Modeling the Requirements For Radiation Shielding

(How detailed should it be and when should it be done)

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Abstract

This paper examines the use of radiation dose modeling as a tool, like that of mechanical and thermal modeling, for designing spacecraft and electronics packaging. It concludes that dose modeling that uses detailed structural and material information can significantly contribute to designs of spacecraft and electronics packaging (board's location, order, and circuit layout) that minimize spacecraft mass and volume as well as minimizing the need for secondary radiation shielding. The paper opens with a critiquing of traditional equivalent thickness spherical aluminum modeling (ETSAM) of a spacecraft. It then suggests an improved application of ETSAM for the reader who only wants estimate post-design radiation doses. Finally, the paper provides a generic example, using the software tool NOVICE, for how spacecraft structure can be used to reduce the radiation dose experienced by internal electronics. The dose reduction in turn suggests how the mass and volume of the generic spacecraft example can be reduced without increasing radiation exposure.

INTRODUCTION

The need for radiation shielding to protect electronics is too frequently discovered after the spacecraft has been designed and the electronics has been packaged (board's location, order, and circuit layout.) Dynamic/static mechanical and thermal modeling are considered to be key tools for spacecraft design but radiation modeling typically is not. The radiation modeling is instead employed as a diagnostic tool to determine if secondary radiation shielding is necessary. Frequently the radiation modeling is in an overly simplistic form, such as "equivalent thickness spherical aluminum modeling", ETSAM. As will be shown in this paper ETSAM, in its traditional form, is not a satisfactory tool for design and hardly satisfactory as a dose assessment tool. A more advanced application of ETSAM will be discussed that provides a reasonable assessment of post-design radiation dosage. But neither the traditional or the more advanced form of ETSAM is satisfactory as a design tool. There are more sophisticated radiation modeling tools that provide valuable dose assessment information and can, by the degree of their sophistication, support design. This paper uses a generic spacecraft example to demonstrate the capacity of one advanced radiation modeling tool, NOVICE, to contribute to design that reduces dose and provides insight for reduction of the spacecraft's mass and volume without sacrificing radiation protection.

DISCUSSION

Equivalent Thickness Modeling

<u>Traditional</u>

ETSAM represents a spacecraft as an aluminum spherical shell of thickness that supposedly is equal to the shielding capacity of the spacecraft's material mass. Any additional shielding, e.g. local secondary shielding, is represented as a concentric layer of aluminum, where the additional shielding is necessary to reduce the total incident dose at the point of interest. The result is a hollow aluminum sphere, or solid aluminum sphere, for which the annual thickness, or radius, is the sum of the two parts. Figure 1(a) is an example of ETSAM. The 1.2-cm thick aluminum shell is the sum of a concentric 0.254-cm (100-mil) equivalent aluminum representation of a spacecraft and a 0.946-cm aluminum shield necessary to reduce the annual dose at the center, point A, to 1.03 krad(Si) for the 2.35 Grad(Si)/year geosynchronous Earth orbit, GEO, environment.

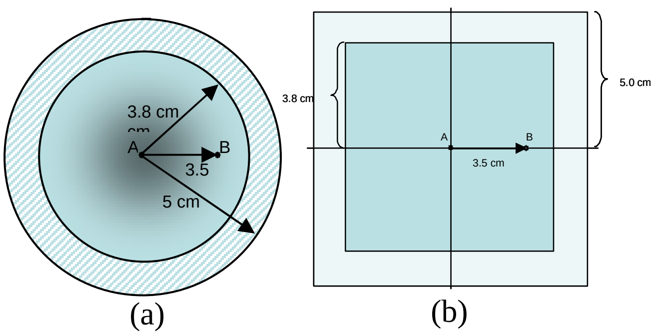

Figure 1. - Cutaway view of equivalent thickness spherical (a) and cubic (b) aluminum representation of a spacecraft and shield.

If the spacecraft is homogenous and spherically shaped, the shielding is concentric, and the point of interest is at its center then the 0.946-cm thickness would be reasonably correct. But if the location within this spherical spacecraft is some other location then the annual dose for this thickness is different. At point B the dose it is 0.71 krad(Si)/yr thus a mass savings can be made by using a smaller thickness of shielding. (The dose is lower at point B because the effective thickness of the shell is larger for a significant portion of the 4Pi solid angle at this point.

