Observation and Analysis of Single Event Effects On-board the SOHO Satellite

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***Abstract*--SOHO, the ESA solar observation satellite, has experienced a large number of Single Event Effects (SEEs) since its launch in December 1995. This paper details events believed to be induced by cosmic rays or protons. Self switch-off power supply events in the service module and in the payload module will be detailed as well as Single Event Upsets (SEUs) in the Solid State Recorder (SSR) and in the Global Oscillation at Low Frequency (GOLF) instrument. Power system events are believed to originate from transient SEUs in linear components. SSR and GOLF SEUs are seen to respond to solar particle events. Relevant ground verification testing will be presented and upset predictions are compared with observations.**

I. Introduction

SOHO (the SOlar and Heliospheric Observatory) is a scientific international satellite dedicated to the study of the Sun and the interplanetary medium. SOHO is in a Halo orbit around the Lagrangian point L1 that is located 1.5 million-km from the earth in the sunward direction. The orbit has a 6-month period covering 200000 km x 650000 km in the ecliptic plane and 120000 km out of the ecliptic plane. Being outside the earth's magnetosphere, it has so far experienced a relatively quiet environment, with Galactic Cosmic Rays (GCRs) and small solar energetic particle events occasionally providing a more dynamic component.

During five years of successful operations, SOHO also experienced a large number of SEEs, all of which were recoverable. These events, as covered here, can be reported for a) various power supply units (PSUs), b) the Solid State Recorder and c) the Global Oscillation at Low Frequency instrument.

A major ESA ground simulation and test program followed up the more serious SOHO power system events. As earlier investigations suggested, these power system events were believed to originate from transient SEUs in linear components [1]-[6]. So high priority was given to reproducing *flight* conditions and using flight lot devices for testing.

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II. SOHO SEU

A. Power Supply Events

The SOHO Electrical Power SubSystem (EPSS) has to regulate, distribute and control power from the solar array and batteries. All EPSS functions are redundant and protected by current limiters. Four identical Power Distribution Units (PDUs) provide mainbus power to: the service module electronics (SVM), the attitude and orbit control system (AOCS), and two supplies for experiments and heaters on the payload module (PLM1 and PLM2). Individual redundant Power Supply Units (PSU) power the various service sub-modules, control systems and scientific instruments. These PSUs are the subject of the following reported 'self switch-off events', observed in the Service Module and in the Payload Module.

Service Module

For the service module, seven Emergency Sun Reacquisition's (ESR's) and three Battery Discharge Regulator (BDR) events are suspected to be SEE related. All ten events, of which four were recoverable power switch-off events (PSU reset), occurred during normal operations with bus, load, voltage, current and temperature nominal. The other Attitude Control Unit (ACU) PSU event, the Central Data Management Unit (CDMU) PSU switching event (from prime to redundant PSU) and the Attitude Anomaly Detector off-pointing event (spurious signal), are all believed to be software related. Table I details the ESR events and Table II the BDR events.

TABLE I
ESR EVENTS

Date	Unit	Event
04/12-1996	ESR	Attitude Control Unit – PSU reset
19/11-1997	ESR	Attitude Control Unit – self switch-off
03/03-1998	ESR	Centrale Data Mana. Unit – switched
28/11-1999	ESR	Attitude Control Unit – PSU reset
07/01-2000	ESR	Attitude Anomaly Detector – spurious
28/11-2000	ESR	Attitude Control Unit – PSU reset
14/01-2001	ESR	Attitude Control Unit – PSU reset

The 07/01-2000 ESR is not PSU related but the signal path includes a linear component (PM139) also used in the critical path of the PSUs.

As BDR switching requires over-voltage or over-current triggering, we can only assume 'false triggering' as the most likely cause.

TABLE II
BDR EVENTS

Date	Unit	Event
12/01-1997	BDR1.2	Switch-off triggered by protection
01/04-1997	BDR1.1	Switch-off triggered by protection
16/05-1998	BDR2.1	Switch-off triggered by protection

A preliminary assessment of the BDR design revealed a protection circuit using PM139 comparators, however, as this design (and the used flight parts) has not been ground tested, we can only speculate that the likely cause was related to transient SEUs.

Payload Module

Recoverable power switch-off events have also occurred in the Variability of solar IRradiance and Gravity Oscillations (VIRGO) instrument. A total of seven events occurred, four self switch-off events (no abnormal voltage/current behaviour) and three latch-up events (high current measured) in the Data Acquisition System (DAS), as shown in Table III.

