CHARGING SIMULATIONS FOR A LOW EARTH ORBIT SATELLITE WITH SPIS USING DIFFERENT ENVIRONMENTAL INPUTS

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ABSTRACT

In the different standards for space plasma environments as well as in well-established tools for the assessment of spacecraft charging effects like the SPENVIS tool there are multiple different plasma definitions given for a low earth orbit (LEO) auroral worst case environment. In this paper 3D charging simulations of a LEO satellite with body mounted solar arrays (SAs) are presented using four different plasma environments. The simulation results show a wide range of possible charging states of the satellite ranging from basically uncritical situation up to results showing high potential gradients with a high possibility of discharges. The results of the performed simulations are aimed towards a consolidation of the environment definitions for updates to come of the corresponding environmental standards in Europe to be applied by industry in the design of LEO polar orbiting spacecraft.

1. INTRODUCTION

Spacecraft charging to high potentials including large gradients on the satellite surfaces can cause electrostatic discharges (ESD) which can lead to local damage of surfaces or even to complete loss of the satellite. These effects were first observed on high altitude satellites in the geosynchronous orbit and a lot of work has been devoted to the study, analysis and prediction of these effects. For satellites orbiting the earth in LEO spacecraft charging has not been a topic of special interest. However, anomalies observed on the DMSP satellite program have been traced back to be caused by ESD due to strong differential charging of the satellite in the so called auroral oval [1].

This region has to be passed by all polar orbiting LEO satellites. So, it is of interest for satellite manufacturers to be able to assess the risks imposed by surface charging as well as to analyse different methods for risk mitigation. With the recent availability of dedicated simulation tools for the 3D simulation of spacecraft charging effects like the SPIS tool [2] in Europe, the main focus lies on the correct definition of the ambient plasma conditions to be used in the simulations. However, the plasma definitions which can be found from different sources like the ECSS standard [3], the ESA supported online tool SPENVIS [4] as well as values used in simulations of the DMSP charging [5] differ remarkably both for the high energy particle spectrum as well as the cold background plasma.

In this paper the mentioned environmental inputs from the different sources will be used as input for SPIS simulations of a generic LEO satellite with body mounted solar array (SA). Utilizing this methodology the quantitative impact of the different environment definitions can be analysed and the calculated potentials as well as potential gradients can be compared against values reported in literature.

The paper is organised as follows: In section 2 the satellite model along with the basic settings for the SPIS simulations is given. The different plasma environments used in the simulations are given and explained in section 3 followed by the presentation and discussion of the results of the simulations in section 4. The conclusions are given in section 5.

2. SIMULATION SETUP

2.1 Satellite Model

For the analysis in this paper the satellite model shown in Figure 1 has been generated, where the colours correspond to the surface materials listed in Table 1.

The model shows the typical features of an earth observation satellite with an accommodation of the SAs in a roof top like configuration which is typical of LEO satellites with a drifting polar orbit. On the NADIR side some details are included in the model representing the antennas for telemetry and telecommand (TMTC) as well as an antenna for the payload data transmission. One big dish antenna as well as a phased array antenna at the front side of the satellite are incorporated into the model to account for the scientific instruments installed on the platform.

Colour	Description	SPIS Material
Red	Antennas PSG121 White Paint	PSG120
Blue	Thermal Control MLI Kapton 50 µm	Kapton
Green	Thermal Control Radiators Teflon 125 µm	Teflon
Yellow	SA structure, bare epoxy	Epoxy
Cyan	Solar Cells	CERS

Table 1: Assignment of the surface material properties and the corresponding SPIS materials for the satellite model