But spacecrafts are not typically spherically shaped. Figure 1(b) is a cubic representation of the same spacecraft and shielding. The annual dose at point A is 0.81 krad(Si) and at point B it is 0.64 krad(Si). The dose at point B is again smaller than it is at point A because of the effective larger thickness of the cubic shell. Both doses are less than for the spherical representation's corresponding points. So, it is possible that a reasonable mass savings in shielding may be realized simply if a somewhat faithful representation of the spacecraft is chosen. Thus, ETSAM, as it is commonly employed, is not a good choice for modeling or dose assessment..

There is another fault with using traditional ETSAM. The thickness of the aluminum shield must be converted to that for the actual material used for shielding. This is traditionally accomplished by using the ratio of aluminum's density to that of the material. If the material is tungsten the ratio is 2.7/19.3; the value yields a tungsten thickness of 0.132 cm. But this thickness of tungsten, concentric to the 0.254-cm aluminum representation of the spacecraft, yields an annual dose at point A, Figure 1(a) of 1.43 krad(Si). Thus the ETSAM conversion method underestimates the amount of tungsten shielding that is required. For more advanced material shielding concepts, such as PolyRAD® [1], the dose at point A, Figure 1(a), is 1.33 krad(Si). This dose, although still too large, is smaller than for tungsten because PolyRAD®'s stopping power is larger than tungsten's.

Advanced

The following is a simple example for advanced ETSAM that provides better assessments of dose.

The example is for a location in a cubic spacecraft midway its center and one face, P, see Figure 2. The respective material thicknesses of the eight equal-area faces and the intervening components between the orbital environment and the location are assumed to be T_1, T_2, T_3, T_4, T_5, and T_6 units of equivalent units of aluminum thickness. Approximate values of the solid angles, based on corresponding angles in the X_pY_p-plane, are 4.427, 1.287, 1.713, 1.713, 1.713, and 1.713.

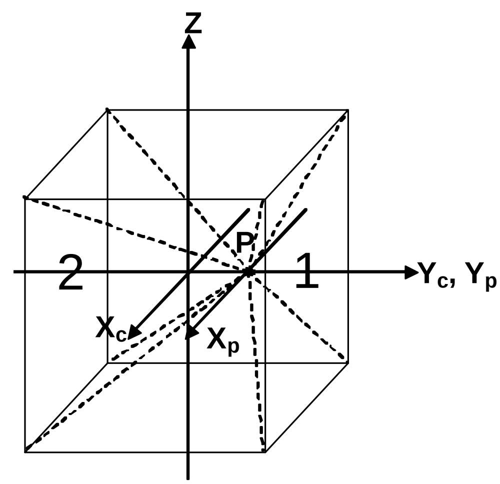

Figure 2. - Cubic spacecraft and point of interest mid-distance the center and face 1.

A more rigorous set of values may be determined using the definition of a solid angle as the area of a unit sphere.

The dose D at the point in Figure 2 is determined as follows. The dose D_i, for each of the six thicknesses, is determined for the center of an aluminum sphere, thickness T_i, using traditional ETSAM. Thus the dose is expressed as the sum of the doses for the six faces of the cube for which each is weighted for its solid angle:

$$D = (4.427 \times D_1 + 1.287 \times D_2 + 1.713 \times D_3 + 1.713 \times D_4 + 1.713 \times D_5 + 1.713 \times D_6)/12.566 .$$

Any secondary shielding, in the form of aluminum, that is required for each solid angle to reduce the dose D_i is determined, as explained in the preceding section of this paper, by adding the shield's thickness to the thickness of the spacecraft's corresponding face. The final step is to determine what the thickness is for the material, for example tungsten, that is used for the secondary shielding. A Stopping Power Correction Factor, SPCF, is required for a reasonably accurate estimate. The following table, for protons and for electrons, provides respective sets of SPCF's that were determined from NIST stopping power tables[2] for four materials.

