Analysis of Surface Charging for a Candidate Solar Sail Mission Using Nascap-2k

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The characterization of the electromagnetic interaction for a solar sail in the solar wind environment and identification of viable charging mitigation strategies are critical solar sail mission design tasks. Spacecraft charging has important implications both for science applications and for lifetime and reliability issues of sail propulsion systems. To that end, surface charging calculations of a candidate 150-meter-class solar sail spacecraft for the 0.5 AU solar polar and 1.0 AU L1 solar wind environments are performed. A model of the spacecraft with candidate materials having appropriate electrical properties is constructed using Object Toolkit. The spacecraft charging analysis is performed using Nascap-2k, the NASA/AFRL sponsored spacecraft charging analysis tool. Nominal and atypical solar wind environments appropriate for the 0.5 AU and 1.0 AU missions are used to establish current collection of solar wind ions and electrons. Finally, a geostationary orbit environment case is included to demonstrate a bounding example of extreme (negative) charging of a solar sail spacecraft. Results from the charging analyses demonstrate that minimal differential potentials (and resulting threat of electrostatic discharge) occur when the spacecraft is constructed entirely of conducting materials, as anticipated from standard guidelines for mitigation of spacecraft charging issues. Examples with dielectric materials exposed to the space environment exhibit differential potentials ranging from a few volts to extreme potentials in the kilovolt range.

I. Introduction

THE characterization of the electromagnetic interaction for a solar sail in the solar wind environment and identification of viable charging mitigation strategies are critical solar sail mission design tasks. Spacecraft charging has important implications both for science applications and for lifetime and reliability issues of sail propulsion systems. Charging calculations of a candidate 150-meter-class solar sail spacecraft for the 0.5 AU solar polar and 1.0 AU L1 solar wind environments are performed. A model of the spacecraft with candidate materials having appropriate electrical properties is constructed using Object ToolKit. The spacecraft charging analysis is performed using Nascap-2k[1], the NASA/AFRL sponsored spacecraft charging analysis tool.

Two nominal and atypical solar wind environments appropriate for the 0.5 AU and 1.0 AU missions are used to establish current collection of solar wind ions and electrons. The environment referred to as Environment A was taken from IMPs 6, 7, and 8 data[2], where IMP is the Interplanetary Monitoring Probe mission. Environment B uses

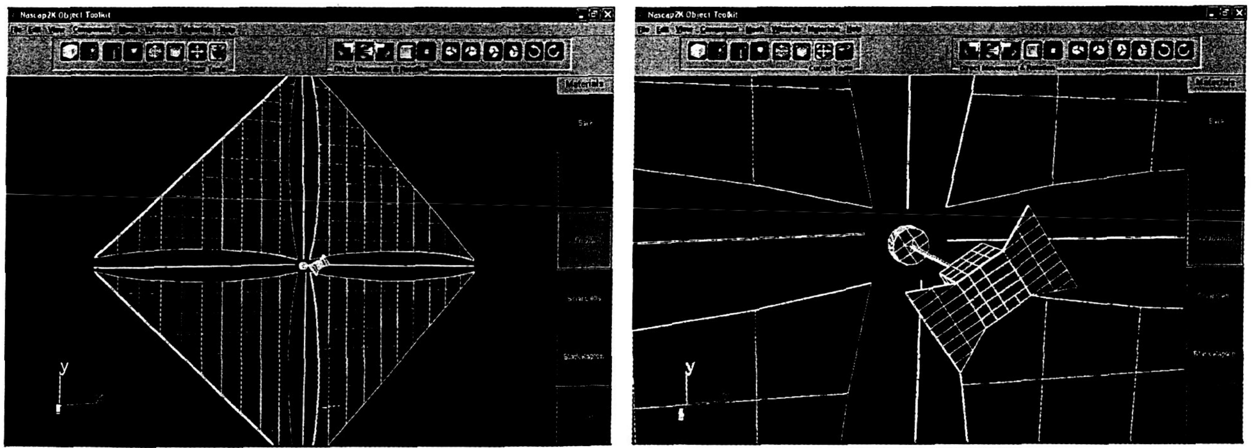
Ulysses data[3], which has an orbit of approximately 2 to 5 AU. Finally, a geostationary orbit environment case is included to demonstrate a bounding example of extreme (negative) charging of a solar sail spacecraft.

