SPACE ENVIRONMENT THREATS AND THEIR IMPACT ON SPACECRAFTS IN NEAR EARTH ORBITS

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ABSTRACT

Though space activities are known to be risky, space is a harsh environment and the human space activities have increased the threat in near earth orbits. From the natural space environment to the debris, there is a growing threat to the safety of access to, and use of, space. Natural space environment threats include radiation surges caused by solar flares which can: damage on-board satellite microchips, interrupt short-wave radio transmissions, and cause errors in navigation systems. Measures to mitigate solar radiation effects are important for the safety of space operations. Specific to near earth space activities are debris, above 600 kilometers they will remain a threat for a long time (decades or centuries). There have already been a number of highly destructive and costly incidents involving space debris collisions with civil, commercial, and military spacecrafts. It is clear that the consequences of collisions between space debris and spacecraft can be disastrous (e.g. The Space Shuttle has been hit several times; French, Russian and American satellites have been damaged; the Long Duration Exposure Facility, a school bus-sized satellite, recorded more than 30000 impacts by debris or meteoroids during six years in orbit). While major collisions have so far been rare, there have been several incidents of varying severity motivating the protection against space debris. It is also important to note that at least three spacecrafts were damaged by solar flare events in the last three years. Understanding the risks related to the space environment is essential to insure the quality, reliability, efficiency and safety of space programs. After outlining the space environment components (space debris, solar flairs, etc.), their influence on the spacecrafts will be studied. Followed, is the classification of the threats according to their severity and likelihood of occurrence. The last combined with a status about the evolution of: (1) each threat and (2) the space activities; allows a better view of the situation. Will follow an analysis that reveals the main threats on which a mitigation plan should be developed to minimize or prevent their effect on space activities. This paper will review and discuss the risks associated to the space environment and outline a strategy to mitigate their effect on space programs, in order to insure a minimum safety standard for the growing number of space activities.

I. INTRODUCTION

Space environment describes major points which are important to understand and to address conditions existing in space that would impact the operation of spacecraft. Although, the environment is directly linked with physical elements such as space weather, space debris to name a few. It should be noted that some of these physical elements are directly the results of space field dynamics like economy, rising of new space nations, direction of the space activities, etc.

The study of the space environment is vital for the safety of spacecrafts, mainly in near Earth orbits, which covers the orbital altitudes used by spacecrafts with applications which are directly linked to the activities on the Earth. These applications cover both civil and military needs. In this regard, near Earth orbits can be defined from few hundred kilometers to 50 000 kilometers altitude above Earth.

Space environment is highly dynamic and it imposes a constant threat to space assets. Issues raised due to these threats include safety of spacecraft operations and classification of the threats of the space environment according to likelihood of occurrence and their severity. When considering these threats, both natural and man-made sources have to be taken into consideration with their influences on spacecraft's hardware and operation, and also human spaceflights.

II. SPACE ENVIRONMENT ELEMENTS

Many different elements contribute to the space environment above Earth. These could either be natural like high energy particles, micrometeorites or man-made like space debris, active spacecrafts. Space environment elements do not just affect the space based assets but also influences daily life on Earth. All these elements are briefly described in this section.

A. High-energy particles

High energy particles in the space environment consist of protons and charged ions. According to Hilgers et al. [1], there are three sources of high-energy particles in the space environment around Earth:

- High-energy electrons and protons trapped in the Earth's magnetic field
- High-energy protons and heavier ions resulting from energetic 'events' close to the Sun
- Galactic cosmic rays, originating from outside the solar system

B. Plasma

Plasma is fourth state of matter and consists of free moving electrons and positive ions. Earth's plasma extends from few hundred kilometers to few thousand kilometers in altitude. At lower altitude the main cause of plasma is UV radiation from Sun, which results in plasma formation in ionosphere, which is important for ground-to-ground signal propagation and satellite-to-ground signal propagation.

