# Disruptive Effects of Earth's Orbit Environmental Conditions on Spacecraft Electronic Systems

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**Abstract**
The impact of disruptive factors originating from the space environment on spacecraft is highly significant in terms of design, operations, and safety. Factors such as solar wind, ionizing radiation, atomic corrosion, particle collisions, extreme vacuum, low gravity, and temperature changes affect spacecraft. Space agencies and research institutes have been working for years to model these effects. In the context of Fault-Tolerant Control (FTC) in spacecraft, numerous preventive measures are taken against disruptive factors of the space environment, aiming for spacecraft to perform their missions reliably for extended periods in space. This study represents the effects of the space environment in Earth's orbit and the precautions taken against these effects during the development and operation of spacecraft systems.

**Keywords:** Space Environment, Earth Orbit, FDIR, Disruptive Effects, Fault, Failure, FTC

## 1. Introduction

The Earth is surrounded by a dense atmospheric layer consisting of various layers with different properties. While atmospheric pressure and protective effects are most noticeable near or below sea level, these protective effects decrease at higher altitudes. [1], [2] In the literature, although there is no absolute altitude for space transition due to the rarification of the atmosphere, the Kármán line, located at approximately 100 kilometers (62 miles) above sea level, is generally accepted as a defining level for space conditions. [3] As it is approached to the Kármán line the Earth's atmosphere significantly thins out, but the altitudes of satellites in Earth orbit can vary widely, typically ranging from 80 to 36,000 kilometers, depending on the specific mission. [4]

Different orbital positions around Earth are utilized for various purposes such as telecommunications, television broadcasting, Earth observation, remote sensing, positioning, and defense. Depending on the mission payloads onboard, some spacecraft operate in low altitudes even below the Kármán line (<100 kilometers), while deep space exploration systems like interplanetary probes can be positioned millions of kilometers away from the Earth. For instance, although both serve similar purposes, the Hubble Space Telescope operates at an altitude of approximately 547 kilometers (340 miles), whereas the James Webb

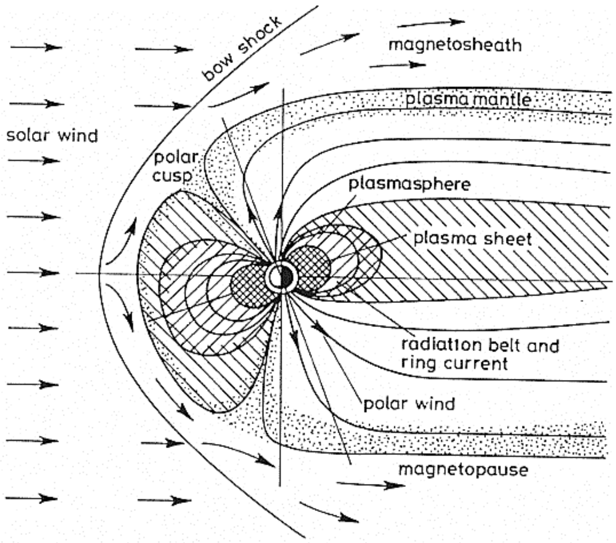
Telescope is positioned in an orbit at an altitude of approximately 1.5 million kilometers (0.93 million miles), serving as an example of this diversity.

While there is no exact boundary for space, space-based engineering methods are used in the design of human-made vehicles from an altitude where atmospheric density decreases and the Thermosphere begins above 80 kilometers. Space systems operate beyond Earth's protective atmospheric layer are exposed to various challenging conditions that can affect their performance, functionality, life time and overall mission success. Some of the major disruptive factors that affect spacecraft systems include:

- Plasma from the Sun directly or the galaxy,
- Electromagnetic radiation and ionizing radiation particles,
- Solar wind characterized by coronal mass ejections based on solar flares,
- Magnetic field interference triggered by the Magnetosphere,
- Surface degradation based on atomic oxygen in the lower regions of the Thermosphere,
- Physical impact effects of meteoroids and debris,
- Temperature fluctuations between radiative solar heat - space darkness and periodic cycles,
- Vacuum conditions,
- Microgravity.

