Chapter

The Impact of Space Radiation Environment on Satellites Operation in Near-Earth Space

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Abstract

Energetic particles and electromagnetic radiation (EM) from solar events and galactic cosmic rays can bombard and interact with satellites' exposed surfaces, and sometimes possess enough energy to penetrate their surface. Among other known effects, the scenario can cause accelerated orbit decay due to atmospheric drag, sporadic and unexplainable errors in functions of sensitive parts, degradation of critical properties of structural materials, jeopardy of flight worthiness, transient and terminal health hazard to both onboard passengers and astronauts, and sometimes a catastrophic failure that can abruptly end satellite mission. The understanding of the dynamics of the space radiation environment and associated effects is critically important for satellites design and operation in ionospheric plasma environment, in which satellites are designed to function. In this chapter we review some satellite anomalies associated with the space radiation environment and conclude with mitigation effort that can reduce such impact.

Keywords: solar activity, energetic particles, radiation environment, single event effects, total ionizing dose, impact mitigation

1. Introduction

Solar activity drives dynamic changes in the atmosphere and ionosphere that can affect the performance and reliability of satellites in near-Earth space environment, as well as ground-based technological systems and services that rely on them. This condition is referred to as space weather. The principal medium through which the Sun's activity is communicated to the region of the near-Earth space environment, is the solar wind, which occurs in form of a continuous outflow of streams of energized charged particles and/or momentary eruption of large-scale, high-mass plasma known as coronal mass ejections (CMEs). Sources of energised particles and strong magnetic energy also include the solar flares and galactic cosmic ray, originating from outer space. The energetic particles and electromagnetic radiation from these processes form the near-Earth radiation environment and can be divided into (i) trapped radiation environment and (ii) transient radiation environments. The charged particles that are trapped or confined by the Earth's magnetic field to certain regions in space such as the Van Allen belts form the trapped radiation environment. The transient particles environment consists of energetic particles from solar events, and galactic cosmic radiation that exist in the interplanetary space regions and in the near-Earth regions. Satellites and other space application systems are vulnerable to both trapped and transient energetic particles since they are basically designed to operate in the space plasma environment. The particles can bombard and interact with satellites' surfaces, and sometimes posses enough energy to penetrate their exposed surfaces with possible access to their electrical, electronic and electrochemical components (EEECs). This scenario can induce sporadic and unexplainable errors in sensitive parts of spacecrafts, degrade the critical properties of their structural materials, jeopardize the flight worthiness of spacecrafts, constitute transient and terminal health hazard to both onboard passengers and astronauts, and even lead to total failure that can end the mission of affected spacecrafts [1, 2].

There are documented cases or evidence of satellites anomaly associated with space weather (or space radiation environment). In their study, Iucci et al. [3] verified and quantified the linkage between a large fraction of spacecraft anomalies and space weather perturbations. They compiled a large database of about 5700 anomalies registered by 220 satellites in different orbits over the period of 23 years (1971–1994). Their findings revealed that very intense fluxes (>1000 particles cm^{-2} s^{-1} sr^{-1} (pfu) at energy >10 MeV) of solar protons are linked to anomalies registered by the satellites in high-altitude (>15,000 km) near-polar (inclination >55°) orbits and to a much smaller extent to anomalies in geostationary orbits. They also reported that elevated fluxes of energetic (>2 MeV) electrons >10 8 cm^{-2} d^{-1} sr^{-1} are observed by the Geostationary Operational Environmental Satellites (GOES) on days with satellite anomalies occurring at geostationary and low-altitude (<1500 km) near-polar (>55°) orbits [3]. On the 22nd and 23rd of March 1991, an intense solar event occurred, which resulted to severe geomagnetic storms. This strong solar flare event with high energetic solar radiation caused disruption in high latitude point-to-point communication, and solar panel degradation on GOES-6 and -7 satellites, and was estimated to have decreased the expected lifetime of GOES-7 by 2 to 3 years. During the event, high energetic solar particles also increased the frequency of single event upsets (SEU) recorded by the spacecrafts; up to six geostationary satellites, including GOES-6 and -7, and the Tracking and Data Relay Satellite (TDRS)-1 had about 37 reported cases of SEU during the main phase of the event. SEU will be explained in detail in Section 3.2. Other impacts associated with this solar activity include the loss of automatic altitude control of the National Oceanic and Atmospheric Administration (NOAA)-11 satellite, increased satellite drag due to the heated atmosphere, which necessitated a massive update of the North American Air Defense Command (NORAD) catalogue of orbiting objects, and the complete failure of the geosynchronous orbiting Maritime European Communication Satellite (MARECS)-1 as a result of critical damage to its solar panels [4, 5].

On September 2009, South Africa's SumbandilaSat (in low Earth orbit [LEO]) was reported to have experienced a power distribution failure due to radiation shortly after its launch, which rendered the Z- and Y-axis wheel permanently inoperable. However, the satellite continued to work as a technology demonstrator until 25 August 2011 when it failed completely. Its failure was again attributed to solar storm event, which caused the satellite's onboard computer to stop responding to commands from the ground station [6]. On 5 April 2010, Galaxy 15 spacecraft (at geosynchronous altitudes) was reported to have experienced an anomaly that caused it to stop responding to any ground command [7]. The failure was attributed to an onboard electrostatic discharge (ESD), which led to a lockup of the field-programmable gate array within the spacecraft baseband communications unit. The interaction of the spacecraft with substorm-injected energetic particles caused the ESD after the spacecraft experienced surface and deep dielectric charging. A concise documentation of many other cases of satellite anomalies and losses that have been attributed to space weather can be found in several literatures (e.g., p. 33 of Refs. [8] and [9].

