

Total Ionizing Dose Effects on Commercial ARM Microcontroller for Low Earth Orbit Satellite Subsystems

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Abstract: Despite the harshness of the space radiation on satellite electronic components, some Commercial Off The Shelf (COTS) can sustain such harsh environment. Thus, the low-cost advantage of the COTS can be utilized given that these electronic components meet the technical design requirements of the targeted satellite subsystem. Because of the complexity of microcontrollers and their various integrated functionality, they present a hardness assurance challenge. A careful technique was followed in analyzing the space radiation effects. Then rigorous tests should be conducted to test the performance of the candidate microcontrollers under these effects. This paper presents the predicted dose depth curve and the total ionizing dose test results for a commercial ARM microcontroller for Low Earth Orbit (LEO) satellites. Such test results help estimate the effect of space environment on the microcontroller and decide if such microcontroller is an accepted candidate for LEO missions or not.

Keywords: Microcontroller, COTS, TID, satellite, ARM

1. Introduction

The space radiation constitutes an inhomogeneous and dynamic environment that is responsible for many effects on electronics subsystems on-board satellite. Such space environment consists of high-energy and/or ionizing particles (protons, heavy ions and electrons) which induces many observable effects. These effects cause performance degradation that can affect any system's operation [1].

Total ionizing dose effect is one of the most important cumulative long-term ionizing damage due to protons and electrons. The exposed devices to those particles can suffer from threshold shifts, increased device leakage (& power consumption), timing changes, and decreased functionality [1].

Although the space environment has a low dose rate of $\sim 10^{-4}$ to 10^{-2} rad/s. But the long mission durations (years) resulting in a large accumulated radiation doses. Low Earth orbit (LEO) total ionizing dose (TID) exposure can range from 4 Krad(Si)/yr to 40 Krad(Si)/yr for effective shielding thicknesses of 10 mils of aluminum. At these levels, commercial parts may be vulnerable to failure within the course of a 1-year mission. Accordingly, candidate parts need to be characterized and qualified against the requirements of a spacecraft mission.

The Telemetry subsystem is used to collect the data of the satellite sensors (temperature, digital and analog) and record them into its storage memory then sends it to the Ground Control Station (GCS) during communication sessions [2].

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To select a microcontroller for LEO satellite telemetry module, the candidate parts are investigated in this paper. The listed microcontrollers with desirable technical specifications don't have enough radiation testing data. Only single controller has been tested according to the radiation level of the targeted mission. This paper presents the results of testing the first candidate microcontroller for our telemetry project. The related work is first explained in section 2. Mission requirements are discussed in section 3. While the telemetry subsystem and its requirements are presented in section 3. Section 4 demonstrates the experimental method. Section 5 discusses and analyzes the results. Finally, the conclusion will be in section 6.

2. Related Work

Firstly, a survey was conducted to select appropriate COTS components for the telemetry subsystem as will be demonstrated in this section. Quinn et al. [3] select different Microprocessors (MSP430, Hercules, Stellaris, Tiva and Zynq) to replace space hardened microprocessors, due to its lower cost and power, but they were not tested for radiation sensitivity. The tested microprocessors went through SEL, SEU, and SET tests. The results of these tests showed that most of the components are sensitive to SEUs, fewer are sensitive to SETs, while the flash based MSP430 and feRAM based MSP430 were sensitive to high current and SEL[3].

Tairbank et al. [4] tested two microcontrollers LPC2148 produced by NXP Semiconductors and STM32F417IGH6 manufactured by STMicro. The TID test results showed that the flash of the LPC2148 can no longer be written after 20-25 krad (Si), most parts are non-functional above 55 krad (Si), some latchup or high current events in neutron, and destructive latch in Xenon LET =58.78 Mev-cm²/mg where the LET stands for "Linear Energy Transfer" which characterizes the energy lost along its linear path in silicon. While, STM32F417IGH6 showed two SEUs events in neutron irradiation. The test done on evaluation board where SEUs observed in proton and non-destructive latch-ups observed with all ions > LET=2.19 Mev-cm²/mg [4].

