Satellite Anomalies and Their Causes

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Abstract: This paper presents a comprehensive analysis of satellite anomalies and their underlying causes. It examines the influence of the space environment—including coronal mass ejections, high-speed solar winds, solar proton events, cosmic rays, and energetic particles in radiation belts—on satellite operations across different orbits (LEO, MEO, GEO). Emphasis is placed on mechanisms such as single event upsets, deep-dielectric charging, and surface charging, which can disrupt onboard electronics and lead to significant operational anomalies. The study utilizes statistical data from extensive databases and discusses advanced models and technologies for space weather forecasting and monitoring. Based on these findings, risk mitigation strategies are proposed, including the implementation of shielding, grounding, redundant systems, and radiation-hardened components. The paper highlights the need for a multidisciplinary approach to enhance satellite resilience in the dynamic space environment.

Key words: space weather, satellite anomalies

1. Introduction

Satellites have become indispensable tools for global communications, navigation, weather forecasting, and scientific research. Despite their sophisticated design, these platforms are not immune to operational anomalies—unexpected malfunctions or performance degradations that can jeopardize entire missions. To develop effective risk mitigation strategies and enhance the resilience of satellite systems, it is essential to understand the underlying causes of these anomalies.

One of the dominant drivers behind satellite anomalies is the space environment, primarily governed by solar activity. Coronal Mass Ejections (CMEs) are massive expulsions of plasma and magnetic fields from the Sun's corona, capable of triggering severe geomagnetic storms. These storms can disturb satellite orbits, degrade onboard instruments, and even induce electrical currents that disrupt critical electronic circuits. For example, NASA Earth science teams have documented cases where CME-induced storms compromised data transmission and sensor performance (It's Always Sunny… Space That's Problem Satellite Teams, n.d.; Spaceclimate.bas.bg, n.d.).

Similarly, High-Speed Solar Winds (HSS), originating from coronal holes, also have a significant impact on satellite operations. Although these winds are generally less intense than CMEs, they disturb the Earth's magnetosphere and can trigger substorm processes that upset the electrical equilibrium on satellite components by accumulating charge, thereby increasing the risk of undesired electrical discharges (Kunches, Poppe, and Tegnel, n.d.).

During Solar Proton Events (SPEs), brief bursts of high-energy protons penetrate through the protective shielding of a satellite, leading to both surface and internal charging. Such events can trigger electrical discharges that damage sensitive electronics, as observed, for example, on GOES-13 where sensor malfunctions were directly linked to SPEs (Wang et al., 2022).

In addition to these solar phenomena, cosmic rays—high-energy particles originating from outside the solar system—can induce anomalies by ionizing electronic components. This ionization often results in Single Event Upsets (SEU), where a single bit in a memory cell flips, potentially causing erroneous commands or even a complete system restart. The Hubble Space Telescope, for instance, routinely experiences SEUs, necessitating constant corrective actions from ground control.

Another significant factor is the influence of trapped energetic particles. These particles—such as protons and heavier nuclei with energies ranging from tens to hundreds of MeV—are concentrated in Earth's inner radiation belt (approximately two Earth radii from the planet). Satellites passing through this region are particularly vulnerable, as prolonged exposure to these charged particles can lead to cumulative radiation damage and trigger SEU (Iucci, N., et al., 2005)

2. Distinguishing Impacts on Satellites in Different Orbits

2.1. Low Earth Orbit (LEO) Satellites

Satellites positioned in Low Earth Orbit (approximately 160 km to 2000 km above the Earth's surface) are especially sensitive to space weather effects due to their proximity to the atmosphere and the Earth's radiation belts. For example, the Hubble Space Telescope frequently encounters high-energy cosmic rays and trapped ions, leading to Single Event Upsets (SEU) and cumulative radiation damage. In addition, geomagnetic storms triggered by CMEs and HSS can cause atmospheric expansion, resulting in increased drag that accelerates orbital decay and creates operational anomalies. Simultaneously, different orbital inclinations affect the degree of exposure to geomagnetic activity and charged particle fluxes (Shen, H.W., et al. 2021)