2. Solar activity and the space radiation environment

The Sun's activity varies with time and position on the Sun, and characterized by 11-year cycle, which can be divided into solar minimum and solar maximum phases. The sunspots (and other solar indices such as solar radio flux) are viewed as main indicators of solar activity cycle. They are transient phenomenon seen as dark patches against photospheric bright background on the Sun. Observations made over the past two centuries have shown that the number of sunspots vary periodically, moving from minimum to maximum count approximately every 11 years. **Figure 1** show a historic sunspot number. The latest solar cycle (cycle 24) peaked around year 2014. Currently, solar activity is on the decline and has been predicted to reach its minimum in late 2019 or 2020, while the solar maximum is expected to occur between 2023 and 2026 [10].

Solar energetic events such as high-speed solar wind streams (HSS), solar flares and CMEs that give rise to solar particle events and geomagnetic storms affecting the space environment are more frequent during solar maximum. Therefore, their impact on the atmosphere and air-based technology are expected to be higher during this phase of the solar cycle than the declining or minimum phase. Solar events and associated phenomena mainly contribute to trapped and transient energetic particles in near space that constitute the space radiation environment, in addition to galactic cosmic ray from outer space. The summary of types of space radiation, their origin or sources, and where they are important is shown in **Figure 2**.

2.1 The trapped particles

When charged particles from the solar wind encounters and interacts with the Earth's magnetic field, it compresses it sun-ward, forming the magnetosphere (see, **Figure 3**). This scenario creates a supersonic shock wave known as the Bow Shock. The solar wind drags out the night-side of the inner magnetosphere. This extension is known as the magnetotail. Although the magnetosphere is constantly being bombarded by charged particles, they are being deflected and cannot easily penetrate the region; however, some particles gain entrance through the polar region and become trapped in the Earth's magnetic field. The trapped particles are contained in one of two doughnut-shaped magnetic rings surrounding the Earth called the Van Allen radiation belts, **Figure 3**. The inner belt contains a fairly stable population of protons with energies exceeding 10 MeV. The outer belt contains mainly electrons

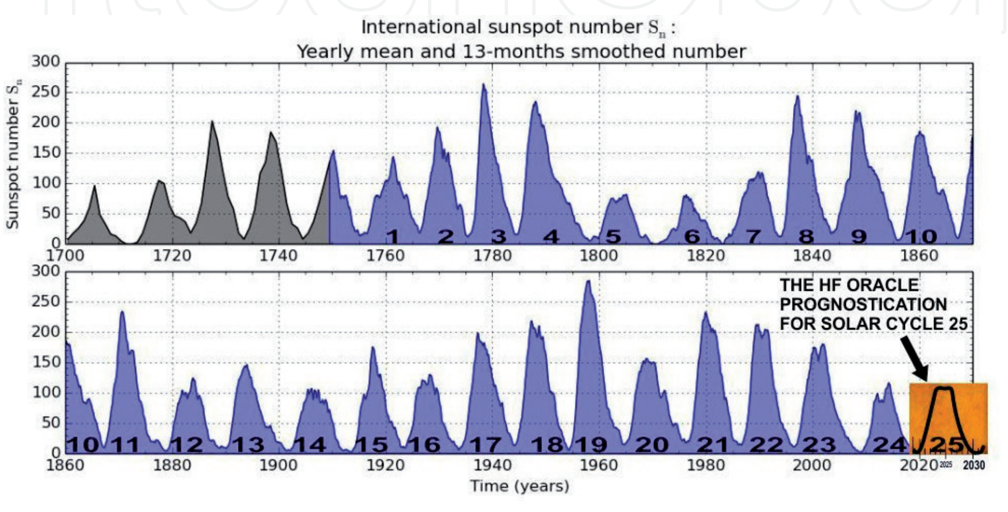

Figure 1.
Historic sunspot number (source: SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium).

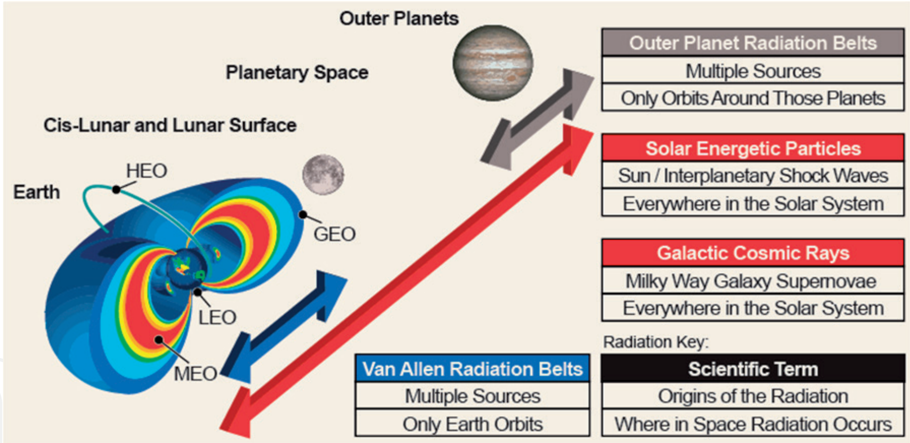

Figure 2.
Summary of types of space radiation, their origin or sources, and where they are important in the outer planets, planetary space and Earth, including the low Earth orbit (LEO), geostationary orbit (GEO), medium Earth orbit (MEO) and high Earth orbit (HEO) (source: Ref. [11]).

