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Single-Event Upset Effects on the Clementine Solid-State Data Recorder

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The sensitivity of the Clementine 2.1-Gbit solid-state data recorder (SSDR) to single-event upsets was characterized in ground tests. Subsequent in situ measurements of the ambient radiation environment by experiments onboard Clementine permitted evaluation of the ability of models of the single-event phenomenon in the SSDR to be tested using actual data. Initial results from the analysis reveal a nearly constant background upset rate of ~71 bit flips/day for the SSDR. There is no obvious correlation with a solar proton event recorded by Clementine and several other spacecraft on Feb. 20–21, 1994, indicating that the SSDR was not sensitive to protons. The constant rate is thus interpreted as being a function of the galactic cosmic-ray heavy-ion environment. A pronounced lunar orbit altitude dependence has also been identified in the data though the cause has not yet been unambiguously identified.

I. Introduction

AS part of the normal housekeeping functions on the Clementine spacecraft, the solid-state data recorder (SSDR) is continuously monitored for single-event upsets (SEUs) during the mission. These data can be correlated with the radiation environment and upsets on other Clementine instruments to determine the performance of the SSDR and its error detection/correction capabilities and to serve as a monitor of SEU rates. The purpose of this paper will be to review the results of an analysis of the SEU rate observed by the SSDR during the Clementine mission. Following a brief summary of the characteristics of the SSDR, the SEU rate will be compared with the ambient environment and with the Clementine orbit. The correlations (or lack thereof) between these parameters will then be used to evaluate the efficacy of the preflight predictions of the behavior of the SSDR in the space environment. The intent of this evaluation, as in the case of related studies,[1] will be to provide insight into the effects of the space environment and spacecraft operations on an advanced complex, SEU-sensitive system.

II. Solid-State Data Recorder

Here only a synopsis of the SSDR will be provided sufficient to understand its behavior for the purposes of the SEU analysis. The Clementine SSDR has 2.09 Gbits of usable storage capacity [actually 2.9 Gbits, of which 786 Mbits are for error detection and correction (EDAC)]. The design incorporates redundant EDAC with active fault management and built-in test capabilities. The recorder employs commercially available 4-Mbit × 1 Hitachi dynamic random-access memories (DRAMs) and has a data throughput greater than 20 Mbit/s with a bit error rate of less than 10^{-10}. The Clementine sensor data were compressed before being stored in the SSDR using a Joint Photographic Expert Group (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 can 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 ~1.5 million 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 are corrected and counted, whereas double bit errors are 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 a SEU detector. The upsets, however, must be specifically monitored for 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 in principle this might yield directional information on the particles causing the upsets, it has not proven possible to physically map these memory locations onto the boards. The SSDR can map around problem areas by ground command if the SSDR detects noncorrectable single bit errors; this apparently was not necessary in flight. Although the actual memory size was over 2 Gbits of usable memory, the storage requirement was ~1.6 Gbits, leaving ~400 Mbits for 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 (CPT), the

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dosimeters, and the Radiation Reliability and Assurance Experiment (RRELAX).[2] A dosimeter was placed near the SSDR to monitor the total dose (at this location it 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 prior to lunar injection when Clementine was briefly in the Earth's radiation belts and through to near the end of the mission during Earth flyby prior to leaving the Earth–moon system. (Note: Clementine, after being dormant for a year, was reacquired in April 1995.)

The SSDR scrubs (checks for bit errors) at rate of 1.3–1.5 Mbytes/s, depending on whether information is being read into or out of the SSDR. It therefore takes about 3 minutes 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 where the entire memory was always scrubbed). Fortunately, on the average, the memory usage was constant from day to day throughout the lunar mapping phase of the mission. However, as will become evident, there may have been operational procedures during the 5-h lunar orbit that caused periodic variations in the bit error rate as monitored at the ground.

III. DRAM SEU Testing

The Hitachi DRAM was tested at the Brookhaven National Laboratory tandem Van de Graaff accelerator. Tests were at 25°C on delidded devices[3,4] using two ions, 102-MeV C^{12} and 129-MeV F^{19}, and at variable incident angles to obtain a wider range of effective linear energy transfer (LET) values. At normal incidence, the LETs for the two ions were 1.4 and 3.6 MeV $\cdot$ cm^2/mg, respectively. The maximum LET of fluorine at a 69-deg incident angle was only 10 MeV $\cdot$ cm^2/mg, which is 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.[4] for the same device, which extended to much higher LET values and hence provided a more accurate saturation cross section. These data are illustrated in the upset cross-section plot, Fig. 1.

