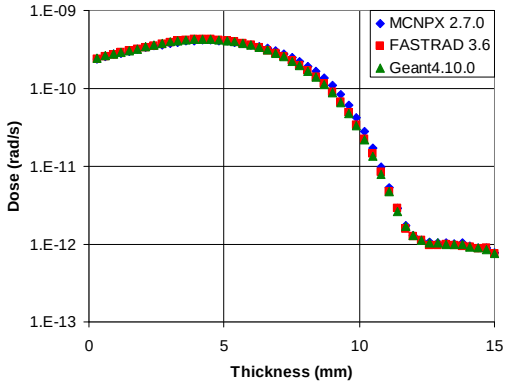

Fig. 2, Deposited dose in Aluminum layers according to the crossed thickness for: MCNPX (blue diamond), FASTRAD (red square), and GEANT4 (green triangle).

The ratios between deposited doses obtained with each tool are displayed in Fig. 3.

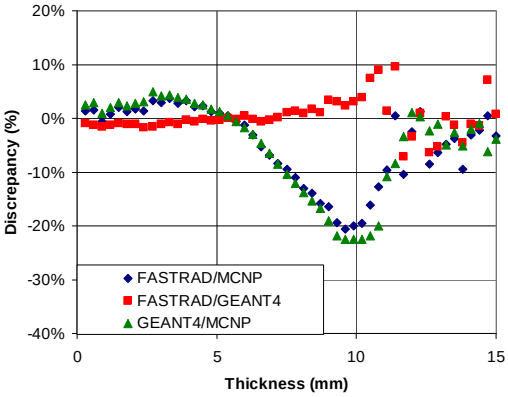

Fig. 3, Ratio between deposited dose from FMC tools in Aluminum layers according to the crossed thickness: FASTRAD to MCNPX (blue diamond), FASTRAD to GEANT4 (red square), and GEANT4 to MCNPX (green triangle).

Dose values are almost identical from the surface up to 6 mm (less than 5% difference). Results diverge above 6 mm:

- FASTRAD and GEANT4 values remain very similar, with a difference between 10% and -8%
- MCNP values are higher by up to around 20% (maximum discrepancy at 10 mm Al).

The deposited dose beyond 12 mm is due to secondary photons. The weak convergence observed through the

appearing fluctuations is explained by the low number of particles reaching these layers. Obtaining a better accuracy was not necessary for this part of the study since the secondary photons are investigated in a separate devoted simulation.

Electrons deposit slightly more energy in the first layers in the FASTRAD and GEANT4 simulations than in MNCPX. Two processes may explain this difference: more interactions create more secondary particles and more lateral straggling. The first process leads to an increase in particle number. The second one increases the length of the particle trajectories inside each layer. Electrons, as all charged particles, deposit energy along its trajectory in material. The amount of transmitted energy depends on the particle trajectory length. The combination of these processes can explain the higher deposited energy for FASTRAD and GEANT4 compared to MCNPX.

Beyond 6 mm, FASTRAD and GEANT4 simulate fewer particles as a higher number of primary electrons interacted during the secondary particle creation, and the lateral straggling induces a decrease in the electron longitudinal range. Less particles deposit less dose explaining the lower dose results of FASTRAD and GEANT4 with respect to MCNPX.

Similar calculations were performed for representative materials such as Carbon, Copper, Silicon Dioxide, Kapton, Tungsten, and Gallium Arsenide. Table I summarizes the discrepancies between the different FMC codes for representative thicknesses appearing in satellites, units or electronic component packages.

TABLE I
5 MEV ELECTRON FMC DISCREPANCIES FOR REPRESENTATIVE THICKNESSES

MATERIAL	THICKNESS (MM)	FASTRAD/ MCNPX	FASTRAD/ GEANT4	GEANT4/ MCNPX
ALUMINUM	0.3	1.4%	-1.0%	2.4%
	0.9	-0.6%	-1.5%	0.9%
	2.1	1.8%	-1.1%	2.8%
	5.1	0.9%	0.0%	1.0%
	8.1	-13.1%	1.0%	-13.9%
	10.2	-19.5%	4.4%	-22.9%
CARBON	1.2	-1.5%	-1.2%	-0.3%
COPPER	0.1	3.6%	-3.7%	7.6%
SIO2	0.4	1.8%	-0.7%	2.5%
	0.8	-1.1%	-0.3%	-0.8%
	2	0.5%	-1.1%	1.7%
	5.2	1.8%	-0.7%	2.5%
	8	-1.8%	-0.1%	-1.8%
	10	-8.0%	0.4%	-8.3%
KAPTON	0.5	0.1%	-1.3%	1.4%
TUNGSTEN	0.050	6.5%	-10.0%	18.3%
	0.100	6.6%	-0.1%	6.7%
ASGA	0.2	7.4%	-1.2%	8.7%

