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Experimental investigation and modelling of surface potentials of materials under electron spectra representative of isotropic GEO worst-case environments

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Abstract—This paper presents a novel approach used to test surface material charging under electron flux representative of space conditions below 400 keV. A series of severe environments for surface charging at geosynchronous orbit is extracted from Van Allen Probes data and compared to previous Los Alamos National Laboratory measurements. Middle Earth orbit data presented in this paper does not show major differences with respect to geosynchronous orbit data when looking at electron fluxes integrated above 10 keV. Most differences occur below 10 keV. The experimental protocol used to test material properties consists in adapting the electron flux to worst-case conditions. It is shown that the material properties required to predict electrostatic discharges occurrence must be measured with such an adaptive ground setup.

Index Terms—spacecraft charging, space environments, flight data, ground testing

I. INTRODUCTION

Estimating worst-case surface charging remains a challenge because it depends on the complex interaction between the spacecraft and its environment. One of the key aspects is to perform ground testing of covering materials under space-like conditions. This is a long-standing challenge because of the numerous physical processes that are involved in surface charging. Test conditions must also adapt to worst-case environments extracted from new flight data.

Flight data show that hundreds to thousands of volts of negative potentials are observed on spacecraft at geosynchronous orbit when the spacecraft is in the sector especially when it is in Earth eclipse [1]-[2]-[3]. High differential voltages of covering dielectrics with respect to the structure were measured in the past [4] but too few spacecraft are equipped with dedicated instrumentation to allow extrapolating to other situations. The space industry performs testing campaign using small size coupons to predict the response of materials sensitive to charging hazards under flight

representative conditions. These data can be used as is and/or serve as inputs of larger scale simulations using numerical tools [5]-[6]-[7]-[8] that combine the three-dimensional geometrical description of a given spacecraft, the physical mechanisms ruling the behavior of its covering materials and, finally, the energy distribution of worst-case environments [9]-[10].

The objective of this paper is to present the results of an experimental campaign dealing with surface charging under electron spectra that are representative of severe environments measured on GEO spacecraft. Section II presents specifications obtained from the analysis of recent GEO data, including LANL and Van Allen Probes (RBSP-A and RBSP-B). We will in particular focus on the ratio between high and low energy electron fluxes. Section III describes how the ONERA/SIRENE facility that is equipped with electron accelerator and guns has been upgraded to allow representing electron spectra below 400 keV, in addition to the classical $kp>5$ energy differential flux in use at ONERA/CNES for more than a decade. Section IV presents surface charging test results obtained with new specifications and compare them to a numerical model. Section V discusses how the radiation induced conductivity resulting from the penetration of high energy electrons can strongly differ from one specification to another and result in very different behaviors.

II. SPACE ENVIRONMENTS AT GEO

A. Van Allen Probes Data

A series of severe or worst-case electron environments for surface charging was previously compared in [3]. The data came from NASA and ECSS guidelines, that use the SCATHA event on April 24th, 1979. Extra environments were extracted from 15 years of LANL data using fluxes averaged over 86 seconds and 15 minutes, that is, representative of differential charging time scales.

In this section, we present our analysis of 56 months of Van Allen probes data from Jan 2013 to Aug 2017 (version 3 of data available from https://www.rbbsp-ect.lanl.gov/data_pub). The RBSP A and RBSP B potentials are estimated with the ion peak method of [3] also used in [2], from the data extracted from HOPE instrument. HOPE measures electron and proton fluxes

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from a few eV up to 50 keV. HOPE data are interpolated with data from MAGEIS instruments (electron and proton fluxes above 30 keV). Each measurement corresponds to a flux averaged over 23 seconds. The measured electron flux is corrected with the probe potential to get the undisturbed ambient flux following [3].

Fig. 1. Proton energy distribution during the charging event on Feb 8th, 2013, the same as reported in [11]. The black curve represents the ion peak related to the Van Allen Probe potential.