Table 1. - Stopping Power Correction Factors

Protons				
MeV Range	Ratio of Material's Stopping Power to that of Al			
	Cu/AL	Graphite/Al	W/Al	Kapton/Al
.1 to .5	0.564	1.636	0.315	1.543
.5 to .1	0.675	1.374	0.353	1.394
1 to 10	0.751	1.266	0.455	1.293
10 to 100	0.828	1.172	0.598	1.197
100 to 500	0.864	1.136	0.671	1.168
Electrons				
.01 to .1	0.824	1.190	0.595	1.218
.1 to 1	0.866	1.128	0.701	1.166
1 to 3	0.895	1.066	0.809	1.112
3 to 7	0.946	1.024	0.970	1.065

For the GEO electron environment, 0.254 cm (tungsten) equates to 1.27 cm (aluminum):
1.27 cm (aluminum)0.7 x (19.3/2.7) x .254 cm (tungsten).
The inverse relationship may be used to determine the thickness of a material,e.g. tungsten, from that of aluminum in the first part of this advanced application of ETSAM.

Radiation Modeling for Design

Examples of popular software modeling tools include NOVICE[3], Space Radiation[4], TIGER[5], and SPENVIS[6]. While the latter three are more sophisticated than traditional ETSAM none are as capable of modeling materials and structures as is NOVICE. NOVICE is the radiation modeling tool used for this report.

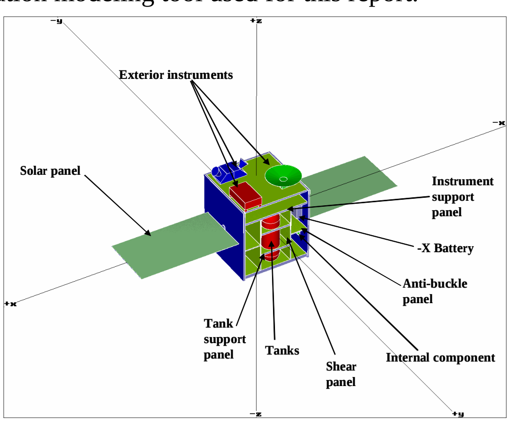

Figure 3. – Aspect view of generic spacecraft as modeled using NOVICE

The Spacecraft

A view of a generic model of a spacecraft, with its +y exterior panel removed, is shown in Figure 3. This model combines aspects of a number of actual spacecraft bus designs that have flown in space. This generic model's structure and components are based on mechanical/thermal design values but are non-specific to any particular design. The panels are aluminum or graphite/epoxy, the batteries are lithium, the solar panels are silicon on structural substrates, the exterior instruments are material correct, the internal components are electronic panels with individual components, and the tanks (there are three aligned in the Y-directions) are hollow, titanium-walled and filled with appropriate fuel and oxidizer.

The dose is modeled at the three locations, as shown in Figure 4: an outside location, to determine the orbital annual dose; an interior location on the instrument panel, where an electronics box for a flight experiment was designated to be placed for one of spacecraft represented by the generic model; and an alternative, non-designated location between a battery and a shear panel which will be considered in this paper as an alternative placement of the electronics box.

The doses for the three locations, for solar maximum and minimum conditions in GEO and MEO environments, are shown in Figure 5. The designated location on the instrument panel is an order of magnitude more than that between the shear panel and battery. (The latter location was never considered during the mechanical and thermal design of the actual spacecrafts which this model embodies even though at the time of their design integrated-use-of-the-structure wss considered to be a desirable advanced design concept.)

