

# A Study of the Space Environment and its Impacts on Satellites

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**Abstract:** This work was aimed at studying the space environment as well as its impacts on satellites in space. The work adopted the use of the review and explanatory research methods. The analysis revealed that the space environment is characterized by features such as extreme thermal gradients ranging from direct solar exposure to deep-space cold, as well as intense ionizing radiation from solar particle events and galactic cosmic rays. The result also indicated that some impacts of the space environment on the satellites are atmospheric drag, extreme thermal cycling, atomic oxygen erosion, surface charging and electrostatic discharge, single event effects, and total ionizing dose. It was concluded from the results that the space environment has numerous impacts on satellites, and these impacts have serious challenges on the operations or performances of satellites in space.

**Keywords:** Atomic Oxygen Erosion, ionizing radiation, Single Event Effects, space environment, Thermal Cycling.

## I. INTRODUCTION

The space environment is a region characterized by various phenomena such as extreme thermal gradients from direct solar exposure to deep-space cold; intense ionizing radiation from solar particle events, galactic cosmic rays, and trapped particles in the Van Allen belts; and variable solar and geomagnetic activity that induces drag and electromagnetic disturbances. Even if the radiation tolerance of a satellite system is high, its overall reliability will decrease when subjected to high radiation for too long (Toshihiro et al., 2022). Radiation could cause a variety of damage effects in the components of a satellite, including degradation of the electro-optical properties of the electrical components and single-event effects (Tzintzarov et al., 2021). The primary sources of space radiation include solar radiation, cosmic rays, the Van Allen radiation belts, solar flares, geomagnetic storms, micrometeoroids, and space debris. Each of these sources contributes to the degradation of semiconductor materials through mechanisms such as ionization, defect formation, annealing, and other effects on materials and devices in spacecraft. The specific sources of radiation that affect a particular spacecraft will depend on its orbit and the time of year (Sulaiman et al., 2025).

However, the mechanisms that are responsible for much of the vulnerability are not exclusive to protons. Cumulative effects such as total ionizing dose (TID) and displacement damage are also caused by the populations of trapped energetic electrons that form the Van Allen belts. For example, the injection of energetic electrons could cause additional radiation exposure to satellites undergoing electric orbit-raising, equivalent to a 6.5-

year operation in geostationary orbit (Horne & Pitchford, 2015). Satellites are exposed to a variety of sources of potentially damaging space radiation. One of the most important of these is the population of high-energy electrons that lies trapped by the Earth's magnetic field—the so-called Van Allen belts. During an extreme space weather event, trapped electron fluxes in the Van Allen belts can increase by several orders of magnitude in intensity, leading to an enhanced risk of satellite damage (Hands et al., 2018).

## II. RESEARCH METHODOLOGY

This study employs both the review and explanatory research methods to achieve a clear and comprehensive understanding of the topic. The explanatory research method is used to provide detailed discussions of key concepts and processes, helping to clarify how different aspects of the space environment affect satellite systems. It enables the study to break down complex ideas into simpler, more understandable explanations. The review research method complements this by examining and synthesizing findings from recently published scholarly works. Through this approach, the study identifies important trends, compares existing contributions, and highlights relevant insights from the research area. This ensures that the discussion is grounded in current knowledge and supported by credible academic sources. Both methods are integrated in the analysis of the impacts of the space environment on satellites, combining clear explanations with evidence from literature. The materials used for this research are secondary sources, including textbooks, peer-reviewed journals, conference papers, and reliable online resources such as academic websites and educational videos. These sources were selected based on their relevance and recency, ensuring the reliability and validity of the study.

## III. RESULTS AND DISCUSSION

### A. Space environment

Space is defined as the region beyond the atmosphere. The space environment is the collection of physical and natural conditions found in outer space that affect spacecraft operations, including vacuum, radiation, charged particles, plasma, micrometeoroids, and variations in temperature and magnetic fields, all of which influence the performance, reliability, and lifespan of satellites (Wertz et al., 2011). The space environment is a region characterized by various phenomena such as extreme thermal gradients from direct solar exposure to deep-space cold; intense ionizing radiation from solar particle events, galactic cosmic rays, and trapped particles in the Van Allen belts; and variable solar and geomagnetic

activity that induces drag and electromagnetic disturbances. Even if the radiation tolerance of a satellite system is high, its overall reliability will decrease when subjected to high radiation for too long (Toshihiro et al., 2022).



