Spacecraft Charging – New Light on Thresholds, Effects, and Mitigation

Integrity ★ Service ★ Excellence

16 Nov 2015

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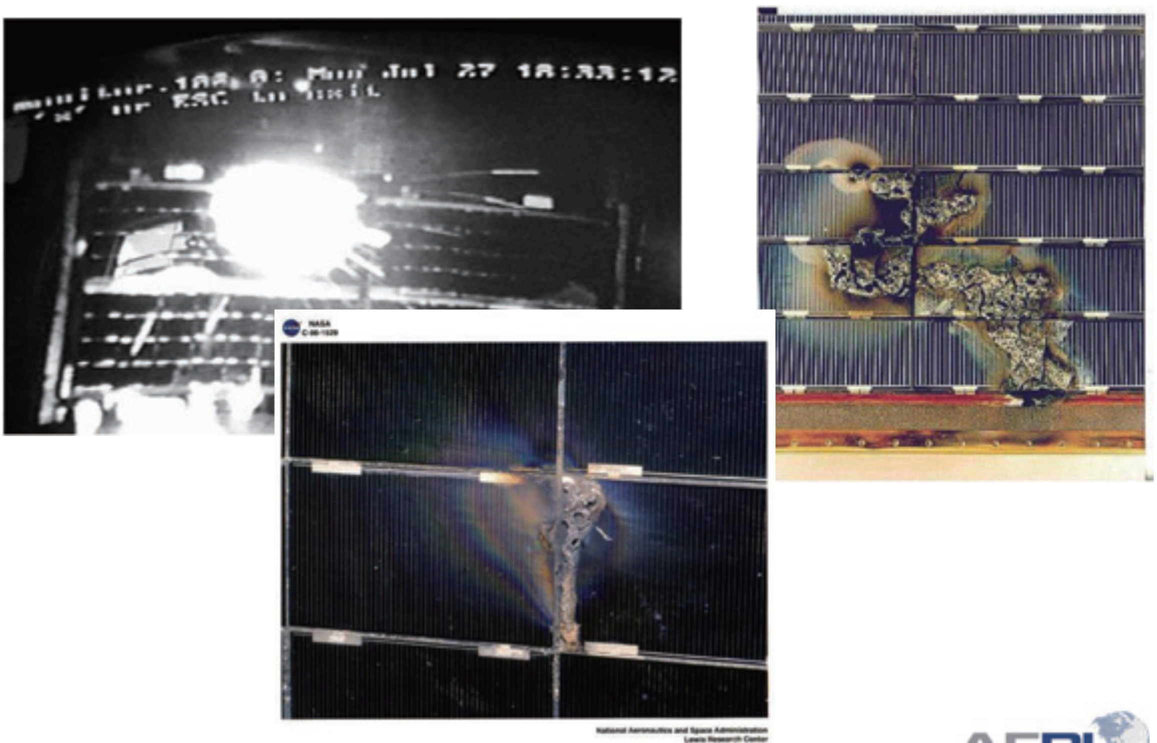
Sustained Arcing Effects



A Few Famous Satellite Failures

- Anik E-1 and E-2 (1994) – deep dielectric electron charging during severe geomagnetic storm led to communications disruptions lasting for days
- Tempo-2 and PAS-6 (1997) – sustained arcs from geomagnetic substorm ESDs caused complete Loss of Mission (LOM)
- ADEOS-2 (2003) – micrometeoroid strike (?) during auroral charging event led to sustained arcing and caused complete LOM
- Galaxy 15 (2010) – ESD caused electronics problem coming out of eclipse during severe geomagnetic substorm, recovered after 8 months adrift
- DMSP-15 (2011) – computer upset after large total internal dose from X-class flare X-rays
- Echostar 129 (2011) – temporary (24 hr) pointing/positioning loss after huge peak in GOES >2 MeV ("killer") electrons
- SkyTerra-1 operated by LightSquared (March 7, 2012) – knocked out for 3 weeks due to SEU caused by energetic protons & CME
- Other March 2012 anomalies – Venus Express, HughesNet-Spaceway 3

Basic Types of Spacecraft Charging

- **Surface Charging**
  - Caused by particles of 10 eV –100 keV
  - Usually what is referred to as Spacecraft Charging
  - By and large, particles do not bury themselves so deeply they can't escape in minutes to hours
  - ***Flux*** dependent, on electron fluxes at energies > 9 keV
  - Depends on surface and bulk conductivity of materials