These factors necessitate robust engineering solutions to ensure the reliability and functionality of spacecraft operating in the harsh conditions of space. The various disruptive factors expressed above and visually represented in Figure 1 result in a range of satellite anomalies, including singular event upsets, electrostatic charging and discharging, electromagnetic interactions, surface degradation due to corrosion, outgassing, particle collisions, simultaneous overheating and cooling cycles, and uncertainties in the dynamic behavior of the liquids, gases and moving components on a spacecraft due to microgravity.

Figure 1: Representation of Solar Interaction, Earth's Physical Characteristics, and Atmospheric Factors for Earth Orbit [5]




To model the disruptive factors of space environment, several space research missions have been conducted, led by the European Space Agency (ESA) and the United States National Aeronautics and Space Administration (NASA). These missions include spacecraft dedicated to observing the Sun, such as the Solar and Heliospheric Observatory (SOHO) and Solar Orbiter, the Double Star satellites, as well as various constellations of satellites in Low Earth Orbit (LEO) for continuous sensing of the environment. These satellites enable detailed modeling of the Magnetosphere and as an overall system they can measure coronal mass ejections and the speed of the solar wind hours before they reach Earth. [6] Through measurements and models generated from these missions, it becomes more possible to mitigate many space-based disruptive factors during the development, launch, and operational phases of satellite systems, as well as tolerate potential anomalies that may arise.

## 2. Fault Types and Failure Management

In safety or mission critical space systems, the Fault-Tolerant Control (FTC) approach is employed to prevent the adverse effects of the space environment and failures due to faulty or incomplete design. In space systems with limited serviceability, the Fault Detection, Isolation, and Recovery (FDIR) structure, which fulfills the core functions of FTC, plays critical roles in reducing mission interruption durations, optimizing mission lifetimes, and minimizing operational losses. FDIR, with its multi-layered architecture, also includes essential functional components required to prevent failures and catastrophic disasters in spacecraft systems. [7] In space systems, the concepts of faults and failures, upon which FDIR's core functions are built, can be defined as follows:

*Fault:* A fault is an abnormal condition that disrupts the operation of system functions in a way that can lead to failure. [8] Faults can result in a decrease in the benefits obtained from the relevant functions or intermittent or complete interruption.

*Failure:* Failure refers to the event where one or more normal functions of the system cease to operate due to fault(s), leading to the termination of related operational capability or the operation in a manner that does not produce expected benefits. [9 - 11]

The terminological relationship between faults and failures is closely related, with faults being defined as abnormal root causes that can lead to failures, and failures representing the resultant events caused by these root causes.

The increasing end-user demand from space services, along with the associated technical complexity and commercial expectations for projects, does not allow for an ideal solution from all perspectives. Therefore, especially in the case of commercial space systems, an optimization is shaped by concepts such as fault tolerance, reliability, durability, as well as scheduling and cost. All of these concepts are managed based on factors such as the criticality level of the system, its overall design, technical specifications, fault-generating capacity, and potential sources of faults. The types of faults that can occur in space systems are summarized below.

*Hardware Function Failures (Hard Failures):* Hardware function failures refer to the situation where a sensor or equipment completely ceases to operate in the event of a fault, and the output values either return to zero or the component produces outputs aimed at a passive state, such as high impedance. These failures can also occur due to interface communication issues within the system or power supply problems related to the sensor or equipment. [12]

*Data Deviation Failures (Bias Failures):* Bias failures occur when sensors or equipment exhibit an abnormal constant output after a certain period or when measurement offsets that do not actually exist within the normal measurement range are observed. These erroneous outputs can result from incorrect hardware initialization, operation, or communication problems. In such types of faults, the source component transmits incorrect data to the system.

*Data Drift Failures:* Environmental factors have a significant impact on the operational performance of hardware and sensors. Environmental conditions such as temperature, pressure, humidity, acceleration, energy-charged particles, electrostatic charging can affect the calibration of equipment, leading to temporary drifts in the output data of equipment or sensors. These drifts can vary depending on the duration and intensity of the environmental factors and typically contribute to an increasing measurement fault budget over time.

*Inconsistent Data Faults (Outlier Failures):* In this type of fault, equipment or sensors produce incorrect values in the output data in the form of short spikes or drops. This situation can be attributed not only to equipment faults caused by environmental factors but also to issues related to communication interfaces within systems. [13]

Fault-tolerant systems are designed by anticipating unusual conditions during the development phase and establishing a system capable of dealing with factors related to these conditions. Rather than rendering the entire mission completely non-operational, the goal is to ensure that when any component of the system loses its functionality, the primary function can still be maintained, even if at a reduced level. [14] These methods generally aim for self-stabilization, focusing on bringing the system closer to a fault-controlled state through FTC measures.