Results from the charging analyses demonstrate that minimal differential potentials (and resulting threat of electrostatic discharge) occur when the spacecraft is constructed entirely of conducting materials, as anticipated from standard guidelines for mitigation of spacecraft charging issues. Examples with dielectric materials exposed to the space environment exhibit differential potentials ranging from a few volts to extreme potentials in the kilovolt range. For brevity, not all cases are discussed here. However, for completeness, the results for all cases are shown in the summary charts for each orbit.

II. Nascap-2k Solar Sail Spacecraft Model

The three dimensional spacecraft model was constructed with the Object ToolKit (OTK) geometric modeling software supplied with Nascap-2k. The sail component is divided into four individual triangular components with each section consisting of a 5 μm (micrometer) thick Kapton® backside and an aluminum frontside (sun facing) material with a 212 m hypotenuse and 150 m sides. The spacecraft bus structure providing support to the sail-connecting booms is an aluminum cylinder 1 m in diameter and 0.5 m in height. Four Kapton® booms 150 m in length and 10 cm in diameter represent the sail support structures. A single 10 m Kapton® boom extending out of the sun-facing side of the spacecraft connects the spacecraft bus to the solar array and instrument structure, with the solar array spacecraft being aluminum. Two solar arrays extend in the x-direction with solar cells covering the sunward side and black Kapton® coating the backside. Electrical properties for all materials used on the spacecraft are the Nascap-2k defaults.

Figures 1a and 1b show an entire view of the model and a close up view of the spacecraft, respectively. While the booms are not physically connected to the sail and spacecraft in the model, Nascap-2k assumes electrical connection unless specified otherwise. All conducting elements of the model are designated Conductor 1, except for the solar arrays which are biased five volts (V) positive relative to Conductor 1 and are given the designation Conductor 2.



1 a. 1 b.

Figure 1. Front view (1a) and close up view (1b) of the candidate solar sail model as built in Object ToolKit, the model development tool in Nascap-2k. The front of the sails is a user defined material called "Front", which has the material properties of aluminum. The back of the sail is "Back" and the boom material is "Boom", which are both user defined materials and have the material properties of Kapton®. The sail spacecraft and the solar array spacecraft both are aluminum. The front of the solar array is a Nascap-2k default material of "Solar Cell" and the back side of the solar array is another Nascap-2k default material of "black Kapton®".

III. Environments

Charging analyses of the spacecraft model were performed using the Nascap-2k surface charging model, which requires environment inputs to define the conditions in the space environment. A variety of environments were used: four interplanetary environments and one geosynchronous environment. In all cases, the currents were computed analytically. Table 2 shows the input parameters for the different environments used in each of the analyses.

As indicated in Table 2, there were two environments used for 1 AU and 0.5 AU solar wind regions. For both of the regions and both environments, calculations were done in which the sun angle was normal to the sail front, 30° off sail front normal, and 55° off sail front normal. Nascap-2k does not presently decouple the sun and plasma angle, therefore the plasma angle of incidence for each run is the same as the sun angle for interplanetary (1 AU and 0.5 AU) regions. The photoemission spectrum used for the solar wind cases is the default spectrum provided by Nascap-2k for the individual materials. When performing a Nascap-2k charging analysis for environments where it is suspected the results will yield positive numbers (such as a solar wind environment), a more detailed photoemission spectrum than the default is needed. Nascap-2k gives the option of enabling a photoemission spectrum for specific materials. Details of the photoelectron energy spectrum are not as important when the spacecraft is charged negative because all emitted electrons are repelled from the surface.