- **Deep Dielectric Charging**
  - Caused by particles of 200 keV and above
  - Also referred to as Bulk Charging, or Internal Charging
  - By and large, particles bury themselves deeply enough that it takes days or weeks to escape
  - ***Fluence*** dependent
  - Depends on bulk conductivity of materials

GEO Spacecraft Surface Charging

- **Spacecraft charge** because the net fluxes of electrons and ions to the surface are not the same
  - Why not? Because F = Nvq, and in a plasma, the electrons and ions are of about equal density and in approximate thermal equilibrium, where $E_e = E_i = (3/2)\ kT$
  - $½\ m_e\ v_e^2 = ½\ m_i\ v_i^2$
  - Thus, $v_e = v_i\ (m_i/m_e)^{1/2}$
  - Even for hydrogen, $(m_i/m_e)^{1/2} \sim 43$
  - Thus, electrons impinge on uncharged surfaces > 43 times as fast as ions
- **Spacecraft surfaces charge** until their potentials repel electrons and the resultant electron and ion currents to surfaces become equal
  - The Current Balance Equation!
- **As a rule of thumb** – In eclipse, spacecraft charge negatively to potentials about equal to the temperature of the plasma, T.
  - GEO plasmas typically have T ~ 5000 eV, but in geomagnetic substorms T can reach ~ 80,000 eV

The Current Balance Equation

- **In equilibrium, there can be *no net charge flux* to a spacecraft**

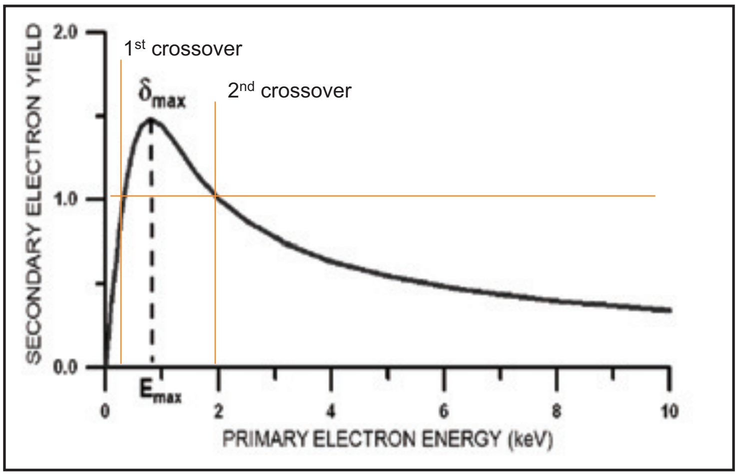
- **Current Balance Equation:**

Electron Flux (F_e) - Backscattered Electrons (F_{be}) - Secondary Electron Emission (F_{se}) – Photoemission (F_{pe}) = fn (ϕ) = Ion Flux (F_i),
where ϕ is the local potential

- **Equilibrium** is established on an electron repulsion timescale, which is less than a microsecond. Thereafter, the Current Balance Equation holds

- **The Current Balance Equation** holds for an entire spacecraft (yielding the so-called **Absolute or Frame Potential**) and for individual dielectric surfaces (yielding the so-called **Differential Potentials**)Usually, backscattered electrons are considered to be part of the secondary electron emission flux, and secondary electrons produced by ions striking the surface are ignored

GEO Surface Charging – Secondary Electron Emission



Notional Secondary Electron Emission Curve

- Secondary electron yield for many material surfaces can be greater than unity for a range of incident electron energies
- For electron energies between the 1st and 2nd crossover points, each incident electron <u>decreases</u> the spacecraft negative charge
- For MgF_2 anti-reflection coated solar cell coverglasses, δmax ~ 6, and 2nd crossover is about 9 keV – hence F (E>9 keV) increases charge

