Impact of the Detector Definition on the Reverse Monte Carlo Calculation Results

Pierre Pourrouquet, Vincent Traisnel, Athina Varotsou, Guy Rolland, and Robert Ecoffet

***Abstract*—Most of the TID, Total Ionizing Dose, calculations for electronic devices based on Reverse Monte Carlo methods consider a point as the detector. This assumption is made whereas the area sensitive to TID is a volume. However, the shape and size of this volume is difficult to estimate. A parametric study using FASTRAD® has been performed to compare TID results obtained using different detector shapes and sizes, to values computed using point detectors. Multiple geometrical models from the simplest one to the most realistic one allowed to get a large spectrum of data and perform a thorough analysis. An equivalent study was performed for external materials and its results are also shown. Recommendations on detector choice are given at the end of this paper.**

***Index Terms*—Ionizing dose calculation, Radiation hardness assurance, Reverse Monte Carlo, Satellite radiation model**

I. INTRODUCTION

RECENT improvements of the Reverse Monte Carlo method (RMC) in calculation tools dedicated to space environment allow engineers to rely more and more on this calculation technique to carry out their radiation analysis including the TID calculation. It was already the case for external materials as the alternative sector-analysis method is not applicable for the ionizing dose calculation in materials different from Silicon or Gallium Arsenide. Nevertheless using the RMC method raises a certain number of issues such as the reliability of the results and the relevance of performing a point detector calculation as representative of the dose deposited in a volume. The first issue was addressed in previous studies [1], [2], and [3] whereas the study presented in this paper focused on the second one.

A first part is dedicated to the definition and location of the detectors inside the device die. It also includes the description of the geometrical models, from the simplest to the most realistic, representing a whole spacecraft. Comparisons between the TID calculation results considering these different models are then presented before being analyzed. All models and calculations were respectively built and performed using FASTRAD® v3.7. Recommendations regarding the impact of using point detectors for an RMC TID calculation are finally expressed in the conclusion.

II. MODEL DEFINITIONS

A large number of geometrical models has been used for this study. The first part is dedicated to the different detector models: cube, slab and point. The following parts describe the geometrical models used to represent the shielding provided by component packages, unit structures, and satellite platform.

A. Detector models

All the detectors have been inserted into a silicon die. For all the models, this die has been represented by a box made of silicon with 1 mm x 1 mm as lateral dimensions and 250 micrometers as thickness.

Slabs and cubes have been selected as representative of the volumes sensitive to TID. The different studied dimensions are 1, 10, and 100 micrometers. All detector volumes are made of Silicon.

Cube detectors have been inserted at the center of the die surface as shown in Fig. 1 and slabs cover the entire die surface as displayed in Fig. 2.

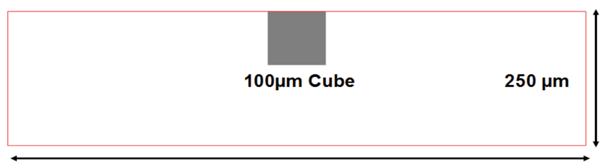

Fig. 1. Cross section view of a 100 µm cube detector volume (in grey) inserted in the silicon die (red box).

Fig. 2. Cross section view of a 100 µm thick slab detector volume (in grey) inserted at the top of the silicon die surface (red box).

Point detectors have been inserted at the center of the die at different depths below its surface. These depths have been selected so that the point detectors be located at the center of

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the corresponding detector volumes, i.e. 0.5, 5, and 50 micrometers for 1, 10, and 100 micrometers respectively. Fig. 3 contains a 100 µm cube volume detector and the corresponding 50 µm deep point detector.

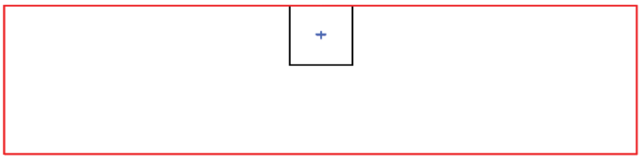

Fig. 3. Cross section view of a 100 µm cube detector volume (in black) and its corresponding point detector (blue cross) located 50 µm under the die surface (red box).

