Progress in Spacecraft Environment Interactions III: The Role of Structural Shielding Mass in Avionics Performance in Single Event Effect Environments

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Independent of radiation shielding considerations, basic human spaceflight requirements naturally lead to relatively large, massive spacecraft structures, at least compared to most uncrewed spacecraft. The structural mass of crewed spacecraft provides shielding mass depths (>10 g/cm^2), substantially greater than those typical of uncrewed spacecraft (< 1 g/cm^2).

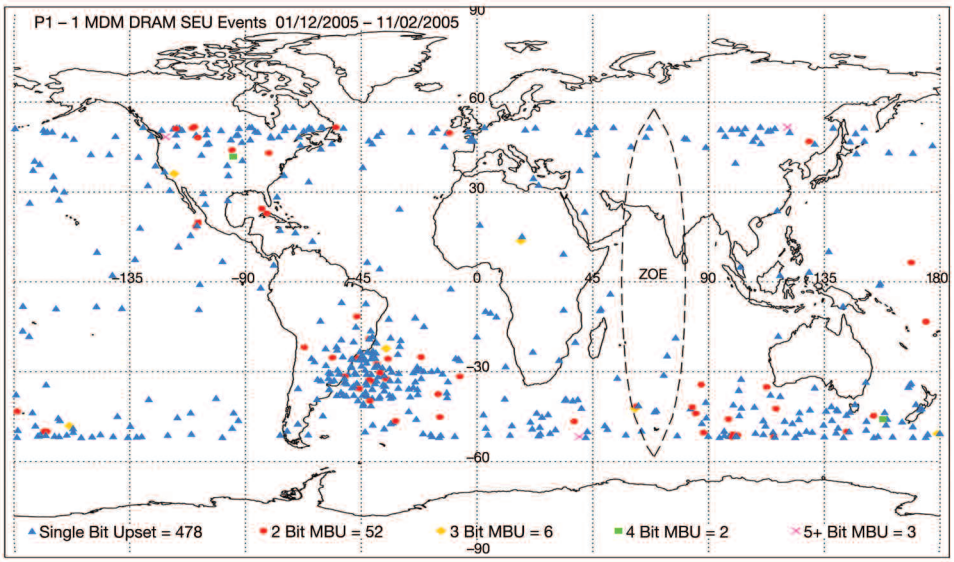

Fig. 1. *Geographical distribution of MDM CMOS DRAM SEUs for a typical external MDM.*

While attenuating the natural space radiation environment, the greater shielding mass depths characteristic of crewed spacecraft generate a secondary or induced radiation environment as a result of interaction between the structural materials and the primary radiation environment. For example, space shuttle, the Russian space station Mir (1996 – 1998), and the International Space Station (ISS) shielding depths are large enough to be comparable with the inelastic collision lengths of energetic galactic cosmic rays (GCRs). Hadronic showers (i.e., secondary particle cascades consisting of energetic protons, neutrons, mesons, and nuclear fragments) initiated in the ISS or shuttle structural shielding mass by inelastic collisions of high-energy GCRs are expected to make a larger contribution to the Single Event Effect (SEE) environment than would be the case in less massive spacecraft, thus offsetting the attenuation effects of the larger shielding mass to some degree.

Similarly, the hadronic showers initiated by GCR collisions with air nuclei in Earth's atmosphere produce secondary particle cascades leading to the Pfotzer radiation maximum, a concern for aircraft avionics, at altitudes near 20 km, corresponding to an atmospheric shielding mass of about 50-60g/cm^2 of air. Both SEE and total ionizing dose effects are less severe at altitudes higher and lower than the Pfotzer maximum although, of course, the maximum itself is much less severe than the unattenuated radiation environment outside the atmosphere. The existence of the Pfotzer maximum at a particular shielding depth in Earth's atmosphere raises the question of whether or not similar secondary ionization maxima are an important factor affecting avionics SEE performance for comparable shielding depths in massive spacecraft.

The configuration of the U.S. segment of the ISS in late 2005, Flight/Stage LF-1, contained more than 600 SEE-susceptible avionics boxes and 3,000 devices susceptible to SEE-induced functional interrupt. During 4 years of flight, a total of 11 in-flight anomalies have been observed that may be SEE related. No destructive SEE events have been observed. None of the SEE-related anomalies show any correlations with solar energetic particle events, flight through the South Atlantic Anomaly (SAA), or flight at high latitudes as predicted during the ISS design and verification process, which used the worst-case SEE design environments in combination with the (conservative) assumption of shielding masses, for purposes of design and verification, that were one-third to one-fifth the actual value.