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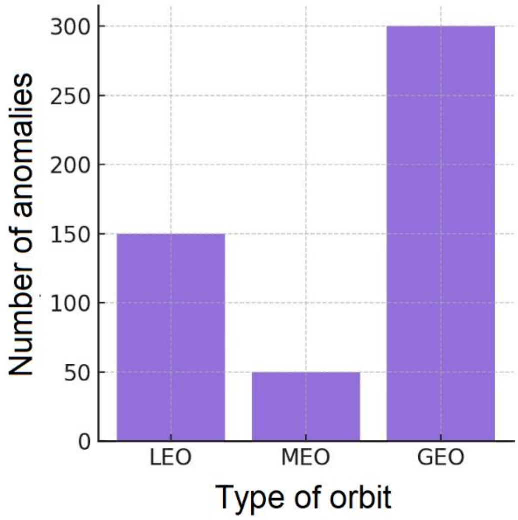

Figure 1. Distribution of recorded satellite anomalies by orbit type (LEO—Low Earth Orbit; MEO—Medium Earth Orbit; GEO—Geostationary Orbit), summarizing data from 1971 to 1994. The NOAA/Iucci database demonstrates the highest anomaly occurrence in GEO satellites. Geostationary spacecraft experience intense particle fluxes from Earth's magnetosphere (particularly during geomagnetic storms), leading to a dominance of charging effects and internal damage in this orbit. MEO (navigation) and LEO satellites report fewer anomalies, primarily influenced by cosmic rays and protons (see text).

Data sources: NOAA NGDC; Iucci et al. (2005)

2.2. Medium Earth Orbit (MEO) Satellites

Satellites in Medium Earth Orbit (from 2000 km to 36,000 km above Earth) play a crucial role in global navigation systems, such as GPS. These satellites traverse regions with high concentrations of energetic charged particles, especially within the Earth's radiation belts, which increases the risk of radiation-induced anomalies such as SEU and long-term component degradation.

2.3. Geostationary Earth Orbit (GEO) Satellites

Satellites located in Geostationary Orbit (approximately 35,786 km above Earth) maintain a fixed position relative to the planet's surface and are essential for communication and weather monitoring. Although they experience minimal atmospheric drag, they are vulnerable to Solar Proton Events (SPE) and intense solar radiation. Prolonged exposure to high-energy particles, particularly during periods of heightened solar activity, can lead to cumulative damage in their electronic systems.

2.4. Orbital Inclination Considerations

For satellites in low Earth orbit, the orbital inclination plays a pivotal role in determining the nature and severity of space weather impacts. For example, satellites in polar orbits—those that pass over the poles—are more strongly exposed to auroral phenomena and intense particle fluxes, increasing the likelihood of operational anomalies. Conversely, satellites in equatorial orbits may encounter different dynamics in their interactions with Earth's magnetic field, leading to a variety of operational challenges (Zheng, Y. 2014)

