

Numerical Simulation of Spacecraft Charging Attributed to Ionospheric Plasma in Polar and Equatorial Environment

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Abstract The presence of spacecraft in ionospheric plasma can change plasma properties, vice versa plasma can lead to charge buildup on spacecraft. The level of charging, through electric potential of spacecraft, initially depends on plasma density. However, simulations done on four LEO satellites, i.e. ERS 1, MIDORI, ASCA and FUSE 1, showed that charging level depends on plasma electron temperature rather than plasma density which satisfied the Boltzmann's relation in the absence of high-energy electrons from aurora. The higher the plasma electron temperature the more spacecraft exposed to negative charging. It is assumed that plasma ions and electrons are collisionless or in Maxwellian distribution. It is found that there is no strong relation between density and charging level. Furthermore, there exists insignificant different of charging between polar and equatorial satellites. It means that the placement of satellite in polar or equatorial region, as long as the presence of auroral electrons is excluded, will suffer similar level of charging which is less than 5V (negative). Since spacecraft are exposed to negative charge, electric field generated by spacecraft potential, together with mesothermal motion effects, deflects ion trajectory into downstream region leading to ion void region. The ion density is reduced compared to electron density, but there is no significant different of ion void feature between polar and equatorial satellites and capacity building of beneficiaries.

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Nomenclature

Plasma: a gas of charged particles, consisting of equal numbers of free positive and negative charge carrier

Mesosonic/mesothermal motion: motion of LEO spacecraft in plasma environment where spacecraft orbital velocity is larger than ion thermal velocity, but smaller than electron thermal velocity.

Wake: a region behind the spacecraft where the plasma density differs from the initial state.

Ion void: a decrease of ion density inside the wake.

Anomaly: malfunction on spacecraft due to various sources (electrical/mechanical problem, space weather, command errors)

Plasma density (n): degree of ionization of plasma (unit: m^{-3})

Inclination (i): tilt of the orbital plane of spacecraft from the Earth equatorial plane (unit: degree (deg))

Thermal velocity: the velocity of particle in which its kinetic energy is equal to the average energy of all particles in a system (V_e for electrons and V_i for ions)

Orbital velocity: velocity of spacecraft (V_{sc}) which moves in the orbital plane around the celestial body such as Earth.

Spacecraft charging: buildup of charge on/inside the spacecraft materials.

Debye Length: the scale where the mobile charge carriers, such as electrons, screen out electric fields in plasma

Current density (J): number of electric current per cross section area (unit: A/m^2)

1. Introduction

The presence of ionospheric plasma in low Earth orbit (LEO) regime, ranging from 200 to 1000 km altitude, can affect satellite performance leading to various effects such as surface charging, spacecraft failure or anomaly and mission degradation (Koons et al., 2000). During quiet condition, the average charge buildup triggered by background plasma (ionospheric plasma) is less than 5V and mostly results in negative charging (Ahmad, Usui, & Miyake, 2019). This is due to mobile electron moves faster than ion, so that the impact of incoming electron onto spacecraft is more dominant compared to incoming ion. Since the property of ionospheric plasma changes associated with geomagnetic and solar activities, its effect on spacecraft in terms of charging varies giving rise to various effects depending on number of fluxes interacting with spacecraft surface.

Numerous failures on LEO spacecraft have been reported with regard to rapid changes of ionospheric plasma such as European Remote Sensing (ERS-1) and AQUA (Ahmad, et al., 2018). The rapid changes mostly come from precipitated auroral electrons affecting plasma properties surrounding LEO spacecraft. The question of how effective the changing plasma impacts on LEO spacecraft was raised. The presence of auroral electrons somewhat insignificantly contributed to high voltage or severe charging on spacecraft (Ahmad, Usui, & Miyake, 2018). Nevertheless, in the absence of photoelectron, in most cases auroral electrons play a role in contributing to high voltage charging on spacecraft in space (Anderson, 2012).

Numerical simulations have been performed in accordance with spacecraft and plasma interaction in LEO environment assuming plasma as well as charged particles are Maxwellian distribution. This assumption, in most of cases, was taken to simply draw the form of interaction between spacecraft and plasma. Another question is raised of how significant ionospheric plasma impact on spacecraft in polar and equatorial regimes. In present paper, polar and equatorial satellites are categorized based on its orbital inclination (i) at which $i < 45^\circ$ for equatorial, whereas $i > 45^\circ$ for polar satellite.

