Overview of Radiation Single Event Effects Issues as Experienced at the European Space Agency/ESTEC.

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Abstract

This overview paper will start with a short introduction of the space environment, with strong focus on issues directly relevant to radiation Single Event Effects (SEE) in components, the main subject of this paper. Radiation test facilities used for SEE testing will be described and testing constrains discussed. The background and use of the 'Reference SEU Monitor' system will be summarized, followed by recent PROBA-II/TDM orbital data. Finally some ESA spacecraft anomalies will conclude this overview paper

1. Introduction

Cosmic-Ray effects in microelectronic like Single Event Upset (SEU) and Single Event Latch-up (SEL) has been of major concern in satellite electronics since the '70 and continued over the years to be of increased concern. The reason for this is primarily increased sensitivity to upset events due to smaller feature sizes of modern semiconductor technologies. The same amount of charge deposit by a Cosmic-Ray particle can now cause Multiple Bit Upset (MBU) or even destructive effects in devices. So SEE hardness assurance ranging from ground testing to modeling and prediction has been the subject of intensive development over the years and much progress has been made in these areas. This paper will summarize some of the more interesting SEE disciplines as experienced over 30 year at the European Space Agency/ESTEC.

2. Space Environment

Prior to discussion of the mechanism of Single Event Effects it is useful to briefly recapitulate the nature of the space environment. Here the most important part of the cosmic ray environment is galactic cosmic rays which originate outside the solar system but are associated with the galaxy [1]. Cosmic rays are isotopic, highly energetic charged particles with energies ranging from KeV to GeV and beyond. Fluxes are generally few per cm^2 per seconds but vary with the solar cycle. These particles are either trapped by the Earth's magnetic field or passing through the solar system. They consist of electrons, protons and highly charged nuclei. The most numerous particles are protons with smaller populations of alpha particles (helium nuclei) and decreasing numbers of heavier nuclei. The cosmic ray environment has been very well documented and useful curves present the integral Linear Energy Transfer (LET) spectra for different orbits as part of the CREME suite of programs by Adams. As an example, the LET spectra shown in Fig. 1a, are applicable to low circular Earth orbit at 400 Km (close to the International Space Station orbit of 409/430 Km/Inclination 51,6º) which clearly show the protection by the Earth's magnetic field when changing the orbit inclinations from 30º to 90º. For a better understanding of the influence of the environment on a semiconductor device, a typical SEU cross-section (cm^2/bit) curve has been superimposed as Fig. 1b (right scale). Note the saturated cross-section to be about 1E-6 cm^2/bit and the LET threshold to be around 1MeV(mg/cm^2).

Trapped radiation by the Earth's magnetic field consists of a very broad spectrum of energetic charged particles, in general known as the 'Van Allen radiation belts'. These radiation belts in an idealized dipole space layout, according to the AP8 and AE8 models [1], can be seen in Fig. 2. Based on Earth radii (horizontal axes), note the difference in satellite orbit altitudes between most Earth observations satellite (and ISS) at < 1000 Km (primarily seeing protons) compare to Geostationary satellites at 35.786 Km (about 6 Earth radii) primarily seeing electrons.

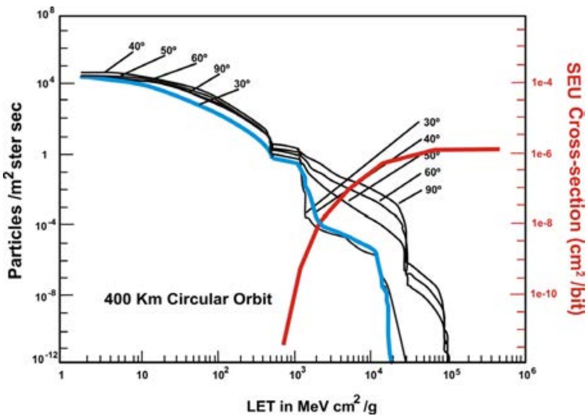

Fig. 1. a) - left, Integral spectra of flux versus Linear Energy Transfer. b) - right, Typical SEU device sensitivity.

