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Analysis of Single-Event Upset Rates on the Clementine and Cassini Solid-State Recorders

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As part of a "data mining" effort to evaluate the value of ground testing in predicting the performance of microelectronics in space, the responses to single-event upsets of the Clementine 2.1 Gbit solid-state data recorder and two Cassini 2.5 Gbit solid-state recorders were analyzed. As the systems were tested for single-event upset sensitivities before flight, in situ estimates of the environments allow evaluation of single-event upset models and ground tests to predict flight performance using actual data. The recorders' dynamic random access memories, despite having different manufacturers, have similar single-event upset cross sections, permitting a comparison of environmental effects for two very different missions (lunar versus Saturn). Earlier studies had revealed upset rates of ∼71 (Clementine) and ∼280 bit flips/day (Cassini) due to the galactic cosmic ray background. Whereas there was no obvious correlation with solar and trapped protons for Clementine, the Cassini solid-state recorders demonstrated responses to both. This difference was explained by applying the Cassini proton cross sections to the Clementine observations, which showed that the proton upset rates were too low to be observed by Clementine. This study completes the original Clementine analyses and demonstrates agreement between Cassini upsets and the Jet Propulsion Laboratory SATRAD proton model. Finally, the pronounced lunar altitude dependence of Clementine upsets is shown to fit galactic cosmic ray flux variations due to lunar shielding.

Nomenclature

D	=	distance of Clementine spacecraft from moon, km
F_p	=	hourly flux of 100 MeV protons, number/cm^2
R_L	=	lunar radius (1738 km)
S	=	total single-event upsets accumulated over time interval T (upset bits)
T	=	time duration of observing interval, days
T_{bits}	=	total number of solid-state data recorder bits subject to upset (∼2 Gbit)
σ_P	=	proton cross section for dynamic random access memories (assumed to be 5×10^{-14} cm^2/bit based on Oki Electric Industry Co., Ltd. dynamic random access memory at 100 MeV)
Ω	=	percentage of the 4π solid angle blocked by the moon

Introduction

As PART of the normal housekeeping functions on the Clementine and Cassini spacecraft, the Clementine solid-state data recorder (SSDR) and the Cassini solid-state recorders (SSRs) were continuously monitored for single-event upsets (SEUs) during their respective missions. These data have been correlated with the radiation environments either observed or modeled at each spacecraft to determine the performance of the recorders, to evaluate their error detection/correction capabilities, and to serve as a monitor of SEU rates. The two solid-state recorder designs, although built by different manufacturers (SEAKR Engineering, Inc., and TRW, respectively) using different dynamic random access memories (DRAMs) and flying in very different environments (lunar and Saturnian), exhibit similar upset cross sections so that their performance can be intercompared and contrasted. The Clementine results were originally evaluated in Garrett et al. [1], whereas the Cassini data were evaluated in Swift and Guertin [2]. The latest Cassini upset rates at Saturn were first presented by Seal [3], who demonstrated an apparent correlation between the SSR upsets and the Saturnian proton radiation environment. The purpose of this paper will be to review the results of these previous analyses and develop a consistent model of how these systems responded to the galactic cosmic ray (GCR), solar proton event, and trapped proton environments. Following a brief summary of the characteristics of the SSDR and SSR systems, the SEU rates will be compared with the ambient environments and with the lunar and Saturnian orbits. The correlations (or lack thereof) between these will then be used to evaluate the efficacy of the preflight estimates in predicting the behavior of solid-state recorders in the space environment. The intent of this evaluation, as in the case of related studies [1,2,4], will be to provide insight into the effects of the space environment and spacecraft operations on advanced, complex SEU-sensitive systems and determine the credibility of preflight testing and modeling of SEU rates.

Solid-State Data Recorders

Here, only a synopsis of the Clementine SSDR and Cassini SSRs sufficient to understand their behaviors for the purposes of the SEU analysis will be provided. The Clementine SSDR has 2.09 Gbit of usable storage capacity (actually, 2.9 Gbit of which 786 Mbits are for the error detection and correction, or EDAC). The design incorporates redundant EDAC with active fault management and built-in test capabilities. The recorder used a commercially available

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4 Mbit × 1 Hitachi DRAM and had a data throughput greater than 20 Mbits/s with a bit error rate of less than 1 part in 10 billion. The Clementine sensor data were compressed before being stored in the SSDR using a jpeg chip set with a compression ratio as large as 10:1. As the intent of the Clementine mission was to qualify advanced microelectronics such as the SSDR so that they could enhance future space missions, the inherent risks in flying such a new, unique system with a known SEU sensitivity were considered well worth taking. The outstanding success of the SSDR in processing $\sim 1.5 \times 10^6$ images (not one bit upset resulted in lost data and there were no double-bit errors detected) clearly supports the validity of this assumption.

The SSDR memory is scrubbed and EDAC applied; single-bit errors (SBE) were corrected and counted whereas double-bit errors were only counted (here, double-bit errors refer to two bit errors in one stored word; the bits are not physically adjacent). As a result, the SSDR is capable of being used as an SEU detector. The upsets, however, must be specifically monitored and reported; the SEU count is a part of the real-time telemetry and thus not time tagged until the data are recorded on the ground. The memory address of the upset can be determined and used to create an upset memory map, but this was not done in flight. Although the actual memory size was over 2 Gbit of usable memory, the storage requirement was ~1.6 Gbit, leaving ~400 Mbits for the replacement of damaged memory.

The Clementine housekeeping data on the SSDR status were monitored throughout the mission for evidence of SEUs. These data were time tagged and separately compiled for comparison with the radiation data from the Clementine charged particle telescope, dosimeters, and the radiation reliability and assurance experiment (RRELAX) by Soli et al. [5]. A dosimeter was placed near the SSDR to monitor total dose (total dose at this location was too low to measure and did not have a measurable effect on the SSDR performance). The primary purpose of the dosimeters was to monitor passages through the radiation belts and the solar proton event environment. The SSDR was monitored for upsets during the early portions of the mission before lunar injection when Clementine was briefly in the Earth's radiation belts through to near the end of the mission during Earth flyby before leaving the Earth–moon system. (Note: Clementine, after being dormant for a year, was reacquired in April 1995 and the stored data were downloaded.)

