

United States Spacecraft Charging Overview

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M. Mandell, V. Davis, Leidos

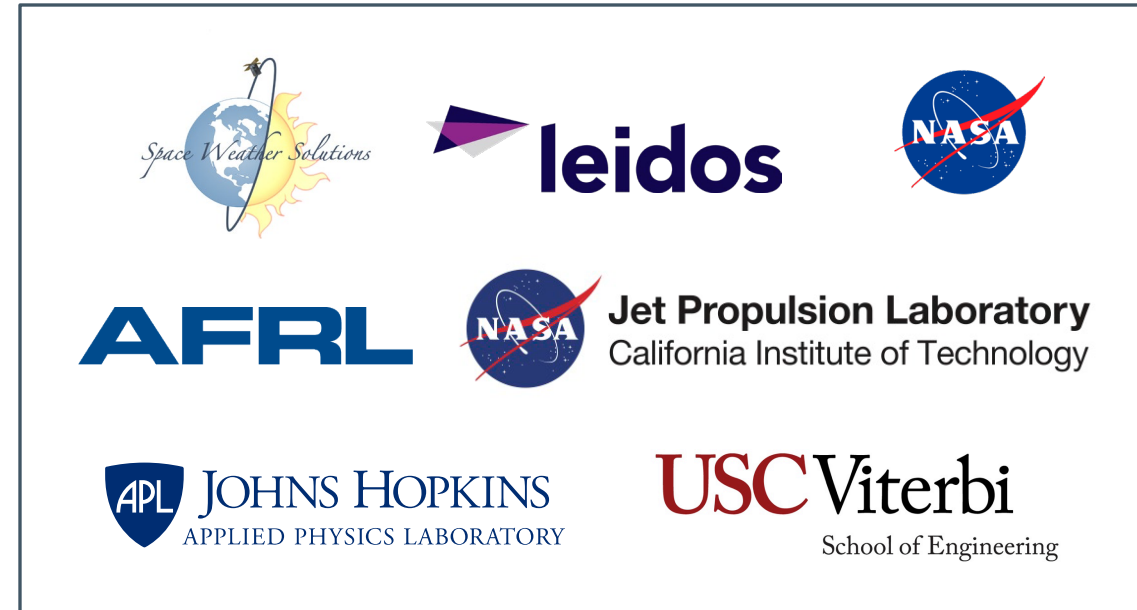
J. Likar, APL

R. Hoffmann, D. Cooke, Z. Gibson, J. Shah, US AFRL

J. Minow, NASA

J. Wang, University of Southern California

Emeritus: H. Garrett, A. Whittlesey

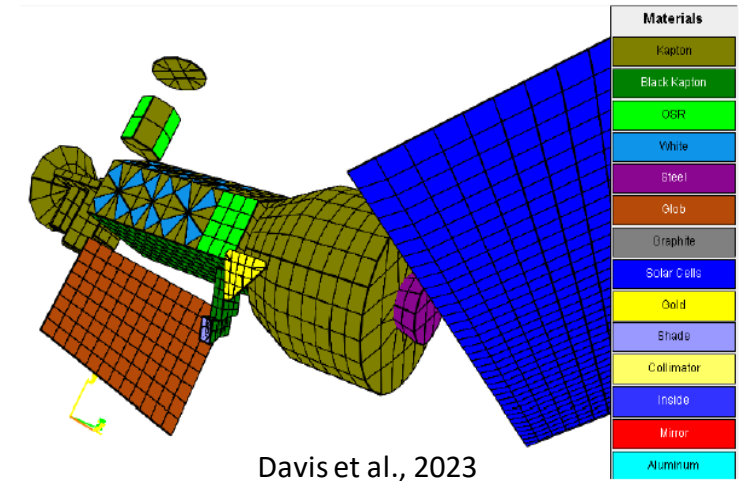


Overview

- Lunar charging
- Charging Activities
 - NASA, APL, JPL, and AFRL
- Test Facilities
 - JPL, AFRL, NASA, Industry
- Model development and use

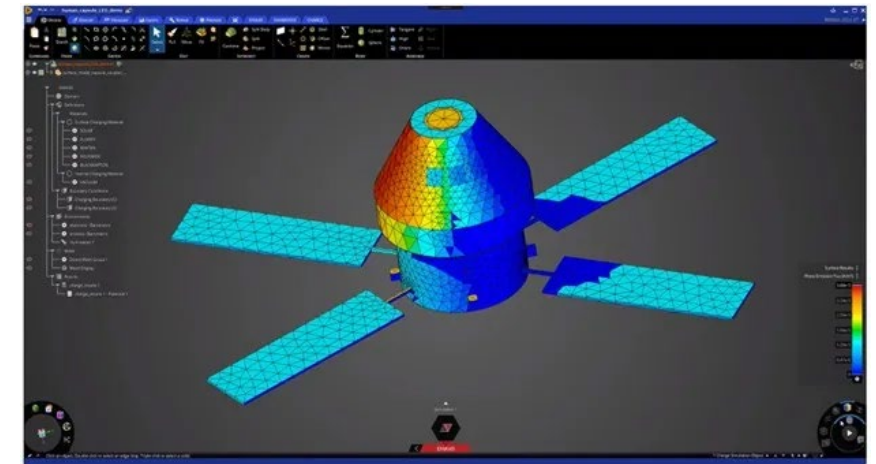
U.S. Use of Charging Codes

- Nascap-2k (surface charging)
 - Developed and maintained by Leidos on contract to Space Force and NASA
 - Version 4.5 released in 2024
 - Standard surface charging tool for NASA and the US aerospace industry
- EMA Charge Plus (surface and internal charging)
 - Commercial software developed by Electro Magnetic Applications
 - Surface and internal charging
 - Sophisticated 3D modeling
- NUMIT V2.0 (internal charging)
 - 1D internal charging code
 - Maintained and distributed by JPL
- NUMIT 3D (internal charging)
 - 3D internal charging code based on Geant4 and COMSOL electrostatic solution
- US continues to use codes developed by international organizations
 - Space Environment Information System (SPENVIS) charging codes (DICTAT, EQUIPOT)
 - FASTRAD (internal charging)
 - Spacecraft Plasma Interaction Software (SPIS)
 - NOVICE



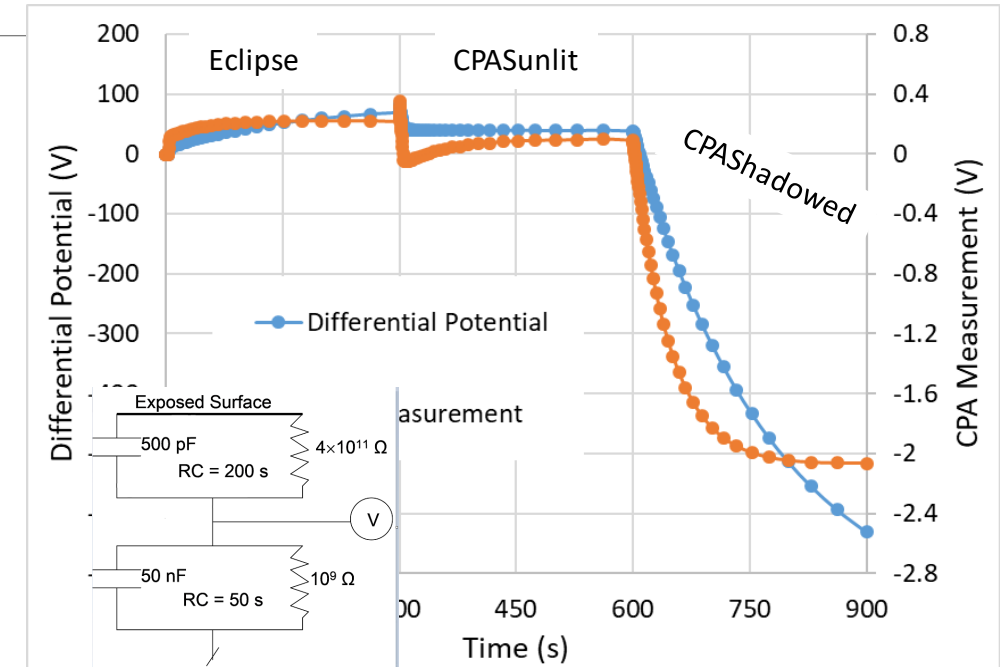
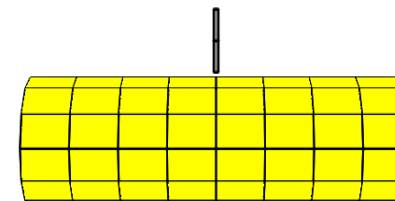
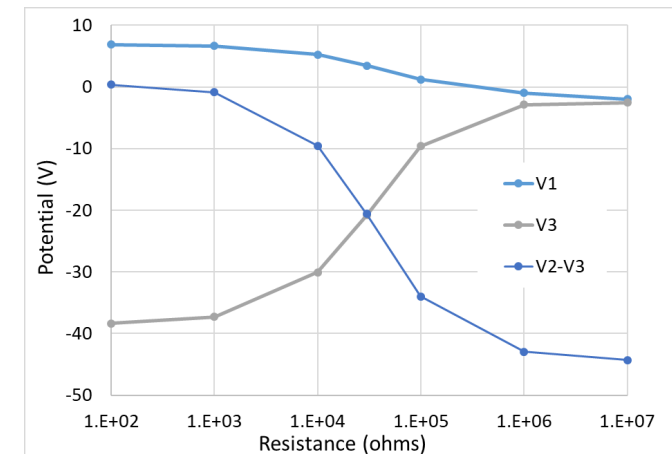
Davis et al., 2023

Figure 3. DMSP Spacecraft Model Constructed in Object Toolkit.