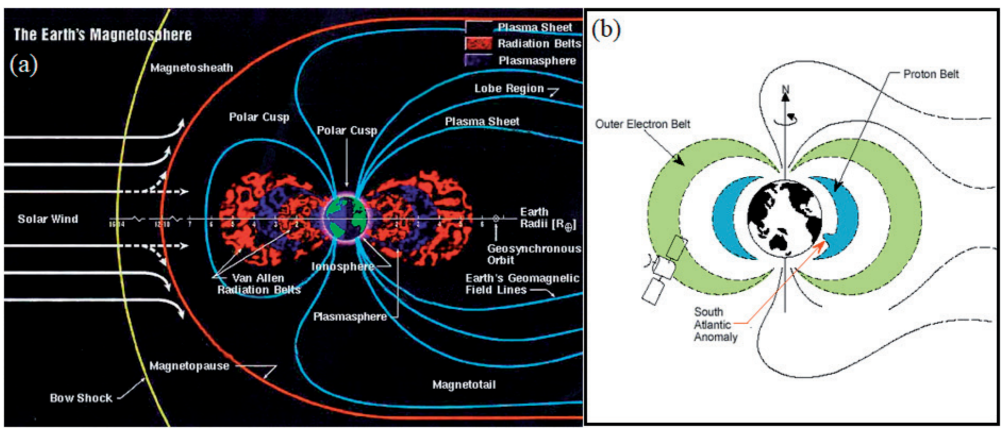

Figure 3.
(a) The Earth's magnetosphere showing the Van Allen radiation belt. (b) Outer and inner (proton) belt (source: Ref. [12]).

with energies up to 10 MeV. The charged particles which compose the belts circulate along the Earth's magnetic lines of force. These lines of force are known to extend from the area above the equator to the North Pole, to the South Pole, and then circle back to the Equator. There is a part of the inner Van Allen belt (VAB) that dips down to about 200 km into the upper region of the atmosphere over the southern Atlantic Ocean off the coast of Brazil. This region is known as the South Atlantic Anomaly (SAA). The dip results from the fact that the magnetic axis of the Earth is tilted approximately 11° from the spin axis, and the center of the magnetic field is offset from the geographical center of the Earth by 280 miles. The largest fraction of the radiation exposure received during spaceflight missions has resulted from passage through the SAA. Low inclination flights typically traverse a portion of the SAA up to six or seven times a day (see **Figure 3**).

2.2 The transient particles

The transient particles or radiation environments consist of particles from solar events such as solar wind, solar flares, CMEs and galactic cosmic radiation in the interplanetary and near-Earth space regions. The solar wind consists of relatively low energy electrons and protons that can significantly affect externally mounted spacecraft components. Solar flares are also a major contributor to the overall ionizing radiation level. A solar flare can emit and accelerate energetic particles or protons in the interplanetary space that can reach Earth within 30 minutes of the flare's peak. CMEs can propagate into the solar wind and drive shocks, which in turn accelerates solar energetic particles, and also deflect the galactic cosmic rays (GCRs) entering the heliosphere [13, 14]. CME can cause geomagnetic storms and other associated phenomena, leading to large-scale disturbances with adverse consequences in the geospace environment that can affect satellite systems.

2.3 Galactic cosmic radiation

Galactic cosmic radiations (GCR) are not directly connected to our Sun. They originate from outside the solar system. GCR consists of ionized atoms ranging from a single proton up to a uranium nucleus. The flux level of these particles is very low. Notwithstanding, they produce intense ionization as they pass through matter because they travel at a speed that is very close to that of light, and because some of them are composed of very heavy elements such as iron [15]. The energy of cosmic rays is usually measured in units of mega electron volt (MeV), or the giga electron volt (GeV). Most GCRs have energies between 100 MeV and 10 GeV. Cosmic rays include essentially all of the elements in the periodic table; about 85% protons, 14% alpha particles, and 1% heavy nuclei [16]. The Earth's magnetic field provides natural shielding from both cosmic and solar particles depending primarily on the inclination and secondarily on the altitude. As inclination reaches auroral to polar regions, a satellite is outside the protection of the geomagnetic field lines. At polar orbits intense fluxes of energetic electrons, known as precipitating electrons, propagate down along magnetic field lines (and create the aurora), and as altitude increases, the exposure to these particles gradually increases [12].

3. Effects of space particles and radiation environment on satellites operation in near-Earth space environment

When charged trapped or transient particles from solar events or cosmic sources bombards and interacts with the exposed surfaces of spacecraft, their effects can affect the system in a several ways. The effects from the natural space environment include spacecraft charging (SC), single event effects (SEEs), total ionizing dose (TID), and displacement damage (DD). However, the specific effect depends on the type of incident particle, its energy and probably the source. Trapped heavy ions do not have sufficient energy to generate the ionization required to cause SEEs, and they do not make a significant contribution to TID. Galactic cosmic rays and cosmic solar particles, which are heavily influenced by solar flares and trapped protons in the radiation belts, can cause SEEs, but electrons are not known to cause SEEs. Although their physical mechanisms are different, the ionizing radiation of the space environment causes both TID and SEEs. Charged particle effects in the space environment are summarized below according to the particle source.