The ISS multiplexer/demultiplexer (MDM) units are the computers used to build the ISS distributed data, command, and control network. Figure 1 shows the geographical distribution of single event upsets (SEUs) that occurred in a typical external (outside the pressurized elements) MDM

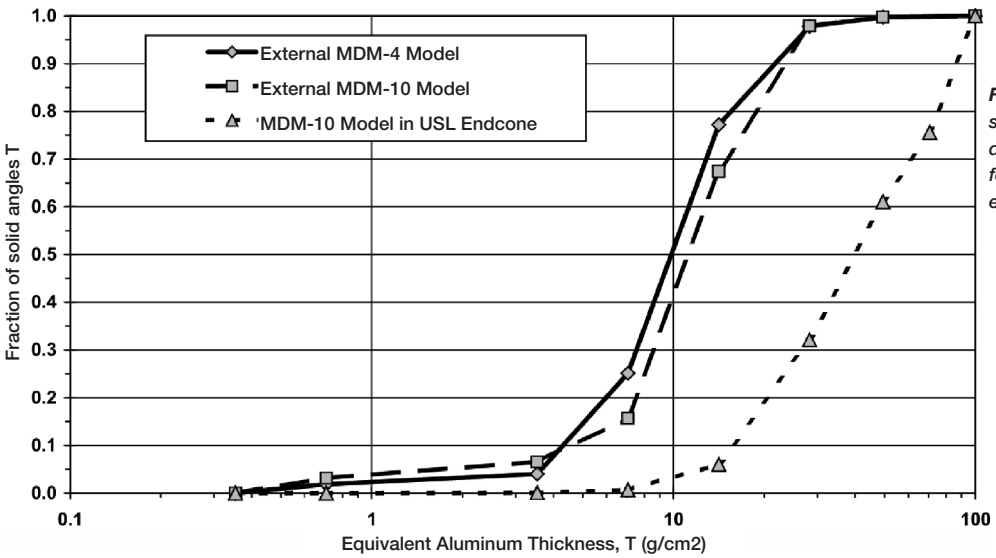

Fig. 2. Spacecraft shielding mass distribution functions for internal and external ISS MDMs.

ISS MDM: Median Shielding	On-orbit SEU Count: SEU/238 days	SEFA Predicted SEU Count: SEU/238 days	FOM Predicted SEU Count: SEU/238 days
Lab-1: 40 g/cm2	488	966	468
Lab-1: 40 g/cm2	490	966	468
P1-2: 10g/cm2	536	6309	1673
S1-1: 10g/cm2	488	6309	1673

***Table 1.** Observed SEU counts for internal and external MDMs and predicted rates using two different SEU rate estimation methods (see text).*

complementary metal-oxide semiconductor (CMOS) dynamic random access memory (DRAM) during 2005. The upset count is greatest in the SAA and at high latitudes, as expected.

The internal and external MDMs are in significantly different shielding mass environments, as shown in figure 2. The observed SEU count for the internal and external MDMs is compared in table 1, as are the rates predicted using the Scott Effective Flux method and Peterson's Figure of Merit (FOM) method. Given that SEE rates can span several orders of magnitude, are random events, and are subject to error detection and correction mitigation, methods that overestimate the rate by less than a factor of 10 are more than adequate for spacecraft design and verification purposes, so the Peterson FOM approach is more than adequate for our purposes here. The internal and external MDMs have nearly the same observed SEU rates despite the large difference in shielding mass, and the FOM method makes more accurate predictions of rates. Nonetheless, the FOM method is obviously overestimating the effectiveness of the higher shielding mass for SEU rate mitigation. Because it is based on the Cosmic Ray Effects on Micro-Electronics software suite (1996 revision), SEE environment rate calculation package FOM significantly underestimates secondary particle production in heavily shielded environments by overestimating shielding attenuation effects.

Ongoing work in this area includes use of the multi-particle radiation transport software to accurately calculate linear energy transfer (LET) flux and spectra under various shielding depths of aluminum for both the ISS orbital environment and the near-Earth interplanetary environment. Our preliminary results demonstrate no important differences in LET flux and spectra when comparing 10 grams/cm^2 and 40 grams/cm^2 of aluminum shielding mass, largely as a result of secondary particle contributions to the flux and spectra at the larger shielding depth. These results predict that the SEU rates should be about the same in the two different shielding mass environments.