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Pre- and Post- Flight Radiation Performance Evaluation Of The Space GPS Receiver (SGR)

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Abstract

SSTL (Surrey Satellite Technology Ltd), in collaboration with ESA/ESTEC, have recently developed a state-of-the-art, low cost GPS (Global Positioning System) receiver payload for use on small satellites. The Space GPS Receiver (SGR) is currently flying in low earth orbit (LEO) on the TMSAT micro-satellite and the UoSAT-12 mini-satellite and will also be flown on the TiungSAT-1 micro-satellite, and ESA's PROBA satellite. The SGR has demonstrated autonomous on-board positioning and has provided an experimental test-bed for evaluating spacecraft attitude determination algorithms.

In order to reduce development time and costs, the SGR consists solely of industry standard COTS (commercial off-the-shelf) devices. This paper describes the ground-based radiation testing of several payload-critical COTS devices used in the SGR payload and describes its on-orbit performance.

I. Introduction

A. The Global Positioning System

GPS is used for accurately determining positions (on land, sea, in air and space), through measurements of the range between the unknown position, and GPS satellites whose positions are known. Such techniques are extensively used for land and sea navigation but have only recently been used on board spacecraft for the autonomous determination of spacecraft position.

In 1993, the Portuguese satellite PoSAT-1, was the first micro-satellite, to make use of a GPS receiver payload [1]. This payload demonstrated spacecraft position to within 100 meters.

B. The Space GPS Receiver (SGR)

In July 1998, a new, dual-antenna, GPS receiver (the SGR-10) was launched into a 98° inclination, 820km altitude orbit on-board the TMSAT micro-satellite [3]. A similar receiver (the SGR-20), possessing five antennas, was launched on the UoSAT-12 mini-satellite [4] (300kg) into a 64.6° inclination, 638 km x 654km orbit. A schematic of the SGR payload is shown in Fig 1.

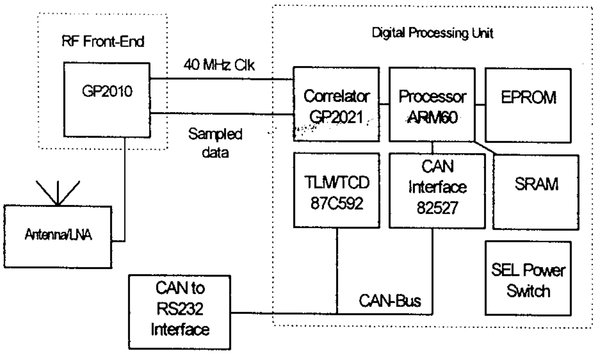

Fig 1. Schematic Of The SGR Payload

The SGR is based on Mitel Semiconductors (formally GEC Plessey) GP2000 chip-set (the GP2010 and GP2021). The GP2010 down converts the raw RF signal and samples into a 2-bit digital signal used by the Digital Processing Unit. The GP2021 takes the digitised signal and correlates it with an internally generated GPS code in order to lock onto, and decode the GPS signals. Optimal operation of the GP2021 is achieved using the ARM60B, the central microprocessor used in the SGR payload. The ARM60B is a 32-bit, low power, RISC processor that operates at 20MHz and is capable of executing 14-20 million instructions per second (MIPS).

As part of the development program the SGR payload was evaluated in terms of its sensitivity to ionizing radiation. In order to carry out this evaluation, several potentially radiation sensitive, payload-critical devices (the GP2010, GP2021, ARM60B, 87C592 CAN (Controller Area Network) micro-controller, IS61C1024 SRAM and AM27C256 EPROM) were identified. A description of each device is given in Table 1.

Table 1. Description Of SGR Devices

Device	Function	Manufacturer	Process
GP2010	RF down conversion	GEC Plessey	Bi-polar
GP2021	GPS Channel Correllation	GEC Plessey	CMOS
ARM60B	Microprocessor	GEC Plessey	CMOS
87C592	Microcontroller	Philips	CMOS
AM27C256	UV EPROM	AMD	CMOS
IS61C1024	SRAM	ISSI	CMOS

The radiation test results for these devices are of great interest to the space-related GPS community.