TABLE III
VIRGO EVENTS

Date	Unit	Event
09/09-1996	VIRGO	Crashed – self switch-off event
07/05-1997	VIRGO	Latch-up - self switch-off event
20/05-1997	VIRGO	Latch-up – self switch-off event
26/05-1998	VIRGO	Power fail – self switch-off event
12/07-1999	VIRGO	Latch-up in DAS – (1^{st} SEL)
11/02-2000	VIRGO	Latch-up in DAS – (2^{nd} SEL)
30/03-2001	VIRGO	Latch-up in DAS – (3^{rd} SEL)

For the Large Angle and Spectrometric COronagraph (LASCO) instrument, five events point in the direction of being power switch-off related, however, triggering could also have come from external sources. The first three events are all listed as over/under voltage detections causing LASCO to shut down and requiring reboot. The fourth event caused the electronic box to hang-up and required a reboot. This event occurred during commanding operations and could be software related. The fifth event, showing the LASCO PROM card to be off and requiring reboot, could also be software related. These events occurred as shown in Table IV.

TABLE IV
LASCO EVENTS

Date	Unit	Event
19/03-1996	LASCO	Voltage anomaly – requiring reboot
10/06-1996	LASCO	Voltage anomaly – requiring reboot
19/12-1996	LASCO	Voltage anomaly – requiring reboot
26/04-1998	LASCO	Hung-up – requiring reboot
28/03-2000	LASCO	PROM off – requiring reboot

Detailed analysis of the various power supply schematics identified a number of analog IC's which, in combination with latches, could cause power supply switch-off. Possible SEU/latch scenarios include the following components:

Attitude Control Unit, PSU

PM139 Quad Voltage Comparator
UC1707J Dual Channel Power Driver
UC1842J Current Mode PWM Controller

Central Data Management Unit, PSU

PM139 Quad Voltage Comparator
UC1707J Dual Channel Power Driver

LASCO, PSU

PM139 Quad Voltage Comparator
UC1707J Dual Channel Power Driver

VIRGO,PSU

PM139 Quad Voltage Comparator

B. Solid State Recorder

The SSR on-board SOHO is used as the primary mass storage with a capacity of 2 G-bit. This version is designed with memories from Texas Instruments (TI), the SMJ44100 type (process S2.1), which is a 4Mx1 Dynamic RAM. The SSR is protected against latch-ups and data corruption caused by SEUs is minimised through error correction using Hamming code. With this code any single bit error in one word can be corrected. To properly reduce the bit error rate, a scrubbing function continuously "cleans" the memory. This function reads the data stored in memory and corrects it if needed. Each 16-bit word is read every 29 minutes when the full capacity, 2 G-bit, is used. Each error corrected SEU also increments an SEU counter.

From April 1, 1996 until August 30, 2001, the observed SEU rate has been plotted as shown in Fig. 1. The average upset rate fluctuates around one SEU per minute, ranging from 0.5 to 1.2 when averaged over 4 hours. The large peak, on November 6, 1997, and even larger peaks on July 14, 2000, and November 9, 2000, happened during major solar flares. In addition to the solar events, the effect of solar activity is apparent in the decline in the upset rate as solar maximum is approached. This history is highly coherent with ground-level neutron monitor data.

The mission interruption gap, starting June 25, 1998, was due to operational mistakes causing the loss of power – and temporary shutdown of SOHO. After the recovery in July 1998 the SSR was re-commissioned on September 17, 1998, ending the gap of 85 days. The second gap of 43 days, from December 21, 1998 to February 2, 1999, was due to the loss of a gyro. Subtracting some additional short-term service interruptions, the SSR has provided a total of 1562 days of in-orbit SEU data up to August 30, 2001, and continues to provide more.