The interpretation of upset cross sections for DRAMs is a complex issue as a number of factors must be considered.[5,6] These include 1) failure of the secant correction to obtain an effective LET 2) charge diffusion, which makes it likely that the charge collection volume is much larger at high LET, where diffused charge makes a more substantial contribution to the cross section than at low LET, and 3) statistical variations in threshold voltage, which can cause a small fraction of the memory elements to be far more susceptible to SEU than the average bit in the memory. A technique to examine this latter factor has recently been developed and applied to several DRAMs.[7] These results showed that the cross section of a DRAM varies by nearly six orders of magnitude. Such large variations are probably due to the increased SEU sensitivity of small numbers of access transistors with smaller initial threshold voltage. Thus, the curve is initially very flat, increasing slowly with LET. The data on the Hitachi DRAM show a similar trend: the charge collection volume at low LETs is very small and is probably dominated by prompt charge. At higher LETs, the cross section rises abruptly when the LET is sufficient to upset a typical rather than a marginal access transistor. This trend is shown by the Hitachi results. However, a secant correction, such as applied to the Brookhaven data, fails badly in this steep region of the curve. At high LET values, the curve does not saturate, but continues to increase gradually with increasing LET. This is caused by multiple-bit upsets from diffused charge. The charge collection volume is much larger in this region than in the shoulder at low LET.

The predicted upset rate prior to launch (based on a Weibull fit to the values in Fig. 1) and the expected galactic cosmic ray (GCR) environment was $\sim 7.5 \times 10^{-12}$ SEU/bit $\cdot$ s for a shielding thickness of 60 mils and a 90%-worst-case GCR environment.[8] This gave a prelaunch predicted upset rate of 1300 SEU/day for a total device memory of ~2 Gbit. The data also suggested that the critical LET was as low as 1.5–3.6, implying that the DRAM could be sensitive to the low-energy proton environment (below ~10–100 MeV) and its "knock-on" heavy ions.[9] As will be discussed, there was much more shielding present around the 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. The additional shielding will have a much greater effect on SEU from protons than from the GCR environment. Indeed, although the tests of the Hitachi DRAM imply a sensitivity to proton upset, the GCR upset rate is approximately 30 times greater, with the result that protons will cause a measurable difference in the SEU rate only during a major solar proton event. Finally, the actual GCR environment was not as severe as the 90%-worst-case GCR environment used in preflight models, there being only one moderate solar proton event observed during the mission. These issues will be explored further.

IV. Celementine Mission Trajectory

An important factor in deciphering the SSDR SEU rate is the spacecraft orbit. An essential feature of the Clementine orbit is its high inclination. Following the launch on Jan. 25, 1994 (day 25 for Jan. 1 = 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 by the Interstage rocket motor. This orbit had a perigee of ~500 km and an apogee of ~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 experiment,[2] the spacecraft made a very brief passage through the proton and electron belts on days 45 (Feb. 4, 1994) and 46 (Feb. 5, 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 (Feb. 20 and 21, 1994). Clementine achieved lunar polar orbit on day 50 (Feb. 19, 1994) and left lunar orbit on day 123 (May 3, 1994). Lunar mapping started on day 56 (Feb. 25, 1994) and was completed on day 112 (April 22, 1994). The spacecraft ceased

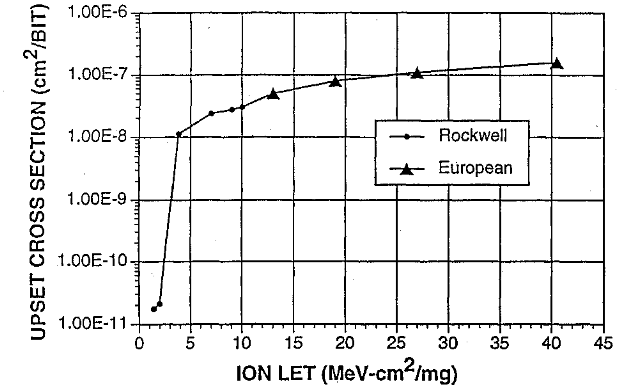

Fig. 1 Hitachi 4-Mbit × 1 DRAM heavy-ion soft-error upset cross section (cm^2/bit) as a function of LET in MeV $\cdot$ cm^2/mg.[3,4]