Nascap-2k Developments

- Increased limits
 - Surface cell number
 - Grid Size
- Improved treatment of cavities
- Circuitry
 - Interconductor capacitance
 - Interconductor resistance
- Examples
 - Charge Plate Analyzer
 - Response of instrument to changing environment
 - Tether system
 - Voltages on 200 m tether system as function of tether resistance





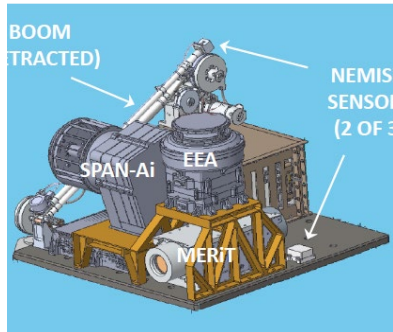
NASA Charging Activities

- Design work for upcoming Gateway missions
 - Radiation belt transit of the initial PPE and HALO modules using electric orbit raising
 - Artemis (Orion and Gateway modules) docking in outer radiation belt (McCollum et al., 2023)
- Auroral charging in low Earth polar orbits remains a design consideration for NASA programs and has recently been considered in a number of anomaly investigations.
- Space weather launch constraints use to protect James Webb Space Telescope during radiation belt transit from electrostatic discharge from surface and internal charging (Minow et al., 2023; this conference)
- Lunar charging
 - Lunar charging analysis for Artemis lunar programs including Gateway space station and lunar surface systems
 - Recent work by Borovsky et al predicting surface potentials of 10's to 100's kilovolts from spacecraft charging has serious implications for NASA's long-term plans for exploration of the Moon (Borovsky et al., 2021)
- NASA-HDBK-4002B update released June 2022 <https://standards.nasa.gov/>

*NASA's Headed Back to the Moon



HERMES



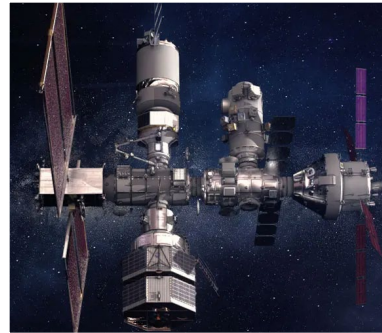
- Heliophysics Environmental Radiation Monitoring Experiment Suite
- Instrument package on the Gateway - 3 particle instruments and a set of magnetometers.

Orion



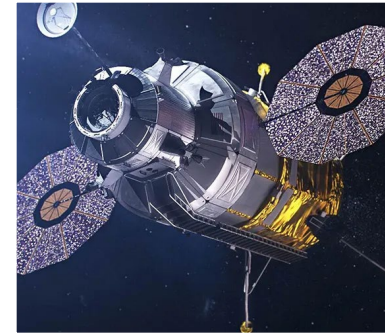
- Spacecraft that will transport astronauts to and from Earth and Gateway.

Gateway



- Space station that will remain in lunar orbit. Astronauts will go back and forth from the Gateway to the surface of the moons via the HLS.

Human Lander System



- Spacecraft that will transport astronauts to and from Gateway and the surface of the moon.

Artemis Base Camp



- Permanent residence on the lunar surface.

*NASA with commercial and international partners

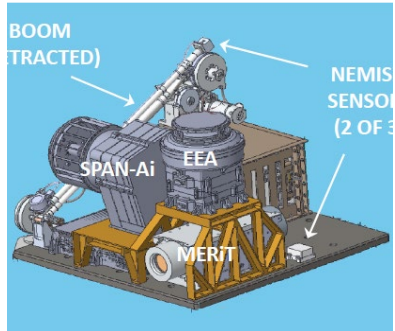
Image credit: Paterson and Spann,
"Science from Gateway with HERMES"

Image credit: <https://www.nasa.gov/specials/artemis/index.html#how>

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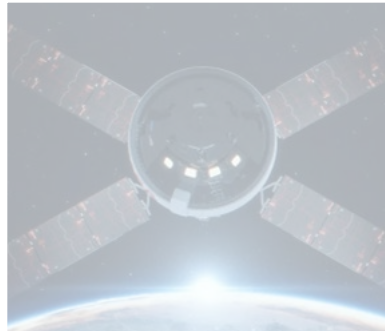


HERMES



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- Instrument package on the Gateway - 3 particle instruments and a set of magnetometers.

Orion



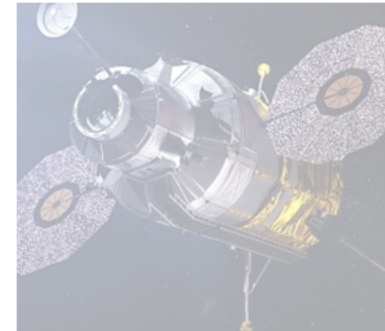
- Spacecraft that will transport astronauts to and from Earth and Gateway.

Gateway



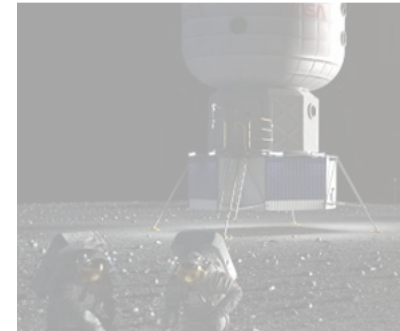
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Image credit: Paterson and Spann,
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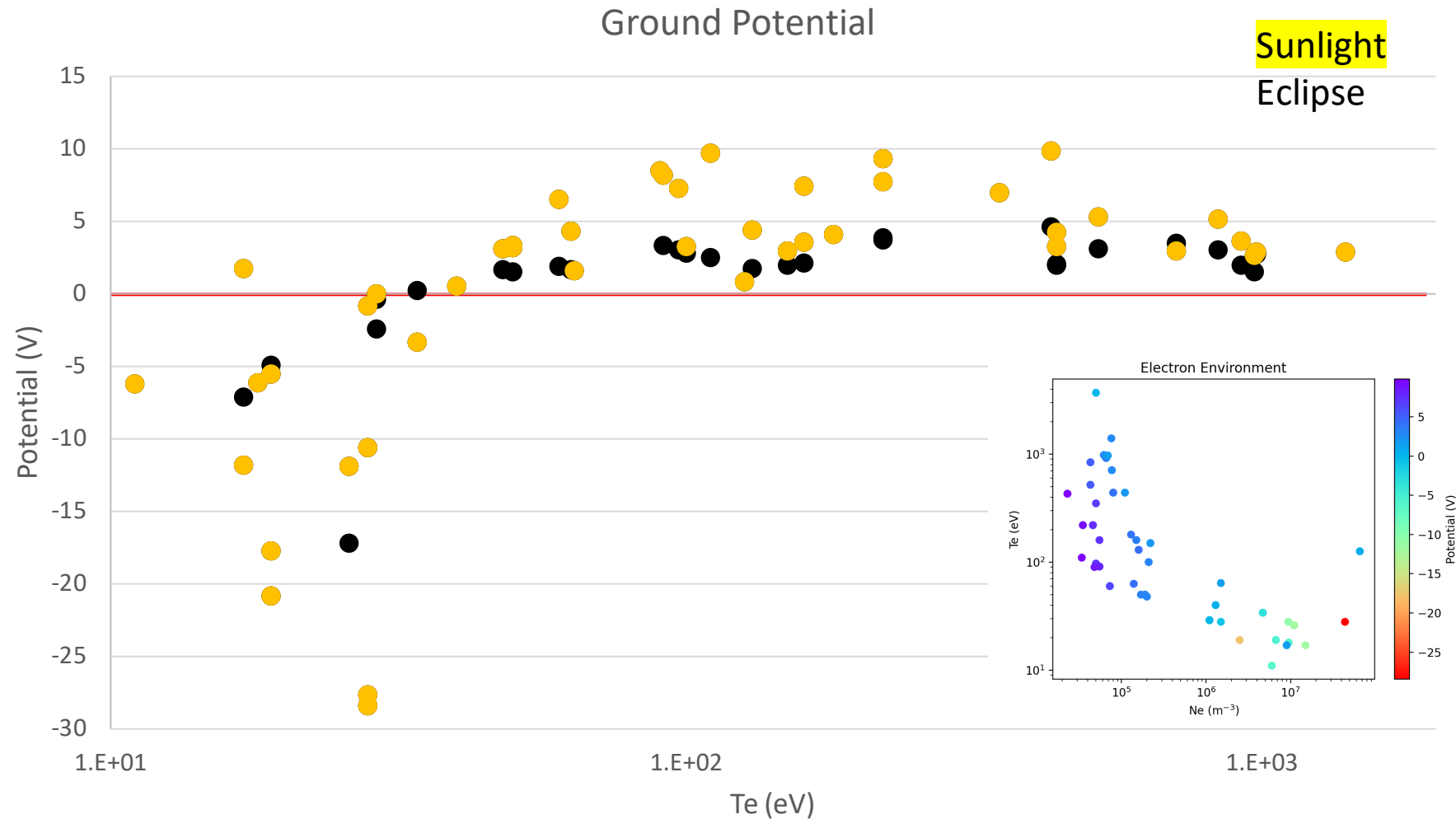
Image credit: <https://www.nasa.gov/specials/artemis/index.html#how>