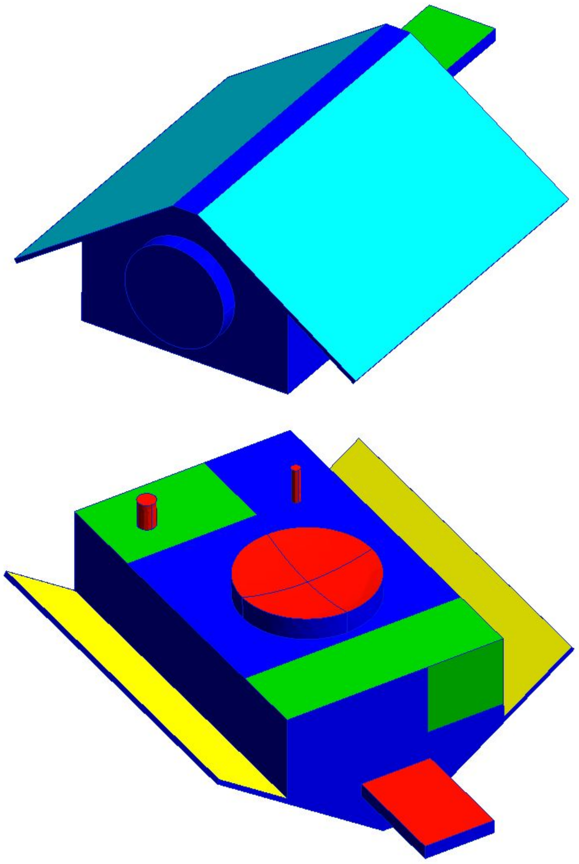

Figure 1: Satellite model used for the simulations; rear space view (top), front NADIR view (bottom)

2.2 Numerical Settings of the SPIS simulations

For the simulation of the charging of a satellite in the LEO auroral plasma the electrons are modelled using the Maxwell-Boltzmann fluid model. This is needed since a modelling with the particle in cell (PIC) method with the very short time steps needed for the fast electrons would lead to unpractically high simulation times. The ion population is included in the SPIS model using the PIC method. For the typical LEO altitude of about 800 km Oxygen ions are used for the simulations. The PIC model is mandatory for the ions in order to be able to correctly address the satellite velocity of 7000 km/s leading to the ram/wake effect influencing the ion collection.
All simulations shown in this paper are carried out considering eclipse, which is one of the main conditions needed for critical charging in LEO orbits. So, photoemission is deactivated in the simulations. Secondary electron emission both from electrons as well as protons is considered in the model.
The duration of the simulations is set to 60 s which corresponds to the typical time a polar orbiting satellite needs to pass through the dedicated auroral ovals where the worst case plasma conditions are present.

3. PLASMA ENVIRONMENT DEFINITIONS

In this chapter the different plasma definitions used for the simulations are described. There are in principle two different definitions used for the high energy auroral electrons which are combined with two different densities for the cold background plasma present in LEO orbits. This then results in four different plasma definitons for the simulation of the surface charging of the satellite.

3.1 SPENVIS Fontheim Environment

The first definition for the high energy electrons is derived using the pre-defined plasma environment in the SPENVIS tool [4] called "Cold single Maxwellian and Fontheim electrons" (Fontheim). The definition given in the SPENVIS tool is a discrete particle density for different energy bands. The given electron density distribution is no Maxwellian distribution. So, for the use in the SPIS tool the population has to be fitted by a Maxwellian plasma distribution.
This fitting has been performed graphically with the constraint that the total particle density in both models shall be the same. The results of the fitting are presented in Figure 2. It can clearly be seen that the Maxwellian low energy distribution is perfectly fitted while the high energy electron part is not perfectly matched to the SPENVIS values. However, since the high energy maximum is reproduced quite well the chosen fit is considered to be representative for worst case simulations in this environment.
The Fontheim high energy electron spectrum will be used in the simulations with the initial fitted low energy background plasma and a reduced cold plasma density of 125 cm^{-3} as stated in [3]. All used environment definitions are summarized in Table 2.

3.2 ECSS auroral Environment

The high energy auroral electron distribution as specified in the current ECSS standard [3] is defined in phase space by a function defined in sections with a constant particle density for energies below a certain

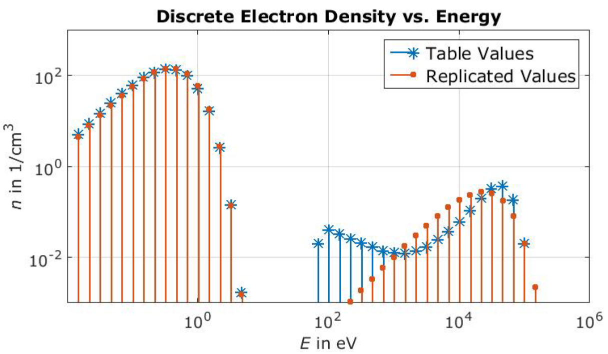

Figure 2: Fitting of the SPENVIS Fontheim plasma (blue stars) definition by a Maxwell Boltzmann distribution (red dots) needed for the SPIS simulations