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Unfortunately the Earth's field is tilted by 11° in respect to the rotation axis and offset by approximately 500 Km towards the West Pacific, causing the radiation belt (protons and electrons) to go down to a low altitude over the South Atlantic (over Brazil). This anomaly is primarily a problem for low Earth orbiting satellites, since a proton rich zone, known as the South Atlantic Anomaly (SAA), causes additional problems when a satellite passes through. Examples of spacecraft SEE problems from the SAA will be shown later in the paper.

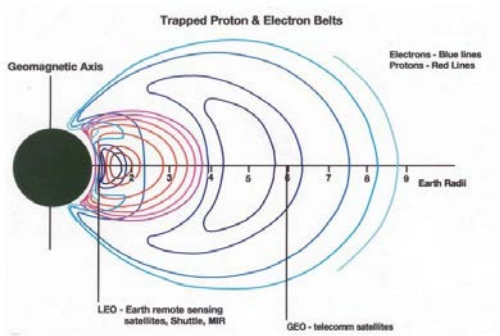

Fig. 2. Contours of trapped protons (inner belt) and trapped electrons (outer belt) versus Earth radii = 6371 Km.

Finally solar particle events, solar flares burst or Coronal Mass Ejection (CME), are large eruptions of plasma from the sun. These events tend to be proton rich, can lasts for days and causes significant disturbance in interplanetary space and the magnetosphere. Due to their high fluence, these types of event can cause significant or permanent damage to satellite systems such as Total Ionizing Dose (TID), Displacement Damage (DD) and both transient and permanent SEEs. Some examples of spacecraft SEE problems during solar particle events will also be discussed later in this paper.

3. Single Event Effects

So as briefly mentioned, the natural space radiation environment contains different energetic particles capable of causing significant damage to spacecraft components (Displacement Damage or Total Ionizing Dose damage) resulting in degraded component performances or failures. Single Event Effects often results in temporary loss of performance or catastrophic failures (if a device or system is not protected).

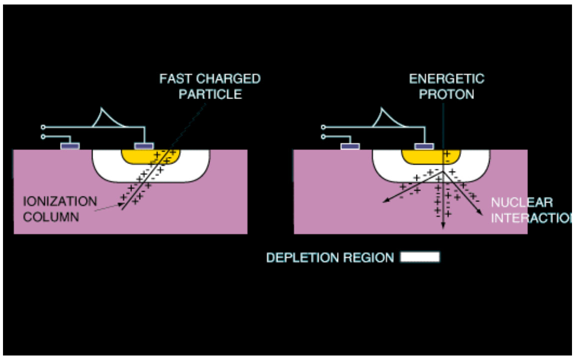

Fig. 3. Transient spike (or SEU) in a CMOS cell caused by an ion hit (left) or proton nuclear reaction (right).

In satellite systems, many different types of SEE have been experienced with Single Event Upset (SEU) or 'soft error' or 'bit-flip' as the most common event. An SEU is the change of state of a bistable element caused by the impact of an energetic heavy ion or proton. However, in simple transistor structures such as shown in Fig. 3, Single Event Transient (SET) spikes can be produced (as indicated) when a particle deposits sufficient charge in the sensitive region. In complex satellite systems, even spikes can be of concern if they have sufficient magnitude and duration, to reach and trigger latches or comparators [2]. In addition to SEU and SET, Multi Bit Upset (MBU), Multi Cell Upset (MCU) and Single Event Functional Interrupt (SEFI) are other non-destructive events commonly experienced. Of destructive events, Single Event Latch-up (SEL), Single Event Gate Rupture (SEGR) or Single Event Burn-out (SEB) are some of the more common events to be avoided.

