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The Impact of Space Radiation on Spacecraft Electronics: Adverse Effects on Measurement Processes and Strategies for Mitigating Data Corruption

Abstract

The article investigates the effects of cosmic radiation on spacecraft electronics and measurement systems, as well as ways to prevent system failures. In contrast to interplanetary, magnetospheric and ground-based effects, this study provides a brief summary of the main effects of cosmic radiation on satellite and spacecraft electronics.

The intensity of solar activity includes the complex effects of geomagnetic storms that can endanger the life of satellites and spacecraft, as well as adverse effects on spacecraft measurement processes and electronics due to electromagnetic emissions and energetic particles. During operation, the spacecraft is constantly exposed to radiation from various high-energy particles, which can lead to performance degradation and operational failures. In some cases, particles with sufficient energy penetrate the satellite surface, causing errors in measured values. Such events can lead to mismanagement of the overall system and even permanent system failure. It is important to understand the dynamics of the space radiation environment and related factors for the sustainable operation, design and operation of spacecraft according to the intended environment. This study investigates various anomalies related to the space radiation environment and outlines some strategies to mitigate their effects.

Keywords: *cosmic radiation, effects of cosmic rays, reliability of electronics, radiation induced errors, degradation of electronic components, mitigation strategies*

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Kosmik radiasiyanın kosmik gəmilərinin elektronikasına təsiri: ölçmə proseslərinə mənfi təsirlər və məlumatların korlanmasının azaldılması strategiyaları

Xülasə

Məqalədə kosmik radiasiyanın kosmik aparatların elektronikasına və ölçmə sistemlərinə təsirləri, eləcə də yaranan sistem nasazlığının qarşısının alınması yolları araşdırılmışdır.

Planetlərarası, maqnitosferik və yer əsaslı təsirlərdən fərqli olaraq, tədqiqat kosmik radiasiyanın peyk və kosmik aparatların elektronikasına əsas təsirlərin qısa xülasəsini təqdim edir. Günəş fəaliyyətinin intensivliyinin peyk və kosmik aparatın uzun ömürlülüyünə xələl gətirə bilən geomaqnit fırtınalarının kompleks təsirləri, eləcə də elektromaqnit emissiyaları və enerji hissəcikləri səbəbindən kosmik aparatın ölçmə prosesinə və elektronikasına mənfi təsirləri daxildir. İstismar zamanı kosmik gəmi müxtəlif yüksək enerjili hissəciklərdən davamlı radiasiyaya məruz qalır ki, bu da performansın azalmasına və uğursuz əməliyyatlara səbəb ola bilər. Bəzi hallarda kifayət qədər enerjiyə malik hissəciklər peykin səthinə nüfuz edərək ölçülən dəyərlərdə xətalara səbəb olurlar. Bu kimi hadisələr ümumi sistemin səhv idarə edilməsinə və hətta sistemin qalıcı olaraq sıradan çıxmasına səbəb olur.

Kosmik gəmilərin dayanıqlı işləməsi, onun nəzərdə tutulan mühitə uyğun dizayn edilməsi və istismarı üçün, kosmik radiasiya mühitinin dinamikasını, əlaqəli faktorları başa düşmək vacibdir. Bu işdə kosmik radiasiya mühiti ilə bağlı bir neçə anomaliyalar araşdırılmış və onların təsirlərini azaltmaq üçün müəyyən strategiyalar qeyd edilmişdir.

Açar sözlər: *kosmik radiasiya, kosmik şüaların təsiri, elektronikanın etibarlılığı, radiasiya səbəbli yaranan xətalar, elekton komponentlərin deqradasiyası, radiasiyanın azaldılması strategi-yaları*

Introduction

Space radiation can have a substantial impact on space technology by affecting the functionality and robustness of equipment used in space missions. There are several different types of space radiation, including solar particle events, which are high-energy particles from the Sun, Van Allen radiation belts, which are radiation pockets trapped in Earth's magnetic field, and galactic cosmic rays (GCRs). Radiation is released into space by particles from a variety of sources, both inside and outside of our solar system. The radiation effects of these particles can cause damage and failure to the electrical and electronic systems in satellites or spacecraft. Together, they both add to the radiation environment in space.