C. The Polar, LEO Radiation Environment

Single Event Effects (SEEs) can be induced by trapped protons, galactic/solar cosmic rays (CRs) and solar energetic particles (SEPs). The SGR has been designed to operate in a typical UoSAT type (near polar, sun-synchronous, 600-900km altitude) orbit. Table 2 shows the contribution of each source of ionizing radiation inside a typical UoSAT micro-satellite[1] in the TMSAT orbit defined previously. This data was obtained using the SPACE RADIATION software [5] which includes CREME [6] the AP8 and AE8 environment models [7].

The dose rate inside UoSAT spacecraft in this orbit has been measured by instruments such as CREAM and CREDO [8][9] as being 1-2 rad(Si)/day.

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[1] Affording an average shielding thickness of 3 g.cm^{-2} (Al)

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Table 2.

Source	Criteria	Orbit Averaged Particle Flux
Trapped Protons	E > 1 MeV	15-50 cm^{-2} s^{-1}
GCRs	LET > 2 MeV cm^2 mg^{-1}	6 x 10^{-4} cm^{-2} s^{-1}
Typical Solar Flare. Based on (Oct89) Event	Proton E > 1MeV	70 cm^{-2} s^{-1} (1-2 days duriation)

II. Total Dose Testing

The GP2010, GP2021, ARM60B and 87C592 were total dose tested at the University Of Surrey, using a ^{60}Co source[2]. A separate test board was designed for each device. During irradiation the devices were biased and, in the case of the GP2010, clocked. After each exposure the static bias current drawn by each device was measured, and the devices tested for functionality as part of the SGR payload. At least two samples of each device were tested. The AM27C256 EPROM was tested for total dose susceptibility at ESA/ESTEC (dose rate of 3.0 Krad(Si)/hour). The results are summarised in Tables 5 and 6 at the end of this paper.

III. Single Event Effects Testing

Individual GP2021, ARM60B, 87C592 and AM27C256 devices underwent heavy-ion radiation testing at the Heavy Ion Facility (HIF), Université catholique de Louvain (UCL), Belgium. The IS61C1024 SRAM underwent proton testing at the Paul Scherrer Institute (PSI), Switzerland. No overall system tests could be carried out due system complexity (e.g. requirement to track GPS satellites). The results of these tests are given below.

A. ARM60B

The ARM60B was tested for single event upsets (SEUs), single event latchup (SEL) and *soft resets*. Soft resets are associated with SEUs occurring in control registers and which cause the processor to operate in an unspecified mode.

SEU testing was carried out in 'dynamic' mode i.e. the DUT was actively exercised during exposure to the beam and errors counted as the test progressed. Device current was monitored throughout. Traditional SEL was not seen in any test, however, micro-latchup type behaviour was observed. Figs 2, 3 and 4 show the SEU, soft reset and micro-latchup cross-section curves, respectively, for the ARM60B[3].

