Single Event Effect Flight Data Analysis of Multiple NASA Spacecraft and Experiments; Implications to Spacecraft Electrical Designs

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Abstract

We present the spaceflight Single Event Effect (SEE) data for the emerging commercial technologies utilized in multiple NASA spacecraft and experiments. Analyses of device performance as well as design implications of the flight results are discussed.

I. INTRODUCTION AND BACKGROUND

As spacecraft become driven more and more to reduce parameters such as power, weight, volume, and cost, while requiring increased characteristics, emerging commercial technologies have come to the forefront. These technologies include high speed and low power CMOS and fiber optics. Types of integrated circuits (ICs) that utilize these technologies range from complex microprocessors to dense static random access memories (SRAMs). Several spacecraft that are in orbit utilize these types of device in their spaceflight systems or as experiments.

The Total Ozone Mapping Spectrometer (TOMS) is a joint US/USSR scientific experiment launched aboard a USSR Meteor-3 spacecraft. The TOMS/Meteor-3 is the first NASA mission to place a Solid State Recorder (SSR) into orbit as the main data recording device for the instrument. This SSR is a memory-based array of SRAMs utilized for storing science and engineering telemetry on-board the spacecraft. SSRs provide advantages over traditional tape recorders in many respects. These include reduced power, weight, volume, random access to addressed data without the penalty over a tape search, accommodating burst data transfers, selective data playback, ease of data compression, elimination of ground-based data reversal, etc... The TOMS/Meteor-3 SSR utilizes an array of Hitachi 256Kbit (32k x 8) SRAMs. Earlier sets of spaceflight SEE data have been presented previously [1,2].

The Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) is the first in a series of Small Explorer spacecraft being managed by GSFC. In order to meet mission constraints of power, weight, and volume, newer enabling technologies were utilized in the spacecraft's

command and data handling subsystem known as the Small Explorer Data System (SEDS). These technologies include a SSR similar to TOMS/Meteor-3 in terms of utilization of the same Hitachi 256 kbit SRAMs, but also include the SEDS MIL-STD-1773 Fiber Optic Data Bus (or SEDS 1773 bus), the Intel 80386 microprocessor family , surface mount technology, etc... The SEDS 1773 bus, utilizing commercially available fiber optic transmitters and receivers, is the first known utilization of a fiber optic data bus as an in-line spacecraft subsystem. Again, earlier sets of SEE flight data on the SSR have been presented [1,2]. In addition, ground and initial flight SEE results on the SEDS 1773 bus are published in the literature [3,4,5].

The Cosmic Ray Upset Experiment (CRUX) is an electronic package launched in August, 1994 aboard the Advanced Photovoltaic and Electronics Experiment (APEX) spacecraft. This space experiment is designed specifically to test the SEE characteristics of several types of SRAM (256Kbit to 1 Mbit) devices as well as power MOSFETs. Only the SRAMs will be discussed herein. Initial SEE spaceflight CRUX results have been demonstrated elsewhere [6,7]. Results on the APEX SSR (which utilizes Dynamic RAMs or DRAMs) have been published elsewhere [8].

Table 1 summarizes the salient characteristics of each spacecraft and the devices being observed for SEE. Note that two of the spacecraft (SAMPEX and TOMS) are polar low Earth orbiting (LEO) missions, while APEX is placed in a highly-inclined, highly-eccentric orbit. The devices being pursued for this study are the commercial technology SRAMs, in the two SSRs and in the flight experiment, and the SEDS 1773 bus. We point out that the EDI device is a repackaged die from a different vendor, and that Hitachi/Elmo SRAM is a Hitachi die repacked by Elmo.