Lunar Charging

- MSFC Natural Environments Group is leading the surface charging analysis for the Gateway program
- HERMES Instrument Science Teams providing additional research in areas of surface and internal charging.
 - J. Green, “Understanding, Specification, and Prediction of Lunar Space Weather”
 - Identify distinct plasma regions using Gaussian Mixture Model (GMM) and perform surface charging analyses for these environments to produce a database of expected charging levels. Also doing trade studies with different Nascap-2k material properties to see how much that affects the charging levels.
 - Internal charging - Statistical characterization of the location, time persistence, and spectrum of the electrons from THEMIS Artemis and calculate the accumulated charge
 - I. Jun, “HEMERA: HERMES Modelling and Enhanced Response Analyses”
 - Nascap-2k analyses focusing on the HERMES instrument and how the Gateway charging could affect observations

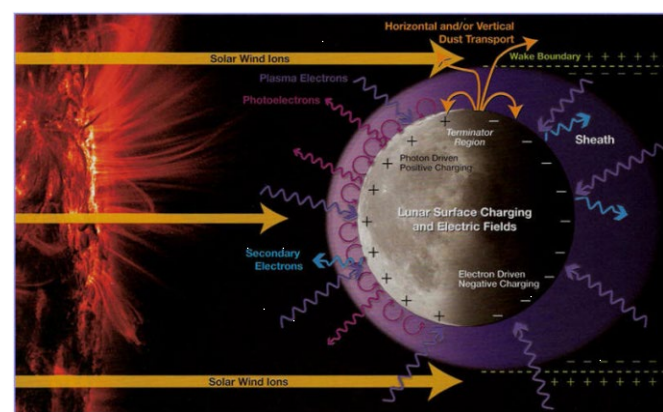


HERMES: Surface Charging Results



Multi-Scale Investigations of Charging Effects on the Lunar Surface

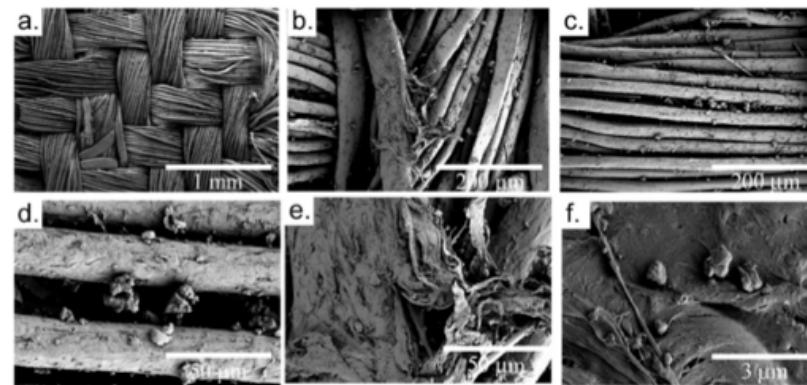
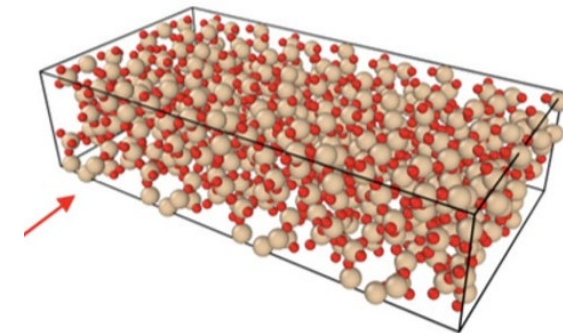
Carried out the first multi-scale modeling to connect global lunar charging environment, local astronaut charging, dusty spacesuit charging, and charging effects on materials (over 10 orders of magnitude in length scales)



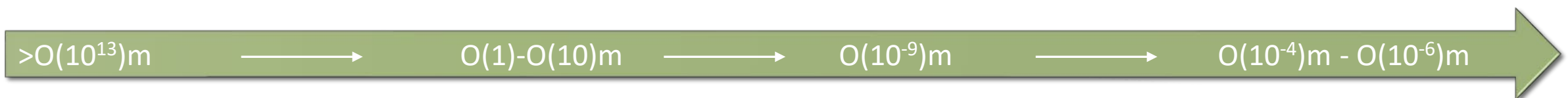
Global Scale Data Analysis



Local/Micro Scale PIC Simulations of Plasma Charging

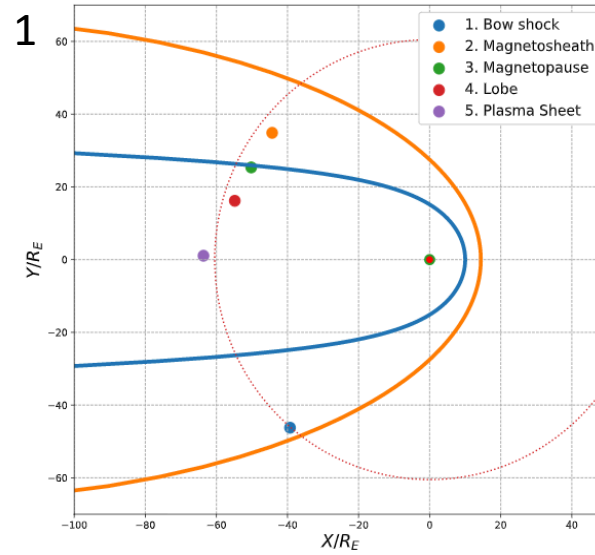
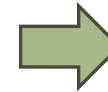
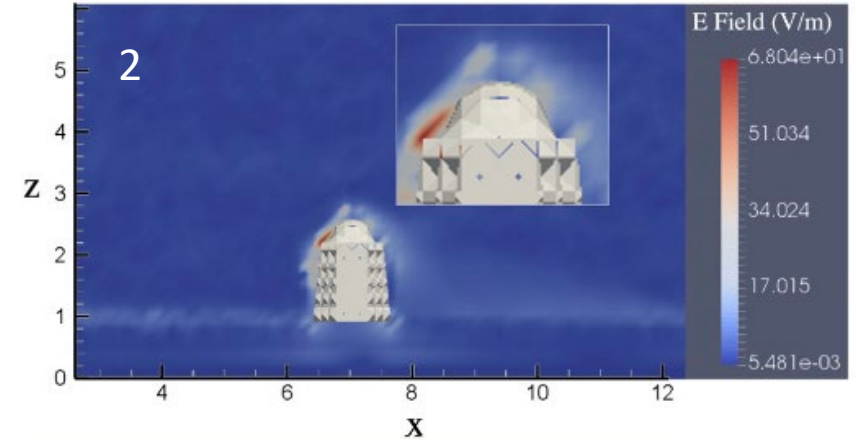
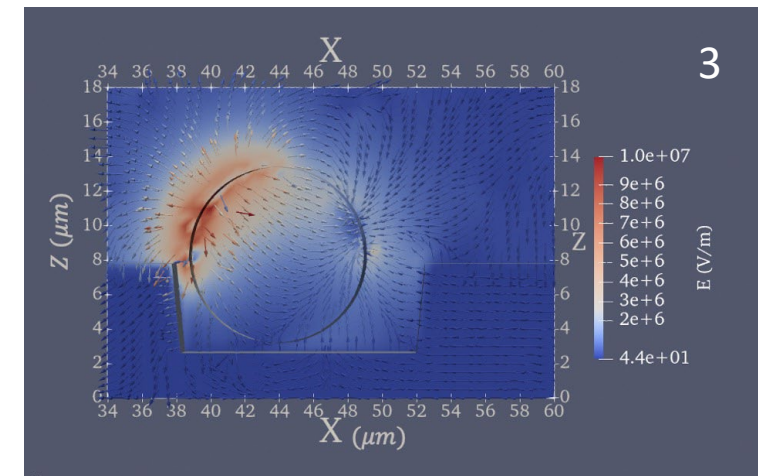
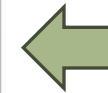
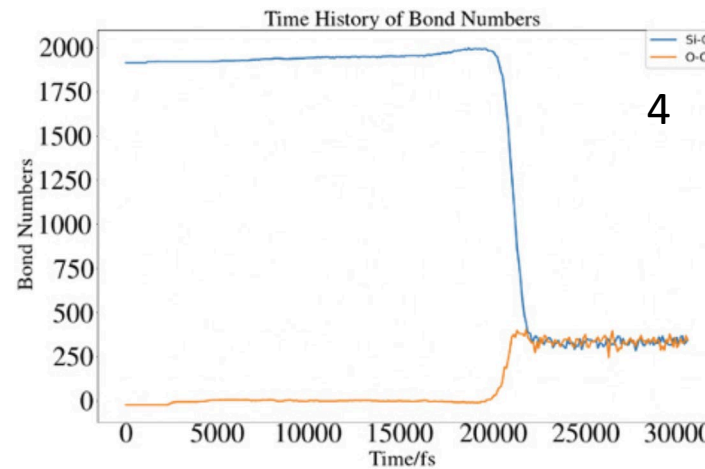


