Review Paper: Error Detection and Correction Onboard Nanosatellites

Caleb Hillier and Vipin Balyan

Abstract The work presented in this paper forms part of a literature review conducted during a study on error detection and correction systems. The research formed the foundation of understanding, touching on space radiation, glitches and upsets, geomagnetism, error detection and correction (EDAC) schemes, and implementing EDAC systems. EDAC systems have been around for quite some time, and certain EDAC schemes have been implemented and tested extensively. However, this work is a more focused study on understanding and finding the best-suited EDAC solution for nanosatellites in low earth orbits (LEO).

Keywords Error control · Nanosatellite · FPGA · Radiation · EDAC

1 Introduction

The main focus of this study is preventing and overcoming the effects of radiation in memory onboard nanosatellites. The issues that need to be addressed are the single event upsets (SEUs) and multiple event upsets (MEU) caused by space radiation. This study will take a logical approach to EDAC systems, starting with space radiation (the cause), glitches and upsets (the error), geomagnetism (high probability of occurrence areas) EDAC schemes (solutions), and implementing EDAC systems (implementation).

All research is related and done for nanosatellites orbiting at low earth orbits (LEO). By referencing a number of articles and journals, a board understanding of EDAC systems is established. This review was assembled from a number of papers observations. Using the information and knowledge gained during the completion of review, a thesis topic was identified and motivated. Also included in this paper is the comparison of EDAC systems, based on foundation principals, capabilities, and applications. At the end of this paper, all important aspects relating to EDAC systems will be discussed fully, and the finding will conclude that further work on

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Table 1 Effects of charged particle in a space environment [1]

Spacecraft charging	Total ionizing dose	Displacement damage	Single event effects
Surface charging from plasma Deep dielectric from high-energy electrons	Trapped protons and electrons Solar protons	Protons Electrons	Protons: both trapped and solar Heavy ions: both galactic cosmic rays and solar events

EDAC systems in the nanosatellite field is still a needed and interesting field to work in.

2 Methodology

2.1 Space Radiation

Space radiation is a general term given to ionizing radiation found in space. This form of radiation is made up of highly energized particles which are mainly protons and heavy ions. The sources of space radiation are identified by NASA's Space Radiation Analysis Group (SRAG) in the following manner: "There are three naturally occurring sources of space radiation: trapped radiation, galactic cosmic radiation (GCR), and solar particle events (SPEs)" [3]. According to sources on radiation, SPEs have the biggest impact on satellites. The effects of radiation are often minor; however, there are some extreme examples of incidents occurring that have caused space missions to fail [4].

Radiated solar particles are responsible for electronic malfunctions, deterioration of materials, and surface charging and discharging. Due to the severe impact radiation can have on a satellite, radiation is considered to be a fundamental and important factor when it comes to the design and operations of satellites [5]. The effects of charged particles in a space environment are summarized using Table 1. Table 2 shows the three main sources of the radiation in space along with their effects on CMOS devices.

It is important to ensure that all electronic devices and components used to make up any space system have been tested and are able to resist the dose of radiation they might be exposed to. This is essential to ensure data integrity and reliability.

2.2 Glitches and Upsets

A glitch is defined as a sudden, usually temporary malfunction or fault of equipment. Glitches experienced by a satellite can be caused by many factors, such as hardware

Table 2 Effects of radiation on CMOS devices [2]

Space radiation environments and their effects on CMOS devices		
Radiation source	Particle types	Primary effects in devices
Trapped radiation belts	Electrons	Ionization damage
	Protons	Ionization damage; SEE in sensitive devices
Galactic cosmic rays	High-energy charged particles	Single event effects (SEEs)
Solar flares	Electrons	Ionization damage
	Protons	Ionization damage; SEE in sensitive devices
	Lower energy/heavy-charged particles	SEE

problems, corrupted software, or space weather. The exact cause of glitches and upsets is often hard to determine, especially when satellites are exploring unknown areas of space and interplanetary space.