Results from FASTRAD and GEANT4 are almost identical (difference lower than 5%) except for the very thin surface of Tungsten (10% difference). Differences between FASTRAD and MCNPX, as well as GEANT4 and MCNPX, are higher but only for the highest aluminum thicknesses (more than 8 mm). Nevertheless, differences do not exceed 23% (GEANT4/MCNPX for 10 mm Aluminum). For other materials, discrepancies are always lower than 10% with most of them lower than 5%.

These results suggest that for a real space environment application FASTRAD and GEANT4 will predict very similar doses and that MCNPX will give higher dose results in the case of thick shielding. This needs to be validated using a realistic electron space environment spectrum.

B. Proton simulation

Similar beam and target configurations were considered for the proton simulations. As for electrons, the cumulated thickness of the successive layers is defined to be larger than the proton range. Four different energies were used for the mono energetic beams: 10, 50, 100, and 300 MeV. This energy range is representative of the proton environment around the Earth.

The physical processes involved for protons of such energies include electromagnetic and nuclear interactions. FASTRAD, like Shieldose [8], does not take nuclear interactions into account. MCNPX integrates this specific physics by default, whereas the GEANT4 user can choose to integrate it or not in the simulation. Comparisons between FASTRAD, GEANT4 with (Nuc) and without (Em) nuclear reactions, and MCNPX have been performed.

Table II gives the maximum discrepancy between FASTRAD and GEANT4 results for five materials: Aluminum, Copper, Tungsten, Kapton and Glass. Their thicknesses were smaller than 30 mm of equivalent Aluminum. This value was chosen because the deposited dose behind more than 30 mm of equivalent Aluminum will not have an important impact on the total dose inside a satellite. The total dose at component level is mostly due to particles crossing smaller thicknesses.

For each material and energy, two values are given: the first column shows the difference between FASTRAD and GEANT4 Em (without nuclear interactions), and the second column shows the difference between FASTRAD and GEANT4 Nuc (including nuclear interactions).

TABLE II
MAXIMUM DISCREPANCY BETWEEN FASTRAD AND GEANT4 IN %

PROTON ENERGY (MEV)	AL		CU		W		KAPTON		GLASS	
	Em	Nuc	Em	Nuc	Em	Nuc	Em	Nuc	Em	Nuc
10	5	5	5	5	5	7	10	10	5	5
50	1	6	5	8	3	4	2	6	13*	10
100	1	6	1	3	1	3	3	7	1	6
300	1	12	1	16	1	13	3	18	1	18

* Bragg peak not occurring in the same layer in FASTRAD and GEANT4

Em and Nuc indicate if only electromagnetic processes or nuclear interactions also, are taken into account for the GEANT4 calculation.

As it can be seen, the difference between FASTRAD and GEANT4 Nuc does not exceed 7% for energies up to 100 MeV and 18% for 300 MeV. The 13% difference observed for the Glass at 50 MeV is due to the fact that the Bragg peak is not occurring in the same layer for both tools. More generally,

the biggest differences are encountered at the Bragg peak. The energy range from 10 to 300 MeV covers the high energy proton spectrum encountered around the Earth. These results suggest that neglecting the process of nuclear interactions does not have an important impact on the dose calculation in a proton space environment.

The same comparisons were made with MCNPX. Results are displayed in Table III. Important dose discrepancies have been observed. As in the previous case, they appeared at the Bragg peak layer ("Br" column in the table). A second column has been added in the table for each material. It contains the difference taking into account all the layers but the one corresponding to the Bragg peak. These additional columns do not exist for protons above 50 MeV because the Bragg peak occurs beyond 30 mm of equivalent Aluminum.

The discrepancies are here limited to 10% except for the glass and for 300 MeV protons with a maximum difference of 18%.

