Sectoring Methods for High Energy Proton Shielding Calculation on Satellite Structure

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ABSTRACT

Two approximate calculation models for a cosmic radiation shielding in low earth orbit satellite are compared with detailed 3-dimensional calculation results. One is a sectoring method and the other is a chord-length distribution method. Shielding calculation is performed for a RADFET device of KITSAT-1 under the assumed environment at SAA(South Atlantic Anomaly) location with AP-8 radiation spectrum model. Both approximate models showed good agreements with 3-dimensional detailed Monte Carlo calculation in two dose detector locations.

1. INTRODUCTION

Semi-conductor devices installed in space satellites are the key devices that limit the lifetime and performance of space mission. However, those are very susceptible to cosmic radiation effect. Risks of faults and failures are especially high with state-of-the-art commercial integrated circuit devices. Therefore, high-energy cosmic radiation shielding calculation is the starting point of satellite configuration design procedure and risk estimation. Proton and associated secondary particles are the major sources for shielding calculation in the LEO(Low Earth Orbit) mission. MCNP-X and LCS(Lahet Code System) are available for this problem of proton transport calculation. These code systems, however, have some limitations for the space applications. Radiation source environments are extremely variable to the satellite location on the orbit. Sensitivity of devices to faults is high depending on the geometric configuration and associated energy attenuation. In this study, effectiveness of approximate models – sectoring method and chord-length method are evaluated and compared with detailed Monte-Carlo calculation methods.

2. SPACE RADIATION ENVIRONMENT

In LEO, radiation environments is comprised energetic protons up to several hundreds MeV together with electrons up to several MeV. The standard models of the trapped protons and electrons, still used in these days, are AP-8 and AE-8 published by the NASA/National Space Science Data Center from data obtained during past several tens years. AP(E)-8 model is generally used to analyze for radiation environment of LEO satellite. In this study, shielding calculation is performed for KITSAT-1 which has the orbit parameter in Table 1. Radiation source spectrum changes continuously along the satellite orbit trajectories, in a real situation, but the highest source level location at SAA(South Atlantic Anomaly, altitude : 1306 km) is assumed to be kept with AP-8 model radiation spectrum for this benchmark calculation study.

Table 1. Orbit parameters for KITSAT-1

Orbit parameter	
Perigee Height (km)	1306.1
Apogee Height (km)	1326
Inclination (degree)	66.08
Size (mm)	352 × 356 × 670
Weight (kg)	48.7

3. SATELLITE MODELING FOR SHIELDING CALCULATION

KITSAT-1 has the complex structure with stack structures of PCB(printed circuit board) on aluminum and epoxy package plates as shown in Figure 1. There are two TID(Total Ionizing Dose) detecting devices – RADFET-1 and RADFET-3 at DSPE/CRE stack. RADFET-1 is located near the boundary surface and RADFET-3 is at the center of the stack. The purpose of this study is to measure the effectiveness of approximate methods. Therefore, As shown in Fig.2, a simple ideal structure of KITSAT-1 is modeled with homogeneous material slab of different thickness. The structured materials are assumed to be aluminum and epoxy only. Calculations are done for two locations of total dose measurements, RADFET-1 and RADFET-3.

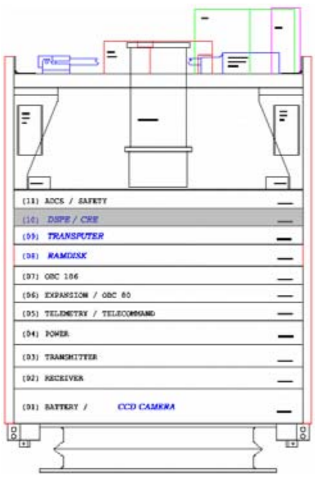


Figure 1. Configuration of KITSAT-1 satellite

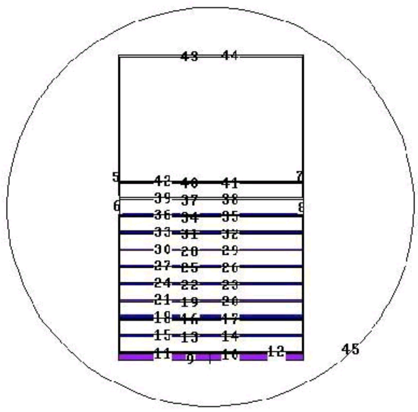


Figure 2. A calculation model of KITSAT-1

4. CALCULATION MODEL

The shielding calculation for KITSAT-1 is performed by two approximate models. Each calculation results are compared with the result of 3-D detailed calculation with Monte Carlo code. The followings are description of two approximate models and results of 3-D Monte Carlo calculation.