The first warnings for single events upset were first brought to light by Wallmark and Marcus in 1962 [6]. SEUs are errors that occur in electric and digital circuits. According to NASA, these SEU occur: "When charged particles lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs" [7]. MEU occurs when two or more bits are upset by a single ion. These upsets are usually soft errors and can be corrected by onboard EDACs or prevented using hardened devices.

There are numerous examples of satellites being affected by glitches and upsets. The Magellan spacecraft on route to Venus suffered both power panel and star tracker upsets after being exposed to a solar flare [8]. Intelsat officials reported on the January 13, 2011 that their Intelsat's Galaxy 15 telecommunications satellite was unable to receive any commands from earth for eight months due to electrostatic discharge that caused a major software error [9].

The source of these types of glitches can normally be determined by analyzing the housekeeping data of the satellite. The referred articles are relevant to this review as solving the problem of glitches and upsets is ultimately the aim of an EDAC system.

2.3 Geomagnetism

Geomagnetism refers to the earth's magnetic field. This field expands into outer space from the earth's core, effecting orbiting spacecraft and also deflects particles from outer space. Figure 1 provides a well laid out illustration of the magnetic fields produced by the earth, as well as the factors that influence it.

Geomagnetism is directly linked to radiation, as its fields cause particles to be trapped, which results in belts like the Van Allen Radiation Belts. The Van Allen

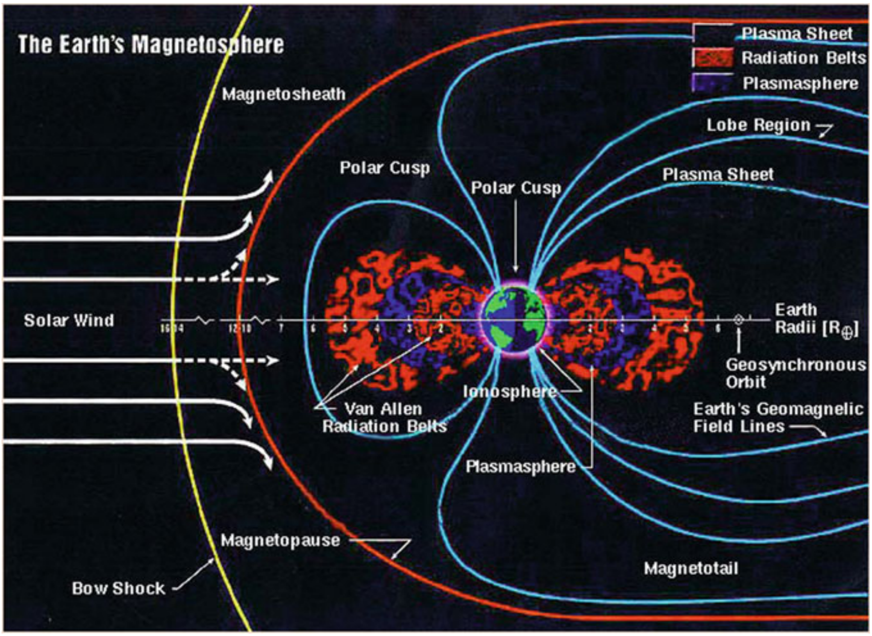

Fig. 1 The earth's magnetosphere [10]

Radiation Belts contain highly energized particles which can have devastating results on unprotected satellites. In 2012, NASA launched two Van Allen Probes spacecrafts with the mission of "study two extreme and dynamic regions of space known as the Van Allen Radiation Belts that surround Earth" [11]. Figure 2 shows both the inner and outer radiation belts.

When discussing radiation with regards to nanosatellites, the South Atlantic Anomaly (SAA) is the main culprit of single error upsets (SEUs) and multiple error upsets (MEUs). The South Atlantic Anomaly (Fig. 3) is the area where the earth's magnetic field is at its weakest. This means it is the area where the Van Allen Radiation belt is the closest to earth.