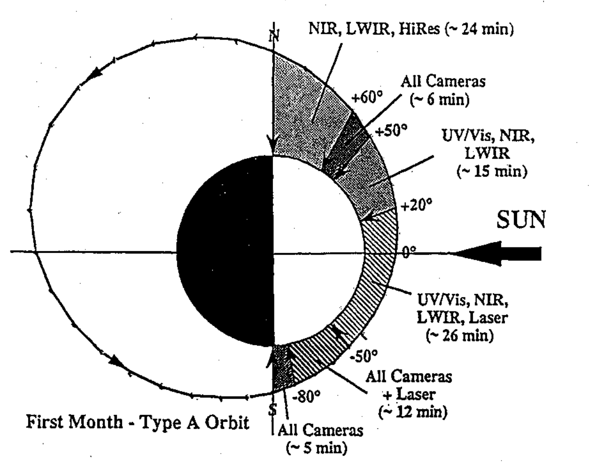

Fig. 2 Schematic mapping plan during lunar orbit for first month of activity when periselene was in southern hemisphere.

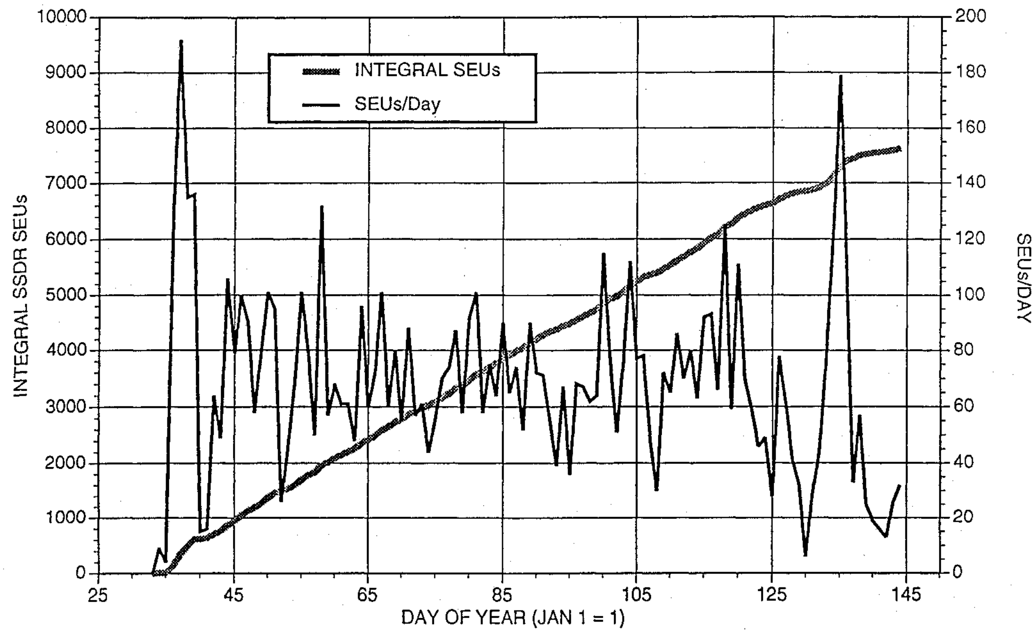

Fig. 3 Plots of the Clementine SSDR integral SEU count (thick line) and daily SEU rate (thin line) as functions of mission duration (Jan. 1 = day 1).