Fig. 1: Space environment (Source: NASA)

### B. Impacts of space environment on satellites

The following are some impacts of space environment on satellites or spacecrafts.

#### 1. Total Ionizing Dose

Total Ionizing Dose (TID) is defined as the cumulative amount of ionizing radiation energy absorbed by a material, especially semiconductor devices, over a period of time in the space environment. This radiation mainly originates from high-energy protons and electrons trapped in Earth's magnetic field, especially within the Van Allen radiation belts, as well as from solar particles released during solar events. As satellites repeatedly pass through these regions, they are continuously exposed to radiation, leading to a steady accumulation of absorbed energy. This energy creates trapped charges within the insulating layers of electronic materials over time. This leads to gradual degradation in the performance of onboard computers and memory systems. Solar panels are also affected, as radiation damages their structure and reduces their ability to generate electrical power, resulting in a continuous decline in energy supply.

According to Zhang et al. (2021), analysis of on-orbit satellite thermal data shows that repeated thermal cycling can result in gradual deformation of structural components and subtle misalignment in sensitive optical systems. Their study on the Insight-HXMT satellite demonstrated that although active thermal control systems maintain operational limits, long-term exposure to thermal cycling causes structural strain that can affect imaging precision and payload stability over time. Similarly, Ersoy (2024), in a review of space thermal management systems, reported that thermal cycling remains one of the most persistent challenges in spacecraft engineering. It was further explained that repeated temperature fluctuations cause degradation of electronic packaging, fatigue in solder joints, and stress accumulation in multi-material interfaces due to mismatched coefficients of thermal expansion.

#### 2. Single Event Effects

**Single Event Effects (SEE)** are defined as radiation-induced disturbances in electronic devices caused by a single high-energy particle interacting with a sensitive region of a component. Unlike cumulative effects such as TID, SEE occurs instantaneously and can disrupt the normal operation of a device in a very short time. **Single Event Effects** are mostly caused by cosmic rays and high-energy protons, which

originate from deep space or solar activity and possess enough energy to penetrate satellite shielding. When one of these particles strikes a transistor or memory cell, it deposits charge along its path, which can momentarily alter the electrical state of the device. More serious effects include latchup, where an unintended current path forms within the device, potentially causing excessive current flow and overheating. In extreme cases, this can lead to burnout, permanently damaging the component. In the work by Xie et al. (2023) on space radiation effects on microelectronics, it was observed that high-energy protons and heavy ions are primary drivers of single event upsets in modern integrated circuits. In the same way, Mattos et al. (2024) reported that in memory devices, as data retention elements, SEEs are usually observed as the corruption of the stored data. However, other effects can be observed, such as the occurrence of damaging current increases in parasitic elements of the circuit and functional mismatches during operation.

#### 3. Surface Charging and Electrostatic Discharge (ESD)

**"Surface charging" and "electrostatic discharge" (ESD)** refer to the accumulation of electrical charge on different parts of a satellite's surface and the sudden release of that charge in the form of a spark or arc. The primary cause of surface charging is the interaction between the satellite and the surrounding plasma environment. In regions such as geostationary orbit, especially during geomagnetic disturbances like substorms, changes in electron and ion flux can lead to uneven charging of the surface of the spacecraft or satellite. These discharge events can damage sensitive electronics, disrupt onboard systems, or even destroy components such as solar array strings. According to Lai et al. (2023), the interactions between energetic electrons in the space plasma environment and satellite surface materials can lead to differential charging across spacecraft structures. It was reported by them that insulating materials accumulate charge more rapidly than conductive surfaces, and this creates voltage differences that can exceed breakdown thresholds, thus resulting in electrostatic discharge events. As observed by Michelagnoli et al. (2024), as the satellite passes through the Van Allen radiation belt, the satellite will interact with sun radiation and the plasma environment, and these interactions usually result in the accumulation of net electrostatic charge on the external surfaces of the spacecraft, leading to a potentially hazardous configuration for the nominal operation and survivability of the payload, as it may induce harmful electrostatic discharges (ESDs). The work further highlighted that those electrostatic discharges can propagate across spacecraft surfaces and couple into internal electronics, leading to operational anomalies such as data corruption or permanent hardware damage in severe cases.