The SSDR scrubbed (checked for bit errors) at a rate of 1.3–1.5 MB/s, depending on whether information was being read into or out of the SSDR. It therefore took about ~3 min to scrub the occupied memory. The key issue is that the SSDR only scrubs memory currently in use. For most of the mission up through lunar departure, this was variable (after lunar departure, the SSDR was placed in a mode in which the entire memory was always scrubbed). Fortunately, on the average, the memory usage on a day-to-day basis was constant throughout the lunar mapping phase of the mission. However, as will become evident, there may have been operational procedures during a 5 h lunar orbit that caused periodic variations in the bit error rate as monitored at the ground.

The Cassini spacecraft, launched in October 1997 to investigate Saturn and its moon Titan, carries two SSRs with a total of 2.5 Gbits of memory (2.1 Gbits of usable data) per recorder. Each of the TRW-designed recorders contains 720 4-Mbit Oki Electric Industry Co., Ltd. (OKI) DRAMs, organized as 1×10^6 addresses by 4 bits. A recorder actually uses only 640 of the DRAMs; the other 80 are spares that can be activated if some of the "base" devices fail during the mission. A photograph of a side of one of the six memory boards is shown in Fig. 1. The three large devices are custom application-specific integrated circuits (ASICs) that control access, refresh, and error scrubbing for 40 DRAMs each. The ASICs are designed with a special radiation-hardened process and are immune to single-event upset effects. The 60 smaller devices are OKI 4-Mbit DRAMs [2]. An identical array of 60 DRAMs is to be found on the opposite side of each board for a total of 120 DRAMs per board. The DRAMs can withstand a total dose of greater than 50 krad(Si) and are immune to latch-up up to a linear energy transfer (LET) above 120 MeV · cm^2/mg. They are, however, highly sensitive to SEUs [6–8]. EDAC is used by the recorders to deal with the SEU problem.

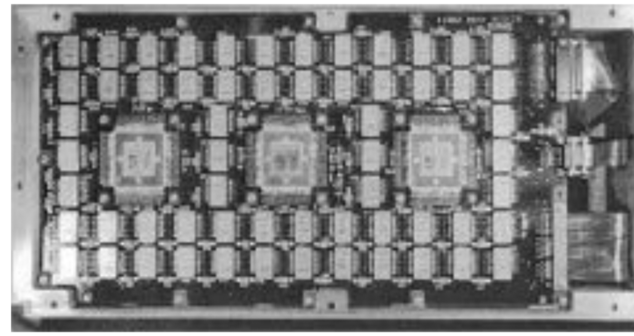

Fig. 1 Cassini SSR memory board [2].

Extra shielding (equivalent to 0.5 in. of Al) was placed around the SSR boxes to reduce the number of SEUs from solar particle events.

The EDAC approach uses an extended word length of 39 bits: 32 bits are for data, and the other 7 bits are for a Hamming code. This format allows detection and correction of single-bit errors and detection (without correction) of double-bit errors. It cannot detect triple-bit errors, but the probability of triple-bit errors is extremely small. The memory is scrubbed of single errors about every 9 min. The number of corrected single-bit errors and uncorrected errors is recorded and transmitted as part of the engineering telemetry. This provides a history of the overall performance of the EDAC system. It also provides an indirect way to estimate the radiation environment during flight. The record of single-bit errors on the "B" side (B-SBE) of the Cassini SSR was the basis of the analyses carried out in this paper.

Dynamic Random Access Memory Single-Event Upset Testing

The Clementine Hitachi DRAM was tested at the Brookhaven National Laboratory's Tandem Van de Graaff Accelerator Facility. Tests were at 25°C on de-lidded devices [8,9] using two ions, 102 MeV C^{12} and 129 MeV F^{19}, and at variable incident angles to obtain a wider range of effective LET values (the points labeled "Rockwell" in Fig. 2). At normal incidence, the LET for the two ions were 1.4 and 3.6 MeV · cm^2/mg, respectively. The maximum LET of fluorine at a 69 deg incident angle was only 10 MeV · cm^2/mg, which was too low to establish the saturation cross section. Over the range of overlap, however, these data were in good agreement with earlier data from Harboe-Sorenson et al. [8] for the same device, which extended to much higher LET values and hence provided a more accurate saturation cross section (labeled "European" in Fig. 2). These data are illustrated in the upset cross section plot, shown in Fig. 2 [8,9]. Similar data for the OKI DRAMS (used in Cassini) are presented in Fig. 3.

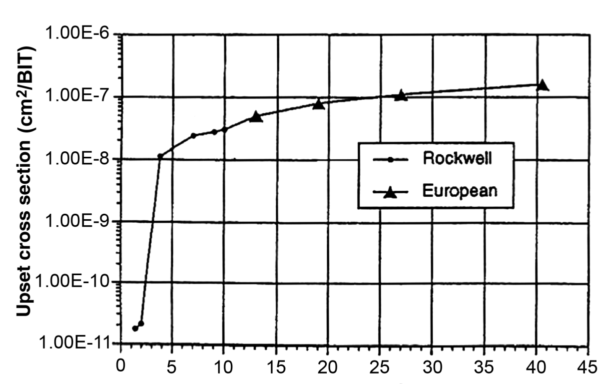

Fig. 2 Hitachi 4 Mbit × 1 DRAM heavy-ion soft-error upset cross section (cm^2/bit) as a function of LET in MeV · cm^2/mg [1]. The points labeled European are from work by Harboe-Sorenson et al. [8] whereas those labeled Rockwell are from work by Rockwell International Corp. [9].