From an article written by Y. Bentoutou, the effect of radiation on board the Alsat-1 spacecraft is shown clearly in Fig. 4. The orbital location of each upset that occurred from the November 29, 2002 to October 12, 2009 is plotted. It can be noted that the majority (±80%) of SEU fell within the SAA [13].

From the provided information on Geomagnetism, its connection and relevance to nanosatellites design and implementation becomes clear. It is important that methods and schemes are designed that will allow nanosatellites to withstand and operate normally within environments produced by SSA and others.

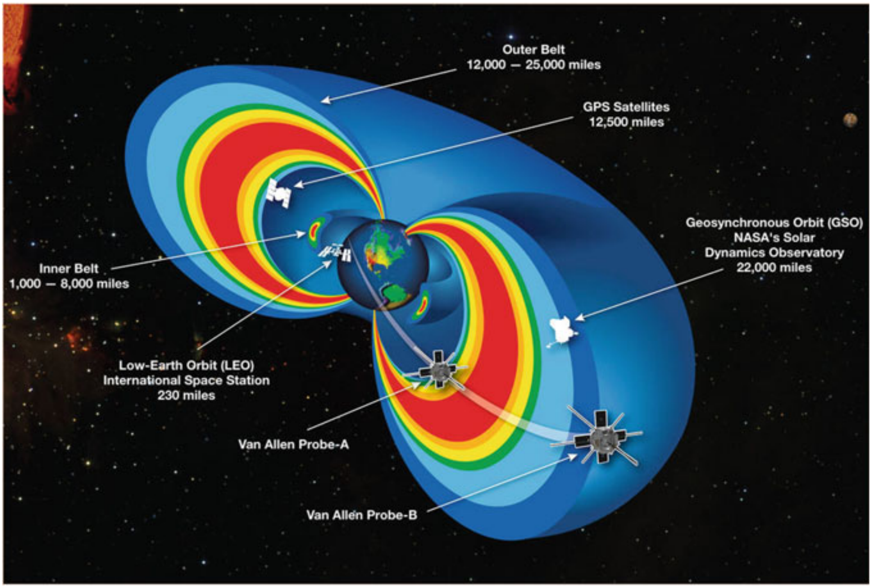

Fig. 2 ERBs including 2 Van Allen Probes satellites [12]

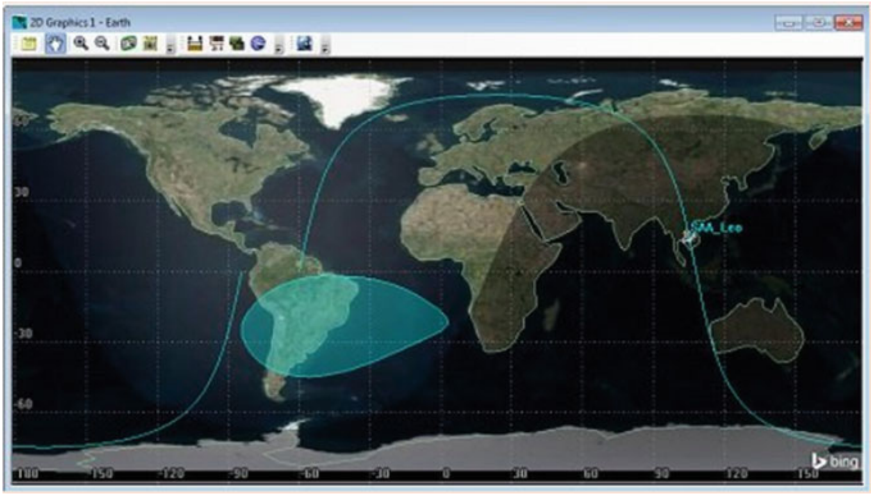

Fig. 3 SAA using STK SEET [14]