The present paper aims to analyze the charging and spacecraft environment in polar and equatorial regions. In order to analyze environmental condition in aforementioned regimes, Electro Magnetic Spacecraft Environment Simulator (EMSES) has been used. EMSES was developed (Miyake & Usui, 2009) based on Particle-In-Cell (PIC) method. In this simulator, a large number of particles distribute around spacecraft in specific volume inside imaginary box and solvable through equation of motion. Moreover, the interaction between spacecraft and macro particles is solvable through Maxwell's equation.

Environmental condition around LEO spacecraft is depicted by ionospheric plasma parameters such as density and temperature in addition to magnitude of magnetic field. All those parameters are beneficial to analyze the level of charging on spacecraft including distribution of plasma ions and electrons around the charged object presented in present study.

2. The Methods

In this study, four LEO satellites, i.e. two polar and two equatorial, have been used as a case study listed in Table 1. Those satellites were selected since they were exposed to severe failures and appeared to be related to induction from on-orbit environment. Most of failures on satellites listed in Table 1 has been acclaimed to experience total loss or permanent failure, so that those satellites can not be operated anymore as seen through Satellite News Digest (SND) database (<http://sat-index.co.uk/failures/>). Notice that we can not assure that the total loss comes from the surface charging solely. The complex mechanism of anomaly might trigger the failure on spacecraft.

In spite of satellite data, ionospheric parameters such as plasma density as well as temperature were employed as the input parameters for EMSES simulation. The parameters attained from International Reference Ionosphere (IRI) 2016 model (Bilitza et al., 2017) were chosen coincided with the day of reported failure on spacecraft. The used plasma parameters can be seen in Table 2.

Density and temperature of plasma were taken according to altitude and local time of each LEO satellite obtained from IRI 2016 data shown in Table 3. Since IRI 2016 data also cover hourly data, the selection should be done in which the data can describe satellite environment at the time of satellite reported to experience failure. The aim of selecting param-

Table 1. LEO satellites attributed to failures

Satellite name	Orbital inclination (deg)	Altitude (km)	Failure
ERS 1	98	770	total loss
MIDORI	98	800	total loss
ASCA	31	570	total loss
FUSE 1	24	750	reaction wheel error

Table 2. Ionospheric plasma parameters used for simulation

Satellite	Failure date	Temperature (K)		Plasma density, n (m^{-3})	Type
		e^-	p^+		
ERS1	10 Mar 00	1458.2	1103	1.4853E+11	polar
MIDORI	24 Oct 03	1988.7	1562.7	7.8485E+10	polar
ASCA	15 Jul 00	1974.1	1261.3	3.1720E+11	equatorial
FUSE 1	25 Nov 01	2321.6	1670.1	1.6037E+11	equatorial

Table 3. Input parameters for EMSES simulation

Input parameters	Source
Plasma density (cm^{-3})	IRI 2016
Electron temperature (K)	IRI 2016
Ion temperature (K)	IRI 2016
Plasma flow speed (m/s)	Calculation (Mach 6)
Magnetic field (mT)	NOAA