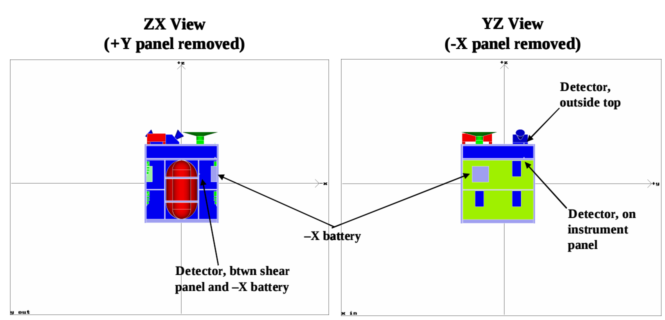

Figure 4. – Detector locations for modeling the dose

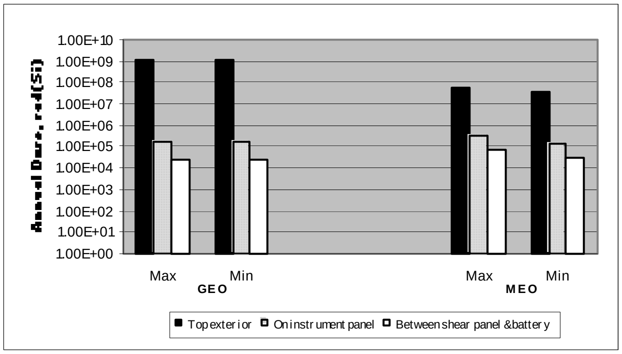

Figure 5. – Dose for three locations of the spacecraft structure

The lower dose at the location between the shear panel and the battery has a larger implication than just a smaller amount of required secondary shielding. It also suggests that the space between the instrument support panel and the top exterior panel can be eliminated thus eliminating that portion of the outside panels. This does not sacrifice the structure's capacity to provide shielding because the paneling that replaces that of the instrument support and top panels will be less in total thickness but provide the same effective shielding thickness. This plus the smaller outer panels are less in mass and volume than the original design. This is particularly important for the GEO missions.

The Experimental Electronics Box

The electronics box used for this paper consists of eight 3-U boards, a half-height I/O board, a backplane board under which are four devices (e.g. dc/dc converters), and enclosure. The box is similar to several that have been used for a flight experiment. The 8 3-U boards are identical; on each is a 6-by-10 array of identical devices as shown in Figure 6a which is an aspect view for which the enclosure has not been included. Each component on the board, as well as the board and the connectors and the D-to-D converters are material correct. Each board could have been a different layout of devices, each device different, but the nature of the results and the discussion

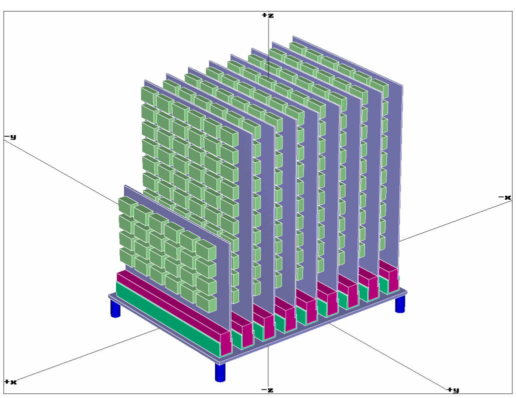

Figure 6a. – Aspect view of modeled experimental electronics box, enclosure removed

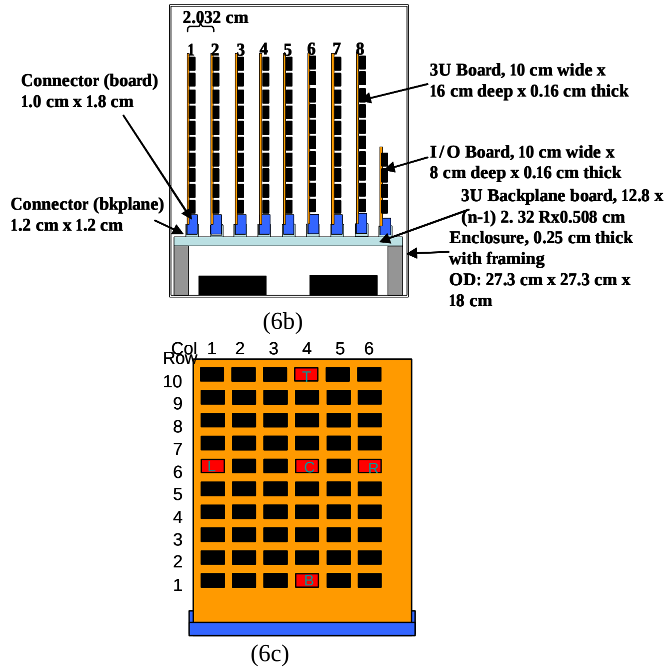

Figure 6b and 6c. – Numbering of eight 3-U boards and dose locations on each board

that follows would have been the same. Figure 6b, a side-view cutaway of the experimental electronics box, defines the numbering of the eight boards. Figure 6c depicts the locations on each board that were selected for dose modeling. The dose is at the center of respective device.