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Table 1. Salient Spacecraft Characteristics

Spacecraft      Launch     Orbit         Orbit         Devices Under
                Date       Inclination   Altitude      Test (DUTs)
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SAMPEX          7/92       82°           580 x 640 km  Hitachi 256k SRAMs,
                                                        MIL-STD-1773 F/O Data
Bus
TOMS/           8/91       82°           1200 km       Hitachi 256k SRAMs
METEOR-3
APEX/CRUX       8/94       70°           362 x 2544 km Micron 1M SRAMs
                                                        EDI 1M SRAMs
                                                        Hitachi/Elmo 1M SRAMs
                                                        Micron 256k SRAMs
                                                        EDI 256k SRAMs
                                                        IDT 256k SRAMs
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The purpose of this experiment lay in the extension via the analysis of longer time periods of SEE data on these spacecraft as well as to provide lessons learned suitable to both spacecraft designers and radiation effects experts.

II. TECHNICAL APPROACH

The flight data was processed using NASA/GSFC's Radiation Effects and Analysis Sections's SEE flight data analysis system. Capabilities include various plotting packages able to plot data

in formats ranging from B-L coordinates (important for monitoring radiation belts versus free space SEUs), geographic coordinates (Mercator) projections, daily plots of SEUs versus day of year, and perhaps even data animation such as versus orbit track and time.

The data is processed using custom-software, manual analysis, and commercial software packages (EXCEL and IDL) for personal computer (PC)-based platform. TOMS data, in particular, requires extensive manual "cleaning". Engineering noise [1] has been theorized as the cause of memory errors observed on the spacecraft that correlate to tracking of orbital position (i.e., blocks of bits that remain "stuck" at a value tracking the position of the spacecraft during its orbit).

III. SEE DETECTION METHODS

For convenience, we shall divide this section into two arenas: detection of SEEs in memory devices, and those that occur in the SEDS 1773 bus.

Both SAMPEX and TOMS utilize Hamming code for error detection and correction (EDAC) schemes. Hamming code is a simple block error encoding (i.e., an entire block of data is encoded with a check code) that will detect the position of a single error and the existence of more than one error in a data structure [9]. By determining the position of the error, it is possible to correct this error. Most designers describe this method as single bit correct, double bit detect. This EDAC scheme is common among current solid-state recorders flying in space [for example, 1,10] including both SAMPEX and TOMS. When a system performs this EDAC procedure, it is called scrubbing (i.e., scrubbing of errors from good data). An example (SAMPEX) would be a 40-bit wide memory bus having a 32-bit data path and 8-bits of Hamming code. This is known as a (32,8) code. TOMS, on the other hand, employs a (64,8) scheme. Hamming code methods are traditionally recommended for systems with low probabilities of multiple-bit upsets occurring from a single ion strike in a data structure (e.g., only a single bit in error in a byte of data would be acceptable).

TOMS also employs a built-in test (BIT) EDAC feature. This method essentially performs a read of an unused memory location, compares the read value with a known value, and writes back the correct value if the two values differ.

The CRUX memory EDAC method is somewhat similar to the TOMS BIT method; a value (either all digital ones or zeroes) is loaded into the device every 21.33 hours and then loaded with the value's complement for the following time period. The stored values are then read, compared with known data, and modified via a write to the memory location if incorrect. This is simply known as a read-modify-write scheme.

Table 2 reviews each of the memory-based spacecraft for their EDAC and telemetry information. The amount of memory as well as how often EDAC is being performed is of additional interest.

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Table 2. Memory EDAC and Telemetry Information

Spacecraft   EDAC                    EDAC           Telemetry Frequency/
                                     Frequency      # hits
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SAMPEX       Hamming Code (32,8)    every 5 mins    every 5 mins/26.5Mbytes
TOMS/        Hamming Code (72,8)    every 16 secs   every 128 secs/128 Mbits
METEOR-3     BIT Pattern Testing
APEX/CRUX    Read/Modify/Write      every 5 mins    every 5 mins/~70 Mbits
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The SEDS 1773 employs a different style of EDAC: a system level protocol method. This system utilizes among its error control features two methods of detection: parity checks and detection of a non-valid Manchester encoding of data. Parity, being a single bit at the end of a structure, says simply whether an odd number or an even number of ones were in that structure. This method detects an error if an odd number of bits are in error, but if an even number of errors occurs, the parity is still correct (i.e. the parity is the same whether 0 or 2 errors occur). Additionally, this is a "detect only" method of mitigation and does not attempt to correct the error that occurs. The second method detects if the data, which is Manchester-encoded, is in the proper format. Ground testing has shown that Manchester-encoding errors are the prime mechanism for expected SEUs [4].This military standard has a system level protocol option of retransmitting or retrying a bus transaction up to three times if these error detection methods are triggered. Thus, the error detection schemes are via normal methods, while the error correction is via retransmission.