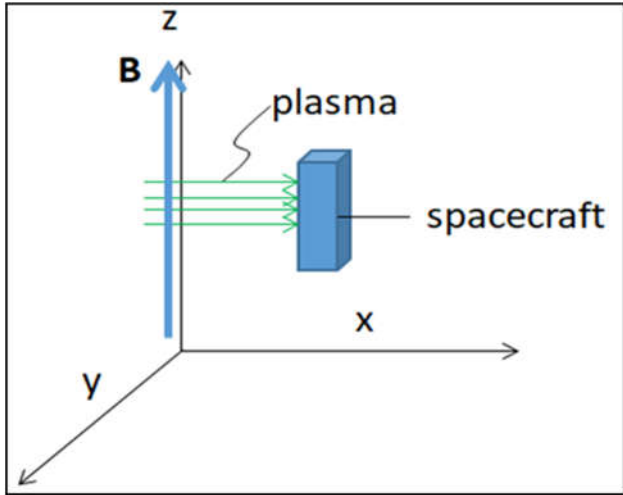


Figure 1. Interaction between spacecraft and ionospheric plasma

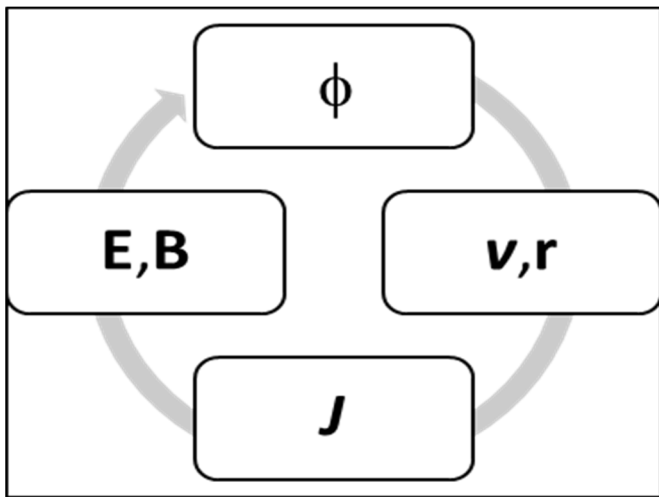


Figure 2. A brief computational scheme for spacecraft charging

ters during perturbed condition tends to see the form of interaction between satellite and local plasma in polar and equatorial regimes. In addition, simulation done during perturbed condition is more interesting in terms of charging than that of during quiet condition where the plasma effect is negligible.

The use of plasma density is related to Poisson’s equation to find the electric potential, together with the temperature of electron and ion which is strongly bounded to thermal velocity through the equation of motion of particles (Lorentz force). The magnetic field is applicable through Maxwell’s equations giving rise to the electric field and current. Since average orbital velocity of spacecraft in LEO environment is

of the order of 7-8 km/s, plasma flows correspond to ion acoustic wave, being comparable to mach 6. It gives rise to shock wave where the density of electron and ion dramatically changes compared to initial plasma density. Instead, the density at the rear side of the charged object is reduced in particular order compared to the front side. All aforementioned input parameters contribute to the current balance incoming to/outgoing from spacecraft materials resulting in charging.

In order to apply environmental parameters into simulation using EMSES, some assumptions have been used, i.e. ionospheric plasma flows toward the spacecraft, while the spacecraft is relatively fixed in the frame; spacecraft geometry is shaped-box resembling a slab with dimension 12 x 12 x 36 cm and lies on the center of the imaginary box. We should point out that the real size of spacecraft which is of the order of meter is impractical due to EMSES limitation. It means that we can only perform the simulation by assuming spacecraft as a slab of the order of centimeter; direction of magnetic field is perpendicular to spacecraft motion. The form of interaction between spacecraft and plasma can simply be illustrated through schematic diagram shown in Figure 1.

In Figure 1, B represents magnetic field in +z direction and plasma flows in +x direction. We set the direction of magnetic field and plasma flow corresponding to the $E \times B$ drift at which the flow direction is perpendicular to magnetic field (Baumjohann and Treumann, 1997). The impact of auroral electrons as well as photo electrons are neglected for practical purpose. It is important to note that the use of real geometry of spacecraft in simulation is really difficult due to time consuming process and needs larger space domain. Here, the volume of box domain is 128 cm^3 with the grid cell size of 1 cm and involving 5000 iterations in total. Due to plasma thermally flows in mesosonic motion in LEO, the speed of plasma ion can be approximated relatively constant with respect to spacecraft, thus plasma ion velocity is negligible. On the other hand, plasma electrons impact spacecraft from any directions with approximated thermal velocity 170 times ion thermal velocity. In the present study, we only performed simulation in particular direction for simplicity and computational scheme can be seen in Figure 2 (Taken from Miyake and Usui (2009) with a little modification).

In Figure 2, the position (r) and velocity (v) of particles, through the equation of motion, are used to get the current density (J) which is then used to obtain the magnetic field and electric field through Maxwell’s equations. The electric potential is acquired by imposing electric field through Poisson’s equation. The detail implementation of Maxwell’s equation, equation of motion and Poisson’s equation in spacecraft charging can be seen in Miyake and Usui (2009). In the present paper we focused on simulation by adopting some spacecraft as case study.