At higher altitude, Earth's magnetosphere influences the plasma. According to Hilgers et al. [1], magnetosphere can be divided into three plasma regions based on plasma energy and density. These are:

- Cold ionospheric plasma region – Low energy (~0.1eV) and high density (upto 106 cm-3)
- Plasmasphere – Low energy (~ 1eV) and medium plasma density (10-1000 cm-3)
- High-temperature plasma region – High energy (100-10KeV) and low density (in the order of 1 cm-3)

C. Electromagnetic Radiation

The electromagnetic radiation consists of electromagnetic spectrum from radio to gamma rays. Sun is the main source of electromagnetic waves, with a small portion also generated by human activities.

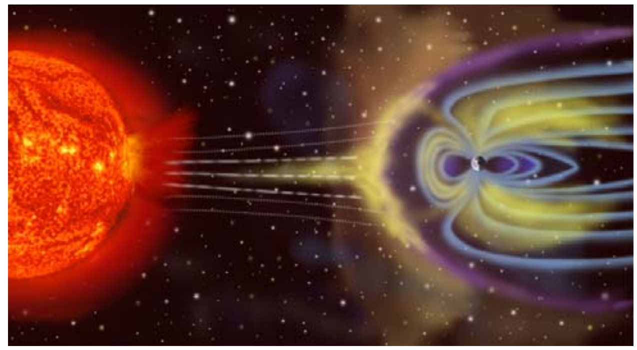

Fig 1. Earth's magnetosphere embedded in solar wind [3]

D. Geomagnetic field

The magnetic field surrounding Earth is referred to as 'geomagnetic field'. The magnetic poles of Earth are not completely aligned with geographic north and south poles. Earths geomagnetic field reverses direction every 70 000 years Apart from helping in navigation, Earths magnetic field also protects us from solar wind by reflecting the charged particles coming from Sun.

The shape of Earths magnetosphere is determined by the distortion of geomagnetic field by solar wind plasma. On the Sun side, the boundary of magnetosphere ("magnetopause") is roughly, about 15 R_E from center of Earth and on the night side, cylinder shaped with radius of about 20-25 R_E; where R_E is Earths radius (Fig 1). Earths Magnetosphere also contains two radiation belts, called inner and outer radiation belts. The inner radiation belt consists of protons with energies in the range 10-100 MeV, whereas outer radiation belt contains electrons and ions with peak energy of about 65 keV.

E. Atomic environment

Atomic environment is predominant only in the lower Earth atmosphere. Atomic oxygen is also found in the low earth orbits. High energy neutral particles are produced by charge exchange in high energy charge particle regions, which contributes to the space environment effects.

F. Micrometeorites

Micrometeorites are small extraterrestrial particles that enter Earth's atmosphere. Its can either be made of rock, metal, or a mixture of both. They pose threats to the spacecrafts in the near earth orbits because of their high relative velocities.

G. Space Debris

Space debris is man-made objects in orbit around the Earth that no longer serve any useful purpose. The sources of space debris are: entire or parts of spent rocket stages, entire or parts of defunct satellites, explosion fragments and mission related objects.

H. Active Spacecrafts

Any man-made system that is functioning in space is defined as active spacecraft. These spacecrafts can be manned or unmanned and can orbit around the Earth in different orbits (Low Earth orbit (LEO), Medium Earth Orbit (MEO), Geosynchronous Earth Orbit (GEO) and Highly Elliptical Orbits (HEO)). Type of orbit used for the spacecraft is dependent on the spacecraft's application.

I. Orbital perturbation

Orbital perturbation of spacecrafts is result of the interplay of the following perturbations:

- Geopotential perturbations: are the results of the Earth's oblateness which causes asymmetries in the Earth's gravitational field.
- Third body perturbations: are caused by gravitational forces of the Sun and the Moon.
- Aerodynamic perturbations: spacecrafts moving through a rotating Earth atmosphere cause aerodynamic perturbations with superimposed wind patterns.
- Radiation pressure perturbations: are generated as the result of the interaction between the photons and the spacecraft.

III. Space Environment Threats and Their Impact on Spacecrafts

Space environment threats on spacecrafts in near earth orbit could be either natural or manmade. Natural threats arise mostly due to solar activities, micrometeoroids, energetic particles and cosmic radiation, whereas manmade threats are caused primarily by space debris.