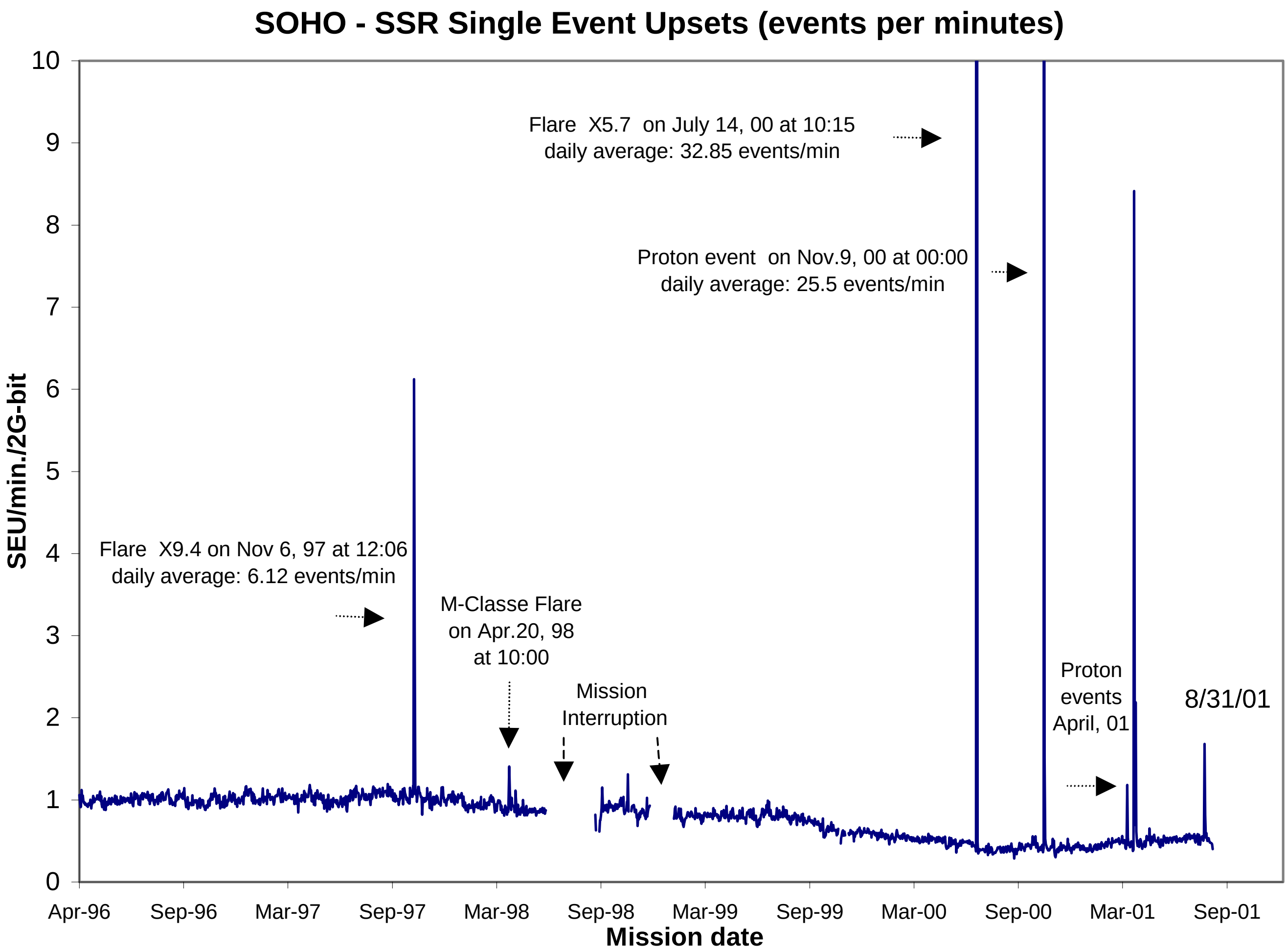

Fig. 1. SEU upset rate for 2 G-bit T.I. 4Mx1 DRAMs.

C. GOLF Instrument

The GOLF instrument on-board SOHO aims to study the internal structure of the Sun by measuring the global oscillation spectrum in the 10^{-7}-10^{-2} Hz range. The spectrum is determined through the Doppler shift measurement of the sodium element viewed in the photosphere.

The GOLF instrument consists of 3 units: the Sensor Unit, the Data Processing Unit (DPU) and the Power Supply Unit. In this paper we concentrate on the DPU, which is configured around a CMOS microprocessor 80C86 and SRAMs, Matra MHS (now ATMEL) CP65656EV-45 32Kx8. The software is resident inside a bipolar PROM. As the bipolar PROM is very power hungry, the program is loaded into SRAMs when the experiment is switched on and the PROMs are switched off. To compensate for the SEU susceptibility of the SRAMs, a Hamming code is used for error detection and correction. This implies 16 bits of useful code plus 6 bits of Hamming control. When an error occurs inside the 22-bit word, it is detected and corrected before being executed by the microprocessor. The processor background task continually scans the program area in the RAM to find SEU errors and correct the 22-bit data. At the same time a flag is raised in order to inform the operator of the SEU error. The total area scanned in the RAMs with the Hamming code is 23352 bytes, thus 186816 bits.

The GOLF instrument has recorded SEU data since January 1, 1996. Here, data are presented until January 31, 2001, covering a monitored period of 1723 days (GOLF was also off for 105 days during the SOHO interruption). A total of 69 SEUs were recorded including 15 events occurring during solar flares. With the average upset rate of 1 SEU per 32 days (not including the flare SEUs), or a mission distribution as shown in Fig. 2, the basic SEU trend shown by the SSR appears to be confirmed. It is worth noting that there is no convincing explanation for the statistical SEU fluctuations recorded for the first 6 months of the mission whereas the remaining period reflects well the solar activity pattern. During the solar flare of November 6, 1997, 3 events were recorded on the same day. The July 14, 2000, flare saw 9 SEUs and the November 9, 2000, another 3 SEUs. These flare SEUs are plotted as triangles (Δ) in Fig. 2.