IV. FLIGHT DATA RESULTS

With the plethora of possible graphs and data that could be presented, we will attempt to summarize key results and show data graphs for representative time periods and devices. We will also present summarized data in tabular formats.

A) SAMPEX and TOMS SSR Results

Both SAMPEX and TOMS SSRs have performed successfully since their respective launches. The SAMPEX SSR has performed flawlessly: no discernible engineering noise is evident and all data has been captured without loss. Even with its engineering noise, the TOMS SSR and its EDAC have successfully collected 100% of the spacecraft science and engineering telemetry.

All SEUs observed on both spacecraft have been single bit errors; no multiple bit errors have been noted. Figure 1 illustrates the number of upsets observed per day as a function of Julian day of year for the SAMPEX SSR. Note the variance of SEUs from day-to-day; this tracks well with the precession of the mission orbit and its associated passes through the Earth's trapped proton belts causing peaks and valleys in the daily SEU rates.

It is important to notice that the number of upsets detected per day in the SAMPEX SSR has varied on a yearly basis closely tracking the solar cycle and its associated impact on trapped proton fluxes (AP8MIN and MAX).The average number of upsets per day for the SSR has varied from 100 in 1993 to 120 in 1994 and back to 116 thus far in 1995. Again, all the SEUs observed have been corrected for an effective 100% data collection rate.

Figure 2 provides a Mercator projection of the SAMPEX SSR SEUs for a more recent portion of the mission lifetime than previously presented [1]. Figure 3 illustrates a similarly more recent data set for TOMS. Several items are of importance. One may easily observe the densely shaded region of upsets in the South Atlantic Anomaly (SAA): a densely proton-populated region of the Earth's trapped proton belts that "dips" in the South Atlantic region due to the variance between the main dipole term and the geographic poles. Over 90% of the SEUs observed have been in the SAA with the remaining SEUs most likely being caused by galactic cosmic rays at the higher latitudes. This is consistent with previous data sets.

No information is gathered on these two spacecraft concerning whether the SEUs transition from a stored zero value to a one (0-to-1) or vice-versa (1-to-0). No destructive single event latchups (SEL) or microlatchups have been detected on either mission. The flight data correlates well with the radiation ground test data presented by Koga, et al... [11]. Pre-flight SEU rate predictions [1] are well within a 25% margin of observed in-flight averages. Table 3 summarizes the results of the SAMPEX and TOMS data.

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Table 3. SAMPEX and TOMS SSR Results
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Spacecraft	Device	In-flight Upsets/bit-day x 1E6	Predicted Upsets/bit-day x 1E6	Multiple-bit Upsets	Stuck bits	SEL
SAMPEX	Hitachi 256k	4.21	3.832	No	No	No
TOMS/ Meteor-3	Hitachi 256k	3.12 [1]	3.32	No	No	No

B) CRUX Memory Results

Table 4 provides the notable results for the CRUX experimental devices. Figure 4 illustrates the number of upsets observed for the Hitachi/Elmo 1 Mbit SRAM per day as a function of Julian day of year. Note again the effect the precession of the orbit causes as certain days experience higher levels of proton fluxes than others.

