LETTER

TID characterization of COTS parts using Radiotherapy Linear Accelerators

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Abstract Ionizing radiation can disturb electrical and electronic devices. These devices need to be tested and qualified to operate under special environment conditions such as those present in nuclear or space applications. Radiation effects must be considered when designing systems that must have high mean time between failures and are exposed to radiation. This paper shows how common radiotherapy linear accelerators (LINAC) can be used to characterize the Total Ionizing Dose (TID) effects on electronic devices. This work presents the principal radiation-induced effects on a Raspberry Pi Compute Module board, as good representative of typical Commercial Off-The-Shelf components. The Monte Carlo method used and the procedure for TID characterization are shown.

key words: TID, COTS, Raspberry Pi, Monte Carlo method, LINAC, gamma rays.

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

Electronic devices are often exposed to exceptional radiation levels, in many different fields of operation, not only in space. This is the case of electronic parts being used in X-rays machines or High Energy Physics applications \[1\] [2]. In order to reduce costs, it is not always possible to use Radiation Hardened electronic parts in ground based applications. It is important then, to understand how radiation affects commercial grade electronic parts.

The purpose of the work reported here is to perform a Total Ionizing Dose test on the popular Raspberry Pi Compute Module CPU System On Chip (SoC), as a potential embedded system for ground based instrumentation or even space applications such as cubesat/nanosat missions.

The use of a linear radiotherapy accelerator (LINAC) to characterize the device TID is a different approach as the common one used such a \(^{60}\)Co source [3] or hadronic colliders. Reported results represent the performance of a specific device produced at a specific time and place. As with all commercial parts, the design and/or fabrication technology may be changed at any time and may have a significant impact on the device performance in a radiation environment.

2. Radiation effects

2.1 Radiation in nuclear medicine

The use of ionizing radiation in oncology has led to high radiation environments close to the human body. Nuclear medicine imaging procedures use radiopharmaceuticals exposing patients to moderate levels of radiation depending on radioisotopes. Radiation therapy treatments use high-energy particle beams as X-rays to kill cancer cells.

2.2 Radiation in electronic devices

The most widely used electronic manufacturing technology is CMOS, thanks to its low consumption and extreme integration density. These advantages make it ideal for devices that use batteries and that must have a small size.

Electronic devices can be affected by radiation sources in different ways producing changes in important electric parameters. Electronic devices working in a radiation environment (Nuclear Medicine, Space, etc.) may end up failing and causing a malfunction of the circuit where they are working [4].

Ionization can produce effects due to the cumulative (total ionization dose, TID) nature of the generated charge and transient effects called Single Event Effects (SEE) generated by the action of a single particle.

The effects of the radiation in semiconductors can be grouped in two main groups: Non-Destructive effects and Destructive effects [5]. Non-destructive effects are those that can cause a temporary failure the system can recover of and destructive effects are those that can finally cause a permanent damage in the system [6].

Detailed information about radiation test can be consulted organization such as ESA [7] or NASA [8,9]

Total Ionizing Dose (TID) effect is one of the main effects on irradiated components. When a device is exposed to radiation for a certain amount of time, there is a cumulative ionizing dose inside it, and when it is high enough, the
device might fail to work. TID [10] is a long-term failure mechanism and can be described by a mean time to failure.

3. Radiation therapy linear accelerator

Nowadays there are linear accelerators able to generate high energy electron beams for radiation therapy. The most typical block diagram representing a therapy linear accelerator is the one shown in Figure 1. [11]

We can distinguish the following main components in the accelerator: Microwave source (A), pulses generator (B), electron source (C), accelerator guide (D), magnetic deflector (E), primary deflection plate (F), equalizer (G), dose monitor (H), collimator (I), electric and safety systems (K), the control system (L), and the treatment table (M).

The electrons are generated by thermionic effect, and are accelerated at speeds close to light, to be subsequently directed to a target that is usually tungsten and copper (source of radiation beam). When the electrons collide with the target, they slow down rapidly, thus producing electromagnetic radiation, as a result of the loss of braking energy or bremsstrahlung.

The effect of the photon beam is continuous [12], and its maximum energy will be equal to that of the incident electrons. One third of the maximum energy of these incident electrons will be equal to the average energy of the photon beam. Photons would appear in all directions, but for energies between 4 and 20 MeV that are handled in clinical accelerators, it predominates directionally forward as shown in Figure 2, which shows the angular distribution for the photons produced by Bremsstrahlung for different energies.