4. European Component Irradiation Facilities

So in order to evaluate the radiation sensitivity of components, a great deal of ground simulation testing is carried out. Different irradiation sources and test sites are used, with Co-60 gamma being the most commonly used for TID testing, and low energy protons for displacement damage. Less well known are the irradiation sources and sites used for SEE testing. Several accelerator facilities have ions and proton energy suitable for SEE testing. Three of these facilities, all under ESA contract, will be described here, and examples of heavy ion and proton single event upset (SEU) data given.

Fig. 4. ECIF logo/ESA's Test Locations.

4.1 Proton Irradiation Facility (PIF).

The first external test facility to be part of European Component Irradiation Facility (ECIF) was the Proton Irradiation Facility (PIF) at Paul Scherrer Institut, Villigen, Switzerland. This facility under ESA contract

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since 1992 was moved around to many different beam line locations over the years. Today, the PIF is convenient located in the PROSCAN area of PSI where a permanent modern set-up for component and material testing is installed. A very user friendly set-up allows experimenters to perform tests on their own following a short set-up and calibration exercise. Proton energies between 10 to 300 MeV are used most of the time [3].

4.2 Heavy ion Irradiation Facility (HIF).

Following an initial evaluation and assessment period in the early 90's, the second external test facility to be part of ECIF was the Heavy-ion Irradiation Facility (HIF) at the Centre de Recherches du Cyclotron, Université catholique de Louvain (UCL), Belgium. This facility became official part of the ECIF in 1996 but has seen quite a few upgrades since the opening. Interesting at the HIF is the two ion cocktails available, a high LET cocktail covering LETs between 1.7 and 55.9 MeV/(mg/cm²) with ion ranges in silicon of 80 to 43 microns and a high ion penetrating cocktail covering LETs between 1.2 and 32.4 MeV/(mg/cm²) with ion ranges in silicon of 266 to 92 microns.[4].

The second ion cocktail was developed since packaging and assembly technology changes in modern memory devices pushed heavy ion testing to take place from the back side of a device. Initial when comparing front and back side SEU test results as shown in Fig. 5, using the HIF high LET cocktail, it soon became clear that deeper ion penetration was required. As can be seen at low LET for Ne and Ar ions without tiling (maximum ion penetration) identical SEU results were obtained for front and back side testing. However, when tilting the back side tested device or going to higher LETs, Kr and Xe (less ion penetration), clear drops in SEU cross section sensitivity indicate incorrect testing [5]. Unfortunately the new high penetrating ion cocktail had Kr as the highest LET at 32.4 MeV/(mg/cm²) - not quite sufficient for a full device characterization. However, this issue was further evaluated and assessed at a new facility at the University of Jyväskylä, Finland.

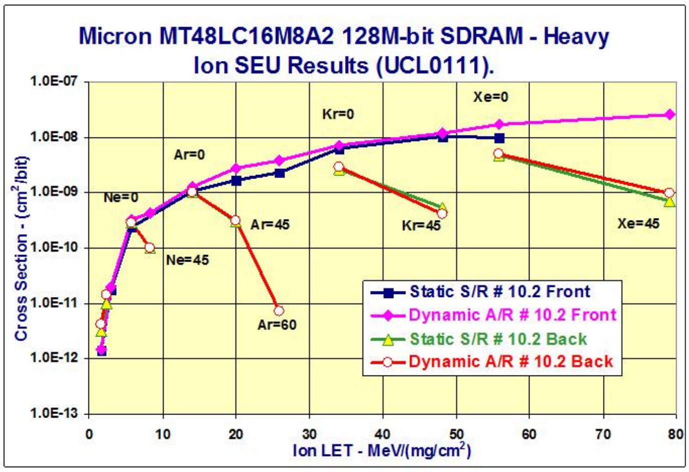

Fig. 5. Front and back-side irradiation SEU results from HIF.