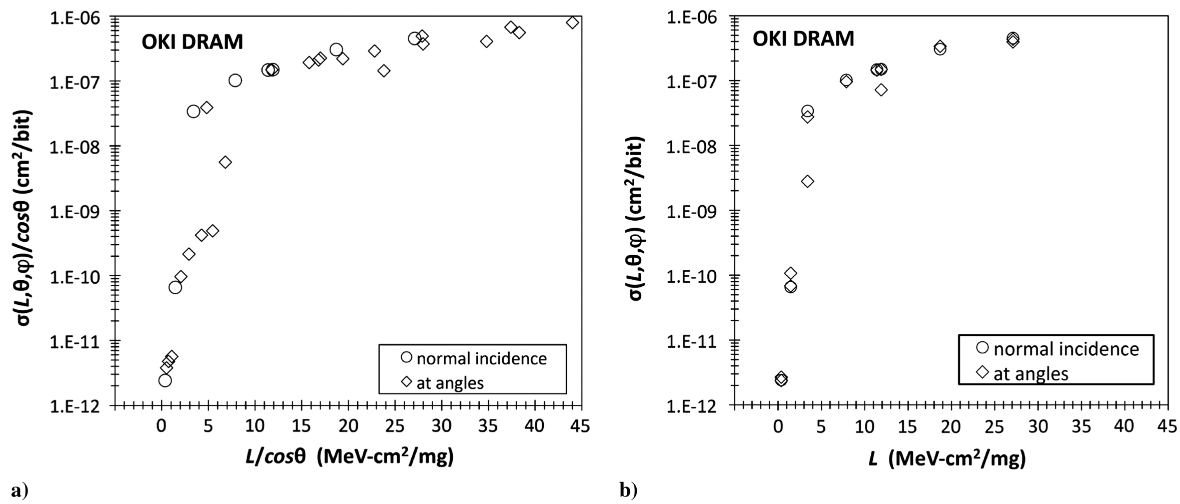

Fig. 3 Plots of the SEU per bit cross section for the OKI DRAM (the per bit cross section is the per device cross section divided by 4 × 10⁶ bits per device): a) OKI DRAM cross section data in traditional cosine-law plotting format, and b) cosine variations removed from OKI DRAM plot.

The interpretation of upset cross sections for DRAMs is a complex issue as a number of factors must be considered [10,11]. These include 1) the use of the cosine correction to obtain the effective LET, 2) charge diffusion, and 3) statistical variations in the threshold voltage. A technique to examine this latter factor was developed and applied to several DRAMs [12]. The cross section of a typical DRAM increases by nearly six orders of magnitude with LET between $\sim$0 and $\sim$5 $\mathrm{MeV \cdot cm^2/mg}$. The critical or threshold LET is obtained from the cross section data and defines the minimum LET at which upsets will occur. The data in Figs. 2 and 3 for the Hitachi and OKI DRAMs illustrate this trend with critical LETs of $\sim$3 and $\sim$4 $\mathrm{MeV \cdot cm^2/mg}$, respectively.

Cross section data for the OKI DRAM were taken from Guertin et al. [13] (note: there is a mismatch between figures and captions in that reference; they are reproduced correctly in Fig. 3). Figure 3a uses the traditional "cosine law" plotting format, based on the directional cross section, denoted here as $\sigma(L, \theta, \varphi)$, where L is the ion LET, θ is the tilt angle (angle between the particle trajectory and the direction perpendicular to the device surface), and φ is the rotation angle (or azimuth angle [13]). The directional cross section is experimentally defined to be the number of SEU counts divided by beam fluence when fluence is measured in a plane perpendicular to the beam. The traditional plotting format divides the directional cross section by the cosine of the tilt angle, which is equivalent to measuring fluence in the device plane instead of a plane perpendicular to the beam. This quantity is plotted against the effective LET, which is the ion LET divided by the cosine of the tilt angle. For many devices, this cosine law plotting format is applicable in the sense that data points measured at different tilt angles line up on a single smooth curve, until the tilt becomes too extreme. However, the scatter in Fig. 3a indicates that the cosine law is not applicable to the OKI DRAM. An alternate approach, shown in Fig. 3b, plots the directional cross section against ion LET. The scatter is greatly reduced, indicating that the cross section is roughly isotropic. This isotropic behavior was theoretically predicted from a diffusion analysis in Guertin et al. [13].

The physical reason for the more gradual increase in cross section at low LET values has been discussed by Wrobel et al. [14]. As noted by Petersen [15], cross sections below $\sim 10^{-10}$ $\mathrm{cm^2/bit}$ have a negligible effect on the GCR upset rate. However, the rate calculations in this paper were done using the entire range of experimental values in Fig. 2. Protons, on the other hand, are another matter because the large abundance (in some environments) compensates for the small cross sections. Proton-induced upsets are discussed later.

Before concluding this section, consider the prelaunch upset rate predicted for Clementine. The predicted upset rate for the Clementine SSDR DRAMs (based on a Weibull fit to the values in Fig. 2) was $\sim 7.5 \times 10^{-12}$ $\mathrm{SEU/bit \cdot s}$ for a shielding thickness of 60 mils and a 90% worst-case GCR environment [16]. This gave a prelaunch predicted upset rate of 1300 SEU/day for a total device memory of $\sim$2 Gbits, a rate that turned out to be $\sim$20 times higher then actually observed. The data also suggested that the Hitachi DRAMs could be affected by LETs as low as 1.5–3.6 (Fig. 2), implying that the DRAM could be sensitive to the low energy proton environment (for reference, near $\sim$1 MeV, the LET for a proton peaks at ~ 0.6 $\mathrm{MeV \cdot cm^2/mg}$) and its "knock-on" heavy ions.** As will be discussed, a partial explanation of the overprediction of the upset rate was that there was much more shielding present around the Clementine recorder than originally assumed; the actual shielding around the recorder was 80 mils(Al) from just the SSDR case itself, with extensive internal shielding from adjacent electronic components and approximately 150 mils of spacecraft structure. Indeed, although the tests of the Hitachi DRAM implied a sensitivity to proton upset, the protons did not show a measurable enhancement over the GCR SEU rate for Clementine even when passing through the proton belt and during a minor solar proton events (SPEs). Finally, the actual GCR environment encountered by Clementine were not as severe as the 90% worst case used for the preflight estimate. These issues will be explored further in the following.