A. Natural Threats

Solar Activity

Sun is the source of electromagnetic radiation, solar wind, and plasma. UV and X-ray photons from Sun reaching Earth's atmosphere, ionizes the ionosphere, which have significant influence on the ground-to-ground as well as satellite-to-ground telecommunications.

Cosmic rays and high energy solar particles are scattered by solar wind and interacts with Earths atmosphere to produce high energy particles. Galactic cosmic rays interaction with Earths atmosphere produces protons which constitute the inner radiation belt.

Solar eruptions include two main phenomena's – Coronal Mass Ejections (CME) and solar flares. CMEs are eruptions of magnetized plasma, expanding outwards from Sun's corona. The ejected high energy particles move along interplanetary magnetic field lines. Solar flares are sudden and rapid release of magnetic energy in the solar atmosphere.

CME and solar flare events causes high dose of radiation in the earth orbit, causing degradation and/or damage to the operational satellite. Apart from higher atmospheric drag in the low earth orbits, it can also cause altitude loss due to high background radiation noise (thus interfering with star trackers).

Geomagnetic storms

Geomagnetic storms are disturbances in the magnetosphere, which is associated with CME or solar flare event in Sun. The shock wave due to solar wind pressure can cause damage to the spacecraft in the near earth orbits. The satellites in low earth orbit experiences more atmospheric drag whereas high altitude satellites may experience electronic component failures due to radiation overdose.

High-energy particles

The high energy charges particles generated by Sun or that coming from outside the solar system causes electronic component and structural material degradation. Geostationary and GPS-satellites are more prone to radiation and have more chances of component failures. Single event effects, memory failures, high error rates, CCD damage are few examples of the impact of high energy particles on space systems. The sensors are very sensitive and there high radiation environment (especially during solar storm) results in high level of background noise which makes the data useless.

Electromagnetic radiation

The visible and IR region of the electromagnetic radiation causes thermal effects in the space systems. Whereas UV, X-ray and γ rays causes ionization and thus generation of secondary particles in the material, which can cause material degradation or damage.

Space Plasma

Systems in space plasma experience electrical phenomena's such as surface charging, arc or coronal discharge and induced electric current. The induced potential in the cold ionospheric region and solar wind ranges between few volts to few tens of volts whereas it is could reach few several tens of volts in the high-temperature region. According to Hilgers et al. [2], electrons with energy of the order of 1 keV can create

SEU on CCD directly or indirectly accessible from space.

Atomic Environment

The atomic environment in the lower atmosphere of Earth causes atmospheric drag and thus impacts the trajectory and re-entry of the spacecraft in the low earth orbit. Atomic oxygen chemically reacts with the spacecraft surface, thus degrading it over time.

Micrometeoroids

Because of their high relative velocities, micrometeorites could be quite damaging to the active spacecrafts in the earth orbits. Direct mechanical impact on the spacecraft can puncture the surface. Impact velocities can be between 5 to 30 km/s.

Orbital perturbations

Orbital perturbations cause changes to one or several of the orbital elements. Depending on the type of perturbation, it can make Short-periodic, long-periodic and secular changes in orbital elements.

B. Manmade Threats

Space Debris

Space debris impacts on spacecrafts can vary from small surface pits for small objects (µm size), clear holes on the surface (mm size), to spacecraft destruction (partially or completely) because of the impact energy and resulting shockwaves for impactors larger than a few centimeters. Impact velocities for space debris are usually in a range of 0 to 15 km/s [4].

One conjunction with these velocities of an aluminum sphere with a 1 cm diameter frees the same amount of energy as an exploding hand-grenade. However, rather than the relative velocity between the impactor and the object, other parameters affect the severity of the collision. These parameters are direction of collision, sizes and shapes of the object and impactor and type of materials.

The likelihood of collision between spacecrafts and space debris varies dependent on the orbit. This is due to number of objects in each orbit which is much higher in Low Earth Orbit and less in Geosynchronous Earth Orbit. Debris flux for two sample orbits (ENVISAT and GEO) are illustrated in figures 2 and 3 which are generated using MASTER 2005.