4.3 RADiation Effects Facility (RADEF).

The increasing demand for radiation testing at accelerators attracted ESA and the space community to the RADiation Effects Facility (RADEF), University of Jyväskylä, Finland, some years back. Initial test campaigns showed capabilities at RADEF that were not present at the HIF. Ions initially available were assessed and complemented with new types. Higher ion energies resulting in much deeper ion penetration ranges allowed successful reverse side irradiation of thinned Integrated Circuits (ICs). This facility was officially commissioned in 2005 as the third external ESA facility under the ECIF [6].

Ion Cocktail M/Q=3.7	Energy MeV	Range µm Si	LET MeV(mg/cm²)
$^{15}N^{4+}$	139	202	1.9
$^{20}Ne^{6+}$	186	146	3.7
$^{30}Si^{8+}$	278	130	6.7
$^{40}Ar^{12+}$	372	118	10.1
$^{56}Fe^{15+}$	523	97	18.8
$^{82}Kr^{22+}$	768	94	30.4
$^{131}Xe^{35+}$	1217	89	55.0
JYFL – Ion Cocktail produced for ESA April 2005			

Table I. RADEF cocktail of ions – LET experimental values.

Since the opening in 2005, energy loss measurements of heavy ions in silicon took place at RADEF. Details of these test have been published in [7][8][9] whereas here, LET values as presented in Table I, has been updated from SRIM values to experimental values in silicon. See ECIF cocktail calculator at the RADEF www pages [9a].

5. Testing for SEE

The complexity of performing heavy ion SEE testing on advanced ICs often requires a dedicated test system capable of running the device under test (DUT) at its maximum speed, and with critical steps like initialization, read and write operations to take place during periods of no beam exposure [5]. Often the DUTs need to be prepared prior to test [10] with re-packaging of the die, removal of packaging material or thinning the die for back-side irradiating. Several different test modes are often required under different voltage and temperature conditions. Latch-up protection features and SEFI recovery concepts are needed as well as knowledge of the

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DUT technology when performing the error analysis. Some of the problems related to DUT thinning will be further discussed below.

With RADEF ion penetration in silicon as listed in Table I, the goal for thinning devices is 50 micron but as earlier discovered, thickness non-uniformity represents a major problem [11]. All thinned devices used by ESA were checked for thickness variations by Interferometry. Examples of device thinning variations can be seen in Fig. 6, for a Samsung DDR-II die of 9.1 mm x 8.2mm. The center part is thinned to 35/45 micron with the corners to 75/85 micron. Obviously if we use a RADEF Xe-ion we could risk a SEU distribution as shown in Fig. 7 (for the lower/right quarter of the die). Here SEU (each spot) are assigned to their physical locations and we see no or only a few upsets in the corner part. Without this information, we probably had assuming a full tested die, and produced a wrong SEU cross section sensitivity. Now we at least can correct this sensitivity with the number of bits not tested or calculate the SEU cross section sensitivity based on upsets from the center part only [12]. However, now the second problem arises – what LET value shall we assign to this test. Here it is interesting to note that different stopping power codes give different LET values! For example, SRIM and LET Calculator codes produce LET values, for the RADEF ions, with a difference of 2% to 12% [7]. So in order to clarify this inconsistency, all 7 ions at RADEF were measured over the energy range of 1-10 MeV/u and new LET values established (see Table I). But what LET value should be assigned, the surface value of 55.0 MeV/(mg/cm²), the value at 30 micron of penetrating – 62.1 MeV/(mg/cm²) or the one after 60 micron of penetration 67.7 MeV/(mg/cm²) or just one value in the middle! By knowing all details around the test, several SEU cross sections sensitivities versus LET values could be correctly assigned – but only if details as addressed above are known [5][9][11].

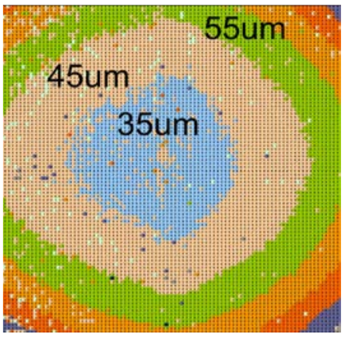

Fig. 6. Back-side thinned DDR-II memory – thickness in um.