Atomic Scale MD Simulations of Material Response



Micro-scale charging induced by dust on EVA spacesuit surface may lead to material breakdown under even moderate space weather conditions

1. Global scale plasma environments based on ARTEMIS and OMNI data
2. Local Scale PIC simulations of astronaut charging
3. Micro-scale PIC simulations of dusty space suit charging
4. Atomic Scale MD simulations of material dielectric breakdown



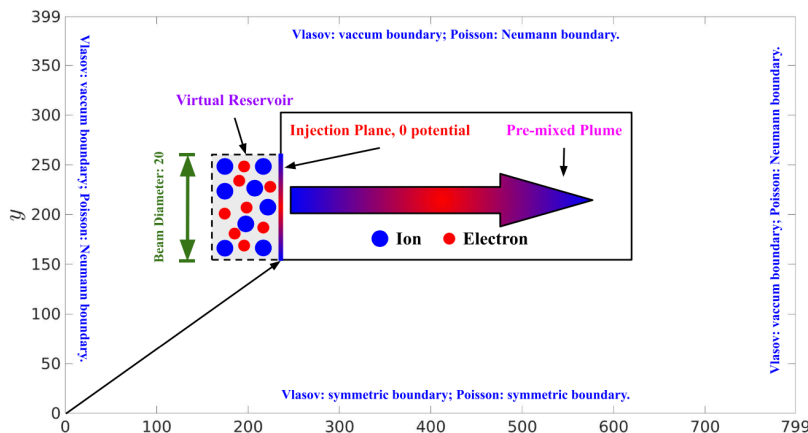
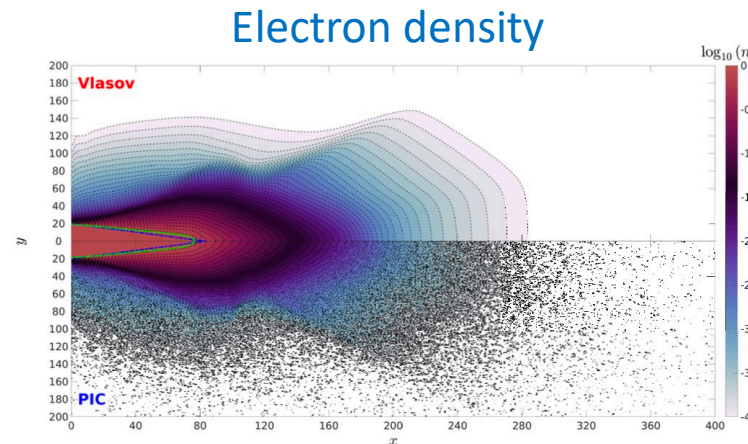
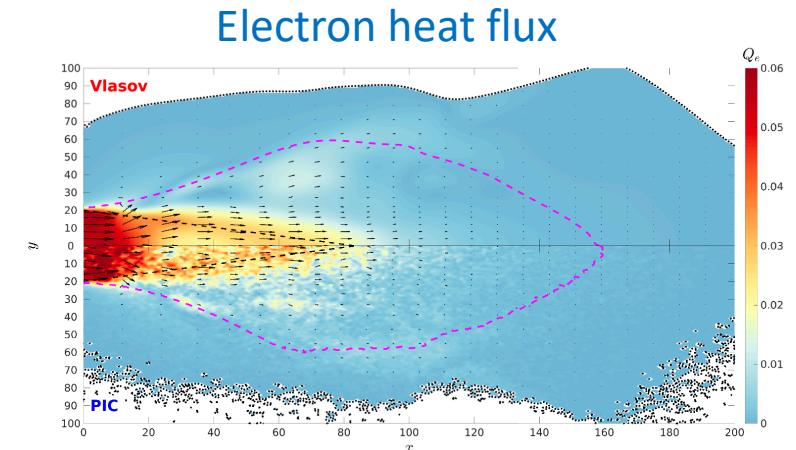
Vlasov Simulations of Plasma Interactions

- USC has developed the first grid-based Vlasov simulation model for electric propulsion and spacecraft-plasma interactions
- Comparison of grid-based Vlasov and full PIC simulations of electric propulsion plume

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

PIC: 10,000 macro-particle/cell at beam exit

- The Vlasov model successfully eliminates the interference of particle noise in fully kinetic PIC simulations
- Vlasov modeling results are currently being applied to develop microscopic physics based electron thermodynamics closure for macroscopic spacecraft-plasma simulation models



Electrostatic Discharge Activities



Jet Propulsion Laboratory
California Institute of Technology

JPL's Natural Space Environments Group supports every flight project at JPL for the ESD discipline. Examples include:

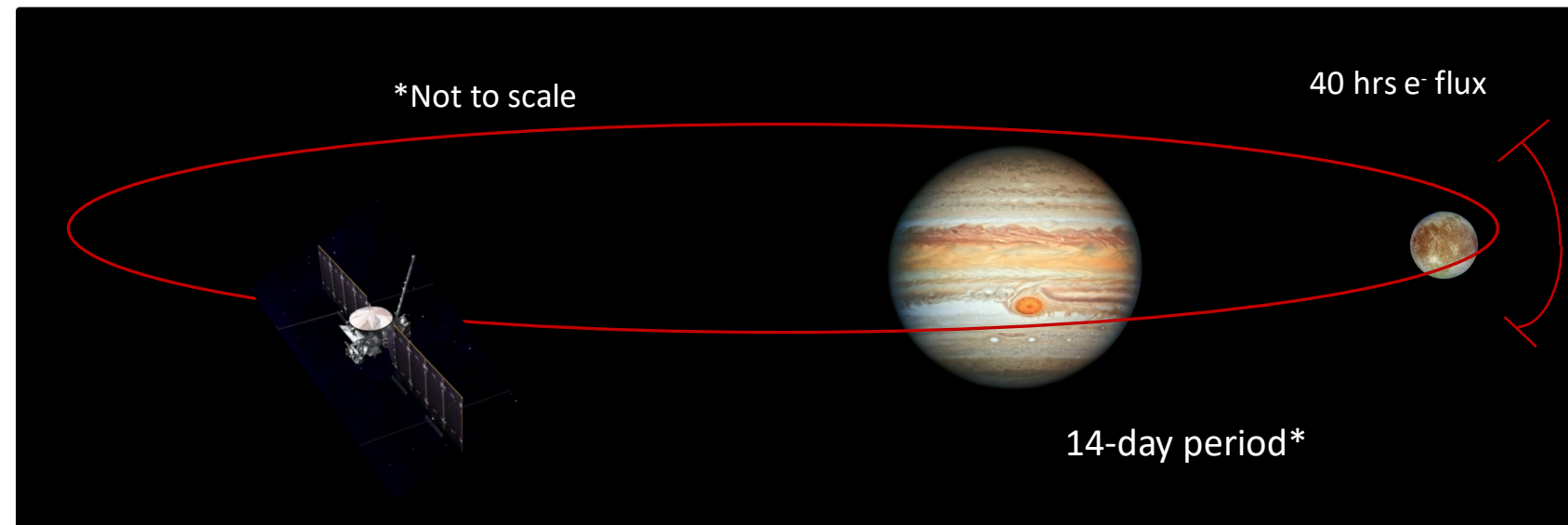
- Europa Clipper Mission (Planetary Science)
- NEO-Surveyor (Planetary Defense)
- Sphere-X (Astrophysics)
- NISAR (Earth Science)