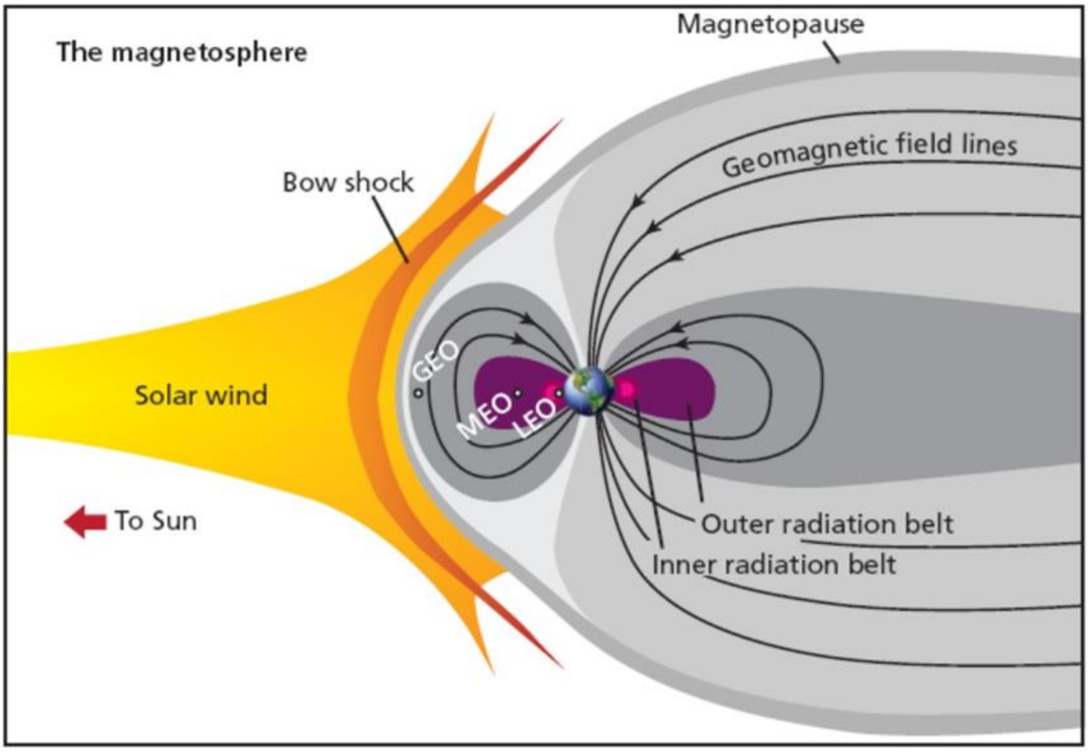

Figure 2. Schematic of the Earth's magnetosphere, with several regions labeled wheresatellite anomalies often occur, including the Van Allen Radiation Belts (Inner andOuter), and typical satellite orbits (GEO, MEO, and LEO). Courtesy of RAND Corporation, www.RAND.org

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3. Space Environmental Effects and Their Consequences on Satellite Systems

3.1. Single Event Upsets (SEU)

Definition:

SEUs occur when a high-energy particle—such as a cosmic ray or solar energetic proton—strikes a sensitive area within a satellite's electronics (e.g., microprocessors or memory cells). This impact can cause a bit flip, changing its value from 0 to 1 or vice versa.

Impact on Systems:

SEUs can disrupt onboard computers, leading to erroneous commands being sent to subsystems, corruption of telemetry data, or even spontaneous resets of critical systems. This issue is especially severe for satellites in Low Earth Orbit (LEO) and Geostationary Orbit (GEO), where exposure to cosmic rays and solar particles is significant (Misfeldt, M., et al. 2023)

3.2. Deep-Dielectric Charging

Definition:

Deep-dielectric charging occurs when high-energy electrons penetrate the surface of satellite materials and become trapped within dielectric layers—such as insulation or printed circuit boards. Over time, the accumulated charge can reach critical levels, eventually leading to a sudden and often catastrophic discharge.

Impact on Systems:

When the stored charge is abruptly released, it can cause severe internal damage to the satellite's electronics, including failures in power systems, sensors, and communication equipment. This effect is particularly hazardous for satellites that spend extended periods in regions with intense energetic particle exposure, such as the inner radiation belts (Lam, H.-L., et al. 2012).

