

An Analysis of Surface Charging of Satellite in Orbit

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Abstract

The Spacecraft Plasma Interaction Software (SPIS) has been employed to perform surface charging analysis of a generic GEO satellite in orbit. This study focuses on investigating the surface charging behaviour of a spacecraft under varying space plasma conditions, with particular emphasis on comparing Single Maxwellian and Bi-Maxwellian plasma distributions and analysing the effect of photoemission across various conductive surface materials. For each distribution type, simulation are carried out under both normal and worst-case plasma conditions to examine the extent of surface potential buildup. In addition, the effects of enabling and disabling photoemission which represent the presence and absence of Sun (eclipse) are analysed to understand their role in mitigating or exacerbating spacecraft charging. This study provides insight into how different plasma environments and emission mechanisms influence charging behaviours on spacecraft surfaces.

1. Introduction

Space weather refers to the dynamic and time-dependent conditions in the space environment that can impact both space-based and ground-based technological systems, as well as posing risks to human health and safety. The space environment is inherently complex and ever-changing, with the Sun serving as the primary driver of space weather effects. The Sun continuously emits charged particles, varying magnetic fields, and high-energy cosmic rays. These interactions can have significant effects on spacecraft, potentially leading to data loss, reduced performance, service interruptions, and, in severe cases, total spacecraft failure [1]. Geostationary satellites, which operate at approximately 35786 kilometers above the Earth's equator, are particularly vulnerable to space weather effects [2]. Their fixed position relative to the Earth can make them indispensable for telecommunication, weather monitoring and broadcasting [3]. On the geosynchronous orbit (GEO), experimental studies have shown that the spacecraft can be charged severely on the post-midnight magnetic sector because of the electrons flowing extremely fast during the geomagnetic storms. Photoemission also plays an important role where it significantly impacts spacecraft operations by causing them to develop a positive electrical charge when exposed to sunlight. When sunlight, particularly UV radiation, strikes a spacecraft's surface, photons (light particles) can transfer their energy to electrons in the material. If the photon's energy exceeds the material's work function (the energy needed to remove an electron), the electron is ejected from the surface. Besides, geomagnetic storms are phenomena that occur in the center of the nightside magnetosphere, known as the magnetotail, because of the high solar wind pressure and strong southward directed solar magnetic fields [4]. Research has shown that the plasma environment in geosynchronous orbit (GEO) can cause satellite surfaces to accumulate significant negative charges relative to the surrounding plasma, which remains unaffected by the spacecraft's presence [5]. This process is known as spacecraft charging. Spacecraft charging happens when the dielectric materials on a spacecraft are exposed to the external space environment, either directly or almost directly. This can lead to electrostatic discharges (ESDs) that may interfere with onboard electronics or damages materials. In recent years, this phenomenon has been linked to nearly half of all spacecraft anomalies, with some incidents resulting in complete mission failure [6]. This study focuses on

analyzing surface charging on geostationary satellites under Single Maxwellian and Bi-Maxwellian distributions in GEO plasma environment. This research also investigates the role of photoemission in charge balance and examines the influence of different surface materials on spacecraft charging behavior, ultimately aiming to enhance understanding and mitigation of charging-related risks in the GEO environment.

2. Literature Review

This section reviews more detail about the critical aspects of space weather and its effects on geostationary satellites, focusing on the surface charging phenomena caused by interactions with the space plasma environment. Furthermore, previous research and study that have been done on spacecraft will also be reviewed in this section.

2.1 Space Environment

Space environment is the large void that occupies the empty area of the universe outside the atmosphere or surface of any planet. The structure of the space environment is dynamic and intricate. It is made up of charged particles, plasmas, electric and magnetic fields, neutral species, solar and space debris, meteoroids, and galactic radiation that can seriously harm a spacecraft, reducing its lifespan and performance [7].

2.2 Surface Charging

Hot electrons with energies ranging from several keV to tens of keV are the primary source to surface charging. While surface charging to high voltages typically does not cause immediate risks to spacecraft, electrical discharges caused by differential charging can damage surface materials and generate electromagnetic interference, potentially harming electronic components. Surface charging is predominantly influenced by variations in low energy plasma parameters surrounding the spacecraft and the photoelectric effect induced by sunlight. Due to the low energy of the plasma, this type of charging does not penetrate the spacecraft's interior components. Electrons with energy in the 10's of keV do not penetrate satellite surface materials but accumulate near the surface. These electrons along with incident plasma and solar UV radiation interact with materials acquire charges such that the net current between the surfaces and the surrounding plasma becomes zero. However, surface voltages are generally nonzero, sunlit areas tend to acquire slightly positive charge while shadowed areas often become negatively charged relative to the plasma. For conductive surfaces, the potential tends to be uniform, either positive or negative relative to plasma.