Table 2. Charging Environments for Nascap-2k Analyses. Electron density (ρ_e) and temperature (T_e), ion velocity (v_i), temperature (T_i), and density (ρ_i), Debye length, and sun angle and intensity are given for Environment A and B for 1 AU, for Environment A and B for 0.5 AU, and for the environment used for the geosynchronous charging analysis[4].

	1 AU Environment A	1 AU Environment B	0.5 AU Environment A	0.5 AU Environment B	GEO worst case
ρ_e	12.8 cm^{-3}	3.28 cm^{-3}	4.27 cm^{-3}	13.1 cm^{-3}	1.12 cm^{-3}
T_e	11.13 eV	55.4 eV	10.6 eV	68.2 eV	12 keV
v_i	327 km/s	863 km/s	702 km/s	863 km/s	
E_i / T_i	558.2 eV	3888 eV	2573 eV	3888 eV	29.5 keV
ρ_i	12.8 cm^{-3}	3.28 cm^{-3}	4.27 cm^{-3}	13.1 cm^{-3}	0.236 cm^{-3}
Debye length	7 m	31 m	6 m	17 m	770 m
Sun	Intensity = 1, Angle incident: normal, 30° and 55° from sail normal	Intensity = 1, Angle incident: normal, 30° and 55° from sail normal	Intensity = 4, Angle incident: normal, 30° and 55° from sail normal	Intensity = 4, Angle incident: normal, 30° and 55° from sail normal	Intensity = 1, Angle incident: 30°, 55°, and 180° from sail normal

However, when a spacecraft is charged positive, a fraction of the photoelectrons with energy less than the spacecraft potential are retained, and the outgoing current is only a fraction of the total photoelectron current. Geosynchronous (GEO) surface charging runs were conducted for the sun angle of 30°, 55°, and 180° from sail front normal. The 180° case (sun incident directly to the sail backside) was included to represent a possible loss of attitude control. For all GEO cases, Nascap-2k assumes an isotropic plasma. The photoemission spectrum for the GEO cases was the default non-material-specific photoemission spectrum of a 2eV Maxwellian. The solar wind charging cases were run to equilibrium and the geosynchronous charging cases were run for 900 seconds, a typical time for a charging event in geosynchronous orbit.

The environment used for Environment A came from Feldman, el al.[2]. Environment A at 1 AU is a low speed solar wind environment. Environment A at 0.5 AU is a high speed solar wind environment scaled to 0.5 AU. For both, the electron density (N_e) was derived using

$$N_e = N + 2\left(\frac{N_\alpha}{N}\right)N \tag{1}$$

where N is the proton density, N_α is the helium density, and α denotes a doubly ionized helium molecule. The environment used for Environment B was taken directly from Ulysses data sets. Ulysses is a solar polar orbiting spacecraft with an orbit of 2-5 AU. The data came from the SWOOPS (Solar Wind Observations Over the Poles of the Sun) instrument onboard Ulysses[3]. The 1 AU environment is a high speed solar wind case. The 0.5 AU case is scaled directly from Environment B 1 AU. Different solar wind environments were intentionally used so as to get a larger cross section of environments. Density and temperature for both 0.5 AU cases were obtained using the following scaling laws[5]

$$v(r) = const \tag{2a}$$

$$\rho(r) = \rho r^{-2} = \frac{\rho_{1AU}}{R_{1AU}^2} r^{-2} \tag{2b}$$

$$T_i(r) = T_i r^{0.57} = \frac{T_{i,1AU}}{R_{i,1AU}^{0.57}} r^{0.57} \tag{2c}$$

$$T_e(r) = T_e r^{0.30} = \frac{T_{e,1AU}}{R_{e,1AU}^{0.30}} r^{0.30} \tag{2d}$$

where v is the velocity, ρ is the density, T is the temperature, the variable R is the distance from the Sun to the Earth (1 AU), and r is the distance from the Sun to the location of the solar sail. The 90% worst case geostationary environment found in Purvis, et al.[4] is the GEO environment surface charging standard used for all GEO cases.