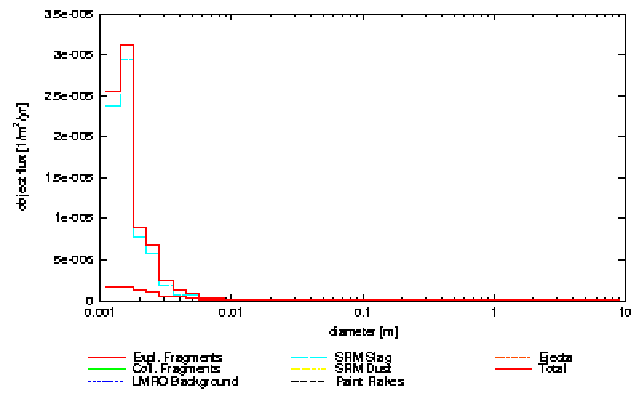

Figure 2: 2D flux distribution vs. impact diameter for GEO

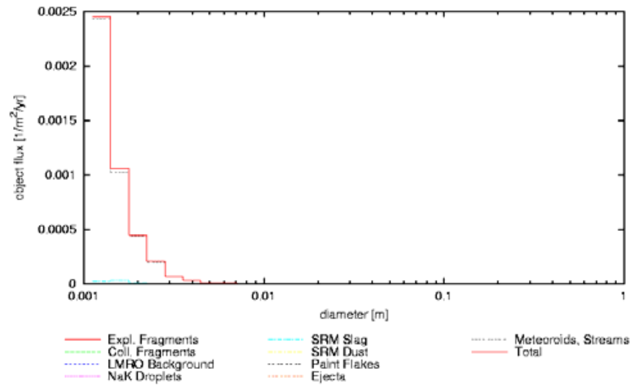

Figure 3: 2D flux distribution vs. impact diameter for ENVISAT

Active spacecrafts

Active spacecrafts can affect other spacecrafts unintentionally or intentionally. Unintentional effects include frequency disturbances and collision dangers (especially during spacecraft maneuvering). However, the likelihood of these events is extremely low since frequencies are assigned by International Telecommunication Union and spacecraft operators check the risk before and during maneuvering their spacecrafts.

On the other side, intentional effects can vary from signal jamming and frequency disturbances to more serious consequences like making the other spacecrafts non-functional (temporarily or permanently) or destroying the spacecraft. Currently, no fully-functional systems are available to be able to detect and identify these possible threats (space situational awareness system).

The effect of space environment elements on space systems in near Earth orbits is summarized in table 1.

Space Environment Threats	Effect on space system
CMEs/Solar Flares	Atmospheric drag, Material

	degradation, Electronic component failure
Geomagnetic Storms	Atmospheric drag, electronic component failure
High Energy Particles	Deep dielectric charging, single-event effects, memory failure, degraded sensor performance
Electromagnetic Radiation	Thermal effects, ionization, material degradation
Space Plasma	Surface charging, Induced electric current, Arc discharge
Atomic Environment	Chemical reaction with surface, Ionization, Atmospheric drag
Micrometeorites	Puncture
Space Debris	Puncture, degradation, collision
Orbital perturbations	Short-periodic, long-periodic and secular changes in orbital elements
Active spacecrafts	Unintentional: frequency disturbances Intentional: frequency disturbances, electromagnetic fields, partial/total damage

Table 1: Space environment elements and their effects

IV. Classification of Threats

The space environment threats can be classified based on the severity and the likelihood of the threat. However, the likelihood of threats on spacecrafts varies dependent on the position of the spacecraft while the severity of the threat is dependent on other factors.

Position of the spacecraft in orbit plays a major role in consideration of the threat likelihood. Three different regions which are considered are:

- Low Earth orbit (LEO): Defined as orbits from 200 km to 1 200 km above the Earth's surface.
- Medium Earth Orbit (MEO): Defined as orbits having apogees greater than 3000 km but less that 30 000 km.
- Geosynchronous Earth Orbit (GEO): Defined as a region in space at an altitude of about 36 000 km.