Fig. 1 presents the proton energy distribution measured by RBSP-A/HOPE on Feb 08, 2013 from 0 PM to 4 PM. The black curve represents the spacecraft potential. A few hundreds of volts negative is observed around 2 PM. This perfectly matches previous results [11]. The histograms of charging events measured on Van Allen Probes over 56 months are presented in Fig. 2 considering the occurrence of potentials, MLT position, month and Kp index. The events can be splitted in two series : below and above -500 V. [11] showed that some hundreds of volts of negative potential have been reached at Sun even though the satellites were fully conductive. This is confirmed by Fig. 3 that represents the number of events associated with satellite potentials between -100 and -500 V as a function of the L-shell radiation belt parameter (L^*) and magnetic local time (MLT). Tens of events have been detected with a spacecraft fully at Sun. Our analysis, similar to what was performed in [3], shows that the worst potentials (thousands of volts negative) have been obtained during equinox season around midnight MLT around GEO orbit ($L^* \sim 5.5-6$), suggesting the satellites were in eclipse during these events, see Fig. 4. Such event combines enhance electron flux and the absence of photoemission, which is very efficient at reducing the impact of the ambient plasma. One point worth to be noticed is the relatively moderate values of Kp index during the charging events, from values as low as 3 and no more than 7. This is consistent with previous findings ([1]-[2]-[3]). Charging events do not necessarily require high values of Kp to occur.

Fig. 2. Histograms of Van Allen Probes charging events between Jan 2013 and Aug 2017 as for the occurrence of a) negative potentials (given in absolute value), b) MLT position, c) month and, d) Kp index.

B. Severe Electron Fluxes above 10 keV

The same methodology as in [3] has been used to compute the most severe environments in terms of electron flux above 10 keV (referred as FE10k). Fig. 5 presents the electron energy distribution function for different L^* as compared to previous data obtained at GEO on LANL spacecraft.

Fig. 3. Map of charging events with a potential in the range [-500 V; -100 V] as a function of L and MLT.

Fig. 4. Map of charging events with a potential in the range [-5000 V; -1000 V] as a function of L and MLT.

Fig. 5. Electron energy distribution of RBSP FE10k worst events as a function of L^* , compared to LANL worst cases at GEO

The measurements performed on RBSP and LANL spacecraft qualitatively agree with each other at GEO. A quantitative analysis indicates that the FE10k 23 seconds averaged RBSP data slightly exceed the FE10k 86 seconds averaged LANL data above 20 keV, at GEO. Inversely, the latter significantly exceed the former between 1 and 10 keV. We suggest that RBSP FE10k specification could be worst than

FE10k LANL because of reduced generation of secondary electrons. Extra efforts should be conducted in the future to compare numerically the impact of such an environment on a realistic 3D spacecraft.

III. ADAPTATION OF GROUND FACILITIES

A. SIRENE Facility

SIRENE is a sophisticated and unique ONERA/CNES test facility especially designed for the study of surface and internal charging of space materials and satellite components under extreme environment (usually geostationary orbit radiation conditions). This facility is able to reproduce the geostationary electron spectrum in the energy range [0-400 keV]. It allows realistic assessment of potential built up in geostationary orbit. Its flexibility allows the simulation of extreme environments different from the geostationary one, e.g., Middle Earth Orbit (MEO) or other planetary radiation environments. This facility is widely used as well for the characterization of radiation induced conductivities of space materials in vacuum. Using the high energy electron beam and a high incoming flux on the sample (up to 10 nA.cm^{-2}), we are able as well to perform radiative ageing on the material. Space materials, such as polymers, adhesive or coverglasses can then be aged in SIRENE with equivalent flight durations equal to several months or years. The electron spectrum simulation was initially achieved by the use of two monoenergetic electron beams (20 and 400 keV), these two beams being diffused in energy and angle to produce a space-like electron flow with a good flux homogeneity in a diameter equal to 20 cm on the sample holder. The nominal integrated fluxes used for the 20 keV monoenergetic beam and the distributed 0-400 keV one are respectively equal to 250 pA.cm^{-2} and 50 pA.cm^{-2} but these different fluxes can be changed independently. Electron impact the surface with a quasi-normal incidence angle. The temperature of the sample holder can be controlled in the range $[-180^\circ \text{C}, +250^\circ \text{C}]$ allowing to reproduce the temperature variations of materials on flight. A pumping system allows experiments at vacuum of around 10^{-6} mbar. It is instrumented with a contact-less electrostatic probe, current measurement systems and non-contact pulsed electro-acoustic device (PEA).

