

**IAA-XX-14-0S-0P****Using the NANOSATC-BR1 to evaluate the effects of space radiation incidence on a radiation hardened ASIC**

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The nanosatellites concept has expanded the possibilities of testing new design techniques which mitigate the effects of radiation environments (outer space, particle accelerators, nuclear radiations, etc) on integrated circuits (IC). The interaction between radiation and silicon, more specifically MOS devices, gives origin to two classes of problems: a cumulative long term ionization damage denominated Total Ionization Effects (TID) and instantaneous radiation dose effects denominated Single Event Effects (SEE). In order to overcome such problems, two main approaches are usually considered: the usage of a radiation hardened manufacturing process or the employed of commercial CMOS process along Radiation Hardening By Design (RHBD) techniques. Recently, the last one has been more adopted due restrictions and low demand, however it requires an exhaustive design process and testing. The NANOSATC-BR1 is composed by scientific and technological payloads and it is being used for environmental test. One of their technological payloads is the Santa Maria Design House (SMDH) ASIC, which is intended to detect the fault transient type (bit-flip) related with SEE events along with performance degradation originated by accumulated dose. Data error rate and degradation will be collected over the life of the satellite and sent to Earth for analysis. This work presents a strategy to evaluate the radiation hardening design techniques applied in the SMDH ASIC, providing the qualification and validation of components, which could thus be used with reliability in future projects.

**Circuit Description**

The circuit was designed with the intention of performing functional tests

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during ionizing irradiation in the Low Earth Orbit (LEO). The SMDH ASIC, named here as Test Chip 1 (TC1), is composed with two test digital circuits and a set of transistors. It is controlled by the SMDH Control Block, responsible by generating the stimulus, capturing and storing the responses.

### 1. Test Chip 1

The main objectives of the TC1 are:

- Begin the functional validation of cell library created to enable the design of radiation tolerant circuits, where the on-off driver will be the first of these circuits to be designed;
- Obtain through radiation test in earth the first results of the cell library tolerance to the effects of ionizing radiation, more precisely the TID and SEE effects.

#### Sub-circuits

The TC1 consists of:

- Pulse Generator: Digital block that controls the pulses generation for activation/deactivation of secondary circuits as relays. This circuit follow the technical specifications of a Low Voltage-High Power Command (LV-HPC) defined in the Space Discrete Interface Document [1]. Built from a set of the radiation hardened library cells designed by SMDH, it contains the digital portion of the on-off driver (2x4 mux, counter, reset logic). This circuit has dedicated pins for the SMDH Control. It could be evaluated in relation to the TID and SEE.

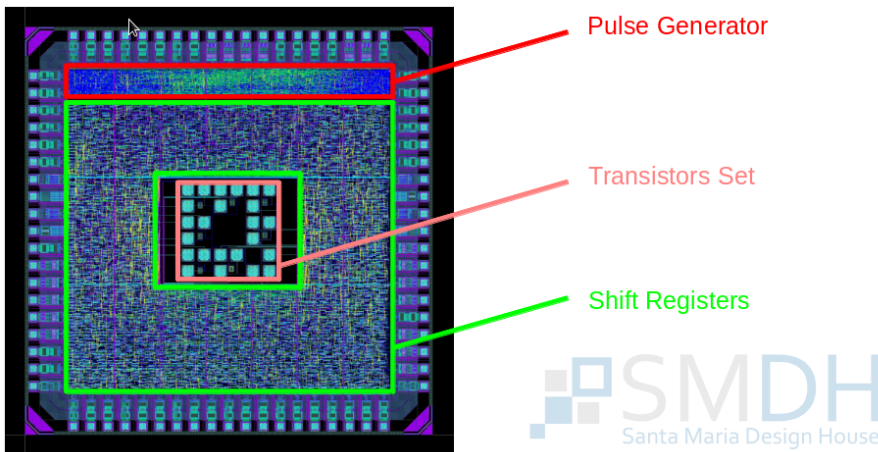


Fig. 1. Test Chip Layout.