2.3 Mathematical Model and Parameter Selection

A. Current Balance Equation

The process of spacecraft surface charging results from the interaction between the spacecraft and its surrounding environment. The level of charge depends on factors such as the spacecraft's shape, the properties of its surface materials, velocity and the characteristics of the space plasma environment. The surface potential of a spacecraft represents a dynamic equilibrium established by the movements of various charged particles to and from its surface. In the absence of sunlight, electrons and ions from the plasma interact with the spacecraft depositing on its surface. Under stable ionospheric conditions, the motion rate of plasma can be mathematically represented as [8].

$$v = \sqrt{\frac{2E}{m}} \quad (1)$$

B. Photoemission Current Balance Equation

According to Kirchhoff's law, at equilibrium, the total current entering a node must equal the total current leaving it. This means that the surface potential, ϕ must be such that the net current is zero. In other words, all contributing currents including those from incoming electrons, incoming ions, emitted secondary electrons, backscattered electrons, photoemission and any other possible sources must sum to zero. It is necessary to consider the photoemission current that a spacecraft surface emits under sunlight. The photoemission current frequently surpasses the ambient currents during quiet times (when there aren't any strong magnetic storms), positively charging a typical spaceship surface. Given that sunlight-generated photoelectrons in a geosynchronous environment usually contain a few. If the surface potential is higher than a few volts positive, they are unable to depart. Consequently, sunlight charging usually occurs at a voltage of just a few volts. This requirement is captured by the current balance equation, which defines the surface [9].

$$\sum J_k(\phi) = 0 \quad (2)$$

C. Environment Parameters of GEO

The plasma at geosynchronous Earth orbit can be mathematically described using a distribution function known as the Maxwellian distribution function. This function quantifies the number of particles (electrons or ions) within an infinitesimally small volume of space that falls within a specific velocity range. If plasma is modelled as a single population characterized by average values of number density and particle velocity (or equivalent, energy or temperature), the resulting approximation of the actual distribution is referred to as a single Maxwellian fit. Table 1 shows the Single Maxwellian distribution function with electron number density & temperature and ions number density & temperature parameters [5].

Table 1 Single Maxwellian parameters of GEO plasma environment [5]

Parameter	Normal-case Environment	Worst-case Environment
Electron number density, cm ⁻³	1.09	1.12
Electron temperature, keV	4.83	12.0
Ion number density, cm ⁻³	0.58	0.236
Ion temperature, keV	14.5	29.5

If the plasma distribution is modelled as a combination of two distinct plasma components, the resulting approximation is referred to as a Bi-Maxwellian fit. Observational data indicate that this two-component model effectively represents the plasma population both electrons and ions for approximately 80% of the time. In contrast, a single Maxwellian fit is sufficient for about 10% of the time. It has also been observed that particle temperatures are higher under worst-case environmental conditions compared to normal conditions. This implies that spacecraft experience higher levels of charging during worst-case environments than under normal operating conditions [6]. Table 2 shows the Bi-Maxwellian distribution function.

Table 2 Bi- Maxwellian parameters of GEO plasma environment [5]

Parameter	Normal-case Environment		Worst-case Environment	
	#1	#2	#1	#2
Electron number density, cm ⁻³	0.78	0.31	0.8	1.9
Electron temperature, keV	0.55	8.68	0.6	26.1
Ion number density, cm ⁻³	0.19	0.39	0.9	1.6
Ion temperature, keV	0.8	15.8	0.3	25.6

3. Methodology

This section aims to explain the different methods and approaches that are used in developing the project sequentially in detail. The explanation is about the simulations which are carried out using SPIS software. Initially, a comprehensive literature review is conducted to understand the effects of space weather and its parameters, particularly surface charging on satellites under single Maxwellian and Bi-Maxwellian especially during normal and worst-case conditions. The next step involves developing a generic satellite with different surface materials. The effect of photoemission which arises from exposure to solar radiation, will be assessed. Photoemission will be enabled to simulate sunlight conditions and disabled to simulate eclipse conditions.