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Table 4. CRUX SRAM Results
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CRUX Device Upsets [7]	Upsets/bit day x 1E-6 [1]	Multiple bit Upsets	Stuck bits	SEL	% of Number of 0=>1, 1=>0
Micron 1M	11.1	No	No	No	98, 2
EDI 1M	12.484	No	Yes	No	54, 46
Hit/Elmo 1M	7.423	Yes	Yes	No	65, 35
Micron 256k	51.495	Yes	Yes	No	77, 23
EDI 256k	3.701	No	Yes	No	46, 54
IDT 256k	24.087	No	Yes	Yes	77, 23

One additional fluctuation is based on the number of SEUs transitioning from 0-to-1 or 1-to-0

which affects the daily number of SEUs observed as well. For the Hitachi device [7], 65% of the upsets have been from the 0-to-1 mode. Hence, remembering that the device is programmed to all zeroes for one 21.33 time period, then all ones for the next leads one to observe greater consecutive day variance than one might expect if a single data pattern was utilized. Preliminary proton ground test results agree with this. The Hitachi devices that were irradiated from the same lot as those flown showed a prevalence of between 63 to 68% of the flight proton- induced upsets being from 0-to-1 transitions. Preliminary ground test proton data on the EDI 1 Mbit, Micron 1 Mbit, and IDT 256 kbit agrees similarly with the observed flight results. No ground test proton data has yet been collected on the other CRUX devices.

Figures 5 and 6 are Mercator projections of the Hitachi SEU flight data that has been "binned" into the same altitudes as those encountered by the SAMPEX and TOMS SSRs respectively. One may easily note the prevalence of the SAA- induced upsets for this device in addition to the similar shape of SEUs versus the two SSR missions. Again, greater than 90% [6] of the SEUs observed for all the CRUX SRAMs are proton-induced. As one would expect, the TOMS-binned CRUX data shows a higher number of SEUs than the SAMPEX-binned data, due to the higher total amount of memory (128M vs. 26.5M). At the higher altitude of TOMS, the proton fluxes, expecially those of higher energies, are more intense.

Further CRUX results showed that two of the devices (Hitachi 1 Mbit and Micron 256 kbit) experienced multiple-bit upsets. In a near 300 day time period, approximately 50 double-bit (two bits in the same byte) errors occurred in the Hitachi device, while the Micron 256 kbit SRAM demonstrated one double-bit and one triple-bit SEU. The majority of the Hitachi multiple-bit upsets have been seen in the SAA. Again, preliminary proton ground test experiments on the Hitachi device agree with this result.

All CRUX devices sans the Micron 1 Mbit detected the occurrence of a temporary stuck bit thus far during the mission. This is loosely defined as a memory cell that has upset to an incorrect value that is not able to be corrected by a simple device write. These particular stuck bits, however, disappeared after some timeframe (seconds, minutes, hours) and were able to be rewritten with the correct data values.

A potential SEL condition was observed on the IDT 256 kbit. Current consumption was monitored on the board and not on the device level, thus monitoring of device current consumption to detect SEL would only occur if an extremely high current on a device was observed. The symptom for this potential SEL was the reading of all ones values for a single device rather than zeroes for an entire 21.33 hour time period. A cycling of power to this board corrected this problem.

Reference [7] also presents information regarding the SEU variance from devices of the same SRAM type that were observed during the CRUX mission. This variance was wide for certain device types even though all test samples were thought to be from the same wafer lot. Verification of this (same lot) is being investigated further.

C) SEDS 1773 Bus

The SEDS system detects the number of retransmissions (or retries) that occur following an SEU. Ground test data [3,4] has shown that all SEUs observed by the system are in the form of non-valid Manchester errors causing a bus retry. For SAMPEX, a single retry is enabled. This is all that has been necessary. Calculations by LaBel, et al... [4] have shown that the probability of a failure of a retried message is extremely small. Indeed, all bus retries have been successful. Thus, the effective bit error rate (BER) is zero.

Figure 7 illustrates the number of bus retries occurring per day versus Julian day of year. Note, again, the variance of SEUs from day-to-day mimicking the results from the SSRs.