The Reverse Monte Carlo dose calculation process depends on the detector type:

- For volume detectors, the dose is obtained by dividing the calculated deposited energy inside the volume by its mass,
- For point detectors, the calculated transmitted fluence is converted into a dose using the stopping power for charged particles and the mass energy-absorption coefficients for photons.

B. *Simple models*

Simple models have been used in the study to analyze the impact of detector choice without adding additional elements that can have an impact on the result, such as the component package, the unit structure, and the satellite platform. Thus the models were made of simple silicon dies mounted on a PCB, in polyimide glass, surrounded by equivalent hollowed aluminum boxes representing the shielding provided by the unit structure, and the satellite platform. The satellite is represented by a 2-meter cube with a 0.5 mm thickness and the unit structure is a 0.8 mm thick box, as shown in Fig. 4.

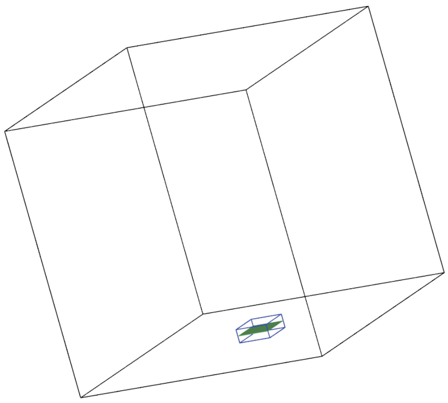

Fig. 4. Simple geometrical model: satellite equivalent hollowed cube in black, unit equivalent hollowed box in blue and PCB inserted inside in green.

The next step was to consider realistic component packages around the silicon dies. It allowed to study their specific impact. Different packages have been used according to their material composition (Fig. 5):

- Metallic TO39 in Iron,
- Plastic SO14,
- Ceramic FP14.

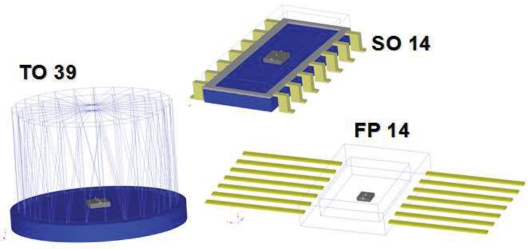

Fig. 5. Package geometric models: TO39 in Iron, plastic SO14, and ceramic FP14. Each one contains a silicon die including the different detectors.

C. *Realistic Satellite model*

The satellite model used for the comparison is SAC-D [4]. The complete 3D model of the ICARE-NG equipment was set at its actual location. This unit model contains the housing, the different electronic boards, and the electronic sensitive components within their actual packages.

SAC-D radiation model used for this study is displayed in Fig. 6.

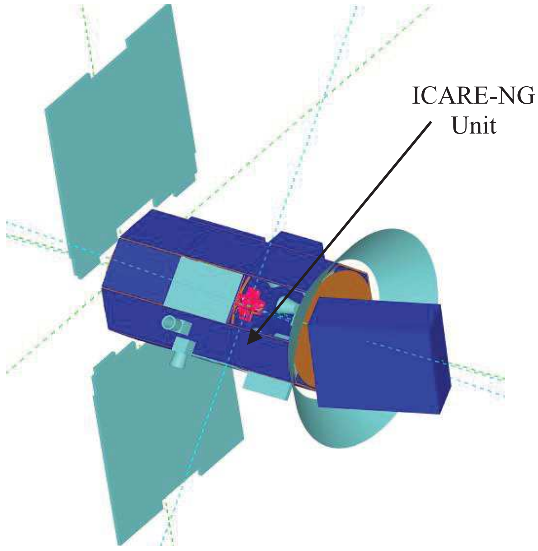

Fig. 6. Realistic geometrical model: satellite structure including the ICARE-NG Equipment.