3.1 Geometrical Modeling of a Generic GEO Satellite

Fig. 1 shows a 3D simulation model of a generic GEO (geostationary orbit) spacecraft setup. The spacecraft body is assigned face groups 8501-8503, while the solar array uses 8506-8507, indicating different surface properties or materials. The top antenna is tagged as 8504, and the circular antenna as 8505. The external boundary group which defines the limits of the simulation space, is set as 9000, and the computational volume, representing the plasma environment around the spacecraft, is 9500.

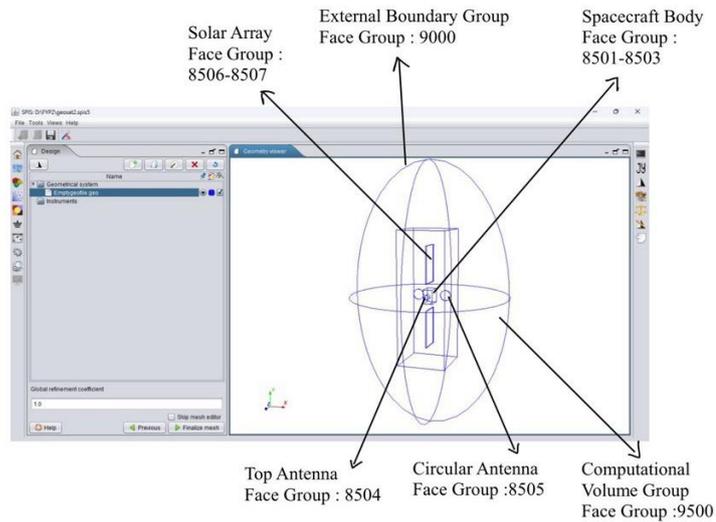


Fig. 1 3D simulation model of a generic GEO satellite

3.2 Material Definition for Spacecraft in Group Editor

In this step, the material properties of the spacecraft surface are defined using the Group Editor in SPIS. The choice of material is critical in determining how the spacecraft will interact with surrounding plasma environment, particularly under various space weather conditions. Combination of conducting and semi conducting materials was used for each spacecraft to exhibit different behaviors, which directly influence surface charging. Table 3 shows the material properties of the spacecraft structure.

Table 3 Material properties of the spacecraft structure [5]

Face Group Id	Group Type	Component Description	Material Properties
8501	Spacecraft surface group	Spacecraft body	ITO coating material properties
8502	Spacecraft surface group	Spacecraft body	ITO coating material properties
8503	Spacecraft surface group	Spacecraft body	ITO coating material properties
8504	Spacecraft surface group	Antenna	Aluminium 2K material properties
8505	Spacecraft surface group	Antenna	Aluminium 2K material properties
8506	Spacecraft surface group	Solar Array	Solar cell (Cerium doped +MgF2) material properties
8507	Spacecraft surface group	Solar Array	Solar cell (Cerium doped +MgF2) material properties
9000	External boundary group	-	-
9500	Computational volume group	-	-

3.3 Configuration of Global Parameters

Tables 1 and 2 present the global plasma environment parameters used in the SPIS simulation. These parameters define the characteristics of the space plasma under both normal-case and worst-case conditions, allowing the simulation to assess spacecraft charging behavior under varying environmental severities.

4. Results and Discussion

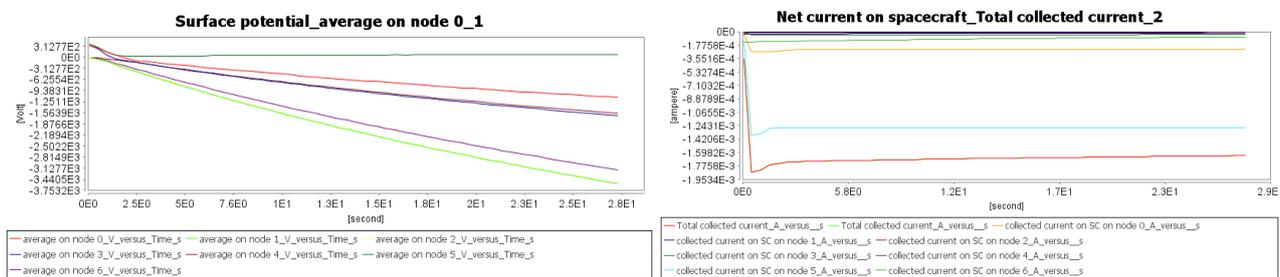
This section presents the results obtained from initial simulations using SPIS software. These results provide early insights into the charging behavior of a spacecraft in a plasma environment, serving as a foundation for more detailed analysis and further investigation. In this section, detailed simulation results are presented for