The dose profiles in GEO and MEO for the electronics box and no spacecraft are shown in Figures 7a and 7b. The top of each card receives a larger dose than at its bottom for the same reason that in Figure 1 point A receives a larger dose than does point B. That reason being that the effective thickness of the shielding provided by the backplane and the lower portion of the 3-U boards is larger over a larger solid angle. The dose is smaller for the 4 inner cards, cards 3 – 6. The array of devices on each board is offset to the left, see Figure 6c, so the right side of the array receives less dose. So a small change in the location of a device can contribute to dose reduction. The presence of the I/O card is the reason for why the bottom location on card 8 receives much less dose than its other four locations. Magnitude of the difference of the dose for an inner board and that of an outer board is larger, as is the dose in general, is larger for MEO than for GEO. Thus, the advantage of board location for dose reduction is more significant for MEO. But the ratio of the high dose to low dose implies a somewhat more significant effect of board location for the GEO environment, 17.8 for GEO vs 14.5 for MEO. Which is the more significant depends on the devices in question but for either environment the dose varies an order of magnitude with location.

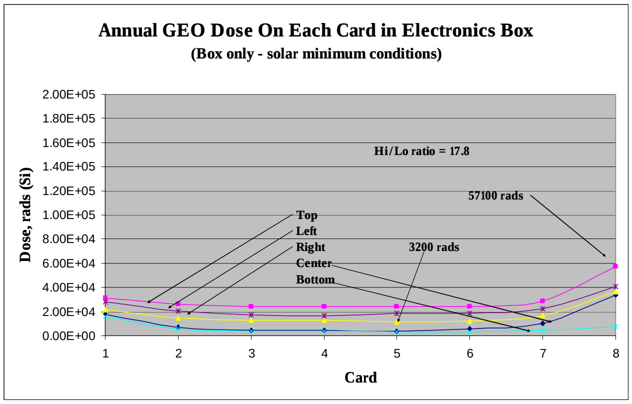

Figure 7a – Annual dose for a GEO environment at each of 5 locations on the 8 cards

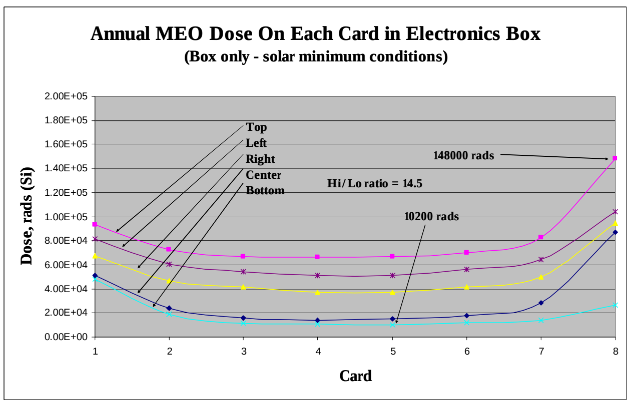

Figure 7b – Annual dose for a MEO environment at each of 5 locations on the 8 cards

Even though the influences of board location and device location on a board may appear obvious, having studied the data in Figures 7, surprisingly few electronic box designs give consideration to the dose when deciding the order of boards on a back plane board or the location of a device on a particular board. The more esoteric aspects, such as using the heights of neighboring devices to reduce the dose at a particular device, have been even less considered. Thus even though dose is considered to be important it seldom influences the design layout of a board or board order's location thus the use of remedial shielding; yet the data in Figures 7a and 7b suggest radiation dose modeling should be included as a design tool.

Combined effects of spacecraft and electronic box

When an electronics box is located inside a spacecraft the magnitudes of dose at the locations within the box are very different and far more complicated. This section of the discussion shows this to be the case and suggests that dose modeling is an important, if not vital, design tool.

As indicated earlier with the introduction of generic spacecraft the instrument support panel, shown in Figure 3, was the designated location for experimental electronics boxes in the spacecrafts represented by the generic design. Figure 8 shows the electronics box located on the support panel. The box is on its side with its base facing outward, towards the YZ-plane exterior panel on the –X side. The corresponding doses for the five locations on each of the eight boards for solar minimum conditions in GEO and in MEO are shown in Figures 9a and 9b. Solar maximum doses are larger but the distributions are the same.