IV. 1 AU Charging Results

The complete set of surface charging analyses for the candidate 150 meter sail model yields seventeen different surface charging cases for a range of space environments and surface (conductor, insulating) materials. Results from the 1 AU environments are presented here as being representative of solar sails in near Earth (for example, L1) environments.

A. Analysis

The first case for discussions uses Environment A at 1 AU, normal sun and plasma incidence to the Sail front, and an insulating Sail back. The exposed conductors and Sail front (which has material properties of aluminum) are 6.684 volts. The sail back (which has the material properties of Kapton®) has a potential of -42.45 volts. This yields a maximum differential potential from Sail front to back of 49.13 V. The solar array voltages range from 4.65 to 6.54 V. Booms in darkness have a maximum voltage of -77.75, which yields a maximum differential charge from boom to ground of 71 V.

The second case for discussion uses Environment A at 1 AU, 30° off-normal sun and plasma incidence to the Sail front, and an insulating Sail back. Potential results can be seen in Table 3. The exposed conductors and Sail front (which has material properties of aluminum) are 6.315 volts. The sail back (which has the material properties of Kapton®) has a potential of -42.46 volts. This yields a maximum differential potential from Sail front to back of 48.78 V. The solar array voltages range from 3.35 to 5.2 V. Booms in sunlight have a maximum voltage of -77.75 while booms in darkness range in potential from -42.46 to -77.75 V, which yields a maximum differential charge of 71.4 V from boom to ground.

The third case for discussion presented here uses Environment B at 1 AU, 55° off-normal sun and plasma incidence to the Sail front, and an insulating Sail back. Potential results can be seen in Table 3. The exposed conductors and Sail front (which has material properties of aluminum) are 8.13 volts. The sail back (which has the material properties of Kapton®) has a potential of 1.72 volts. This yields a maximum differential potential from Sail front to back of 6.41 V. The solar array voltages range from 6.72 to 8.24 V. Booms in darkness have a maximum voltage of 3.12 V while booms in sunlight range in potential from 3.12 to 8.83 V, which yields a maximum differential charge from boom to ground of 5.01 V.

The fourth case for discussions uses Environment A at 1 AU, 30° off normal sun and plasma incidence to the Sail front, and a conducting Sail back. Potential results can be seen in Table 3. The exposed conductors and Sail front (which has material properties of aluminum) are 5.104 volts. The sail back (which now uses the material properties of aluminum) has a potential of 5.104 volts as well. This yields a maximum differential potential from Sail front to back of 0 V. The solar array voltages range from 5.104 to 6.056 V. Booms in sunlight range in potential from -4.741 to -77.80 V while booms in darkness range in potential from -19.98 to -77.8 V, which yields a maximum differential charge from boom to ground of 72.70 V. If the booms are conducting as the Sail back is in this case, then the differential potential would be negligible.

B. Summary of Results

Table 3 shows the summary of results for all 1 AU charging cases using Environments A and B (see Table 2). The angle of sun and plasma incidence is normal, 30°, and 55° to the sail front. All cases have an insulating sail back except for an additional 30° incidence case using Environment A. The summary of potentials for each case is shown.

Table 3. Potentials in volts for the 1 AU charging cases using the Environments A and B (see Table 2), normal, 30°, and 55° incidence to the Sail normal. An insulating Sail back was used for all cases except one, which used a conductive Sail back.

Environment	A				B		
Sail back	Insulating	Insulating	Conducting	Insulating	Insulating	Insulating	Insulating
Angle	Normal	30°	30°	55°	Normal	30°	55°
Exposed Conductor / Sail front	6.684	6.315	5.104	5.349	10.57	9.9	8.13
Sail back	-42.45	-42.46	5.104	-42.48	1.92	1.89	1.72
Solar Array	4.65 to 6.53	3.35 to 5.2	5.104 to 6.056	3.223 to 5.148	8.2 to 9.09	8.42 to 9.76	6.72 to 8.24
Boom in sunlight		-77.75	-4.741 to -77.80	-4.02 to -77.77		1.65 to 7.04	3.12 to 8.83
Boom in eclipse	-77.75	-42.46 to -77.75	-19.98 to -77.80	-77.77	1.69	1.65	3.12
Max. differential φ from sail front to back	49.13	48.78	0	47.83	8.65	7.98	6.41

V. 0.5 AU

For brevity, the detailed results for the 0.5 AU cases are not discussed here. However, all results are shown in Table 4. They are for all 0.5 AU charging cases using Environments A and B (see Table 2). The angle of sun and plasma incidence is normal, 30°, and 55° to the sail front. All cases have an insulating sail back except for an additional 30° incidence case using Environment A. The summary of potentials for each case is shown.

