Six-Faces Induced Margins on Dose Calculation and Proposal for a New Satellite Geometry Exchange method

Athina Varotsou, Pierre Pourrouquet, Rémi Benacquista, Renaud Mangeret, Lee Pater, Giovanni Santin, Hugh Evans, Denis Standarovski, Robert Ecoffet

***Abstract*—Very often the satellite platform geometry as well as the equipment one are confidential and cannot be shared between partners in a space project. In order to perform radiation analysis at electronic component level, the 6-faces method is commonly used for geometry information exchange between primes and subcontractors. However, this method is known to be quite conservative. In the frame of the ESA funded project GTREFF the margins induced by the use of the 6-faces method were identified and analyzed for a typical geostationary mission. Following this, a new method was proposed and studied in the frame of a CNES funded project, with promising results.**

***Index Terms*—6-faces, FASTRAD, satellite geometry, Ray Tracing**

I. Introduction

In the frame of the Radiation Hardness Assurance (RHA) process for a space mission, calculations of Total Ionizing Dose (TID) received at component level are performed using 3D Ray Tracing or Monte Carlo analysis. Satellite and equipment 3D mechanical models are imported in dedicated radiation analysis tools and simplified in order to gain computation time while staying conservative. The platform is modelled by the prime contractor describing the shielding provided by the satellite panels, heat pipes, antennas, and other electronic units. At electronic equipment level, the subcontractor model includes the main elements providing radiation shielding: the mechanical structure, PCB and electronic part packages. In order to complete the RHA process at equipment level, the complete information on the shielding geometry around the equipment is needed. However, in many cases this information is confidential: the platform 3D model cannot be communicated to the equipment manufacturer. The 6-faces (6F) method was conceived to facilitate the geometry information exchange between prime and subcontractor while preserving confidentiality. It is a simplified representation of the shielding provided by the other elements of the satellite, expressed as equivalent Aluminum thickness on the six faces of a box.

Although the 6F method is very practical and safely conservative, it is known to often provide too high dose estimates. The goal of the GTREFF ESA project was to quantify this conservatism and explain it in order to propose solutions for optimizing shielding and budget for geostationary (GEO) missions. This project initiated the investigation on potential alternative methods. GTREFF stands for “GEO Telecoms Radiation Tools Efficiency Improvement with Methods and Geometry Exchanges for Industrial Tools” [1]. The project was initiated in 2014 under ESA funding by a consortium led by TRAD with partners: Kallisto Consultancy, RadMod Research, Airbus Defence and Space (ADS) and Thales Alenia Space (TAS).

Following this initiative, a CNES funded study started with the goal to investigate on an alternative method for geometry information exchange between space industry actors.

In this paper, first the 6F method is presented in detail in section II and then results of the margin assessment and relative analysis are presented in section III. The new method is presented in section IV.

II. Current Geometry Exchange Process: 6 Faces method

The 6F method is based on the conversion of the satellite complex shielding distribution into a representative hollow box with variable face thicknesses. It requires the creation of a representative 3D radiation model, based on the satellite mechanical model, as well as the dose depth curve corresponding to the mission environment. The 6F thickness calculation process is detailed in Figure 1.

The first part of the analysis is the calculation of the equivalent shielding thickness in all directions around the equipment. For this, a point detector is inserted at the center of the equipment and then the equipment is removed from the model in order to consider only the shielding provided by the

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satellite and other units around. A Ray Tracing analysis is performed on this detector to obtain the sector file, containing the equivalent Aluminum shielding thickness for each direction.

The second part of the analysis is the post-processing of this sector file into an equivalent 6F box. In addition to the dose depth curve, the dimensions of the box must be defined. The most commonly used assumptions are: a large cube of 1 or 2 meters width or a box closely surrounding the equipment. For each box face, the post-processing tool averages the dose due to all directions crossing it. This dose is then converted into an equivalent Aluminum thickness based on the dose-depth curve. This thickness is assigned to the studied box face.