Typical activities are:

- ESD environment definition
- NASCAP-2k simulation
- NUMIT simulation
- Material property testing
- Charging testing with electron beam
- Requirement compliance check

Examples of more detailed activities are:

- Internal charging requirement generation and assessment for cryogenic missions having otherwise benign environments (NEOS, SPHEREx)
- Charging assessment for sample tube exchange between Perseverance and MSR SRL (including Martian dust charging)
- Triboelectric charging assessments (Mars rover, lunar rover – CADRE, Venus balloon)
- Study on lunar dust removal using low energy electron beam (50 – 500 eV)



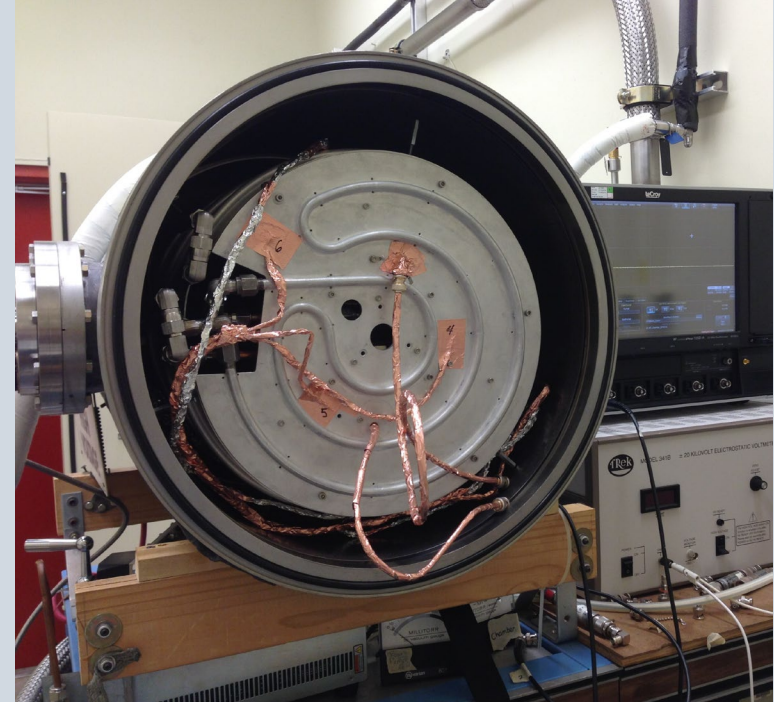
Test Facilities

- Dynamitron
 - POC: Steve.McClure@jpl.nasa.gov
- RATT Lab (Reliability Assurance Technology Testing Laboratory)
 - POC: Allen.Andersen@jpl.nasa.gov



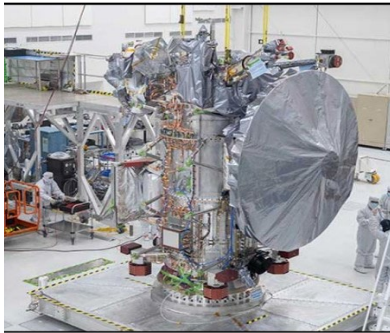
Jet Propulsion Laboratory
California Institute of Technology

17TH SCTC, AVIGNON, FRANCE



Selected Recent Hardware Deliveries and Mission Development

Europa Clipper



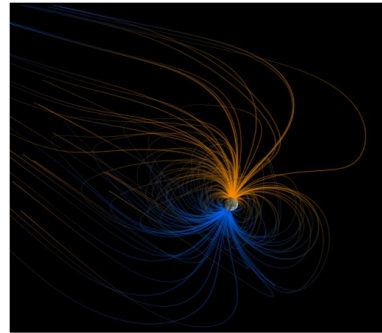
- Delivered the spacecraft communications, power and propulsion systems
- Delivered PIMS and Europa Imaging System (EIS)
- V&V highlighted at several SCTC
- Launching Fall 2024

PIMS & RadMon



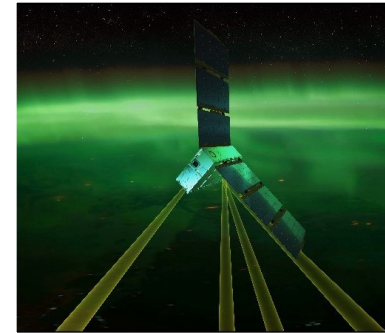
- The Plasma Instrument for Magnetic Sounding (PIMS) installed on Clipper
- Includes four Faraday Cups (Nadir, Zenith, Ram and Anti-Ram)
- RadMon (installed on Clipper) includes Charge Rate Monitors (CRM)

CINEMA



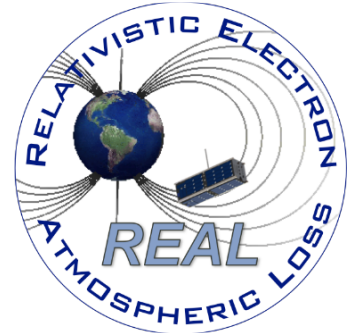
- Cross-Scale Investigation of Earth's Magnetotail and Aurora (CINEMA) selected for further development as SMEX concept
- 9 polar Cubesats; each with ECP and MAG
- Final SMEX mission select Late 2024

EZIE



- The Electrojet Zeeman Imaging Explorer (EZIE) to study currents between the aurora and magnetosphere
- 3 polar 6U Cubesats w/ variable spacing
- Citizen science component (EZIE-Mag)
- Launching Fall 2024

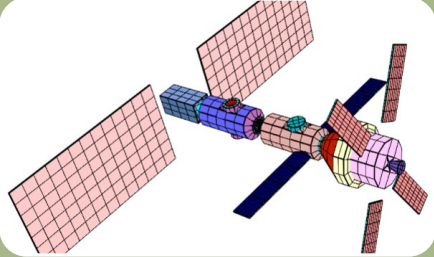
ECP



- Montana State University (MSU) led Relativistic Electron Atmospheric Loss (REAL) 3U Cubesat relies on an APL ECP
- Variable energy ranges over 5 pitch angles
- Launching late 2024

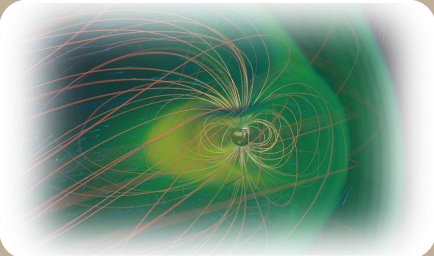
Space Weather & Low Cost Planetary Exploration

Spacecraft Charging and Space Weather



HERMES

- Supporting Space Hazards led Interdisciplinary Science Team (IDS) study
- Developed plasma models based on THEMIS / ARTEMIS observations
- Evaluated surface charging impacts based on Gateway orbital regimes
- Evaluated propagated uncertainty in surface charging based on materials



Space Weather

- Headquarters for Center for Geospace Storms (CGS)
- Delivered Science & Observation Gap Analysis for NASA
- OVATION-Prime model (auroral precipitation) incorporation into SET4D
- Navy Ionosphere Model for Operations (NIMO) validation