Hirofuni [5] used COTS components for development of cub-satellites. He presents that the most problems of using COTS in space are the heavy dose in the LOW orbit which cause SEU and SEL[5]. While Kingsbury et. al.[6] tested the effect of TID on COTS components which commonly used on CubeSats. They tested different types of electronic components such as PIC microcontrollers, SD memory and crystal oscillator. The PIC24 microcontroller fails after 24 Krad

3. Mission Requirements

The targeted Telemetry module is planned to be used on the upcoming NARSS mission. Table 1 shows the orbital parameters of this mission which is planned to be launched in 2019. So this section demonstrates the radiation environment modeling for this mission and its Telemetry system requirements.

a. Definition of Radiation Environment and its Effects

The first step in COTS selection is to define the expected environment that the device must survive in. Our targeted mission parameters in Table 1 determine the space effects on the used electronic components. SPENVIS tool is the easiest way to perform the analysis of the orbital parameters. It is an online service provided by ESA that includes many industry-standard space radiation effects analysis tools in an easy-to-use interface. [7]

Table 1. Targeted Mission Orbital Parameters

| Parameter | Value |
|---------------------|------------|
| Orbit Type | Circular |
| Semi-major Axis | 7039.00 km |
| Apogee | 668 km |
| Perigee | 668 km |
| Eccentricity | 0.001 deg |
| Inclination | 97 deg |
| True Anomaly | 0 |
| Argument of Perigee | 0 |
| Orbit period | 1.63 hrs |
| Launch window | 2019 |
| Lifetime | 1 year |

Firstly, the TID will be calculated theoretically using SHIELDDOSE2 model (with shield 1mm) for one year [4]. The SHIELDDOSE2 is a Model in SPENVIS package [7]. The resulted curve for dose depth define the mission top-level dose requirement. Figure 2 shows the contribution of the different space environment particles (trapped electrons and protons and solar protons) to the total dose. The required TID at 1 mm thickness is calculated for one year, three years and five years. It is found to be 1.72 krad, 4.5 krad and 6.73 krad respectively.

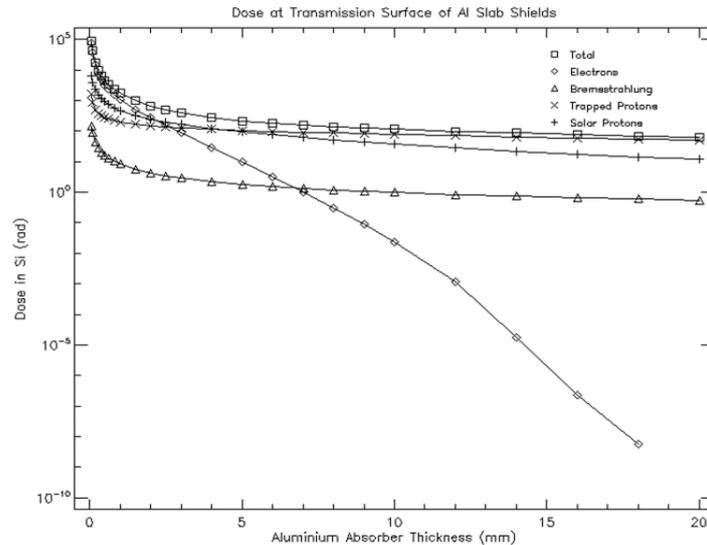


Figure 1. Dose Depth Curve for 1-year mission

b. The System Requirements

The Telemetry module is divided into two units: data-acquisition unit and processing unit. The data acquisition unit includes Temperature Sensors Commutator (TSC), Digital Sensors Commutator (DSC) and Analog Sensors Commutator (ASC) as shown in Figure 2. On the technical side, the telemetry module should include certain peripherals to meet the system requirements and required functions while maintaining a certain performance level. The subsystem will contain a master board and slave boards. The master is responsible for many

functions; it has to control and monitor the slaves, ensures the synchronization of the whole Telemetry system and collects the desired Telemetry Measurements from the slaves. Finally, the master process the collected telemetry data and sends them to the On Board Computer (OBC) upon request.

