A Tutorial on Spacecraft Charging

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SHEILDS CONFERENCE
7 April 2016
**SPACE CLIMATE**: Statistical Description of the Solar-Terrestrial Environment parameterized by solar and geomagnetic activity type and intensity

**SPACE WEATHER**: Processes associated with the temporal and spatial variability in the Solar-Terrestrial Environment

**SPACE ENVIRONMENTAL EFFECTS**: Effects of the space environment on man-made systems (e.g., impulsive disruptions, long-term degradation, etc.)
Motivation: Radiation Effects on Space Systems

- Electrostatic Discharge (ESD)
- Circuit Damage
- Reduce Solar Panel Efficiency
- Material degradation
- Contamination of sensitive optics
- Interference with scientific measurements
Intro: The Concept of “Ground”

“Ground” on Earth: An arbitrary (but consistent) designation of an electric potential = 0

Electronics Case (Conductive)

Lucky!

Unlucky!

REALLY Unlucky!

(An argument for polarized plugs!)
We like ground points in our circuit.

- Important for safety
- “Absolute” voltage reference for circuit components
- Can serve as a current sink
- Reminds us of best practices (e.g. avoiding ground loops)

Hard-wired grounding of electrical case: **Safe!!**

“Ground” on Earth: Don’t take that third prong for granted!
Intro: There is no “ground” in space!

Conundrum: There is no “ground” in space!

How do we characterize “Spacecraft Charging”?

Definitions:

**Charging** is a voltage relative to some reference potential

**Spacecraft frame charging** is commonly referenced to the ambient space plasma potential

**Differential surface charging** commonly describes the voltage between an electrically-insulated component and the s/c frame
Fundamentals: Space, Plasma, and Frame Potentials

Vacuum Space Potential

\[ V = k \frac{q_1}{r_1} \]

P is just a point in space.

Potential of q1 at P

Plasma Potential

Shielding due to the charge screening

Debye Length: a function of ambient plasma (electron) temperature and density

\[ \lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e q_e^2}} \]

In Vacuum: Space Potential \( \rightarrow 0 \) as \( r \rightarrow \infty \)

In Plasma: Local Plasma Potential is referenced off of space potential as \( r \rightarrow \infty \)

Convention: Let Plasma Potential == 0

We commonly use “space” and “plasma” potentials interchangably
Langmuir probes provide:

- Plasma electron and ion density and temp
- S/C potential
- Plasma Potential

Characteristic I-V Langmuir Probe Curve

CUBESTAR from U. of Oslo
http://cubestar.no/
To derive the equation for the potential of a stationary, passive conducting object: balance the electron and ion fluxes & assume the election and ion temperatures are the same

- Mean speed of the particles in a plasma is given by
  - \( u = \text{mean speed} \)
  - \( \alpha = \text{species (electron or ion)} \)
  - \( k = \text{Boltzmann’s constant} \)
  - \( T = \text{temperature} \)

- Flux (particles per unit area per unit time crossing a surface) is given by \( \Gamma_\alpha = \frac{n_o u_{o,\alpha}}{4} \)

- The electron density is given by \( n_e = n_o \exp\left(\frac{e\Phi}{kT_e}\right) \)

(This represents the electron density at the surface of a conducting object charged to \( \Phi \). In a space plasma, \( \Phi \) will be negative, so \( n_e \) will be less than the ambient plasma density \( n_o \))

- Electron flux = ion flux \( n_o \exp\left(\frac{e\Phi}{kT_e}\right)\sqrt{\frac{8kT_e}{\pi m_e}} = n_o \sqrt{\frac{8kT_i}{\pi m_i}} \)

- Assume the electron & ion temperatures are the same \( \exp\left(\frac{e\Phi}{kT}\right) = \sqrt{\frac{m_e}{m_i}} \)
Satellite Surface Charging

■ Solve for potential, $\Phi$

$$\Phi = \left( \frac{kT}{e} \right) \ln \left( \frac{m_e}{m_i} \right)$$

■ In an oxygen plasma (near earth),

$$\Phi \approx -10 \left( \frac{kT}{e} \right) \approx -1V$$

For thermal ionosphere plasma temp = 0.1 eV

QUESTION: OK, in LEO the spacecraft might charge up to -1V, but... who cares about that?