Research

Large amounts of protons and electrons, along with helium and other heavier nuclei, are produced by the sun's fusion process and are carried towards Earth by the solar wind. The sun emits this solar wind in all directions, but the flow of these particles varies in response to solar flares and sunspot activity (Osman, 2012).

Apart from solar particles, there are also particles originating from other stars and heavy ion sources like Supernovas and Novas in our galaxy and other galaxies. These ionizing particles are the main source of radiation danger in interplanetary space. These particles are affected by the magnetic field of a planet or the earth, resulting in the formation of radiation belts, called Van Allen radiation belts in the case of Earth, which contain protons in the inner belt and trapped electrons in the outer belt. A space vehicle's trajectory has a major impact on the radiation's composition and intensity.

Numerous spacecraft observations have demonstrated that in both the northern and southern hemispheres, higher electron concentrations are detected between 45 and 85 degrees latitude, suggesting a lower altitude for the belts. Relatively low electron concentrations are found for orbits with less than 30 degrees of inclination. In the Atlantic, a region known as the South Atlantic Anomaly (SAA) near Argentina and Brazil has relatively high concentrations of electrons because of the earth's asymmetric magnetic field (National Research Council, 2012b).

Apart from the electrons and protons that are trapped in Van Allen radiation belts, the spacecraft is also exposed to radiation threats from galactic cosmic rays, which are high-energy heavy ions in space, and secondary X-rays, also known as brachial radiation, which are particles that enter spaceships and pierce their skin as they lose energy. This kind of radiation is a substantial portion of the total component that results in the effects of the total dosage (Patterson & Richard, 2013).

Additionally, different amounts of protons, heavy ions, and lower energy electrons are contributed by solar flares. During periods of high solar activity, solar flares, which happen randomly at different times, can cause extremely high particle fluxes for hours or days

As mentioned before the space radiation effect varies by their sources:

- Trapped particles: Van Allen belts: electrons, protons, heavy ions.
- Solar wind: electrons and protons (Cade & Chan-Park, 2015).
- Solar Energetic Particles (SEP): protons, heavy ions, electrons, Flares, Coronal Mass Ejections (CMEs).
- Galactic Cosmic Rays (GCR): protons and heavy ions.

Galactic Cosmic Rays (GCRs)

The high energy particles that come from sources outside our solar system.

Most galactic cosmic rays are composed of protons and ionized heavy nuclei with energies ranging from ~1 MeV/nucleon to over ~10,000 MeV/nucleon, which are of galactic and/or extragalactic origin (Osman, 2012). Ninety-nine percent is hydrogen and ten percent is helium. The other components that are well-known make up the remaining 1 percent. GCR electrons typically do not greatly increase radiation effects.

With increasing separation from the Sun, the GCR flux in interplanetary space increases gradually. Together with the solar cycle, the solar wind also modulates the GCRs inversely. GCR intensity peaks at the highest solar activity and troughs at the lowest. Variations in the solar wind's magnetic field are the source of this modulation.

Propagation of GCRs into the inner solar system is hindered by turbulence in the field known as associated with solar maximum, which also effectively scatters the particles. As the solar wind field relaxes during solar minimum, GCRs can more easily reach the inner solar system. The ability of Earth's geomagnetic field to successfully deflect lower-energy particles shields the planet from incident GCRs and solar energetic particles. Particles in the polar regions with nearly vertical velocities are mostly parallel to the magnetic field due to the geomagnetic field's approximate dipole characteristics. From a single proton to the nucleus of uranium, ionized atoms make up GCR. These particles flow at an extremely slow rate. However, due to their near-light speed and the fact that some of them are composed of extremely heavy elements like iron, they cause strong ionization when they pass through matter (Spence & Harlan, 2013).