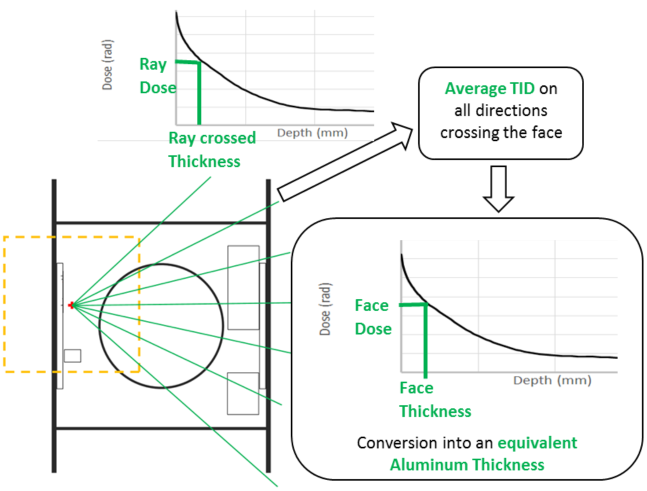

Figure 1. Thickness calculation process for one 6F box face. The 6F box dimensions and location are represented by the dashed box in the left part.

The above analysis is performed at platform manufacturer level. For the final radiation analysis, the detailed model of the unit under study is placed by the equipment manufacturer inside the provided 6F box, in order to consider the shielding provided by all the other elements of the satellite.

III. GTREFF ESA Project: Margins Assessment

One of the main parts of the work performed during the GTREFF ESA project was dedicated to the quantification of the TID calculation conservatism based on a 6F description of the satellite shielding. TRAD was responsible for this part of the work, performing the calculations and analyzing results.

A. Satellite and equipment 3D radiation models

The two Large Satellite Integrators (LSI) partners, ADS and TAS, provided realistic FASTRAD [2] radiation models on which to perform the analysis (Figure 2):

- GEO satellite models containing structure panels, tanks, thermal control elements and representative equipment represented by hollow Aluminum boxes.
- equipment models made of external and internal structure, PCBs and electronic components. The latter are also modelled in detail, including a die with a point detector, where the calculation will be performed, and a package (Figure 3).

The cases defined for the study are presented in Table 1. In total, 311 targets (point detectors inside electronic components) were studied in three different equipment and two different platforms. In order to study a variety of different shielding configurations we placed the equipment units at different positions in the spacecraft. Figure 4 presents the different shielding configurations related to the platform only, at each equipment position, with a zoom performed at low thicknesses (where the majority of the dose comes from based on the dose-depth curve). The figure shows the cumulative sector number as a function of shielding thickness, i.e. the number for sectors with a thickness less than the corresponding thickness value. This can be directly obtained from the sector file produced from the center of each equipment without considering the equipment.

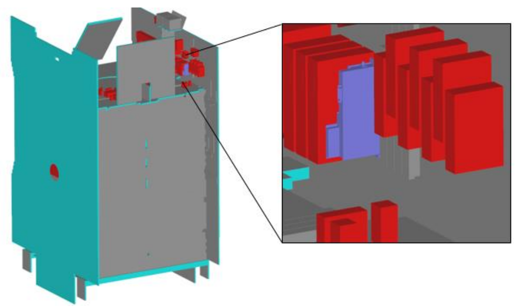
Figure 2. Example of a complete satellite and equipment radiation model used for the study (CASE 1). All models are made with FASTRAD. The MLI is not displayed.

The shielding distribution related to each unit is shown in Figure 5 for a couple of positions in each case. In order to obtain this, the satellite platform has been removed from the model. The two positions shown for each equipment represent the two extremes: one that sees very thin shielding and one that sees only higher thickness shielding.

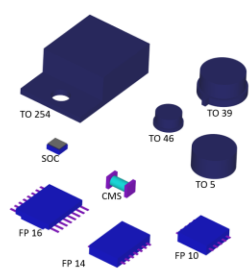

Figure 3. Examples of electronic component package models used for the study (FASTRAD).