3.1 Spacecraft charging (SC)

Spacecraft charging (SC) is the build-up of charge on spacecraft surfaces or in the spacecraft interior; SC causes variations in the electrostatic potential of a spacecraft surface with respect to the surrounding plasma environment, and potential variations in different portions of the spacecraft [17]. The major natural space environments which contribute to SC include the thermal plasma environment, high energy electrons, solar radiation and magnetic fields. Although SC has many effects, electrostatic discharges appear to be the most dangerous of all. Electrostatic discharges can cause structural damage, degradation of spacecraft components and operational anomalies due to damages to electronics. SC can be categorised into two: Surface charging which include differential charging, and internal dielectric charging. Surface charging is caused by low energy plasma (<100 keV) and photo-electric currents. Surface charging can either be absolute or differential. Absolute charging occurs when the satellite potential relative to the ambient plasma is charged uniformly, while differential charging occurs when parts of the spacecraft are charged to different potential relative to one another. Differential charging can also be caused by satellite self-shadowing. The charge control mechanism, and differential charging in spacecrafts are depicted in **Figure 4**. Differential charging of spacecraft surfaces is more detrimental than the absolute charging (relative to ambient plasma). The former can have a discharge effects that can disrupt satellite operations such as physical materials damage and electromagnetic interference (EMI) generation, and resultant transient pulses. Discharge consequences also include noise in data and wiring, sputtering and attraction of chemically active species [18]. Differential charging has been reported after geomagnetic sub-storms, which result in the injection of keV electrons into the magnetosphere.

Internal charging is caused by high-energy electrons (>100 keV), which penetrate into the spacecraft equipment where they deposit charge inside insulating materials [8]. Internal discharge is more damaging since it occurs within dielectric materials and well-insulated conductors, which are in close proximity to sensitive electronic circuitry [19]. Based on data from the Combined Release and Radiation Effects Satellite (CRRES) obtained at GEO, most environmentally induced spacecraft anomalies result from deep dielectric charging and the resulting discharge pulses and not from surface insulator charging or single-event upsets [20].

3.2 Single event effects (SEEs)

Single event effects (SEEs) are individual events which occur when a single incident ionizing particle deposits enough energy to cause an effect in a device. SEEs are generally caused by two space radiation sources: high energy protons, and cosmic rays. Single event phenomenon can be classified into four: (i) single event upset (SEU), (ii) single event latch-up (SEL), (iii) single event burnout (SEB) and (iv) single event gate rupture (SEGR). SEU is a change of state caused by ions or electromagnetic radiation striking a sensitive node in a micro-electronic device, such as in a microprocessor, semiconductor memory, or power transistors. The state change is a result of the free charge created by ionization in or close to an important node of a logic element (e.g., memory bit). The error in device output or operation

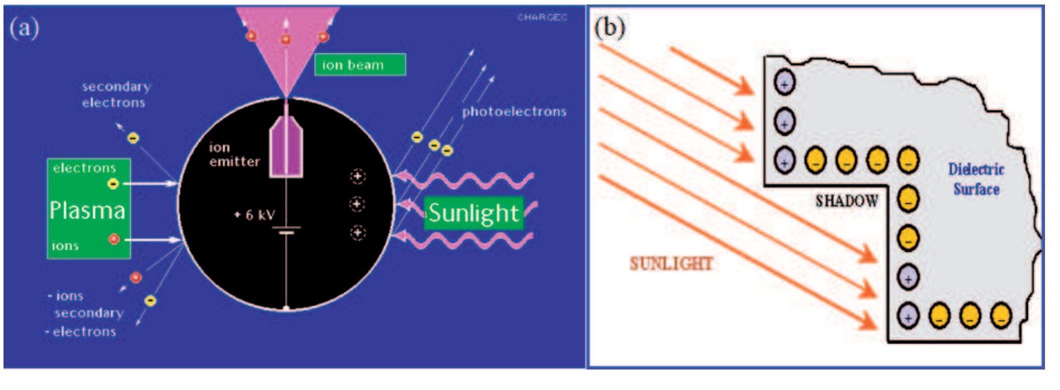

Figure 4.
(a) Satellite's charge control mechanism, and (b) differential charging in satellites due to self-shadowing (source: Ref. [12]).

caused as a result of the strike is called a soft error. The mechanisms for heavy ion and proton SEU in devices (e.g., dynamic random access memories (DRAM)), and galactic cosmic ray energy deposition in devices are depicted in **Figure 5**. SEU can cause a reset or re-writing in normal device such as in analogue, digital, or optical components, and may also have effects in surrounding interface circuitry. A severe SEU is the single-event functional interrupt (SEFI) in which an SEU in the device's control circuitry places the device into a test mode, halt, or undefined state. The SEFI halts normal operations, and requires a power reset to recover [1].

SEL is used in integrated circuits (ICs) to describe a particular type of short circuit which can occur in an improperly designed circuit. It is the generation of a low-impedance path between the power supply rails of a MOSFET circuit that can trigger a parasitic structure which disrupts proper functioning of the part and possibly even leading to its destruction due to over-current. SELs are hard errors, and can cause permanent damage. It can results in a high operating current, above device specifications, drag down the bus voltage, or damage the power supply. Latch-up can be caused by protons in very sensitive devices [22]. An SEL is corrected or cleared by a power off–on reset or power strobing of the device. SEL is strongly temperature dependent. If power is not removed quickly, catastrophic failure may occur due to excessive heating or metallization or bond wire failure [23].

SEB is a condition caused by high current state in a power transistor. It is a highly localized phenomenon, and includes burnout of the drain-source in power MOSFETs and BJTs, gate rupture, frozen bits, and noise in charged-coupled devices (CCDs). SEGR is the formation of a conducting path or localized dielectric breakdown in the gate oxide resulting in a destructive burnout. It occurs at MOSFETs, BJTs, and CMOS.