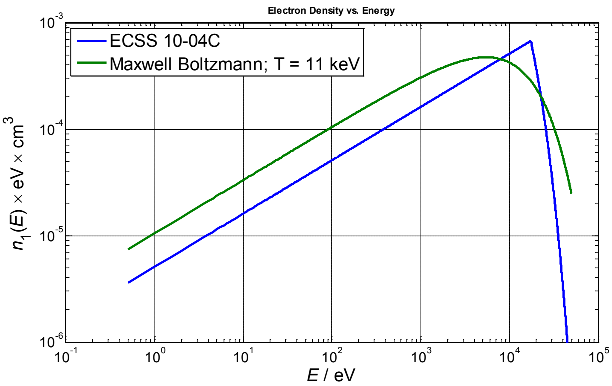

Figure 3: Fitting of the ECSS auroral electron distribution (blue) with a Maxwell Boltzmann distribution (green) needed for the SPIS simulation

threshold and an exponentially falling tail for the higher energies. For a use in the SPIS software this distribution has to be fitted using a Maxwell Boltzmann distribution. The fitted curve in comparison to the original distribution is shown in Figure 3. The energy of the peak in the Maxwellian distribution has been chosen at slightly lower energies than in the ECCS curve to address for the increased particle density at higher energies produced by the Maxwell-Boltzmann distribution.

The high energy spectrum is again used with two different plasma densities for the cold background plasma derived by the requirement of 125 cm^{-3} given in [3] and a value of 3000 cm^{-3} as reported in [5].

3.3 Qualitative Comparison of the Environments

The parameters of the four described plasma environment which will be used for the simulations of the generic earth observation satellite in SPIS are summarized in Table 2.

The inspection of the values given in Table 2 reveals that the different environments which are derived from the various sources are differing significantly.

Plasma Definition	Population	Density in cm^{-3}	Energy in eV
SPENVIS Fontheim	Ions 1	812.4	0.2156
	Electrons 1	809.9	0.2156
	Electrons 2	1.482	12940
Fontheim; ECSS cold background	Ions 1	125	0.2
	Electrons 1	125	0.2
	Electrons 2	1.482	12940
ECSS	Ions 1	125	0.2
	Electrons 1	125	0.2
	Electrons 2	10.78	11000
ECSS; Cooke cold background	Ions 1	3000	0.2
	Electrons 1	3000	0.2
	Electrons 2	10.78	11000

Table 2: Summary of the Maxwell-Boltzmann parameters used for the simulations

So, the ECSS environment is very harsh with a density of the high energy electrons being a factor of 8 higher than in the Fontheim environment. This increase in the high energy electron density is accompanied by a reduction of the cold background plasma by a factor of nearly 6 leaving less low energy ions for compensation of negative charging potentials. Although Cooke [5] used a very similar high energy particle density as the one given in ECSS the density of the cold background plasma is increased by a factor of 24. So, it is expected that the results for the surface potentials on the satellite will vary strongly.

4. SIMULATION RESULTS

In the following sections the results of the 3D SPIS simulations for the derived plasma parameter inputs are presented. As already mentioned in the brief discussion of the Maxwellian plasma parameters, the results of the charging simulations show a wide variety of surface potentials.

4.1 SPENVIS Fontheim Environment

The time dependant results calculated for this environmental input are shown in Figure 4. The potentials on the satellite surfaces assume moderate to low values and approach the equilibrium state already within the simulated time span of 60 s. The structure ground potential reaches a value of about -130 V. This directly reveals an inverted potential gradient (IPG) of 130 V on the SA since the averaged surface potential on the cover glass is close to 0 V.

The averaged surface potentials on the surfaces on the satellite body are all in the range of -130 to -220 V which indicates no further critical charging states.

The spatial potential distribution after 60 s on the satellite is given in Figure 5. It can be seen that the potential on the Kapton surfaces can locally drop to values below -200 V, especially on the rear side where the surfaces are in the wake. The lowest potential on the satellite is visible on the edges of the deployable solar array panels where potentials down to -420 V are visible.