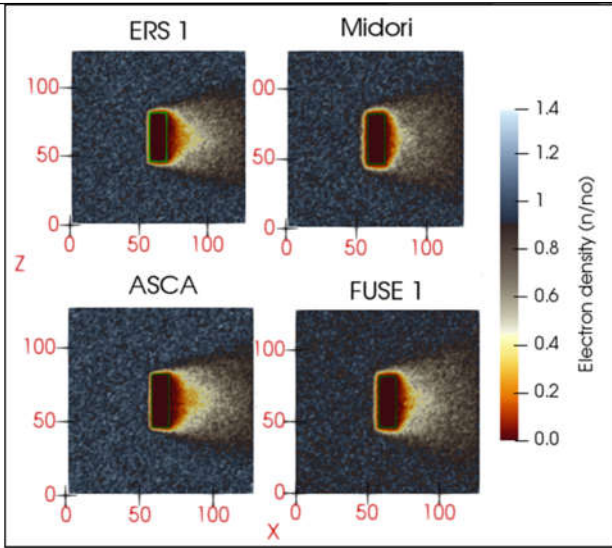


Figure 3. Distribution of plasma electrons around LEO spacecraft. The green-square indicates spacecraft position in the center of the simulation box ($58 \text{ cm} < x < 70 \text{ cm}$).

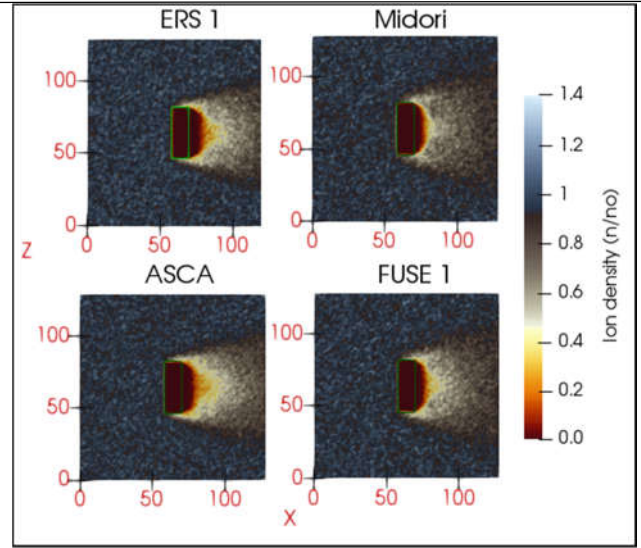


Figure 5. Distribution of plasma ions around spacecraft. Spacecraft position lies on grids $58 \text{ cm} < x < 70 \text{ cm}$ represented by green-square

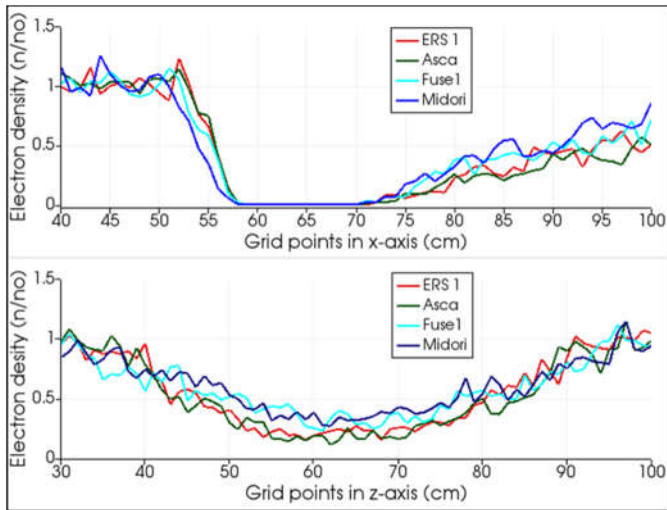


Figure 4. Electron distribution along horizontal (upper) and vertical (lower) direction of spacecraft motion. Part of simulation box is shown. Density (n) is normalized with initial plasma density (n_0).

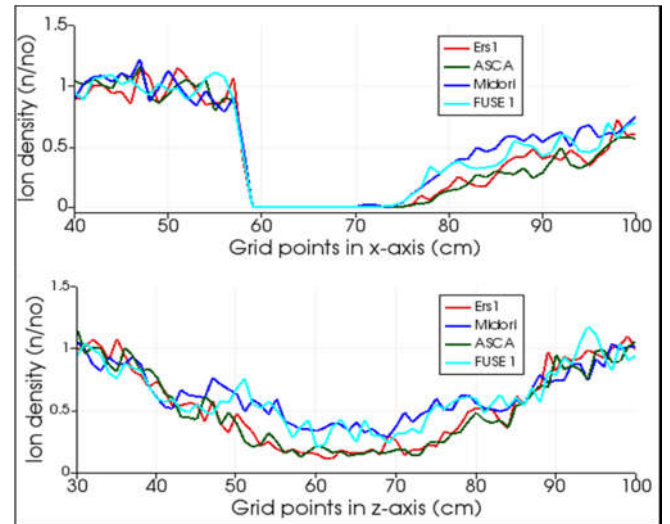


Figure 6. Plasma ion distribution along horizontal (upper) and vertical (lower) directions. Spacecraft location is at the center of simulation box ($58 \text{ cm} < x < 70 \text{ cm}$)

