Honeywell Radiation Tolerant General Purpose Processor

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Abstract *— When designing electronic systems for space applications, engineers must take into consideration the extreme operating conditions of space environment. Electronics devices operating outside the Earth atmosphere are exposed to very high/low temperatures and radiation. Radiation exposure is very dangerous for electronic systems because it can compromise their operation. Semiconductive components are sensitive to accumulated ionization as a result of radiation exposure. Honeywell Aerospace is currently testing a general purpose processor (GPP) unit designed to be radiation tolerant. This will allow the device to device to be used in various space applications.*

Key Terms *— Galactic Cosmic Rays (GCR), General Purpose Processor (GPP), Radiation, Single Board Computer (SBC), Van Allen Radiation Belts.*

INTRODUCTION

GPPs are used for applications that require handling a massive amount of data that a single Application-Specific Integrated Circuit (ASIC) or Field-Programmable Gate Array (FPGA) will not be able to handle. They are designed for a variety of computation tasks and can be useful for many space applications that require data transfer between embedded systems.

All electronic space applications face exposure to radiation environment. Radiation exposure degrades electronic components reducing their normal operating life cycle and eventually can cause the device to fail completely. There are two principle sources of radiation; these are galactic cosmic rays (GCR) and radiation emanating from the Sun, solar particle events (SPE). The energy particles emanating from the Sun are mostly protons; these are trapped in zones known as Van Allen Radiation Belts.

Since space applications face the constraint of radiation exposure, Honeywell took on the challenge of designing a radiation tolerant general purpose processor (RT-GPP). This device will be a first in the market. The design team used radiation tolerant components available on the market for the build. These radiation tolerant devices are governed by the Defense and Logistics Agency (DLA) which is part of the United States Department of Defense.

RADIATION BACKGROUND

Radiation is a form of energy that is emitted or transmitted in the form of rays, electromagnetic waves, and/or particles. In some cases, radiation can be seen (visible light) or felt (infrared radiation), while other forms like x-rays and gamma rays are not visible and can only be observed directly or indirectly with special equipment. [1]

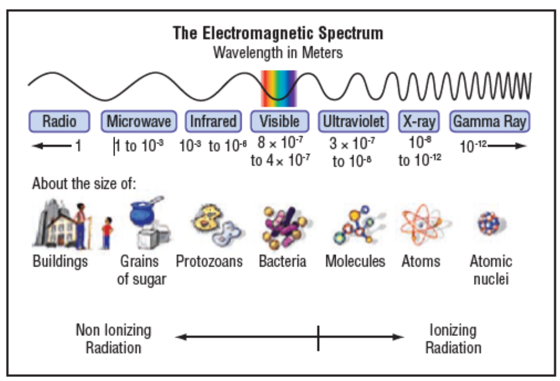

Figure 1
Electromagnetic Spectrum [1]

The motion of electrically charged particles produces electromagnetic waves. These waves are also called "electromagnetic radiation" because they radiate from the electrically charged particles. They travel through empty space as well as through air and other substances. Scientists have observed that electromagnetic radiation has a dual "personality." Besides acting like waves, it acts like a stream of particles (called photons) that has no mass. As shown in Figure 1, the photons with the highest energy correspond to the shortest wavelengths and vice versa. The full range of wavelengths (and photon energies) is called the electromagnetic spectrum. [1]

Radiation Types

The ionizing properties of radiation are dependent on the energy of the particles. Non-ionizing radiation has low energy and is not able to move electrons from the materials it traverses. Ionizing radiation has enough energy to ionize an atom or molecule by completely removing an electron from its orbit, thus creating a more positively charged atom. The most common types of ionizing radiation in space are GCR and SPE. The average energy for these common particles is shown on Figure 2.

Maximum Energies of Particles	
Particle Type	Maximum Energy
Trapped Electrons	<10 MeV
Trapped Protons & Heavy Ions	<100 MeV
Solar Protons	>1 GeV
Solar Heavy Ions	>10 GeV
Galactic Cosmic Rays	>1 TeV

Figure 2
Maximum Energies of Particles [2]

GCRs are usually measured in units of MeV, for mega-electron volts, or GeV, for giga-electron volts. One electron volt is the amount of energy gained when an electron is accelerated through a potential difference of 1 volt. Most galactic cosmic rays have energies between 10 MeV and 10 GeV. GCR originates outside the solar system. In general, GCR is composed of ionized atoms that have had their surrounding electrons stripped away and are traveling at nearly the speed of light. They can cause the ionization of atoms as they pass through matter and can pass practically unimpeded through a typical spacecraft, satelite or the skin of an astronaut. For the most part, the Earth's magnetic field provides shielding for spacecraft from galactic cosmic radiation. However, as Figure 3 shows, cosmic rays have free access over the Polar Regions where the magnetic field lines are open to interplanetary space.