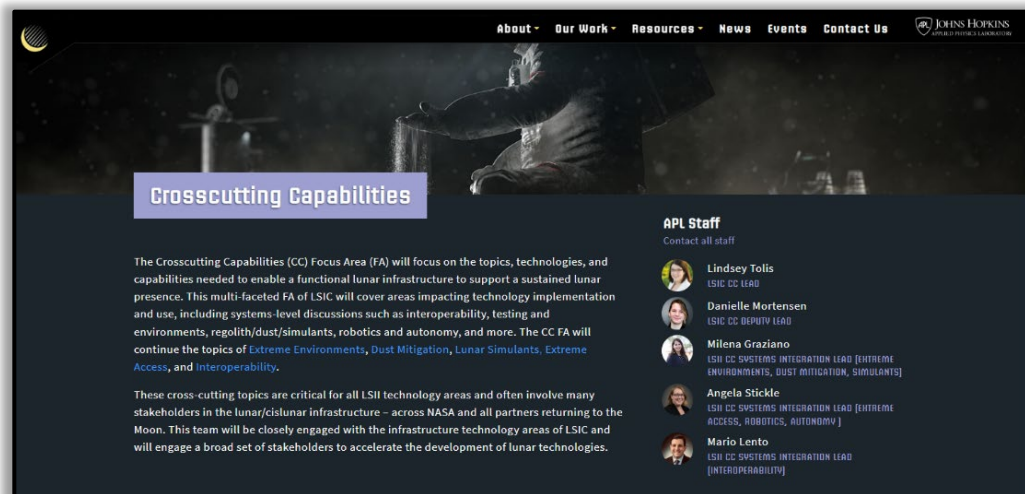
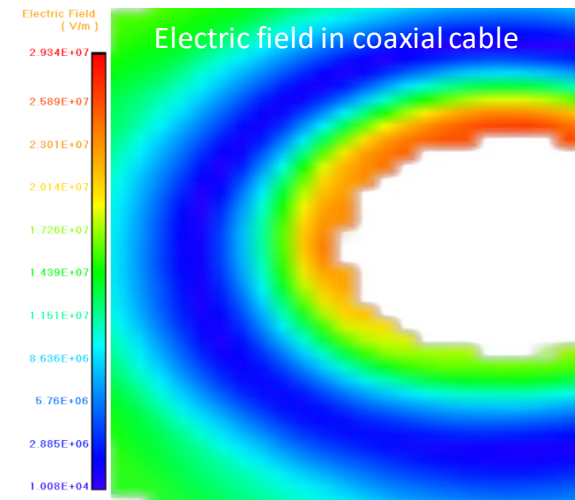


Space Weather Table Top eXercise (TTX)

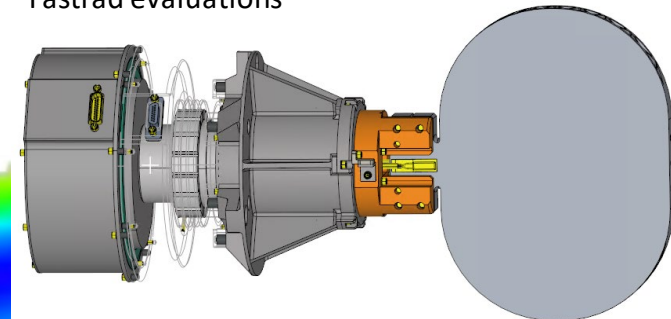
- Leading SWx preparedness exercise for NOAA, NASA, NSF & FEMA
- Participants from DOD, FEMA, EPA, OSTP, CISA, DOE, DOT and more
- Simulates series of events and impacts in near-earth space and on earth
- Scheduled Spring 2024

Empirical and Analytical Updates

- Ramp down on the test program for Europa Clipper
- On-going configuration studies and pre-work for a series of chambers
 - VLEO plasma & neutrals
 - Laser / HV EMP
 - Lunar surface / dust / dirty
- Leading the Lunar Surface Innovation Consortium (LSIC) Focus Area (FA) inclusive of Space Weather and Plasma Environments (SWPE)
- Tribo-charging risk assessments performed for the Dragonfly rotorcraft at Titan
- Correlation study of VAP MagEIS fluxes against ERM currents; established “turn-on” energy for each plate
- Continued evaluations and benchmarking of 3D internal charging (IESD) tools
 - Fastrad
 - Ansys Charge Plus (EMA3D Charge)
 - SPIS



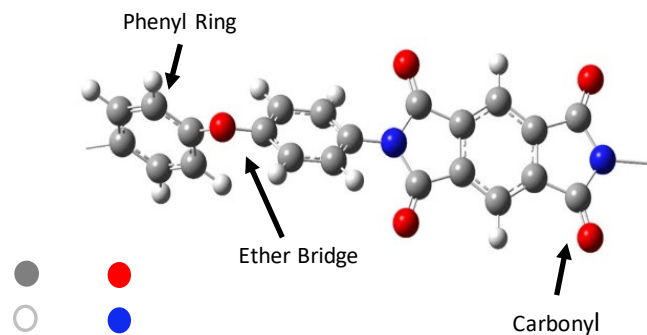
Europa Clipper MISE instrument (below) used in Fastrad evaluations



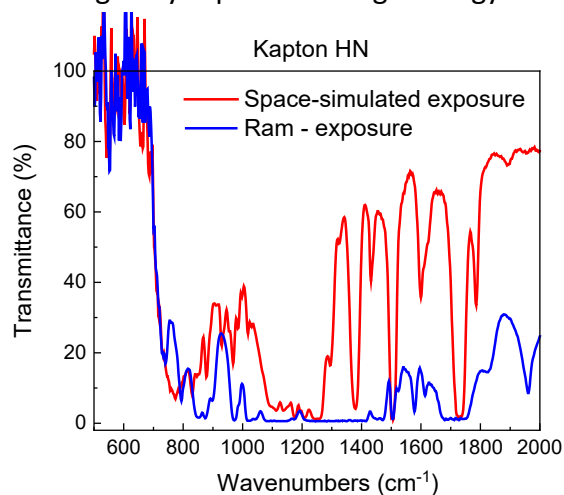


In Vacuum Material Aging

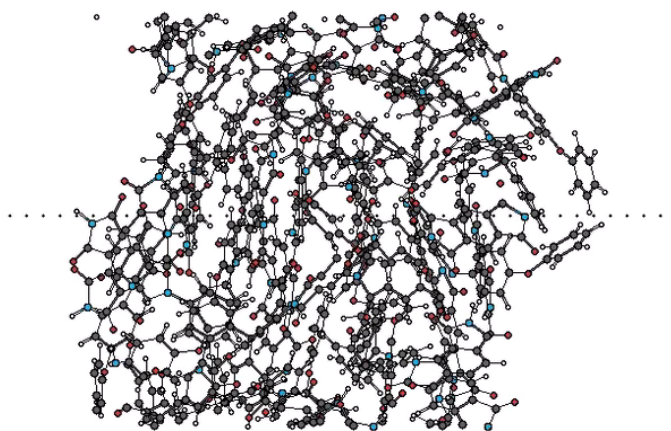
AFRL



Polyimide monomer showing moieties most likely to be damaged by exposure to high energy electrons.



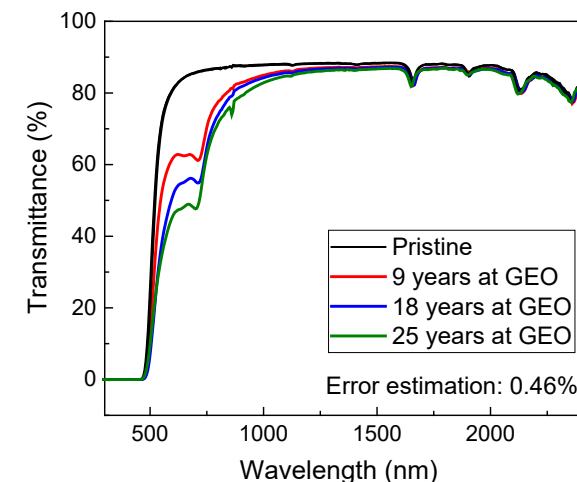
FTIR spectrum showing chemical differences between simulated space weathering and ram-exposed flight materials.



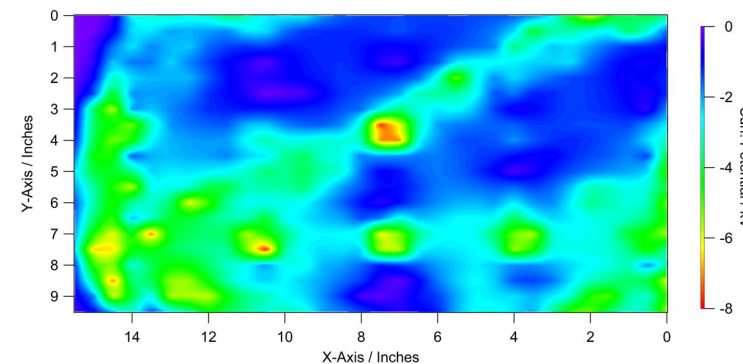
Density functional theory (DFT) simulation showing the interaction of a high energy electron and a polyimide slab.