Natural protection against solar and cosmic particles is offered by the Earth's magnetic field, which is mainly dependent on altitude and inclination. A satellite leaves the geomagnetic field lines' shield when its tilt reaches the polar aurora. As altitude rises, exposure to these particles progressively increases due to the aurora produced by precipitating electrons, which are intense streams of energetic electrons that propagate downward along magnetic field lines in polar orbits.

Solar Particle Events (SPEs)

High-energy particle eruptions are superimposed on background sunlight by the Sun's continuous emission of charged particles, known as the "solar wind," which have kinetic energies ranging from 1 eV to 10,000 electron volts (10 keV). These particles move away from the Sun in a radial direction and have a density of approximately 10 particles per cubic centimeter. Solar Energetic Particles, or SEPs, are accelerated to high energies by solar electromagnetic fields and are linked to periods of high solar activity. In contrast, solar particle events (SPEs) are times of noticeably increased particle fluxes (Tribble & Alan, 2010).

Particles with kinetic energy far above the megaelectron volt range and up to a few gigaelectron volts can have intensities that are orders of magnitude higher than galactic cosmic radiation at comparable energies, and they can last for hours or days. Protons with an alpha particle addition of approximately 9–10% make up these particles, but they are also enhanced by energetic particles with higher nuclear charge. While the relative amounts match the abundances found in the heliosphere and solar atmosphere, the specifics of the abundances differ dramatically between events. Electronics are seriously at risk from these particles because of their high energy and quantity.

The peak flux of an SPE decreases with distance from the Sun, but not in a simple way. Momentum events driven by a localized source on the Sun decay approximately between $\frac{1}{r^2}$ and $\frac{1}{r^3}$. Gradual events driven by a rapidly evolving shock originating from the Sun are not easily characterized. Peak flow can even increase to an astronomical unit before slowly decreasing (Aguilar, 2010).

Trapped Radiation Belts

Earth's magnetic field traps a smaller percentage of heavy ions, like O+, in ring belts, resulting in radiation that is mostly composed of high-energy protons and electrons. There are at least two zones on this toroid, which is referred to as the Van Allen Belt: a high mountain zone, also called the outer belt, and a low mountain zone, also called the inner belt. High-energy protons (tens of MeV) and high-energy electrons (one to ten MeV) make up the inner belt, which stretches hundreds of kilometers to an altitude of roughly 6,000 km. The outer belt, which is sufficiently extended to 60,000 km in altitude, is primarily made up of high-energy electrons. Because the Earth's main field predominates, the inner belt zone is comparatively stable. The majority of the temporal variations in this population take place as the solar cycle advances and variations in Earth's neutral atmospheric density at a specific altitude lead to variations in the altitude at which radiation particles are scattered. By contrast, there are significantly larger temporal fluctuations in the outer belt, which is more affected by Earth's highly variable geomagnetic tail (Olive, 2014).

Radiation Impact on Electronics

So, what types of electronic systems are used on satellites? Depending on their function, a spacecraft's fundamental components are separated into two categories: the payload and the platform or bus. The structure subsystem, telemetry subsystem, tracking and command subsystems, power and distribution subsystem, thermal control subsystem, and attitude and speed control subsystem are the five fundamental subsystems that make up the platform and support the payload. The mechanical structure, which provides stiffness to withstand stress and vibration, is the structural subsystem. Additionally, it shields electronic equipment from radiation. The subsystems responsible for telemetry, tracking, and command consist of antennas, receivers, transmitters, and sensors that measure temperature, voltage, current, and tank pressure. Additionally, it gives the status of different spacecraft subsystems. The spacecraft's batteries are charged by the power and distribution subsystems, which transform solar energy into electrical energy. Extreme temperatures can be avoided by electronic devices with the aid of the thermal control subsystem (Getley et al., 2010).