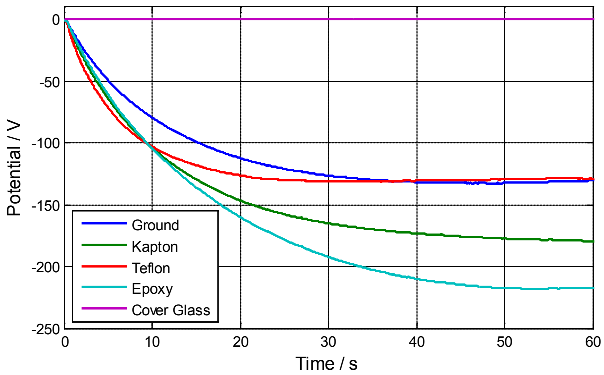

Figure 4: Time dependent averaged surface potentials on the satellite model for the SPENVIS Fontheim plasma

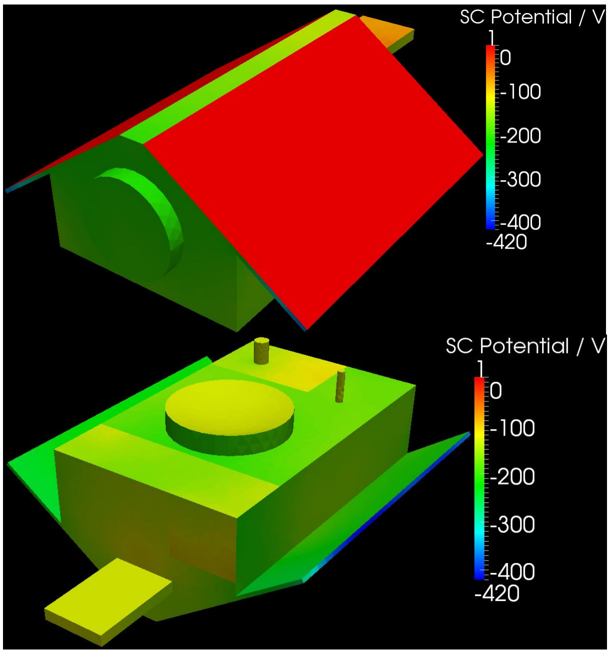

Figure 5: Spatial surface potential distribution on the satellite after 60 s exposure to the Fontheim plasma; rear SPACE view (top), front NADIR view (bottom)

The criticality of the simulated charging in this environment can be considered to be very low, since the direct potential gradients (DPGs) are well below the ECSS threshold of 1000 V. The IPG is only slightly above the ECSS value of 100 V which is considered very conservative. It is expected that the satellite can be operated in the simulated plasma definition without any additional design measures.

4.2 SPENVIS Fontheim with ECSS cold background

The charging in this environment with reduced cold background plasma density is more critical as can be directly seen in the surface potential given in Figure 6. The potentials drop very fast and the equilibrium state is not reached in the 60 s simulation time. The structure potential is drops down to -640 V and the averaged surface potentials on the satellite body reach values as low as -1 kV whereas the cover glass potentials are still close to 0 V due to the strong secondary electron emission.

The surface potential distributions in Figure 7 show a minimum surface potential of -1.1 kV on the radiator surfaces. Although still visible, the influence of the ram and wake effect is less pronounced in this scenario.

The decrease of the cold background plasma density leads to a large influence on the charging of the satellite. The reduced amount of ions available for the compensation of the negative charging caused by the auroral electrons leads to much more critical potentials. So, the IPG is now increased to 640 V, where the triggering of primary arcs on the SA has to be considered. The direct potential gradients have also increased, however, the threshold values are still not violated so that no electrostatic discharges (ESDs) are expected on the satellite body.

The increased criticality of the simulated charging results implies that in this case the satellite design has to be done with more care regarding the mitigation of and the robustness against charging effects. So, it has to be assured that the SA is able to withstand the expected ESDs without permanent damage and design measures for the avoidance of secondary sustained arcs have to be taken. Additionally, choices of the used surface materials could be reviewed. The usage of conductive ITO coatings on the radiator surfaces can help to limit the negative charging of the structure which then directly also leads to a reduction of the dangerous IPG observed on the SA.