Raspberry Pi Compute Module is based on a SoC (System on chip) BCM2835 from Broadcom (Figure 3). It conceals an ARM1176JZF-S core at 700 MHz. The ARM1176JZFS core [14] is based on the ARM6 architecture and includes FPU and VFP extension to the ARM instruction set. An ARM processor is one of a family of CPUs based on the RISC (Reduced Instruction Set Computer) architecture developed by Advanced RISC Machines (ARM).

ARM processors are extensively used in consumer electronics devices such as smartphones, mobile devices, etc. Because of their reduced instruction set, they require fewer transistors, which enables a smaller die size for the integrated circuitry. The smaller size, reduced complexity and lower power consumption makes them suitable for battery-based devices.

The most popular Raspberry Pi system is the B version but not the Compute Module because this one needs additional hardware to be added to make it work. The decision to use the Compute Module instead of the B version is based on the fact that this system can work in the Industrial temperature grade and the use of an external SD card is not needed because it uses its own Flash eMMC memory to store the Operating System and User Application. The less components the less power consumption and system complexity and we can limit the effects of the ionizing radiation. The mechanical layout of the Compute Module is compatible with the DDR2 SODIMM (200pin), this means that is a compact version of the most common Raspberry Pi, designed especially for embedded use. The module itself does not contain any additional connector and can be easily integrated in a custom electronic design.

One of the Compute Module (Figure 4) main advantages apart from the reduced cost, reduced set of components inside the board (video, Ethernet, USB) and the absence of the SD Card for program and data storage is the capability to work with a GNU/Linux (multitask and multi user) Operating System distribution, providing us high programming flexibility and computation power.
The board is composed by the Broadcom BCM2835 SoC, a 512MByte Elpida SDRAM and a 4 Gbyte eMMC Flash. The choice of the BCM2835 CPU as candidate for TID is based on the popularity of the Raspberry Pi board. More than 12 million Raspberry Pi systems have been sold in five years and is a well-known and proven system for embedded applications. The Broadcom SoC itself includes a huge amount of peripherals and components inside, but for our testing purposes and TID characterization, only the Core and few of them (I2C, SPI, GPIO, USB and UART) will be used and monitored during testing.

The Compute Module itself is not functional if there is no external hardware to provide power supply and access to the SoC pins, this is achieved by means of a mother board where the Compute Module can be plugged in. This mother board has a reduced set of components and provides us with an USB connection to communicate with the CPU.

5. Irradiation Simulation

5.1 Monte Carlo Method

The Monte Carlo method is a mathematical model that allows us to simulate any system. In general, systems are simulated when precise experimental measurements cannot be made but when its global behavior can be modeled by means of a probability distribution. This technique is applied in many fields, not only in the field of radiation, but also in mathematics (evaluations of integrals), environmental engineering (growth of forests and pollution studies), economics (market analysis and GDP growth), quantum chemistry (interaction of DNA molecules) and many other applications.

From the first article published by Berger [15] where the bases of the method are described and later from the work of Raeside [16], where the Monte Carlo method is applied to medical physics, the number of works published in recent years and interest in this method of calculation has only increased [17,18]. There are many Monte Carlo codes applied for the simulation of radiation transport such as EGS4, MCNP, PENELOE [19], etc. that have been widely applied in the simulation of radiation generators as well as the transport of electrons and photons in all types of conditions and media [20]. In our case, we have used the PENELOE code to model our experimental system.

Monte Carlo simulations of the electron dose in water were performed using the penEasy package, which is a structured general-purpose software for PENELOE [21] that allows the coupled transport of photons, electrons and positrons in a wide range of energies, in any kind of material and complex geometry. PENELOE, which is free, open source and distributed by the NEA, has been successfully used in the simulation of linear accelerators and cobalt units [20]. In addition to PENELOE, a generic software called penEasy [22], has been developed, providing models of radiation sources and allow us to calculate different magnitudes of interests.

5.2 Simulation

Through the penEasy code the photon beams coming out from the linear accelerator ELEKTA INFINITY where simulated in a simplified way as well as the geometric arrangement of the electronic components to be irradiated. Through this simulation the dose ratio was determined in the electronic component (Si) respect to the absorbed dose at the point where the ionization chamber is located. The spectrum shown in Figure 5 is the one obtained for the photon source when a simple linear accelerator head is used.