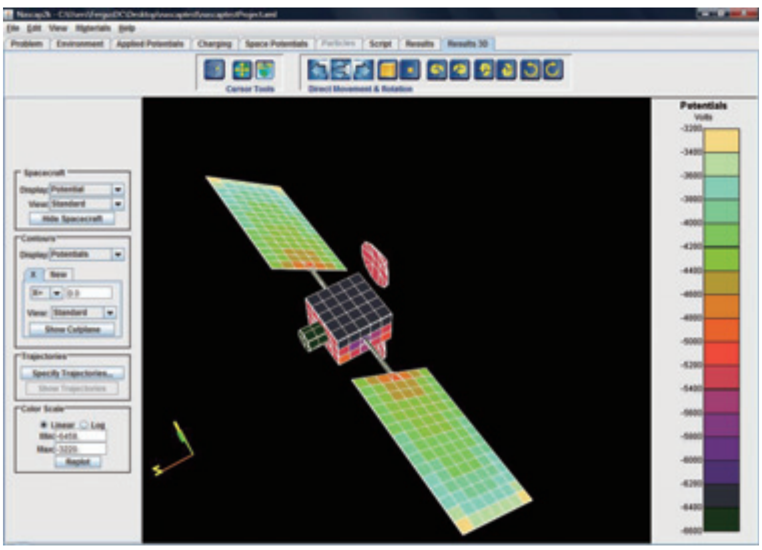
GEO Surface Charging - Photoemission

- **The Photoelectric Effect – Cause of Photoemission**
  - Because of the photoelectric effect, incident photons with energies greater than the electron work function (usually UV) will liberate an electron from the surface
  - For one-sun UV illumination, many material surfaces have photoemission of about 2×10^{-5} amps/m^2 = 2 nanoamps/cm^2
  - For many GEO plasmas, this is more than the electron flux to an uncharged surface
  - Thus, sunlit spacecraft surfaces lose much of their charge
- **Differential Charging**
  - There is no photoemission when satellites are in eclipse (part of each orbit when the sun is near the equator)
  - When satellites emerge from eclipse, suddenly those surfaces in sunlight can lose much of their charge
  - Differential charging can occur between surfaces in sunlight and in shade
  - Most charging-related problems occur in a few hours after a satellite leaves eclipse

Surface Charging – Important Surface Materials Quantities

- **Secondary Electron Emission Characteristics - electron and ion bombardment**
    - **Maximum δ, incident energy of maximum δ**
- **Photoemission**
- **Bulk resistivity (Ω-m)**
- **Surface resistivity (Ω/□, "ohms per square")**
- **Thickness**
- **Density**
- **Atomic weight**
- **Dielectric constant**
- **Breakdown strength (V/mil)**

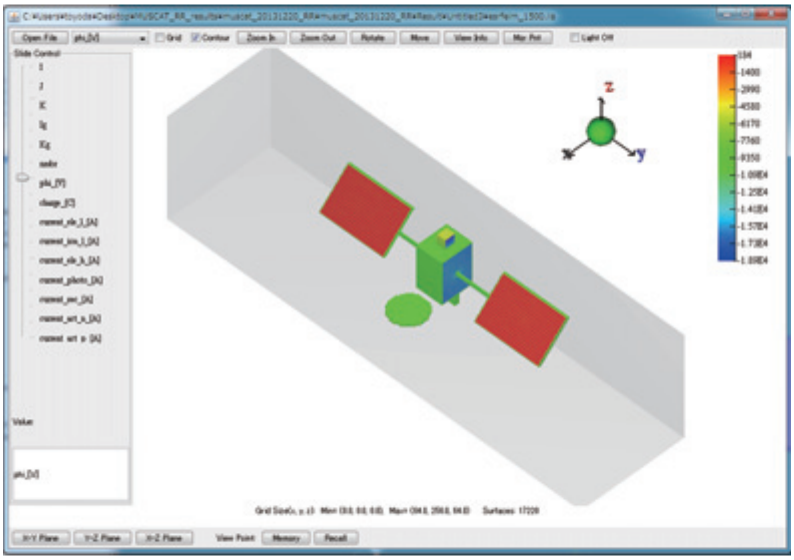
GEO Surface Charging - Simulations



- The US default standard is **Nascap-2k** (NASA-Air Force Spacecraft Charging Analysis Program)
- Uses Boundary Element Method (Green's functions) to determine potentials on spacecraft surfaces, particle tracking to change surface potentials
- Models full magnetic field effects
- Due to EAR/ITAR restrictions, not available to non-US citizens

GEO Surface Charging - Simulations

- The JAXA default standard is **MUSCAT** (Multi-Use Spacecraft Charging Analysis Tool)
- Fully 3D particle code
- Can be applied to spacecraft in LEO, PEO and GEO.
- Its algorithm is a combination of PIC and particle tracking.
- Commercially available
- Other codes exist (ie SPIS, Coulomb-2)



GEO Surface Charging - Effects

- **ESD (Electrostatic Discharge)**
  - If differential charging leads to large electric fields between adjacent surfaces (E ~ 100 volts/mil or V ≈ 400 volts), a discharge can take place
  - Discharges the full capacitance of spacecraft surfaces relative to each other
  - Discharges are most frequent at so-called “triple points” where a conductor, an insulator, and the space plasma join
  - Discharges can also be breakdowns of insulated surfaces (dielectric breakdown)
  - Impacts on systems
    - Solar cell damage, surface (thermal control) damage, contamination, computer upsets, EMI
- **Sustained Arcs**
  - ESD can evolve into a sustained arc (solar-powered) between solar array strings when adjacent cells are at different power system-imposed voltages
  - Impacts on systems
    - Complete permanent loss of power, structural degradation, loss of attitude control, etc.