Other units are modeled as hollow aluminum boxes representative of the shielding they provide within the satellite platform.

Furthermore, a selection has been carried out among the electronic components present in the ICARE-NG unit. Three component pairs have been selected according to their received dose. Each pair corresponds to a certain dose level and are presented in Fig. 7:

- High: SOT23 components whose packages are made of Carbon Epoxy,
- Low: TO258 parts with a Kovar package,
- Mean: TSSOP16 and WG10A whose packages are respectively made of Aluminum Oxide and Carbon Epoxy.

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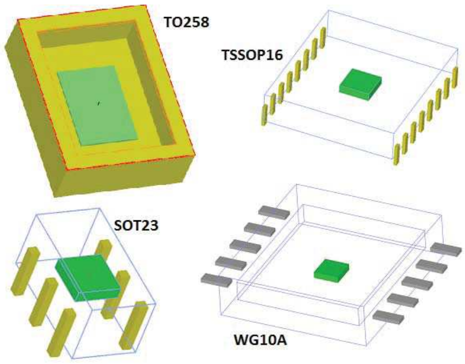

Fig. 7. Package geometric models studied for the realistic satellite model. Each one contains a silicon die (green box) including the different detectors.

D. External materials

An additional part of the study was about the external materials focusing on optical devices. The different studied materials were:

- Zerodur, and Silicon carbide, SiC, for mirrors,
- NBK7 for lenses.

The geometrical models were cylinders with a 5 cm radius and a 2 cm thickness set on each face of an aluminum hollow box, 2 meter wide and 0.5 mm thick, representing the shielding provided by the satellite platform (see Fig. 8).

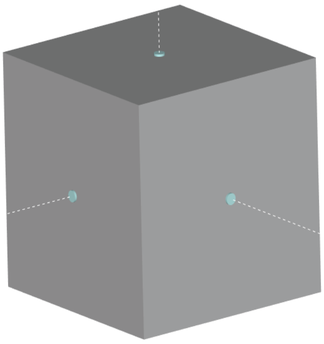

Fig. 8. Geometric model used for external material study. In this example blue cylinders made of NBK7 are set on each face of the equivalent satellite platform (grey box).

Volume detector dimensions were studied from 1 µm to 1mm and point detectors located accordingly from 0.5 µm to 500 µm.

III. Particle Environment Description

Three different space environments have been considered in this study covering the range of particles and energies that may be encountered in space:

- SAC-D mission [4], typical of LEO missions mainly made of trapped protons,
- GEO mission, for which fluxes were calculated using OMERE [5] and includes solar protons (ESP model with an 85% confidence) along with trapped electrons (upper case IGE model) and protons (solar minimum AP8).
- JUICE mission [6], made of high energetic electrons reaching up to 1 GeV.

IV. Results on Silicon Dies

The absolute discrepancies for the different cases are divided into three categories (the colors chosen for the next tables are also indicated):

- Negligible below 10% (green),
- Small between 10 and 20% (orange),
- Large above 20% (red).

The study on detectors will be separated into two parts: first the focus is on the effect of the size of the volume detectors or the depth of the point detectors; then the detector shape is studied. The impact of each environment type, electron and proton, is independently shown.

A. Study on detector size/depth

In the next three tables, each colored case corresponds to the highest discrepancy observed between doses calculated for different sizes and depths considering a detector type, a particle type, and, for Table II, a device package. For example, the left half of the tables corresponds to the highest discrepancies observed for electrons, i.e. considering the electrons present in the Juice and the GEO missions. For each particle type, each column corresponds to a certain detector type and each line to the sizes compared. For points, the equivalent depths are considered, i.e. 0.5µm wrt 5 µm for the 1µm wrt 10 µm line.