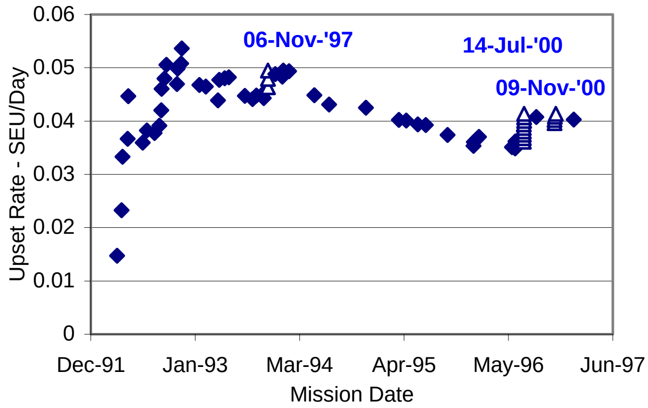

Fig. 2. GOLF - SEU in MHS CP65656EV (186816 bits).

III. Ground Testing

SOHO flight spare devices were ground tested for SEU at the Heavy Ion Irradiation Facility at the cyclotron at UCL, Belgium (analog IC's and SRAMs), at the Twin Tandem at Brookhaven National Laboratory, Long Island, USA (DRAMs) and at the Proton Irradiation Facility, PSI, Switzerland. To obtain the best possible basis for comparison, various SOHO applications and their associated operating conditions were used during these tests [7].

A. Power Supply Events

Details of the various linear IC tests can be found in [7], however here, a short summary of relevant information, test conditions and results, will be presented.

LM/PM139 Quad Voltage Comparator – AD/PMI & NSC

Test Conditions:

Two test configurations were used, one representing the VIRGO design with VDD = 10.0 V and input levels of 300 mV/290 mV (and for comparison 300 mV/250 mV) and one as a comparator with VDD = 10.0 V and differential input level of about 50 mV.

Heavy Ion Results:

Very different transient SEU test results for the two test conditions were obtained as given in graphical form in Fig. 3. For VIRGO nearly every transient event also changed the state of the circuits latch, representing power supply switch-off. Slightly lower transient events were measured when using higher delta input levels, as reported in [7]. Typical transient waveforms were rail to rail and up to 2 microseconds duration.

Proton Results:

For the VIRGO set-up, no transient SEUs were detected at 300 MeV and a fluence of 5 x 10^{10} protons/cm^2. Comparator testing showed cross section sensitivities as shown in Fig. 4 with transient waveforms similar to those observed during heavy ion testing (rail to rail and up to 2 microseconds).

As can be seen from Fig. 3 and Fig. 4, no noticeable differences in the upset sensitivity can be reported for the two LM/PM139 types tested, the Analog Devices/PMI JM38510/11201SCA and the National Semiconductor LM139J B9718AB.

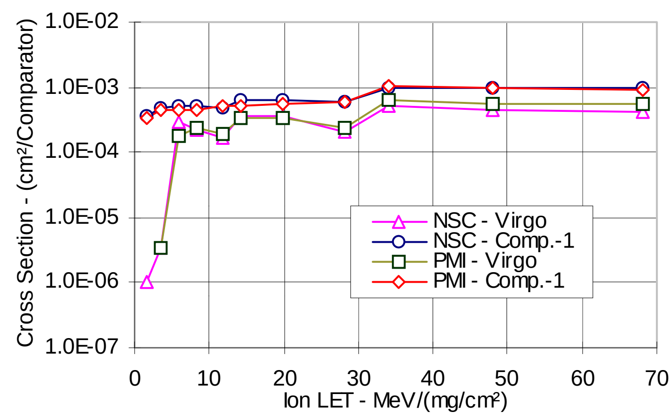

Fig. 3. NSC LM139J and AD/PMI PM139 Heavy ion SET results – VIRGO and Comparator tested.

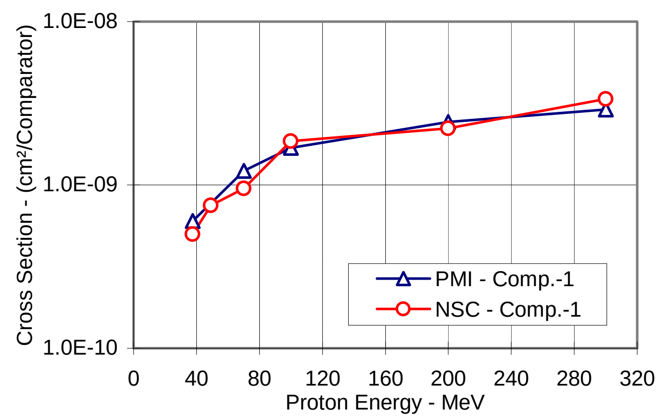

Fig. 4. NSC LM139J and AD/PMI PM139 Proton SET results – Comparator 1 tested.