4.1. APPROXIMATE MODEL

Approximate model is used as an alternative method to up-to-date detailed Monte-Carlo methods.

Complex structure of satellite is modeled into multiple regions which are approximated as an one dimensional slabs. In this study, sectoring method and chord-length method are used as approximate model. There are two key points of using approximate model. The one is determination of slab thickness and the other is calculation of dose-depth curve.

4.1.1. Sectoring Method

In sectoring method, a proton particle is assumed to be travel as an incident ray to a point of interest from the boundary surface locations on divided angle sectors as shown in Fig 3. The thickness of shield in each angular sector is evaluated as a penetrating beam depth along the track direction. The areal fraction of each sector surface on the source sphere is used as normalization factor when dose-rate is calculated. The followings are the calculation steps used in sectoring method.

① Define the geometry of structure within a calculation boundary sphere. Locate all the material structures to be included in the calculation in a convenient co-ordinate system.
② Divide a solid sphere around the point of interest into sectors.
③ Calculate the average thickness of material in each sector. If different materials included in the calculation, use areal density or convert to the equivalent thickness of some standard material(aluminum).
④ Use the dose-depth curve to calculate the dose through the thickness of material for each sector and multiply each by normalization factor associated with each sector.
⑤ Sum the result from each sector to get the total dose estimate for the point of interest by using Eq.1.

$$\dot{D} = \sum_{i=1}^{N} [\dot{D}(t_i) \times (A.F.)_i] \qquad (1)$$

where $\dot{D}$ = total dose rate
i = number of sector
A.F. = areal fraction of sector surface on source sphere

Fig. 4 shows the calculated aluminum shield thickness for each sector in case that number of sector is 26. Thickness for RADFET-3 is larger than for RADFET-1 because of their location in satellite.

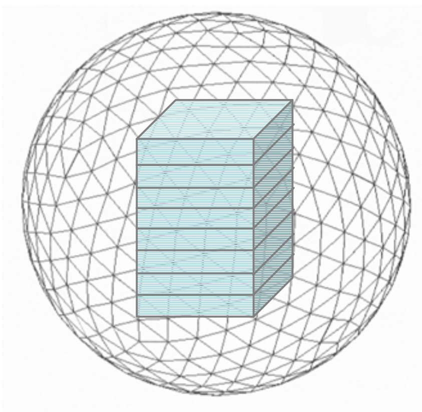


Figure 3. Model for angular sector division in sectoring method

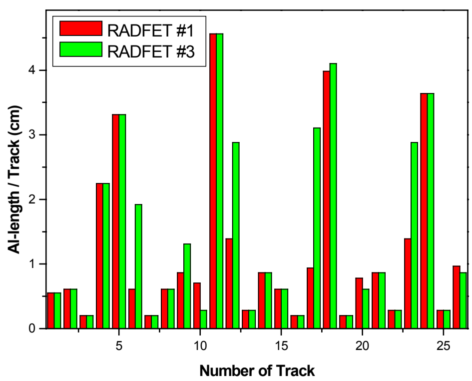


Figure 4. Thickness of aluminum for each sector

4.1.2. Chord-length Method

In chord-length method, a position of proton generated on source surface is selected arbitrarily by random selection, and chord-length distribution is estimated by calculating the thickness of shield to RADFETs from each source location. Fig.5 shows the chord-length distribution of RADFET-1 and RADFET-3 using 2,000 times random number generation to select source position and 150 thickness group(0.0 mm – 167.0 mm). The probability distribution of each chord-length is used as normalization factor when dose-rate is calculated. The followings are the calculation steps used in chord-length method.