In the frame of the current study, SIRENE has been amended to improve its flexibility and get close to the different spectra met in space, especially worst-case ones. For this purpose, a third 100 keV electron gun has been installed on this facility and the beam diffusion system has been improved. We can then enhance the flux homogeneity on the sample holder and get a good fit with the required spectra on the overall energy range. With the amended irradiation system, we can then come to a dispersion on the flux of the 20 keV, 100 keV and 400 keV beams of only 10 % along the 20 cm length of the sample holder (versus 20-30 % for the previous system).

B. Reproduction of WC Electron Spectra

Fig. 6 and Fig. 7 present integral values of surface current density of various electron environments. It is the integral over 2π steradian and above a given energy of the electron current

density j_e . For a Maxwellian electron spectrum of total density N_e and of temperature T_e , j_e would be equal to $-qN_e\sqrt{kT_e/2\pi m_e}$, with q the elementary charge, k the Boltzmann constant and m_e the electron mass. Our new irradiation system allows producing worst case spectra met in space using a quasi-unidirectional electron flux, as we can see in Fig. 6 for the FE10k worst case spectra measured on LANL [3]. The SIRENE spectrum is of course tunable in regard of the spectrum required by the user, as we can see in Fig. 7 where the FE10k-15min from LANL spectrum is compared to the 'Kp > 5' spectrum.

Fig. 6. LANL FE10K 15min and 86 worst-case spectra [3] reproduced in the SIRENE facility (red curve)

Fig. 7. Comparison between SIRENE simulated FE10K spectrum and SIRENE simulated spectrum Kp>5

IV. MATERIAL SURFACE CHARGING

A. Experimental Procedure

Three different space used polymers (100 μm thick PTFE, 100 μm thick PEEK, and 127 μm thick Kapton®) have been irradiated to measure their charging behavior under two electron spectra : 'Kp>5' and 'FE10K-15min from LANL' (referred by FE10k only in the following). The experiments have been performed at room temperature. The electric surface potential has been measured along the different samples using a moveable Kelvin probe. It is then possible to draw the evolution of the maximum surface potential as a function of irradiation time.

B. Experimental Results

We can observe from Fig. 8 and Fig. 9 strong differences on

the charging behavior of the different materials between both spectra. Charging kinetics is much higher for the FE10K spectrum with potentials reaching around -3000 V after 15 minutes irradiation. For the Kp>5 spectrum, the charging behavior is smoothed by the effect of high energy electron flux that significantly enhances radiation induced conductivity. For the FE10K spectrum, the flux of high energy electrons is much lower leading to a lower electric bulk conductivity for the three materials and therefore to a higher charging kinetics that could lead to stronger discharge hazards. We have to be careful however about the fact that radiation history (before the worst-case spectrum occurrence) can strongly affect and smooth the charging behavior of the irradiated polymers.