- Shift Registers: This block is composed of 10 shift registers circuits

with different configurations. Shift register is a circuit formed by a sequential chain of registers (flip-flops): the output of a register is connected to the input of the next and so on. There are two shift registers sub-groups: half are designed with standard cells, and another half are designed with rad-hard cells. There is a dedicated set of pins to interface with these two groups of sub-circuits. The shift registers have two different lengths: 256 and 1024. Some settings have a sequence of 0, 4 or 8 inverters in order to evaluate the SEE electrical masking which occurs when a SEE is attenuated by a combinational circuit. The shift registers have the following schematic:

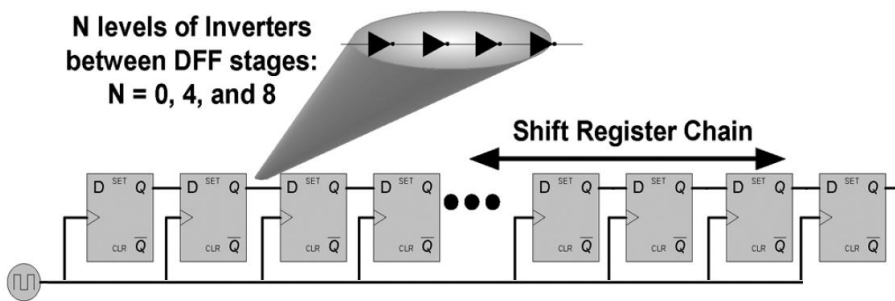


Fig. 2. Shift registers [2].

It permits analyze the SEE tolerance of the memory cells from the standard and rad-hard library.

- **Transistors Set:** The transistors set contains isolated transistors, both tolerant to radiation, such as non-tolerant. It allows the characterization of them in relation to TID and IxV curves. It is not tested as part of the technological payload.

In the NanoSatCBR1 context, only Pulse Generator and Shift Registers blocks are evaluated. The evaluation of the Transistors Set requires the use of micro-tips.

### SMDH Control

This block is an integral part of the synthesized FPGA circuit and implements the following features:

- Stimuli generation to TC1;
- Capture and pre-processing of generated responses by TC1;

- Storage control responses on BRAM 1 block.

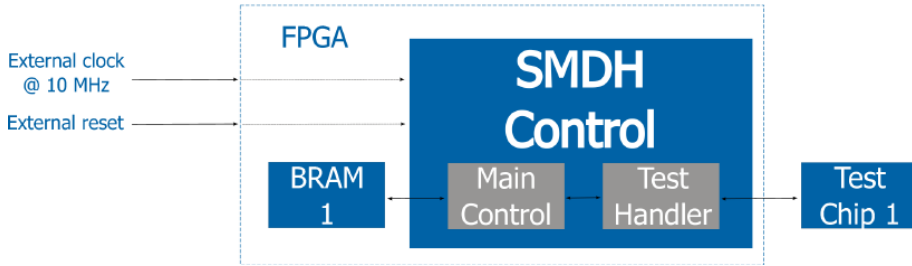


Fig. 3. SMDH Control block diagram.

## Tests

The tests are generated constantly from the time that the FPGA receive a configuration command after the reset. A timestamp is produced with a count that is only continuous during the tests. When the time arrives at the maximum count, a packet is sent with no error indication. This package is to ensure that the test environment is running and to keep the total execution time count of the tests.

Test	Bits response	Execution Time (us)
PG_ACTIVE	4	1920
PG_NO_PULSE	4	1920
PG_PULSE_OFF	4	1920
SR_PATTERN_GEN_ALT_256	5	1024
SR_PATTERN_GEN_ALT_1024	5	4096
Total	22	10880

Table 1. Tests generated by Test Handler.

### 1. Evaluation

There are standards and specifications that must be followed for development and testing circuits to be tolerant to radiation effects. In the test was followed the set of rules and documents from ESA - European Space Agency, describing the test methods and evaluation of integrated circuits for space applications.

The standard ESCC Basic Spec. No. 22900 - Total Dose Irradiation Steady-State Test Method [3] describes the procedures that should be followed to perform the ionizing radiation effects (TID) tests in ICs.

