Fluctuation of Satellite Charging in the Low Earth Orbit Regime due to Interaction with Ionospheric Plasma

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Abstract. Low Earth-orbiting satellites will always interact with the ionospheric plasma, leading to disruption of satellite operations, depending on the impact of the interaction. Under normal circumstances (without interference), the magnitude of the fluctuation in satellite charging is less than 5V (negative). Any disturbance from charged particles will cause the satellite to experience a more drastic voltage drop of the order of a few hundred volts (negative). The identification of fluctuations in satellite charging is carried out by reviewing the space conditions around the satellite, characterized by several parameters such as density, energy, and plasma temperature, as well as the saturation density of the satellite. To strengthen the analysis, this study deepens the flux changes with an energy of the order of MeV along the satellite orbit. The results of the study show that several low-earth orbit satellites experience a fairly high saturation density, which is correlated with fluctuations in electron flux in some regions traversed by the satellite, such as the polar and the SAA regions. The results confirm that the two regions could be a danger zone for both polar and equatorial satellites.

1. Introduction
Satellite charging is one of the primary contributors to the damage or anomalous behavior of satellites in orbit [1-2]. In general, the phenomenon of satellite charging is caused by the interaction of the satellite with energetic particles and ambient plasma, which is mostly protons and electrons [3]. The dominant interaction of particles on Geosynchronous Earth Orbit (GEO) satellites, around 36,000 km altitude, is caused by charged particles (energetic particles), while the contribution of ambient plasma is negligible [4].

Conversely, satellites placed in Low Earth Orbit (LEO) experience different interactions compared to GEO satellites [5]. The dominance of randomly moving electrons becomes the main contributor to the current equilibrium interacting with the satellite. In this case, the thermal velocity of the plasma electrons is much larger than that of the plasma ions \((V_{\text{th e}} \approx 43 \ V_{\text{th i}})\). In the case of satellites placed in the LEO regime, the motion of the plasma ions is lower than that of the satellite, so that its motion is relatively constant in the satellite's frame [6]. The difference in plasma thermal velocity and satellite orbital velocity in the LEO environment leads to an effect called mesothermal, which causes the plasma density to fluctuate in the vicinity of the satellite [7].

It is well known that satellites placed in the LEO regime have an average speed of 7.5 km/s, which is equivalent to Mach 6 [8]. The orbital velocity of the satellite, which is much larger than the thermal velocity of the plasma ions, causes the effect of plasma ions to be insignificant, thus its contribution is often neglected in every simulation [9-11]. The present study is preferably focused on the interaction of plasma electrons and satellites. Given that the plasma electrons are very dynamic, especially during the magnetic storm events, the impact of the interaction will also be different in each anomaly case.
Knowing the dynamics of the space environment, especially around satellite orbits, is very important to identify potential damage to a satellite [12]. In this study, an analysis of the space environmental conditions around the LEO satellite orbit is carried out using several parameters characterized by the ambient plasma, in addition to identifying the impact of its interaction on the satellite surface. The parameters used in the present study are taken according to the altitude of the satellite in the absence of perturbation from the earth's magnetic field. The aim of the present study is to determine the magnitude of the overall charging experienced by the satellite. Notice that the interaction mechanism only comes from the ionospheric plasma without involving the influence of charged particles (aurora). Thus, the magnitude of the satellite charging is shown by the current balance incoming to or outgoing from the satellite.

2. Data and Method

Satellite data (http://www.sat-index.co.uk/failures/) and environmental parameter data are the two types of data used in this study. Satellite data includes object identity and its orbital parameters, while environmental data consists of density and ambient plasma temperature (https://omniweb.gsfc.nasa.gov/), in addition to the magnitude of the magnetic field (https://www.ngdc.noaa.gov/geomag). The environmental parameter data was taken at the time the satellite experienced an anomaly. The format of these two datasets can be seen in table 1.