## 3. Effects of Environmental Conditions in Earth Orbit

Since the early years of space exploration, numerous spacecraft failures have been documented. These failures have led to various fields of study, including thermal control and radiative heat dissipation, redundant semiconductor integrated circuits, electromagnetic compatibility, radiation shielding, electrostatic discharge, and specialized materials.

In space missions, specially designed space-grade components are used to cope with challenging conditions such as the vacuum environment, thermal cycles, and most importantly, radiation effects. However, due to the reasons mentioned above, in order to minimize costs and production time, the use of standard commercial-off-the-shelf (COTS) or military-grade materials is also considered a practical approach in space systems. [15] Nevertheless, materials of this kind are not produced for operation in space environments and can lead to significant faults under space conditions. Therefore, if they need to be used, non-space-grade materials should be chosen based on the environmental conditions in which the system operates. The selection balance is expected to be determined by the heritage gained from many systems that have experienced mission success or even failures in the past. This section provides specific clarification regarding Earth orbit’s environmental conditions.

**3.1.High-Energy Gas Molecules**

The Thermosphere is the outermost layer of the Earth's atmosphere. It primarily consists of neutral gas particles and exhibits stratification based on the molecular weights of gases. In the lower regions of the Thermosphere, the most common gas component is oxygen, while in the higher regions, helium and hydrogen molecules, which have higher velocities but lower specific weights compared to oxygen, are predominantly present. [16]

Due to the absorption of high-energy solar radiation, the temperature in the Thermosphere can reach thousands of degrees. In this region, the direct ultraviolet energy from the Sun, combined with the increased exospheric temperature, enhances the kinetic energies of gas molecules. Under high energy and low pressure conditions, gas molecules can gain enough energy to overcome the gravitational forces between their own atoms. This phenomenon occurs primarily in the upper regions of the Thermosphere (>400 kilometers) and leads to the dissociation of oxygen molecules ($O_2$) into individual oxygen atoms (O). Oxygen atoms in their monatomic state are highly reactive and can contribute to the formation of oxide compounds in spacecraft through various chemical reactions. [17]

In particular, spacecraft in the Thermosphere are subjected to chemical and physical reactions supported by high collision energies ranging from 4 to 5 eV due to the high speed difference between the spacecraft and atomic oxygen in the environment. These reactions result in surface degradation, erosion, and material contamination in spacecraft over time. [18] Due to this situation, it is essential to take certain critical measures against atomic oxygen, especially in spacecraft that are in Low Earth Orbit for extended periods, such as long life satellites, the International Space Station or Space Shuttle. One of the primary measures is the selection of materials resistant to atomic oxygen erosion and oxidation, especially on the outer surfaces of the spacecraft. Specific films and paints used for protection can create protective oxide layers that make the spacecraft's surface relatively cooler and more oxidation-resistant. Additionally, the oxidation resistance of systems can be increased by using materials such as aluminum, stainless steel if necessary, and polymers or composites that have been strengthened through specific processes on the outer surfaces. [19] Additionally, when positioning active units, it would be certainly preferred to refrain from placing electronic components outside of the multi-layer thermal blankets or the structural envelope and to avoid incorporating design features that might enhance erosion, such as sharp edges or corners in the satellite's geometry.

**3.2.Factors Related to Solar Energy**

Satellites, in their orbital cycles around Earth or other planets, often find themselves in the shadow of these celestial objects. This situation occurs cyclically, creating a thermal cycle characterized by direct solar energy radiation, as well as deep space cooling due to low-energy radiation in the absence of direct sunlight.

In space, heat originates from the Sun's radiation, the reflection of sunlight from celestial bodies like Earth, and the heat radiated by Earth itself. These three heat sources are reported as the fundamental heat sources that sustain satellites in Low Earth Orbit [20], [21]. However, spacecraft themselves have components that generate heat. The thermal cycle resulting from all these environmental and internal conditions leads to challenging issues for satellites. These issues include thermo-elastic instability, application limitations due to exceeding the working temperature ranges of electronic components, thermal stress, material fatigue, and fatigue, electrical effects (changes in resistance, capacitance, and other electrical properties), and sealing faults.