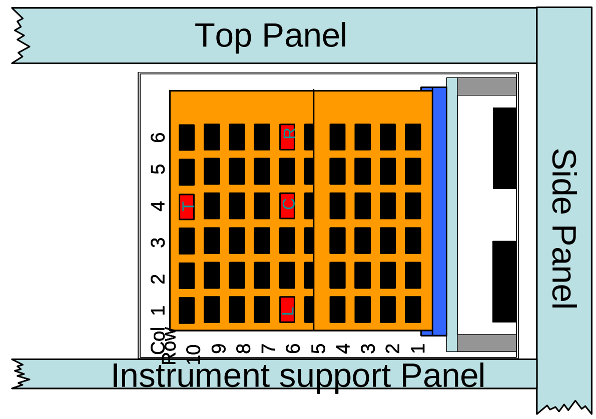

Figure 8. – Mechanically-designed location and orientation of the electronics within the spacecraft

As in the case of just the electronics box, and for the same reasons, the doses at the top are larger than those at the bottom. But with the box on its left side the dose is smaller for that side because of the shielding provided by the underlying structure of the spacecraft. The center is farther from the instrument support panel thus the dose is larger than the left side for the same reasons cited for the discussion of the doses at points A and B in Figure 1.

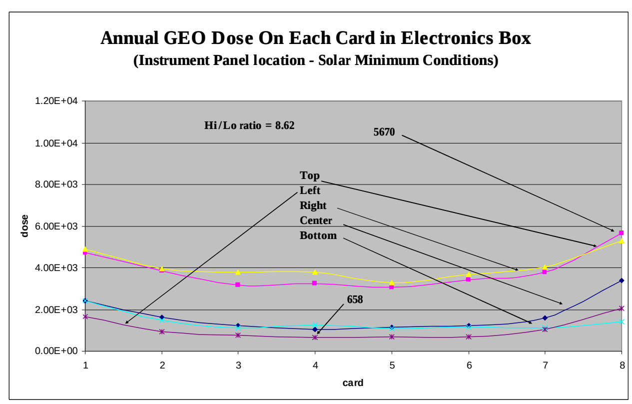

Figure 9a. – GEO dose distribution at five locations, on each of the eight cards, for the box location and orientation shown in Figure 8.

The doses at the top and right are more distinct from the other three locations because the exposure solid angles for the other three are more subtended by the additional shielding provided by the spacecraft's side and underlying structure. The distribution of doses from card 1 to card 8 are the same as for the box alone but with less uptake on the card-8 end because the additional shielding provided by the spacecraft evens out the distribution of the shielding as compared to the box enclosure only. The flatter curve means the location of the more dose-sensitive devices is more flexible.

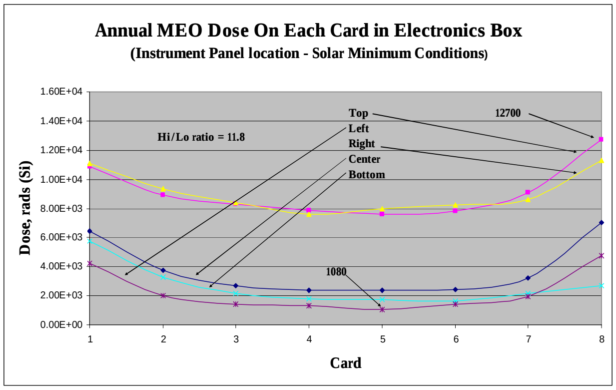

Figure 9b. – MEO dose distribution at five locations, on each of the eight cards, for the box location and orientation shown in Figure 8.

For the actual spacecrafts/missions alternative locations for the experimental electronics box were not considered. Figure 10 shows the instrument box located between the battery and the shear panel. The dose magnitudes, Figures 11a and 11b, for this location are an order of magnitude less than those in Figures 9a and 9b. The lowest doses for the alternative location are, respectively for the GEO and MEO environments, 7% and 4% of those for the highest doses at the designated location. This suggests substantially less secondary shielding for radiation sensitive electronic devices.

If the alternate location is used then the space between the instrument support panel and the top panel is not required. Thus the height, and corresponding mass, of the spacecraft in the Z direction can be reduced. The single panel replacing the combined support and top panels would be thinner than that of the combined two. Any reduction in net shielding can be compensated by a thicker top of the

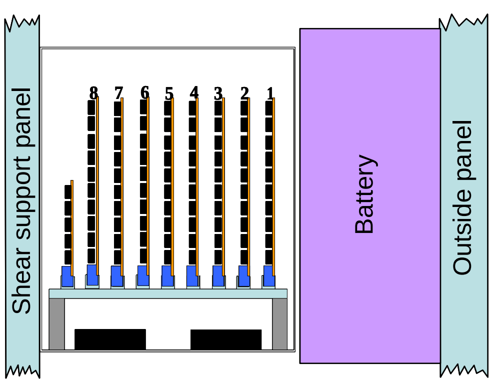

Figure 10. – Electronics box located between battery and shear support panel

box's enclosure. The net effect is additional mass reduction. If the battery and the electronics box are raised until the battery in the immediately under the single top panel then very likely the top of the enclosure need not be thicker. Raising the battery up does not necessarily cause an increase in the moment because the instrument box is lower than at the designated location and the mass is less due to the reduction of the spacecraft's height.