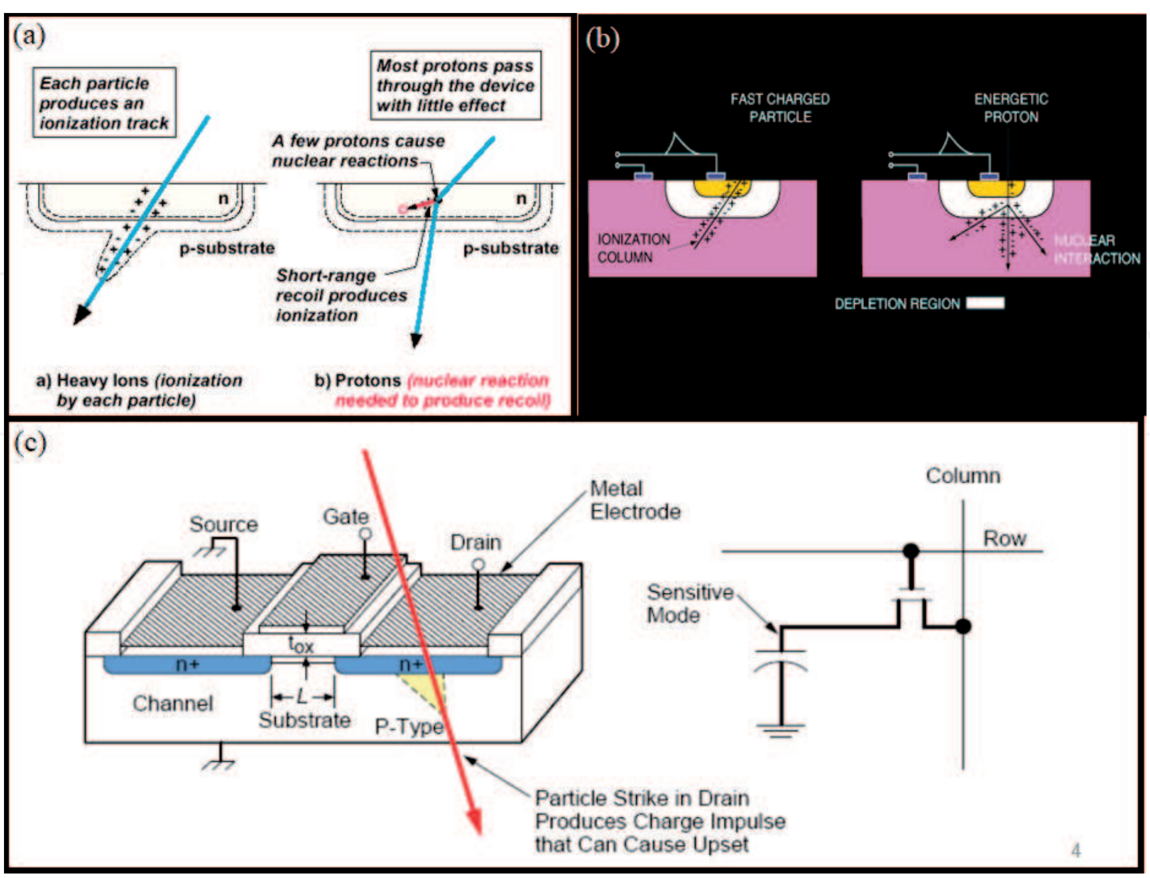

Figure 5.
(a) Mechanisms for heavy ion and proton SEU, (b) schematic showing how GCR deposit energy in an electronic device [12], and (c) upset mechanism for dynamic random-access memories (DRAMs) (from Ref. [21]).

Solar flare particle events pose the most extreme SEU producing environment, especially for spacecraft in interplanetary space [24]. Experiments aboard CRRES showed a significant increase during a solar flare [25]. Based on CRRES's data, most SEUs come from high energy protons through nuclear interactions and not through direct deposition from either protons or cosmic rays [20]. For LEO satellites, trapped protons, especially in the SAA, are the greatest SEE threat.

3.3 Total ionizing dose (TID)

Total ionizing dose (TID) refers to the amount of energy that ionization processes create and deposit in materials such as semiconductor or insulator when energized particles pass through it. TID can result in device failure or biological damage to astronauts. Radiation-induced trapped charges can build up in the gate oxide of a MOSFET and cause a shift in the threshold voltage. Such device cannot be turned off even at zero volts applied, if the shift is large enough. Under this condition the device is said to have failed by going into depletion mode [26]. TID is mostly due to electrons and protons, mainly from solar energetic particle event and passage through the SAA. In low Earth orbit, the main dose source is from electrons and inner belt protons, while the primary source is outer belt electron and solar protons in geostationary orbit. The first recorded satellite failure resulting from total dose was the Telstar. The satellite was launched a day after the Starfish nuclear test on 9 July 1962. The nuclear weapon of about 1.4 Megaton was detonated at an altitude of about 400 km above Johnston Island in the Pacific Ocean. The explosion produced beta particles (electrons) that were injected into the Earth's magnetic field, forming an artificial radiation belt. This artificial electron belt lasted until the early 1970s. Consequently, Telstar experienced a total dose 100 times that expected before its total failure. Up to seven satellites were destroyed by the Starfish nuclear test within 7 months mainly from solar cell damage [12].

3.4 Displacement damage (DD)

When energetic particles are incident on a solid material, they lose their energy to ionizing and non-ionizing processes as they travel through the material. The consequence of the energy loss is in the production of electron–hole pairs and atoms displacement or displacement damage. Vacancies (i.e., absence of an atom from its normal lattice position) and interstitials (i.e., movement of displaced atom into a non-lattice position) are the primary lattice defects that are initially created. The combination of a vacancy and an adjacent interstitial is known as a Frenkel or close pair. Two adjacent vacancies can form a defect known as divacancy. Also, larger local groupings of vacancies may occur in irradiated silicon. A defect resulting from vacancy and interstitials being adjacent to impurity atoms is known as defect-impurity complexes. Once formed by incident radiation, the defects will reorder to form more stable configuration. The extent to which defects alter the properties of bulk semiconductor material and devices depends on nature of the particular defects and the time following the creation of defect at a given temperature.