The last subsystem of the attitude and speed control subsystem is the orbit control system, which is made up of actuators such as thrusters and reaction wheels that apply the torques and forces required to orient the vehicle to the proper orbital position and sensors that measure the orientation of the vehicle. A typical attitude and control system would consist of inertial measurement units (IMUs), pulse wheels, sun, earth, and star sensors, as well as the electronics needed to process the signals and regulate the satellite position. Energy deposition in the target object is generally the primary result of radiation-matter interaction. This energy deposition produces a range of effects, depending on the kind of particle and the energy and physical processes working in the target material/structure (Nwankw, 2010).

Often, through flight experience with actual anomalies, engineers and operators have learned how radiation interacts with satellites and creates these hazards. Not all satellite anomalies are caused by space radiation, and it is challenging to estimate the exact probability of radiation-induced anomalies in systems that are currently in orbit due to a few factors, such as reporting regulations, restrictions on confidential data, and the custom of classifying anomalies as known behavior only after the damage limitation and root cause have been established. The main issues are cumulative radiation damage, single event effects (SEEs), and electrostatic discharge (ESD). The primary cause of satellite charging, which can result in ESD, is electrons. Particularly near the end of the spacecraft's life, total ionization dose (TID) is a concern, and TID failures are frequently preceded by gradual degradation (Horne, 2012).

Impacts of Single-Event Effects on Spacecraft

Electronic parts like sensors, transistors, and integrated circuits can be harmed by high-energy particles. The impacted systems may experience malfunctions, decreased performance, or even catastrophic failure as a result of this damage. Furthermore, radiation can materially harm solar panels, spacecraft structures, and other devices, shortening their useful lives.

Electronic systems essential to spacecraft operations are susceptible to destruction, degradation, or disruption due to high-energy particle interactions. An impact from a single particle on the spacecraft's electronics results in SEEs. Comparatively speaking, TID is a cumulative effect that lasts the entire spacecraft's lifetime. The free charge that is left over after ionizing particles leave their mark is a similarity shared by TID and SEEs. In SEEs, a single particle displaces free of charge as it passes through matter. Under TID, free charges for radiation through material have an cumulative effect over the mission's duration (Patterson & Richard, 2013).

Radiation-related faults such as SEU, SEL, and SEB can manifest at any phase of a mission and in various space environments. These issues arise when a charged particle enters a sensitive region in an active semiconductor device, depositing enough charge to interfere with its normal functioning. This disruption can take place at any moment due to the particle's presence, which may primarily stem from the space environment or result from secondary interactions between the primary collision particle and the materials nearby.

When a particle passes through an electronic component, bits of free charge are produced, and atoms are ionized. An incorrect outcome might occur if this charge builds up in the component in a way that mimics or interferes with the device's regular operation. It can, for instance, output or receive random data from a device or alter the state of a memory. In more extreme circumstances, the charge may cause a short circuit, and the current that flows through it may completely or partially destroy a component. Recoverable impacts to catastrophic failure of the entire system are possible outcomes, depending on the electronic component's vulnerabilities, operation, and timing of the SEE (Jibiri, Nwankwo, & Kio, 2011).

The effects of a nondestructive SEE vary depending on the device's operation at the time of the SEE. These inaccurate results won't have a major or lasting impact on the spacecraft if the processors' overall logic is able to isolate, ignore, or repair the damage. The capacity of the spacecraft designers to foresee potential problems throughout their operational life in all pertinent operating environments is a critical component in dealing with SEEs.

When the components' radiation response is sufficiently understood, it becomes feasible to model the consequences of radiation-related malfunctions and failures prior to the devices being installed on the spacecraft.

A partial or total loss of part functionality requires significant intervention (e.g. power cycling of the part) to restore functionality, which can also corrupt large amounts of data, commonly referred to as a single-event functional interruption. Single event phenomenon can be classified into four:

(i) single event upset (SEU),
(ii) single event latch-up (SEL),
(iii) single event burnout (SEB),
(iv) single event gate rupture (SEGR).