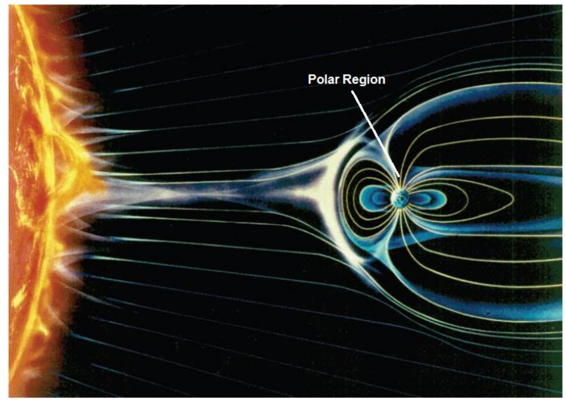

Figure 3
Effects of the Solar Wind and GCR [1]

As Figure 4 shows, SPEs are produced by a flow of energetic electrons, protons, alpha particles, and heavier particles into interplanetary space. These represent a considerable hazard to semiconductive and electronic devices operating in space. Large SPE events are highly random in nature but tend to occur during periods of intense solar activity. These events can lead to high radiation doses in short time intervals.

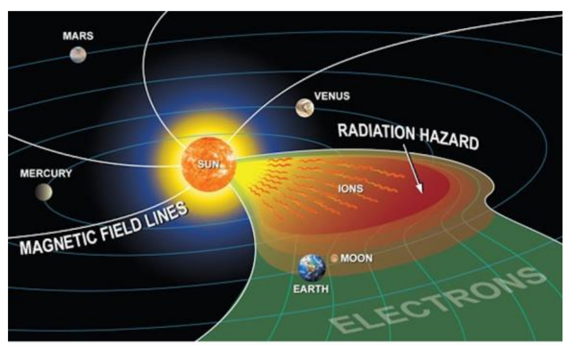

Figure 4
Solar Particle Events [3]

The effect of such a high flux of particles can have severe implications on the lifetime of the electronic system and their internal components. It can also affect the performance of instruments onboard a spacecraft or satellite. The most energetic particles arrive at Earth within tens of minutes of the event on the Sun, while the lower-energy population arrives over the course of a day. They temporarily enhance the radiation in interplanetary space around the magnetosphere, and they may penetrate to low altitudes in the Polar Regions.

Earth is surrounded by a magnetic field that looks something like the field you see around a bar magnet when you use iron filings to make it stand out better. The Earth's magnetic field helps protect us from space radiation such as solar flares and GCR by deflecting many of the particles before they reach us. This magnetic field also traps charged particles within it like an invisible magnetic prison. The trapped particles are so numerous that they form into donut-shaped clouds as seen on Figure 5 with the Earth at the center.

These clouds stretch thousands of miles above Earth's surface at the equator. Scientists call these the "van Allen Radiation Belts" because they were discovered by Dr. James van Allen using one of the first satellites launched by NASA in 1958. The radiation in the van Allen Belts consists mainly of electrons and protons. The inner belt, located between about 1.1 and 3.3 Earth radii in the equatorial plane, contains primarily protons with energies exceeding 10 MeV.

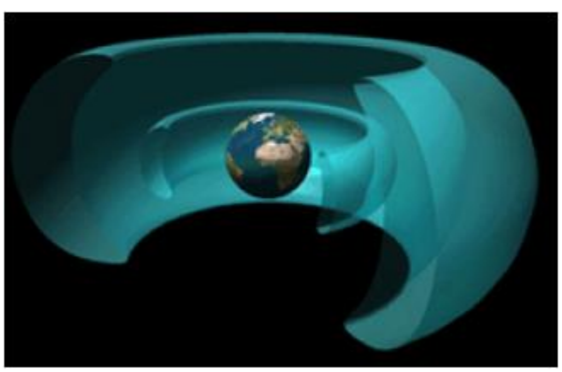

Figure 5
Location of Van Allen Inner and Outer Belts [4]

The radiation belts are highly important primarily because they provide a shield for the harmful effects of high-energy particle radiation for man and electronics.