The effectiveness of radiation-induced displacement damage depends on factors such as bombardment condition, particle type and energy, irradiation and measurement temperature, time after irradiation, thermal history after irradiation, injection level, material type, impurity type and concentration [27]. Displacement damage causes degradation of materials and device properties. **Figure 6** depicts the collision between an incoming particle and a lattice atom, causing the displacement

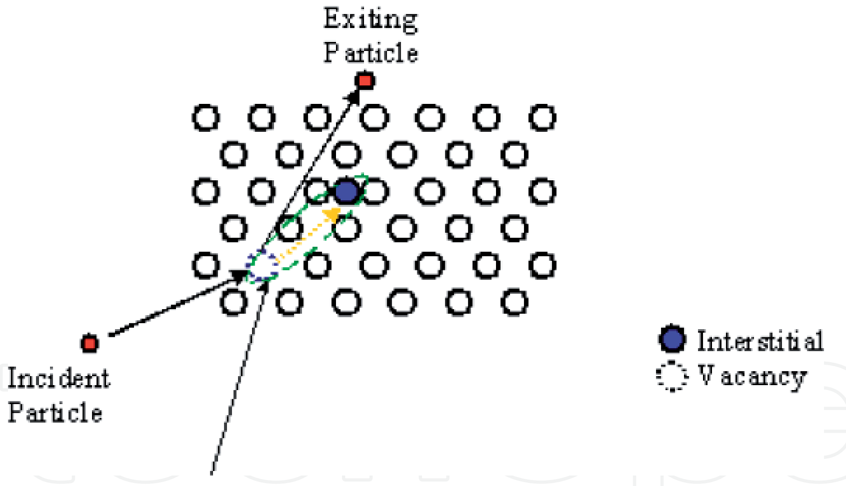

Figure 6.
Displacement of atom from its original lattice position by incoming particle through collision [12].

of the atom from its original lattice position. Displacement damage can also degrade minority carrier lifetime, and a typical effect would be degradation of gain and leakage current in bipolar transistors [12].

4. The stopping power, range of particles and deposited dose in spacecraft materials

The review presented here include portion of the work [1], part of which was published in [2]. We analyzed particles, electrons and protons flux of various energies from NOAA database for 3 months (April–June 2010). The mass stopping power, range and possible deposited dose of protons were calculated, and applied to the scenario of possible interaction of the particles with satellite surface and its electrical, electronic and electrochemical components.

4.1 Stopping power

Stopping power is the average energy loss of a particle per unit length (measured in MeV/cm) when passing through the material. Charged particles are known to ionize the atom or molecule which they encounter when passing through matter, and they lose energy in the process. The stopping power depends on the type and energy of the particle and on the properties of the material it passes. Although numerical values and units are identical for both quantities, the Stopping power refers to the property of the material while energy loss per unit path length describes what happens to the particle. The density of ionization along the particles path is proportional to the stopping power of the material because the production of an ion pairs requires a fixed amount of energy [28]. The Bethe-Bloch formula for stopping power derived from relativistic quantum mechanics is given by:

$$S = -\frac{dE}{dx} = \frac{4\pi z^2 k_0^2 e^4}{m v^2}\left[\ln\frac{2mv^2}{I} - ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

where z is the atomic number of the heavy particle, e is magnitude of the electron charge, m is the electron rest mass, c is the speed of light, I is the mean excitation energy of the medium, v is the velocity of the particle and k_0 is the Boltzmann constant ($= 8.99 \times 10^9$ N m^2 C^{-2}).

The mass stopping power of the material is obtained by dividing the stopping power by the density (ρ) of the material. It is a useful quantity because it expresses the rate of energy loss of the charged particle per g/cm^2 of the medium traversed [28].

$$S = -\frac{dE}{\rho dx}$$

4.2 The range of particle

The range R of a particle (e.g., proton) of initial kinetic energy E_k and mass m is the mean distance it travels before coming to a stop. R depends on the particle type, initial energy and the material through which it traverses. A theoretical approach to the determination of charged particle range utilizes stopping power expression. The range of a proton computed by numerical integration of the stopping power using the continuous slowing down approximation (CSDA) is given by:

$$R = \int_{E_{min}}^{E_{max}} \left(-\frac{dE}{\rho dx}\right)^{-1} dE + R(E_{min})$$

where R (E_{min}) is the measured range at minimum energy E_{min} which is added to the integral equation and treated as a constant for a particle and material. For the calculations of ranges for proton E_{min} is taken to be as 1 MeV as much data is available at 1 Mev. R (E_{max}) is the measured range at maximum energy E_{max}.

In previous work we used the empirical relations suggested by [28] to calculate the mass stopping power of particles in spacecraft materials [1, 2]. However, we anticipate limitations in the equations because they were originally formulated for low energy particles. Values obtained using Bethe's equations are higher and assumed more accurate at higher particle energies.

4.3 Dose deposition and absorption

The total ionizing dose (TID), explained in Section 3.3, 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 (radiation absorbed dose) or the SI unit which is the gray (Gy). 1 Gy = 100 rads = 1 J/kg. The total accumulated dose on a satellite depends on orbit altitude, orientation, and time spent in orbit. To compute TID we need to know the integrated particle energy spectrum, $\o(E)$ or the fluence as a function of particle energy. The dose is a function of the particle flux. It becomes important as the spacecraft spends more time in the space radiation environment. The stopping power is used to determine dose from charged particle by the following relationship:

$$D = \varnothing \frac{dE}{\rho dx}$$

where $\varnothing$ is the particle fluence (i.e., the number of particles striking the material over a specified time interval).