Single-event latch-up (SEL), single-event burnout (SEB), or single-event gate rupture (SEGR) are examples of destructive SEEs that can cause catastrophic part failure. Single event upset SEU is the permanent but reversible flipping of one or more bits. As previously mentioned, SEU is a state change brought on by ions or electromagnetic radiation hitting a microprocessor, semiconductor memory, or power transistor, among other sensitive nodes in micro-electronic devices. The state change is a result of the free charge created by ionization in or close to an important node of a logic element (memory portion etc.).

Soft errors are those that result from strikes in the output or operation of equipment. The processes by which galactic cosmic ray energy is deposited in devices and how heavy ion and proton SEU work in them (Osman, 2012). Normal devices like analog, digital, or optical components may experience a reset or rewrite due to SEU, which can also affect nearby interface circuitry. A fatal SEU is a single-event disruption of operation caused by a SEU in the control circuitry of the device, which results in the device entering a test mode, stopping, or entering an unknown state.

A specific kind of short circuit that can happen in a circuit that is not properly designed is referred to as a short circuit occurrence locus in integrated circuits. A parasitic structure that interferes with a MOSFET circuit's normal operation and may even cause it to explode from overcurrent can be caused by the creation of a low-impedance path between the circuit's power supply rails. Hard mistakes, or SELs, have the potential to do irreversible harm. That may cause the power supply to be damaged, the bus voltage to drop, the operating current to exceed device specifications, or all the above.

Very sensitive devices may experience latch-up due to protons. An on-off-on reset or power strobe of the device rectifies or clears a SEL. Temperament has a significant impact on SEL. Bond wire failures, excessive heating, or metallization can all lead to catastrophic failure if power is not cut off quickly. The condition known as SEB is brought on by a power transistor experiencing excessive current. This phenomenon is very localized and affects power MOSFETs, BJTs, and charge-coupled devices in the following ways: gate breakage, frozen bits, and noise.

Destructive burnout in the gate oxide is caused by a conductive path forming or a localized dielectric breakdown, known as SEGR. MOSFETs, BJTs, and CMOS all experience it.

Total Ionizing Dose (TID) and Displacement Damage (DD)

The cumulative effects of long-term radiation exposure on electronic components. A material's electrons interact with charged particles or photons during their passage through it, ionizing certain atoms and forming electron-hole pairs as a result. These effects compound in insulators, such as MOSFETs. The total energy lost by the particles to the material through interactions with the electrons is used to measure the accumulated trapped charge, which is measured by the accumulated ionization. Consequently, the total energy known as the total ionizing dose transferred to the material by ionization from all ionizing particles per unit mass of material is a useful metric (Patterson & Richard, 2013).

TID can lead to equipment malfunctions or biological harm to astronauts. It is mainly caused by protons and electrons. Absorbed dose, a measurement of the energy absorbed by matter, can be used to calculate TID in both scenarios. A unit of measurement for the absorbed dose is either the SI unit gray (Gy) or the rad (abbreviation for absorbed radiation dose; 1 rad = 100 Erg/g).

$$1 \text{ Gy} = 100 \text{ rads} = 1 \text{ J/kg}$$

The solar energetic particles, secondary Bremsstrahlung photons, and trapped protons and electrons are used to calculate the TID. Displacement damage is the result of nuclear interactions, typically scattering, which cause lattice defects. Long-term cumulative nonionizing damage from protons, electrons, and neutrons is another cause of displacement damage. A lattice atom's nucleus is struck by an incoming particle, which causes the atom to move from its initial lattice position.

Electrons with energies greater than 160 keV, neutrons, and protons of all energies are the particles causing displacement damage. Displacement damage, though caused by protons in solar cells and bipolar (BJT) devices, is generally less concerning than single-event effects, or TID. Degradation of gain and leakage current in bipolar transistors is a typical consequence of displacement damage, which shortens the minority carrier lifetime. Linear energy transfer, or LET, is the total energy loss per unit of travel. Usually, the LET is normalized by dividing by the medium density; MeV-cm2/mg is the most widely used unit of measurement (Garrett, 2012).