### Circuit behavior assessment test

Even with correlation between the variations in the space environment and the system effects [4], the circuit was designed to be tolerant to radiation effects and shall provide the same performance to the limit of requirements for which it was designed to operate. The shift registers was implemented to assess the effects of interaction with heavy ions that have enough energy to cause instantaneous events that can directly influence the circuit functionality. Two types of SEE were evaluated in the tests:

- SEL - Single event latch-up: will be observed variation in the power supply. The occurrence of SEL is a condition characterized by causing loss of functionality of the device due to a single event (single event), caused by cosmic rays, for example, when induces a high current consumption. This type of event can cause permanent damage to the device, and requires that the circuit is turned off and then re-established the power to return to normal operation.
- SEU/SET - Single Event Upset/ Single Event Transient: the presence of errors in the output circuit will be observed. SEU/SET are characterized by the presence of errors observed in the operation of the circuit resulted by radiation caused by ions or electromagnetic energy in sensitive nodes of the integrated circuit structure.

## **Results**

In all planned tests was possible to observe the errors caused by instantaneous radiation. In Table 2 is shown the characteristics of X-ray flux in the space environment according with their severity level defined by the National Oceanic and Atmospheric Administration (NOAA). This data is collected and monitored by the Geostationary Operational Environmental Satellite (GOES-15). Despite X-rays are not a main source of SEE in digital circuits, the increase in X-rays flux generally indicates the occurrence of a solar flare. In Table 3 is shown the relation between SEE and the solar X-ray flux classified according with the Table 2. The highest severity levels R4 and R5 were omitted due no occurrences were reported during the experiment. At higher X-rays fluencies the number of SEE detected on the system increases. The measurement data shown that the IC was exposed to a high X-ray flux during the first two weeks of September 2014. These dates coincide with the strong solar flare that took place on 10 September 2014 which generated emissions of solar energetic protons (SEP).

Radio Blackouts			GOES-X ray peak brightness by flux *
<b>R5</b>	Extreme	Complete HF(High Frequency) blackout on the entire sunlit side of the Earth.	$2 \times 10^{-3}$
<b>R4</b>	Severe	HF radio communication blackout on most of the sunlit side of the Earth for one or two hours.	$1 \times 10^{-3}$
<b>R3</b>	Strong	Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth.	$1 \times 10^{-4}$
<b>R2</b>	Moderate	Limited blackout of HF radio communication on sunlit side, loss of radio contact for ten minutes.	$5 \times 10^{-5}$
<b>R1</b>	Minor	Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact.	$1 \times 10^{-5}$
* Flux, measured in the 0.1-0.8 nm range, in $\text{W}\cdot\text{m}^{-2}$ . Based on this measure, but other physical measures are also considered.			

Table 2. NOAA Space Weather Scale for Radio Blackouts

Data Sets	Dates		#SEE detected	Data from EMBRACE # Events by severity		
	From	To		R1	R2	R3
1	20/06/14	30/06/14	0	0	0	0
2	01/07/14	12/08/14	996	6	1	0
3	12/08/14	13/08/14	297	0	0	0
4	13/08/14	15/08/14	17	0	0	0
5	15/08/14	17/08/14	88	0	0	0
6	17/08/14	19/08/14	146	0	0	0
7	19/08/14	23/08/14	170	0	0	0
8	23/08/14	23/08/14	1089	2	0	0
9	23/08/14	24/08/14	1338	1	0	0
10	25/08/14	27/08/14	1622	1	0	0
11	27/08/14	28/08/14	0	0	0	0
12	28/08/14	01/09/14	0	0	0	0
13	01/09/14	02/09/14	0	0	0	0
14	02/09/14	15/09/14	2529	6	1	1
15	15/09/14	16/09/14	0	0	0	0
16	09/22/14	09/22/14	0	0	0	0

Table 3. Total number of SEE detected in all shift-registers and pulse generator.

Figure 4 shown the SEE tolerance of two shift-registers with 256 stages and 8 inverters between each chain. The blue bar corresponds to the shift-registers designed using the conventional digital cells provided by the foundry. On the other hand, the red bars represents the radiation hardened digital cells designed by SMDH. It is remarkable to mention that radiation hardened cells

designed by SMDH proved tolerance to SEE with X-rays events of severity R1 and R2. In relation to the R3 event, the designed cells reported some errors by SEE. The amount of errors in the shift-registers designed using the standard cell library is comparatively larger than the shift-registers using rad-hard cell library.