To achieve thermal stabilization for the components of the system, various efforts are made to either cool down or heat sensitive electronic units. The outer surfaces of the satellite front-end are covered with multi-layer insulation blankets, radiator surfaces, and heat pipes are used to facilitate heat transfer between hot and cold regions and heat dissipation surfaces. When planning the thermal control stability of the system, internal and external thermal loads affecting the spacecraft, the operating temperatures of sensitive components, and the storage conditions of satellite liquids and gases are taken into account.

Surfaces that are exposed to the Sun directly for extended periods can reach high temperatures depending on their geometry and material properties. In Figure 2, the color changes and blistering effects that occurred on a sample KRS-5 coating due to continuous ultraviolet radiation from the Sun during NASA's Long Duration Exposure Facility (LDEF) tests are shown.

Figure 2.a. Pre-flight coated KRS-5 sample [20]

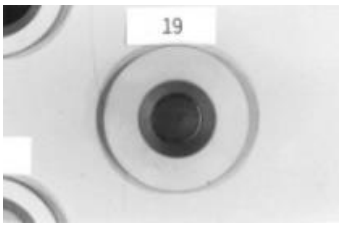



Figure 2.b. Thermal fatigue observed in post-flight coated KRS-5 sample [20]

Studies have reported that over the entire orbital cycle, the thermal loads on the spacecraft's surface increase approximately linearly over time, with seasonal variations depending on the angle formed by the spacecraft's orbital plane with the sunrays and the orientation of the spacecraft's surface [22].

### 3.3.Effects of High-Energetic Particles

In Earth's orbits, there are high-energy particles arriving from the Sun and deep space, as well as proton charges influenced by Earth's magnetic field. These individual particles directly impact spacecraft systems, altering recorded data or causing permanent damage to data storage electronics.

Particles associated with ionizing radiation can be grouped according to their sources, including protons, electrons, and heavy ions found predominantly in Earth's Van Allen radiation belts, cosmic neutrons and gamma rays, and solar flare particles containing protons and heavy ions. Solar flares, which occur on the Sun, can emit ionized gas, or plasma, from the solar corona towards Earth and deep space. During such X-ray radiation events from the Sun, the atmosphere becomes ionized, transforming into an electron-rich environment known as the ionosphere. This situation can majorly disrupt telecommand and telemetry radio frequency communications of the spacecraft systems. In a similar solar storm event in 1991, significant disturbances were recorded in the solar panels of the GOES-6 and 7 satellites. This storm led to a reduction in the operational life of the GOES-7 satellite by up to three years. During the same period, the frequency of Single Event Effects (SEE) recorded by other spacecraft systems in Low Earth Orbit also increased. [16] Various types of Single Event Effects (SEE) that can occur in space are listed below.

### 3.3.1. Plasma-Related Electrostatic Charging

Differences in electrical potential between the spacecraft's surface and the surrounding plasma in space can lead to the spacecraft becoming electrostatically charged. Due to the potential of the external plasma environment to cause rapid dissipation of this charge, sudden discharges of electrical energy can lead to various electrical malfunctions in the spacecraft's electronic equipment. These issues can include false switching activities in electronic equipment, amplifier gain failures, and various other electrical faults.

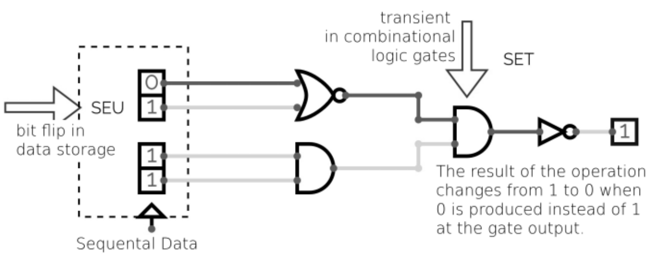
To prevent electrostatic discharges, equipment that can handle charge dissipation should be identified, and measures should be taken to prevent physical damage to electronic systems in the event of an electrostatic discharge. For this purpose, spacecraft often employ grounding methods based on Faraday cages, which are designed with multiple connections, balanced configurations, and current loops. In cases where discharges still occur, Single Event Effects (SEE) can be mitigated by using reliable hardware and software control systems at the lower levels ($0^{th}$ and $1^{st}$ layers) of the Fault Detection, Isolation, and Recovery (FDIR) system.