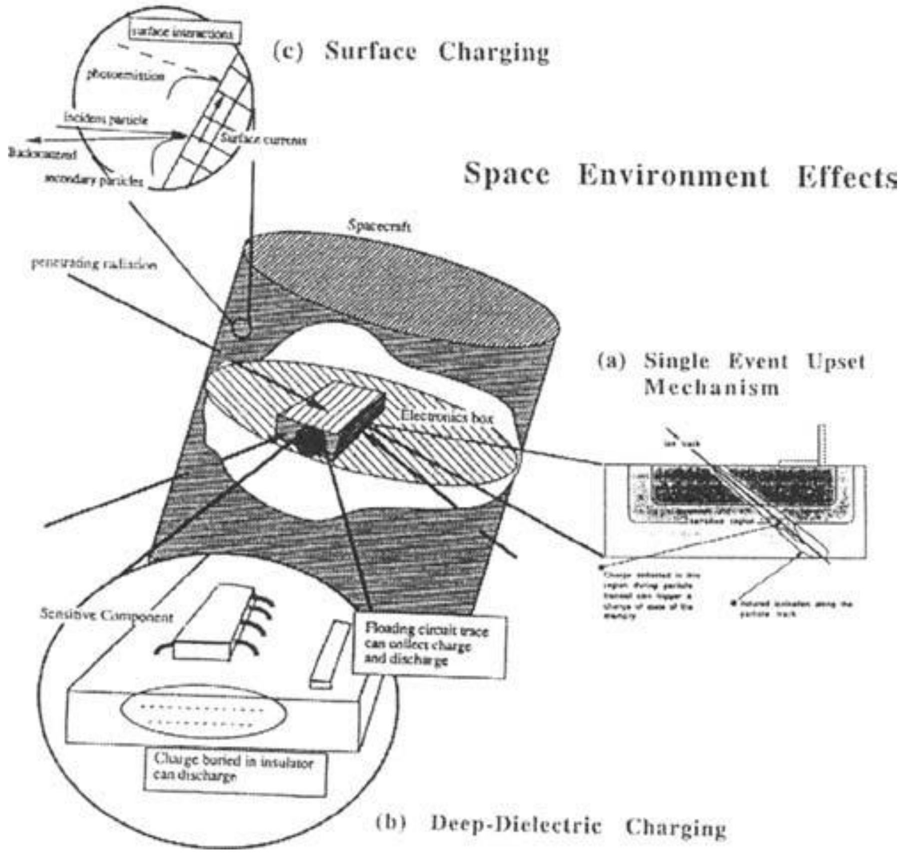

Figure 3. A schematic diagram illustrating space environmental effects due to (a) single event upsets, (b) deep-dielectric charging, and (c) surface charging, adapted from Robinson (Robinson, P.A., 1989), (NASA Handbook 4002B. 2022)

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3.3. Surface Charging

Definition: Surface charging refers to the accumulation of electrical charge on the external surfaces of a satellite due to interactions with the surrounding space environment, such as charged particles encountered in the Earth's magnetosphere.

3.3.1. Absolute Surface Charging:

This occurs when the entire satellite accumulates a uniform electrical charge. If the satellite transitions into a different plasma environment or if there is a sudden change in space weather conditions, a rapid discharge can occur.

Differential Surface Charging: This happens when different parts of the satellite acquire different levels of charge, creating strong electric fields between these areas. Such differences can trigger discharges that damage sensitive components.

Effects on Equipment: Surface charging can lead to several types of discharges, including:

3.4. Flashover (Discharge Between Surfaces):

Definition: A discharge that occurs between two regions with significant differences in accumulated charge, caused by differential surface charging.

Effects on Equipment: This discharge can damage external sensors, solar panels, or communication antennas, resulting in partial or complete loss of functionality.

3.5. Punch-Through (Internal Discharge):

Definition: A discharge occurring between the internal electronics and the external surface, usually as a result of deep-dielectric charging.

Effects on Equipment: This type of discharge can cause catastrophic internal damage, leading to irreversible harm to critical subsystems such as power distribution units or onboard computers.

3.6. Discharge to Space (Surface-to-Plasma Discharge):

Definition: Occurs when the charged satellite surface discharges its electrical charge directly into the surrounding plasma environment.

Effects on Equipment: The resulting surge can disrupt communication links, interfere with onboard electronics, and in extreme cases, lead to a complete operational loss of the satellite.

Referenced examples include studies from Galaxy 15 (Galaxy 15, n.d.), the NASA Handbook (NASA Handbook 4002B, 2022), and discussions on radiation-hardened technologies (Radiation hardening, n.d.).

4. Data

The investigation of satellite anomalies induced by the space environment is of critical importance, especially as our dependence on satellite technologies continues to grow. In today's interconnected world, satellites underpin global communications, navigation, weather forecasting, and scientific research. However, these highly sophisticated systems are not immune to disturbances—unexpected malfunctions and performance degradations that can have profound consequences on mission success. Therefore, a detailed understanding of the relationship between space weather phenomena and satellite performance is essential for developing reliable predictive models and effective mitigation strategies.

