

United States Spacecraft Charging Overview

Linda Neergaard Parker, Space Weather Solutions, Myron J. Mandell, Victoria A. Davis, Leidos,
Insoo Jun, Wousik Kim, Nelson Green, Allen Andersen, JPL, Joseph I. Minow, NASA, Justin Likar, APL,
Joseph Wang, University of Southern California,
Ryan Hoffmann, David Cooke, Zachary Gibson, and Jainisha Shah, AFRL

Abstract—The United States (US) has a strong history of spacecraft charging studies which predates the first Spacecraft Charging Technology Conference (SCTC) in 1976. Significant progress has been made since the 14th SCTC was held in the Netherlands where the US last presented a country summary to the SCTC. We present here a high-level survey of spacecraft charging work performed since 14th SCTC. Our presentation will include work from the US Space Force, the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), Johns Hopkins Applied Laboratory (APL), industry, and academia. We include flight contributions, latest design specifications, ground testing, modeling and simulation, model development, facilities, anomaly study advancement, and various collaborations within the US charging community.

Index Terms—Country Overviews

I. MOTIVATION AND BACKGROUND

THE United States (US) has a long and storied history with spacecraft charging, from the Spacecraft Charging At High Altitudes (SCATHA) spacecraft program in the 1970's which measured the spacecraft response to the environment and developed techniques to mitigate the effects, to development of the first full-scale spacecraft charging model, the NASA and Air Force Charging Analyzer Program (NASCAP) [1, 2, 3, 4, 5]. The US activities have grown to include performing of charging analysis for missions, material and instrument testing, and further model development. Our community not only includes NASA, US Air Force and Space Force, but federal partners such as the Jet Propulsion Laboratory (JPL), Johns Hopkins Applied Research Laboratory (APL), and the Aerospace Corporation, academia including the University of Southern California (USC) and Utah State University (USU) just to name a few, and many private companies. In this paper, we will discuss recent spacecraft charging activities, including new mission development, testing advancements, and model improvements.

II. BACK TO THE MOON

NASA, along with its commercial and international partners, is preparing to send astronauts back to the lunar orbit and ultimately to inhabit a lunar base through the Artemis Program. The Gateway is a space station that will remain in lunar orbit. This will serve as a “home base” for astronauts to go back and forth to the lunar surface. Orion is the spacecraft that will transport astronauts from Earth to Gateway, and the Human Landing System (HLS) is the spacecraft that will transport astronauts from Gateway to the lunar surface. Finally, the Artemis Base Camp will serve as the home-base for astronauts

on the lunar surface. The Marshall Space Flight Center (MSFC) Natural Environments group is leading the charging analysis for the Gateway program. Additionally, the Heliophysics Environmental Radiation Monitoring Experiment Suite (HERMES) is an instrument package that will be deployed on the Gateway. It is a set of three particles instruments and magnetometers. The HERMES Instrument Science Teams provide additional research in the areas of surface and internal charging. Two such grants are *Understanding, Specification, and Prediction of Lunar Space Weather* led by Dr. Janet Green and *HEMERA: HERMES Modelling and Enhanced Response Analyses* led by Dr. Insoo Jun. Both studies will enhance our understanding of lunar charging.

In addition to NASA's Artemis Program, JPL and APL both have long heritage of developing spacecraft missions. JPL's Natural Space Environments Group supports every flight project at JPL for the electrostatic discharge (ESD) discipline. Examples include:

- Europa Clipper Mission (Planetary Science)
- NEO-Surveyor (Planetary Defense)
- Sphere-X (Astrophysics)
- NISAR (Earth Science)

Current missions that APL is developing or supporting include the Europa Clipper, Cross-Scale Investigation of Earth's Magnetotail and Aurora (CINEMA), the Electroject Zeeman Imaging Explorer (EZIE), and Montana State University (MSU) led Relativistic Electron Atmospheric Loss (REAL) cubesat mission. APL developed the Plasma Instrument for Magnetic Sounding (PIMS), radiation monitors, and Europa Imaging System (EIS) for the Europa Clipper. The CINEMA mission will make use of polar orbiting cubesats, each with an energetic charged particle detector (ECP) and a magnetometer. EZIE will study currents between the aurora and magnetosphere and is set to launch in fall 2024.