As it can be seen, the thickness distribution can be very different between different equipment but also inside one equipment between one position and another.

TABLE I
Study Cases

CASE N°	Satellite model	Equipment model
1	A	A
2	B	B
3	B	C
4	B	A
5	B	C

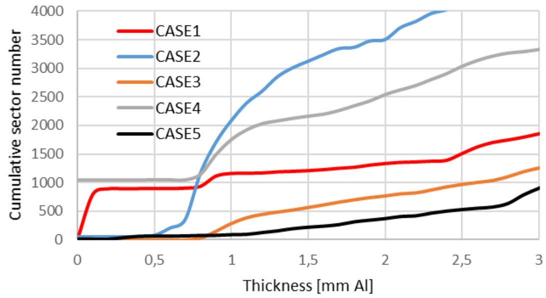

Figure 4. Shielding configurations (zoomed-in for <3 mm equiv. Aluminum) related to the platform, depending on the position of each equipment inside the satellite. Each point corresponds to the total number of sectors with thicknesses less than a certain thickness value.

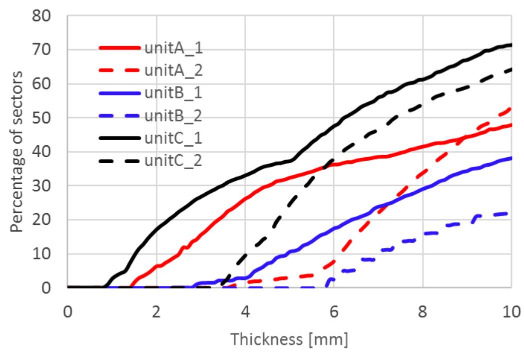

Figure 5. Shielding configurations (zoomed-in for <10 mm equiv. Aluminum) related to each unit and to the position inside them.

B. GEO radiation environment

The radiation environment is represented by a dose depth curve considering the average trapped electrons and the solar protons fluences encountered for a GEO mission. This curve was obtained with the SHIELDOSE-2 [3] model for a solid sphere geometry using the OMERE tool [4]. The dose transmitted through Aluminum shielding is calculated considering electrons, protons and Bremsstrahlung photons.

C. Calculation method and tools

FASTRAD v3.8 was used for all TID calculations in this project. It includes the Ray Tracing method as well as 6F post processing tools. The Ray Tracing calculations were performed using 7200 sectors and the slant method, combined with the solid sphere dose-depth curve described above. Several other post-processing tools of FASTRAD were used in order to analyze calculation results and the script module of FASTRAD was used in order to treat the large amount of calculations and outputs in an efficient way.

The Reverse Monte Carlo (RMC) method of FASTRAD was not used for the 6F margin assessment presented here, however it was used in the frame of the GTREFF project for studying the Ray Tracing/RMC ratio for various shielding configurations, with results presented in [5].

D. Margins analysis

In order to quantify the conservatism of the 6F method, Ray Tracing calculations have been performed on two models for each CASE presented in Table 1:

- the complete satellite and equipment radiation model (results are referenced as *RT* in the graphs and following text),
- the complete equipment model placed inside the 6F Aluminum box (results are referenced as *6F*).

A comparison was performed between the two TID results for each studied CASE and is presented hereunder as a *6F/RT* ratio.

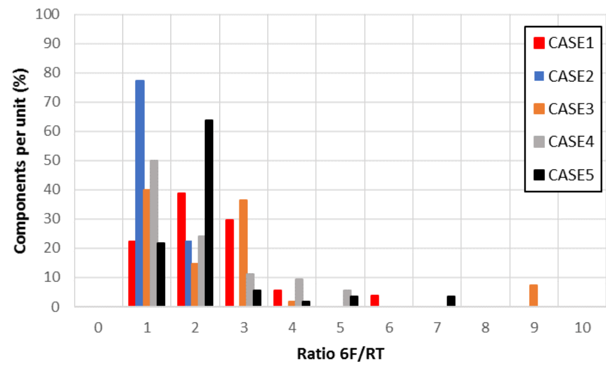

Figure 6. Percentage of components for a specific *6F/RT* TID ratio, obtained for all 5 CASES.