Several extensive databases and research studies have been established to provide valuable insights into this relationship. One of the most prominent databases is maintained jointly by the National Oceanic and Atmospheric Administration's National Geophysical Data Centre and the National Aeronautics and Space Administration's Goddard Space Flight Centre. This database compiles extensive historical data on satellite anomalies associated with space weather and serves as a vital resource for researchers and engineers, allowing trend analysis and the development of predictive models for satellite performance under adverse conditions (Пилипенко, В. А., et al. 2006)

Furthermore, the European Space Agency has initiated the Space Situational Awareness program, which includes a dedicated segment focused on the space environment. This program provides real-time information and forecasts on conditions affecting satellite operations, thereby enhancing the overall safety and reliability of satellite missions (Yağlıoğlu, B. 2012).

Research indicates that various space weather phenomena—such as solar flares and geomagnetic storms—can cause significant satellite anomalies. For example, one study found that during a major storm in 2003, a total of 47 satellites experienced operational anomalies, with some rendered inoperative for extended periods. Additionally, the sensitivity of satellites to the space environment is not static—evidence from the Anik E2 satellite shows a reduction in adverse space weather effects after prolonged exposure, indicating that both satellite design and operational history influence vulnerability (Welling, D. T. 2010).

Other studies have demonstrated a significant correlation between space weather and satellite anomalies. Analyses of satellites in geostationary orbit reveal a clear relationship between geomagnetic activity and the frequency of anomalies, suggesting that continuous monitoring of space weather indices can improve prediction and mitigation. Likewise, further research emphasizes the importance of statistical analyses of space weather data and satellite anomaly records to gain a better understanding of how the space environment impacts satellite systems (Choi et al., 2011; Lohmeyer and Cahoy, 2013).

The need for robust forecasting models is underscored by the increasing risks to satellite operations. A recent study highlighted the importance of accurate modeling of space weather effects on satellites, especially given the rising number of satellite launches and the associated increased risk of space weather disruptions (Dang et al., 2022). Additionally, a risk assessment framework has been proposed to quantify the socioeconomic impacts of space weather on critical infrastructure, including satellite communications, as a means to enhance

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preparedness and response strategies (Oughton et al., 2018).

Moreover, additional databases focusing on satellite anomalies caused by the space environment exist. Notably, the database compiled by Iucci and colleagues includes an extensive collection of anomalies recorded from 220 satellites operating in various orbits from 1971 to 1994. This database incorporates anomalies from Russian Kosmos satellites and integrates both daily and hourly space weather parameters, making it an indispensable resource for researchers studying the correlation between space weather and satellite anomalies.

Furthermore, the Geostationary Operational Environmental Satellites (GOES) series, particularly GOES-13, has been extensively analyzed for its role in monitoring the space environment and its consequent effects on satellite operations. The GOES satellites are equipped with instruments that measure solar proton fluxes and magnetospheric conditions, thereby providing real-time data that can be directly correlated with satellite anomalies (Kress et al., 2021). The intercalibration of solar proton detectors across the GOES series has been documented to enhance the reliability of the data used in anomaly analysis (Rodriguez et al., 2014). Additionally, the development of detailed models for electron fluxes at geostationary orbit, as described by Boynton Boynton et al. (2020), provides satellite operators with situational awareness critical for mitigating the adverse effects of space weather on satellite systems.

The statistical properties of the surface-charging environment at geosynchronous orbit have also been rigorously analyzed by Thomsen and his collaborators. Their work demonstrates that the charging environment can significantly affect satellite performance, underscoring the importance of understanding the mechanisms leading to charging-related anomalies.

5. Detailed Review of Satellite Anomalies and the Impact of the Space Environment

5.1. Satellite Anomalies and the Influence of the Space Environment:

Satellite anomalies can occur due to adverse conditions in the space environment that affect satellite functionality. One of the most notable incidents is the loss of 38 out of 49 Starlink satellites in February 2022. This event was attributed to increased neutral density in the thermosphere caused by a series of moderate geomagnetic storms. The enhanced density results in increased atmospheric drag, which alters satellite orbits and leads to operational problems or even complete loss of the satellite system (Fang et al., 2022; Hapgood, Liu, and Lugaz, 2022; Parker et al., 2024).