| Object   | Height (Km) | Temperature (K) | Electron density, Ne (m⁻³) | Magnetic Field (nT) |
|----------|-------------|----------------|----------------------------|---------------------|
| ERS1     | 788         | 1458           | 1103                       | 1.5.10¹¹            | 26,967              |
| Terra    | 703         | 1235           | 1053                       | 1.1.10¹¹            | 22,428              |
| Fuse1    | 754         | 2322           | 1670                       | 1.6.10¹¹            | 21,337              |
| Aqua     | 704         | 2116           | 1473                       | 4.7.10¹⁰            | 25,742              |
| Orbcom   | 759         | 1345           | 1176                       | 2.4.10⁹             | 23,635              |

The satellite data used in this study comes from satellites placed at an altitude of 700-800 km above the earth's surface. Notice that the altitude region chosen in this study is the region with the densest population (> 600 km) of low Earth-orbiting satellites [13]. The SPENVIS (SPace ENVironment Information System) device is used to simulate particles and satellites using all of the data in table 1. The simulation performed by SPENVIS can be described by a schematic diagram as shown in figure 1.
Figure 1. The schematic diagram for analyzing the fluctuation of charging on LEO satellites

In the present study, the orbital trajectory of the satellite was determined using the model in SPENVIS \[14\] by assuming the orbit of the satellite is circular without any disturbance. For the initial stage, the orbit trajectory is selected to have only 1 segment with a total duration of 1 year. This step is aimed at facilitating the analysis of charging fluctuations, in which the shorter the duration, the easier the analysis process. The time range chosen was to coincide with the solar storm event on July 14, 2000 \[15\] to July 14, 2001. During this period, it was found that a high increase in solar radiation had an impact on changes in density and temperature in the ionospheric layer. Considering the analysis period of 1 year, the orbit characteristics such as altitude, \textit{Right Ascension of Ascending Node}, and \textit{Argument of Perigee} will also fluctuate. The orbital characteristics and the fluctuations of the environmental parameters are simultaneously employed to ensure the fluctuation of the particle flux around the satellite orbit. The results of the data input, as well as the particle model, can be seen more clearly in the next section.

3. Results and Discussion
An investigation of the environmental parameters in the LEO orbit was carried out in order to see the fluctuation of charging on the satellite used in the present study. The first investigation focused on analyzing the variation of the atmospheric density through the plasma electrons and neutral particles shown in figure 2. Plasma electrons are used in relation to the current equilibrium interacting with the satellite, while neutral particles are related to ionization processes that affect the characteristics of the plasma in the atmosphere. The plasma density was set to be an input parameter in the simulation concerning the plasma and satellite interaction, which is the main focus of this study.
In Figure 2, it can be seen that the high density of electrons and neutral particles is dominant at altitudes below 400 km. Notice that many satellites are placed at an altitude above 400 km. However, the contribution of neutral particles to the satellite charging process is insignificant and can therefore be neglected. Therefore, in each simulation, the effect of neutral particles was only considered when the satellites wandered at an altitude of about 200-300 km from the Earth's surface. Considering that neutral particles play a role in the ionization process, it results in plasma ions that also contribute to achieving a current balance on satellites. In this case, the next investigation needs to look at the temperature variations in the LEO regime as shown in Figure 3.

In Figure 3, the plasma temperature tends to increase up to an altitude of 1000 km from the Earth's surface. Therefore, the form of plasma interaction on the satellite can be categorized as mesothermal in the sense that the magnitude of the charging, apart from being density-dependent, also depends on the plasma temperature. Several simulations showed that the higher the density, the lower the satellite's electrical potential. This relation also applied to the temperature, even though it did not always have a good agreement with a potential decrease in every simulation. This indication shows that the interaction between the satellite and ambient plasma should be investigated based on the satellite placement area. As an example, a satellite placed in polar orbit will be slightly different from a satellite in equatorial orbit in terms of the effects of interaction due to the presence of high-energy particles in polar regions.
Figure 3. Temperature variation of plasma electrons and ions in LEO environment.

The contribution of plasma energy to the charging process or the current balance on a satellite is also an important factor in analyzing occurrences of satellite anomaly events. Since the energy of plasma is strongly related to temperature, the plasma energy tends to increase with temperature. In some cases, this energy level reflects the magnitude of the satellite's electrical potential that will be experienced by the satellite in the absence of perturbations.