two conditions which are Single Maxwellian normal-case with photoemission on and Bi-Maxwellian worst-case with photoemission off. These cases illustrate the extreme and average charging behavior under GEO conditions. For the remaining conditions, a summary of the average surface potential values is provided in Table 4.

4.1 Single Maxwellian (normal case) with photoemission

The surface potential distribution across different parts of the spacecraft under a single Maxwellian plasma with photoemission turned on reveals how both material type and solar exposure influence spacecraft charging as shown in Fig. 2(a). Nodes 1 and 2, representing the ITO coated spacecraft body, exhibit the most negative surface potential at -3753.2 V, indicating they are likely located in shadowed regions where photoemission is minimal, allowing significant accumulation of ambient electrons. Node 0, also part of the ITO spacecraft body, is less negatively charged at -938.31 V due to solar exposure that results in some photoemission mitigating the negative charging. The aluminium antenna surfaces represented by nodes 3 and 4 maintain moderate negative potentials of -1563.9 V, reflecting aluminium's higher photoemission efficiency compared to ITO. Furthermore, cerium solar array (node 5) which is directly facing the Sun on x axis, achieves the most positive potential at 312.77 V due to strong photoemission, while node 6 in shadow registers a highly positive negative potential of -3127.77 V, like the shadowed ITO surfaces. However, the graph did not reach equilibrium because the simulation duration required is too long as there were many nodes added to show the difference in all the face groups of satellite reacting to plasma environment.

Fig. 2(b) shows the total collected current due to incoming plasma particles. The collected current begins with a sharp negative value (red), reflecting a high rate of incoming electrons due to positively charged surface, and then levels off as the surface potential stabilizes. The collected current at node 5 is also high. This is because when a surface has a more positive potential than its surroundings, it can create an electric field that attracts electron from plasma. So, although node 5 is emitting electrons due to photoemission, the resulting positive potential may enhance the collection of electrons from the ambient plasma to neutralize the surface.



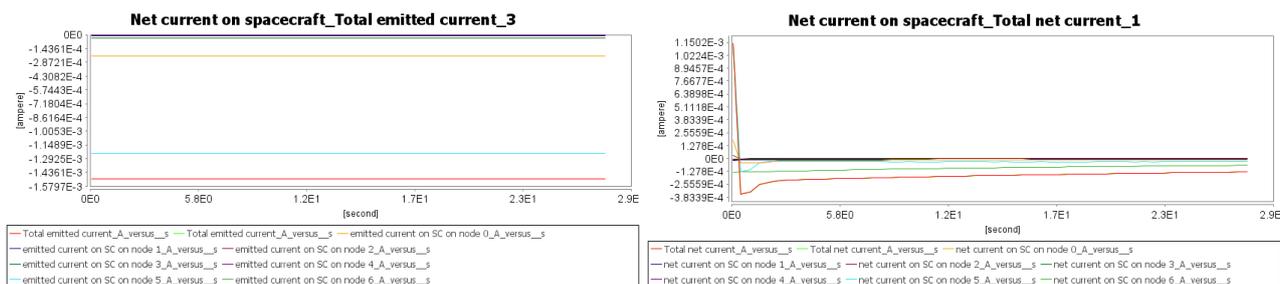
(a)

(b)

Fig. 2 (a) Average surface potential in all nodes graph for Single Maxwellian (normal case) during sunlit; (b) Total collected current on spacecraft

The emitted current in Fig. 3(a) is shown with photoemission, where surfaces exposed to sunlight release electrons into the environment. The solar array node 5 shows significantly higher emitted currents due to the position of the sun, which aligns directly with the x axis of the solar array. Surfaces made of ITO and aluminium exhibit lower emission level.

The net current in Fig. 3(b) illustrates the combined effect of collected and emitted current. Initially, the net current is negative (red) due to dominant photoemission. However, as spacecraft charges positively, it begins to attract more ambient electrons, which increases the collected current. Eventually, this leads to a steady state where the net current hovers close to zero, indicating that the system has reached equilibrium.