For each of these orbits, likelihood levels can be defined based on number of registered occurrences until now (N_{oc}):

- Very seldom (VS): $N_{oc} < 3$
- Seldom (SE): $3 < N_{oc} < 5$
- Often (OF): $6 < N_{oc} < 8$
- Frequent (FQ): $8 < N_{oc}$

Severity of the threats is based on how they affect the spacecraft and/or onboard instruments and/or the whole mission (SOIM). The following definitions are used to distinguish severity of the threats:

- Low (LO): Minor degradation of SOIM (efficient life time decrease of 0%-25%)
- Medium (ME): Partial degradation of SOIM (efficient life time decrease of 25%-50%)
- Critical (CR): Significant failure of SOIM (efficient life time decrease of 50%-75%)
- High (HI): Complete failure of SOIM (efficient life time/functionality decrease of 75%-100%)

Likelihood and severity ranges of threats from each of these components are illustrated in tables 2-4 for different regions.

Threat	Likelihood	Severity
Space debris	SE	LO, ME, CR, HI
Active spacecrafts	VS	Unintentional: LO Intentional: CR, HI
Orbital perturbations	VO	LO, ME
CMEs/Solar Flare	SE	HI
Geomagnetic Storms	SE	HI
High Energy Particles	OF	CR
Electromagnetic Radiation	OF	CR
Space Plasma	OF	ME
Atomic Environment	OF	ME
Micrometeorites	OF	CR

Table 2: Threat classification in LEO

Threat	Likelihood	Severity
Space debris	VS	LO, ME, CR, HI
Active spacecrafts	VS	Unintentional: LO Intentional: CR, HI
Orbital perturbations	VO	LO
CMEs/Solar Flare	SE	HI
Geomagnetic Storms	SE	HI
High Energy Particles	OF	CR
Electromagnetic Radiation	OF	CR
Space Plasma	OF	ME
Atomic Environment	OF	LO
Micrometeorites	OF	CR

Table 3: Threat classification in MEO

Threat	Likelihood	Severity
Space debris	VS	LO, ME, CR, HI
Active spacecrafts	VS	Unintentional: LO

		Intentional: CR, HI
Orbital perturbations	VO	LO
CMEs/Solar Flare	SE	HI
Geomagnetic Storms	SE	HI
High Energy Particles	OF	CR
Electromagnetic Radiation	OF	CR
Space Plasma	OF	ME
Atomic Environment	OF	LO
Micrometeorites	OF	CR

Table 4: Threat classification in GEO

V. EVOLUTION OF SPACE ENVIRONMENT THREATS AND SPACE ACTIVITIES

Since the launch of Sputnik on 4 October 1957, more than 5000 rocket launches have placed around 6600 satellites into orbit. Since then approximately 30 000 larger objects – satellites, rocket upper stages, mission related objects like telescope covers or bolts and fragments from on-orbit explosions were observed by ground-based radar and telescopes. Some 19 400 of these have meanwhile burnt up in the atmosphere currently leaving about 10 600 large objects in Earth orbit. But only 700-850 of these are operational satellites [5].

On 10 July 2006, the catalogue population consisted of 31.2% operational and non-operational payloads (=3179), 17.4% rocket bodies (=1718) and 50.4% debris (=4968). Only about 6% of the catalogue population can be assumed to be operational payloads [6]. Cumulative cataloged objects on orbit per object type and per year and per country are shown in figures 4 and 5 according to ESA's DISOCS Database.

Since years 2001/2002 number of launched seems to settle at 60 launches per year. If the space activities continue "business as usual" without considering mitigation techniques, the risk related to space debris will increase exponentially.

However, some space environment components make significant changes in the number of space debris in LEO; these are mainly solar activity and atmospheric forces which pushes the objects into denser parts of the atmosphere which causes more rapid decay and burning in atmosphere.