III. MODEL USAGE

The US model development has made significant progress in the last few years. Ansys Charge Plus (formerly EMA3D[®] Charge) is a surface and internal charging commercial software developed by Electro Magnetic Applications which allows for sophisticated three-dimensional (3D) modeling of potentials and currents [6]. NUMIT V2.0 is a 1D internal charging code maintained and distributed by JPL [7]. A follow-on to NUMIT V2.0 is NUMIT 3D which extends the capabilities to three dimensions based on Geant4 or MCNP for radiation transport and COMSOL electrostatic solution [8]. AFRL has increased support for the development and modernization of space weather tools like IRENE (AE9/AP9) and modeling tools like Nascap-2k and AF-NUMIT3.

The surface charging model, *Nascap-2k*, is developed and maintained by Leidos on contract to the US Space Force and NASA. Version 4.5 was released in 2024 with significant advancements. These advancements include increasing the limit on number of surface cells to 8000 surface cells. Making this practical required a substantial speedup of Object Toolkit, which was achieved, as well as some more modest speedup of the calculation code. The grid size is now virtually unlimited, allowing good resolution over a large volume. The use of nested grids to resolve important features is retained.

Nascap-2k has long overestimated plasma currents to surfaces in cavities, e.g., interior surfaces of telescope tubes. This situation was improved by implementing a view factor treatment for these surfaces, leading to reduced values that are more reasonable.

The original design of *Nascap-2k* recognized the need to account for capacitance and conductance between conductive elements that was not due solely to geometry, although such circuitry was not initially implemented. These circuit elements may be due to direct contact between the conductors (joint or weld), or to explicit circuit components. This circuit is now implemented in the calculation and may be specified through the graphical user interface (GUI). Examples using the new capability are described in a new NASA document [9].

A simple surface charging detector has been proposed [10] and flown [11]. A simplified circuit for this device is shown in **Fig. 1**. The upper part of this circuit represents the resistance and capacitance of a dielectric surface to its underlying conductor, which is an isolated metal plate.

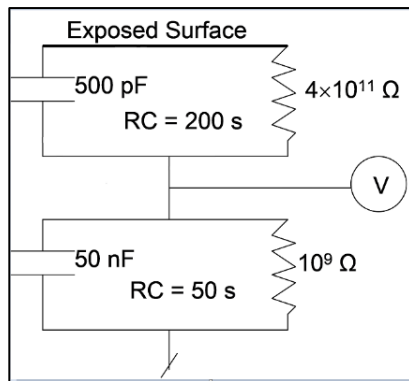


Fig. 1. Circuit model of the Charge Plate Analyzer.

The lower part of the circuit represents interconductor circuitry consisting of a physical capacitor and physical resistor that couple the plate to spacecraft ground. The instrument measures the potential difference between the plate and spacecraft ground.

The new capability allows us to include the interconductor circuitry in a *Nascap-2k* model. Examples of this include modeling of a Charge Plate Analyzer (CPA) and a tether system. **Fig 2** shows the *Nascap-2k* calculated response of the CPA to sudden changes in environment, as the satellite exits eclipse into sunlight and later the CPA becomes shadowed. For the most part, the CPA tracks the differential potential fairly well, but at eclipse exit the CPA shows a sharp transient and slow recovery that does not match the differential potential.

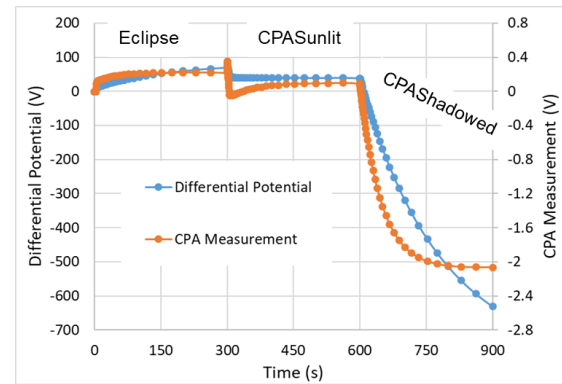


Fig. 2. *Nascap-2k* calculated response of the surface and CPA to sudden changes in environment.