UC1707J Dual Channel Power Driver - Unitrode

Test Conditions:

Two test configurations were used, one representing the BA ACU design with VDD = 15.0 V and input levels of 6.2/ 6.5 V, and one representing the LASCO design with VDD = 15.0 V and input levels of 6.0/3.0 V.

Heavy Ion Results:

Transient SEU results for both the BA ACU testing and for the LASCO testing are shown in Fig. 5. Noticeable is the high sensitivity of the BA ACU driver output and latched SEU output (comparator contributed) compared to the LASCO sensitivity based on the driver output only.

Proton Results:

Expecting low SEU rates, only the more sensitive BA ACU design was tested. At 300 MeV, the transient SEU sensitivity was measured to be 2.0 x 10^{-11} cm^2/device (very low).

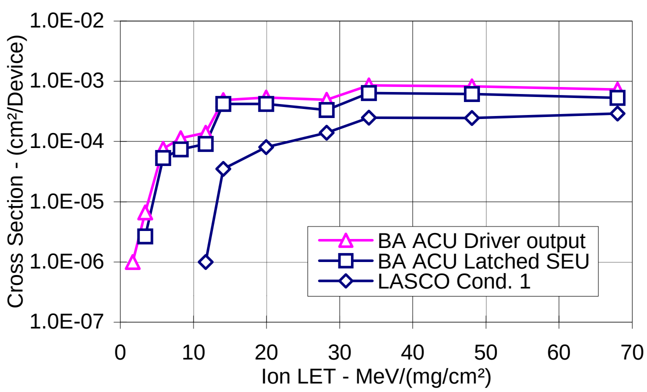

Fig. 5. Unitrode UC1707J Heavy ion SET results – BA ACU and LASCO tested.

UC1842J Current Mode PWM Controller – Unitrode

Test Conditions:

For completeness, this device type was included in the testing even though no representative SOHO design was used. A test set-up providing simulation of instantaneous pulse current control mode was used [7]. Converted pulse width into transient amplitudes is counted as small errors representing phase shifts and large errors representing period mismatch. Table V summarizes obtained transient SEU results.

TABLE V
TRANSIENT SEU RESULTS

Unitrode UC1842J	Current Mode PWM Controller	
	Saturated/device	Threshold
Heavy ion/ Small errors	3.0x10^{-03} cm²	1.7MeV/mg/cm²
Heavy ion/Large errors	7.0x10^{-04} cm²	3.4MeV/mg/cm²
Proton/Small errors	6.0x10^{-10} cm²	70 MeV
Proton/Large errors	8.0x10^{-11} cm²	100 MeV

Overall no latch-ups were recorded in the LM/PM139, UC1707J and UC1842J tests, but there were surprisingly high levels of transient SEUs. Observed transient SEU levels were confirmed [5][10] to depend strongly on test conditions, input levels and loads. Most SOHO designs appear to be sensitive and are able to cause switching, if triggered by heavy ions or protons.

Finally, it is worth mentioning that both the VIRGO and the GOLF instruments use exactly the same power supply design but at different current triggering levels. The GOLF experiment uses an input triggering level three times higher than VIRGO and has not experienced any power switch-off events.

B. *Solid State Recorder*

SMJ44100 4Mx1 DRAM – Texas Instruments

Two T.I. 4Mx1 DRAM devices, mask S2.1, were SEU tested at both BNL and PSI using a dedicated SEE test system. SEU test results, presented as cross section per bit as a function of ion LET or proton energy can be found for heavy ions in Fig. 6 and for protons in Fig. 7. The heavy ion curve shows a very typical saturated cross section level whereas the drop around the LET threshold is unusual. The fall in the curve occurred when testing with Carbon-ions (LET = 1.5 MeV/(mg/cm^2) and having the Device Under Test (DUT) tilted between 30º and 60º. This somewhat strange behaviour is due to the combination of a light ion and the 4Mx1 DRAM topology. The DRAM memory cell used a trench capacitor design with a depth of 7.6 µm and a diameter of 1.3 µm (physical cross section measured). With these dimensions, the length of the ion track through the sensitive volume will be reduced at tilt angles and result in a deposited charge lower than the critical charge required for upsets.