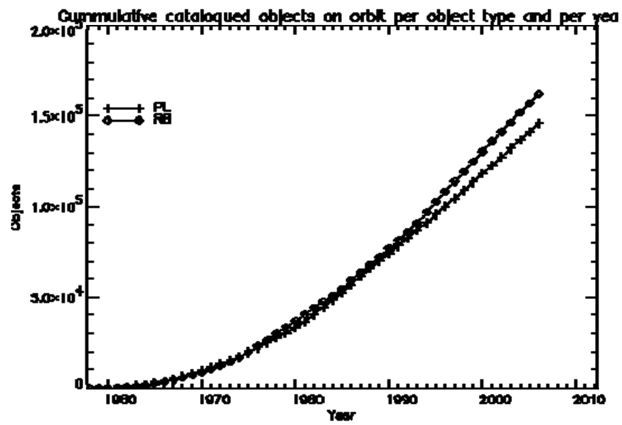

Figure 4: Cumulative cataloged objects on orbit per object type and per year

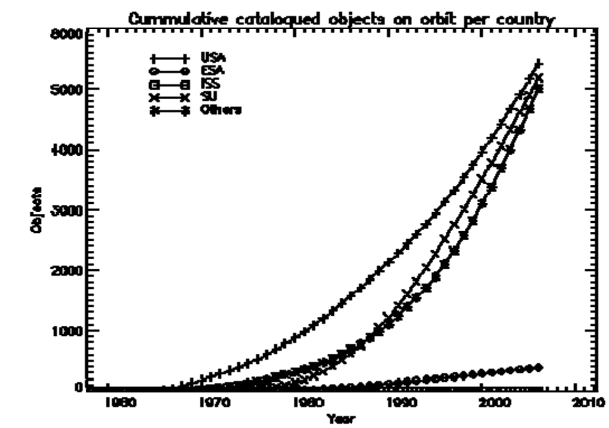

Figure 5: Cumulative cataloged objects on orbit per country

VI. MITIGATION STRATEGIES

Mitigation strategies are devised in all the phases of the project starting from the design phase of the spacecraft. In the design phase, particular emphasis should be put on the measures to be taken to protect the spacecraft from the harsh space environment, especially the geostationary and GPS-type satellites. Use of real time space environment data, like real time solar monitoring data can be quite useful in mitigating the risk to the spacecrafts. Switching off the satellite during solar storms is one of the strategies to reduce the damage to the spacecraft from increased dose of radiation. An integrated system of sensors on-board the spacecraft to check its health and send out warning signals or automatically adapt to the changed conditions in case of a space environment threat could be a way to go in the future.

The threat from man-made components can be reduced by trying to reduce the number of space debris using methods like deorbiting and reorbiting at end-of-life, passivation and discharging the battery at end-of-life. Protecting the spacecraft against the risk related to space debris can mainly be done using shielding techniques for small objects. However, for bigger objects, the only effective method to mitigate the risk is to monitor and track space objects to be able to calculate collision probability. When this probability is bigger than a threshold, then collision avoidance maneuvers should be done to avoid the collision between the spacecraft and the space debris.

For threats related to unintentional and intentional activities of active spacecrafts, development of space situational awareness systems is essential to be able to monitor the spacecrafts, identify their missions and predict their possible threats.

VII. CONCLUSION

Space environment threats to spacecrafts in near earth orbits are real and can have damaging effects. Both natural and manmade threats affect the space systems. In this paper we tried to classify the threats based on their likelihood and severity. Natural threats are more un-predictable compared to manmade threats as fundamental phenomenon behind these is still not fully understood. Modeling these phenomena's in future will help to fill this gap and thus reduce the risk associated with spacecrafts due to these natural threats. Manmade threats are better understood and proactive steps are taken both during the design and operation phases of the project to reduce the risk due to space debris and other active satellites. For small space debris, spacecraft shielding servers the purpose but for larger debris, the effective method to mitigate the risk is to track the space object over time and if required do the necessary collision avoidance maneuver.

Fewer gaps still exists in fully appreciating the risks involved due to space environment. The future work should involve a better understanding of these threats and devising mitigation strategies at each phase of the project. To fully monitor the spacecrafts and to identify possible threats due to space environment, a space situational awareness system is imminent. This will ensure security to the space based assets, which are becoming an integral part of our day to day life.

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