All simulations done in present paper satisfied mesosonic or mesothermal motion in which $V_i < V_{sc} < V_e$ (Hastings, 1995), where V_i and V_e represent thermal velocity of ion and electron, whereas V_{sc} indicates thermal velocity of spacecraft in LEO environment. In addition, the real mass ratio between ion and electron (m_i/m_e) in simulation is used to capture the real distribution of electron and ion in the vicinity of spacecraft especially in the downstream side of charged object (Engwall, 2004). As consequence, it takes time for ion to travel in one cell in simulation box domain compared to electron affecting convergence time.

3. Results and Discussion

In order to show the different forms of interaction, i.e. charging and plasma distribution, between plasma and four LEO spacecraft in polar and equatorial regimes, a phenome-

na called wake is introduced. A wake is formed due to mesosonic motion where incoming electrons impact spacecraft from any directions whereas ions can only impact the front side of spacecraft. As plasma ions travel and interact with spacecraft, a group of electrons will be absorbed by spacecraft material decreasing spacecraft potential resulting in negative charging. The currents balance will be achieved where ions accumulate in region at distance several Debye length from spacecraft surface. Since plasma ions travel slower than spacecraft orbital velocity, it takes time for plasma ions to fill up a region behind spacecraft leading to ion void region or wake region. Simulation done for LEO satellites in present paper showed that there is no significant difference between polar and equatorial satellites in terms of wake structure, indicated by electron distributions, as shown in Figure 3.

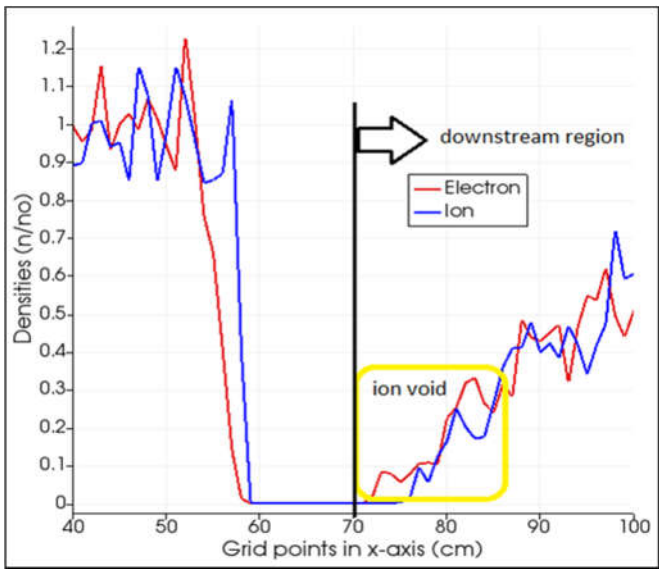


Figure 7. ion void region (yellow square) behind spacecraft. The density of plasma electrons is larger than that of plasma ions. The vertical black line represents the rear boundary of spacecraft’s surface at $x=70$ cm

In general, plasma electrons scatter at the same pattern where the enhanced wake is formed in the downstream side of the charged object. However, the density of plasma electrons at the wakefield (behind spacecraft) is reduced, compared to ram side (spacecraft front) as the electrons pass through the upper and lower edges of spacecraft. The detailed comparison of electrons distribution for LEO satellites can be seen in Figure 4.

In Figure 4 (upper panel), overall plasma electrons on polar satellites spread more elongated compared to equatorial satellites, but the average density is deducted around 2% at $x = 80$ cm. Moreover, this tendency is also seen along vertical direction (lower panel) where the density of plasma electrons on equatorial satellites is higher than that of on polar satellites. Note that spacecraft lies at the center of the box at grids 58 to 70 cm. In order to see the detailed structure of plasma around spacecraft, plasma ion distribution is also presented shown in Figure 5.

In Figure 5, overall plasma ions distribute in similar pattern to plasma electrons distribution where enhanced wake formed behind the spacecraft due to charge buildup over spacecraft surface. The density of ions in the downstream side decreases forming ion void region. As already mentioned that this is due to mesothermal motion of ion which slower than spacecraft orbital velocity leading to time lag for ion distribution behind spacecraft.