Mission Trajectories

An important tool in deciphering the SEU rates can be the spacecraft's orbit. An essential feature of the Clementine orbit, for example, is its high inclination. Following the launch on 25 January 1994 (day 25 for 1 January = day 1), the spacecraft was initially in a low Earth parking orbit with an inclination of 67 deg. Subsequently, the vehicle was placed on an intermediate lunar transfer orbit with a perigee of $\sim$500 km and an apogee of $\sim$127,000 km. While in this orbit, the vehicle had its first (and apparently only) encounter with the trapped radiation belts. As recorded by the Clementine RRELAX [5], the spacecraft made a very brief passage through the proton and electron belts on days 45 (4 February 1994) and 46 (5 February 1994), respectively. The spacecraft fired its main engine on day 45 to raise its orbit to encounter the moon. A solar proton event was observed by the RRELAX between days 51 and 52 (20–21 February 1994). Clementine achieved lunar polar orbit on day 50 (19 February 1994) and left lunar orbit on day 123 (3 May 1994). Lunar mapping started on day 56 (25 February 1994) and was completed on day 112 (22 April 1994). The spacecraft ceased transmitting useful SSDR SEU data on day 151 (1 June 1994) while in Earth–moon transfer orbit.

The majority of the Clementine SEU data was taken during lunar orbit (Fig. 4). The spacecraft always crossed from the south pole of the moon to the side of the moon illuminated by the sun and in an

**Private communication with G. M. Swift at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1994.

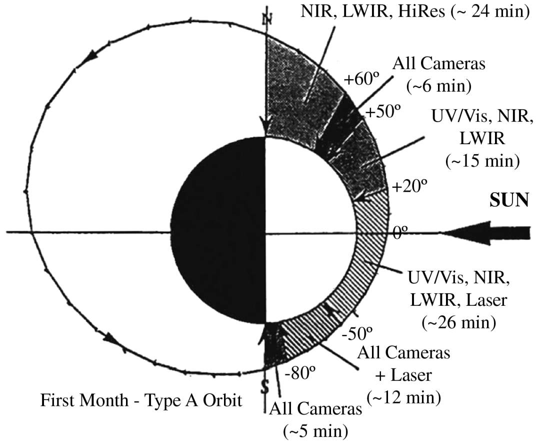

Fig. 4 Schematic of the Clementine lunar orbit for the first month of operations. For this period, the periselene was in the southern hemisphere.

orbit inclined 90 deg to the lunar equator. The Clementine orbit (~2140 km by ~4700 km from the center of the moon, which has a radius of ~1738 km) was chosen to have periselene occur shortly after south pole passage during the first month of operation and somewhat later during the second month (see later).

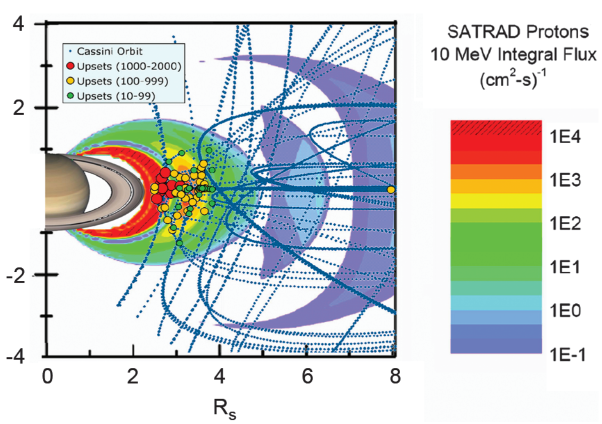

Fig. 5 Orbit traces for the Cassini mission through approximately March 2005 in the range versus latitude plane. Also shown are the locations of the Cassini SSR B-SBE upsets (in units of upsets/hour) and the $E > 10$ MeV Saturn proton fluxes.

In contrast to Clementine's rather simple mission profile, the Cassini mission followed a convoluted, gravity-assisted series of orbits to reach Saturn. Once at Saturn, it has been making numerous flybys of Saturn's various moons and the Saturnian ring plane. During the latter, it has encountered the Saturnian radiation belts. The orbits up to approximately March 2008 and the locations of the SSR B-SBE upsets are plotted in Fig. 5. As will be demonstrated, the SEUs map very closely to the inner Saturnian proton belt as predicted by the JPL SATRAD radiation model [17].

Clementine Mission Single-Event Upset Variations

Except for approximately three to four minor gaps, the single-bit SEUs observed by Clementine were continuously recorded from day 35 (4 February 1994) until day 144 (25 May 1994). The integral upsets are plotted in Fig. 6. A linear fit to this curve in time gives

$$S(T) = 70.73522T - 2215.581 \qquad (1)$$

where S is the total number of SEUs accumulated by time T, T is the date in days (1 January = day 1), and the correlation coefficient is $R^2 = 0.999$. The strong linear trend is clear from the figure. As mentioned earlier, this rate of ~71 SEU/day differed significantly from the premission predicted rate of ~1300 SEU/day for the GCR [1]. In this section, this and other variations in the Clementine SEU rates will be evaluated.

Converting the integral SEU count to a daily SEU rate yields the second curve in Fig. 6 (note: the rate is plotted for the time at the end of the daily interval). This rate has a random variation of about ±25 SEUs/day around the mean of 70.7 SEUs/day. Two peaks (both ~2.5 times the average rate) in the data occur on days 37 and 135. There is no apparent direct correlation with the passage of Clementine through the radiation belts or with the solar proton event as recorded by the on-board RRELAX. Although not shown here, there is also no obvious correlation with numerous low-level proton and heavy-ion events detected by the RRELAX on Clementine [5]. When the daily rate is directly compared with the Earth orbit data, there is an obvious correlation between the pronounced peaks in the SEU rate and the transfer orbits (as opposed to the lunar orbit period); however, the phasing with distance from the Earth is not clear, as both peaks in Fig. 6 appear to occur well outside the $\sim 10 R_E$ boundary of the trapped belts.