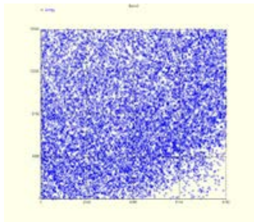

Fig. 7. SEU distribution of a ¼ of the die of Fig.6.

6. Reference SEU Monitor

Earlier attempts to compare SEU data from different test facilities often failed due to slightly different test set-ups and test conditions. Now, the same test system – referred to, as the “Reference SEU Monitor” can be used every time.

In summary, the Reference SEU Monitor system was presented as a simple and reliable beam monitoring system which could be used at the accelerator and accepted by both the SEE experimenter and beam provider in support of beam calibrations. This system, based on SEU in a well calibrated 4 Mbit SRAM as the detector element, was assembled and tested in 2005 in collaboration with HIREX Engineering [13]. With its simple control from a laptop or PC, monitoring of SEUs are directly compared with pre-calibrated SEU curves, previously obtained at heavy ion, proton and neutron facilities. The ‘detector element’ a 4 Mbit SRAM from Atmel (AT60142F), has a die area of 6.1 mm x 11.2 mm. The layout of the motherboard and the detector board can be seen in Fig. 9, with the ‘detector element’ having the lid taped on (for protection). Many experimenters have confirmed the need for such a reference system at the accelerator [14] and even beam provider now find the new version attractive. The new version of the Reference SEU Monitor is slightly improved with the ‘detector element’, the Atmel AT60142F SRAM, now in a hybrid configuration with 4 dies, see Fig. 10. This allows better beam profile and homogeneity checks, since the 4 dies now cover a much larger area, approximately 20 mm x 20 mm.

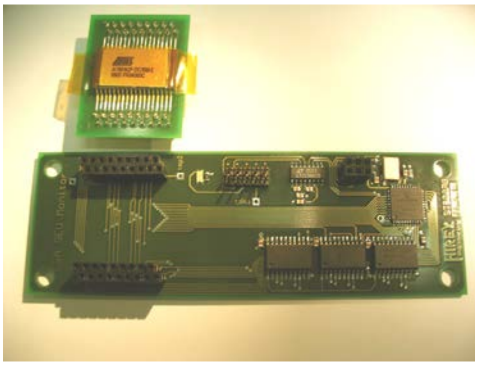

Fig. 9. “Reference SEU Monitor” system.

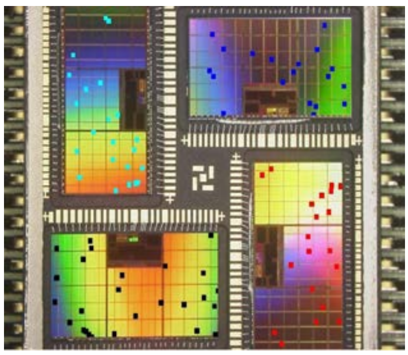

Fig. 10. SEU in the new detector element, the AT68166 MCM.

As detailed in an NSREC 2008 paper [14] this ‘reference standard’ appear to have helped many researchers and are even used routinely at many accelerators as part of the beam calibrations. However, as also outlined in [14] the ultimate goal would be to have a space ‘reference standard’. This opportunity started in 2009 with the Technology Demonstration Module (TDM) to be flown on-board the ESA PROBA-II satellite.