Finally, a 15x15x10 cm$^3$ solid water phantom was used to collect the absorbed dose in a three-dimensional matrix (1 mm$^3$ bins) with the Si inserted in it.

For our Monte Carlo simulation, a total of 5x$10^8$ simulated photon histories were used. Regarding the simulation control parameters, C1 and C2 (used to fix the mean free path between elastic events) where adjusted to 0.07 (typical value for our geometry and Energy) and simulations where carried out with EABS (absorption energies) of 20 KeV for the photons. The values for the inelastic collisions cut-off energy (WCC) and bremsstrahlung cut-off energy (WCR) where adjusted to 150 KeV and 20 KeV respectively.
Fig. 5 Spectrum of photons

The whole test setup dose simulation with solid water blocks and electronic component is shown in Figure 6. Doses on Si where obtained by the extrapolation of the measured dose in the ionizing chamber position (5 cm) to the middle of the Si zone.

Fig. 6 Monte Carlo Simulation of the Test Setup

This linear accelerator is fully devoted to Radiotherapy and can be configured to produce photons beams from 6MeV to 15MeV, as well as electron beams of 6, 9, 12 and 15 MeV. The irradiation fields can have a size up to 40x40 cm² at Surface-Surface Distance of 100 cm. The LINAC sends pulsed beams (600 packets/second) but can be considered for our tests as continuous since the radiation interact with matter randomly, the events are independent of each other and the interaction times are lower than $10^{-14}$ s.

6.3 Results
The Monte Carlo simulation for a 10x10 cm² field of 6 MeV photon beam in the linear accelerator compared to the experimental measurements is shown in Figure 7, a good alignment between simulation and experimental results can be observed. The error in the data obtained is 2s.

6.4 Test Setup
The linear accelerator incorporates a series of laser beams provide accurate position of the target into the treatment table (Figure 8). To ensure that the radiation is homogeneous in the electronic component it has been placed in a water solid (Standard Imaging) block in order to avoid electronic non-equilibrium problems in the target to be radiated (the irradiation inside the device will not be homogeneous). The target has been irradiated to a depth of 2 cm of water solid, a Source-Surface Distance (SSD) of 88 cm and to a
600 cGy/min. In our case a 3x3 cm² area has been defined.

A thermocouple was placed on top of the CPU chip to monitor the temperature during the test. This provides information about the health of the chip showing an abnormal increase of the temperature if a SET, SEL effect occurs as explained in Chapter 2. The system connects with the control room by means of an Ethernet cable and an SSH connection that provides a Linux Terminal to run/stop tasks and to monitor the connection with the Compute Module (Figure 9).

A second interface board designed to read analog to digital converters, I2C, SPI chips and UART is also available to verify test the different system buses.

6.4 Software
The Compute Module multi-tasking (Raspbian) [24] capability allows us to have a Linux terminal running a test program and another one to check the CPU load, and processes running in it.

Two different sets of software have been coded and developed using Python 2.7 [25]. A simple program will calculate sequentially prime numbers and show them as soon as they are discovered and also a timestamp every 1 second, to check that everything keeps up and running. The aim of this task is to check the CPU health when is irradiated in the accelerator room.

A program will check the status of the Compute Module checking the integrity of the UART, SPI, I2C and GPIO buses in the control room after the irradiation.

6.5 Testing Method
The Broadcom BCM2835 SoC is not a radiation tolerant component and is not designed to fulfill with the space missions specifications [26]. It does not implement EDAC or redundancy. The aim of the test proposed is to obtain a clear idea on how this SoC reacts to the different radiation phases in terms of an overall functionality. Two different phases have been differentiated for the tests.

Irradiation Phase:
The Target is positioned, fixed on the treatment table (Figure 8) and its nominal behavior is verified by means of an SSH connection when irradiated with a 6MeV photon beam.

Functional Phase:
The CM is transferred to control room, connected to a new mother board to be sure that the peripherals (I2C, SPI, UART, USB and GPIO) remain operational for 5 minutes after the irradiation phase was finished. If the functional test result is OK, the system will be irradiated again in the accelerator room.

6.6 Tests Results
The Table I, shows the different doses and results of each test. The doses where not homogenous because there was uncertainty of what was going to be the response of the system after or during each irradiation dose.

During the last two irradiation phases the system stop sending the prime number calculated and the 1 second timestamp for at least 30 seconds. After the system absorbed a TID of 66.83 krad, was not possible to stablish a SSH connection with the Compute Module and the test was finished. The rest of the system remained “Nominal” when checked, but as the Compute Module was not 100% operational, we decided not to continue with the tests.