Although several radiation information can be found for slave microcontroller due to cubesat heritage, this is not the case for master microcontroller, which forced us to conduct the radiation testing for that candidate controller. The technical specs of the master microcontroller board are as following:

- external memory interface
- a high processing power not less than 40 MIPS
- Two Serial Peripheral Interface (SPI).
- Two UARTs

The next section shall present the space environment test results for several candidate master microcontrollers and its technical specifications. Then one of them shall be selected to be tested.

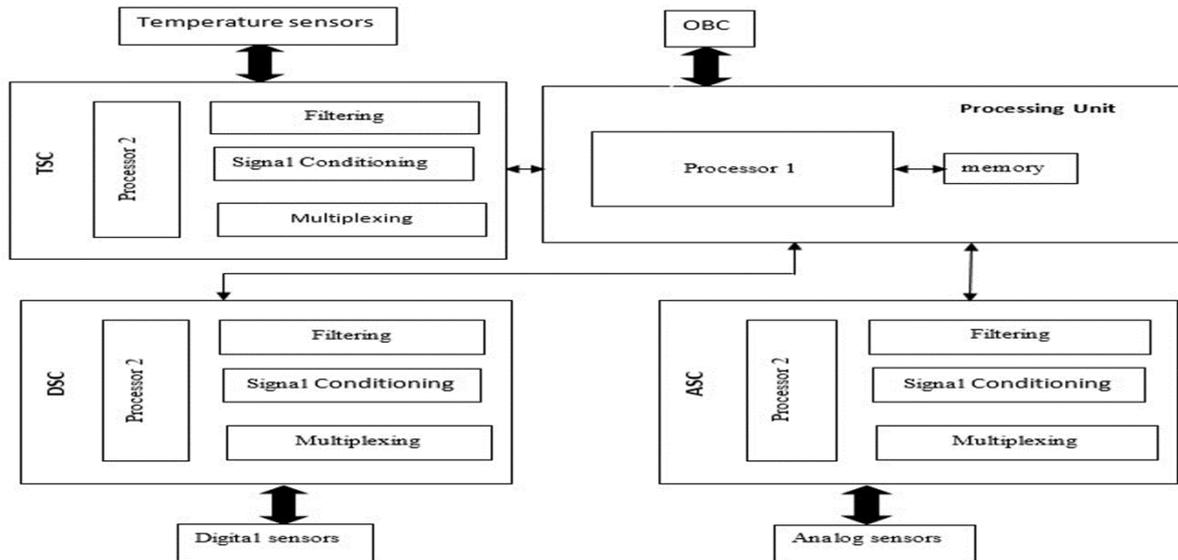


Figure 2. General block diagram of TLM module

4. Components Selection

The success of a space mission depends on a number of factors including design (radiation tolerant, de-rating, redundancy, etc.), part selection and degree of unit and system testing. ECSS-Q-ST-60-15C [8] is an excellent reference for the design factors that impact system functionality and reliability.

The first step in component selection is selecting the components that meet the main technical requirements of the system. The components must be filtered according to space environment tests results. Finally, the most suitable components shall be selected.

The selection of components for space applications is not an easy process. So, we investigated different candidate microcontrollers that meet our technical requirements. The selection of the microcontroller is conducted according to the functional requirements of the system, the assessment of the parts radiation sensitivity, and their space heritage. Usually we will not find a non-space hardened component that meets all the technical requirements and all the space

environmental parameter. Sometimes we may need to release some technical constrains or provide a protection mechanize against space environment effects.

The technical specifications of the candidate microcontrollers with assessment based on radiation sensitivity and space heritage are listed in Table 2. The radiation hardness of the microcontrollers is concluded on the basis of radiation databases and relevant radiation tests.

The selection of master microcontroller was a difficult job, due to the lack of space environment information for such powerful microcontrollers. The space heritage plays an important role in assuring the initial acceptance of such controllers in space except the LPC2378 and TI Tiva which didn't have space heritage, but the LPC was tested for TID and passed the required level by the mission. Space heritage means that the microcontroller can withstand space TID, but doesn't specify to what extent. Such case was faced with both AT91SAM9G20 and STM32F1. TID testing is a mandatory requirement, thus we need to conduct that test before we can use any processor. As such testing is not easy to conduct, we choose to carry on the technical selection of the microcontroller, and then conduct the test on it. If it failed we would retest the next candidate in the list. The three candidates were ordered according to their suitability for the requirements. Then the first candidate was selected to be tested for TID.