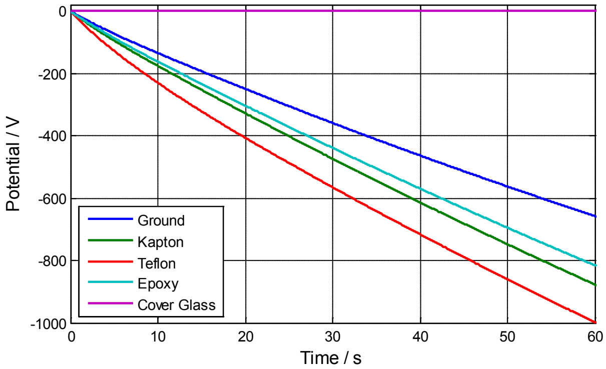

Figure 6: Time dependent averaged surface potentials on the satellite model for the Fontheim plasma with reduced cold background density

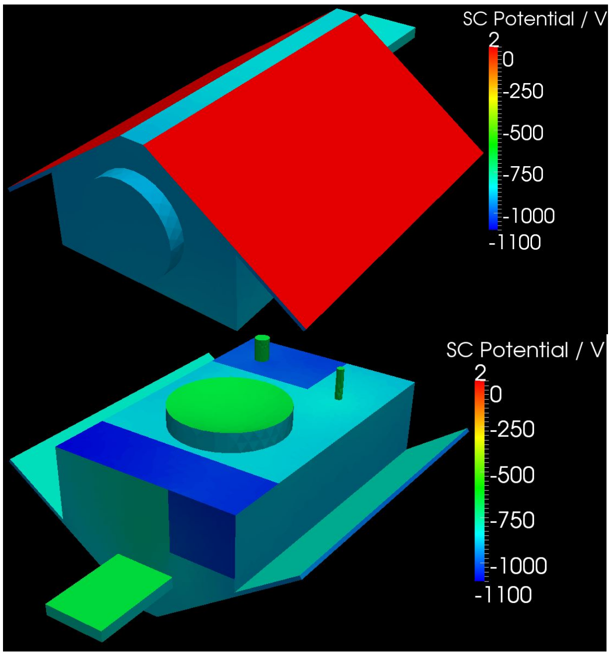

Figure 7: Spatial surface potential distribution on the satellite after 60 s exposure to the Fontheim plasma with reduced background plasma density; rear SPACE view (top), front NADIR view (bottom)

4.3 ECSS auroral environment

It is expected that the plasma definition as given in the current version of the ECSS standard [3] will lead to the most critical charging potentials. The structure potential in this environment definition drops to a value of -4kV after the final simulation time of 60s as can be seen in Figure 8. However, even after a very short exposure time of only 10 s the structure potential already reaches a critical value of -1 kV. The potential on the solar array cover glasses is still very close to 0 V which leads to IPGs directly corresponding to the calculated structure potentials. The averaged surface potentials on the dielectric surfaces on the satellite body show now also strong differential charging on the order of several kV between individual materials.

The spatial surface potential distribution given in Figure 9 shows, that the minimum potentials are on the order of -7.3 kV on the radiators and -5.3 kV on the Kapton parts of the surface.

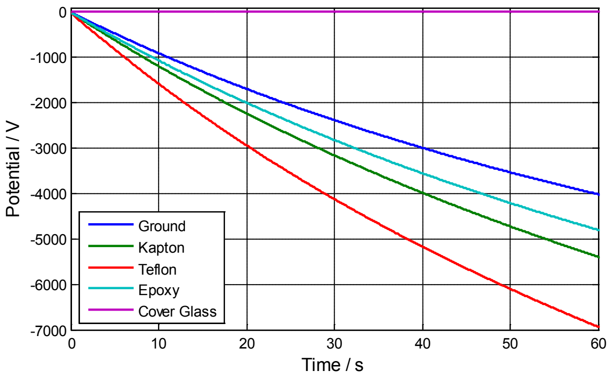

Figure 8: Time dependent averaged surface potentials on the satellite model for the ECSS auroral plasma