AFRL continues to study the chemical dynamics of spacecraft materials as they are exposed to individual components of the space environment and how those dynamics drive relevant physical properties. (i.e. reflectivity, conductivity, etc.)

We have also established the “Lab-to-Orbit” National Center of Excellence with the objective of providing more accurate environmental simulations and hastening the adoption of novel materials.



Optical transmission of polyimide given various GEO equivalent electron fluxes.

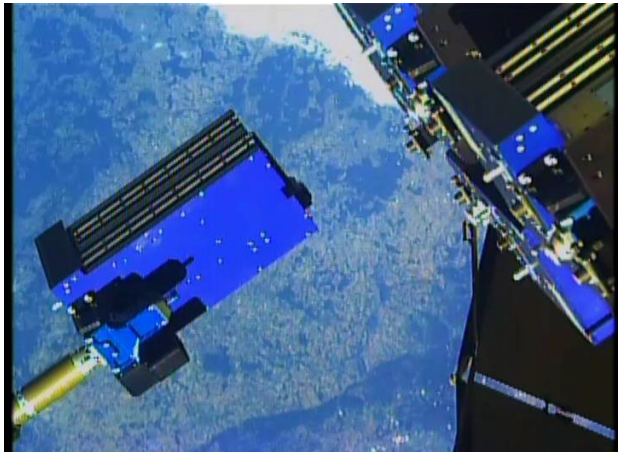


Surface potential scan of insulating surface after 5 years GEO equivalent electron flux.



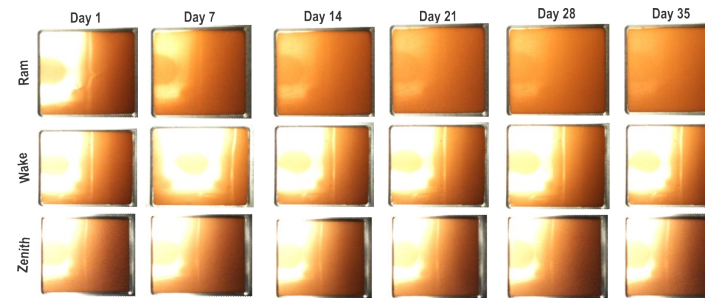
On Orbit Material Aging

AFRL



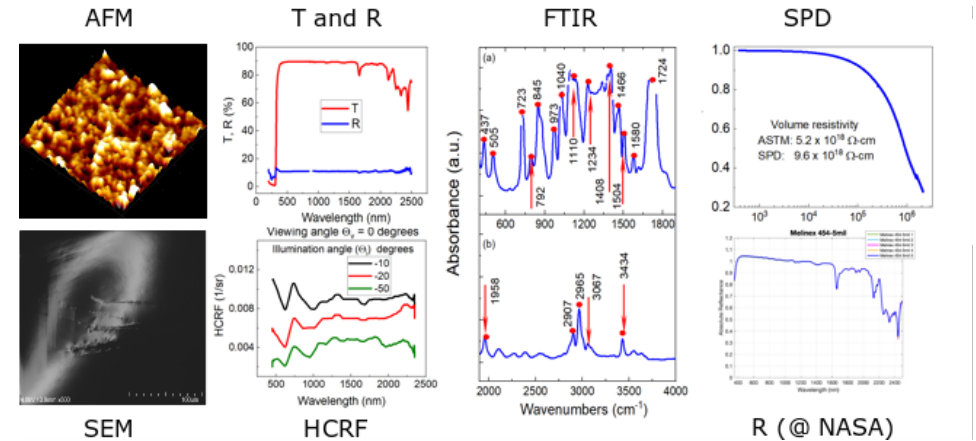
Launch and installation of MISSE flight facility July 2022.

AFRL is part of a team that has launched and recovered 14 materials from the ISS as part of the MISSE-16 program. These materials have undergone extensive pre and post flight analysis, as well as a concurrent ground-based simulated flight exposure. It is the intent of this program to elucidate the differences between flight exposure and simulated exposure and provide benchmark material characterization, to which simulated exposure can be compared.



In-flight imaging of ram, wake, and zenith exposed Kapton HN samples.

Material	Trade name
PMDA	Kapton® CR, Kapton® CS, Kapton® WS, Kapton® XC, Kapton® TF, Kapton® HN, DR9
PET	Melinex® 454, Mylar® 021
PI/POSS	CORIN® XLS, Thermalbright® N
LCP	Zenite®
CFRP	Economyplate™
GFRP	G-10/FR4 Glass Epoxy
Aluminum oxide	Alumina



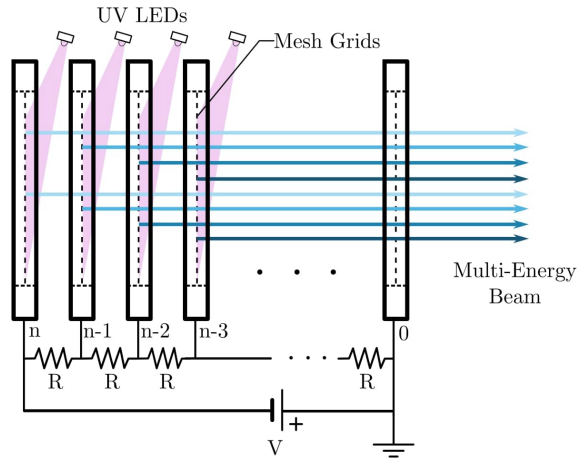
Material flown on MISSE-16 (above) and pre/post flight characterization performed (below).

Jainisha R. Shah, Ryan C. Hoffmann, (Air Force Research Laboratory, Kirtland AFB); Daniel P. Engelhart (University of New Mexico); Gregory P. Badura (Georgia Tech Research Institute); Heather M. Cowardin (NASA Orbital Debris Program Office); Jacqueline A. Reyes (University of Texas at El Paso); Timothy R. Scott (DuPont de Nemours);, Sydney E. J. Collman (Assurance Technology Corporation)

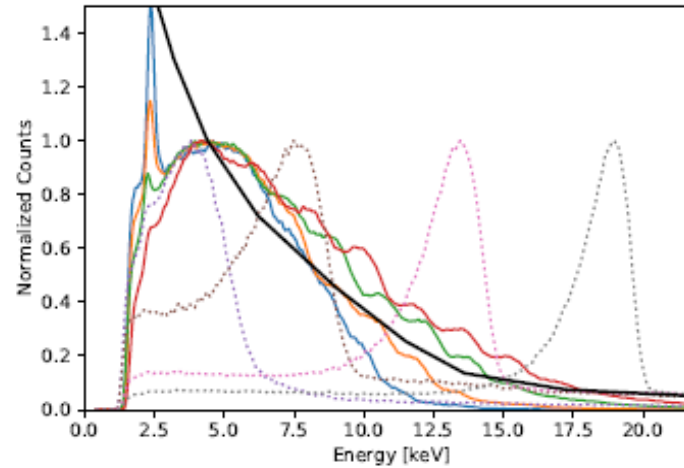


Space Weather Simulation

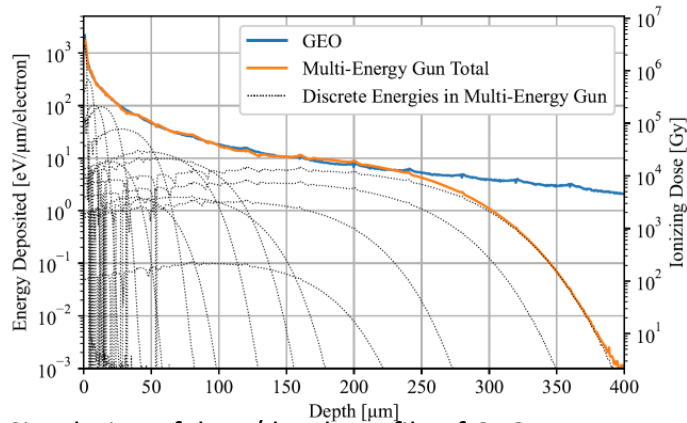
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Simplified schematic of staged electron emission