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7. Technology Demonstration Module

The TDM is a component radiation effects experiment focusing on SEEs in memory devices in order to address and study the difference between flight and ground events**.** The TDM consists of four different radiation effects experiments in order to study the in-flight performance of: 1) SEUs in the 'Reference SEU Monitor' (4 SRAM devices in the hybrid configuration), 2) Latch-up events in 4 different SRAM devices, 3) in-flight technology demonstration of 8 G-bit FLASH memories, and 4) measure of the local TID environment employing RADFET dosimeters. The flight unit of the TDM as shown in a folded out configuration in Fig. 11, has the 16 Mbit SRAM Multi-Chip Module operated in the same Static mode as in the Reference SEU Monitor system (right hand side board at the front).

Fig. 11. The TDM Flight Unit folded out.

The TDM was manufactured by QinetiQ (Belgium) under ESA contract. The TDM was integrated into the Advanced Data & Power Management System (ADPMS) as part of the ESA satellite PROBA-II (Project for On-Board Autonomy). PROBA-II was launched on November 2nd 2009 into sun-synchronous 800 Km polar orbit. The 265 gram TDM was switched-on on February 15th 2010 and has produced reliable radiation data since. Further details and a first set of TDM orbital data can be found in [11]. A second set of orbital data was published in [15] with further reporting under preparation. In Fig. 12, the total number of SEUs and SELs as observed in a month, April 2010, has been plotted on a world map. Here it is very clear that most SEEs are observed when passing through the South Atlantic Anomaly and therefore induced by protons. Very similar proton SEU plots were presented back in 1989 for the UoSAT-2 spacecraft also operating in a polar orbit of 700-800 Km [16][17].

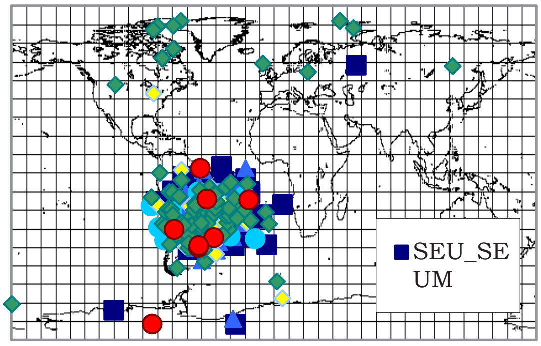

Fig. 12. Location of all TDM SEUs and SELs observed during the month of April 2010.

As part of the earlier TDM evaluation and assessment, Fig. 10, also shows the distribution of SEUs as observed in the AT68166 MCM for the first 1032 hours of analyzed flight data. The 90 SEUs recorded are randomly distribution across all four SRAMs with S1 seeing 23 SEUs, S2 seeing 27 SEUs, S3 seeing 21 SEUs and S4 seeing 19 SEUs. Later analysis revealed a very similar SEU/die distribution and the bit flips rate was established to be 57% changes going from 0 to 1 and 43% changes going from 1 to 0.

In summary, it is interesting to report that the orbital locations of SEU stayed the same for the other four SRAM types flown (the SEL experiment) with 88/89% of SEUs occurring in the SAA, 7/8% of SEUs occurring at the polar horns and 4/5% of SEUs occurring at < 60º north/south but outside the SAA. Very identical numbers can be reported for the SEU Monitor (SAA = 88.6%, >60º = 7.2% and <60º 4.2%). So despite different semiconductor types with some technology differences the % of SEUs appears to occur at the same orbital locations [14][15].

The four different SRAMs used for the latch-up experiment of the TDM, have very different heavy ion SEL sensitivities as shown in Fig. 13, tested at 40ºC. The most SEL sensitive device, the Brilliance Semiconductor's device, is not part of the TDM, but the tested type is the one mentioned in the following paragraph, flown on BIOPAN-5. Over the first 407 days of flight, one SEL occurred in the ISSI IS62 device over the SAA. For the Samsung device we observed a total of 3 SEL. One event was observed at high latitude > 60º north and two events occurred in the SAA. So far no SEL events occurred in the Alliance Semiconductor device where as the ISSI IS61 showed a total of 87 SEL. Grouping the location of these SEL events as for the SEUs, we see 79% SELs occurring in the SAA, 14% SELs at the polar horns and 7% SELs at < 60º north/south but outside the SAA.