Table 4. Potentials in volts for the 0.5 AU charging cases using the Environments A and B (see Table 2), normal, 30°, and 55° incidence to the sail normal. An insulating sail back was used for all cases except one, which used a conductive sail back.

Environment	A				B		
Sail back	Insulating	Insulating	Conducting	Insulating	Insulating	Insulating	Insulating
Angle	Normal	30°	30°	55°	Normal	30°	55°
Exposed Conductor / Sail front	12.02	11.47	9.834	19.75	10.92	17.13	15.79
Sail back	-30.35	-30.38	9.834	-30.15	1.93	1.66 to 2.4	1.64 to 2.56
Solar Array	11.78 to 11.89	10.12 to 10.31	9.943 to 10.27	17.05 to 17.37	8.7 to 10.43	12.55 to 13.62	10.86 to 12.37
Boom in sunlight		2.9 to -63.8	-63.9 to 2.094	13.04 to -63.63		9.89	10.48
Boom in eclipse	-63.79	-63.80	-63.90	-63.63	2.3	1.99	1.87
Max. differential φ from sail front to back	42.37	41.85	0	49.9	8.99	15.47 to 14.73	14.15 to 13.23

VI. Summary of Results

Table 5 shows the summary of results for all geosynchronous charging cases using the 90% worst case environments[4] (see Table 2). The angle of sun and plasma incidence is 30°, 55°, and 180° to the sail front. The 180° case represents loss of attitude control. All cases have an insulating sail back. The 55° case was not discussed in the paper for brevity, but is reported here for completeness.

Table 5. Potentials in volts for the geosynchronous charging cases using the 90% worst case environment (see Table 2), 30°, 55°, and 180° incidence off Sail normal, and an insulating Sail back.

Environment	GEO 90% Worst Case		
Sail Back	Insulating	Insulating	Insulating
Angle	30°	55°	180°
Exposed Conductor / Sail Front	-534	-624.8	-20.21
Sail back	-764.3	-848.4	-1726 to -2326
Solar Array	-599 to -676	-625 to -750	-2016 to -2039
Boom in sunlight	-1220 to -5135	-1292 to -5096	
Boom in eclipse	-5135	-5096	-6341
Max. differential φ from sail front to back	230.3	223.6	300

VII. Conclusions

Seventeen different charging cases were run with five different environments: two environments for 1 AU, two environments for 0.5 AU, and a geosynchronous environment. The majority of the cases have an insulating back for the solar sail. However, for two cases (1 AU and 0.5 AU using Environment A) a conducting back was used for comparison. There are no differential charging levels between sail front and back for these cases. Referring to the cases with a dielectric Sail back, Environment A for 1 AU and 0.5 AU runs show larger absolute charging levels (more negative) than the Environment B counterparts, which show no negative charging. The differential charging levels are also larger for the Environment A cases. Charging levels on the boom in eclipse are the largest for all cases. The geosynchronous surfaces charging cases yield the largest absolute and differential charging levels, with the worst being the loss of attitude control case. Absolute surface charging levels of -5000 to -6500 V are seen, with differential charging levels on the order of 250-300 V.