Figure 6 shows the percentage of detectors for a specific *6F/RT* ratio obtained, for each studied CASE. First of all, we conclude that the conservatism of the 6F method is confirmed: all ratios are higher than 1. In fact, ratios can be high, going up to a factor of 10 between the 6F analysis TID and the full spacecraft analysis TID. It can be noted that the majority of results (93%) gives 1 < *6F/RT* < 4 and that only 1% of the ratios exceed a factor of 7. As the same (Ray-Tracing) method was used for both calculations, the dose discrepancies are only due to the shielding representation around the equipment.

Results are presented in Figure 7, as a function of the dose obtained by Ray Tracing using the full satellite model, and in Table 2.

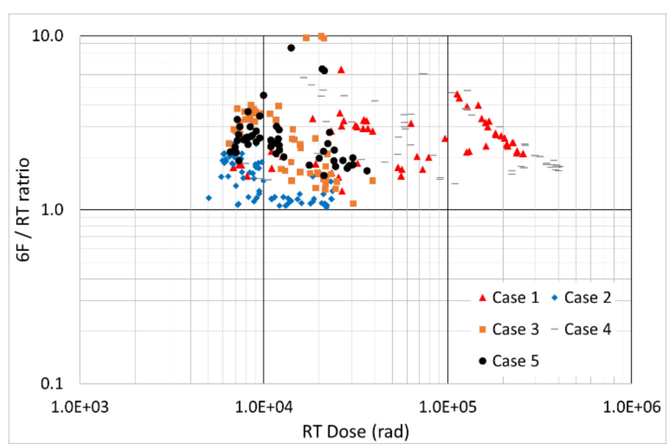

Figure 7. TID 6F/RT ratio as a function of the dose calculated using the detailed spacecraft model.

TABLE II
6F/RT RATIO RESULTS

CASE N°	Dose range (krad)	6F/RT ratio range
1	7 – 258	1.3 – 6.4
2	5 – 24	1.0 - 2.4
3	7 – 39	1.1 – 9.9
4	8 – 420	1.4 – 6
5	7 – 35	1.5 – 7.2

As it can be seen, the *6F/RT* TID ratio does not depend on the position inside the spacecraft, nor on the dose level. However, we observe that the ratios calculated for CASE 2 are low, between 1.0 and 2.4, for dose levels received at component level ranging between 5 and 24 krad (very similar to the dose levels of CASE 3 and 5, but CASE 3 and 5 present a wider range of 6F/RT ratios). In fact, equipment B, used in CASE 2, is bigger and provides more shielding to its electronics than the other two equipment. This can be seen in Figure 5, where we observe that the minimum thickness crossed inside Unit B is 2.4 mm equiv. Aluminum (and this value can be as high as 5.9 mm for some components), while for Unit A it is 1.5 mm and for Unit C it is 0.9 mm. In this case, when the equipment provides significant shielding, the shielding configuration at spacecraft level has a lower impact on the calculated dose and by consequence there is a better agreement between the *6F* and *RT* results.

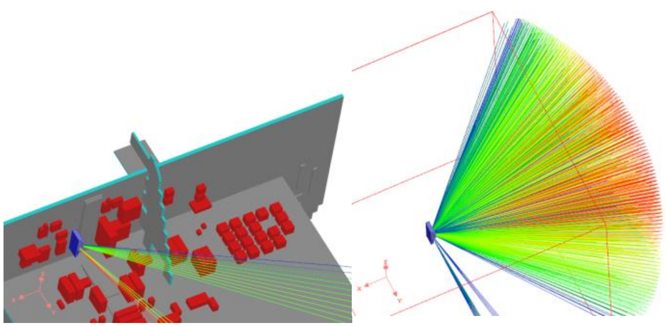

Figure 8. FASTRAD post-processing tool showing sectors crossing thicknesses lower than 3 mm equivalent Aluminum for one component in CASE 4: on the left side when performing the TID calculation using the detailed equipment and satellite model and on the right side when using the detailed equipment model inside the 6F box.