RADIATION EFFECTS ON ELECTRONICS

There are various forms of possible radiation damage. Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductive material. This is known as Linear Energy Transfer (LET). If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen. Severity of the effect is dependent on the type of effect and system criticality. These effects degrade satellite internal components, particularly semiconductor and optical devices. Radiation also induces background noise in detectors, errors in digital circuits and electrostatic charge-up in insulators. Some of these errors can be permanent and others can be cleared or reset depending on the device.

There are three categories of components having the following characteristics:

Commercial Devices

The process and design for commercial devices limit the radiation hardness because they have no lot radiation controls. The customer performs rad testing, and assumes all risk. The hardness levels are the following:

- Total Dose: 2 to 10 krad (typical)
- SEU Threshold LET: 5 Mev/mg/cm^2 with error rate of 10^{-5} errors/bit-day (typical).

Rad Tolerant:

Their design assures rad hardness up to a certain level; they have no lot radiation controls. Devices are usually tested for functional fail only. The hardness levels are the following:

- Total Dose: 20 to 50 krad (typical)
- SEU Threshold LET: 20 MeV/mg/cm^{2}with error rate of 10^{-7} to 10^{-8} errors/bit-day.

Rad Hard:

Designed and processed for particular hardness level; their wafer is lot radiation tested. The hardness levels are the following:

- Total Dose: > 200 krad to >1 Mrad

- SEU Threshold LET: 80 to150 MeV/mg/cm^2 with error rate of 10^{-10} to 10^{-12} errors/bit-day

Total Ionizing Dose (TID) Effects

TID is mostly caused by accumulation of ionized electrons and protons deposited over a period of time. These particles are trapped in the Van Allen Belts and can affect satellites or other systems when their orbits pass through them. Ionization creates positive charges or electron-hole pairs. Accumulation of these electron-hole pairs in insulators/oxides can result in device failure like threshold shifts, leakage current and timing changes. Circuit parameters are changed and ultimately, the circuit ceases to function properly. TID can be measured in terms of the absorbed dose, which is a measure of the energy absorbed by matter. Absorbed dose is quantified using either a unit called the rad (an acronym for radiation absorbed dose) or the SI unit gray (Gy); 1 Gy = 100 rads = 1 J/kg. The image on Figure 6 shows atom displacement as a result of TID.

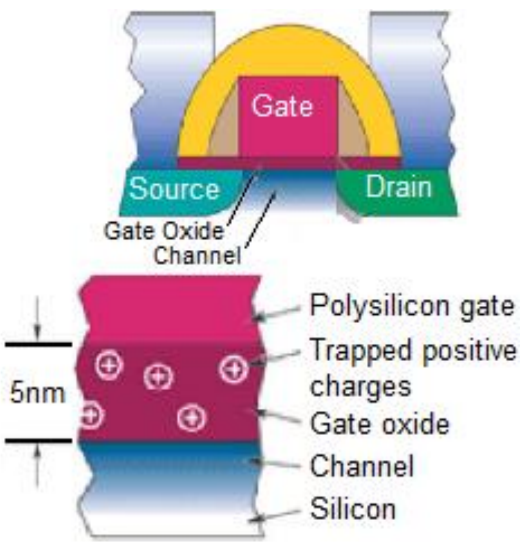

Figure 6
Atom Displacement due to TID [2]

Displacement Damage (DD)

DD is caused as a result of accumulation of crystal lattice defects caused by high energy radiation. The charged particles, mostly composed of protons/ions, displace the silicon (Si) atoms from their proper crystal lattice locations. The changes on the crystal structure cause defects on the device. These changes alter the electrical properties of the device ultimately causing circuit failures.

As shown on Figure 7, a cascade of collisions occurs to a portion of the semiconductor (e.g., Si) lattice atoms. These collisions are produced by the radiation particles on the environment. The result of these collisions causes a vacancy along the tracks of secondary particles and in clusters at the end of these tracks. This defect is commonly known as Frenkel pair defect. A Frenkel pair defect is a type of point defect in a crystal lattice. The defect forms when an atom or smaller ion (usually cation) leaves its place in the lattice, creating a vacancy, and becomes an interstitial by lodging in a nearby location.