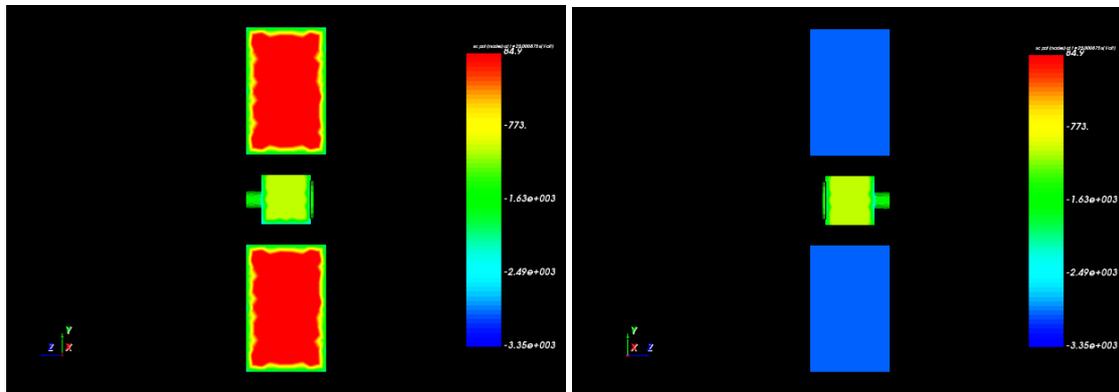


(a)

(b)

Fig. 3 (a) Total emitted current; (b) Total net current

The visualization in Fig. 4 illustrates the surface potential distribution around the spacecraft model in a Single Maxwellian plasma environment under normal conditions, with photoemission enabled. Fig. 4(a) shows the solar array is displayed in shades ranging from green to red, indicating positive potential especially around the surfaces exposed to sunlight where photoemission is strongest. In contrast Fig. 4(b) shows the solar array in a shaded area with no exposure to sunlight, so photoemission does not take place leading to a negative potential. The spacecraft body reaches a surface potential of -1630 V because of its material ITO, which is conductive that distributes charge evenly.

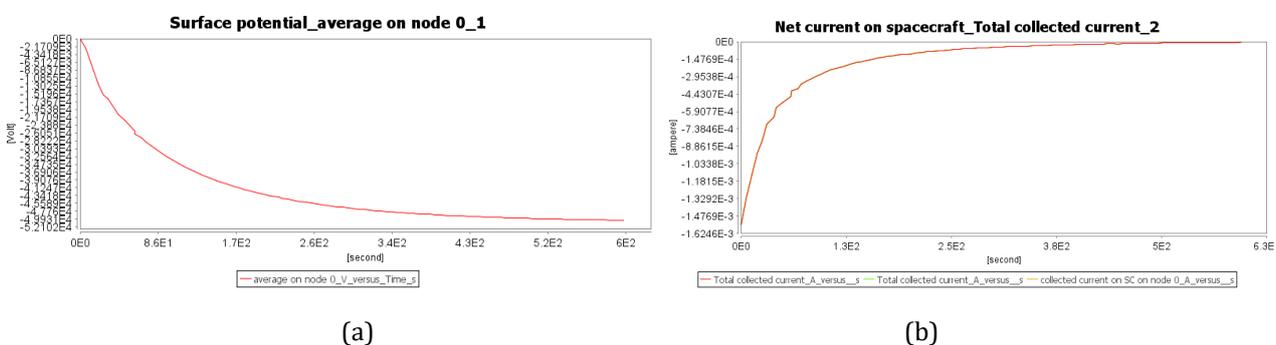


(a) (b)
Fig. 4 (a) Spacecraft facing sun (x axis); (b) Spacecraft at shadow (-x axis)

4.2 Bi-Maxwellian (worst case) with no photoemission

Fig. 5(a) displays the average surface potential over a 600 second simulation under a Bi-Maxwellian (worst case) plasma environment, with photoemission turned off. The curve shows a continuous and steady state decrease in surface potential, starting near 0 V and gradually reaching approximately -52102V. This negative charging trend is a direct result of spacecraft being bombarded by high-energy electrons in the ambient plasma, which are more mobile than ions leading to a net accumulation of negative charge on the spacecraft surfaces. Without sun or photoemission which represent eclipse, it cannot release electrons back into the environment. The spacecraft reaches a stable negative potential where the repelling force of the surface is enough to limit further electron collection, achieving equilibrium.