TABLE III
MAXIMUM DISCREPANCY BETWEEN FASTRAD AND MCNPX IN %

PROTON ENERGY (MEV)	AL		CU		W		KAPTON		GLASS	
	Br	No Br	Br	No Br	Br	No Br	Br	No Br	Br	No Br
10	5	5	25	6	24	5	16	10	18	18
50	6	3	16	3	7	5	10	5	29*	15
100	5		5		4		9		9	
300	13		12		10		15		13	

* Bragg peak not occurring in the same layer in FASTRAD and MCNPX

Br and NoBr indicate if the maximum discrepancy is given taking into account the Bragg peak layer or not. The Bragg peak occurs beyond 30mm of equivalent aluminum for energies above 50 MeV. Values are absolute values.

As a conclusion to this proton analysis, when not considering the Bragg peak, the discrepancies observed between FASTRAD and the other tools, GEANT4 (Em and Nuc), and MCNPX, are similar. They are limited to 10% below 100 MeV protons and to 18% above. Nevertheless, a higher difference appears in the dose deposited at the Bragg peak level even for low energies. The difference reaches 25% at 10 MeV. The difference in the physics of the different tools, especially considering or not the nuclear interactions, explain this difference at the Bragg peak.

C. Photon simulation

A 5 mm thick Copper cylinder has been used to study the creation of secondary photons created from a monoenergetic electron beam. The simulation configuration is given in Fig. 4. The beam incidence is normal to the cylinder surface and a detector sphere with a 50 mm radius is located 1 meter behind the Copper target. This model allows studying the photon creation by the Bremsstrahlung at different levels:

- The emission angles,
- The energy of creation by considering the photon spectrum profile in the detector sphere.

Fig. 4, Photon simulation configuration. The distance scale is not respected.

The calculations were performed with MCNPX, FASTRAD, and GEANT4 for different electron energies: 1, 2, 5, and 10 MeV. The energy cut was set to 1 keV. It indicates that no particle, whether photon or electron, is created with energy below 1 keV.

Table IV presents the discrepancy in the total photon flux between the three tools for each beam energy. The results between FASTRAD and GEANT4 are identical (difference of 2% at maximum). With respect to MCNPX, the discrepancy is limited to 7% for FASTRAD and 9% for GEANT4. The emission angle is thus validated, at least along the incident direction.

TABLE IV
TOTAL PHOTON FLUXES COMPARISONS

ENERGY	1 MEV	2 MEV	5 MEV	10 MEV
FASTRAD / GEANT4	1.7%	-1.5%	-0.5%	-2.0%
FASTRAD / MCNPX	-4.7%	0.2%	6.1%	6.7%
GEANT4 / MCNPX	-6.3%	1.8%	6.6%	8.8%

To study the energy of the created photons, the photon flux ratios between the three tools for the whole photon spectrum have been studied. They are displayed in Fig. 5 for the 10 MeV electron beam. For every tool, the results are similar for energies higher than 100 keV: differences smaller than 6% between FASTRAD and GEANT4, up to 10% between FASTRAD and MCNPX, and below 15% between GEANT4 and MCNPX. Below 100 keV, discrepancies up to 22% appear but there are mainly due to the small number of photons with this energy. This lack of particles induces a convergence issue and so these results should not be taken into account. The photon flux ratios between the three tools are very similar for other electron beam energies as the ones shown here.

The similarities of the emission angles and of the transmitted photon spectra between the different tools allow us to conclude that the emission angles and the photon energy distribution are very similar between the three codes.

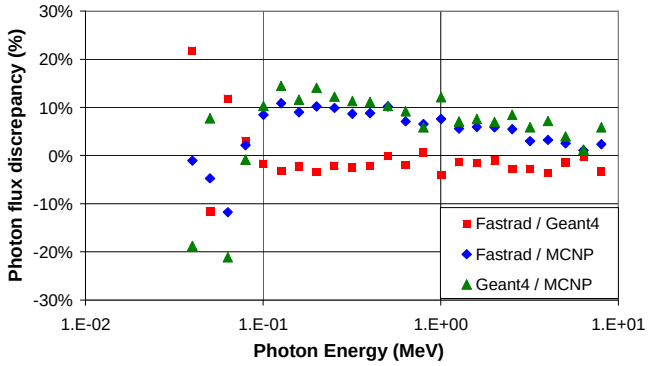

Fig. 5, Ratio between transmitted photon numbers in the sphere detector for a 10MeV electron beam: FASTRAD to MCNPX (blue diamond), FASTRAD to GEANT4 (red square), and GEANT4 to MCNPX (green triangle).