A cursory review of the Clementine SEU data at various time resolutions indicated that a correlation might exist between the position of the spacecraft relative to the moon and the Earth (for example, whether the moon was new versus full). To test this relationship, in the original study of the Clementine SSDR [1], the occurrence of SEUs as a function of the sun–Earth–moon (SEM) angle was determined. Specifically, the time and position of the SEUs

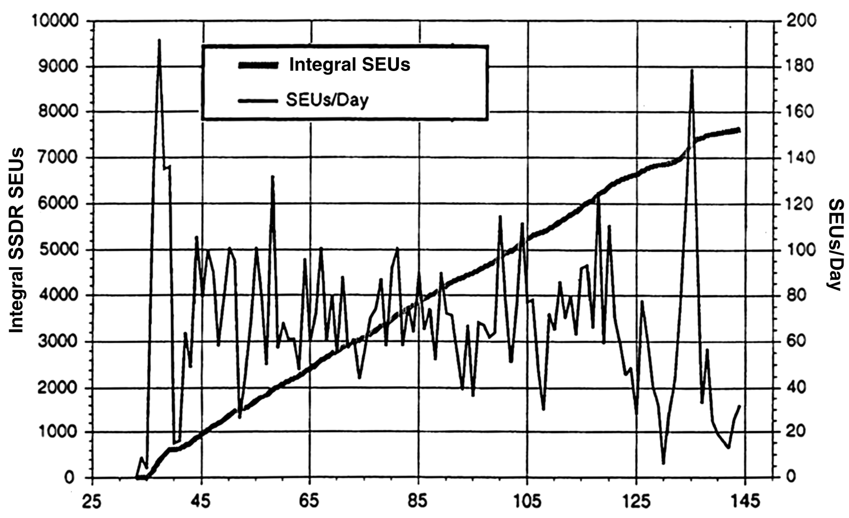

Fig. 6 Clementine SSDR integral SEU counts (thick line) and daily SEU counts (thin line) as functions of mission duration (January 1 = day 1) [1].

were used to place each SEU in a lunar orbit position bin and an SEM bin. To accomplish this, the time after south pole passage when the SEU was observed was divided by the time between two south pole passages to give the fraction of the orbit in which the SEU occurred. The orbital period was divided into eight equal intervals and the SEUs binned. At the same time, the SEM angle was determined for each SEU and the data binned in one of four equal angle intervals of 0–45, 45–90, 90–135, and 135–180 deg (0 deg was full moon, 180 deg was new moon; symmetry reduced the range from 0–360 to 0–180 deg). An additional consideration was that the lunar orbit periselene location changed around day 86. To account for this, the data were further divided into two more groups based on whether the event occurred before or after day 86. The results are presented in Figs. 7 and 8 [1]. These figures show a pronounced variation with lunar orbit when the moon is between the Earth and the sun (i.e., new moon). There is, however, no obvious variation when the moon is full. The computed time of periselene (in terms of percentage of orbital period after south pole passage) is marked for the period before day 86 (Fig. 7) and after (Fig. 8). A minimum in the SEUs (approximately a 60–70% reduction from the maximum) clearly lines up with periselene. Further, it varies as the spacecraft periselene varies.

To help evaluate the apparent variation with lunar orbit, Fig. 9 is a plot of the error rate per day versus distance from the moon. If it is assumed that the solid angle subtended by the moon provides a "shield" from the GCR (assumed to be omnidirectional), then the following equation gives Ω, the percentage of a 4π solid angle shielded by the moon, as a function of distance, D, from the moon:

$$\Omega = 100 \cdot \frac{1}{2} \cdot \left[1 - \frac{(D^2 - R_L^2)^{1/2}}{D}\right] \tag{2}$$

Assuming an upset rate of ~75 errors/day (for 4π unobstructed steradians), $75 \cdot (1 - \Omega/100)$ gives the GCR-induced SEU rate as a function of distance from the moon (e.g., the solid line plotted in Fig. 9). Although not exact, there is reasonable agreement between the prediction and a curve fit to the actual data. This supports the assumption that the varying Clementine SSDR error rate is most likely due to lunar shielding of the GCR flux.

SPEs are another source of upsets. Unfortunately, there were only two [5] small solar proton events during the Clementine mission. Figure 10 is a plot comparing, for the largest of these events, the hourly observed SSDR SEU rates and the predicted SEU rates based on observations by the Geostationary Operational Environmental Satellites (GOES). The predicted rates assume a proton cross section for 100 MeV protons based on the OKI DRAMS (see later). This assumption is based on the similarity between the Hitachi and OKI DRAM LET curves. The SEU upset formula is

$$\mathrm{SEU}_{\mathrm{clem}} = 4\pi \cdot \sigma_P \cdot F_P \cdot T_{\mathrm{bits}} \tag{3}$$

It is clear from Fig. 10 that, at ~1–2 SEUs/h, the solar proton upset rate is "in the noise" compared with the background GCR rate. It is therefore no longer surprising that the Clementine SSDR did not respond to the SPE that occurred during the mission. To summarize [1], the Clementine SSDR demonstrated temporal variations associated with the spacecraft orbit. Four variations have been identified: 1) a nearly constant rate of ~71 SEUs/day, 2) two enhancements of ×2.5 in the SEU rate before entering lunar orbit and

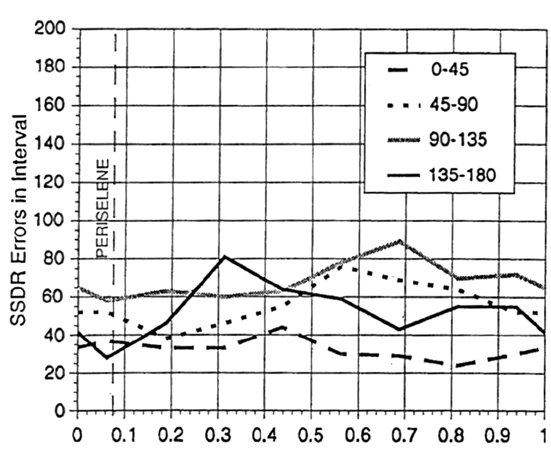

Fig. 7 SSDR SEU errors as a function of the fraction (time) of the orbit after south pole passage versus SEM angle for days 57–85 (0 deg = full moon) [1].