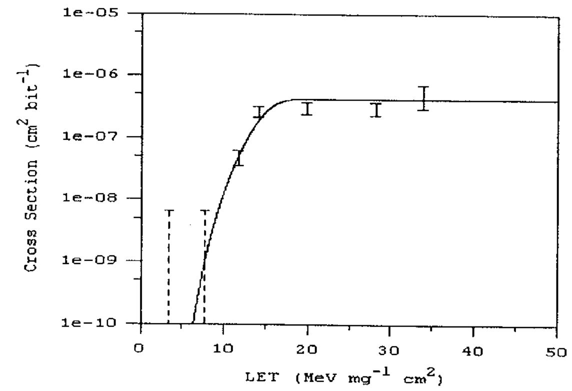

Fig 2. SEU Cross-section for the ARM60B

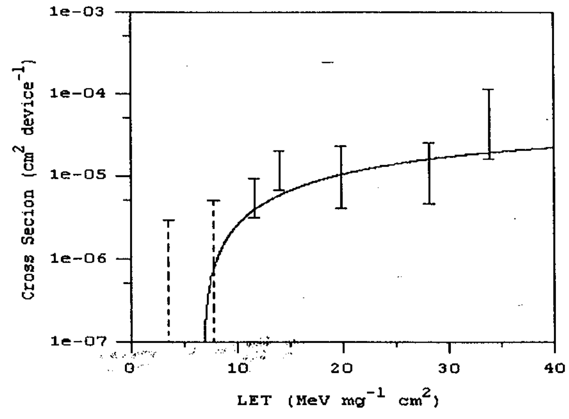

Fig 3. 'Soft reset' Cross-section For The ARM60B

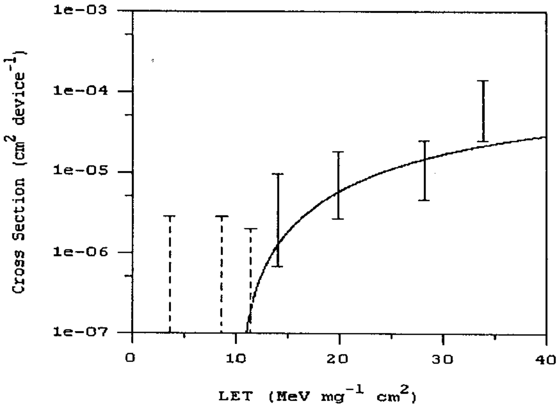

Fig 4. Micro-latchup Cross-section For The ARM60B

These results are summarised in Table 6 and the Weibull fitting parameters described in Table 3.

B. 87C592 CAN Microcontroler

The 87C592 was tested for SEUs, SEL and soft resets. An on-chip watchdog timer was used to detect soft resets and automatically reset the device (devices were not powered down during a soft reset). Traditional SEL was not seen in any test carried out with this device but, as with the ARM60B, micro-latchup behaviour was observed. SEU testing was carried out in 'dynamic' mode. Figs 5, 6 and 7 show the SEU, soft reset and micro-latchup cross-section curves for the 87C592.

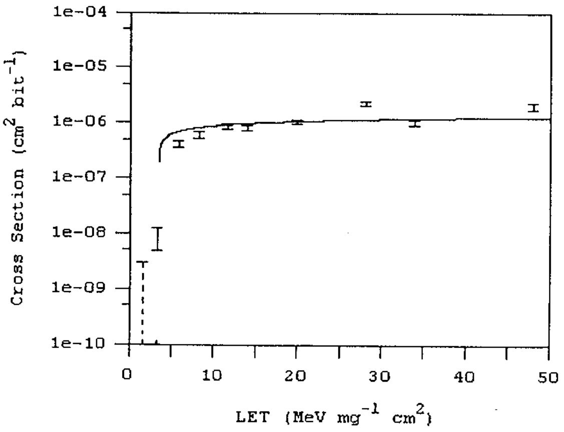

Fig 5. SEU Cross-section for the 87C592

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[2] dose rate of 4.8 Krad (Si)/hour.

[3] In the following graphs, hatched error bars indicate an ion LET at which the device was tested but no SEE was observed. The size of every error bar describes the 95% confidence limits for each individual observation and the solid lines are Weibull curves fitted to the data.