It is again significant to note that the number of retries detected per day on the SEDS 1773 bus has varied on a yearly basis closely tracking the solar cycle and its associated impact on trapped proton fluxes (AP8MIN and MAX).The average number of retries per day for the SEDS 1773 has varied from 9 in 1993 to 11 in 1994 and back to 10 thus far in 1995. Pre-flight retry rate predictions [4] coincide within a factor two (worst-case predicted rate of 18 retries per day).

Figure 8 provides a Mercator plot of the SEDS 1773 bus retries versus geographic coordinates. As one would expect with a system that is sensitive to direct ionization from protons [4], the majority (>95%) of the retries occur in the SAA.

No anomalous behavior has been observed on the SEDS 1773 bus. It should be noted that goal mission lifetime was specified as three years and at the end of that timeframe (July 1995), the SEDS system was still performing nominally.

V. SPACECRAFT DESIGN IMPLICATIONS

Spaceflight SEE data has sparked interest in multiple arenas: environment, device performance, ground test correlation, etc.. We present here implications involved with spacecraft designers needs and design constraints.

A) SSR and SRAM Implications

Single bit errors in a SSR are relatively easily handled by a spacecraft designer using the previously mentioned Hamming EDAC scheme and shown in [1]. However, multiple bit errors, as well as errors such as the temporary stuck bits observed in some CRUX devices, cause more concern. Under Hamming EDAC, these data would be marked as incorrect and a data loss would ensue. This does not necessarily need to be the case.

Other block error codes provide more powerful error correcting codes (ECCs). Among these, Reed-Solomon (R-S) coding is becoming widespread in it's usage [11]. The R-S code is able to detect and correct multiple and consecutive errors in a data structure. An example [12] is what is known as (255,223). This translates to a 255 byte block having 223 bytes of data with 32 bytes of overhead. This particular R-S scheme is able to correct up to 16 consecutive bytes in error. This R-S encoding scheme is available in a single IC as designed by NASA VLSI Design Center [12]. A modified R-S code for a SSR has been performed by software tasks as well [13]. Unfortunately, use of R-S ECC does not enter the design without constraints of its own. Power

consumption, memory overhead, etc..., all must be traded with the probability of non-single bit upsets occurring before the use of R-S coding is included.

A simpler way of reducing multiple-bit upset rates is to choose devices with no physical bits adjacent to any of their logical neighbors, i.e., no two bits in the same byte are adjacent physically [11]. On devices that are nibble or byte- wide structures, this data for commercial devices is not necessarily readily available from the manufacturer, however. Ground testing should be performed to confirm or map out the memory structure of a device. Memory devices that have a single-bit wide structure (i.e., 1 Mbit x 1 as opposed to 128 kbit x 8) are essentially immune to "logical" multiple-bit upsets. A single ion strike may affect two or more bits in the same device, however, they are in logically distinct bytes since the byte would be spread across eight different SRAMs.

If a multiple-bit event occurs, as observed by the CRUX devices, does the impact to the system BER affect the spacecraft performance? More succinctly, if a specified spacecraft has a criteria (typically 1E-5 to 1E-7 errors per bit- day) on its satellite-to-ground link, will 50 double-bit events in 300 days, allow the system to perform within its specification? The answer is simple; it depends on the mission-specific requirements, the EDAC scheme, as well as the precision of the data being captured. It should be strongly noted that other device characteristics (cell density, die size, power consumption, availability, etc..) also must be included in the trade study for device utilization.

Two known spacecraft SSRs [14] have baselined the use of the Hitachi 1 Mbit SRAM for spaceflight despite the possibility of an occasional stuck bit or multiple-bit events. In these cases, the specific multiple-bit upset rates for these SSRs has been deemed acceptable. Both of these spacecraft missions are planning a Hamming EDAC scheme. Thus, there is the possibility of an occasional uncorrectable byte error occurring. In both missions, the system BER even with worst-case pre-flight event predictions was well within project specification. It should be pointed out that these devices were selected primarily by the spacecraft designers for their ultra-low standby current consumption and device availability. With a static mode power in the range of 10 uA versus mA for some other 1 Mbit SRAMs, using these devices in large quantities (100s of MBytes in a SSR) saves the spacecraft enormous amounts of power. This is a key factor to remember; radiation effects are only one necessary portion of device selection amongst many.