Moreover, for each line, the second detector size or depth is considered as the reference for the comparisons. For example the absolute difference for the first line is given in (1).

$$Diff = \frac{Abs(TID(1\mu m) - TID(10\mu m))}{TID(10\mu m)} \quad (1)$$

Simple models

No large discrepancy can be observed for bare silicon dies as indicated in TABLE I.

TABLE I
Results for Bare Silicon Dies

	Electrons			Protons		
Size/Depth	Point	Cube	Slab	Point	Cube	Slab
1µm wrt 10µm						
10µm wrt 100µm						

Similar results are obtained when adding packages around the silicon dies, as shown in TABLE II.

TABLE II
Results for Detectors Surrounded by Packages

	Electrons			Protons		
Size/Depth	Point	Cube	Slab	Point	Cube	Slab
FP14						
1µm wrt 10µm		21%				
10µm wrt 100µm						
TO39						
1µm wrt 10µm						
10µm wrt 100µm						

	Electrons			Protons		
Size/Depth	Point	Cube	Slab	Point	Cube	Slab
SO14						
1µm wrt 10µm						
10µm wrt 100µm						

Negligible discrepancies can be observed for a proton environment. For electrons, small and even large discrepancies exist for specific cases.

In addition, for electron environments, a common trend is observed for the point and slab detectors: doses decrease with detector size /width increase.

The only significant discrepancy is observed for an FP 14 package between doses for 1 µm and 10µm cube detectors in an electron environment. In this case the difference is limited to 21%.

Realistic models

The trends observed for the simple models are also present for the realistic models.

Only negligible discrepancies can be noticed for a proton environment. The discrepancies observed for electrons when considering simple models, are higher, especially for cube and slab detectors, as shown in TABLE III. This is especially true for the cubes with a 44% dose decrease and the slabs with a 25% dose drop between 10 and 100µm. The point detectors follow the same trend in a smaller proportion as the maximum difference does not exceed 11%. The largest discrepancies given here correspond to the calculations performed for the GEO mission.

TABLE III
RESULTS FOR REALISTIC MODELS

	Electrons			Protons		
Size/Depth	Point	Cube	Slab	Point	Cube	Slab
1µm wrt 10µm		29%				
10µm wrt 100µm		44%	25%			

Preliminary observations

The results of this part dedicated to the size or depth of the detectors show trends that exist for simple and realistic models.

The deposited dose in each detector type is the same for all studied cases for a proton environment.

Considering electron environments, the doses decrease with increasing detector size or depth. The decrease in the number of particles able to reach the deeper areas explains it. Part of the electrons is stopped in the first micrometers of the die.

An exception to this rule is observed for the cube detectors between 1 and 10 µm. In this specific case, the small size of the 1µm cube prevents electrons to fully interact, and thus deposit dose in the detector whereas these interactions are possible for a bigger 10µm cube.

B. *Study on detector shape*

This part focuses on comparisons between the results obtained for different detector types considering equivalent size and depth.

In the following tables, each column is specific to the comparisons of 2 detector types, as in TABLE IV, or to a specific package. Furthermore each line corresponds to a specific size or depth, for example the 1µm cubes, 1µm thick slabs, and 0.5µm deep points are compared in the first line.

Simple models

Once again, negligible discrepancies appear for a proton environment except for a few cases with a maximum difference below 11%.

For electron environments, discrepancies decrease with the increase of the detector size or depth (under the surface for point detectors). This trend appears when considering bare silicon dies (TABLE IV) and is more important when packages surround them.

TABLE IV
RESULTS FOR BARE SILICON DIES

	Electrons			Protons		
Size/Depth	Slab / Cube	Cube / Point	Slab / Point	Slab / Cube	Cube / Point	Slab / Point
1µm	29%	21%				
10 µm						
100 µm	24%					

When packages are considered, the highest differences are observed when comparing the volume detectors, cube and slab, with a maximum of 34% for 1µm, 27% for 10µm and no more than 15% for 100µm, as shown in TABLE V.