① Define the geometry of structure within a calculation boundary sphere. Locate all the material structures to be included in the calculation in a convenient co-ordinate system.
② Determine the locations of incident beam on source surface by using random number sampling.
③ Calculate penetrating depth of shield to target. If different materials included in the calculation, use areal density or convert to the equivalent thickness of some standard material.
④ Estimate chord-length distribution for designated thickness group.
⑤ Use the dose-depth curve to calculate the dose through the thickness of material for each chord-length and multiply each by normalization factor associated with each chord-length.
⑥ Sum the result from each chord-length to get the total dose estimate for the point of interest by using Eq.2.

$$\dot{D} = \sum_{i=1}^{N} [\dot{D}(t_i) \times (probability)_i] \tag{2}$$

where $\dot{D}$ = total dose rate
i = number of thickness group
Probability = probability distribution of chord-length

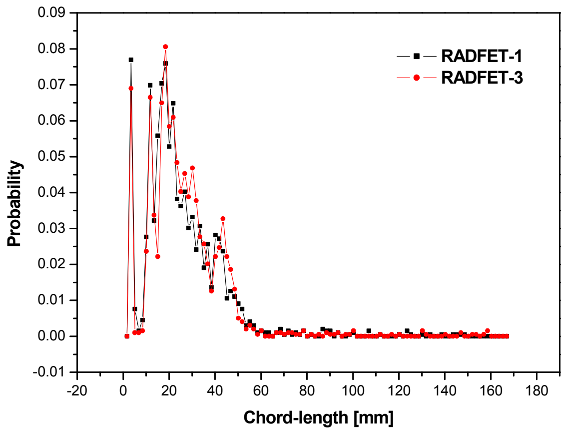


Figure 5. Chord-length distribution of RADFET-1 and RADFET-3

4.1.3. Dose-depth Curve Calculation

In order to use the above approximate methods, dose-depth curve should be calculated in advance. Fig.6 shows the proton spectrum obtained from AP-8 model at SAA. The proton flux behind the thickness of reference material(aluminum) can be calculated by MCNP-X, LAHET and CHARGE, and the dose-depth curve can be obtained from Eq.3. The calculated results from MCNP-X and LAHET are almost same. However, CHARGE underestimated dose than the others upto 10 cm thickness aluminum. These differences are caused from calculation method and applied dose conversion factor(DCF). DCF table was extracted from ICRU Report 49, in case of MCNP-X and LAHET. The transport equation for charged particle is used in MCNP-X and LAHET code, but the simplified attenuation equation model as shown in Eq.5 is used in CHARGE code. In this study, the dose-depth curve calculated by MCNP-X is applied to both approximate models.

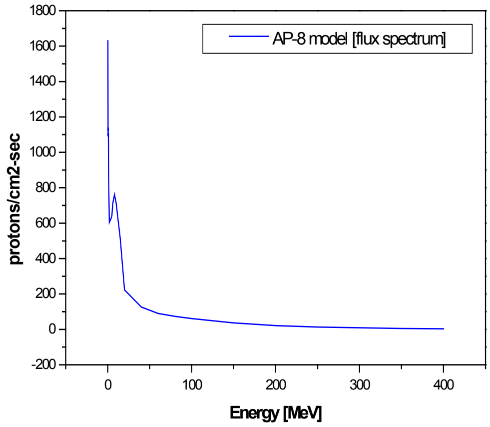


Fig 6. Proton spectrum of KITSAT-1 orbit at SAA location

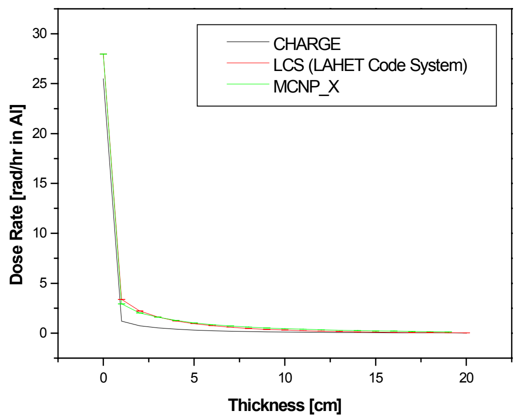


Fig 7. Dose-depth curves for aluminum from SAA spectrum environment

$$\dot{D}(x) = \int_0^{E_{\max}} [(\mu_a / \rho)(E) \times E \times \Phi(x,E)]\, dE \tag{3}$$

where μ_a / ρ : mass attenuation coefficient of shield material
$\Phi(x,E)$: proton flux behind the thickness X