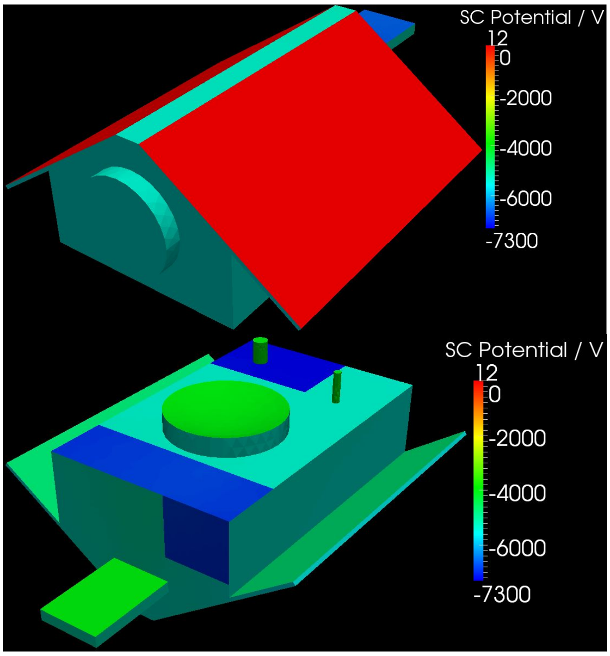

Figure 9: Spatial surface potential distribution on the satellite after 60 s exposure to the ECSS auroral plasma; rear SPACE view (top), front NADIR view (bottom)

The charging in this environment has to be considered very critical with the possibility of ESDs both on the satellite body and the SA. Due to the very high potential gradients present in this environment the triggered arcs are expected to be more hazardous since the amount of stored energy is increased.

It is not expected that simple design measures as described in the previous section are suited for the risk mitigation in this environment. The only possibility in this environment for mitigation of the risks is to cover the complete satellite with conducting materials to eliminate the potential differences. This is usually possible for the radiators and satellite body, however, possibly impacting the thermal design of the satellite. For the solar arrays an ITO coating on the cover glasses would have to be implemented which creates a large effort in the construction and causes additional power losses due to the coating.

4.4 ECSS electrons with Cooke background density

In this final simulation case the high energy auroral electron spectrum defined by ECSS [3] is combined with the cold background plasma density reported by Cooke [5]. The time dependant charging potentials show a structure potential after 60 s of around -630 V leading to a corresponding IPG on the SA. The surface potentials of the other dielectric surfaces do not show any gradients to the structure exceeding the 1000 V threshold, however, it has to be kept in mind that the curves show averaged values.

The spatial surface potential distribution after 60 s is given in Figure 11. In the dense background plasma the ram/wake effect is again clearly visible in the results. So, the Kapton surfaces on the front of the satellite assume potentials around -100 to -200 V whereas the same material on the rear part of the satellite charges to -1.1 to -1.2 kV. The 3D potential distribution now also reveals an IPG on the ram surfaces of the satellite so that ESDs due to this IPG are possible at triple points present at these surfaces (e.g. at the grounding bolts).

The lowest surface potential is visible on the small edges of the deployable solar array where potentials of more than -2.2 kV are calculated. It is expected that this effect is connected with the high background density and the resulting small Debye length which prevents the extension of the negative potential of the other large surfaces deeper into the plasma. This effect then leads to an increased amount of electron current as well as to a decreased ion collection by the SA edges.

The simulations in this case reveal that there is the possibility for discharges on the SA front side due to the IPG of 620 V as well as on the SA edges where the Epoxy resin of blank carbon fibre has a strong direct potential gradient to structure. Additionally, there is a slight risk of discharges at the dielectric surfaces at the

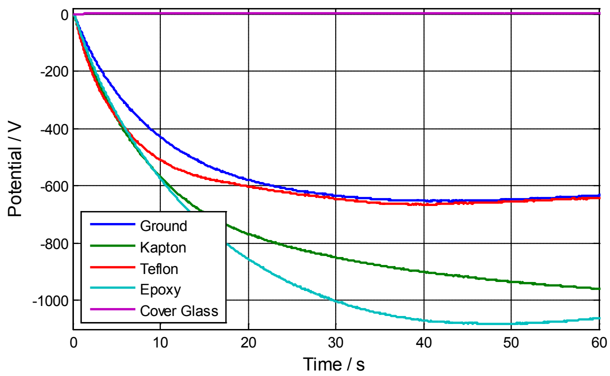

Figure 10: Time dependent averaged surface potentials on the satellite model for the ECSS auroral electrons combined with the cold background used by Cooke [5]