Satellite and space probes typically encounter TID between 10 krad (100 Gy) and 100 krad(Si) (1000 Gy(Si)). The time taken, t (in years) for a satellite's component to fail due to total ionizing dose can be obtained by dividing the maximum absorbed dose or TID threshold by the total absorbed dose per year, given as:

$$t\ (in\ yrs) = \frac{TID_{threshold}}{Dose/yr}$$

We performed theoretical calculations to predict the mean time to failure of a model satellite due to TID. The assumption is that the model satellite's body is made of aluminum alloy and 20 mm thickness (without impact mitigation such as protective coating on the satellite), in which the electrical, electronic and electrochemical components (mainly of silicon (Si) and germanium (Ge) materials) are housed [1, 2]. Our calculations were based on particles with $E \geq 78$ MeV. When particles of this energy range bombard and penetrate the satellite, parts of their energies are lost due to the stopping power of the alloy but the reminder constitute significant dose to the components. With continuous exposure, the dose continues to build over time until the threshold is exceeded leading to completed failure of the affected satellite. Our calculations showed that a dose of 10 krad can build up on the model satellite's component within 3 years and 100 krad within 29 years.

5. Mitigating the impact of space radiation environment

5.1 Spacecraft charging

The electrons impinging on spacecraft surface in the space environment are faster than their ion counterpart because of their very small mass (when compared to that of ions). As a result the ambient electron flux is usually more than the ambient ion flux, leading to high level negative charging of the spacecraft. The regions of concern (in space) for internal charging of spacecrafts is illustrated in [29] and shown in **Figure 7**. Spacecraft charging can be mitigated by the methods of electron emission and ion reception [30]. Electron emission is the method in which a device pulls (or draws) electrons from the spacecraft ground and ejects them into space, while the ion reception is the method in which positive ions arrive at a spacecraft that is negatively charged to neutralize the negative charges. The former method is effective for reducing the negative charge of the spacecraft ground but not effective for dielectric surfaces. As a demerit, the process can lead to differential charging between the dielectric and the conducting ground. The later method is effective for mitigating negatively charged surface (whether dielectric or conductor), and reducing differential charging. However, it has the disadvantage of electroplating the entire spacecraft with extended use. Because each method has advantage (or disadvantage) over the other, the use of a combination of both types has been recommended. Other mitigation methods include plasma emission, partially conducting paint, polar molecule emission, mirror reflection and violet irradiation [31].

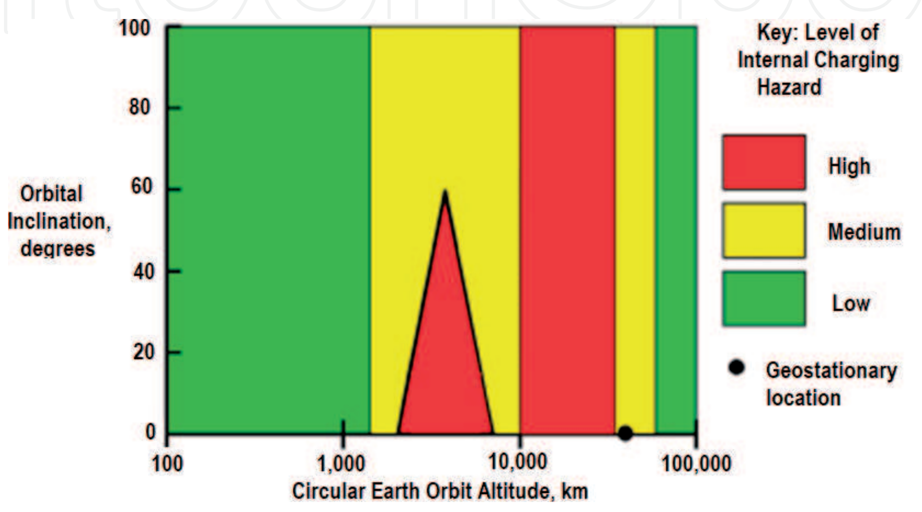

Figure 7.
Regions of concern for internal charging of spacecrafts in space (source: Ref. [29]).

5.2 Single event effects

For memories and data related devices, some of the error mitigation approach or methods include Parity check, cyclic-redundancy check (CRC) coding, Hamming code, Reed-Solomon (R-S) coding, convolutional encoding and overlying protocol (see: Ref. [32] and references therein). Parity is a single bit added to the end of a data structure, such that it states whether an odd or even number of 'ones' was in the structure. The parity method counts the number of logic-one states or 'ones' that are occurring in a data path. The CRC coding method detects if any errors occurred in a given data structure based on performing modulo-two arithmetic operations on a given stream of data, and interpreting the results as a polynomial. The hamming code method detects the position of a single error and the existence of more than one error in a data structure. The R-S code can detect and correct multiple and consecutive errors in a data structure. The convolutional encoding can also detect and correct multiple bit errors. However, it is distinguishable from block coding (e.g., R-S code) by interleave of the overhead or check bits into the actual stream of data instead of being grouped into separate words at the end of the data structure. Errors in the control-related devices can also be mitigated using some of the above mentioned methods. A more effective mitigation approach for control-related devices with complex difficulties (e.g., large scale integration circuitry or microprocessors) is the software-based mitigation, which includes tasks or subroutines dubbed health and safety (H&S). The H&S tasks can perform memory scrubbing that utilizes parity or other method on either external memory devices or registers that are internal to the microprocessor. In the software mitigation methods, the internal microprocessor timers can also be used to operate a watchdog timer or for passing H&S messages between spacecraft systems (see: Ref. [32] for more detail).