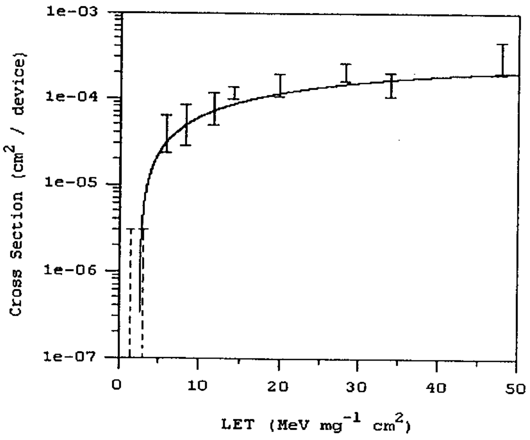

Fig 6. 'Soft Reset' Cross-section For The 87C592

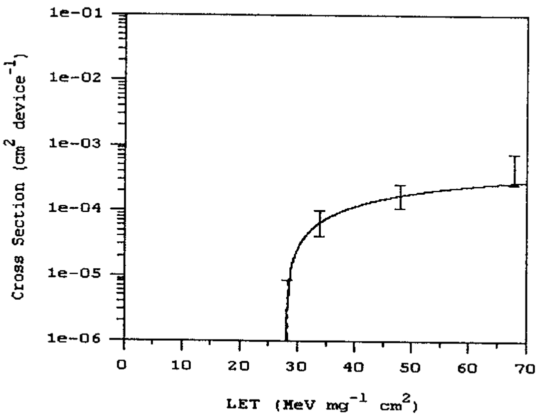

Fig 7. Micro-latchup Cross-section For The 87C592

C. GP2021

SEU testing was not performed on the GP2021 as it was not possible to access the registers for both writing and reading due to the multiplexed register system.

The GP2021 was tested for SEL. Traditional SEL was not seen in any test but micro-latchup was observed. The micro-latchup cross-section curve for the GP2021 is shown in fig 8.

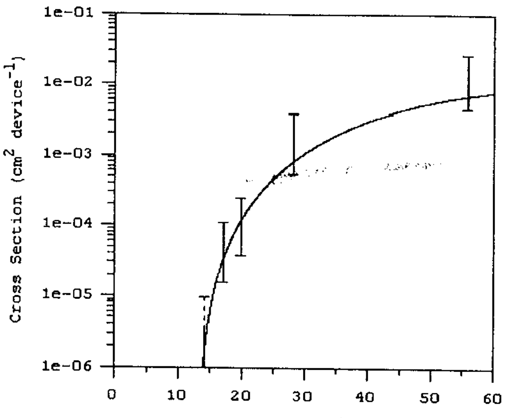

Fig 8. Micro-latchup Cross-section For The GP2021

D. GP2010

The GP2010 is not a digital IC. but is an analogue component, with the exception of the final sampling (conversion from RF to digital) stage. SEE testing was thought inappropriate for this device as:

1. The target area making up the digital section of the die, is very small.
2. Any SEUs that might occur would produce a transient source of signal noise indistinguishable from, and insignificant compared to, the GPS antenna noise.

E. AMD - AM27C256 EPROM

The AM27C256 is used to store software for execution on the ARM60B micro-processor. It was tested for transient (read/write errors), SEU and SEL using heavy ions. Table 4 shows the results of these tests.

F. ISSI - IS61C1024

The IS61C1024 (128K x 8-bit) SRAM is used to store data from the ARM60B micro-processor. This device was tested for proton-induced SEU. Fig 9 shows the SEU sensitivity of the IS61C1024 to protons.

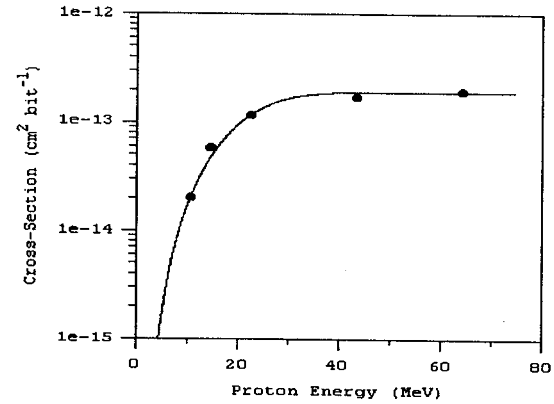

Fig 9. Proton Induced SEU Cross-section For The IS61C1024 SRAM

IV. Predicting Device Behaviour In The Space Radiation Environment

A. Total Dose Effects

The design lifetimes of both TMSAT and UoSAT-12 is 5 years. Total dose effects are not expected to cause a problem for SGR devices in these spacecraft. However, the 87C592 and AM27C256 devices would not be recommended for a long lifetime mission in GTO as their estimated lifetime is expected to be ≈ 2-6 years in this orbit. Table 5 summarises the estimated lifetime of these devices flown in spacecraft given the specified orbits and affording the effective shielding thicknesses, shown (no design margins have been included in these figures).