The distribution of plasma ions for each case of LEO spacecraft can be further seen through the line plot shown in Figure 6. There is no salient difference among four LEO satellites in terms of ion void region where ion density dramatically decreases. For instance, at point $x=90$ cm (upper panel) the average density of Far Ultraviolet Spectroscopic Explorer (FUSE 1; equatorial) is lower than that of MIDORI (polar), but somewhat higher compared to ERS 1 (polar). Further-

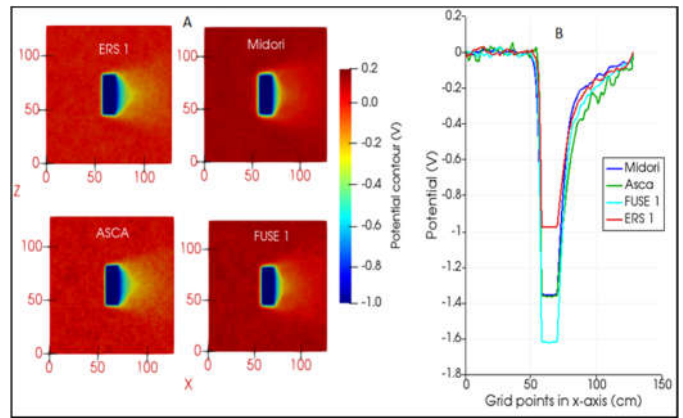


Figure 8. Potential contour of LEO spacecraft (A) and level of spacecraft charging represented by line plot (B). Spacecraft lies on $58 \text{ cm} < x < 70 \text{ cm}$.

more, this feature is also seen through line plot along vertical direction (lower panel) where average density of plasma ions on each LEO spacecraft insignificantly different.

It is of interest that the density of plasma electrons and ions in the downstream region declines monotonically toward the wake center around $z=64$ cm. It means that as the plasma flows into upper and lower edges of spacecraft, a group of plasma especially ions were attracted by spacecraft potential, whereas other groups of plasma travel further into downstream region. It explains why density of plasma on all line plots in Figure 6 (lower panel) have similar features. Plasma ions density drops gradually toward the wake axis from both edges. However, at some points plasma ions can conjoin together due to deflection of ion trajectories by electric fields along the wake axis.

In order to see obviously ion void region behind spacecraft, a line plot indicated the density ratio between electrons and ions is presented as shown in Figure 7. Since the pattern of ion void regions is quite similar for four satellite cases, thus only ERS 1 satellite case is taken to be presented in this paper. It is clear from Figure 7 that the density of electrons is higher compared to ion density. Since electrons more mobile than ions, they can impact on spacecraft’s surface from any directions. On the contrary, ions can only impact from particular direction which is from spacecraft front flowing with drift velocity around 6.5 km/s. As consequence, a shockwave is created in front of spacecraft indicated by increasing ion density due to electric field. Here, ions are accelerated by electric field toward spacecraft explaining collection of ions in front of the charged object. This is why density of ions (blue line) is larger than that of electrons (red line) in the front side.

The structure of wake found in the present paper (see Figure 5) has a good agreement with other findings in which a charged object, such as spacecraft, placed at low Earth orbit environment experiences mesosonic motion leading to a decrease of plasma density especially plasma ions. Another simulation (Wang, et al., 1994) showed that plasma density

decreases behind the plate, placed at LEO environment, forming triangular -shaped ion void (see Figure 3, upper panel in their paper) resembling the features shown in Figure 5. They invented that both density of ion and electron drops monotonically towards the wake axis. The similar feature found by Engwall (2004) where the density of plasma decreases behind a single boom (see Figure 11 in their paper) and an area of ion void formed inside the wake.

The distribution of plasma electrons and ions is strongly related to spacecraft potential. If spacecraft is charged positively, thus electrons will be directed and accelerated by electric field toward the spacecraft. Conversely, if spacecraft is charged negatively, ions will be scattered affecting on ion void or ion focus region formation. In present paper, how effective ionospheric plasma contributes to charge four LEO satellites can be seen in Figure 8.