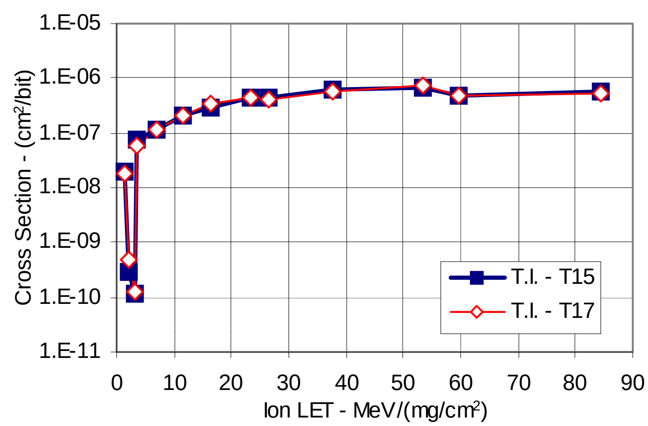

Fig. 6. T.I. SMX44100-80 4Mx1 DRAM Rev. B S2.1. – Heavy ion SEU results

Proton test results shown in Fig. 7 are consistent with the previous data, confirming that this part type is fairly sensitive. The saturated cross section level was measured to be around 4.0 x 10^{-13} cm^2/bit and the energy threshold to be lower than 29 MeV.

C. *GOLF Instrument*

CP65656EV-45 32Kx8 SRAM – MHS

Two SRAM devices from the GOLF flight lot were heavy ion tested at UCL and proton tested at the low energy beam line, OPTIS, at PSI, using the same memory test equipment. Heavy ion SEU results, as presented in Fig. 8, show a similar saturated cross section behaviour as the T.I. DRAMs whereas the LET threshold sensitivity move towards a higher value. This lower SEU sensitivity is also apparent in the proton response as shown in Fig. 9. As a direct per bit comparison, extrapolation to a saturated cross section value would probably come close to

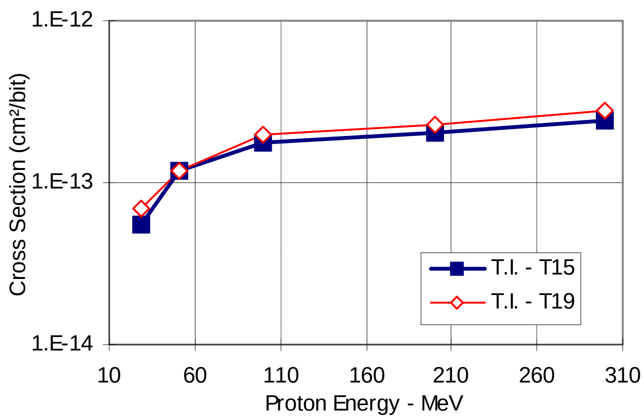

Fig. 7. T.I. SMX44100-80 4Mx1 DRAM Rev. B S2.1. – Proton SEU results

1.0 x 10^{-13} cm^2/bit compared to 4.0 x 10^{-13} cm^2/bit for the DRAM. The proton cross section value around 20 MeV appears to be magnitudes lower.

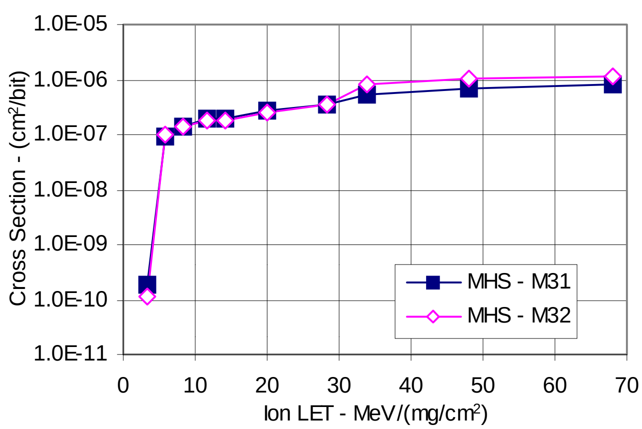

Fig. 8. MHS CP65656EV 32K8 SRAM – Heavy ion SEU results

IV. Predictions

In-orbit upset rate predictions for the various SOHO devices, was carried out using CREME96 [8], and for the memories also SPENVIS (ESA's Space ENVironment Information System) [9]. Interplanetary Galactic Cosmic Ray environments covering the SOHO mission period were used. Experimentally determined cross-sections versus LET/Energy curves, as presented here, were also used. Not knowing the spacecraft shielding for the various components, a standard shielding thickness equivalent to 1 g/cm² Al was assumed. Device dimensions were generally retrieved from the square root of the saturated cross section per bit and assuming a device depth of 2 µm. The predicted number of events as detailed in Table VI is the combined number of events for both heavy ions and proton nuclear reactions.