### 3.3.2.Single Event Effects Due to Freely Moving High-Energy Particles

High-energy particles have the capability to penetrate both the external and internal shields of a spacecraft, and they can collide with the switching mechanisms in semiconductor devices. Such events can lead to temporary or permanent malfunctions in the areas of stored data. SEE (Single Event Effects) is a broad term that encompasses any abnormality or disruption in electronic equipment or systems caused by an energetic particle collision. These abnormalities include Single Event Upsets (SEU) and Single Event Latchup (SEL), among other effects.

*Single Event Upsets (SEU/SET):* SEU refers to the phenomenon where a charged particle collision in a spacecraft causes a memory cell's value to flip to its opposite state. This can result in changes to stored data in digital systems, corruption of running source codes, and disruptions in critical components of mission computers (temporary memories, critical data tables, etc.), leading to temporary malfunctions in spacecraft software. The best-known effects for non-destructive events are Single Event Upsets (SEU) and Single Event Transients (SET). SEU term is specifically classified for sequential data events, while SET refers to single-event effects occurring in combinational operations. In Figure 3, an SEU causing a bit flip in data storage and an example of a SET transient occurring in combinational logic gates, resulting in transient pulses and incorrect evaluations at the component's output are illustrated. [23]

Figure 3. Representation of a Single Event Effect (SEU/SET) on an Example Circuit [24], [25]



*Single Event Latchup or Burnout (SEL/SEB):* SEL and SEB are types of SEEs that can cause erroneous triggering of power switching structures like thyristors or MOSFETs used in spacecraft electronics. SEL leads to permanent parasitic effects in power systems, while SEB can result in a short circuit. In the case of SEB, drivers can become conductive unintentionally, causing permanent damage due to the flow of excessive current. Examples of single-event effects are summarized in Table 1.

Table 1. Examples of Possible Single Event Effects (SEE) in Spacecraft Systems [26], [27]

| **Types of Single Event Effects (SEE)** | **Fault Example** | **Affected Component Examples** |
|---|---|---|
| Single Event Upset (SEU) | Temporary corruption of data stored in memory | Microprocessors, semiconductor memories, and high-power transistor components |
| Multiple Event Upset (MEU) | Inaccessibility of many bits associated with a single-bit change (SEU) in memory | Microprocessors, semiconductor memories, and high-power transistor components |
| Single Event Functional Interrupt | Temporary operational disruptions at the component level | Complex devices with internal state control groups |
| Single Event Transient | Transient glitches | Analog and digital circuits, photonics |
| Single Event Latchup (SEL) | High current-induced single event conditions | Semiconductor metal-oxide technology products (MOS), complementary CMOS circuits |
| Single Event Burnout (SEB) | High current-induced permanent single event conditions | Bipolar junction transistors (BJT), Metal-Oxide-Semiconductor Field-Effect Power Transistors (MOS) |
| Single Hard Fault | Stuck/frozen bits, permanent faults | Logic memory units |
| Single Event Gate Rupture | Permanent faults in systems that polarize when electrical current is applied | Metal-Oxide-Semiconductor Field-Effect Power Transistors (High-Field MOS) and/or programmable memory units |

To protect electronic components' functionality in spacecraft systems, stacked transistor approaches based on internal redundancy or inhibiting current transitions, such as RC delay and DICE latch are being applied. However, while these approaches, as illustrated in the application examples below [28], enhance the circuits' SEE resilience, they may lead to speed reduction in the example in Figure 4.a and require a larger integrated area in Figures 4.b and 4.c.