Fig. 8. Evolution of the surface potential as a function of irradiation time for the three different space-used polymers under 'Kp>5' electron spectrum

Fig. 9. Evolution of the surface potential as a function of irradiation time for the three different space-used polymers under FE10K electron spectrum

C. Numerical Modelling

The second part dealing with charging analysis aimed at performing numerical simulation to assess the charging behaviour of Kapton® under other specific electron environment, such as RBSP spectrum. The first task was to compare the charging behaviour assessed experimentally in the irradiation facility and numerically with the dedicated charge transport model described in [12]. From Fig.10 and Fig. 11, we can observe that the numerical model allows a good prediction of the charging kinetics of dielectrics in different irradiation conditions (here FE10K electron spectrum and Kp>5 electron spectrum). This model has then been applied to assess the charging behaviour of 127 μm thick Kapton® under RBSP FE10K electron spectrum for L between 5 and 5.5. A comparison on the charging kinetics between LANL and RBSP FE10K conditions is presented in Fig. 12. We can notice that the RBSP electron spectrum induces slightly higher charging kinetics than the LANL electron spectrum. This can be

explained by the higher charging current measured on RBSP spectrum (185 pA.cm^{-2}) than the one measured on LANL FE10K (100 pA.cm^{-2}). At the start of the irradiation process, radiation induced conductivity (which should be higher for RBSP due to higher ionizing current) does not affect significantly the charging process and smooth only at low level the charging kinetics.

Fig. 10. Comparison on the surface potential assessed experimentally and numerically (RC model) as a function of irradiation time for $127 \mu\text{m}$ thick Kapton® under FE10K electron spectrum

Fig. 11. Comparison on the surface potential assessed experimentally and numerically (RC model) as a function of irradiation time for $127 \mu\text{m}$ thick Kapton® under 'Kp>5' electron spectrum

Fig. 12. Comparison on the surface potential assessed numerically (RC model) as a function of irradiation time for $127 \mu\text{m}$ thick Kapton® under LANL FE10K electron spectrum and RBSP FE10K spectrum ($5 < L < 5.5$)

V. DISCUSSION

Pending on the selected spectrum and material, charging at a few hundreds or thousands of volts can occur at GEO within a few minutes. The study of worst-case environments is important to define adequate experimental conditions used to test space material charging under electron irradiation. On one

hand, environments with large low energy electron fluxes induce the largest negative differential voltages of insulators, as seen in this paper. They also promote high level of inverted potential gradients, especially on solar arrays, because electrons below 10 keV produce secondary electron emission. On the other hand, surface charging can be significantly reduced by penetrating electrons of energy above 100 keV typically for thin surface coatings. Finally, the radiation history of materials implies ageing whose effects are very difficult to predict. Ageing materials with a dose equivalent to middle and end of life provides valuable information on material charging. A more detailed analysis presented in another companion paper, even though it refers to internal charging, shows that recent history also impacts charging at a given times [13].

The recent update of the SIRENE facility allows tailored sequences of material testing under representative space conditions, including the main effects of the local and historical environment: radiation dose and dose rate, charge deposition and transport across the sample thickness. For new missions, we recommend to assess the worst-case environments in terms of surface charging, looking at the electron fluxes provided by flight instruments if available on that precise orbit, or by default by international guidelines. For GEO, we recommend to perform and compare testing under $k_p > 5$ and under an envelope of GEO worst-cases environments. It would thus provide margins on the ESD risk estimation obtained with the classical $K_p > 5$ environment currently in use at ONERA. SIRENE facility is flexible enough to do that, after some more upgrades to get the full energy range $< 400 \text{ keV}$ covered.

The numerical charging model developed in a previous activity allows predicting charging levels under GEO-like environments with a very limited number of input material properties. However, it is worth noticing that these properties must be measured following a robust and precise procedure in order to be reproducible [14], though versatile enough to adapt to changing environmental conditions (temperature, ageing effects, etc) in order to be representative of space environment conditions. The physical model describing dielectric charging under electron spectra has been successfully compared to ground measurements using electron fluxes representative of $k_p > 5$ and of LANL data at GEO. The extrapolation to RBSP flight data suggests an enhanced risk on orbits located between MEO and GEO than at GEO.