The VIRGO PM139 observed mission rate of 5 events/comparator compare directly with the predicted number. Assuming none of the LASCO UC1707 events to be self switch- off events, the prediction also confirm this by calculating a very low mission probability rate, < 0.1event.

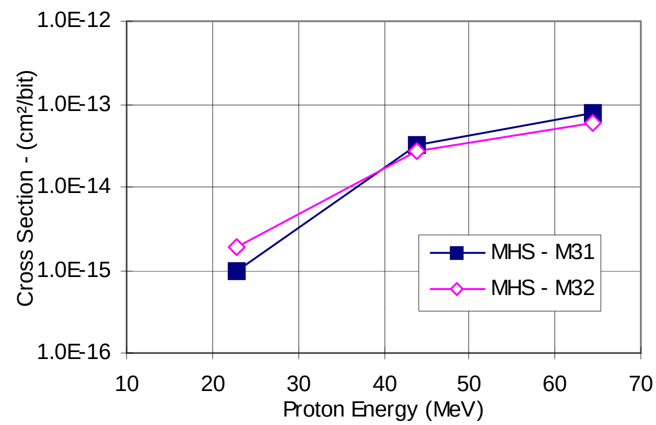

Fig. 9. MHS CP65656EV 32K8 SRAM – Proton SEU results

For the UC1707 BA ACU device, the 2 predicted events come close to the 1 mission observed. So for all three types of transient events analyzed, fairly good correlation exist between observed and predicted numbers, especially when considering the poor statistics involved and uncertainty in many areas. Finally, none of these power supply events is considered to be flare related as no date correlation exist to the flare events causing increased SEU rates in the SSR.

TABLE VI
OBSERVATIONS VERSUS PREDICTIONS

Module	SOHO 5 years	
	Observed	Predicted
VIRGO PM139/Comp.	5 events	5 events
LASCO UC1707/Device	0 events	~0.1 event
ACU UC1707/Device	5 events	3 events
T.I. 4Mbit DRAM/SSR	.82 SEU/min.	.85 SEU/min.
MHS 32K8 SRAM/GOLF	1.7×10^{-7} bit/day	5.8×10^{-7} bit/day

The average observed upset rate for the SSR T.I. devices as given in Table VI is for background events only, thus without the flare SEUs. The average predicted number, also without flare SEUs, come very close. However, when comparing predictions with observations over the mission period, a more true comparison can be established. The observed SEU rate, averaged for December/January each year, has been plotted in Fig. 10 and compared with CREME96/SPENVIS predictions. These predictions were carried out assuming the sensitive volume to consist of a 50/50 transistor/capacitor sensitivity with dimensions of 1.2 x 1.3 x 2.0 µm/1.2 x 1.3 x 7.6 µm. The presented SSR SEU/minutes values are combined heavy ion and proton. The proton (nuclear reaction) contribution was typically in the order of 16 %. The decline in the observed/predicted SSR SEU rate as solar maximum is approaching is clearly visible. However, CREME96 results show a slight underestimate in the beginning of the predictions and do not drop as quickly as the observed rate. The SPENVIS predictions (using the same parameter inputs as for CREME96), just included for comparison in Fig. 10, show a slightly overestimate of events with better correlation towards solar maximum. The variations between the two sets of results, CREME96/SPENVIS, appear to be related to the used – internal solar cycle code.

The last device type in Table VI, the MHS 32K8 SRAM, shows a higher predicted upset rate with a value of 5.8 x 10^{-7} bit/day compared to the observed of 1.7 x 10^{-7} bit/day. The sensitive volume was estimated to be 3.0 x 3.0 x 2.0 µm and the shielding to be 1 g/cm² Al. Not knowing the main reason for this difference, the influence of shielding thickness was calculated. Assuming shielding of 10 mm Al the predicted number changed to about 3.5 x 10^{-7} bit/day, still a factor 2 higher than the observed number.

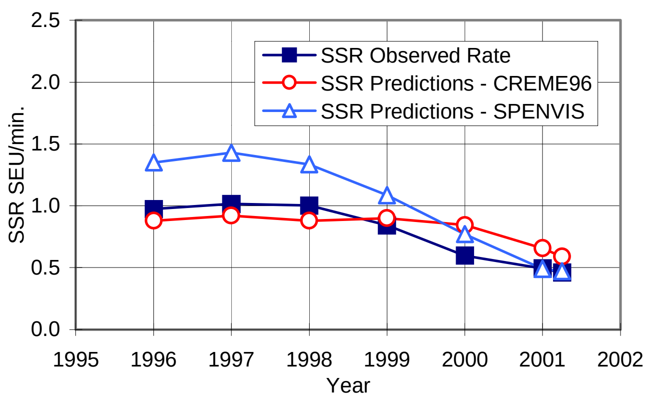

Fig. 10. SOHO SSR SEU Observations versus predictions – T.I. 4Mx1 DRAMs.