Normalization is justified by the fact that it produces similar LETs across various materials for a given particle and energy. LET is likewise influenced by the kind and energy of the encountered particles. Particles with high energy dissipate as they pass through solid materials due to ionizing and non-ionizing reactions. Energy loss causes atomic displacements, also known as displacement damage, and the formation of electron-hole pairs. The two main lattice defects that first appear are vacancies and interstitials. A Frenkel or close pair is the union of space and a neighboring interstitial. A divacancy is a type of defect that forms when two nearby vacancies combine. Moreover, irradiated silicon may exhibit larger local clusters of vacancies.

A defect-impurity complex is a defect created by interstitials and vacancies next to impurity atoms. Once the defects are formed by incident radiation, they rearrange themselves to form a more stable configuration. The kind of defect and the amount of time it takes for the defect to form at a particular temperature determine how many defects change the characteristics of bulk semiconductor materials and devices. The degree of injection, the kind of material, the kind of contamination, the concentration away, the time after irradiation, the measurement temperature, the type and energy of the particles, the time after irradiation, the thermal history after irradiation, and the bombardment conditions are some of the variables that affect how effective radiation-induced displacement damage is (Maurer et al., 2008).

Data Corruption and Mitigation Strategies

Use of special electronics that are resistant to radiation. Conservative circuit design, derating, and shielding are a few ways to reduce influences. The process of shielding involves arranging the right solid materials in a way to protect spacecraft and their occupants from ionizing radiation. Derating, which takes into consideration the case or body temperature, the ambient temperature, and the type of cooling mechanism used, refers to techniques commonly used in electrical and electronic equipment where devices operate at maximum power dissipation less than their rated value. This technique can improve the part's protection by raising the safety margin between the applied stresses and the part's design limits. Protecting delicate components with a physical barrier, like aluminum or composite materials, is known as shielding.

Sensitive components can be shielded from radiation exposure with the use of shielding materials. This method requires weighing the extra weight and expense of the shielding materials against the improved protection they offer.

Utilizing electronic components that are radiation-tolerant or radiation-hardened can greatly increase a spacecraft's ability to withstand radiation-related damage. Higher radiation levels won't affect the functionality of these parts because of their design. Operational amplifiers based on transistors provide the foundation for the signal conditioning of radiation-resistant electronics. JFETs and MOSFETs are two popular types of transistors (Lohmeyer & Cahoy, 2013). A p-n junction transistor, the JFET has a gate terminal that is directly connected to an n-doped region and a depletion region between its source and drain terminals, which are located in the p-doped portion of the semiconductor. The source and drain connections of a MOSFET are linked to their own n-region, while the gate connection is linked to a thin oxide layer covering a more heavily doped n-region.

Although the MOSFET design enables very low current operation of logic or control circuits, it is more prone than the JFET to irreversible radiation damage, specifically to the oxide layer. The MOSFET is more vulnerable to radiation damage because of the insulator and a pole on the gate connection. Applications of Si_3N_4 and sapphire as insulation to increase the radiation hardness of electronics are attractive due to their large displacement energies.

A spacecraft can be made to work even in the event that radiation damages some of its components by designing systems with redundancy and fault detection built in. To preserve functionality and data integrity in the event of radiation-related problems, for instance, multiple redundant systems or the implementation of error correction codes in storage devices can be used. Radiation-related issues can be avoided with careful mission operation planning, such as arranging crucial tasks for times when radiation exposure is lowest.

Furthermore, reducing the effect of space radiation on space technology can be achieved by tracking space weather and instantly modifying mission plans in response to radiation levels. Radiation exposure can be reduced by selecting the right spacecraft orbit and orientation. For example, low Earth orbits (LEO) within Earth's magnetic field can provide some protection from galactic cosmic rays, while higher orbits can reduce the time spent in the harsher radiation environment of the Van Allen belts.