REFERENCES

- [1] Choi, H.-S., J. Lee, K.-S. Cho, Y.-S. Kwak, I.-H. Cho, Y.-D. Park, Y.-H. Kim, D. N. Baker, G. D. Reeves, and D.-K. Lee, (2011), Analysis of GEO spacecraft anomalies: Space weather relationships, *Space Weather*, 9, S06001, doi:10.1029/2010SW000597
- [2] Thomsen, M. F., M. G. Henderson, and V. K. Jordanova (2013), Statistical properties of the surface-charging environment at geosynchronous orbit, *Space Weather*, 11, 237–244, doi:10.1002/swe.20049.
- [3] Matéo-Vélez, J.-C., Sicard, A., Payan, D., Ganushkina, N., Meredith, N. P., & Sillanpää, I. (2017). Spacecraft surface charging induced by severe environments at geosynchronous

- orbit. Space Weather, 15.
<https://doi.org/10.1002/2017SW001689>
- [4] Mizera, P.P. (1981), Charging Results from the Satellite Surface Potential Monitor, Journal of Spacecraft and Rockets, Vol. 18, No. 6, pp. 506-509. <https://doi.org/10.2514/3.57848>
- [5] Roussel, J.-F. , G. Dufour, J.-C. Mateo-Velez, B. Thiébault, B. Andersson, D. Rodgers, A. Hilgers and D. Payan (2012), SPIS multi time scale and multi physics capabilities: development and application to GEO charging and flashover modelling, IEEE Trans. Plasma Sci., Vol 40, N°2
- [6] Thiebault, B., B. Jeanty-Ruard, P. Souquet, J. Forest, J.-C. Mateo Velez, P. Sarrailh, D. Rodgers, A. Hilgers, F. Cipriani, D. Payan and N. Balcon (2016), SPIS 5.1, an innovative approach for spacecraft plasma modelling, IEEE Transactions on Plasma Science, Vol 43, pp 2782-2788. doi: 10.1109/TPS.2015.2425300
- [7] Mandell, M. J., V. A. Davis, D. L. Cooke, A. Wheelock, C. J Roth (2006), Nascap-2k Spacecraft Charging Code Overview, IEEE Trans. Plasma Sci., Vol. 34, No. 5.
- [8] Muranaka, T. , S. Hosoda, J. Kim, S. Hatta, K. Ikeda, T. Hamanaga, M. Cho, H. Usui, H. O. Ueda, K. Koga and T. Goka (2008), Development of multi-utility spacecraft charging tool (MUSCAT), IEEE Trans. Plasma Sci., Vol 36, N°5.
- [9] ECSS (2008), ECSS-E-ST-10-04C, Space environment (<http://ecss.nl/standard/ecss-e-st-10-04c-space-environment/>)
- [10] NASA (2011), NASA-HDBK-4002A, Mitigating In-Space Charging Effects—A Guideline
- [11] L. K. Sarno-Smith, B. A. Larsen, R.M. Skoug, M. W. Liemohn, A. Breneman, J. R. Wygant and M. F. Thomsen, Spacecraft surface charging within geosynchronous orbit observed by the Van Allen Probes Space Weather, 14, 151-164, doi:10.1002/2015SW001345
- [12] T. Paulmier, B. Dirassen, D. Payan, M. Arnaout, "Analysis of Charge Transport and Ionization Effect in Space-Used Polymers Under High-Energy Electron Irradiation", IEEE Transactions on Plasma Science , vol. 45, no.8, August 2017, pp.1933-1937
- [13] P. Sarrailh, R. Pacaud, Th. Paulmier, S. Hess and D. Payan Simulation of the Effect of Time-Dependent Electron Environment on the Internal Charging Dynamic using SPIS-IC, Proc. 15th SCTC, Kobe, Japan, June 2018.
- [14] T. Paulmier, B. Dirassen, M. Arnaout, D. Payan, and N. Balcon, "Radiation-Induced Conductivity of Space Used Polymers Under High Energy Electron Irradiation", IEEE Transactions On Plasma Science, Vol. 43, No. 9, September 2015, pp 2907-2914