A stuck bit was also observed for almost all of the CRUX SRAMs. For the most part, single-bit correct Hamming code would be sufficient to "effectively" mitigate this condition. However, it does raise the issue of a second SEU causing a normal bit-flip in a second bit of the same byte. This should have a very small probability of occurrence and is only of concern in missions that must have a zero BER.

A potential SEL was also observed. As with a multiple-bit upset, Hamming code ECC would be ineffective in data correction, but R-S coding would correct the data, assuming a wider memory structure than a single byte. However, the use of R-S ECC would not necessarily aid in the detection of the SEL, but simply correct the errant data bits. Device current consumption must be monitored as well. However, some SRAMs (Hitachi 1 Mbit, for example) have a very low

standby current consumption. Even with 20 MBytes of memory on a card or in a cube, current consumption is a function of device activity for that board. If SEL occurs, it would be detected at the board level during standby mode. In typical spacecraft, standby, or static, mode is the prevalent operating scenario for a SRAM device in an SSR during mission operations. This type of analysis is very specific to the device type utilized and the individual currents that are related to the device SEL.

Additionally, SSR designs typically utilize "spare" memory: either an extra memory card or spare devices. If a device fails (from SEL or through attrition), memory management systems may be designed to map around the failed component. Thus, the system is capable of being designed to provide a reliable fault tolerant solution to a SEL as long as the current drawn by the failed device does not affect the operation of its surrounding devices or board.

As has been observed throughout the literature in recent years, proton-induced SEUs dominate the upset rates for commercial memory devices for those missions that enter the proton belts for portions of their orbits. Designers should be made aware of this fact.

It is interesting to note that several CRUX devices had significant variance in upset rates from 0-to-1 versus 1-to-0. This may affect certain system design constraints such as the choice of fill patterns or synchronization symbols. Again, with the proper use of EDAC, the system designer need not be concerned.

It should also be pointed out that it would be easiest for designers to utilize devices that have only single-bit SEUs occurring. Unfortunately, as noted out previously, this is not always the best choice for other device characteristics.

A last concern is the SEU variance noted on devices from same lot on the CRUX mission. The implication here is less clear. Lot verification for SEE events on commercial-type devices has been recommended by the radiation effects community for some time. If there truly is a wide variability between devices of the same lot, the recommended philosophy must be rethought as well. If the devices turn out to be from separate lots, however, then SEE testing of each lot is recommended.

B) SEDS 1773 Bus Implications

Previously [5], we have presented a series of lessons learned from the development and ground irradiation testing of the SEDS 1773. We will present here the lessons learned from spaceflight.

In essence, the prime lesson for spacecraft designers is the overwhelming success of the SEDS 1773 bus. All data has been successfully passed between spacecraft systems with an effective system BER of zero. Previous data [3,4] have pointed out that the system worked even during a solar flare in October of 1992. An increase in retry rates was observed, but all bus retries were successful even during this time period.

This first use of fiber optics data bus technology has paved the way for future higher speed and performance fiber optic communication systems to be utilized in spaceflight. Reference 15 and

its discussion of higher rate fiber optic data bus radiation testing is but one of many efforts emerging in this arena.

VI. CONCLUSIONS

We have presented summary SEE data from three different spacecraft and their associated commercial-technology devices: SRAMs and the SEDS 1773 fiber optic data bus. This has included trending data over extended time periods as well as discussion of particular events.

Successful mission achievement and the implications of their in-flight SEE performance have allowed spacecraft designers to consider the use of higher performing systems that utilize denser memory devices and faster fiber optic links for future satellites.

VII. ACKNOWLEDGEMENTS

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