Using the existing prediction tools in order to predict the number of SEUs occurring during solar particle events did led to values far from observations. The October 1989 particle event, available in the SPENVIS package (not yet publicly available), had a proton spectrum similar to the event of July 14, 2000. Using this mode, the SSR SEU predicted rate was orders of magnitudes higher than seen. This is probably due to the ion composition model which was that contained in CREME96. The available prediction tools do not yet have the option of adding a known ‘particle event spectrum’ so no serious attempt could be carried out using the SOHO information at present. However, the ‘specific event’ option is under preparation for a future SPENVIS release and this issue will be re-visited.

V. CONCLUSIONS

A fair number of confirmed ‘self switch-off’ power supply SEU events on-board SOHO have been reported. The early suspicion that these events were caused by transient spikes produced by a small number of linear integrated circuits induced by cosmic rays or protons, has been substantiated through test results and predictions presented in this paper. This analysis also confirms the importance of performing SEE tests with application configurations and operating conditions as close as possible to those used in the actual mission [5][10]. Particularly in the case of linear IC’s, the accuracy of predictions is strongly dependent on representative test conditions applied during ground testing.

The SEU data collected from the 2 G-bit SSR represents a unique set of observations providing valuable information about DRAM memory behavior and are a good indicator for the changes occurring in the more energetic SOHO environment. In addition to the solar flare events observed, the effect of solar activity is apparent in the decline in upset rate as solar maximum is approaching. Fairly good agreements were obtained between the observed and predicted (CREME96/SPENVIS) SEU behavior over the five years. The simulations using actual SOHO dosimetry data for flare and background predictions are still in progress and can, unfortunately, not be reported here.

VI. REFERENCES

[1] R. Koga, S. D. Pinkerton, S. C. Moss, D. C. Mayer, S. LaLumondiere, S. J. Hansel, K. B. Crawford and W. R. Crain, “Observation of SEUs in Analog Microcircuits”, IEEE Trans. on Nucl. Sci., NS-40, No. 6, Dec.’93, pp 1838-44.

[2] R. Ecoffet, S. Duzellier, P. Tastet, C. Aicardi and M. Labrunee, ”Observation of Heavy Ion Induced Transients in Linear Circuits”, 1994 IEEE Radiation Effects Data Workshop, pp 72-77.

[3] D. K. Nichols, J. R. Coss, T. F. Miyahira and H. R. Schwartz,” Heavy Ion and Proton Induced Single Event Transients in Comparators”, IEEE Trans. on Nucl. Sci., NS-43, No. 6, Dec.’96, pp 2960-67.

[4] S. H. Penzin, W. R. Crain, K. B. Crawford, S. J. Hansel, J. F. Kirshman and R. Koga, “Single Event Effects in Pulse Width Modulation Controllers”, IEEE Trans. on Nucl. Sci., NS-43, No. 6, Dec.’96, pp 2968-73.

[5] R. Koga, S. H. Penzin, K. B. Crawford, W. R. Crain, S. C. Moss, S. D. Pinkerton, S. D. LaLumondiere, and M. C. Maher, “Single Event Upset (SEU) Sensitivity Dependence of Linear Integrated Circuits (Ics) on Bias Conditions”, IEEE Trans. on Nucl. Sci., NS-44, No. 6, Dec.’97, pp 2325-32.

[6] K. A. LaBel, A. H. Johnston, J. L. Barth, R. A. Reed, and C. E. Barnes, “Emerging radiation hardness assurance (RHA) issues: A NASA approach for space flight programs”, IEEE Trans. on Nucl. Sci., NS-45, No. 6, pp 2727-36, Dec. 1998.

[7] R. Harboe-Sørensen, F. X. Guerre, H. Constans, J. van Dooren, G. Berger and W. Hajdas, ”Single Event Transient Characterisation of Analog IC’s for ESA’s Satellites” RADECS’99 Fontevraud, France, Sep.’99, pp 573-81.

[8] A. J. Tylka et al., “CREME96: A revision of the cosmic ray effects on micro-electronics code”, IEEE Trans. on Nucl. Sci., NS-44, No. 6, Dec. ’97, pp 2150-60.

[9] www.spenvis.oma.be/spenvis/intro.html

[10] A. H. Johnston, G. M. Swift, T. F. Miyahira and L. D. Edmonds, “A Model for Single-Event Transients in Comparators”, IEEE Trans. on Nucl. Sci., NS-47, No. 6, Dec. 2000, pp 2624-33.