GEO Surface Charging - Mitigation

- **Keep Differential Charging to a Minimum**
  - Coat all exterior surfaces with conducting materials, ground all surfaces to a common ground point
  - If possible, use frame charging mitigation (ie plasma contactor or ELF type)
  - Allow no floating conductors
  - If solar arrays not conductively coated, keep secondary electron emission from coverslides high
- **Keep ESD currents out of sensitive circuits**
  - Put all electronics inside a Faraday cage
  - Use grounded shields on all wiring
- **Prevent Sustained Arcs on Solar Arrays**
  - Use string wiring that prevents adjacent cells from having > 40 V potential difference (parallel strings, leapfrog wiring, or another solution)
  - Use diodes to prevent other circuits from contributing to arc current
  - Keep string (and solar cell) currents below about 1 A

LEO Surface Charging – Introduction

- **Near the equator in Low Earth Orbit (LEO) the plasma densities are high (10^4-10^6/cm^3) and plasma temperatures are low (0.1-0.25 eV)**
  - Equilibrium "floating potential" is low (< 1 V, typically)
  - Atomic oxygen is predominant ion species, so $(m_i/m_e)^{1/2} = 171$
- **In LEO, the spacecraft orbital velocity (~7.5×10^3 m/sec) is greater than the ion thermal speed but less than the electron thermal speed (see next slide)**
  - So-called mesothermal condition
  - Creates plasma wake behind spacecraft
    - Ions are too slow to fill in the wake
    - Electrons are repelled from wake by slight negative space charge (a few volts)
- **Charging in LEO is caused by exposed power system voltages, and current collection from plasma as modified by local potentials**

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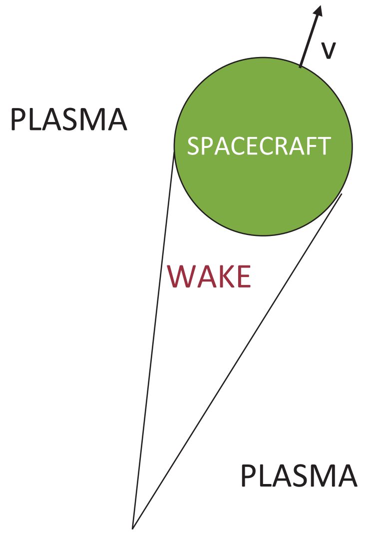
Wake in LEO



- **Spacecraft in LEO are moving supersonically with respect to the ions**
  - **There is a wake left behind, where ions cannot enter**
- **The wake is devoid of electrons, as well as ions**
  - **Tiny excess of electrons inside wake repels all other electrons**
  - **Wake is electrically almost exactly neutral**
- **Ions are collected as a supersonic stream on the front face**
- **Electrons are collected isotropically outside the wake**

LEO Charging – Wakes and Sheaths

- **Wakes are very deep**
  - Ion and electron densities down by factor of ~ 10^4
  - Means currents (both types) only collected on ram side of spacecraft
  - Electron collection takes place approximately isotropically on ram side
    - $A_{el} = ½ A_{tot}$
  - Ion collection takes place almost totally directed onto ram side
    - $A_{ion} = A_{ram\ projection}$
- **Only local plasma can interact with spacecraft**
  - For uncharged bodies, "plasma sheath" only extends out to about one Debye Length $\boldsymbol{\lambda_D = (kT/4\pi ne^2)^{1/2} = 743\ (T/n)^{1/2}}$ **cm**, where n is electron number density (cm^{-3}), and T is the electron temperature (eV, 1 eV = 11000 Kelvin)
  - Electric fields are screened out at distances beyond the sheath
  - For a n= 10^6 (daytime LEO) and T = 0.2 eV (daytime LEO), $\boldsymbol{\lambda_D = 0.5}$ **cm**
  - At night (n=10^4, T=0.1), $\boldsymbol{\lambda_D = 7}$ **cm**
  - For charged bodies, the sheath extent becomes progressively larger, but usually smaller than a spacecraft
  - Means that for ion collection, A_{ram} is ~ constant, regardless of potential