It is shown through Figure 8 that level of charging on polar satellites differs from equatorial satellites in which overall equatorial satellites have lower potential compared to polar satellites. The level of charging is strongly depending on electron temperature rather than plasma density. The more electron temperature increases the lower potential on spacecraft, and vice versa. It explains ions recollection behind spacecraft shown in Figure 5 in which the more spacecraft exposed to negative charge the more ions trajectories deflected and attracted toward spacecraft surface. In this simulation, it is clear that electron temperature plays an important role in driving spacecraft potential.

It can be shown that there exists insignificant different of charging on polar as well as equatorial satellites in the perspective of density changes shown through ion void region formation and charging level represented by spacecraft potential. All simulations done on aforementioned satellites show that charging level on spacecraft depends on plasma electron temperature. Due to its mobility, plasma electrons impact on spacecraft surface more frequent than plasma ions leading to negative charging. As the current balance is settled up, the net charging on spacecraft then drive plasma ions distribution giving rise to ion void region formation where inside this region the density of ions dramatically decreases compared to electrons density.

The levels of charging on LEO spacecraft in present paper can be categorized as low level charging which are less than 3V (negative) even though simulations done using environmental parameters during disturbed condition. It can be inferred that the level of charging on both polar and equatorial satellites is independent on satellite altitude and inclination. However, in some occasions polar satellite can be exposed to high-voltage charging during its auroral oval passage. It has been shown through numerous studies such as in case of Defense Meteorological Satellite Program (DMSP) (Colson & Minow, 2011) and FREJA (Cooke, et al., 2016) satellites charging.

The nominal level of charging which is less than 5V on spacecraft in LEO environment also has a good agreement with particular simulation (Wang, Qiu, & Qin, 2008) using small KAPTON box and large aluminum box (see Figure 3 in their paper). They found that both boxes were exposed to low level negative charging around 3.6 V (large box) and 5.5V (small box). This similar finding was also certified by Engwall (2004) which presented low level negative charging behind the tilted boom (see Figure 12a and b in his paper) where the obtained minimum potential of -0.8 V. Although the simulation was quite different compared to the present study, the electric potential in the downstream region (wake) showed conformable agreement in which LEO spacecraft, in the absence of auroral electrons, were exposed to insignificant charging.

As previously mentioned, that we imposed some assumptions to perform simulation to get the structure of wake as well as the level of charging on LEO satellites. However, we should accentuate that all results obtained from this simulation are valid along with the assumptions drawn in this study. For instance, the exclusion of auroral electrons and the choose of spacecraft geometry might affect the level of charging including the wake structure behind the charged object like spacecraft. The presence of auroral electron can charge the spacecraft in extreme level of the order of kilovolt (kV), while the wake structure turns out to be ion focusing of which the density of ions rapidly increases. However, in the present paper we only focus on presenting the spacecraft-plasma interaction in LEO environment apart from extreme condition.

Conclusion

Numerical simulations have been done to investigate the level charging on four LEO satellites during perturbed condition. Plasma parameters employed as input for EMSES simulation describes the strength of interaction between plasma and spacecraft through electric potential. Moreover, the interaction also affects plasma distribution in the vicinity of spacecraft. The inclusion of plasma effects taken during the day of failure on LEO spacecraft gives rise to low-level charging which is less than 3V (negative) and there is no significant different of charging between polar and equatorial satellites.

The level of charging on spacecraft is purely driven by plasma electron temperature rather than plasma density. The higher electron temperature the lower electric potential on spacecraft. It is also obvious that level of charging is independent on satellite orbit, e.g. altitude and inclination. Although plasma density is altitude dependence, it seems that its contribution to charge the object is not as high as electron temperature known through the present simulation.

Another interesting feature is the presence of ion void region due to mesothermal motion of plasma around spacecraft. There is no significant different of ion void feature between polar and equatorial satellites. Initially, it was expected that ion void feature on polar satellites is more elongated and plasma ions reduced sharply than those of equatorial satellites. This feature is fairly irregular. Thus, it can be concluded that the impact of ionospheric plasma on polar and equatorial satellites, through charging, results in insignificant charging.

Abbreviations

LEO: Low Earth Orbit

ERS: European Remote Sensing

ASCA: Advanced Satellite for Cosmology and Astrophysics

FUSE: Far Ultraviolet Spectroscopic Explorer

EMSES: Electro Magnetic Spacecraft Environment Simulator

PIC: Particle-In-Cell

SND: Satellite News Digest

IRI: International Reference Ionosphere

NOAA: National Oceanic and Atmospheric Administration

DMSP: Defense Meteorological Satellite Program

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