Taking into account the few micron thickness of the sail membranes, these differential charging levels suggest electric fields on the order of 10^6 to 10^7 volts/meter across the sail membrane, which exceeds the reported dielectric strengths of the insulating materials used in this study. Nascap-2k predicts differential potentials of many tens of volts from Sail front to back in the solar wind environments, both 1 AU and 0.5 AU. Kilovolt potentials can develop in the geosynchronous substorm environment, with differential potentials from Sail front to back in the hundreds of volts. The greatest potentials develop, as expected, on the insulating support structures in eclipse. Conductive surfaces on the backside of the sail and on the boom support structures yield an equipotential spacecraft surface and reduce (and possibly eliminate) the threat of discharges due to differential charging that could damage the thin film sail. A case was run scaling the sail and boom sizes to 150 m hypotenuse and 106 m sail sides. This run showed no appreciable difference in charging levels than the same case with the large sail model. This is a reasonable Nascap-2k result considering the particle flux is the major component to surface charging levels and they are the same regardless of size of sail. This shows that decreasing the size of the flight sail from those in this study alone will not help to alleviate the differential surface charging problems.

This analysis addresses the development of differential potentials on a generic solar sail using standard solar sail materials. As the solar sails are conducting, the location of differential potentials is design dependent. Several related issues remain that should be considered in the development of a specific design. In this study, the vacuum deposited Aluminum is assumed to be perfectly conducting. However, the thin layer of Aluminum may not be able to support the surface current density necessary to maintain the entire surface at the same potential. This could become a particularly important source of differential potentials for large sails that are conducting on both sides but have an insufficient number of grounding points. Electrons with energy greater than about 5 keV, present in substantial numbers during a geosynchronous substorm or auroral event, would penetrate the vacuum deposited Aluminum and deposit in the underlying Kapton®, Mylar, or Kevlar stop ribs. This "deep dielectric charging" mechanism is another source of high electric fields within the sail. Over time, there may be significant changes in the surface conductivities due to ultra violet radiation and micrometeoroid impact. While the differential potentials that can develop between the front and back surfaces when the back surface is insulating are likely to be small enough not to cause discharges in isolation, a micrometeoroid impact could trigger a discharge. There is also the possibility that photo emitted electrons could provide current to sustain a discharge. Finally, in the low plasma density of the solar wind, any exposed sail surface potentials can extend to distances on the order of the sail size, potentially disturbing plasma environment measurements.

These results are for a candidate solar sail model with minimal design information. Assumptions have been made for the grounding scheme and material conductivity. A surface charging analysis for specific solar sail designs, spacecraft geometry, grounding schemes, grommet locations, and material properties incorporating possible locations of instrument packages using multiple environments (as this study did) would be beneficial. It is advised to test flight-ready materials and use the properties gathered from the testing directly in the Nascap-2k surface charging analyses for the best possible flight comparison. However, it is impossible to test and analyze exactly the materials as they will fly over time in space.

Acknowledgments

Ulysses moments were provided courtesy of Dr. B. Goldstein of JPL through the National Space Science Data Center at Goddard Space Flight Center. Work for this paper was supported in part by contract NAS8-00187 and NASA's In-Space Propulsion Program.

References

[1]M. J. Mandell, V. A. Davis, B. M. Gardner, I. G. Mikellides, D. L. Cooke, J. Minor, "Nascap-2k, An Overview," *Proceedings of the 8th Spacecraft Charging Technology Conference*, 2003.

[2]Feldman W.C., J.R. Asbridge, S.J. Bame, and J.T. Gosling, Plasma and Magnetic Fields from the Sun, in *The Solar Output and its Variation*, (ed.) Oran R. White, Colorado Associated University Press, Boulder, 1977.

[3]Bame, S.J., D.J. McComas, B.L. Barraclough, J.L. Phillips, K.J. Sofaly, J.C. Chavez, B.E. Goldstein, R.K. Sakurai, "The Ulysses Solar Wind Plasma Experiment," Astronomy and Astrophysics, Supplement Series, Ulysses Instruments Special Issue, Vol. 92, p. 237 – 265, 1992.

[4]Purvis, C. K., H. B. Garrett, A. C. Whittlesey, N. J. Stevens, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects," NASA TP 2361, 1984.

[5]Burlaga, L. F., *Interplanetary Magnetohydrodynamics*, Oxford University Press, 1995.