Figure 4.a. RC Time Delay [28]

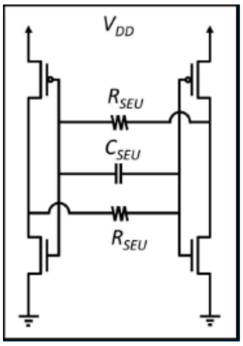



Figure 4.b. Stacked Transistor [28]

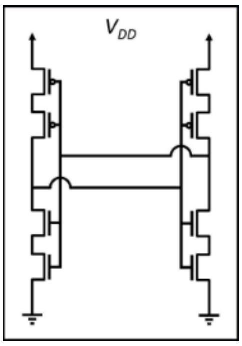
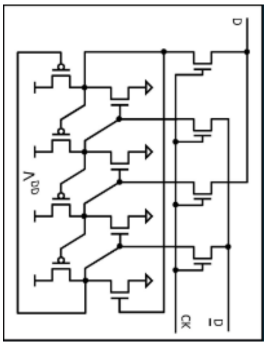



Figure 4.c. DICE Latch [28]



Credit: Sandia National Laboratories

The production of integrated circuits for space applications involves methods such as reducing the dimensions of components using tools like "plated wire," triple redundancy, and the use of fault detection and correction methods with auxiliary bits.

While efforts are made to reduce the effects of single-event incidents through the selection of radiation-resistant materials, especially during the relatively long missions of spacecraft like communication satellites, high-energy particles accumulate over time and can lead to widespread performance degradation in electronic components. Over time, degradation mechanisms can become significant and result in increased failure rates, rendering redundancy ineffective.

Two parameters that determine the mission life of a spacecraft are the Total Ionizing Dose (TID), which represents the accumulated particle charges trapped in device components, and the Displacement Damage Dose (DDD), which indexes the damage affected to semiconductors. Today, electronic material selection is tailored to the mission orbit characteristics, new materials undergo verification tests following MIL, ESA, and NASA standards, and electrical shielding is implemented at the system, equipment, and electronic component levels, especially for sensitive components on the spacecraft.

### 3.3.3.Effects Related to Plasma and Magnetic Fields

In the Thermosphere, atoms charged with energy ionize by shedding electrons from their outer orbits. Consequently, the Thermosphere provides a rich environment in positively charged ions and free electrons [29]. While electron densities are approximately equal everywhere in the ionosphere, ion and electron densities can vary significantly with altitude, latitude, magnetic field strength, and solar activity [5]. These variations can lead to the generation of electromagnetic and electrostatic charges on spacecraft. As a spacecraft passes through the ionized region of the Thermosphere, it may be exposed to uneven flows of ions and electrons. Plasma flow on the spacecraft's surface can charge specific surfaces, affecting electrically polarized components within the system, such as solar panels.

LEO spacecraft passing through plasma are known to experience voltage levels in the thousands of volts; however, charging in GEO can often reach even higher levels. The choice of grounding configuration is determined by the magnitude of the charging. Polar charging in spacecraft can lead to sensor reading offsets, potential arcing that could cause malfunctions in sensitive electronic circuits, accumulation of residual currents, and material erosion. High-amplitude charging can trigger uncontrolled arcing within the spacecraft, leading to permanent electrical faults. For instance, the Intelsat K Satellite in GEO orbit experienced an electrostatic discharge due to a geomagnetic storm that began in January 1994, causing a failure in reaction wheel control circuit. As a result, the satellite experienced performance issues during orientation maneuvers, as well as fluctuations in antenna alignment. In 1985, the GPS 5118 Satellite also encountered unexpected switching events in its motor driver circuits due to electrostatic discharge [16].

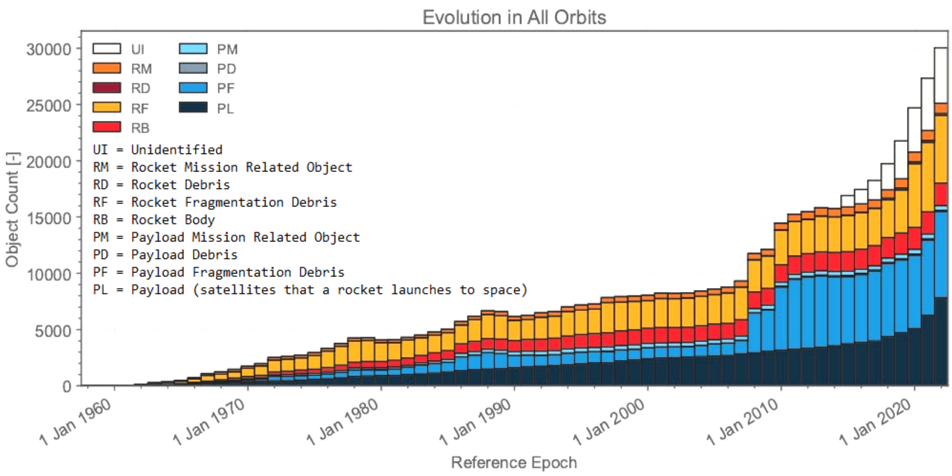
Today, spacecraft systems employ various measures to mitigate the impact of electromagnetic phenomena. These measures include but not limited to encapsulating (shielding) electronic units within grounded structures, utilizing specialized filters and twisted pair cables, shielding cable harnesses, and implementing suitable grounding methods at the system level in accordance with load characteristics.