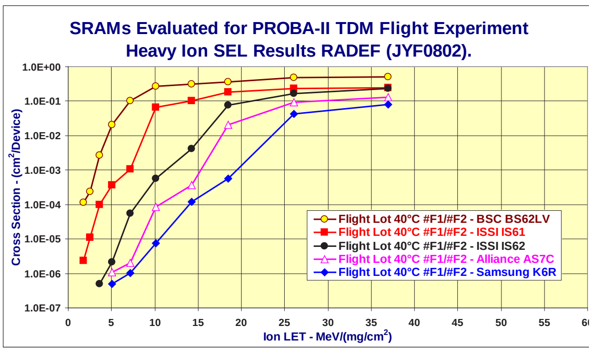

Fig. 13. SRAMs Latch-up sensitivities at 40 ºC.

Altogether, the presented flight data shows that all experiments are working well and that the TDM is running reliably. SEU and SEL rates appear to be

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stable over the analyzed flight period and no indications of problems can be reported to the end of August 2011, however, the present analyzed SEU/SEL database is still too small for extensive conclusions.

8. SEE Spacecraft Anomalies

Spacecraft anomalies in general are not the type of PR any project like to see published. However, over the years, at a technical level, a lot have been learned from these failures. Here, I just like to summarize two ESA spacecraft event which probably helped many other projects, one proton SEL related event and transient SEU events in the same spacecraft.

The first event goes back to July 1991 when ESAs Earth Resources Satellite (ERS-1) was launched into a 784 km sun-synchronous polar orbit. As part of the payload, one of the non-ESA instruments carried was the Precision Range and Range Rate Equipment (PRARE). After 5 days of operating this experiment shut down immediately following a transient over current condition and could not be restarted. This switch-off occurred during a pass over the South Atlantic, as shown in Fig. 14. During the first 5 days of operation a fair number of other anomalies were noted including SEUs and a slave processor reboot.

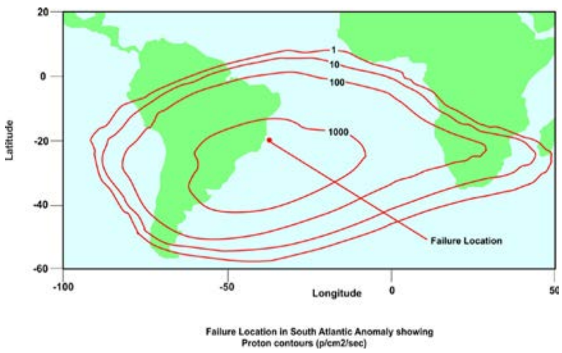

Fig. 14, ERS-1/PRARE Failure location, proton latch-up.

Ground testing took place at the PIF/PSI facility using 30/60 MeV protons and the engineering model of PRARE. Soon it became apparent that a NEC D4464G 64 Kbit CMOS SRAM memory was causing latch-up and the full orbital failure condition simulated. Additional heavy ion testing of 'flight spare devices' also revealed latch-up occurrences even at extreme low LETs [18]. As of today I still do not recall any other device to be more SEL sensitive, however, a very similar SEL event in May 2005 caused ESA's BIOPAN-5 on-board FOTON-2 (altitude 280/305 km) to fail at the location shown in Fig. 15. This time it was an 8 Mbit SRAM from Brilliance Semiconductors going into a latch-up condition during the 5th orbit. This device type, identical to the one tested in [14] has a SEL sensitivity similar to the NEC devise with a heavy ion SEL cross section threshold below 2.0 MeV/(mg/cm²), as shown in Fig. 13. For both events, no ground SEE testing of the flown/failed device type was carried out prior to flight!

Fig. 15, FOTON-2/BIOPAN-5 Latch-up location.