B. Single Event Effects

The SEE behaviour of SGR devices has been estimated for an SGR payload on board the TMSAT micro-satellite. This satellite has an orbit altitude of 820 km, an orbit inclination of 98° and affords an average shielding thickness of 3 g.cm^{-2} (Al). Using the SPACE RADIATION software, the differential proton energy and GCR LET spectra were generated for protons and GCRs inside the TM-SAT spacecraft. The GCR induced SEE rates were derived by multiplying the differential GCR LET spectrum with the ion LET cross-section curves, and summing over all GCR LETs.

For the ARM60B and 87C592, proton induced SEEs were estimated from the ground based heavy-ion test results. A semi-empirical formula (Equ 1.) of the form

$$\sigma(E) = \sigma(\infty)\left[1 - \exp\left(-hY(E)^{m}\right)\right]^{n} \qquad \text{(Equ 1)}$$

where:

$\sigma(E)$ = the SEU cross-section [cm^2 proton^{-1} bit^{-1}];

$\sigma(\infty)$= the limiting SEU cross-section at high energy (≥1,000 MeV);

$Y(E)$ = a linear function of the proton energy going to zero at some apparent threshold, A;

h,m,n= fitting parameters;

has been derived by Peterson [10] in an attempt to predict the proton induced SEE cross-section from experimental heavy-ion test data for any particular device. With a single fitting parameter, A (the apparent threshold), the best-fits to existing ground-based test data were found using Equ 2, the so called Bendel 1-parameter model.

$$\sigma(E) = (24/A)^{14}\left[1 - \exp\left(-0.18Y(E)^{0.5}\right)\right]^{4} \qquad \text{(Equ 2)}$$

$$Y(E) = (18/A)^{0.5}(E - A)$$

where:

A = the apparent threshold parameter [MeV];

E = proton energy [MeV];

$\sigma(E)$ = the SEU Cross-Section [× 10^{-12} cm^2 proton^{-1} bit^{-1}];

The heavy-ion LET threshold (the LET at which the device cross-section is 10% of the saturated cross-section ($L_{0.1}$)) was derived for each heavy-ion cross-section curve and the Bendel-A parameter (A= $L_{0.1}$ +15), derived [9]. This was substituted into Equ 2. in order to generate the proton-induced SEE curve for each device. The proton-induced SEE curves were multiplied by the differential proton energy spectrum inside the TMSAT satellite, and summed over all proton energies.

Table 6 shows a summary of the ground based heavy-ion data and gives estimates of the SEU, soft reset and micro-latchup rates for SGR devices on board TMSAT.

V. Discussion

The 87C592 appears to be a soft device and is estimated to be ≈ 100 times more susceptible to SEU than a typical bulk SRAM subject to the same radiation environment [12]. The SGR employs 1 micro-controller, and so we would expect to see ≈ 0.1-0.2 upsets/day in this device. Whether these upsets manifest themselves as observable errors[4], is dependent upon the micro-controller function and the percentage of time for which it is vulnerable to SEU phenomena [13].

The ARM60B SEU sensitivity is comparable to that for a typical bulk SRAM. Only one ARM60B micro-processor is flown on TMSAT and UoSAT-12 and thus we expect there to be only 1 upset every 4-5 years, on average. Whether these upsets are seen at system level will also depend upon the application software (typically each register's duty cycle << 1 and so it is unlikely that any upsets have, so far, manifested themselves as observable upsets at system level).