An electromagnetic tether consists of a small upper body located a substantial distance above a much larger lower body, connected by a conductive tether. Orbital motion through Earth's magnetic field creates a potential difference so that the upper body is positive and collects electrons while the lower body is negative and collects ram ions. The example (**Fig. 3**) considers a 200 m tether with approximately 45V induced potential difference. If the tether root is shorted to the lower body (left side of **Fig. 3**) current flows freely through the tether and the floating condition puts the upper, electron-collection body at +7V and the lower, ion collecting body at -38V. If the tether root is an open circuit at the lower body (right side of **Fig. 3**) the two bodies float separately, so that the entire potential drop of 45V occurs along the tether and may be measured at the lower body. The new capability (interconductor resistance) allows us to map the intermediate states between the open and shorted conditions, predicting the potentials and currents at each body and the measured potential of the tether root as a function of the load resistance.

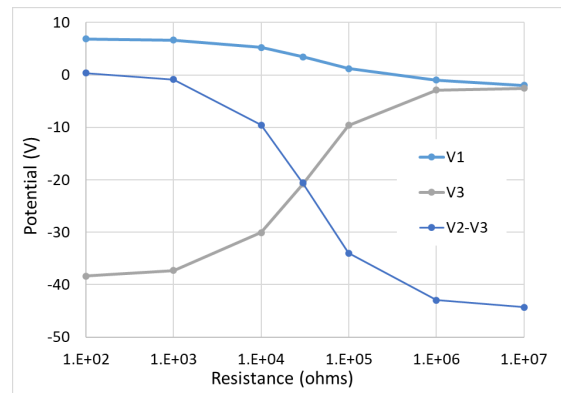


Fig. 3. Potentials on tether system as a function of the resistance between the tether stub and lower body, showing upper body potential (V1), lower body potential (V3), and potential across the resistor (V2-V3).

The University of Southern California has carried out the first multi-scale modeling to connect the global lunar charging environment, local astronaut charging, dusty spacesuit charging, and charging effects on materials. This multi-scale charging encompasses over 10 orders of magnitude in length

scales. The global scale plasma environments used are based on ARTEMIS and ONMI data, while the local scale astronaut charging and micro-scale simulations of dusty space suit charging (**Fig. 4**) both use particle-in-cell (PIC) simulations. The atomic scale of material dielectric breakdown is modeled with molecular dynamics simulations.

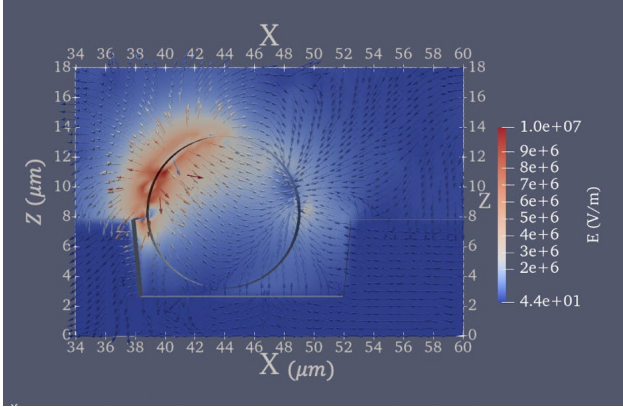


Fig. 4. Plot of a dust particle embedded in a spacesuit. The strong micro-scale electric field is caused by charging at dust-spacesuit interface.

USC has also developed the first grid-based Vlasov simulation model for electric propulsion and spacecraft-plasma interactions using equation (1). The Vlasov model eliminates the interference of particle noise in a fully kinetic PIC simulation. These results are being used to develop microscopic physics-based electron thermodynamics closures for macroscopic plasma simulation models.

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f_\alpha + \mathbf{a} \cdot \nabla_{\mathbf{v}} f_\alpha = 0, \quad \mathbf{a} = \frac{-q_\alpha \nabla \Phi}{m_\alpha} \quad (1)$$

In addition to these spacecraft charging codes, the US continues to benefit and use codes developed by international organizations. These include Space Environment Information System (SPENVIS) charging codes (DICTAT, EQUIPOT), FASTRAD (internal charging), Spacecraft Plasma Interaction Software (SPIS), and NOVICE.