Because of their extremely low mass, electrons impact the surface of spacecraft in the space environment more quickly than ions do. Because of this, there is typically a significant negative charge on the spacecraft because the flow of electrons in the environment is greater than the flow of ions. It is possible to reduce spacecraft charging by using ion reception and electron emission techniques. Ion reception is the process of positive ions entering a negatively charged spacecraft to balance the negative charges, whereas electron emission is the process of removing electrons from the spacecraft's bottom and ejecting them into space. The former technique works well for lessening the floor of the spacecraft's negative charge, but it is ineffective on dielectric surfaces. The possibility of a differential charge between the conductive mass and the dielectric as a result of the process is a drawback. The latter technique works well for lowering differential charges and attenuating negatively charged surfaces, whether they are conductors or dielectrics. However, it has the disadvantage of electroplating the entire spacecraft with extended use. Because each method has advantages or disadvantages over the other, the use of a combination of both types has been recommended.

Regarding the effect on data, error mitigation techniques or methods for storage and data-related devices include convolutional coding, parity checking, cyclic redundancy check (CRC) coding, Hamming code, Reed-Solomon (R-S) coding, and overlying protocol. A single bit called parity is appended to the end of a data structure to indicate if an odd or even number of "ones" were contained within it. The number of logical ones, or "ones," that occur in a data path is counted using the parity method. Through modulo two arithmetic operations on a given data stream and polynomial interpretation, the CRC coding method determines whether errors have occurred in each data structure. The Hamming code technique locates a single error and indicates whether multiple errors are present in a data structure. A data structure's multiple and consecutive errors can be found and fixed by the R-S code. Multiple bit errors can also be found and fixed with convolutional coding.

Instead of being grouped into distinct words at the end of the data structure, the overhead or checking bits are interleaved into the actual stream of data, which sets it apart from block coding. Some of the previously mentioned techniques can also be used to lessen errors in the devices related to control. A more potent mitigating strategy for managing linked devices with intricate issues like software-based mitigation such as large-scale circuitry or microprocessors, which consists of operations or subroutines known as health and safety. The H&S tasks could perform memory scrubbing on external memory devices or microprocessor internal registers using parity or other techniques (Sayyah, Macleod, & Ho, 2011).

The internal microprocessor timers in software mitigation methods can also be used to relay H&S messages between spacecraft systems or to run a watchdog timer. A more complex or well-designed model should consider the distinct impacts of various solar forcing mechanisms that result in variations in the densities of ions and neutral particles. The creation of thorough warning systems for solar energy events is a crucial approach to mitigation. Determining the degree of solar activity's influence on the satellite and Earth's environment is a significant challenge, despite the fact that it can be predicted days in advance. Thus, accurate solar activity monitoring is necessary to forecast atmospheric or ionospheric reactions to solar events and the ensuing effects on satellites in orbit. In general, taking into account the satellite's orbit and trajectory is also crucial. The outer Van Allen radiation belt affects satellites in geostationary orbit (GEO) and medium Earth orbit (MEO). In the South Atlantic Area (SAA), spacecraft are exposed to the highest percentage of radiation during spaceflight missions; LEO satellites experience the strongest particle fluxes in this region.

Conclusion

This article presents research on the general effects of space radiation on space technologies and simple mitigation strategies. A clear and present hazard for spacecraft in orbit is space radiation caused by solar activity.

To effectively design and operate spacecraft, it is imperative to understand the dynamic responses of the atmosphere and ionospheric layers to solar radiation and particles and how these responses affect space weather. The nature, energy, and source of the incident particles, the spacecraft's orbit, and/or its location during solar energy events affect the specific effects of the radiation environment on the satellite.

The protection of the component can be enhanced by radiation mitigation techniques by increasing the safety margin between the design limits of the component and the stresses caused by particle impact.

However, solar maximum should receive more attention in any mitigation efforts because this is when the impact rate is highest. During solar maximum, severe solar storms can occur that are beyond the capability of current mitigation strategies. These storms can cause sudden, large increases in radiation levels and high SEEs. Systems that offer both high performance and long life can be achieved with careful component selection, shielding, and design. However, space radiation can have a significant impact on spacecraft electronics design. New technological concerns must be understood to improve system reliability.

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