$$\begin{aligned} \Omega \cdot \nabla \Phi_j(r,\Omega,E) - \frac{\partial}{\partial E}[S_j(E)\Phi_j(r,\Omega,E)] + \sigma_j(E)\Phi_j(r,\Omega,E) \\ = \int \sum_k \sigma_{jk}(\Omega,\Omega',E,E')\Phi_k(r',\Omega',E')\, d\Omega' dE' \end{aligned} \tag{4}$$

where $S_j(E) = \dfrac{4\pi N Z_1^2 Z_2^2 e^4}{mv} \times [\ln(\dfrac{2mv^2}{(1-\beta)^2 \times I_2})]$

$$\Phi(x,E) = \Phi_0(x,E) \times e^{\Sigma_{n.e.}(x,E)\cdot t} \tag{5}$$

where $\Phi_0(x,E)$: incident proton flux
$\Sigma_{n.e.}(x,E)$: proton non-elastic scattering cross section of shield material

4.2. REFERENCE MODEL (MCNP-X)

In this study, 3-dimensional detailed calculation is performed by using MCNP-X that is available to transport analysis for high energy charged particle. Fig.8 shows the proton flux densities at locations of RADFET-1 and RADFET-3. The relative error in Monte Carlo calculation is converged to less than 10 %. The flux at RADFET-3 is lower than flux at RADFET-1, located at the peripheral side, because RADFET-3 is located at the center of the structure. The calculated fluxes are converted to dose with the DCF obtained from ICRU Report 49. The dose rates are 2.188 rad/hr at RADFET-1 and 2.092 rad/hr at RADFET-3. The dose level of RADFET-1 is 4.6 % higher than RADFET-3. In this study, these results from MCNP-X are used as the reference data to compare with the results of approximate methods.

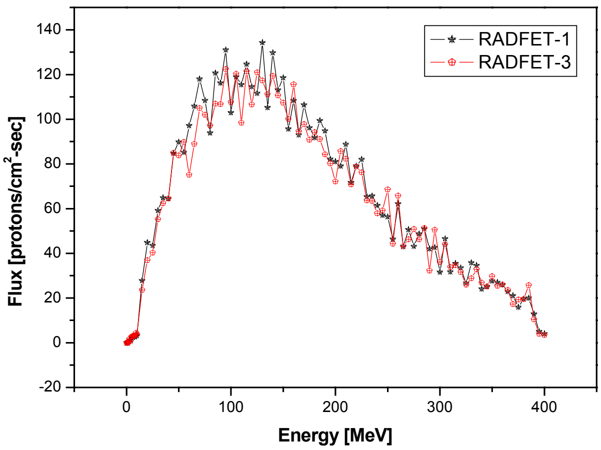
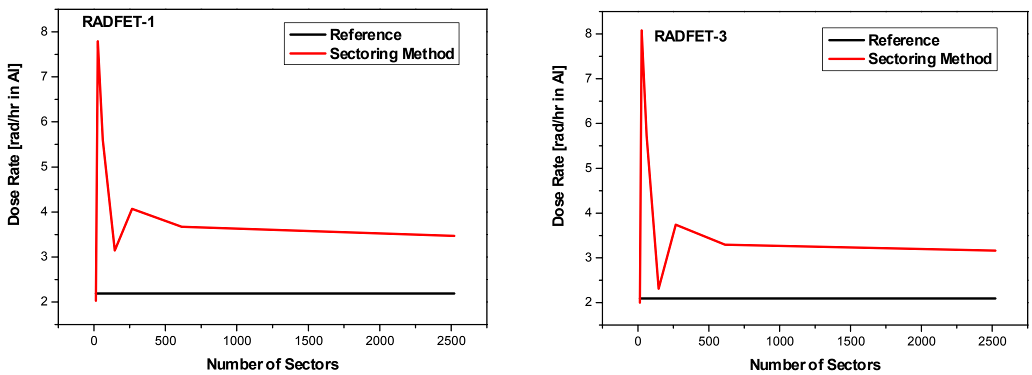


Figure 8. Calculated fluxes at two locations by MCNP-X detailed model

5. RESULTS of SECTORING METHOD

Calculations are repeated from 14 sectors to 2,522 sectors. Dose rates from sectoring method and 3-D detailed calculation are compared in Fig.9. As increasing number of sectors, the result is converged. The location effect of RADFET-1 and RADFET-3 is showed in Table. 2. Considering 95 % confidence level of detailed calculation result, the location effect estimated by sectoring method is well agreed with detailed calculation result effectively.