2.4 EDAC Schemes

EDAC systems are responsible for ensuring reliable data transfer between the satellites onboard computer and its local memory. An EDAC system is a software solution

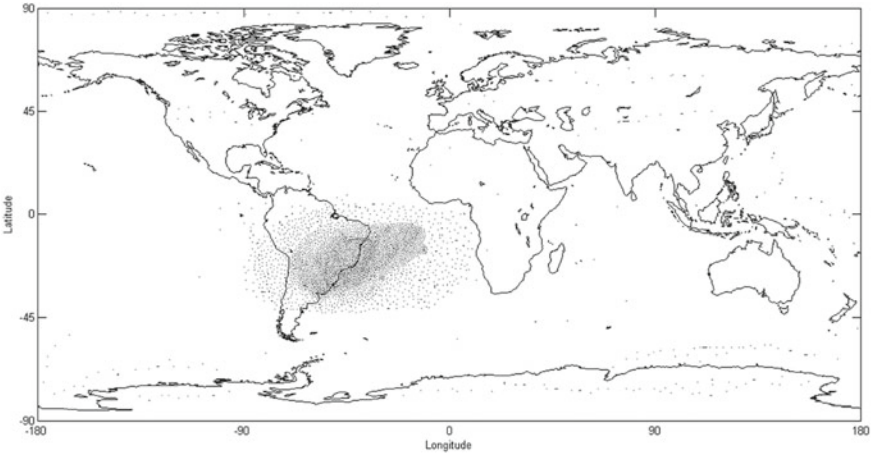

Fig. 4 Orbital position of OBC386 Ramdisk memory upsets [13]

to prevent the effects of radiation on a satellite. There are a number of EDAC schemes that have been developed during the past few years. However, each scheme has its own advantages and disadvantages. These are summarized in Table 3.

Out of all the EDAC schemes mentioned in Table 3, Reed Solomon and Hamming codes are most commonly used in modern day satellites [13].

An additional EDAC technique has to be mentioned as it is normally implemented together with a software EDAC such as Hamming code. This EDAC technique is referred to as triple modular redundancy (TMR). TMR's definition is dependent on the section/hardware for which TMR is implemented. In simple terms, TMR consists of having three identical devices that perform the exact same operation but communicate through a voter. The voter compares all received information to ensure the information matches and that the right result is returned. Figure 5 shows a block diagram of a TMR-based EDAC system which is implemented for RAM [13]. TMR, however, is not the ideal solution as three times the necessary hardware is needed to perform a single operation. This ultimately adds to the satellite's cost, complexity, and computing time.

2.5 Implementing EDAC Systems

Before getting started, it is important to know what EDAC systems are currently being implemented onboard nanosatellites and if additional hardware is needed in order to implement these EDAC schemes.

First, there are mainly two types of memory that need protection against upsets, namely program memory (SRAM) and Ramdisk. SRAM is faster than Ramdisk and is directly linked to the satellite's OBC, as it is typically used as the CPU cache. This

Table 3 Summary of well-known EDAC schemes

EDAC scheme	SED	SEC	DED	DEC	MED	MEC	Description
Parity code [15]	Yes	No	No	No	No	No	This scheme is considered the simplest and most basic error detection scheme. Using a parity bit, the scheme determines whether the string of bits is even or odd. This is done by evaluating the 1 s contained in the string. Creating two variants, even and odd parity bit
2 of 5 code	Yes	No	No	No	No	No	Most popular was the 2-out-of-5 code, which allows decimal digits to be represented using five bits. This code was implemented in barcodes. The m-out-of-n code makes use of codeword weightings (m) and length (n) to perform error detection. The weighting value normally represents the sum of the 1 s within a codeword
Berger code	Yes	No	No	No	No	No	This unidirectional error detecting code is only capable of flipping ones into zeroes or only zeroes into ones, such as in asymmetric channels. Used mainly in telecommunications. Berger code counts all the ones or zeroes within the information data (k bits long) and then attaches the binary equivalent of the sum to the information forming the codeword ($n + k$ bits)