The GP2021 could not be tested for SEU behaviour. However, upsets in the GP2021 would largely be expected to cause transient (non-fatal) errors which would not affect SGR payload performance. The GP2010 is an analogue device not thought to be susceptible to SEU.

All the devices tested here exhibit micro-latchup behaviour. It was found that the 87C592 and ARM60B devices could operate nominally for at least several minutes in a micro-latchup state (the GP2021 could not be tested for functionality during the latch-up testing). This behaviour has also been reported to occur in other complex processing devices such as the 80386 [14]. The micro-latchup current associated with the GP2021 was found to be unusual. In the majority of cases, successive micro-latchups (no power cycling between micro-latchups) in the GP2021 were found to result in the device operating reaching an apparent limiting value of 190 mA. The device current approached this apparent limiting current as an exponentially decreasing function of incident ion fluence. This phenomena may be representative of different (electrically isolated) areas of the device undergoing micro-latchup at different times during irradiation.

VI. On-Orbit Performance

The TMSAT SGR is still operational to date and has successfully demonstrated on-orbit positioning. No payload current increase has been detected since launch and there have been no software or hardware problems that can be attributed to the effects of ionising radiation.

The UoSAT-12 GPS receiver has undergone an extensive commissioning phase. The SGR has been operational for a total of approx 30 days and only one software crash has been observed during operation. This software crash occurred outside of the SAA and is most likely to have been caused by a software bug in the development software (200kbytes at present). No software or hardware problems can be attributed to the effects of ionising radiation.

The SGR has tracked a maximum of 12 GPS satellites simultaneously and the time-to-first-fix (TTFF), with no initialisation data, is typically 10 minutes (not achieved by orbital GPS receivers before). The SGR has fully demonstrated its positioning capability [15]. On-orbit SGR position/velocity data has been fitted to precise orbit models and show typical position residuals of < 100m (2σ). The SGR has returned phase differencing data from the multiple antennas and this data is currently undergoing analysis.

The PROBA GPS receiver is still undergoing ground-based evaluation tests. For this receiver the operating software is stored in the SGR's own FLASH EPROM and the code is automatically re-booted if the ARM60 watchdog timer times out.

VII. Conclusions

The performance of the devices tested are unlikely to be compromised by total dose effects. All the devices are capable of surviving for at least 10 years in LEO or 2 years in GTO. The 87C592 is thought suitable for use in space but the 87C592 is relatively sensitive to SEUs and alternatives may be used in future missions.

Although the micro-latchup rate of all devices is expected to be very low, the SGR payload current will be closely monitored for micro-latchup behaviour. Micro-latchup may not be detected by some latch-up protection circuitry if the current increase is typically less than twice the nominal payload operating current (this safety margin allows for the gradual increase in operating current caused by total dose effects and for current changes expected during nominal payload operation). Micro-latchups ultimately may cause device failures due to the accompanying elevated rise in operating temperature.

The SGR has a (payload level) over current protection switch. It is designed such that new operating software can be uploaded from the ground station at any time, in case of a software crash or in order to upgrade the SGR with more advanced software. When not in operation the GPS payload is powered down as a matter of routine in order to both save power and to decrease the effects of accumulated total dose.

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[4] Errors that are observable at the system level

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Table 3. Fitting Parameters For Weibull Curves

Device	SEE	Apparent Threshold	Width Parameter	Shape Parameter
ARM60B	SEU	11.6 MeV mg^{-1} cm^2	11 MeV mg^{-1} cm^2	0.5
ARM60B	Soft Reset	6.8 MeV mg^{-1} cm^2	35 MeV mg^{-1} cm^2	1.1
ARM60B	Micro-latchup	10.2 MeV mg^{-1} cm^2	35 MeV mg^{-1} cm^2	1.7
87C592	SEU	3.4 MeV mg^{-1} cm^2	41 MeV mg^{-1} cm^2	0.3
87C592	Soft Reset	2.6 MeV mg^{-1} cm^2	34 MeV mg^{-1} cm^2	0.9
87C592	Micro-latchup	28.0 MeV mg^{-1} cm^2	52 MeV mg^{-1} cm^2	0.9
GP2021	Micro-latchup	44.6 MeV mg^{-1} cm^2	41 MeV mg^{-1} cm^2	2.5
IS61C1024	SEU (Proton Induced)	1.8 MeV	22 MeV	2.5