The second example of spacecraft anomalies is summarized for the Solar and Heliospheric Observatory (SOHO), ESAs solar satellite in a Halo orbit around the Lagrangian point L1 located 1.500.000 km from the Earth in the sunward direction. SOHO experienced a large number of SEEs, all of which were recoverable. Analysis of all SEEs experienced during the first five years of successful operation was report in 2002 [19]. Events were reported occurring in the various power supply units (PSUs), in the solid-state recorder (SSR) and in one of the instrument.

The most illustrative series of event is probably the SEUs as observed in the 2 Gbit SSR. These upsets, between April 1996 and August 2001), was time plotted, as shown in Fig. 16. The initial average upset rate fluctuates around 1 SEU/minutes and changes towards 0.5 SEU/minutes over the 5 year period. The large peaks happened during major solar flares where the daily average event rate even exceeds 32 SEUs/minutes during the July 14, 2000 event. 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 recording was coherent with other observations and predictions.

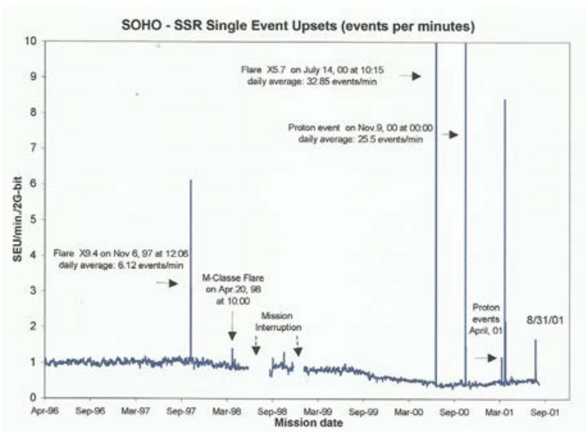

Fig. 16, SOHO SSR Upsets as recorded over 1562 days.

However, the 'self switch-off events' in the redundant and protected power units were really the main concern. Over the reported period, more than 20 power switch-off events occurred during normal

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operations with bus, load, voltage, current and temperature nominal. The suspicion of these events to be SEE related was basically confirmed during a major ground test program using identical test conditions as used by SOHO [2]. Also SOHO flight spare devices were used at both heavy ion and proton facilities. 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 was substantiated through test results and predictions as presented in the paper [19]. This paper also stressed the importance of performing SEE tests with application configurations and operating conditions identical to those used in the mission, particular in the case of linear ICs. This is clearly shown in Fig. 17, with the different SET sensitivities of the Virgo (application) and the comparator mode of operation.

Finally the SOHO transient SEE experienced was used to create a safe margin standard validating future science mission using the same spacecraft platform.

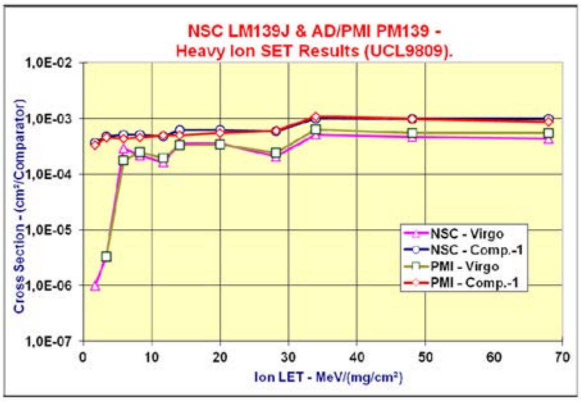

Fig. 17, NSC and PMI 139 Heavy ion SET results.

9. Conclusions

The main objective of this paper was to address some of the more interesting disciplines experienced over more than 30 years at the European Space Agency/ESTEC as a radiation SEE expert. However, most of the presented subjects have previously been proceeding published with a total page number probably close to 100 pages. So for each main subject please read these few pages as guidance and use the various references for detail explanations. The list of references is slightly longer than for a normal proceedings paper but hope this way to be able to guide the reader to further information's.

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