In order to understand why, in some cases, we obtain high *6F/RT* ratios of the TID, we have used the post-processing tools of FASTRAD. We present here an example of detailed analysis. Figure 8 shows the sectors crossing equivalent Aluminum thicknesses lower than 3 mm for a component of CASE 4 for which the TID ratio is equal to *6F/RT* ≈ 6. On the left side of the figure, results are shown when using the detailed equipment and satellite model and on the right side, results are shown using the detailed equipment model inside the 6F box. As it can be seen, there are many more rays crossing thicknesses less than 3 mm in the second case than in the first: it represents 15% of the rays in the case of the 6F analysis and 0.2% of the rays in the case of the detailed spacecraft geometry analysis. As the received dose at component level is primarily due to the low shielding thicknesses (based on the dose-depth curve), the dose calculated with the 6F method will be higher.

Although we can demonstrate the reason of the very high conservatism obtained with the 6F method, we conclude that it is very difficult to predict these cases. The result will depend, for a specific target/position, on the combination of the shielding provided by the equipment and the shielding provided by the platform. In addition, when performing a 6F analysis, the equivalent Aluminum box representing the shielding provided by the platform is defined with respect to the center of the equipment. However, in reality, components are placed on PCBs at different distances from the center of the equipment. This can lead to important differences with respect to the thicknesses crossed in the Ray Tracing analysis.

IV. N-Sector CNES Project: New Geometry Exchange Method

As seen in the previous section, the 6F method can induce important margins in the RHA process. With support from the CNES, a study based on a new idea for a geometry exchange method started in 2017. In agreement with ADS and TAS, the same radiation models as for the GTREFF project were used to test and validate the new method. All developments were made in FASTRAD.

A. *New method principle*

The new method is based on the sector file from the RT method, obtained as described in the first part of the 6-Faces analysis (section II). It corresponds to the shielding provided by all the satellite elements to the equipment. This sector file would be created by the satellite manufacturer and provided to the equipment manufacturer, instead of the 6F hollow box. Then, for the TID calculation at equipment level, the Ray-Tracing calculation is carried out considering the detailed equipment model, and the provided sector file representing the platform. The new proposed method, named N-sector, for combining these two is shown in Figure 9. For each direction *i*, the shielding thickness due to the equipment model is summed to the average value of the thicknesses of a given number *N* of sectors of the provided sector file. The considered sectors are the closest to the direction *i* in the satellite reference frame.

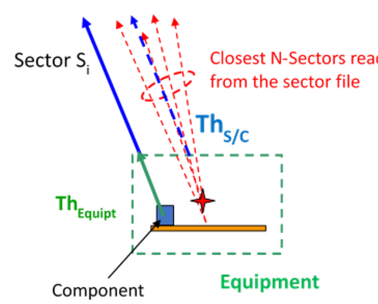

Figure 9. Illustration of the new N-sector method.

It is practically impossible to identify the satellite geometry via the sector file that needs to be provided as input to the analysis at equipment level. However, in order to guarantee confidentiality, the sector file can be crypted or be provided in binary format.

B. Results and analysis

The number *N* of sectors used for each direction has an impact on the calculation results. Different values of *N* were studied in order to define the optimal value for this parameter. Here we will focus on the results obtained for $N = 100$, which gives promising results. It must be noted that the optimal *N* value will probably depend on the total number of sectors used for the sector analysis at prime level. For this study, 7200 sectors were used.

Figure 10 shows the percentage of detectors, for each studied CASE, that give a specific *N-sector/RT* TID ratio, in a similar way as for the *6F/RT* ratio in Figure 6. The *N-sector* TID values correspond to the N-sector method results, with $N = 100$.