Table 4. Heavy Ion SEE Results For AM27C256 (EPROM) Tested In Read Mode

Manufacturer/Capacity / Device I.D.	Fluence (ion cm^2)	Upsets TRANS./SEU/SEL	LET (MeV.mg^{-1} cm^2)	Cross Section cm^2/device		
				Transient	SEU	SEL
AMD 32Kx8 s/n A01	5.0E5	0/(1)/0	68.0	<2.0E-6	2.0E-6	<2.0E-6
	5.0E5	0/0/0	28.2	<2.0E-6	<2.0E-6	<2.0E-6
	5.0E5	0/0/0	11.7	<2.0E-6	<2.0E-6	<2.0E-6

Table 5. Expected Lifetime Of SGR Devices Flown In Various Orbits

Orbit Type	Orbit Definition	Spacecraft Shielding (g.cm^{-2})	Expected Dose Rate (rad(Si)/day)	Time (years) For Functional Failure				
				GP2010	GP2021	ARM60B	87C592	AM27C256
LEO (Polar)	98^0 inc 820 km alt	3	1.0	> 10	>10	>10	> 10	> 10
LEO (Polar)	98^0 inc 820 km alt	5	0.6	> 10	>10	>10	> 10	> 10
GTO	0^0 inc 200 x35800km	3	8.5	> 10	8-10	13-14	5	2.5
GTO	0^0 inc 200 x 35800km	5	7.0	> 10	10-12	15-17	6	3
Molniya	63^0 inc 1250 x 39100km	3	1.1	> 10	>10	>10	> 10	> 10
Molniya	63^0 inc 1250 x 39100km	5	0.9	> 10	>10	>10	> 10	> 10

Table 6. SEE And Total Dose Summaries For SGR Devices

SEE	GP2010	GP2021	ARM60B	87C592	AM27C256	IS61C1024
SEU Threshold LET ($L_{0.1}$) (MeV mg^{-1} cm^2)			10-11	3-4	< 68	
Saturated SEU Cross Section (cm^2 bit^{-1})			2-4 x 10^{-7}	9 x 10^{-7}	2.0 x 10^{-6}	
Expected SEU Rate In LEO (SEUs bit^{-1} day^{-1})			< 1 x 10^{-6}	8 x 10^{-5}	< 1.0 x 10^{-10}	9 x 10^{-7}
Soft reset Threshold LET ($L_{0.1}$) (MeV mg^{-1} cm^2)			8-9	4-10		
Saturated Soft reset Cross Section (cm^2 device^{-1})			1-2 x 10^{-5}	(0.8-3) x 10^{-4}		
Expected Soft reset Rate In LEO (device^{-1} day^{-1})			< 2 x 10^{-5}	2 x 10^{-4}		
Micro-Latchup Threshold LET ($L_{0.1}$) (MeV mg^{-1} cm^2)		15-20	< 14	<28		
Micro-Latchup Cross Section (cm^2 device^{-1})		> 0.01	> 3 x 10^{-5}	> 4.7 x 10^{-4}	< 2.0 x 10^{-6}	
Expected Micro-Latchup Rate In LEO (device^{-1} day^{-1})		< 2 x 10^{-5}	< 0.9 x 10^{-5}	< 2 x 10^{-7}	< 1.0 x 10^{-10}	
TID						
Total Dose For 20% Icc Increase (krad (Si))	> 35	12-14	15-20	11-12	10-12	