(a) for RADFET-1 (b) for RADFET-3

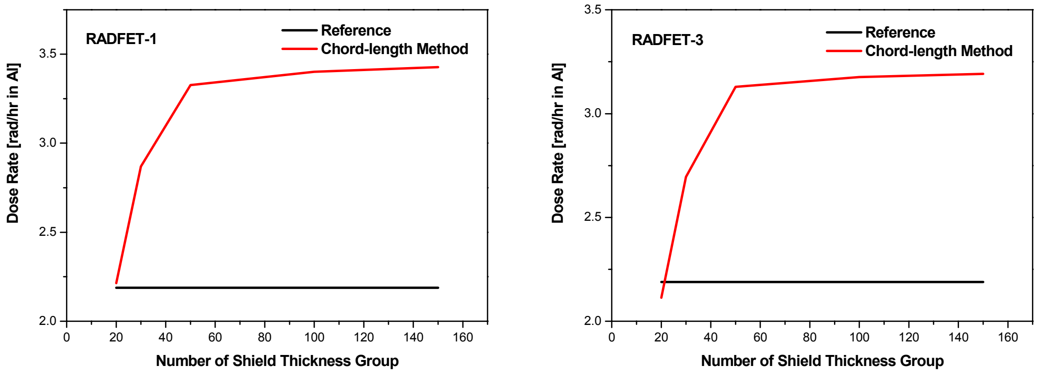
Figure 9. Comparison of results using sectoring method and 3-D detailed model

Table. 2. Dose Calculation Result by Sectoring Method

	at RADFET-1 location	at RADFET-3 location	Relative error between two location
3-D detailed calculation (MCNP-X)	2.188 ± 0.026 rad/hr	2.092 ± 0.025rad/hr	4.6 %
Sectoring Method	3.468 rad/hr	3.163 rad/hr	9.6 %

6. RESULTS of CHORD-LENGTH METHOD

Calculations are performed with various number of incident directions (2,000 – 1,000,000) and shield thickness groups(20, 30, 50, 100 & 150). As presented in Fig.10, the estimated dose rate by chord-length method is affected by the number of thickness group. As increasing number of thickness group, dose rate is converged, but the difference between reference data and the dose rate calculated with chord-length method is rather large. However, as shown in Table 3, the location effect of two RADFETs is consistent with reference model, as it is in sectoring method.



(a) for RADFET-1 (b) for RADFET-3

Figure 10. Comparison of results using chord-length method and detail calculation

Table. 3. Dose Calculation Result by Chord-length Method

	at RADFET-1 location	at RADFET-3 location	Relative error between two location
3-D detailed calculation (MCNP-X)	2.188 ± 0.026 rad/hr	2.092 ± 0.025rad/hr	4.6 %
Chord-length Method (# of incident direction : 1,000,000 # of shield thickness group : 150)	3.427 rad/hr	3.192 rad/hr	7.5 %

Chord-length Method (# of incident direction : 2,000 # of shield thickness group : 150)	3.386 rad/hr	3.093 rad/hr	9.5 %

CONCLUSIONS

In this study, the approximate shielding calculation methods for high-energy proton are developed and the results are compared with 3-D detail model. The proposed two approximate models predicted dose rate higher than MCNP-X with large difference. Error in approximate model seems to be caused by neglecting deflection of incident protons by collision with shield materials. However, the sectoring method and the chord-length method showed good agreements in location dependence with 3-D detailed calculation at two detector locations, and the calculated dose is estimated conservatively.

ACKNOWLEDGEMENTS

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REFERENCES

1. Sung-Joon Kim et al., "Simulation of Shielding Effects on the Total Dose Observed in TDE of KISAT-1," *Journal of Astronomy and Space Sciences*, **Vol.18**, p.71 (2001)
2. Janet Barth, "Modeling Space Radiation Environments," *IEEE NSREC Short Courses*, Colorado, July 21, pp.22 – 48 (1997)
3. James D. Kinnison et al., "Rad Effect in the New Millenium - Old Realities and New Issues," *IEEE NSREC Short Courses*, California, July 20, pp.14 – 16 (1998)
4. James W. Haffner, "*Radiation and Shielding in Space*," Academic Press, New York (1967)