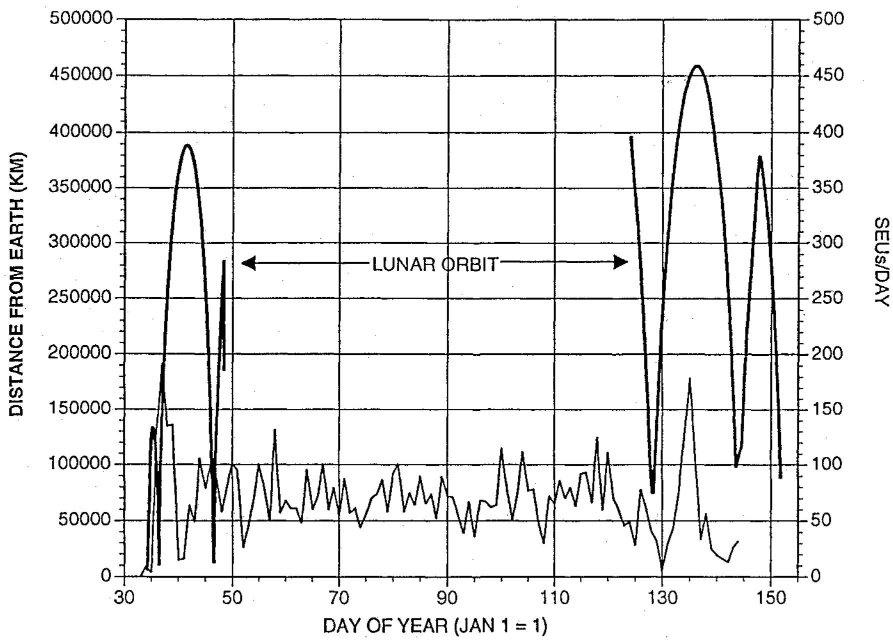

Fig. 4 Clementine SSDR daily SEU rate and distance from Earth vs day of year.

transmitting useful SSDR SEU data on day 151 (June 1, 1994) while in Earth–moon transfer orbit.

The majority of the SEU data were taken during lunar orbit. This orbit is illustrated in Fig. 2. Note in particular that the spacecraft always crosses from the south pole of the moon to the side of the moon illuminated by the sun and that the orbit is 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).

V. Mission SEU Observations

Except for three or four minor gaps, the single-bit SEUs were continuously recorded from day 35 (Feb. 4, 1994) until day 144 (May 25, 1994). The integral of these upsets is plotted in Fig. 3. A linear fit to this curve in time gives

$$S(T) = 70.73522T - 2215.581$$

where S is the total number of SEUs accumulated by time T, T is the date in days (Jan. 1 = day 1), and the correlation coefficient is $R^2 = 0.9991445$. The strong linear trend is clear from the figure. This rate of ~71 SEUs/day differed significantly from the premission-predicted rate of ~1300 SEUs/day for the GCR.

Converting the integral SEU count to a daily SEU rate yields the second curve in Fig. 3. (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. 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 onboard RRELAX experiment. 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.[2] The daily rate is directly compared with the Earth-orbit data in Fig. 4. Although there is an obvious correlation between the pronounced peaks in the SEU rate and the transfer orbits (as opposed to the lunar orbit period), the phasing with distance from the Earth is not

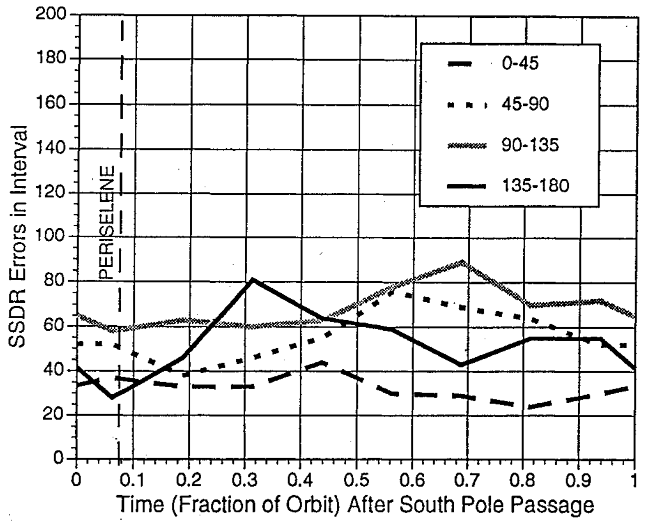

Fig. 5 SSDR SEUs as a function of the fraction (time) of the orbit after south pole passage in terms of the sun–Earth–moon (SEM) angle for days 57 to 85.