5.3 Total ionizing dose

TID on satellites system can be mitigated by methods such as shielding, derating and conservative circuit design [33]. Shielding is the processes of protecting spacecraft (and the occupants) from ionizing radiation using a configuration of appropriate massive materials. Derating refers to techniques usually employed in electrical power and electronic devices in which devices are operated at maximum power dissipation that is less than their rated value, with consideration of the case or body temperature, ambient temperature and the type of cooling mechanism used. This method can increase the safety margin between part design limits and applied stresses, consequently enhancing protection of the part [34]. Hardening of critical components in satellites at design level is also a viable method. This has, however, been the practice of satellite manufacturers. These methods can also be used to mitigate *Displacement damage* because DD is similar to TID as the effect is also cumulative [33].

Other important mitigation approach includes the development of appropriate environmental model that can mimic the perturbed scenarios that are expected under extreme space environmental condition. A well-accomplished or more sophisticated model should account for the individual effects of various solar forcing mechanisms, which cause fluctuations in neutral and ionized density [35]. One other very important mitigation approach to consider is the development of extensive warning system for solar energetic events. Although solar activity can be predicted days in advance but ascertaining their level of impact on the satellite and the Earth environment is quite challenging. Therefore, effective monitoring of solar activity is essential in order to be able to predict atmospheric or ionospheric

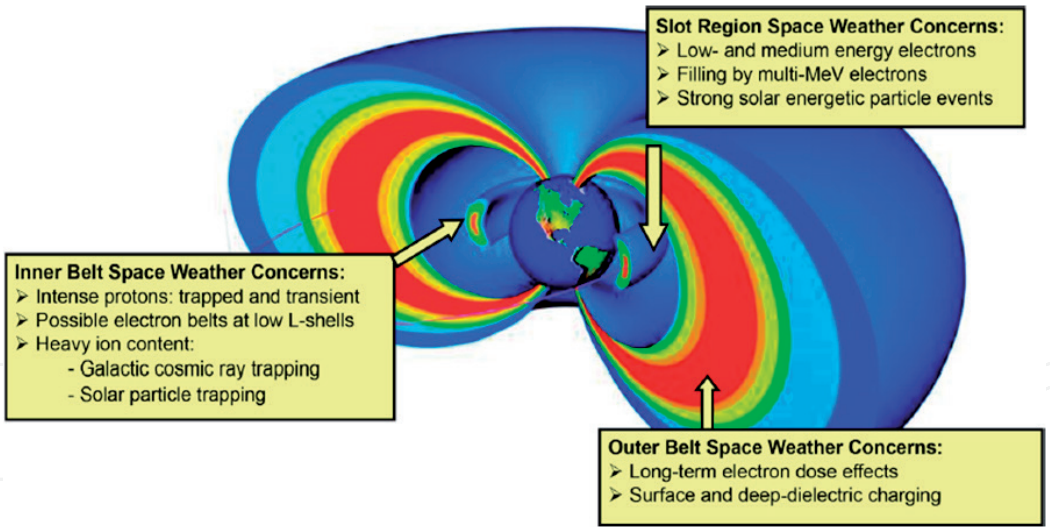

Figure 8.
Schematic diagram of Earth's radiation belts and their space weather concerns (from Ref. [36]).

responses to solar events and their consequence on satellite in orbit. In all, orbit consideration (and satellite's trajectory) is also important. Satellites in medium Earth orbit (MEO) and geostationary orbit (GEO) are subject to impacts of outer Van Allen radiation belt. LEO satellites encounter the most intense particle fluxes in the SAA [36], which is considered to be the main region where spacecrafts receive the largest fraction of the radiation exposure during spaceflight missions. The schematic diagram of Earth's radiation belts and their space weather concerns is shown in **Figure 8**.

6. Conclusion

The space radiation environment driven by solar activity (and galactic cosmic rays) poses potent and unequivocal treat to satellites in near-Earth space. Understanding atmospheric and ionospheric dynamic responses to solar-driven particles and radiation, and their space weather implications are critical and of practical importance to satellites design and operation. The specific effects of radiation environment on as satellite depends on the source, type and energy of incident particle, as well as the satellite's orbit and/or position at the time of solar energetic events. Radiation mitigation measures can increase the safety margin between part design limits and the applied stresses resulting from particles impact, consequently enhancing protection of the part. However, it is important that the solar maximum phase be given more consideration in all mitigation effort because the rate of impact is higher during this interval. Severe solar storms can occur during the solar maximum that can produce huge short-lived increase in radiation levels, as well as high levels of SEEs that current mitigation measures might not be able to bear [37]. Also as dependence on satellites services increase, the economic and societal risk associated with space weather also increases, and likely impact can be unprecedented. In view of this, a contingency plans that include the possibility of switching to or benefitting from other independent satellite services have been recommended [8]. The upcoming multi-constellation GNSS receivers can play a significant role in this regard, such that the individual GNSS receivers will be inherently robust to a satellite service denial. Space weather-induced enhancement of atmospheric drag on satellites and consequent accelerated orbit decay is also a major perturbing force to reckon with, for satellites in low Earth orbit [35, 38–42]. A concise review of the impact and mitigation of this phenomenon will be published in the future. We note that this review (on the space radiation effects on satellites and their mitigation methods) is succinct when compared to the large body of work in the subject area. Therefore, we encourage readers to also consult other well-accomplished texts for specific space radiation effect and the appropriate mitigation approach.

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