5.2. New Models and Technologies for Forecasting and Monitoring:

To address the risks associated with anomalies and improve operational safety, new space weather forecasting models are being developed. For example, the Multiscale Atmosphere-Geospace Environment (MAGE) model provides detailed data on neutral density variations during geomagnetic storms, allowing for better risk prediction for satellites. Modern satellites, such as FY-3E, are equipped with advanced plasma analysis instruments that enable continuous monitoring of the space environment and rapid operational corrections to minimize losses (Fang et al., 2022).Additionally, the integration of artificial intelligence and machine learning algorithms for historical data analysis aids in identifying recurring patterns and improving forecast accuracy.

5.3. The Influence of Solar Activity:

Solar activity, measured by sunspot numbers and the intensity of solar proton events, is a key factor in the occurrence of satellite anomalies. During periods of high solar maximum, intense fluxes of solar particles can cause radiation damage to satellite electronics (Nwankwo, Jibiri, and Kio, 2020). Conversely, some studies indicate that ionospheric anomalies at night may be more pronounced during periods of low solar activity, underscoring the complex relationship between solar activity and satellite performance. Forecasting models that incorporate sunspot variations also contribute to predicting flare events associated with sudden increases in radiation flux (McCloskey, Gallagher, and Bloomfield, 2018).

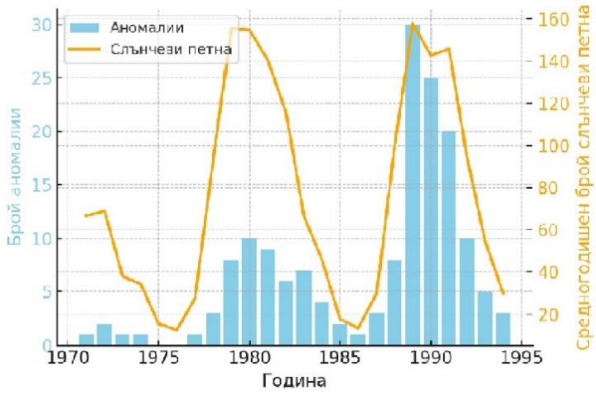

Figure 4: Number of reported satellite anomalies per year (blue bars) compared with the annual average sunspot number (orange line) during 1971–1994. The anomaly data are compiled from the public database of NOAA NGDC (up to 1993) and complemented by the dataset from Iucci et al. (2005) covering anomalies in 220 satellites. The general trend shows an increased number of anomalies during periods of high solar activity (e.g., around the 1990 peak—solar cycle 22 maximum), although certain satellites may exhibit the opposite behavior depending on their dominant physical mechanism

Data sources: NOAA NGDC;

5.4. Geomagnetic Activity and Its Effects:

Geomagnetic storms—triggered by the interaction between the solar wind and Earth's magnetic field—directly impact satellite systems. These storms can cause significant disturbances in the ionosphere, such as changes in Total Electron Content (TEC), which degrade the accuracy of global navigation systems and may even result in physical anomalies in satellites (Wang et al., 2023). Research shows that different types of geomagnetic storms—whether induced by CMEs or high-speed solar winds—have specific effects on the thermosphere, necessitating tailored operational strategies for each type (Panpiboon et al., 2023; He et al., 2023; Nagatsuma et al., 2021).

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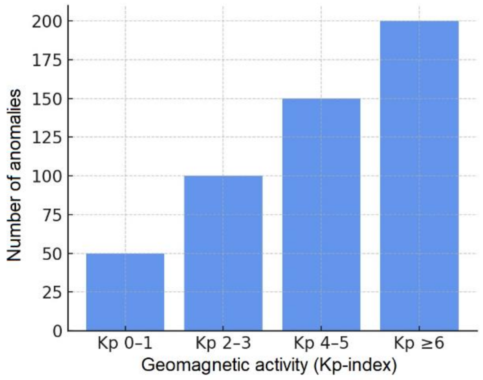

Figure 5: Frequency of satellite anomalies as a function of geomagnetic activity. The chart shows the total number of anomalies recorded during days characterized by different levels of the geomagnetic Kp index (from quiet conditions Kp=0–1 to strong geomagnetic storms Kp≥6). Clearly, anomaly occurrences increase significantly during enhanced geomagnetic activity—a result consistent with previous statistical studies [35]

Data sources: NOAA NGDC anomaly data (1971–1994), Kp index from NOAA/GFZ.