IV. SPACECRAFT MATERIAL STUDIES

On-orbit chemical dynamics of spacecraft materials is one of the major research areas of AFRL. They utilize several in-vacuum analysis techniques including Fourier Transform Infrared Spectroscopy, Directional Hemispherical Reflectometry, and Temperature Programmed Desorption, allowing them to probe the chemical and physical alterations of spacecraft materials during and after simulated space weather exposure. This is done with the intent of providing accurate materials information over the entire lifespan of a given material.

Further, AFRL Space Vehicles Directorate has teamed with the AFRL Materials Directorate to establish the 5.5 million dollar “Lab-to-Orbit” National Center of Excellence with objective of providing more accurate ground-based space weather simulation facilities and methodologies. This effort will provide risk mitigation for adaptation of novel materials.

While ground based simulation of the space environment

remains a priority, it is also critical that these simulations be compared to the effects of actual space weathering. To that end, AFRL is part of a team that launched fourteen materials to the International Space Station where they were exposed to six months of the low Earth orbit (LEO) environment as part of the MISSE-16 program. The MISSE program has flown many missions over the years. However, MISSE-16 was the first to capture on-orbit optical data and provide in-situ analysis of how the materials were degrading. This, along with extensive pre and post flight analysis, provides real-world benchmark for all materials exposed to a simulated space environment and allow AFRL to refine its simulations to be more flight-like.

V. TESTING

The US spacecraft charging material and instrument testing continues to expand and strengthen. One of the major hurdles to anyone trying to simulate the space environment for study is that it is cost prohibitive to generate the broad-spectrum, high-energy electron environment seen in most regions of space. To address this need, AFRL is currently developing a low-cost, multi-energy electron gun that uses staged coaxial emission sources to produce up to fourteen different discrete electron energy populations simultaneously (**Fig. 5**). While this is not a true electron energy continuum, modeling shows that it produces a reasonable approximation of the dose depth profile expected in orbit. The development of this tool will enable AFRL to simulate the space environment more accurately, as well as lower the barrier of entry for anyone wishing to develop space simulation capabilities [12].

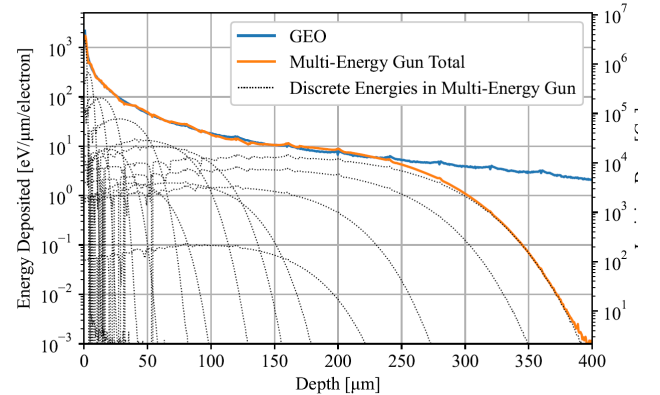


Fig. 5. Simulation of dose/depth profile of GEO spectrum and that of 14 monoenergetic combined stages.

Of course, basic research into material weathering and space simulation is critical, but AFRL still expends considerable resources in more applied testing campaigns. They routinely test new and novel solar array configurations to the ISO 11221 standard as well as custom tests to establish arc mitigation efficacy.

EMA has established the Space Environment and Radiation Effects (SERE) laboratory. The lab is designed to test and analyze materials and components in the space environment. Results can then be compared with simulations from the Ansys Charge Plus code to provide a deeper understanding of the material/component’s expected behavior in the harsh space environment. JPL’s testing capabilities include material

property testing and charging testing with an electron beam using the Dynamitron and the Reliability Assurance Technology Testing Laboratory (RATT Lab). Utah State University and the MSFC Space Environments Effects Test Laboratory continue to be leaders in the space environment testing field.

Development of a Multi-Energy Electron Gun. In AIAA SCITECH 2023 Forum, p. 1396, 2023.

V. CONCLUSION

The US continues to be a leader in the spacecraft charging community with significant improvements to models and testing. We highlight just a few in this paper, and it by no means is an exhaustive depiction of US contributions. We expect many from the US have presentations and papers at the conference highlighting even more of the US contributions. We invite you to read these papers for a more complete representation of the US involvement in spacecraft charging.

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