Fig. 5(b) displays a continuously negative current, indicating that the spacecraft is accumulating ambient electrons from the surrounding plasma, because when photoemission is absent, the surface becomes negatively charged and it starts to attract ions.



(a) (b)
Fig. 5 (a) Average surface potential graph for Bi-Maxwellian (worst case) during eclipse); (b) Total collected current on spacecraft

The graph in Fig. 6(a) shows that the emitted current remains zero throughout the simulation. This is consistent with the setting where photoemission is turned off, meaning the spacecraft materials do not emit electrons due to solar radiation. As a result, there is no positive contribution to the spacecraft's total current

The net current shown in Fig. 6(b) is equal to the collected current because emitted current is zero. It begins with a steep negative slope and gradually flattens as it approaches a constant value. This reflects the spacecraft's transition toward a steady state charging condition dominated by incoming electrons.

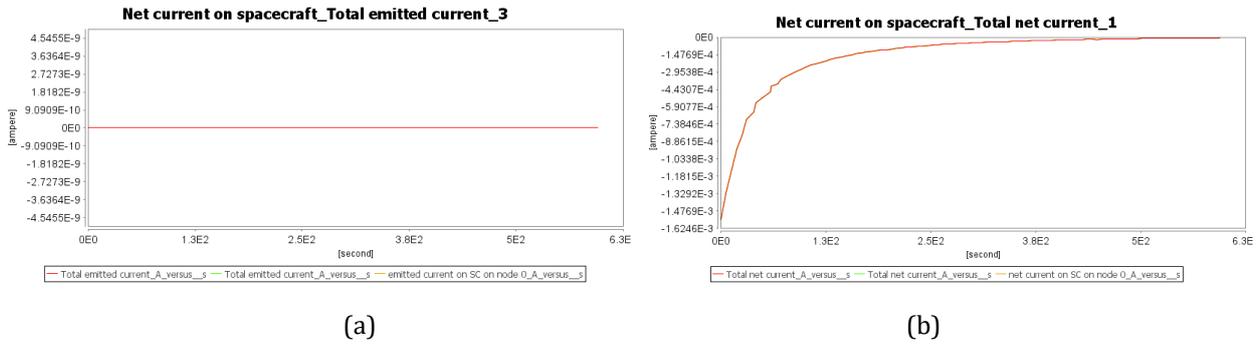


Fig. 6 (a) Total emitted current; (b) Total net current

Based on the surface potential visualization in Fig. 7 with photoemission turned off, the spacecraft experiences a strong negative charging, particularly on the solar arrays. This condition occurs in the context of a Bi-Maxwellian plasma environment, representing a worst-case scenario characterized by high-energy electron populations. As shown in Fig. 7(a) and (b), the solar array on both sides exhibits the most negative surface potentials, which is expected due to semi conducting properties. Meanwhile, components such as the spacecraft body and antenna also display negative potential, though their values are relatively moderate compared to the solar arrays, due to the conductive nature of ITO and aluminium, which helps spread and redistribute charge. Without emission processes to counterbalance the electron accumulation, the spacecraft surface charges to significantly negative values.