5.5. The Role of Orbital Characteristics:

The operational parameters of a satellite's orbit—such as altitude, inclination, and shape—are critical in assessing the risk of anomalies. Solar Radiation Pressure (SRP) can gradually alter orbital elements including the semi-major axis, eccentricity, and inclination, which requires regular corrective maneuvers. Satellites in low Earth orbit are particularly vulnerable to atmospheric drag that increases during geomagnetic storms, while geostationary satellites may need specific maneuvers to maintain their precise positions. Moreover, the choice of electric propulsion systems and the materials used in satellite construction play an important role in determining a satellite's resilience under adverse space conditions (Dorman et al., 2005; Pratiwi et al., 2024).

5.6. The Impact of Local Time on Satellite Anomalies:

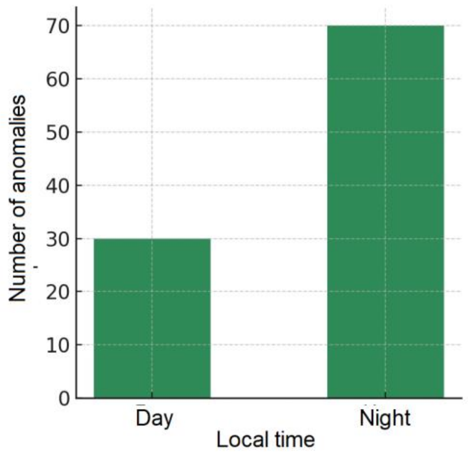

Figure 6: Proportion of anomalies according to local orbital time (day vs. night). Significantly more anomalies occur during orbital night (in Earth's shadow). This finding aligns with satellite operators' observations of increased surface charging events from local midnight to dawn, as the absence of sunlight prevents dissipation of accumulated electrostatic charge.

Data sources: ESA SSA reports

Local time plays a critical role in the frequency and nature of satellite anomalies, as atmospheric and ionospheric conditions vary significantly between day and night.

5.6.1. Geostationary Satellites (GEO):

Studies by Saleh et al. (2017) indicate that anomalies in geostationary satellites are strongly linked to local time. The anomalies are unevenly distributed throughout the day, suggesting that variations in geomagnetic activity lead to the injection of electron populations with distinct seasonal and temporal characteristics.

5.6.2. Low Earth Orbit Satellites (LEO):

According to Ahmad et al. (2018) approximately 65% of anomalies in low Earth orbit satellites occur during the night—from dusk until dawn. This is attributed to increased levels of low-energy electrons and enhanced magnetic disturbances during nighttime, which can overload the satellite electronics and communication systems, leading to a higher frequency of anomalies.

5.6.3. Influence of Solar Activity:

Research by Iucci et al. (2005) shows that satellites exposed to high-energy solar protons can experience up to a 20-fold increase in anomaly frequency at certain times of day, highlighting the importance of local time as a critical paramete in anomaly analysis and forecasting.

5.6.4. Differences Based on Orbital Altitude:

The study by Dorman et al. (2005) demonstrates that satellites operating at different altitudes exhibit varied responses to the space environment, emphasizing the need to consider both orbital parameters and local time when modeling the risk of anomalies.

6. Discussion on Observed Dependencies

Research demonstrates that the relationship between solar activity and satellite anomaly rates is not straightforward—some satellites experience an increase in anomalies during periods of low solar activity, while others are more affected during periods of high solar activity. This difference occurs because distinct space environment factors dominate during different phases of solar cycles.

During periods of solar minimum, the intensity of galactic cosmic rays (GCR) significantly increases, leading to greater particle penetration into near-Earth space. Consequently, this enhances the frequency of Single Event Upsets (SEUs) in onboard electronics, especially noticeable in satellites with polar orbits in Low Earth Orbit (LEO). For instance, anomalies observed by the **FORMOSAT-3** constellation (700–800 km altitude, 72° inclination) predominantly occurred during periods of low solar and geomagnetic activity when GCR intensity peaked.