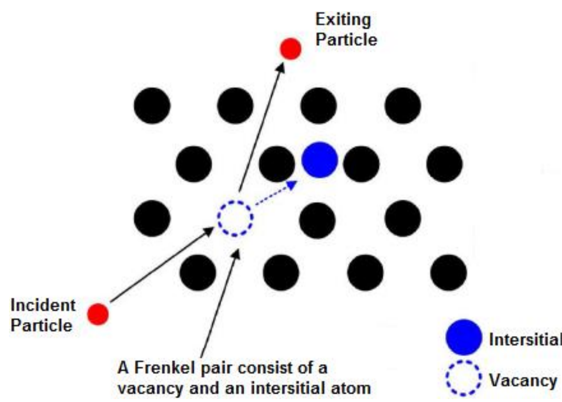

Figure 7
Displacement damage by Frenkel Pair [2]

Single Event Effects (SEE)

SEEs occurs when a single, high ionizing dose particle, depositions on a sensitive region of the device. There are many types of single event effects, which can be either non-destructive or destructive to the device. The severity of the effect can be so small that it can go unnoticed. SEE can occur in many forms:

- Single event upset (SEU)
- Single event transient (SET)
- Single event latchup (SEL)
- Single event burnout (SEB)

When SEE occurs, each ionized particle produces an ionization track as seen on Figure 8.

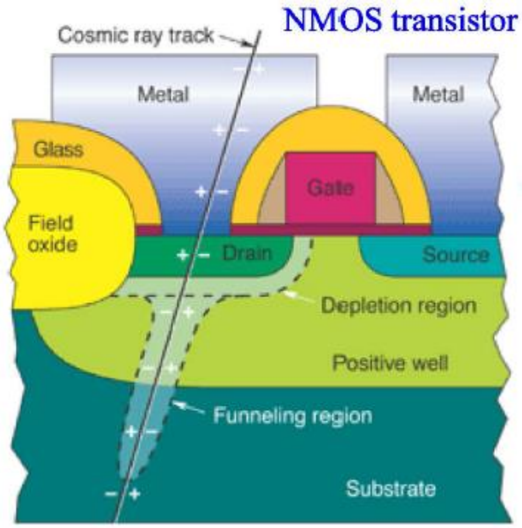

Figure 8
Atom Displacement due to SEE [2]

Single Event Upset (SEU)

The internal charge deposition causes a change of state in a logic circuit (e.g., turning a 1 to a 0 or vice versa). SEU occurs mostly on computer memories and microprocessors.

Possible non-destructive effects include corruption of the information stored in a memory element. Usually, the damage is not permanent damage because the memory element/logic state can be refreshed with a new/correct value if the SEU is detected.

Possible destructive effects include; microprocessor program corruption and freeze in calculation errors. It requires a reset to prevent wrong command execution.

Single Event Transient (SET)

It is caused by a transient current or voltage spike. It may propagate through logic gates, and produce system failures. If this spike is captured by a storage element, the SET becomes a SEU.

Single Event Latchup (SEL)

Produced by unintentional current flow (e.g., short) between components within an integrated circuit, causing circuit malfunction. A latchup causes a bit-flip to be permanent and it cannot exit from the selected logic state. The circuit must be powered down to correct the condition.

Single Event Burnout (SEB)

The electric current in the SEL is not limited and the device is destroyed. This is the most dangerous form of singe event effect because the failure is permanent.

Radiation Exposure Levels by Orbits

The radiation exposure level depends on the operating orbit. The most common satellite orbits are presented on Figure 9 and the radiation exposure level for each are detailed below.

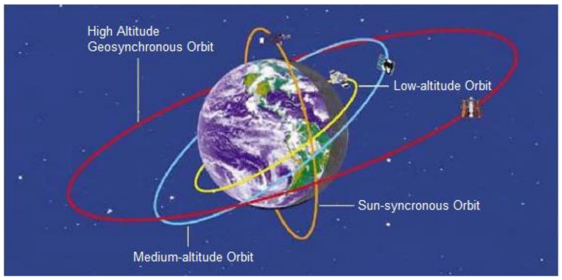

Figure 9
Location of Orbits [2]

Low Earth Orbit (LEO)

LEO is an orbit around Earth with an altitude between 160 kilometers (99 mi) and 2,000 kilometers (1,200 mi). The typical radiation dose due to trapped Van Allen electrons and protons for space vehicles or satellites in low inclination (≈ 28 degrees) is 100-1000 rad(Si)/year.

For Space vehicles or satellites in higher inclinations (between 20 and 85 degrees) in both northern and southern hemispheres, the typical dose rates is 1000-10,000 rad(Si)/year.

Medium Earth Orbit (MEO)

Also called intermediate circular orbit (ICO), is the region of space around the Earth above low Earth orbit with an altitude of 2,000 kilometers (1,243 mi) and below geostationary orbit with an altitude of 36,000 kilometers (22,370 mi).