The LINAC guarantees in an intrinsic way the stability of the irradiation Dose. The different values in each step are due to the lack of prior knowledge about the influence of the LINAC irradiation in commercial grade components and the need to stablish the irradiation damage threshold for this Compute Module CPU SoC.

The results obtained are in line with what has been observed in other experiments [27][28] carried out with the Raspberry Pi Model B version using a $^{60}$Co radiation source. In this case there were no degradation observed prior to 60 krad.

7. Conclusion
The SoC BCM2538 did not exhibited any damage or lack of performance prior to 60 krad. The system experienced a failure after a 66.83 krad TID like loss of communication with the computer and could no longer be able to stablish any SSH connection. No significant temperature changes were observed during the tests. Considering that average TID in Low Earth Orbit satellites (altitude: 400-600 km, 25-50 degrees of inclination) can be around 1 to 3 rads per day [28], this works shows that this CPU would be suitable for cubesats or similar space applications.

The use of Radiotherapy Linear Accelerators [29] can be a valid alternative to the use of a source or common Linear Accelerators.
Accelerators tunnels for TID characterization for COTS systems [30] or components.

| Room P (mBar) | Room T. (°C) | CPU Temp (°C) | Dose step (krad) | TID (krad) | Irrad. Phase | Func. Phase |
|---------------|--------------|---------------|------------------|------------|--------------|-------------|
| 954.2         | 22           | 31            | 1.16             | 1.16       | Ok           | Ok          |
| 954.2         | 22           | 30.8          | 1.16             | 2.32       | Ok           | Ok          |
| 954.2         | 22           | 31.1          | 2.32             | 4.64       | Ok           | Ok          |
| 954.2         | 22           | 31            | 2.32             | 6.96       | Ok           | Ok          |
| 954.2         | 22           | 30            | 2.32             | 9.28       | Ok           | Ok          |
| 954.2         | 22           | 31.4          | 4.65             | 13.93      | Ok           | Ok          |
| 954.2         | 22           | 30.8          | 4.64             | 18.57      | Ok           | Ok          |
| 954.2         | 22           | 31            | 4.65             | 23.22      | Ok           | Ok          |
| 954.2         | 22           | 30            | 8.13             | 31.55      | Ok           | Ok          |
| 954.2         | 22           | 30.4          | 0.86             | 32.21      | Ok           | Ok          |
| 954.2         | 22           | 31            | 0.86             | 33.07      | Ok           | Ok          |
| 954.2         | 22           | 31.2          | 0.86             | 33.93      | Ok           | Ok          |
| 954.2         | 22           | 31            | 0.86             | 34.79      | Ok           | Ok          |
| 954.2         | 22           | 30.4          | 1.72             | 36.51      | Ok           | Ok          |
| 954.2         | 22           | 31.3          | 5.24             | 41.75      | Ok           | Ok          |
| 954.2         | 22           | 30            | 6.28             | 48.03      | Ok           | Ok          |
| 954.2         | 22           | 30.4          | 6.27             | 54.30      | Ok           | Ok          |
| 954.2         | 22           | 30.4          | 6.26             | 60.56      | Fail         | Ok          |

| 954.2         | 22           | 30.4          | 6.27             | 66.83      | Fail         | Ok          |

**Acknowledgements**

This research is supported by the Space Research Group of the University of Alcalá and the Parque Científico y Tecnológico de Castilla-La-Mancha.

**References**

[1] Lili Ding, Simone Gerardin, Marta Bagatín, Dario Bisello, Serena Mattiazzo, Alessandro Paccagnella, Radiation tolerance study of a commercial 65nm CMOS technology for high energy physics application. Nuclear Instruments and Methods in Physics Research Section A. Volume 831. 2016, Pages 265-268, ISSN 0168-9002

[2] B.Blyszm, D.Cady, A. Celik, L.S. Durkin, J. Gilmore, J. Haley, V.Khotilovich, S.Lakdawala, J.Liu, M.Matveev, B.P. Padley, J. Roberts, J. Roe, A. Sanonov, I. Suarez, D. Wood, I. Zawisza, Radiation testing of electronics for the CMS endcap muon system. Nuclear Instruments and Methods in Physics Research Section A: Volume 698, 2013, Pages 242-248, ISSN 0168-9002