Table 2. Technical Specs, TID and Heritage of Candidate Microcontrollers

| Part Number | Freq. | ADC | DAC | UART | SPI | I2C | CAN | RAM | External memory interface | TID | heritage |
|-------------|---------|-----|-----|------|-----|-----|-----|-----|---------------------------|---------------------------|------------------------------------|
| STM32f1 | 72 MHz | 3 | 2 | 5 | 3 | 2 | 1 | | √ | N/A | FoxSat TubSat [12] |
| AT91M40800 | 40 MHz | X | X | 2 | 2 | X | X | X | √ | at 10 krad no degradation | DTU Sat-1[10] |
| AT91SAM9G20 | 400 MHz | 1 | X | 4 | 2 | X | X | | √ | N/A | SOMP Cube-Sat [11], Aalto-1Compass |

5. TID Test for STM32F1

a. Test Conditions

The test was conducted at the Military Technical College Laboratory facilities at Cairo, Egypt. Low dose rate tests were conducted at the ^{60}Co facility. This cell contains Cobalt (Co^{60}) radioactive source. It has a concentric cylindrical container with 172 mm in diameter and 205 mm in height with a maximum irradiated volume capacity of 5000 cc. This cell was designed according to 6-N 433.1. The test was executed inside the radiation cell in the presence of air with dose rate 2.08 kGy/h at the room temperature. The test method for cobalt-60 is laid out in MIL-STD- 883G, method 1019.7 [9]

b. Test Setup

A typical low dose rate test configuration is illustrated in the schematic diagram in Figure.2, demonstrating the arrangement for STM32F1 tests.

DUT was biased during irradiations and internal clock generation program was continuously running. Device were removed from the irradiator for functional testing and returned to the test chamber within one hour if it was still functional. The testing program used the internal clock to generate external clock, this clock is then measured before the sample is returned to the chamber until the program stopped working

Firstly the DUT exposed to pre-calculated doses calculated for one year, three years and five years to be 1.72 krad, 4.5 krad and 6.73 krad respectively as mention in section 3. Dose rates at each step were measured with the Radcal ionization gauge.