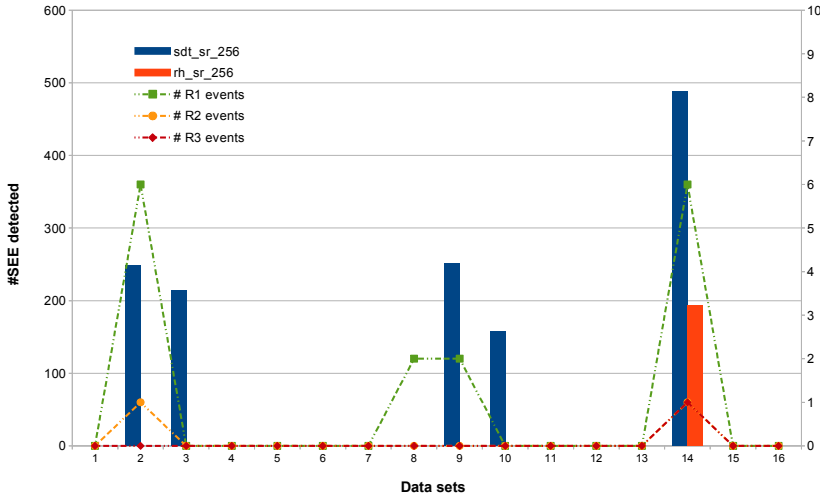


Fig. 4. SEE tolerance comparison of two shift-registers (256 FF, 8 INV).

In order to analyze and quantify the energy levels measured during the R3 occurrence and thus estimate the tolerance of customized cells, in Figure 5 is shown the fluency of SEPs during September 2014 at different levels of energy. During the first two weeks were reported SEPs with energies above 100MeV, which indicates a relation in the number of SEE detected and SEP emissions and validate the radiation hardened characteristics of SMDH's digital cells at this energy levels.

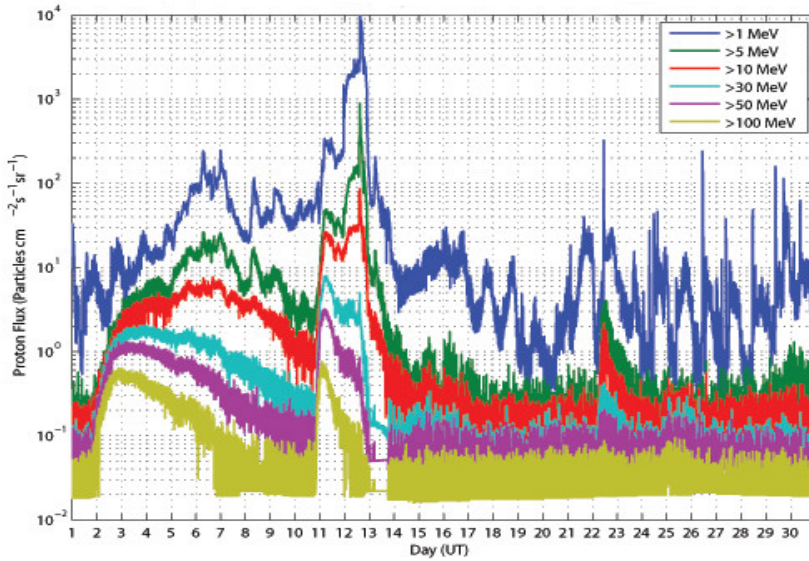


Fig. 5. Solar energetic protons detected by GOES-15 satellite during September 2014.

## Conclusion

The NanoSatCBR1 project developed by INPE and UFSM partnership demonstrated an excellent alternative to consolidate Brazilian space industry. The radiation hardened digital cells designed by SMDH proved a tolerance to solar energetic particles of energies of up to 100MeV. Additionally, the data analysis from GOES-15 satellite allows to relate the X-rays flux with the occurrence of SEE in the integrated circuits. Despite the X-rays originated in solar flares are not the cause of reported SEEs, they are linked with the emission of solar energetic particles (SEP) after a solar flare. This particles travel from the Sun to the Low Earth Orbit and impacts the satellite circuitry. The experiment results exposed the systems effects of the outer space and demonstrated that the radiation hardening design techniques applied in the SMDH ASIC were effective.

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