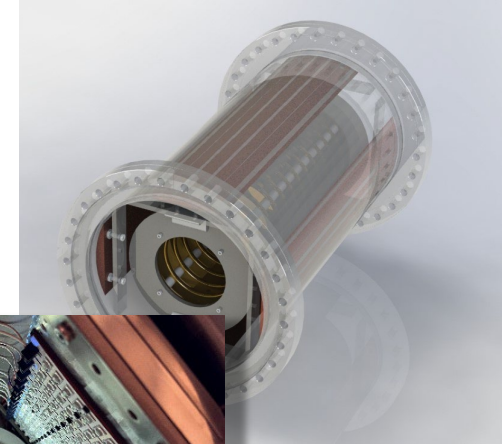
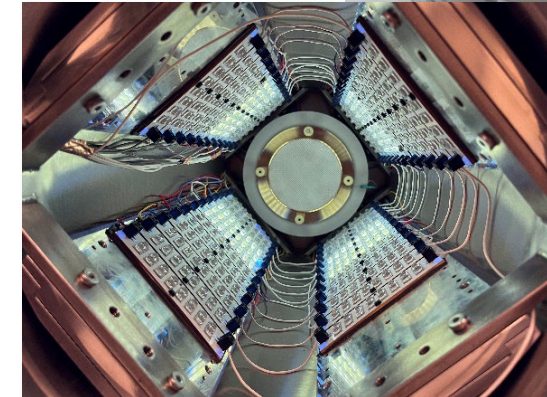
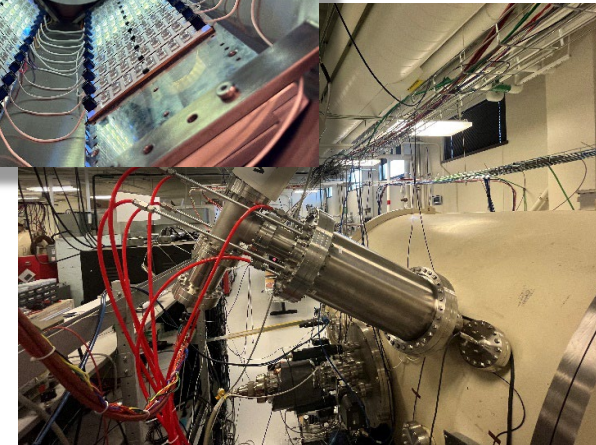


Board spectrum of MEGs emission with <20 keV



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

AFRL is developing a low-cost multi-energy electron gun (MEGs) to improve accuracy of ground-based space weather simulation and avoid the cost of more traditional systems that require high energy accelerators and scattering foils.

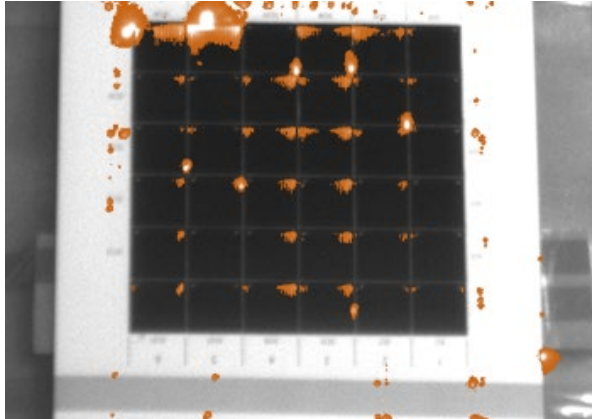


Bengtson, M. T., Hoffmann, R. C., Ferguson, D. C., Shah, J., Collman, S., Han, S., ... & Sharma, P. (2023). Advances in the Development of a Multi-Energy Electron Gun. In AIAA SCITECH 2023 Forum (p. 1396).

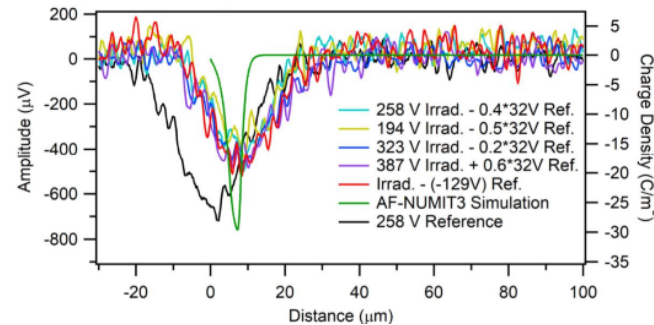


Spacecraft Charging

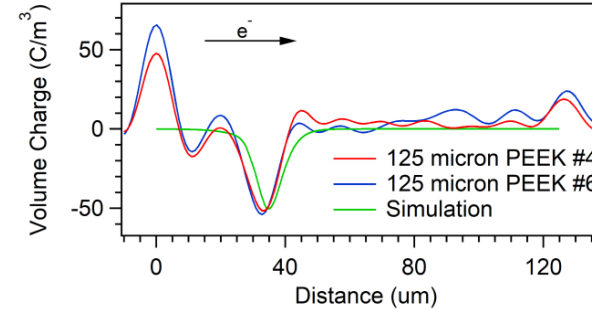
AFRL



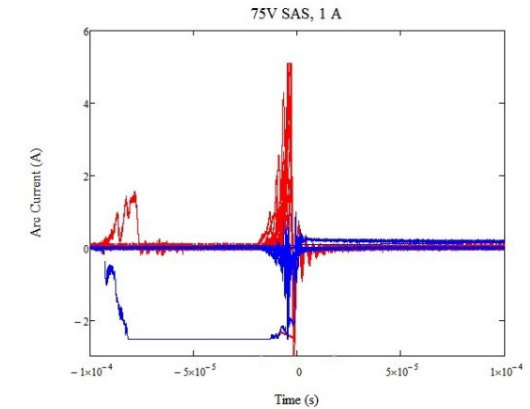
Solar array sample showing arc sites



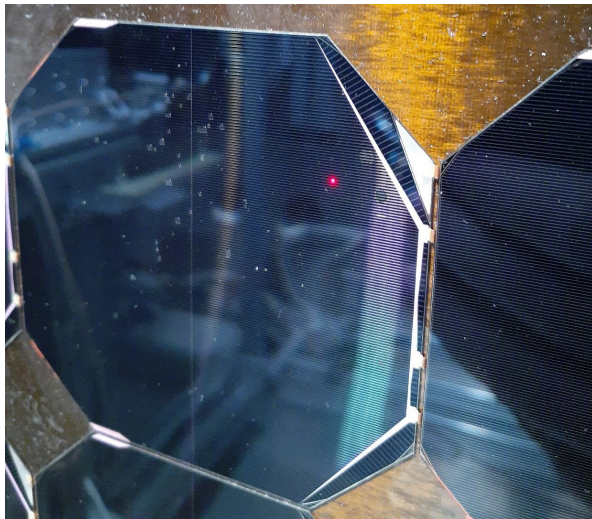
PEEK irradiated with 24 keV electrons compared to simulation data from AF-NUMIT3.



PEEK irradiated with 50 keV electrons compared to simulation data from AF-NUMIT3.



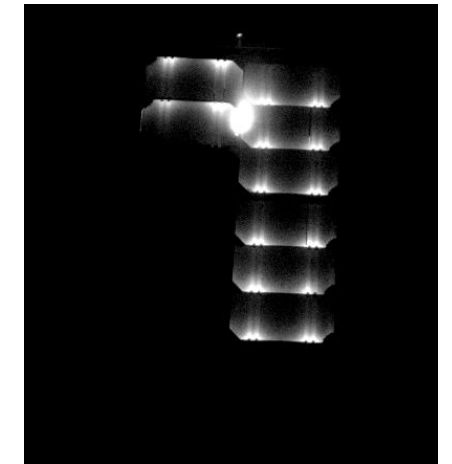
Arc current showing primary arc in red and temporary sustained arcing in blue.



Solar cell showing damage caused by arcing

AFRL continues to develop, validate, modernize, and utilize space weather and modeling tools as well as conducting spacecraft charging testing to both internal and external customers, including the ISO 11221 testing standard. These test primarily involve solar array development and charging mitigation strategies but can also include more exotic systems such as antenna and reaction wheels.

Gibson, Z., "Precise Determination of Charge Distributions in Electron Irradiated Polymers Via Pulsed Electroacoustic Measurements With Applications to Spacecraft Charging" (2023). Utah State University, PhD Dissertation; Gibson, Z., and Dennison, J. R., "A Simple Method for Determining Shallow Charge Distributions in Dielectrics via Pulsed Electroacoustic Measurements." IOP Conference Series: Materials Science and Engineering. Vol. 1287. No. 1. IOP Publishing, 2023.



Solar array emitting light as a result of back bias caused by an arc

Thank you from
the U.S.!

17TH SCTC, AVIGNON, FRANCE



Northern lights seen from Monteagle, TN in southeastern USA

PHOTO CREDIT: J. MINOW