### 3.3.4.Micro-Meteoroid and Space Debris Collisions

All spacecraft are susceptible to significant damage from physical collisions with micro-sized meteoroids and orbital debris fragments. These collisions occur at extremely high velocities and can potentially harm critical systems onboard. Presently, multi-layered system architecture, redundancy and non-coplanar deployment models are being employed to partially manage the consequences of these impacts [30].

The natural micro-meteoroid flux is not constant and can vary over the years. This variation occurs when Earth's orbit intersects with the orbits of comets, allowing micro-meteoroids to enter Earth's orbit. Meteoroids can have cross-sectional areas ranging from 1 millimeter to 10 microns [31]. Micro-meteoroids are not the only risk factor for physical collisions in Earth's orbit. As the number of artificial satellites in Earth's orbit increases, the likelihood of satellite collisions also rises.

Figure 5. Distribution of Space Debris Components [32]



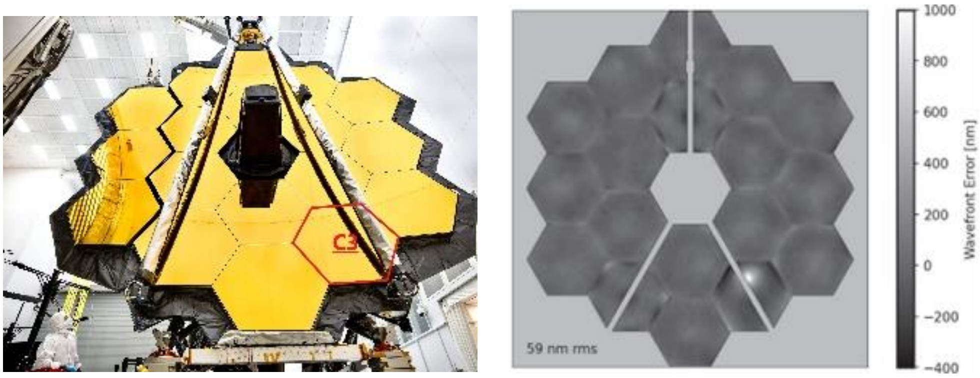

Credits: ESA

In February 2009, an event that was considered highly unlikely occurred when the communication satellite Iridium 33 collided with the military satellite Kosmos 2251 at a speed of 11.7 kilometers per second in a Low Earth Orbit. Such satellite collisions can generate a significant number of debris orbiting Earth uncontrollably, and these components increase the probability of new collisions occurring at any location in Earth's orbit. This situation has led to the formation of a debris belt with characteristics depicted in Figure 5 today.

A study published by Donald Kessler in 1978 [33] suggests that as the frequency of artificial satellite collisions increases, it becomes possible for Earth's orbit to become unusable, resulting in the formation of a complete debris belt (Kessler Syndrome). In such a scenario, the debris flow in orbit can surpass the natural meteoroid flow, and the conditions related to this can fundamentally affect future spacecraft designs. Following the collision between Iridium 33 and Kosmos 2251, it was determined that more than 1302 trackable pieces were created. Some of them later re-entered Earth's atmosphere and disintegrated, but a significant portion of them continues to orbit in Earth's orbit. [34]

Another recent example of a meteoroid collision is related to the James Webb Space Telescope in May 2022. Although the James Webb Space Telescope was designed to withstand bombardment by dust-sized particles traveling at extremely high speeds in the micro-meteoroid environment at the Sun-Earth L2 orbit, NASA authorities announced considerable impact on the telescope [35]. The most significant effects of micro-meteoroids on the system were observed in the hexagonal primary mirror of the C3 segment, as depicted in Figure 6. [36]

Figure 6. James Webb Space Telescope Micro-Meteoroid Damaged Segment C3 [37], [38]




Credits: NASA

Figure 7 illustrates the effects of similar meteoroid collisions on spacecraft. Figure 7.a shows damage to the multilayer insulation covering the Zarya Module of the International Space Station (ISS), while Figure 7.b displays meteoroid damage on the solar panel of the Hubble Space Telescope.