TABLE V
COMPARISONS SLAB/CUBE DETECTORS SURROUNDED BY PACKAGES

	Electrons			Protons		
Size	FP14	TO39	SO14	FP14	TO39	SO14
1µm	34%	28%	28%			
10µm			27%			
100µm						

This effect also exists but is attenuated when comparing point and volume detectors, as can be observed in TABLE VI.

TABLE VI
COMPARISONS VOLUME/POINT DETECTORS SURROUNDED BY PACKAGES

	Electrons			Protons		
Size/Depth	FP14	TO39	SO14	FP14	TO39	SO14
Cube/Point Detectors						
1µm	22%					
10µm						
100µm						
Slab/Point Detectors						
1µm	20%					
10µm						
100µm						

Moreover the doses deposited in cube detectors are always smaller than the ones deposited considering slab and point detectors. The doses deposited considering slab and point detectors are equivalent. Some cases present a dose smaller in slab whereas others indicate the opposite.

Realistic models

As observed for the previous study on detector size, the variations that appear for simple models are also present for components located in a realistic satellite model and are indicated in Table VII.

TABLE VII
RESULTS FOR REALISTIC SATELLITE MODEL

	Electrons			Protons		
Size/Depth	Slab / Cube	Cube / Point	Slab / Point	Slab / Cube	Cube / Point	Slab / Point
1µm	30%	21%	28%			
10 µm	26%	20%				
100 µm	23%					

No dose variation can be noticed for a proton environment.

For electrons, the variations are similar considering JUICE or GEO environment. The highest differences are between results for the volume detectors, slab and cube, with a higher dose for the cube. When comparing volume and point detectors, the discrepancy is smaller (less than 21%) except for the smallest dimension in GEO environment with a 28% difference. It is especially the case between slab and point with a difference below 20% for all other dimensions and environment.

The observation made in the previous paragraph remains true. First, the doses deposited in cube detectors are always smaller than the ones deposited considering slab and point detectors. Then the doses deposited considering slab and point detectors are equivalent.

Preliminary observations

The deposited dose in each detector type is the same for all studied cases for a proton environment.

When considering electron environments, the maximum discrepancies appear for the smallest sizes. As dimensions increase, cube shapes are more similar to the slab ones.

Furthermore the doses deposited in cube are the smallest ones while doses obtained for slab and point are similar. This may be due to the effect seen in the previous part; the small size of the cubes prevents electrons to fully interact.

V. STUDY ON EXTERNAL MATERIALS

As for the components, the study on external materials is divided into two parts: the first one dedicated to the dose evolution according to the volume detector thickness or point detector location, and the second one to the differences between the detector shapes for the same thickness and an equivalent location.

A. *Study on detector size/depth*

This part shows a steep gradient according to the detector thickness or location for all the satellite external. Moreover the dose gradient flattens when reaching higher thicknesses. An example is given in the next Fig. 9 for the Silicon Carbide considering a GEO mission.

As the highest part of the particles, low energy electrons and protons, is stopped at the surface of the materials; their energy is deposited close to the surface giving a high dose. Furthermore the number of the particles reaching higher thicknesses decreases with the thickness. Fewer particles mean less deposited dose.

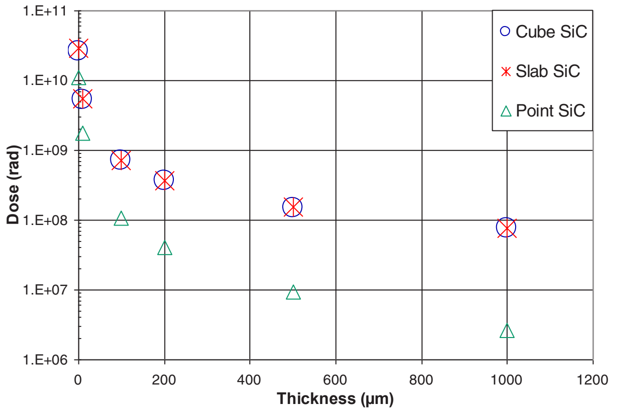

Fig. 9. Dose evolution according to the volume detector thickness and point detector location for SiC.