Generally, in the pre-simulation stage, the amount of charging suffered by the satellite can be seen from the amount of plasma energy. For instance, a satellite placed in an orbit of about 600 km will experience a charging or potential drop of about 0.24V (-0.2V). However, in the presence of disturbances that cause the energy and temperature of ambient plasma to increase, the potential drops can be more extreme, on the order of thousands of volts.

It is interesting that the amount of saturation experienced by satellites in low-Earth orbit appears to be closely related to the density. The saturation level shows the magnitude of the current in the satellite as an interaction with the ambient plasma. A high current saturation indicates that there is a variation in the main voltage from the normal condition. Considering that the normal power consumption is designed within a certain range, the magnitude of the deviation, as a result of interaction, can be an indicator of the performance of the electrical component. The variation of saturation in the LEO regime can be seen in figure 4. It is important to note that the current density saturation in different areas will give different magnitudes of interaction. For instance, the saturation at the front of the satellite (ram) tends to be higher than that at the back of the satellite (wake). However, this condition is not fully satisfied, and thus needs further investigation.

Another important point is the saturation current density experienced by satellites in polar orbits, which is different from that in equatorial orbits. In figure 5, the current density saturation is plotted globally without considering the case-by-case saturation of each satellite anomaly listed in table 1.
It is well known that a low-orbiting satellite's position changes over time. It leads to LEO satellite passes through areas with high or low particle populations. In the present study, the satellites used as a case study frequently pass through a region with varying particle fluxes, as shown in figure 5. It should be noted that the flux variation in figure 5 was obtained by examining higher energy levels of the order of MeV, which can cover the entire satellite path during the selected period. An increase in flux predominantly occurred in the high latitude (polar) and some equatorial regions, e.g., South Atlantic Anomaly (SAA). The variation of fluxes is also generally used to assess the impact of charged particles on satellites. High-energy and flux particles give rise to a potential drop on the satellite. In an extreme case, the satellite could stop operating permanently. In the case of the satellites in table 1, the level of damage varies from partial to total failures.

The profile of particle distribution shown in figure 5 further shows that there are only two regions that are very crucial to driving a potential drop in the LEO regime, i.e., the polar and SAA regions. In general, the energy and flux levels in figure 5 give a voltage change of the order of $10^2$ V (negative charging). Low-orbiting satellites such as ERS 1 and FUSE 1 that suffered serious damage were estimated to have a flux variation shown in figure 5. The remaining satellites, such as Terra, Aqua, and Orbcom X, suffered partial failures associated with an increase in particle flux on the order of $> 20$ keV.
4. Conclusion

The placement of a satellite in space, in spite of affecting its operational lifetime, can also influence its components, systems, or the satellite as a whole. High-energy particles and ambient plasma scattered around the satellite can have a significant effect on the satellite. One of the main contributors to satellite failures or anomalies in space is the charging effects as a result of the interaction between the satellite and ambient plasma. Satellites placed in low earth orbit will interact with the ionospheric plasma for a certain duration, which causes the satellite’s electrical potential to decrease. In the absence of perturbation, the average drop in electric potential is less than 5V (negative). However, in the presence of perturbation from high-energetic particles, the satellite’s electrical potential can decrease dramatically to the order of $10^2$V (negative).

The fluctuation of charging on satellites can be identified through the variation of saturation current density, characterized by several parameters such as density, temperature, and fluxes of plasma electrons and ions. The results of the present study show that the variation of saturation current density is closely related to the variation in plasma density, such that the higher the plasma density, the saturation will increase, giving rise to surface charging on the satellite. In addition, the flux distribution showed that some satellites used as a case study passed through polar and SAA regions with high electron flux. Because density and flux are closely related, it can be inferred that when low-Earth orbiting satellites, as shown in table 1, pass through a high flux area, the saturation current density will also be maximum. This condition can affect the satellite system, leading to a partial or total loss.
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