Satellites on this orbit are mostly used for navigation and communication. The most common altitude is approximately 20,200 kilometers (12,552 mi). The typical radiation dose on this orbit is 100 kRads/year (1 kGy/year)

Geostationary Orbit (GEO)

GEO is a circular geosynchronous orbit in the plane of the Earth's equator with a radius of approximately 42,000 km (26,097 mi) (measured from the center of the Earth). The most common altitude is approximately 35,800 km (22,245 mi) above mean sea level. It maintains the same position relative to the Earth's surface. The typical radiation dose on this orbit is 10 kRads/year. For a typical 10 year mission, the total dose is 100 kRad.

RT-GPP PROGRAM OBJECTIVES

The main objective of this project is to develop a radiation tolerant single board computer (SBC) and have it available as standard product for use in future opportunities.

The RT-GPP project will be leveraged by various space and defense current product offerings. This project serves as a site development opportunity for Puerto Rico by exercising all required disciplines on site with support from mentors located in the United States. It has been designed with refresh/reuse objectives and includes an upgrade path to multi-core processors.

This project will develop Puerto Rico systems/project capabilities to facilitate and manage program work with centers of excellence (COEs) in PR. It will reduce cycle time and cost by having standard product available. RT-GPP will be the baseline for defense and space (D&S) proposals. Figure 10 shows a prototype of the RT-GPP SBC.

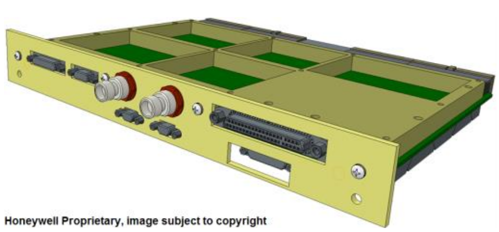

Figure 10
RT-GPP SBC Prototype [5]

RT-GPP FEATURES AND REQUIREMENTS

Structural design is robust with a natural frequency of 426 Hz. Thermal dissipation will be conduction cooled to a chassis card guide of up to 75°C. Power dissipation will be between 17 W and 24 W. The SBC will feature a 1.5 GHz Processor, between 2 to 4 Gb of DDR memory with error correcting code. Triple modular redundancy (TMR) flash memory and Compact PCI connectivity. The communication protocol will be based on MIL-STD-1553. Nominal power will be no greater than 17 W and the weight will be below 5 pounds.

The RT-GPP SBC is a ruggedized, space application, cPCI module. It will be built on a 9U X 240 cPCI chassis with a maximum thickness of 0.250 inches. Will feature cPCI compliance per PICMIG 2.0 R3.0. An aluminum heatsink/frame will provide support for thermal and structural requirements. It will have Calmark wedge clamp for PBA support.

System-level error corrections using radiation-hardening by design as shown on Figure 11 below.

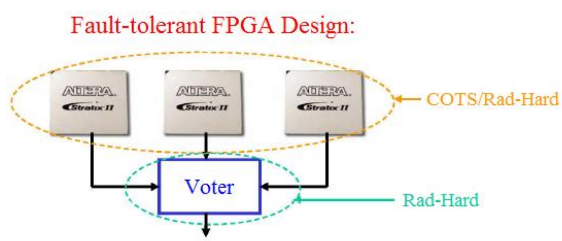

Figure 11
Radiation Hardening by Design [2]

Radiation-hardening by design incorporates error detection and correction of memory (parity bits, Hamming code) using TMR and Voting. Basically, the design uses three copies of the same circuit or processor performing the same functions or computations and a voter performing a "majority vote". This majority vote will select the correct output in case one of the computations gets corrupted by any radiation event. The design also includes a watchdog timer to avoid processor crash; resets the system automatically if an error is detected.

CONCLUSION

The RT-GPP SBC is currently undergoing tests in Puerto Rico and Clearwater, FL facilities. These tests will determine the radiation tolerance level of the whole device.

RT-GPP rugged construction is slated for reuse across space, military and some tough commercial applications. Other potential uses are space payloads, manned space, military avionics, and commercial avionics. It has been designed as a set of reusable electronics modules that can be reused. Initial target application is for space payloads with proposals being currently evaluated by some customers.

Radiation hardness assurance (RHA) consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space environment. RT-GPP design incorporates rad tolerant devices in its construction. As a result, it is expected to be a fully operational rad tolerant device.

Preliminary results for linear acceleration analysis show peak displacement, peak stress, and pyrotechnic shock analysis are within the expected values. Stress will be lower than 38,000 psi.

Preliminary random vibration analysis shows a displacement below 20 mils and a stress of 29,000 psi.

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