B. *Study on detector shape*

Two effects appear when considering detector shape depending whether the compared detectors are both volume or volume and point.

Comparison between volume detectors

As presented in Table VIII, no difference exists between the doses calculated using slab and cube volumes except at surface with a higher dose deposition for slabs compared to the one for cubes. This difference can reach 36% for the JUICE environment.

TABLE VIII
RESULTS FOR VOLUME DETECTORS (SLAB/CUBE)

	Electrons			Protons		
Size/Depth	SiC	Zerodur	NBk7	SiC	Zerodur	NBk7
1µm	36%	35%	30%			
10 µm						
100 µm						
200µm						
500 µm						
1 mm						

As observed in the previous part, the dose deposition is higher at the surface. The small size of the 1µm cube prevents again electrons to fully interact, and thus to deposit dose in the detector. This effect disappears when considering thicker volumes.

Comparison between point and volume detectors

Huge differences exist between the doses calculated using point and volume detectors with a lower value for the point.

In order to compare doses obtained with a point and a volume shape, the point was located at the center of the volume. Because of to the steep gradient according to the thickness, the largest part of the dose in a volume is deposited in the area closer to the surface. Thus the dose level calculated at the center of the volume with the point detector is smaller than the mean dose deposited in the equivalent volume. These differences increase when considering thicker volumes and deeper locations.

TABLE IX
RESULTS CONSIDERING POINT DETECTOR

	Electrons		Protons	
Size/Depth	Cube / Point	Slab / Point	Cube / Point	Slab / Point
1µm	142%	164%		21%
10 µm	193%	203%	69%	70%
100 µm	555%	561%	101%	101%
200µm	794%	785%	130%	128%
500 µm	1478%	1528%	158%	161%
1 mm	2805%	2840%	182%	189%

Observations

The dose calculation results are strongly dependent on the dimensions of the volume detector. Thus choosing a point detector could be the solution to get rid of this size dependence. Nevertheless, the dose calculated for a detector point located at the center of a volume may be very different from the average dose deposited in this same volume.

VI. CONCLUSION

Comparative studies on the detector type have been carried out for TID calculation on electronic devices using the FASTRAD Reverse Monte Carlo tool. It included volume detectors, cubes and slabs, inserted at the center of the silicon die surface, and point detectors set at corresponding locations. Different geometrical models were considered from the simplest to the most realistic ones to represent the shielding provided by the satellite platform, the unit structure, and the device packages.

General impact trends emerged considering as well the impact of detector size/location as the detector type for electronic devices.

No significant discrepancy can be observed when considering a proton environment.

Taking into account electron environments, the doses decrease when the dimension, for volume detectors, or the depth, for point detectors increases. Furthermore the discrepancies between the different detector types decrease in function of the increase of the detector size or depth for point detectors. The doses deposited in cube detectors are the smallest whereas they are equivalent between slab and point detectors.

To sum up, the TID calculated using point detectors is representative of the TID received in the corresponding volumes as their doses are either equivalent or lower.

Considering materials, a steep gradient appears with the depth. Moreover, results for the slab and cube are identical except at the surface whereas results for point detectors located at the center of these volumes are much lower. Therefore a special attention must be paid to the choice of the detector type when performing a dose profile calculation for external materials.

TID is not equivalent at a certain location and in the volume surrounding it. This fact is especially true close to the surface but the difference should be smaller when considering higher thicknesses as the dose gradient flattens with the crossed thickness. This could be investigated in a next study focusing on comparisons between TID calculated at a certain location and in a small volume surrounding it.

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