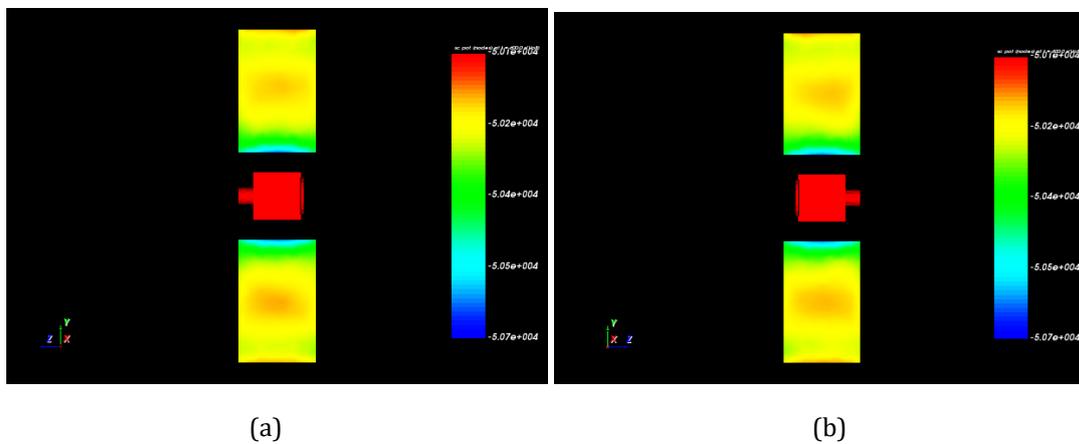


Fig. 7 (a) Spacecraft facing (x axis); (b) Spacecraft at shadow (-x axis)

4.3 Overall Result

Table 4 presents the average surface potential of a spacecraft under different plasma distribution models, plasma conditions, and emission settings. It is evident that photoemission plays a critical role in controlling surface charging. When photoemission is turned on which is when the spacecraft is facing the sun, all simulation cases show either positive or slightly negative average surface potentials, indicating that these emissions help neutralize excess negative charge by releasing electrons from the surface. When photoemission is turned off, which indicates that the spacecraft is in the “wake” region or eclipse, the spacecraft is charged to a negative potential.

For example, under the Bi-Maxwellian Worst Case condition, the potential remains slightly negative at -410.93 V when photoemission is active, compared to an extremely negative -52102 V when photoemission is turned off. Similarly, under the Single Maxwellian Worst Case, the surface potential remains negative (-13.157 V) with photoemission on but drops to -41100 V when photoemission is disabled. This drastic difference highlights how emissions, particularly under sunlight (photoemission), significantly mitigate the severity of negative charging induced by high-energy electron environments.

Moreover, the Bi-Maxwellian plasma model, especially in the worst-case condition, results in the most severe charging effects when emissions are off, due to the presence of a hot electron population with high energy. In contrast, normal-case conditions, regardless of plasma model, result in less extreme potential, showing that charging severity strongly correlates with both plasma characteristics and emission activity. Overall, the analysis demonstrates that spacecraft surfaces are highly sensitive to environmental plasma parameters and benefit greatly from emission mechanisms in reducing harmful charging levels.

Table 4 Average surface potential result

Plasma Distribution	Condition	Spacecraft Position	Average Surface Potential (V)
Single Maxwellian	Normal Case	Facing Sun	1.2082
		Wake region	- 13941
Single Maxwellian	Worst Case	Facing Sun	-13.157
		Wake region	- 41100
Bi-Maxwellian	Normal Case	Facing Sun	4.3683
		Wake region	- 16991
Bi-Maxwellian	Worst Case	Facing Sun	-410.93
		Wake region	- 52102

5. Conclusion

This research shows the spacecraft surface charging is highly influenced by the surrounding plasma environment, emission conditions and material properties. When photoemission is active such that during sunlight exposure, the spacecraft maintains either positive or slightly negative potentials, which helps reduce the risk of electrostatic discharge that may interfere with onboard electronics. In contrast, during eclipse conditions when spacecraft is in the "wake" region, the spacecraft experiences significant negative charging, especially under worst case Bi-Maxwellian plasma environment. For instance, the surface potential dropped as low as -52102 V indicating a dangerous charging state that can compromise satellite operations. Even in normal-case scenario, the absence of photoemission leads to considerable negative charging, highlighting the vulnerability of spacecraft in shaded or eclipse region. Additionally, the results demonstrate that Bi-Maxwellian distributions, particularly in worst-case conditions, lead to more severe charging due to the presence of high energy electron populations. Conversely, single Maxwellian and normal case condition result in milder charging effects. Although photoemission can help in lowering the negative charging, different materials on the spacecraft can still lead to differential charging that could lead to huge variation in potential between two surfaces. These findings underscore the importance of accounting for plasma distribution types and emission conditions in spacecraft design. Effective mitigation strategies such as surface material selection and charging control mechanisms are essential to maintain spacecraft reliability and prevent anomalies or failure caused by extreme charging conditions in space environment.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Sharvina Murugan, Abul Khair Bin Anuar; **data collection:** Sharvina Murugan; **analysis and interpretation of results:** Sharvina Murugan, Abul Khair Bin Anuar; **draft manuscript preparation:** Sharvina Murugan. All authors reviewed the results and approved the final version of the manuscript.

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