V. Reverse Monte-Carlo study

The RMC study is divided into two parts. The first one is focused on the comparisons between FASTRAD FMC and RMC on simple cases taking into account realistic electron and proton space environments. The aim was to verify that all the physical processes present in the Forward method are well implemented in the Reverse algorithm. Then, a comparative study of two RMC codes in a realistic case is carried out.

A. Forward/Reverse Monte-Carlo

A Silicon spherical volume detector is considered for this part of the study. The simple geometries were made of a shell sphere of different thicknesses and materials surrounding the silicon solid sphere detector. The inner sphere radius is set at 10 mm. The gap between the inner radius of the shell sphere and the silicon sphere surface is equal to the thickness of this shell sphere. The model configuration is shown in Fig. 6.

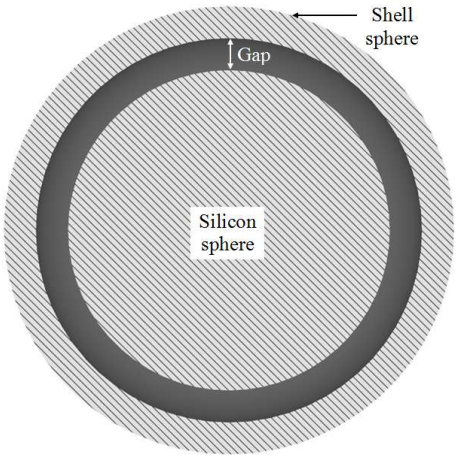

Fig. 6, FMC/RMC study model for a 2 mm thick shell sphere.

Different materials have been used for the shell sphere: Aluminum, Carbon, Copper, Kovar, Tungsten, and Gallium Arsenide.

For electrons, a geostationary (GEO) flux environment is used and for protons, a Low Earth Orbit (LEO) flux environment is used. Both were calculated using the following environment models in OMERE [9]:

- AE8 Max for electrons in GEO,

AP8 Min for protons in LEO.

Table V summarizes the results for representative thicknesses encountered in a satellite for electrons and protons. Some results are missing for protons and are replaced by a '-' sign.

Results between the Forward and Reverse calculation are very similar for the electron and proton sources. Usually differences do not exceed an absolute value of 10%, except in the case of electrons for thicknesses ≥7 mm of Aluminum. Even in these cases, differences do not exceed 15% (30 mm Al). The lower doses obtained with the Reverse method for electrons at high thicknesses may indicate a lack of some of the secondary electrons or photons participation as they become predominant for these thicknesses.

Table V
Electron and proton Results for representative thicknesses

Material	Thickness (mm)	Electron RMC/FMC Discrepancy	Proton RMC/FMC Discrepancy
Aluminum	0.5	-1.7 %	1.3%
	1	-3.3%	0.8%
	5	-1.2%	3.2%
	7	-12%	-
	10	-14%	7.2%
	30	-15%	-
Carbon	1	1.0%	-
Copper	0.1	1.0%	-
Kovar	0.5	-0.8%	0.5%
Tungsten	0.050	7.0%	0.8%
	0.100	9.0%	0.9%
AsGa	0.2	2.0%	-

AE8 Max was used to determine the trapped electron environment for a geostationary mission. AP8 Min was considered for the proton environment at LEO.

B. Reverse Monte-Carlo on real satellite geometries

The last part of the study is dedicated to comparisons between two RMC tools, FASTRAD and NOVICE, taking into account a real 3D spacecraft geometry model including the platform, the units, and the electronic components. Geostationary or LEO environment are considered depending on the particle type studied.

The NOVICE runs were performed by Thales Alenia Space.

Study on protons

The satellite model used for the proton comparison is SAC-D. The complete 3D model of the ICARE-NG equipment was modeled [10] and set at two different locations in the spacecraft corresponding to its actual location and to another one surrounded by more shielding. This unit model contains the housing, the different electronic boards, and the electronic sensitive components within their actual packages.

The proton environment is composed of trapped and solar protons in a LEO orbit. Proton spectra, for the 4 year mission, were obtained using the following environment models in OMERE:

- AP8 Min for trapped protons,
- ESP with a 85% confidence level and an active solar period of 4 year for the solar protons.