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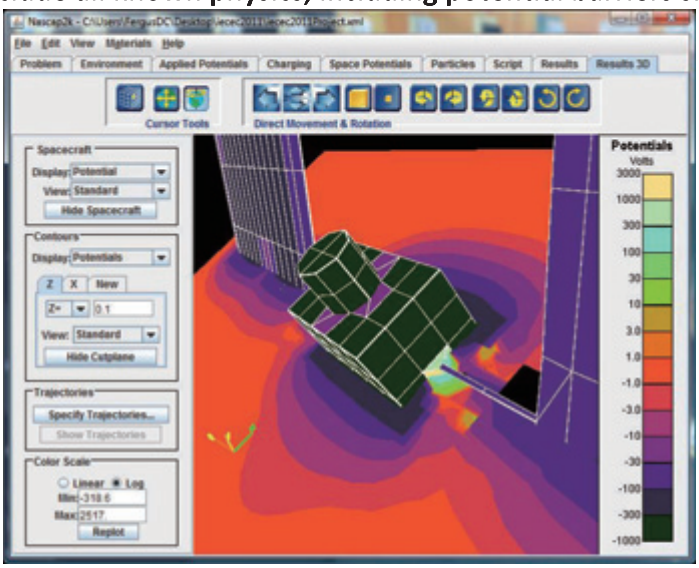
LEO Charging – Solar Array Voltages and Current Balance

- **With Exposed Differential Voltages and a Large Area, the Solar Array Usually Becomes the Major Electron and Ion Collector**
  - **Most solar arrays are grounded on the negative end – spacecraft then becomes an ion collector**
  - **Because electron fluxes are much greater than ion fluxes, most of solar array will be negative w/rt the surrounding plasma (ion collecting) to balance electron collection on the small positive end**
    - Ram ion flux F_i = nvq, $I_i = A_i$ nvq
    - Isotropic thermal electron flux $F_e = 2.68\text{x}10^{-12}$ n $T^{1/2}$ (with T in eV), $I_e = A_e$ [$2.68\text{x}10^{-12}$ n $T^{1/2}$]
    - Setting $I_e = I_i$, $(A_i/A_e) = 22.2\ T^{1/2}$; for T = 0.2 eV, (A_i/A_e) = 10
    - **Rule of thumb – LEO solar arrays “float” about 90% of the string voltage negative of the plasma**
    - “Floating potential” is potential of spacecraft body at the negative end of the solar array

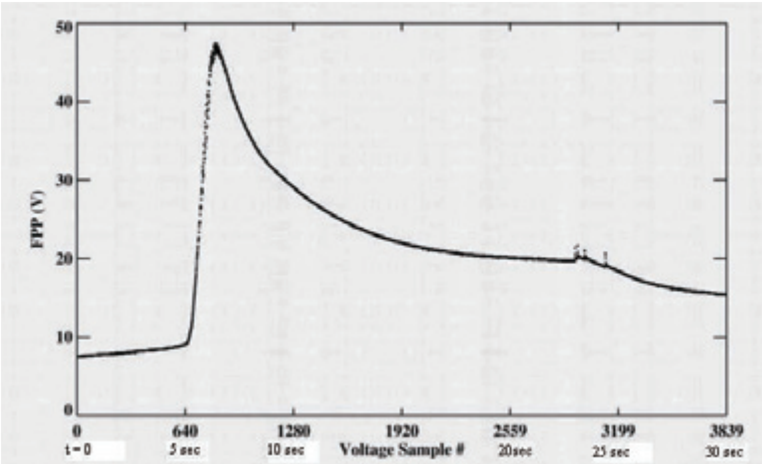
LEO Charging - Simulations

- **NASCAP-2k and MUSCAT**
  - **Do sophisticated wake calculations**
  - **Fully 3-D**
  - **Include all known physics, including potential barriers shown below**



LEO Charging - ISS Rapid Charging Events

- **Rapid Charging Events (RCEs)**
  - **Only occur when plasma densities are low**
  - **Take only a few seconds to develop**
  - **Due to rapid turn-on of arrays after eclipse – capacitive coupling makes dielectric surfaces take on potential of underlying solar cells**
  - **May lead to charging which is a large fraction of the total string voltage**