(continued)

Table 3 (continued)

EDAC scheme	SED	SEC	DED	DEC	MED	MEC	Description
Hamming code [16]	Yes	Yes	No	No	No	No	This scheme adds additional parity bits (r) to the sent information (k). The codeword can be calculated as $n = 2^r - 1$. This means information data can be calculated by $k = 2^r - r - 1$. Using a parity-check matrix and a calculated syndrome, the scheme can self-detect and self-correct any SEE errors that occur during transmission
Extended Hamming code	Yes	Yes	Yes	No	No	No	The original scheme allows SECSED, but with an addition of one bit, an extended Hamming version allows DECSED
Hadamard code	Yes	Yes	Yes	Yes	No	No	Based on unique mathematical properties namely Hadamard matrixes, this linear code allows both DED and double error correction (DEC). This code was used in 1971 by NASA space probe Mariner 9, to send photos of Mars back to Earth [17]
Repetition code	Yes	Yes	Yes	Yes	No	No	This code is one of the most basic codes as it simply resends a message several times. This result is low performance and transfer rates makes the code less than ideal

(continued)

Table 3 (continued)

EDAC scheme	SED	SEC	DED	DEC	MED	MEC	Description
Four dimensional parity code [15]	Yes	Yes	Yes	Yes	No	No	Also referred to as multidimensional parity-check code (MDPC), this code makes use of multiple parity bits. This means the code basically arranges a message into a grid and then generating parity rows according to horizontal, vertical, and cross diagonally. Ideally used for DDR RAM protection
Golay code [18]	Yes	Yes	Yes	Yes	Yes	Yes	This code is a perfect linear error correcting code and makes use of a look-up table. This codes has the following parameters [8, 12, 24] & [7, 12, 23]
BCH code [19]	Yes	Yes	Yes	Yes	Yes	Yes	This cyclic code is constructed using polynomials over a finite field. This code generally uses a linear-feedback shift register (LFSR) to encode the message block and uses syndromes polynomial to determine the error location during decoding. This results in Bose Chaudhuri Hocquenghem (BCH) codes being complex and difficult to implement while requiring significate processing time

(continued)

Table 3 (continued)

EDAC scheme	SED	SEC	DED	DEC	MED	MEC	Description
Reed Solomon code [20]	Yes	Yes	Yes	Yes	Yes	Yes	This non-binary cyclic code is based on univariate polynomials over finite fields. The error locator polynomial is then found using both the syndrome polynomial and Euclidian algorithm. Errors can then be located or pin-pointed by applying the Chien Search Algorithm. Once the error's location is found, the Forney algorithm is used to correct any errors. This results in Reed Solomon (RS) codes being complex and difficult to implement, while requiring significate processing time