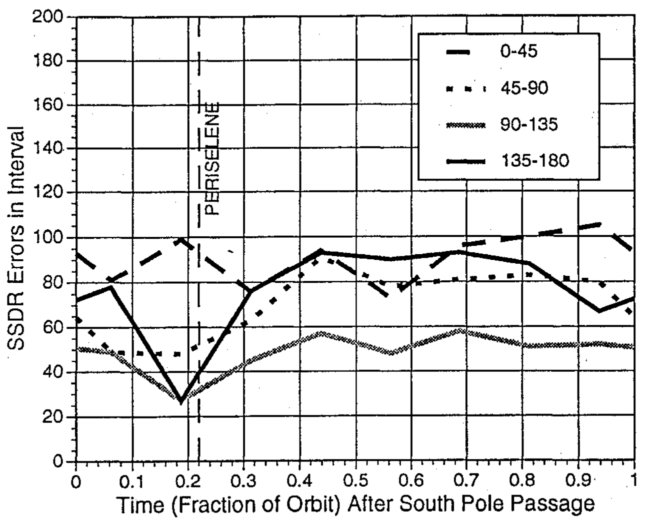

Fig. 6 SSDR SEUs as a function of the fraction (time) of the orbit after south pole passage in terms of the sun–Earth–moon angle for days 85 to 123.

clear—both peaks appear to occur well outside the $\sim 10 R_E$ boundary of the trapped belts.

A cursory review of the SEU data at various time resolutions indicated a correlation might exist between the position of the spacecraft relative to the moon and the Earth (for example, whether the moon was new or full). To test this relationship, the occurrence of SEUs as a function of sun–Earth–moon (SEM) angle was determined. Specifically, the time and position of the SEUs 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 allow for this, the data were further divided into two more groups according as the event occurred before or after day 86. The results are presented in Figs. 5 and 6. 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—see Fig. 2) is marked for the period before day 86 (Fig. 5) and after (Fig. 6). 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.

VI. Discussion

The Clementine SSDR demonstrates 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 after leaving lunar orbit.

3) The presence (absence) of a lunar orbit variation at new moon (full moon).

4) A minimum in the lunar orbit variation at periselene of 30–40% of the maximum count rate around the lunar orbit.

Consider the first finding. Preflight estimates predicted high SEU rate (~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 at the Clementine spacecraft and by several other vehicles. While not conclusive, this indicates that either there were difficulties in the ground measurements of the LET cross section (there may have been problems introduced because of differences in operating voltage between the ground tests and flight—the voltage during testing was 4.5 V, lower than the in-flight voltage), the shielding was much higher than originally assumed, or the GCR environment was more benign than the model. While the first issue cannot be evaluated without further ground tests, variations associated with the latter two can be estimated. 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).

Varying the shield thickness 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. The SSDR memory boards are stacked, and despite knowledge of this stacking design and the external shielding, the lack of information about which board an SEU occurred on prevents an exact estimate of the shielding. Although the Clementine SSDR shielding is thus not precisely known, a review of the spacecraft drawings and conversations with the manufacturer lead us to conclude that the 250-mil thickness is indeed a reasonable estimate for the minimum shielding thickness. As to the GCR fluence, at solar maximum and in the absence of solar proton events, this 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. 1 and the GCR fluences at solar maximum (the lowest level), the SEU rate was estimated to be ~70 SEUs/day. Taking into account that the SSDR was typically operated at 1.6 Gbits or less, the rate would be even lower. Varying the critical LET also demonstrates large variations, indicating that this is probably a major factor in determining the actual SEU rate for the SSDR. Increasing the 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 (since such a high LET is not consistent with the ground tests, it is believed to be unrealistic; even so, the calculation indicates the sensitivity to this parameter). Based on these observations, one plausible explanation for the difference between prelaunch estimates and actual observations is that the observed SSDR daily SEU rate resulted from a lower GCR ambient environment and a thicker spacecraft shield (~250 mils or greater) than originally assumed.

The two peaks at the beginning and end of the mission are more difficult to explain. The obvious assumptions are either that they are associated with passage through the radiation belts or that they 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 in that 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. As to the second point, the SSDR was indeed being operated in different modes during the transfer orbits. A detailed review of the scrubbing procedures and modes during the period day 110 to day 145 showed that although the mode of scrubbing changed from monitoring only that part of memory being written to (up to day 130) to monitoring the entire 2 Gbits (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 moon and/or the Earth are modulating the GCR flux by shielding the spacecraft (the moon by its physical mass, the Earth by its magnetosphere). This possibility will be discussed in more detail shortly.