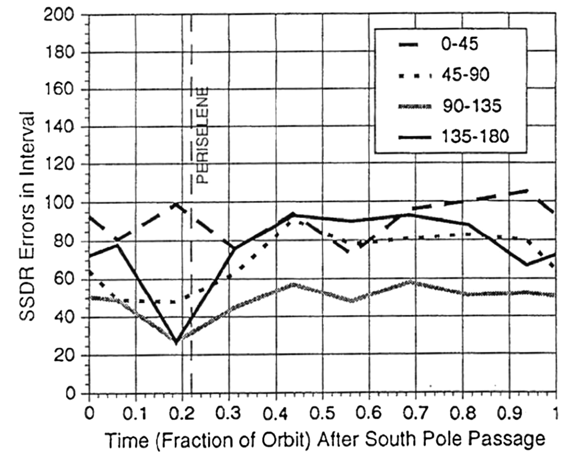

Fig. 8 SSDR SEU as a function of the fraction (time) of the orbit after south pole passage versus SEM angle for days 85–123 [1].

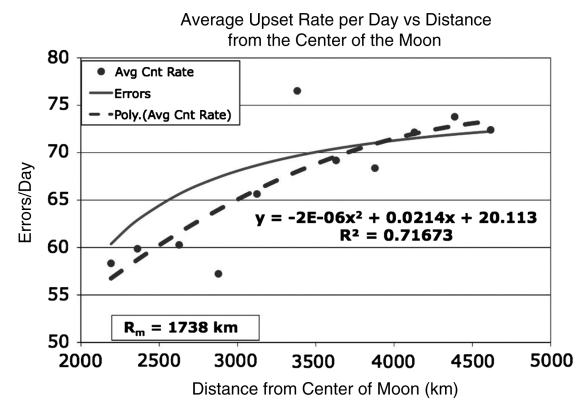

Fig. 9 Clementine SSDR upset rate per day versus distance from the center of the moon. The dashed line is a polynomial fit to the data. Also shown is the predicted upset rate (solid line) assuming that the moon shields the GCR flux.

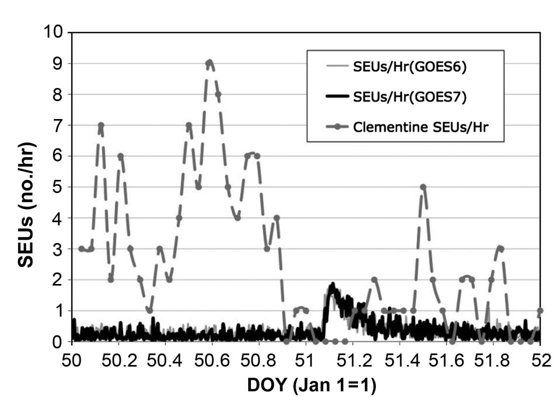

Fig. 10 Clementine SEUs per hour for days 50–52 of 1994 compared to the predicted SEU rates based on GOES-6 and GOES-7 100 MeV proton fluxes. The OKI proton cross section is assumed.

after leaving lunar orbit, 3) the presence (absence) of a lunar orbit variation at new moon (full moon), and 4) a minimum in the lunar orbit variation at periselene of 30% of the maximum count rate around the lunar orbit.

Consider the first finding. Preflight estimates predicted that the SEU rate would be relatively high (~1300/day for 2 Gbits) and that the DRAMs should be affected by protons because of their low critical LET. In contrast to these predictions, the SSDR had no obvious correlation with passage through the proton belt or from a solar proton event that was clearly observed by the Clementine spacecraft and by several other vehicles. Although not conclusive, this indicates that either the shielding was much higher than originally assumed or the GCR and proton environments were more benign than assumed before launch. To test these assumptions, a simple parametric study was carried out by varying the SSDR shielding, the critical LET, and the assumed GCR spectrum over their potential ranges (the original analysis, done before the design was complete, deliberately assumed a 90% worst-case GCR environment and only a 60-mil shield).

Although the Clementine SSDR shielding is not precisely known, a review of the spacecraft drawings and conversations with the manufacturer imply that the 250-mil thickness is a reasonable estimate for the minimum shielding thickness. Varying the shield thickness [1] gives count rates ranging from 700 SEUs/day for a shielding thickness of 250 mils to 1400 SEUs/day for 60 mils for a 90% worst-case GCR environment and 2 Gbits. As to the GCR fluence, at solar maximum and in the absence of solar proton events, it can be as much as a factor of 10 lower than the 90% worst case assumed in the original calculations. Indeed, using the cross section as plotted in Fig. 2 (rather than the simple Weibull fit with a critical LET assumed for the prelaunch estimate) and the GCR fluences at solar maximum (the lowest level), the SEU rate was estimated to be ~70 SEUs/day. Varying the critical LET assumed in the Weibull fit also demonstrated large variations, indicating that this is probably a major factor in determining the actual SEU rate for the SSDR. Increasing the Wiebull critical LET to 5, for example, lowers the 1400 SEUs/day rate for the worst-case GCR environment to 70 SEUs/day without any other assumptions demonstrating the sensitivity to this parameter. Possible explanations for the difference between prelaunch estimates and actual observations are that the observed SSDR daily SEU rate resulted from 1) a lower GCR ambient environment, 2) a thicker spacecraft shield (~250 mils or greater) than originally assumed, 3) a higher critical LET, or 4) low SPE fluxes.

The two peaks in the upset rate at the beginning and end of the Clementine mission are difficult to explain. The obvious assumptions are that they are either associated with passage through the radiation belts or are the result of varying operations of the SSDR (i. e., changing the amount of memory being scrubbed and, hence, the total cross section being monitored). The first assumption breaks down as there is no obvious correlation with distance from Earth and the position of the radiation belts. Indeed, the RRELAX monitors both protons and heavy ions and clearly saw the radiation belts but not at the time of peaks. It is possible, however, that like the SPE rates, the proton belt fluxes were too low to be observed by the SSDR. As to the second point, the SSDR was indeed being operated in different modes during the transfer orbits. A detailed review [1] of the scrubbing procedures/modes between days 110 and 145 showed that the mode of scrubbing changed from monitoring only that part of memory being written to (up to day 130) to the entire 2 Gbits being monitored (between days 130 and 140). The observed SEU rate varied from a minimum to a maximum to a minimum over the same period while memory usage varied randomly. This would imply that, whereas the scrubbing mode affected the observed rate, it probably was not the primary cause of the pronounced SEU enhancement. A third possibility is that the Earth modulates the GCR flux by shielding the spacecraft with its magnetosphere, as discussed with regards to Figs. 7 and 8. Indeed, Fig. 7 implies that the average SEU rate (implying GCR flux) is uniformly down when the spacecraft is in the magnetosphere at full moon. Unfortunately, the opposite behavior is seen in Fig. 8, in which the lunar orbit variations at full moon are higher than the other SEM positions. Thus, although perhaps possible, there is no strong evidence for the magnetosphere being the cause of the SEM modulation.