Figure 7.a. Meteoroid Impact on ISS, NASA [39]

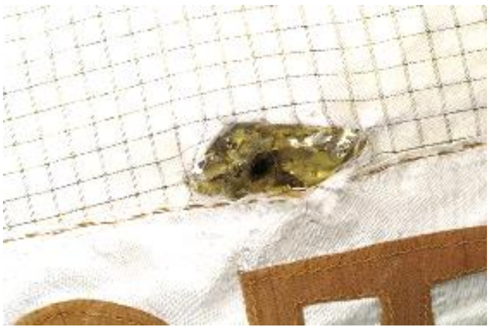
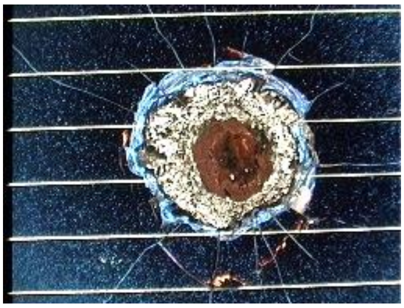


Figure 7.b. Post-flight Solar Panel Damage on Hubble, ESA [40]



If new collisions continue to occur, under specific conditions, it is considered that the orbit belt leading to the realization of the Kessler Syndrome could begin to form within this century and become a significant problem over the next century [33].

### 3.3.5.Outgassing and Material Contamination

Materials produced on Earth may experience outgassing, where gases within the materials are forcibly released and can potentially harm surrounding components due to the vacuum conditions in space. This phenomenon can lead to the formation of unwanted gas or liquid molecules and microscopic material particles in the vicinity of subsystems. These molecules may become in various chemical or physical types such as solvents, lubricants, catalysts, inhibitors, and exhibit properties like conductive or insulating. They may have the potential to contaminate and react with non-coated electrical hardware surfaces and can also adhere to mechanical surfaces, causing roughness and local performance degradation. [41]

To mitigate the effects of the vacuum environment that cause outgassing in materials, it is necessary to select materials with a high outgassing threshold specification or to perform surface treatments to enhance their resistance. Additionally, materials exposed to liquids during the production process on Earth may experience outgassing when introduced into the space environment. To improve their outgassing characteristics, these materials can be subjected to baking process in a vacuum environment before integration into the spacecraft.

Due to outgassing or material degradation, some electronic boards are coated to ensure that the substances generated do not harm electronic equipment. In a vacuum environment, harness can become brittle, leading to breakages in standard insulated cables. Therefore, in the space environment, the use of Teflon-insulated cables is preferred under normal conditions. Additionally, in the selection of space-qualified materials, components containing gases or liquids (e.g., the preference for tantalum and ceramic materials in capacitors) are avoided.

## 4. Conclusion

Contrary to common misconceptions, Earth's orbit is not devoid of matter. It comprises various elements, including gases, meteoroids, space debris, ultraviolet starlight, cosmic rays, galactic radiation, microgravity forces, magnetic fields, and particles resulting from nuclear reactions. These matters collectively constitute the intricate space environment. Given that spacecraft in Earth's orbit are directly exposed to the disruptive influences of these elements, it becomes imperative to implement comprehensive protective measures. To this end, both the European Space Agency (ESA) and NASA have issued a group of standards aimed at enhancing the reliability of space products, as documented in references [42-52]. Nevertheless, despite these concerted efforts, spacecraft systems can still encounter failures due to the challenges posed by the space environment, as noted in reference [16]. Many of these failures, burdening from the harsh conditions of the space environment, serve as tangible illustrations of the adverse effects outlined in this article on space systems, as discussed in references [23].

Adequate documentation regarding spacecraft failures, regularly updated models of the space environment, and the establishment of development procedures and manufacturing processes aligned with established product assurance standards constitute essential components in the pursuit of ensuring the fault tolerance and sustained success of space missions.

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