We observe that for all components the *N-sector/RT* ratio remains above 1, satisfying the industry's criterion of a worst-case approach. However, it stays closer to 1 compared to the *6F/RT* one, meaning that it is more precise. In fact, the high factors of 10 on the calculated TID, obtained when using the 6F method instead of the detailed satellite model, are decreased to a factor of 5 when using the N-sector method. In general, we observe that *N-sector/RT* < 3 for 99% of the components.

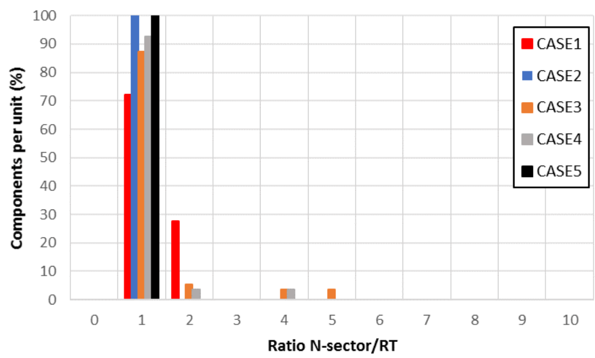

Figure 10. Percentage of components for a specific *N-sector/RT* TID ratio, obtained for all 5 CASES, with N = 100.

Table III presents the N-sector/RT ratio range for each studied CASE. Once again, a better precision of the obtained results, compared to the 6F ones (given in Table II), can be observed.

TABLE III
N-sector/RT ratio results (N=100)

CASE N°	N-sector/RT ratio range
1	1.1 – 2.9
2	1.1 – 1.5
3	1.0 – 5.1
4	1.1 – 4.0
5	1.0 – 1.8

V. Conclusion and Perspectives

The 6F method is used today in order to exchange geometry information between satellite and equipment manufacturers while satisfying confidentiality and conservatism criteria.

The 6F analysis at prime level is time-consuming, however it has been well incorporated in the current RHA process. With the goal of reducing costs, the ESA initiated GTREFF study has allowed to show that the dose obtained using the 6F method can be as high as 10 times higher than the one obtained using the detailed satellite model. This kind of difference can lead to changing a selected component versus another one with a higher TID tolerance or adding specific shielding, in both cases increasing costs.

The study showed that there is no clear way of identifying in advance the components for which the 6F conservatism will be too important. The latter depends on a combination of different parameters, such as the shielding distribution of the equipment and of the platform as "seen" from the component's position. Other parameters not studied here will also have an impact, such as the package of the electronic component and its orientation, as well as the orientation of the equipment inside the satellite.

A new geometry model exchange method is proposed through a CNES supported study with promising first results. Indeed, the N-sector method results are more precise compared to the 6F method ones, while satisfying industrial conservatism and confidentiality criteria.

In order to perform additional validation of the N-sector method, a follow-on study is currently being performed. A larger number of studied cases is used and a prototype module is being developed in FASTRAD with the goal to optimize the process at industrial level. These results will be presented in a future publication.

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References

[1] A. Varotsou et al., "GEO Telecoms Radiation Tools Efficiency Improvement with Methods and Geometry Exchanges for Industrial Tools", presented at the TEC-EES Final Presentation Days, ESTEC, Noordwjik, Netherlands, October 2016.
[2] FASTRAD® software: http://www.fastrad.net.
[3] Stephen M. Meltzer, "Electron, Electron-Bremmstrahlung and Proton Depth-Dose Data for Space Shielding Applications", IEEE Trans. Nucl. Sci. NS-26, 4896 (1979)
[4] OMERE software: http://www.trad.fr/en/space/omere-software/
[5] R. Benacquista, P. Pourrouquet, A. Varotsou, R. Mangeret, C. Barillot, G. Santin and, H. Evans, "Comparison of Ray-Tracing and Reverse Monte-Carlo Methods: Application to GEO Orbit", submitted for presentation at Radiation and its Effects on Components and Systems – RADECS, Montpellier, France, Sept. 2019.