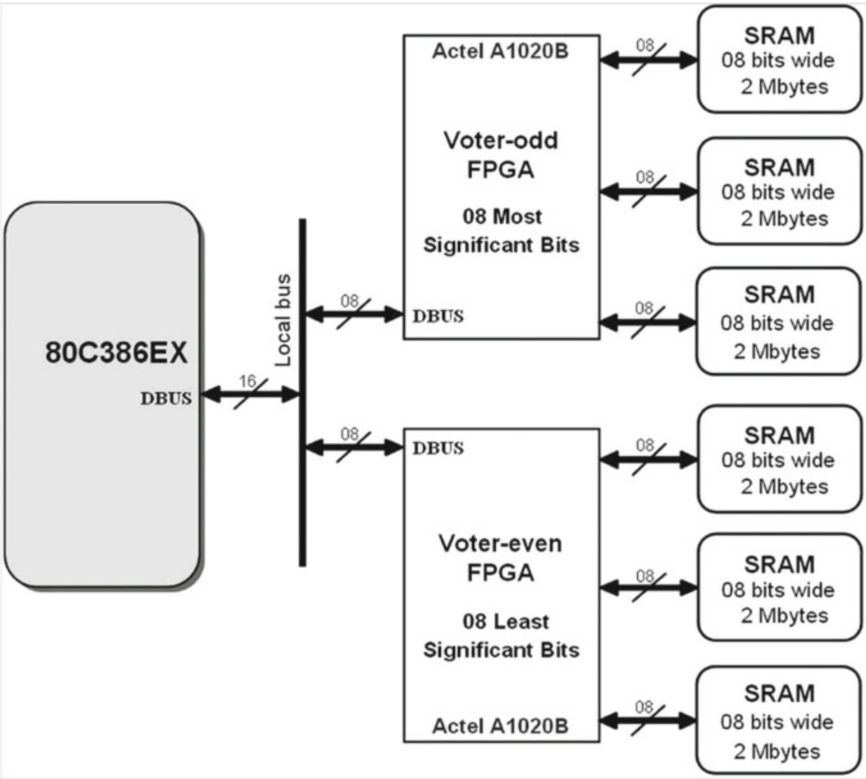

Fig. 5 Block diagram of TMR-based EDAC [13]

implies that the integrity of the information stored within the SRAM is vital to the lifespan and health of the satellite. Ramdisk, on the other hand, refers to the memory that serves as a disk drive, mostly used to store image files and memory-intensive information.

Most commonly used EDAC scheme implemented in nanosatellites for SRAM protection is Hamming code and TMR. These are the most popular schemes because they are relatively easy to implement and have short encoding and decoding delays. RS codes, on the other hand, are more popular for large sets of information, as used in Ramdisk. For this reason, RS codes are known as block codes. RS is popular mainly due to its EDAC capabilities, as it is able to ensure MED-MEC.

From the literature review, it was clear that implementing EDAC systems on FPGA's is quite popular. In a paper by V. Tawar, a four-dimensional parity EDAC scheme was designed, tested, and synthesized on Xilinx FPGA device XC3S500E-4FG320 [21]. A horizontal vertical diagonal (HVD) EDAC was developed for Xilinx [22, 22]. Other examples are orthogonal codes written in Verilog using Altera Quartus-II software [24] and Hamming code implemented on FPGA using Verilog

[16] and Xilinx Spartan-3 FPGA [25], EDAC systems are also implemented in [26, 27].

From the finding of this search string, it is clear that EDAC schemes can be implemented and efficiently tested using FPGA development software. It can also be noted that the most common coding language used in implementation is VHDL or Verilog.

3 Discussion

To summarize, it is obvious that there is a need for designing effective and reliable EDAC systems for nanosatellites. While researching this topic as a whole, information seemed hard to find, however, once broken up into small topics and research areas, the following was found.

The space radiation has caused numerous mission failures. Through further research, it became apparent that some failures are owing to the SEUs and MEUs. These upsets are almost impossible to predict but there are certain areas of space where upsets are more frequent, for example, the Van Allen Radiation belts. Within the context of nano-satellites, which are low earth orbiting (LEO), special attention needs to be paid to the SAA.

It was found that there are a number of EDAC schemes and techniques currently used. Most commonly Hamming, RS codes, and TMR. It was also found that the most effective, non-evasive method of implementing an EDAC system would be to implement the system using an FPGA. Using the above-summarized information as a starting point, this thesis topic will be proposed which will take a more detailed look at the design, development, and implementation of an effective system on chip-based EDAC for nano-satellites.

4 Conclusion

From the literature survey, it is clear that there is a need for research in the area of EDACs. This field is new and constantly evolving as nanosatellites provide a platform from which the boundaries of space and technology are constantly being pushed. As technology advances memory chip, cell architecture is becoming more and more dense, especially with the development of nanotechnology. This creates a growing demand for more advanced and reliable EDAC systems that are capable of protecting all memory aspects of satellites.

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