ANSWER: This charging is due to ambient thermal ionospheric plasma, but it becomes more complicated when higher energy electrons are in the environment.
Different types of S/C Surface Charging

- Incident Electrons
- Incident Ions
- Solar UV Photons
- Reflected Electrons
- Back-scattered Electrons
- Secondary Electrons
- Plasma Sheath "Boundary"
- Photo-electrons
- Isolated Conductor
- Deep Dielectric Charging
- Dielectric (Insulating) Material
- Spacecraft Frame (Conductive) Material
- Conduction
- \( V_c \)
- \( V_d \)
- \( V_f \)
Spacecraft Charging Calculation

Contribution from incident charged particles and resulting secondary, backscattered, and photo electrons

\[
\dot{\sigma} = J_{net} = J_e + J_{sec} + J_{backscat} + J_i + J_{photo} + J_{conduction}
\]

Why modeling spacecraft charging is difficult:
- Currents depend on potentials & fields
- Capacitive timescales vary by orders of magnitude
- Geometrical details are important
- Differential charging barriers limit secondary electrons

Capacitance of insulating surface to chassis is much greater than capacitance of insulating surface to plasma
GEO Environment

- Geosynchronous Earth Orbit (GEO) is located at 6.6 \( R_E \)
- Popular orbit for low-latitude communication satellites

Magnetic Storm \( \Rightarrow \) Particle injection into the ring current

- Ring Current is westward
- Particles energized as they approach Earth
- Energetic Electrons injected into post-midnight
Satellite Surface Charging

- Injection of energetic (E \sim 10\text{s} \text{keV}) electrons into GEO concentrated in post-midnight region

- Statistics show both S/C charging and operational anomalies are concentrated in the same local time sector

Satellite charging probability is compared with operational anomalies, both plotted as a function of spacecraft local time. Each circular ring represents 5% probability of DSCS-III charging to at least -50 V relative to the background plasma (see Habash Krause, 2000). Anomalies are from Jursa, 1985.
During periods of significant geomagnetic activity, the electron environment in GEO is best represented by a two-temperature Maxwellian. See Mullen *et al.*, 1986, for further information. Surface Charging Electrons tend to have energies from 10-50 keV.
Satellite Surface Charging

During periods of significant ring current injection, spacecraft may become significantly charged relative to background plasma. Electron counts are integrated over 20keV-50keV. We use “ion peak” method to determine frame potential $V_f$. 

Example: DSCS III Charging
Xe plasma thrusters have been used for differential charging neutralization based on “alarm” system.

Complex combination of frame and differential component charging mandate delicacy in neutralization.

Using pure electron source to reduce negative frame charging may exacerbate differential charging.
Demonstration of bootstrap charging of a Kapton patch electrically floating relative to a blanketed frame fixed at -1000 V relative to a background quiescent plasma. The patch face is sunlit.

Formation of saddle point as evident from the sequence of spatial potential maps in time. Panels (a) through (f) correspond to 1.0, 5.0, 25, 100, 200, and 300 seconds, respectively.

Sheath formation of small isolated patch results in suppression of photo-electron escape from neighboring surfaces.
Before the formation of the virtual cathode in front of the Kapton patch, initially at a zero potential relative to the plasma, the approximately concentric semi-circles forms a virtual convex lens that guides incoming charging electrons toward the patch, resulting in rapid patch charging.

Strong saddle point configuration of spatial equipotentials results in electron optics resembling a concave lens. Divergent trajectories of electrons result in repulsion of charging electrons away from the Kapton patch.
Potential of a sunlit Kapton patch as a function of time, when the blanketed satellite frame was fixed at -1000 V. An exponential curve was fit to the data, indicating behavior similar to that of an RC equivalent circuit.

Charging current to Kapton patch as a function of time. The blanketed satellite frame was fixed at -1000 V. An exponential curve was fit to the data, indicating behavior similar to that of an RC equivalent circuit.
(a) High energy electrons and ions bombardment.  (b) Formation of deep electron layer.  (c) Attraction of slow ions.  
(d) Anodized discharge. An impact by a high energy ion or meteoroid may trigger a discharge.

(From Lai et al., J. Spacecraft & Rockets, 39, 1, 2002.)
Acrylic specimen is irradiated by energetic electrons

Electrons accumulate inside, creating a cloud-like layer of negative electrical space charge.

As space charge builds, the internal electrical field increases dramatically.

Eventually, the immense electrical stress overcomes the dielectric strength of the acrylic, and electrons are ripped off.

Newly-freed electrons also accelerated by the electric field, ionizing even more acrylic molecules.

**RUNAWAY BREAKDOWN (AKA Discharge)**
The Spacecraft Charging Problem is a complex system of engineering and science (e.g. “What is ground?”)

Spacecraft charging comes in three basic forms: Surface frame, Surface differential, and Deep Dielectric.

The surface charging electrons range in energy from 20 keV to 50 keV.

These electrons are most prevalent in GEO in the post-midnight sector.

Deep dielectric charging can result in static buildup of charge on surfaces of internal s/c components, such as cables and circuit components.

Surface charging mitigation is proven to be effective.

Deep dielectric charge mitigation remains to be a challenge.

*** THANK YOU ***