Perhaps as important in the case of Figure 11 the maximum-to-minimum ratio of dose is smaller. Thus the circuit layout and board order would have been more flexible had this been a consideration in the first place. The comparison clearly suggests that radiation dose modeling can make an important contribution to the design of the spacecraft and its electronics content.

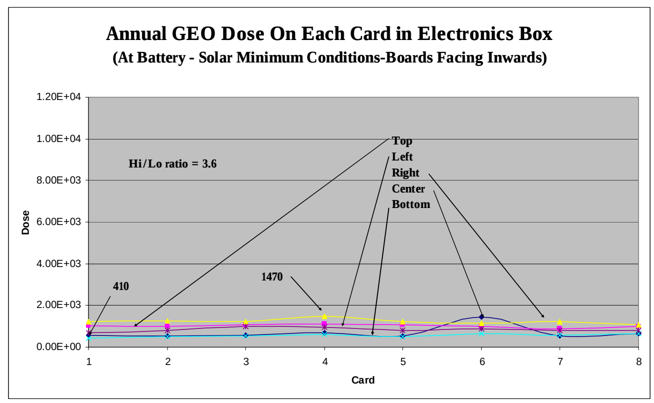

Figure 11a. – GEO dose distribution at five locations on each of eight cards for the box location and orientation shown in Figure 10.

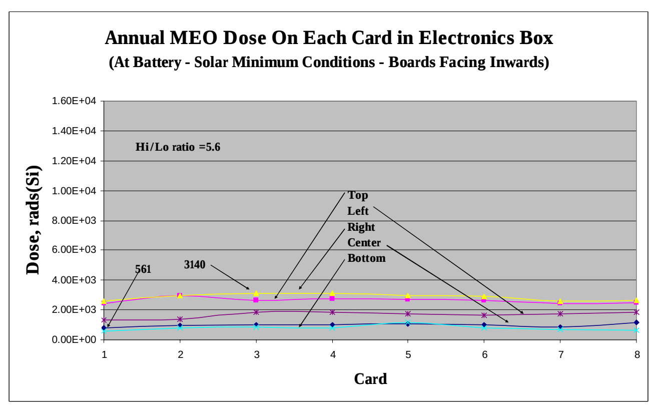

Figure 11b. - MEO dose distribution at five locations, on each of the eight cards for the box location and orientation shown in Figure10.

SUMMARY

Radiation modeling for a simple generic spacecraft demonstrated that the dose at a particular site inside a multi-board electronics box varies with the box's location in the spacecraft by more than an order of magnitude. The modeling furthermore demonstrates that the dose varies in the box another order of magnitude depending on which board and location on that board the dose is modeled.

No demonstration was made for the effects of relocating spacecraft components, such as batteries, antennas, and support electronics, or altering the spacecraft's structure. No demonstration was made for the dose-reduction effects of using board ground planes, densification and altering the layout of a board's population, or changing the separation between the boards, or small changes in the box's enclosure thickness or material. Each of these changes will contribute to a still smaller dose. When the cost of space flight mission, the need for risk mitigation, the significance of radiation effects, and the smaller packaging of more recent spacecraft are considered it is clear that radiation dose modeling should be included as a design tool as well its more traditional use for determining the need for secondary radiation shielding

REFERENCES

1. – PolyRAD® – http://www.PolyRAD.net
2. – NIST – http:/srdata.nist.gov/gateway/. Keyword: stopping power.
3. – NOVICE – Experimental and Mathematical Physics Consultants, P.O. Box 3191, Gaithersburg, MD 20885
4. – Space Radiation: Space Radiation Associates, 1430 Willamette, Suite 1, Eugene, OR 97401
5. – TIGER: Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Bethel Valley, Road, P.O. Box 2008, Oak Ridge, TN 37831
6. – SPENVIS- (This is a WEB-based application) http://www.spenvis.oma.be/spenvis/register.html.