Spacecraft operations cannot be ruled out as a source of the observed Clementine SEU modulations. Although the large variations at the beginning and end of the mission seem to be inconsistent with changes in operation, the lunar orbit variations are so regular that they may be dependent on some repeatable activity on the spacecraft. The SSDR was operated in a uniform manner throughout the lunar mapping phase when the orbital variations were observed. A review of the amount of memory in use, operating temperature, scrub modes, etc., has indicated no significant variations in the SSDR usage. There is, however, one potential operational procedure that may account for both the periselene minimum at new moon and it absence at full moon. As stated earlier, SEU observations are reported in real time. When the spacecraft is at periselene at new moon, it is typically out of sight of the Earth. Any SEU observed during a scrub will not be reported until the spacecraft is again in view. There may thus be a time gap between observing SEUs at new moon periselene as opposed to periselene at full moon, when the vehicle is constantly in view. This does not completely satisfy the observations, as a balancing “spike” soon after periselene would be expected (there may indeed be such a spike in Fig. 7, but it is absent in Fig. 8). Even so, like the lunar GCR shielding, this may account for part of the variations observed.

Cassini Mission Single-Event Upsets Variations

As in the case of the Clementine SSDR, the Cassini SSRs experienced numerous upsets due to the ambient environment. In flight to Saturn, like Clementine, the SSRs experienced upsets due to the background GCR environment and SPEs. Typical background GCR single-bit upset rates near 1 AU were nearly constant at about 280 errors per day in 1997 (Swift and Guertin [2] predicted approximately 180 per day for solar maximum and 890 for solar minimum). In the case of protons, because of the low LET threshold, the OKI DRAMs were predicted to be easily upset by SPEs. As discussed in Swift and Guertin [2], it was expected that the proton-induced upset rate could dominate the heavy-ion rate during a solar flare, and Cassini’s 12-year mission guaranteed that it would experience at least a few significant flares. To evaluate this threat, proton upset testing was performed at Harvard as part of the radiation lot acceptance testing. These test results, giving the OKI DRAM cross section versus protons, are shown in Fig. 11 [2].

Figure 12 compares upsets predicted by Eq. (3) (using $E >$ 100 MeV proton fluxes measured by the GOES-8 and GOES-9) for the SPE event on 6 November 1997 with the observed SSR upsets for the same SPE event (upset data are from Swift and Guertin [2]). Aside from a slight shift in time (due to the spacecraft being 18 deg ahead of the Earth) between the curves, the agreement is quite good. The predictions are within a factor ~2 of the observations for the simple derivation in Eq. (3) (note: Eq. (3) assumes 4π steradians for the solid

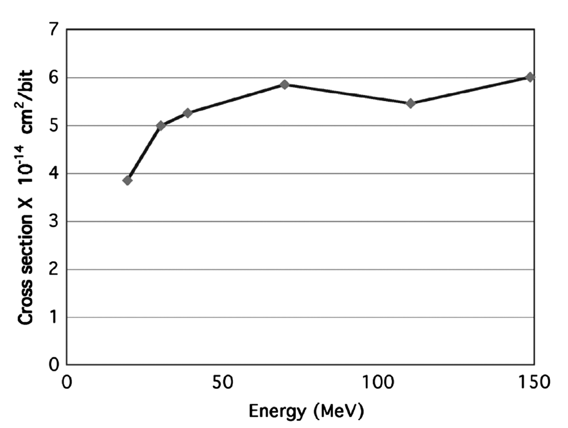

Fig. 11 Proton cross sections for an OKI 4-Mbit DRAM (for part serial number 99). Results adapted from Swift and Guertin [2].

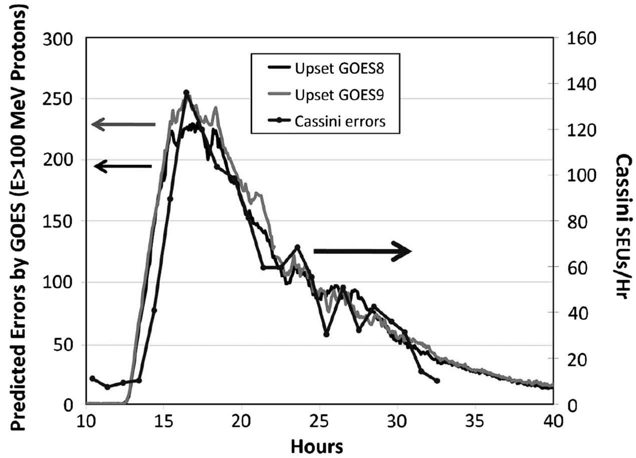

Fig. 12 Comparison between the predicted upsets per hour for $E > 100$ MeV protons measured by GOES-8 and GOES-9 compared with the observed Cassini SSR upsets per hour for 6 November 1997. The predicted upset rates are computed as in Eq. (3). The Cassini spacecraft was 18 deg ahead of the Earth in orbit.

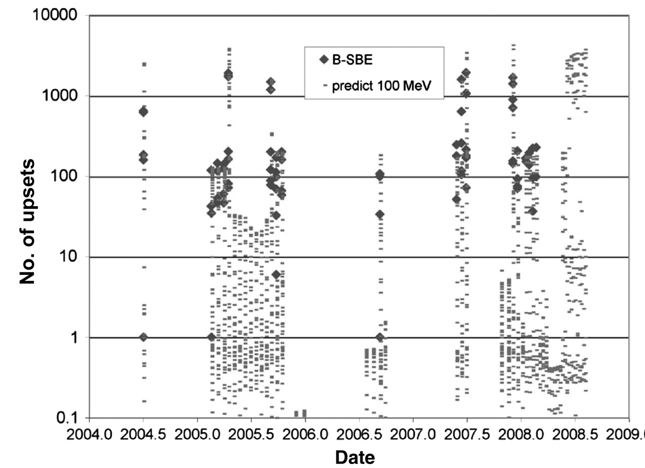

Fig. 14 Complete plot of all predicted proton-induced upsets in the Cassini SSR between mid-2004 and mid-2008. Also plotted are the SSR B-SBEs for the same period [3]. Units are upsets per hour.

angle conversion; shielding by the spacecraft could account for the factor ~2).