Fig. 7 displays the difference between the deposited doses from FASTRAD and NOVICE for each proton source. The doses received from solar particles are much lower than those obtained with the trapped ones at LEO orbit. The observed discrepancies are very small with differences ranging from 3% to 13% for the trapped protons and from -2% to 14% for the solar protons.

A possible explanation for the higher doses estimated with FASTRAD could be the fact that the latter considers secondary electrons and photons created from primary protons.

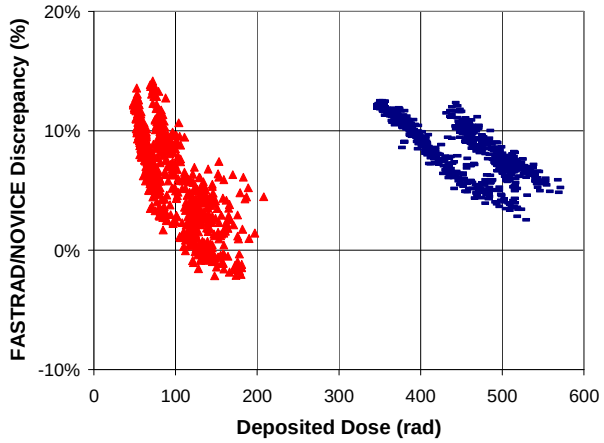

Fig. 7, FASTRAD/NOVICE discrepancy according to the deposited dose in FASTRAD for trapped (blue line) and solar (red triangle) protons. 641 point detectors have been used for the comparison.

Study on electrons

The electron environment considered for this part of the study is only composed of trapped electrons. It corresponds to a 15 year geostationary orbit. The environment spectrum calculation has been performed using OMERE with the IGE 2006 Upper Case model [11]. The calculations were performed in a realistic geostationary satellite platform provided by TAS-FR.

The difference between FASTRAD and NOVICE is shown in Fig. 8 as a function of the deposited dose in FASTRAD.

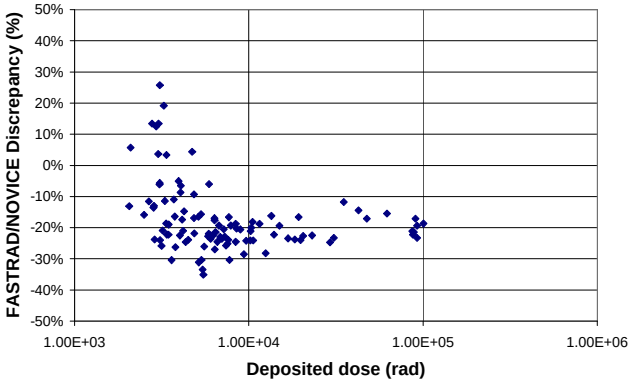

Fig. 8, FASTRAD/NOVICE discrepancy according to the deposited dose in FASTRAD for trapped (blue line) electrons.

The difference observed between the two tools ranges from -35% to 25% with an average difference of -19%. The total dose considers the energy deposited by the primary and secondary electrons, and the secondary photons.

The calculated doses are higher than 3 krad for a 15 year mission. This dose level corresponds to an equivalent aluminum thickness ranging from 6 to 15 mm depending on the considered material. The denser a material is, the smaller its equivalent aluminum thickness is. The discrepancy observed in the thickness range is 15% between the Reverse and Forward Monte Carlo methods, as shown in Table III. But below this thickness, the difference RMC/FMC significantly decreases to reach 3%. This is not what can be observed in Fig. 8. The differences between NOVICE and FASTRAD remain stable around -20% for deposited doses up to 100krad. This difference level cannot be explained by the difference between Forward and Reverse methods but by a difference in the RMC treatment of FASTRAD, and NOVICE.

Different causes can account for this behavior difference: the physics, the biasing techniques, and the physics of the Reverse MC treatment.

Concerning the physics implemented in the two codes, differences exist for specific interactions. For example the Seltzer-Berger model is used in all studied tools except for NOVICE that includes Bremsstrahlung photon production formulas suggested by Koch, and Motz.