Conversely, during solar maximum, intense solar proton events (SPEs) frequently occur, triggering anomalies mainly in higher-altitude satellites. Iucci et al. (2005) reported that, during major proton events, anomaly rates increased approximately 20-fold for navigation satellites in highly inclined Medium Earth Orbits (MEO, >55°) and about fourfold for satellites in

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Geostationary Earth Orbit (GEO). These results explain why navigation systems such as GPS and GLONASS experience the highest failure rates during active phases, whereas other missions may not exhibit such pronounced dependence.

Orbital altitude and inclination are also critical factors influencing vulnerability. Satellites in high, polar orbits (such as GPS) have minimal magnetic protection against particle fluxes and therefore exhibit strong responses to solar eruptions. On the other hand, satellites in lower orbits (LEO) traverse regions such as the South Atlantic Anomaly (a stable belt of trapped protons), which continuously induce SEUs regardless of the solar cycle phase. Specifically, during solar minimum, when additional solar proton events are rare, this inner radiation belt and galactic cosmic rays dominate, leading to increased software resets and failures of sensitive instruments.

Satellites in Geostationary Orbit (~36,000 km, equatorial orbit) experience yet another environment—direct exposure to Earth's outer radiation belt. During geomagnetic storms, plasma density and electrons with energies exceeding 2 MeV rise sharply, causing deep dielectric charging and damage in GEO spacecraft. During intermediate phases of the solar cycle (descending activity), these so-called "killer electrons" become the primary source of anomalies for many GEO satellites, whereas solar protons become less influential. Moreover, surface charging events, predominantly occurring during orbital night (Fig. 4), lead to electrostatic discharges (ESD), damaging satellite interfaces and panels.

In summary, satellites with different orbital parameters and mission types have distinct "risk profiles" regarding space weather impacts. Navigation and military systems in high-inclination MEO orbits are most vulnerable during extreme solar events (SEP), while scientific and communication satellites in lower orbits may experience more anomalies during quieter solar periods, induced by cosmic rays and persistent radiation belts. Understanding these dependencies is essential for mission planning and the development of effective protection strategies, which are discussed in the subsequent section.

Final Observations and the Need for a Multidisciplinary Approach:

Modern research clearly shows that the relationship between the space environment and satellite anomalies is highly complex and multifactorial. From significant incidents such as the Starlink loss in 2022 to the development of innovative forecasting models and monitoring technologies, there is a clear need for an integrated approach that combines physical models, technological innovations, and operational experience. Incorporating local time as a critical parameter allows for more precise analyses that account for both global and local variations in atmospheric and ionospheric conditions affecting satellite operations.

7. Mitigation Strategies

To protect satellites from the adverse effects of the space environment, engineers implement several risk mitigation measures:

7.1. Shielding:

Adding protective layers to sensitive electronic components prevents high-energy particles from penetrating and accumulating in critical systems.

7.2. Grounding and Bonding:

Ensuring robust electrical connectivity among all parts of the satellite minimizes differences in accumlated charge, reducing the risk of electrical discharges. NASA guidelines (NASA-HDBK-4002B) emphasize the importance of these practices.

7.3. Redundant Systems:

Incorporating multiple, independent subsystems guarantees that a failure in one part does not compromise the entire mission, thereby ensuring operational integrity and reliability.

7.4. Use of Radiation-Hardened Components:

Designing electronics using materials and architectures capable of withstanding high levels of radiation is crucial for maintaining functionality under the extreme conditions typical of the space environment.

8. Conclusion

Satellite anomalies arise from the complex interplay between space phenomena—including CMEs, HSS, SPEs, cosmic rays, and trapped energetic ions—and specific charging processes, such as SEU, deep-dielectric charging, and surface charging. By understanding these mechanisms in detail and implementing mitigation measures such as shielding, grounding, redundancy, and the use of radiation-hardened components, we can ensure higher reliability and long-term resilience of satellite systems in the dynamic space environment.

Acknowledgments

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