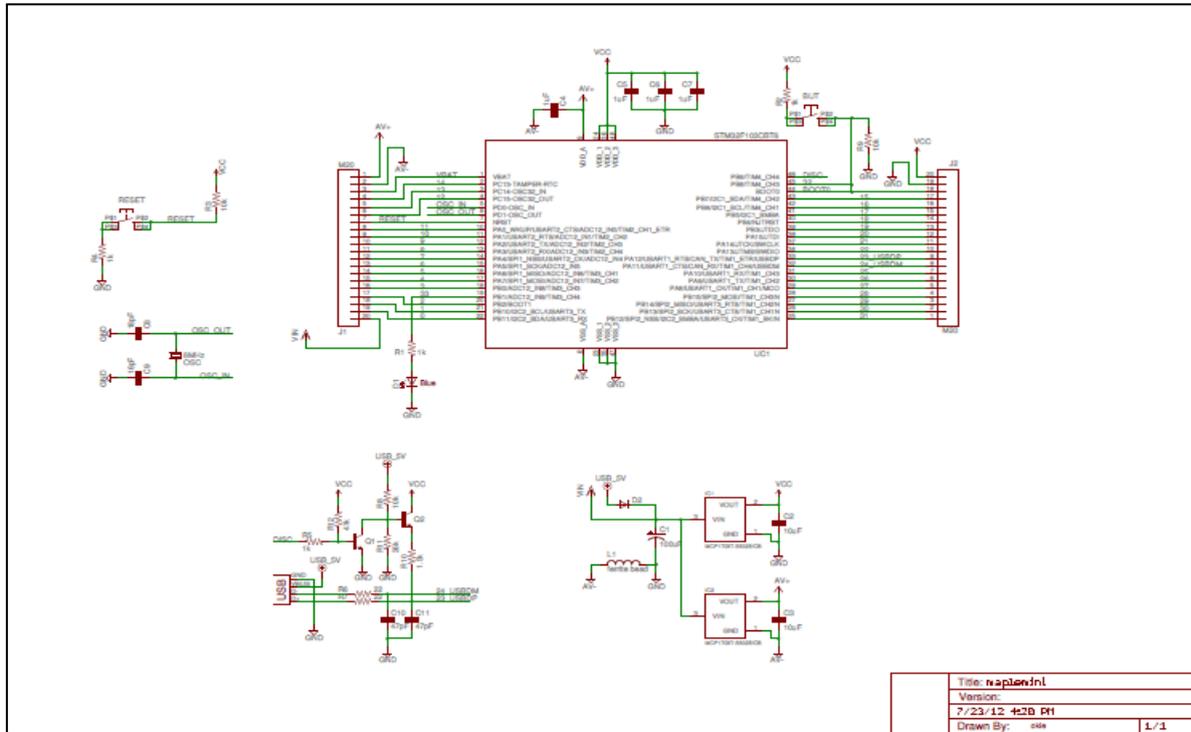


Figure 3. Schematic diagram of test board

6. Results and Discussion

The STM32F1 was irradiated while biased for functional tests operating at 3.3 V, repeating the process for each dose step. After exposing it to 1.72, 4.5 and 6.73krad, the microcontroller passed the test for more than 5 years for the selected orbit. Evaluation of the STM32 clock stability is shown in figure 4 after different steps of doses. As the increase of gamma dose, the clock-cycle frequency slightly decreases and stabilizes afterward till the failure of the microcontroller at 107krad. STM32F1 is TID hardness. The microcontroller failure can be credited to the failure of its flash memory [12], while the clock degradation is mostly credited to the microcontroller oscillator. As can be seen from Figure 4 the actual operating frequency for this microcontroller in space is approximately 85% from its configured frequency. Such degradation should be considered during evaluating the processing capability and subsystem design and requirements when selecting the components.

7. Conclusion

External radiation environment for the targeted mission was predicted based on mission parameters. Accordingly, the TID for five-year mission was calculated to be 6.73 krad. STM32F1 is a suitable microcontroller for the required Telemetry module, since it has all the required technical specifications. STM32F1 is TID hardness. The failure does is determined to be 107krad. The actual operating frequency for this microcontroller in space is approximately 85% from its configured frequency.

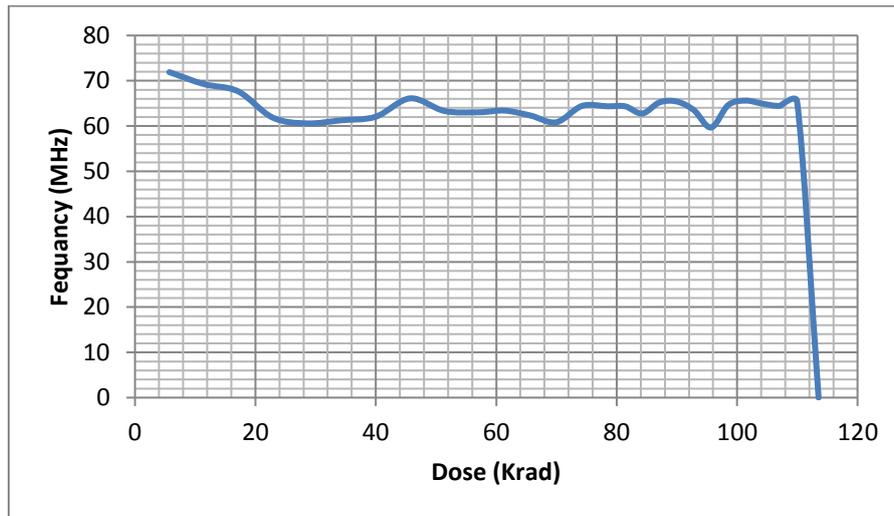


Figure 4 STM32F1 TID test result as a function of clock frequency operating at 3.3V.

8. Acknowledgements

The research in this project is funded by Science & Technology Development Fund (STDF) project ID 15055.

9. References

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