The major biasing technique implemented in all RMC codes is due to the backward tracking of particles from the detector to the world outside the whole geometry. The particle importance (or weight) cannot be known at its creation at the detector level but only when the particle escapes the model as this weight depends on the external particle spectrum. Thus, each tool can choose its own energy distribution of the particles shot from the detector. FASTRAD starts with a flat distribution: the same number of particles whatever their energies. Other tools, such as GEANT4, prefer a distribution according to a 1/E law with E representing the particle energy [2]. These differences in biasing techniques have no impact on the calculation results but rather on the number of particles needed to get an accurate result. The closer to reality the energy distribution is at the detector level, the lower number of particles is needed for an accurate result.

The physics Reverse MC treatment is associated with the techniques present in each tool to modify the particle weight after each physical interaction or geometric steps. This is probably the biggest discrepancy origin because it occurs at each particle step.

Following this review of the possible causes for the result discrepancies observed between NOVICE and FASTRAD, it appears that no single cause can be distinguished. Nevertheless, a deeper analysis has been conducted to narrow down the particles, electrons or photons, responsible for the differences.

The dose transmitted by electrons and secondary photons have been studied separately for each tool. Fig. 9 and Fig. 10

represent the differences taking only into account the transmitted electrons and photons respectively.

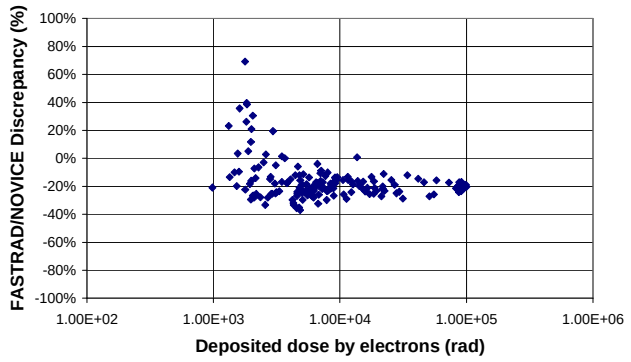

Fig. 9, FASTRAD/NOVICE discrepancy according to the deposited dose in FASTRAD for trapped (blue line) electrons, only considering the transmitted electrons.

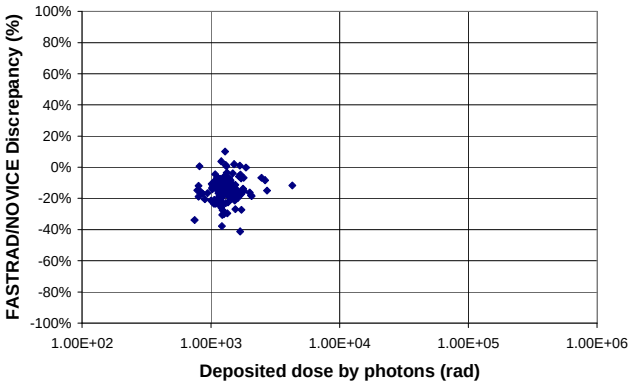

Fig. 10, FASTRAD/NOVICE discrepancy according to the deposited dose in FASTRAD for trapped (blue line) electrons, only considering the transmitted photons.

The deposited dose range from photons is small, ranging from 0.75 to 4.3 krad, compared to the one due to electrons, spreading from 1.3 to 100 krad. The electron discrepancy is around -20% with a more important spread for low doses. For the photons, the differences range from 10% to -40% with a maximum of points between 0% and -20%.

The results presented above represent a typical case of telecom satellites in a geostationary environment. An averaged 20% discrepancy is observed between FASTRAD and NOVICE calculated doses. This discrepancy is similar for electrons and photons. This is expected as the electrons create the photons. Higher doses obtained with FASTRAD are observed for the lower deposited doses. We conclude that secondary electron management is not performed in the same way in the two RMC Tools.

VI. Conclusion

Comparative studies on electrons, photons, and protons have been carried out between FASTRAD Forward and Reverse Monte Carlo modules and other reference FMC and RMC tools, GEANT4, MCNP, and NOVICE.

This study showed a good agreement between studied MC tools, whether for the Forward or the Reverse methods. The very good agreement between FASTRAD FMC and GEANT4 can be expected since FASTRAD incorporates the GEANT4 physics.

Concerning protons, results showed that ignoring nuclear interactions does not have an important impact for space applications. Further studies using a realistic proton space environment could confirm this conclusion.

A tendency for higher calculated doses by NOVICE compared to FASTRAD is visible for electrons and photons in the range of doses that are of interest for space industry, i.e. higher than 10krad.

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