[3] ESA PSS-01-609 Issue 1 (May 1993) Section 19

[4] R. Garcia et al, Introduction to radiation effects and modelling on radiation damage, Reliability and Availability Workshop for the High Luminosity LHC, CERN (2014). https://indico.cern.ch/event/308246

[5] G. Bruiguer and J.-M. Palau. Single particle-induced latchup, IEEE Transactions on Nuclear Science 43(2):522-532, 1996

[6] Sophie Duzellier, Radiation effects on electronic devices in space. Aerospace Science and Technology. Volume 9, Issue 1, 2005, Pages 93-99, ISSN 1270-9638

[7] Sophie Duzellier, Radiation effects on electronic devices in space. Aerospace Science and Technology. Volume 9, Issue 1, 2005, Pages 93-99, ISSN 1270-9638

[8] ESA Radiation reports. https://escies.org/labreport/radiationlist.

[9] NASA, GFSC radiation effects database. http://radhome.gsfc.nasa.gov/radhome/RadDataBase/RadDataBase.html

[10] L. Ratti, Ionizing Radiation Effects in Electronic Devices and Circuits. Legnaro, April 17th 2013

[11] Jose Miguel Barrera Causil, “Caracterización del Haze de Fotonos de un Acelerador Lineal”, Universidad de Colombia. 2012. 18:24 [4] Jose Miguel Barrera Causil. “Caracterización del Haze de Fotonos de un Acelerador Lineal”, Universidad de Colombia. 2012. 18:24

[12] G. Barbottin and A. Vapaille. Instabilities in Silicon Devices, New Insulators, Devices and Radiation Effects. Elsevier, 1999

[13] Khan, F.: The Physics of Radiation Therapy. Minneapolis, Minnesota: Lippincott Williams and Wilkins, 2003

[14] The ARM11 Architecture. Ian Davey, Payton Oliveri. Spring 2009. http://www.cs.virginia.edu/~skadron/cs433_s09_processors/arm11.pdf

[15] MJ Berger. Monte Carlo calculation of the penetration and diffusion of fast charged particles in Method in Computational Physics. Vol 1 Eds. B Alder, S Fernbach and M Rotenberg. Academic Press. New York. 1963

[16] DE Reaside. "Monte Carlo principles and applications". Phys. Med. Biol. 1976.21.181.

[17] Andrea P Review: Monte Carlo techniques in medical radiation physics Phys. Med. Biol. 1991. 36 861-920

[18] Ma C-M, Jiang SB. Monte Carlo modelling of electron beams from medical accelerators. Phys Med Biol 1999:44: R157-89.

[19] Salvat F, Fernández-Varea JM, Sempau J. PENEOPE-2006. A Code System for Monte Carlo Simulation of Electron and Photo Transport. OECD-NEA 2006, Issy-les-Moulineaux, France.

[20] Monte Carlo Treatment Planning An Introduction NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE Report 16 of the Netherlands Commission on Radiation Dosimetry. Netherlands Commission on Radiation Dosimetry Subcommission Monte Carlo Treatment Planning June 2006

[21] J. Sempau, J.M. Fernández-Varea, A. Acosta, F. Salvat, Experimental benchmarks of the Monte Carlo code penelope, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 207, Issue 2, 2003, Pages 107-123, ISSN 0168-583X.

[22] J. Sempau, A. Badal and L. Brualla, "A PENEOPE-based system for the automated Monte Carlo simulation of clincias and voxelized geometries-approch to far-from-axis fields," Medical Physics, vol. 38, (11), pp. 5887-5895, 2011.

[23] http://www- naweb.iaea.org/NAHU/DMRP/documents/CoP_V12_2006-06-05.pdf

[24] https://www.raspbian.org/

[25] https://www.scipy.org/

[26] Space Engineering Technical Requirement Specification ECSS-EST-10-06C

[27] Daniel D. Violette. EEE Parts for Small Missions. Greenbelt,MD. 2014.

[28] SPENVIS. https://www.spenvis.oma.be/

[29] Manuel Bandala, Malcolm J. Joyce.Photon radiation testing on commercially available off-the-shelf microcontroller devices.IEICE Electronic Express/Volume 9 (2012) Issue 5 Pages 397-402

[30] F. Faccio, COTS for the LHC radiation environment: The rules of the gane, 6th Workshop on Electronics for LHC Experiments (2000). https://cds.cern.ch/record/478245

IEICE Electronics Express, Vol.xx, No.xx, xx-xx