#### 4. Atomic Oxygen Erosion

**Atomic Oxygen (ATOX) erosion** is defined as the gradual degradation of satellite materials caused by highly reactive single oxygen atoms present in the upper atmosphere. This effect is most significant in low Earth orbit, where atomic oxygen is abundant due to the breakdown of molecular oxygen by ultraviolet radiation. One of the effects is that thermal control elements, such as multilayer insulation blankets, may become thinner and less effective, disrupting the satellite's ability to regulate temperature. Also, it reduces the effectiveness of thermal control systems and exposes underlying structures to additional environmental stress. As recorded by Dever et al. (2023), long-term exposure experiments on spacecraft materials show that atomic oxygen

is one of the most aggressive environmental factors affecting polymer-based spacecraft surfaces. Their study revealed that some materials like thermal blankets undergo continuous surface erosion due to chemical reactions with atomic oxygen, leading to mass loss and surface roughening over time. In a similar way, Banks et al. (2011) reported that exposure does not only cause surface erosion but also significant degradation of optical properties and thermal control coatings.

### 5. Extreme Thermal Cycling

**Extreme thermal cycling** refers to the repeated and rapid temperature changes experienced by satellites as they move between sunlight and Earth's shadow in orbit. This is mostly caused by the absence of an atmosphere in space. Without atmospheric buffering, satellites are directly exposed to solar radiation when in sunlight and deep cold when in Earth's shadow. This continuous alternation creates intense thermal stress on spacecraft materials and structures. Various components such as batteries are affected, as thermal stress can reduce their efficiency and shorten their operational lifespan. Additionally, thermal insulation systems may degrade, making temperature regulation less effective. According to Zhang et al. (2023), on-orbit thermal analysis of satellites shows that repeated thermal cycling induces gradual structural deformation and stress accumulation in spacecraft components. It was further shown that even when active thermal control systems are in place, long-term exposure still leads to micro-level material fatigue, particularly in joints, connectors, and multi-layer structural interfaces. Also, Eilenberger et al. (2024) examined from their findings that repeated heating and cooling cycles of a spacecraft increase degradation in solder joints as well as electronic packaging materials due to mismatched thermal expansion coefficients.

### 6. Atmospheric Drag

**Atmospheric drag** is the resistive force experienced by a satellite as it moves through the thin residual atmosphere present in low Earth orbit. It acts opposite to the satellite's direction of motion and gradually slows it down, leading to a reduction in orbital altitude over time. The major cause of atmospheric drag is the presence of residual atmospheric particles at low Earth orbital altitudes, especially within low Earth orbit, and this can lead to gradual orbital decay. As the satellite loses velocity, it begins to descend to lower altitudes where atmospheric density is higher, further increasing drag in a feedback loop. Drag also increases operational costs and limits the long-term sustainability of satellite constellations. According to Bruinsma et al. (2023), variations in thermospheric density significantly influence satellite orbital decay rates. Their study shows that solar activity plays a major role in expanding the upper atmosphere, increasing atmospheric density at orbital altitudes and thereby intensifying drag effects. The research emphasizes that even small changes in atmospheric density can lead to measurable differences in satellite lifetime predictions as a result of the excess effects being experienced by various components beyond their designed capacity. Similarly, Emmert (2024) studied thermospheric density modeling and its impact on low-earth orbit satellites. It was reported in the work that atmospheric drag is highly variable due to space weather conditions, particularly solar flux and geomagnetic storms.

### CONCLUSION

This work was carried out to examine the space environment as well as assess its impacts on satellites in space or orbit. The research was carried out using the review and explanatory

research methods. The space environment is a region associated with various features such as extreme thermal gradients from direct solar exposure to deep-space cold and intense ionizing radiation from solar particle events and galactic cosmic rays, the result revealed. The result also showed that some impacts of the space environment on the satellites are atmospheric drag, extreme thermal cycling, atomic oxygen erosion, surface charging and electrostatic discharge, single event effects, and total ionizing dose. It can be concluded from these results that the space environment has numerous impacts on satellites, and these impacts pose serious challenges to the operation or performance of the satellite.

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