Seal [3] observed a striking correlation between upsets in the SSR B-SBE upsets and Saturn's radiation belts. This behavior is illustrated in Fig. 5, which shows the Saturnian proton belts (10 MeV proton integral flux contours from the SATRAD model), the Cassini orbit traces, and, superimposed on the orbit traces, the highest SSR hourly upset rates. The correlation between the trapped protons and the upsets is even clearer when the predicted upset rates for the proton environment are plotted versus the observed upsets (as before, Eq. (3) using the proton cross sections is employed to estimate the SEU rate) in Fig. 13. Assuming that the $E > 100$ MeV protons are the main concern given the Cassini shielding, the figure shows an approximate linear relationship between predicted and observed; quantitative fits imply that the predicted values at 100 MeV are about a factor of 3 higher on the average (compare this with the earlier estimate of a factor of 2 from the GOES–SPE comparison). Again the spacecraft may provide sufficient shielding in one direction to account for this difference.

Even with the agreement shown in Fig. 13, there are still large variations between observed and predicted. This can be seen in Fig. 14, in which the observed and predicted upsets are plotted versus time. Although the correlation of the upsets for rates above ~30 errors/hour is good, below that level the model apparently is "overpredicting" or there is some unrelated selection process that discriminates against the lower upset rates. As an aside, Fig. 14 predicted that Cassini would see enhanced upset rates in the latter half of 2008 when it had more encounters with the proton belts.

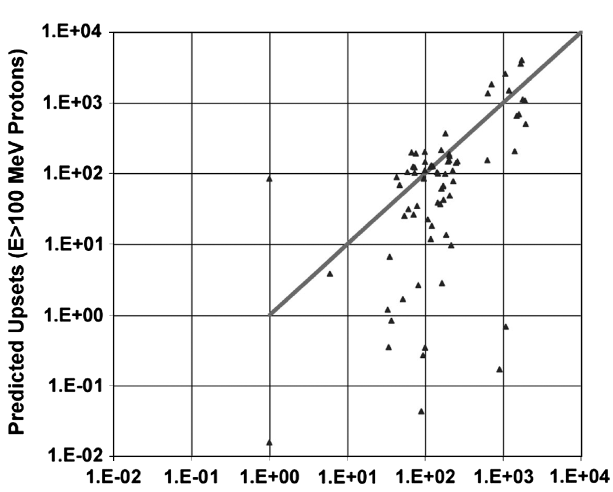

Fig. 13 Predicted (Eq. (3) and SATRAD proton fluxes) Cassini SSR versus observed B-SBE Cassini SSR upsets at Saturn. Units are upsets per hour. The predicted upset rate is estimated at ~3 times the observed.

Conclusions

This study has compared preflight predictions of DRAM GCR and SPE upsets with in-flight observations as a test of current modeling and testing methods. Despite some uncertainties in the sources of the variations, the following statements can be made about these methods vis-à-vis the Clementine SSDR and the Cassini SSRs and their interactions with the space environment:

1) Both the Clementine SSDR and the Cassini SSRs successfully operated in the space environment. Clementine had an observed rate of ~71 SEUs/day, whereas Cassini had a rate of ~280 SEUs/day; these rates are attributed to the background GCR flux. As far as the authors are aware, not one error in the solid-state data recorders has affected operations.

2) Rate estimates before flight were overly conservative by a factor of 20 in the case of Clementine, which assumed a worst-case GCR environment, whereas the Cassini estimates assumed a solar cycle variation that bracketed the observations (180 per day at solar maximum to 890 at solar minimum).

3) The Hitachi and OKI DRAMs were not as sensitive to protons or proton-induced heavy ions as predicted before flight as both spacecraft apparently had adequate shielding to protect against protons below 100 MeV. GCRs were thus the most probable source of SEUs for Clementine during its lunar orbit and for Cassini during cruise (whereas no significant SPEs were observed by Clementine, Cassini did encounter several during its extended cruise phase).

4) Distinct temporal variations relative to mission phase were seen for both missions. In the case of Clementine, large variations in the count rate during the transfer orbits, with lunar position (modulations at new moon), and periselene passage (pronounced minimum in SEU rate at periselene) were observed. Modulations in the GCR by lunar or magnetospheric shadowing effects are believed to have contributed, though the estimated variations were not entirely consistent with the magnetospheric modulation expected. In the case of Cassini, in addition to SPE-induced upsets during cruise, pronounced trapped proton upsets were observed at Saturn during passage through the proton belts.

5) Operational effects are a possible cause of the observed variations for both spacecraft, though Cassini appears to have been operated in a more stable and consistent error detection and correction fashion than Clementine. For Clementine, because the SEU counts were recorded and time tagged only in real time, lags in data collection may have affected estimates of the times of the SEUs.

6) Although this and the companion analyses [1,2] clearly demonstrate the value of in-flight SEU measurements, future experiments of this nature would clearly benefit from enhancements to the monitoring process. First, alter the scrub procedures and operations to maximize the value of the SEU rate data (i.e., time tag the SEU measurements on the spacecraft and have the memory scrubbed in a well-defined, consistent mode throughout the mission; Cassini demonstrated the value of this procedure). Second, record SEU memory locations and have a map between memory logic locations and their physical locations. Third, maintain detailed shielding maps for each of the memory boards. These issues were discussed before launch with both mission teams but, because of cost and the desire for noninterference by the SEU evaluation (it was considered of secondary importance to the basic issue of the successful operation of the solid-state data recorders), were not implemented.

Clearly the solid-state data recorder SEU rate variations deserve further investigation. As an advanced, sophisticated spacecraft system, a solid-state data recorder represents an excellent example of how a complex device interacts with the environment. These studies, while demonstrating the value of ground tests, particularly under realistic operational conditions, also show that the normal uncertainties in the environment affect the upset rate in space and must be taken into account.

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