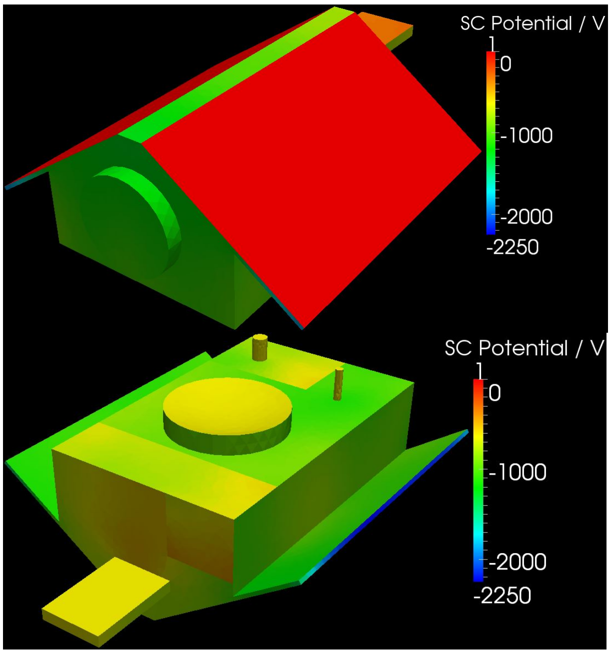

Figure 11: Spatial surface potential distribution on the satellite after 60 s exposure to the ECSS auroral electrons combined with the cold background plasma used by Cooke [5]; rear SPACE view (top), front NADIR view (bottom)

front of the structure due to the IPG generated by the ram effect of the cold ions. The overall criticality is on the same order as already discussed for the simulations of the SPENVIS Fontheim plasma with the ECSS cold background. So, in this case it is also expected that a robust design and minor changes to the satellite surface material distribution can help to mitigate most of the risks observed in this simulation.

5. SUMMARY AND CONCLUSION

The impact of the different plasma environment definitions given in standards, literature as well as surface charging tools has been analysed using 3D SPIS simulations of a typical LEO satellite with body mounted SA.

The simulations showed a wide variety of different charging potentials on the satellite model which is no surprise since the environment definitions itself show large differences in the particle densities.

The adapted plasma environment coming out of the SPENVIS tool has been the most uncritical environment studied here where charging could be observed, however, the potential gradients have not shown risks to the system. A reduction of the background plasma density as proposed by the ECSS standard [3] leads to more critical charging with the possibility of ESDs on the SA. The same statement holds true for the environment composed of the ECSS high energy electron spectrum accompanied with the background plasma density used by Cooke in the simulation for the DMSP satellites [5]. In both cases the risks to the system could be minimized by different design measures such as changing surface material properties and taking care of a SA design robust against arcs and preventing the occurrence of secondary sustained arcs. The surface potentials calculated in these environments are also well comparable with the results reported for the simulations of the DMSP satellites [5].

The use of the full auroral plasma definition as given in [3] with the strong high energy electron spectrum and the rather low background plasma density led to very critical charging on the satellite. The thresholds defined in [6] for both IPG as well as DPG are violated by all surface materials used on the satellite. Additionally, the involved potentials are on the order of several kV which means that the potential ESDs will have a high energy and thus a higher probability for damage to the system. In this environment the only chance to mitigate the risk is a complete charging optimized design with all conducting surface materials on the system including the SA cover glasses.

The wide variety of existing environment definitions and their effect on the results of a 3D surface charging analysis with the SPIS tool are considered a problem from an industrial viewpoint. The current standard gives an environment leading to extreme potentials on the satellite also strongly exceeding the values reported in [5]. Taking into account this in conjunction with the overall low number of reported anomalies on LEO satellites the question on the applicability of the ECSS environment definition arises. At least some information on the probability for the occurrence of such an environment should be given. This is especially interesting taking into account that the references for the high energy distribution and the one for the cold background plasma are coming from two independent observations being combined in the standard. Thus, it is questionable if the combination of these two worst cases should be used to derive an environment which has to be used in the design process of LEO spacecraft.

The high diversity in the environment definitions as well as the impact on the results of the charging simulations makes it necessary to better characterize the worst case auroral plasma definition. This should be taken into account in the planned updates of the European standards for the space environment as well as the charging handbook on the assessment of worst case charging, which is currently under preparation [7].

6. REFERENCES

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