The presence or absence of a regular orbital variation of the SEU rate depending on the position of the moon relative to the Earth and sun may imply a modulation by the Earth's magnetosphere or by spacecraft operational variations. Operational effects will be discussed later; here magnetospheric variations will be considered. If the GCR are indeed the source of the SSDR SEUs, then there would be some modulation expected by the Earth's magnetosphere. In particular, the magnetosphere is well known to modulate the lower-energy GCR and heavy ions associated with solar proton events through the medium of the Earth's magnetic field. While very weak at lunar distances, the magnetosphere can modulate the GCR. Indeed, Fig. 5 implies that the SEU rate (and thus the GCR flux) is uniformly down when the spacecraft is in the magnetosphere at full moon. Unfortunately, the opposite behavior is seen in Fig. 6, where the lunar orbit variations at full moon are higher than the other SEM positions. Thus, although possible, there is no strong evidence for the magnetosphere being the cause of the SEM modulation.

Another variation to be considered is from the lunar orbit. When the moon is in front of the magnetosphere or on its flanks, there is a pronounced minimum in SEUs at periselene. Indeed, when the periselene was moved (Fig. 5 vs Fig. 6), the minimum followed it. This minimum may be due to operational or environmental effects. A possible environmental effect is that when the spacecraft is near the moon, the moon shields the spacecraft from the GCR. That is, the solid angle for GCR as seen by the spacecraft varies from 2π sr at periselene ($\sim$400 km) to 4π sr at aposelene ($\sim$3000 km). This would provide a modulation of a factor of up to 2. Although this might account for the modulation between 45 and 135 deg (along the flanks of the magnetosphere), it is inadequate for 135–180 deg. The observed modulation is, for new moon, closer to a factor of 3. Other anisotropies exist in the GCR and solar heavy-ion fluxes but are either much lower or anticorrelated. For example, it would be expected that the SEU rate might increase as the spacecraft came into view of the sun if the sun were the particle source (the solar-wind magnetic field would of course modulate the flux). Instead, the rate drops as the spacecraft crosses onto the sunlit side of the moon. Thus shielding of the GCR by the moon is a possible contributor to the modulation but certainly not the only cause.

Spacecraft operations cannot be ruled out as a source of the observed 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. 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 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, where 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. 5, but it is absent in Fig. 6). Even so, like the lunar GCR shielding, this may account for part of the variations observed.

VII. Conclusions

Despite uncertainties in the source of the variations, the following statements can be made about the SSDR and its interaction with the space environment:

1) The Clementine SSDR successfully operated in the space environment and has an observed rate of $\sim$71 SEUs/day. Not one SEU affected operations.

2) SEU cross-section measurements and rate estimates prior to flight were overconservative by a factor of 20.

3) The Hitachi DRAMs were not as sensitive to protons or proton-induced heavy ions as expected prior to flight (no obvious correlations with the proton belt or solar proton events were found). This was probably due to a much higher level of spacecraft shielding than originally anticipated. GCRs were thus the most probable source of SEUs.

4) Distinct temporal variations relative to mission phase (peaks in the count rate during the transfer orbits), lunar position (large 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 may contribute, though the estimated variations were either somewhat lower than observed (lunar modulation) or not consistent with the observations (magnetospheric modulation).

5) Operational effects are a possible cause of the observed variations. In particular, because the SEU counts were recorded and time-tagged only in real time, consistent gaps in data collection may have affected estimates of the times of the SEUs.

6) While the SSDR analysis clearly demonstrated the value of the SEU measurements, future experiments of this nature would clearly benefit by additions to the monitoring process. First, the scrub procedures and operations should be altered to maximize the value of the SEU rate data (i.e., one should time-tag the SEU measurements on the spacecraft and have the memory scrubbed in a well-defined, consistent mode throughout the mission). Second, one should record SEU memory locations and have a map between memory logic locations and their physical locations. Third, one should maintain detailed shielding maps for each of the memory boards. These issues were all discussed before launch but, because of cost and the explicit requirement for noninterference by the SSDR experiment (it was considered of secondary importance to the basic issue of the successful operation of the SSDR), could not be implemented.

Clearly the SSDR SEU rate variations deserve further investigation. As an advanced, sophisticated spacecraft system, the SSDR represents an ideal example for investigation of how such a complex device interacts with the environment. It is recommended that further ground tests, particularly under realistic operational conditions, be carried out. Finally, it is hoped that, as Clementine was returned to operation in April 1995, a series of tests will be possible that should settle many of the issues addressed in this paper.

Acknowledgments

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