LEO Equatorial Surface Charging - Effects and Mitigation

- Effects
  - Damage to thermal control coatings – dielectric breakdowns
  - On ISS, life-threatening ESD on astronaut EVA
  - Solar array damage
  - Atomic Oxygen can change charging
- Mitigation
  - Coat all surfaces with dielectrics that can withstand the solar array string voltage
  - Encapsulate conductors on arrays
  - Use low string voltages on solar arrays (< 70 V)
  - Turn-on array voltages slowly (a few minutes)

Deep Dielectric Charging - Introduction

- Electrons of > 200keV can penetrate thermal control blankets, electrons of > 2 MeV and protons of > 10 MeV can penetrate into Faraday cages of spacecraft electronics and bury themselves in dielectrics
- Many spacecraft dielectrics have a charge "bleedoff" time τ of about 10 hours:

$$\tau = \varepsilon_0 \kappa \rho$$

Here, τ is the 1/e time constant, ε_0 is the permittivity of free space, the material dielectric constant is κ, and the bulk resistivity is ρ.

  - Under cold conditions, bleedoff time can reach days, weeks, months or years (as for James Webb Space Telescope)
- When internal electric field exceeds breakdown strength of material, an internal arc occurs
  - Caveat - breakdown strengths are not linear with thickness!

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Deep Dielectric Charging – Resistivities

- Most published resistivities are the result of ASTM test procedures, and are not valid for high resistivities
- Proper resistivity measurements use the charge storage method and must be done in a vacuum
- Bulk resistivities are affected by temperature, electric field, and captured radiation dose in a material (radiation induced conductivity, RIC)
- Testing for the James Webb Space Telescope at low LN2 temperatures at MSFC has shown that even after 10 years of exposure to the radiation environment at L2, arcs can still occur due to deep dielectric charging in cabling

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Deep Dielectric Charging – Effects

- For materials with density > water (1 g/cm^3), range is inversely proportional to density. Use proper tables for your material (NIST website-estar and pstar)
- Most spacecraft place sensitive electronics inside a Faraday cage compliant with NASA TP-2361 (1 mm of Al or Mg or equivalent)
- Breakdowns in cables or dielectric materials can release all of the energy stored in their capacitance.
- Breakdowns can lead to computer latchups, bit-flips in control or communications electronics, permanent damage to integrated circuits, etc.

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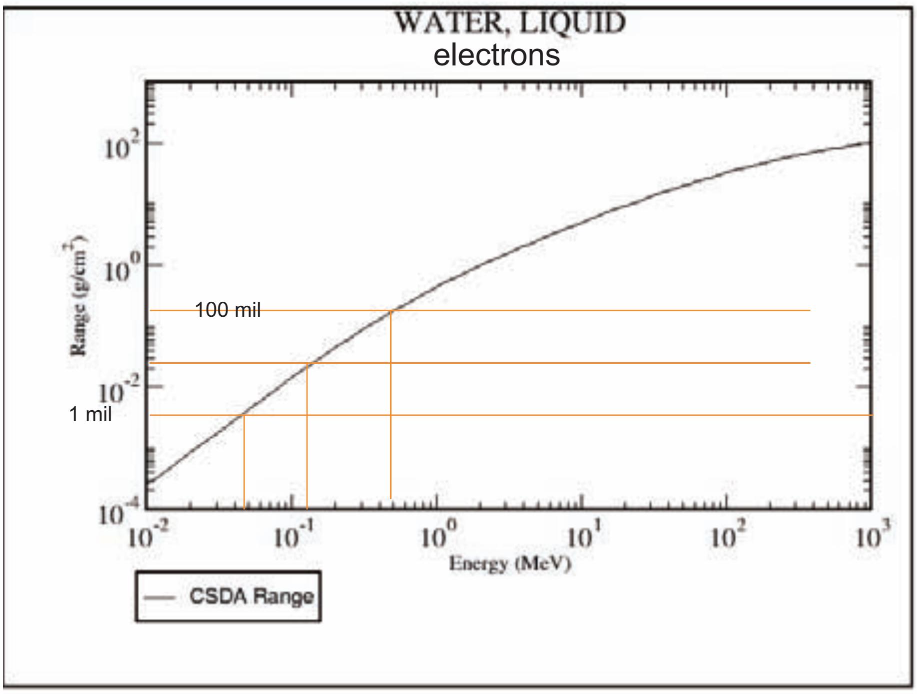
Deep Dielectric Charging – Depth vs Energy – electron example



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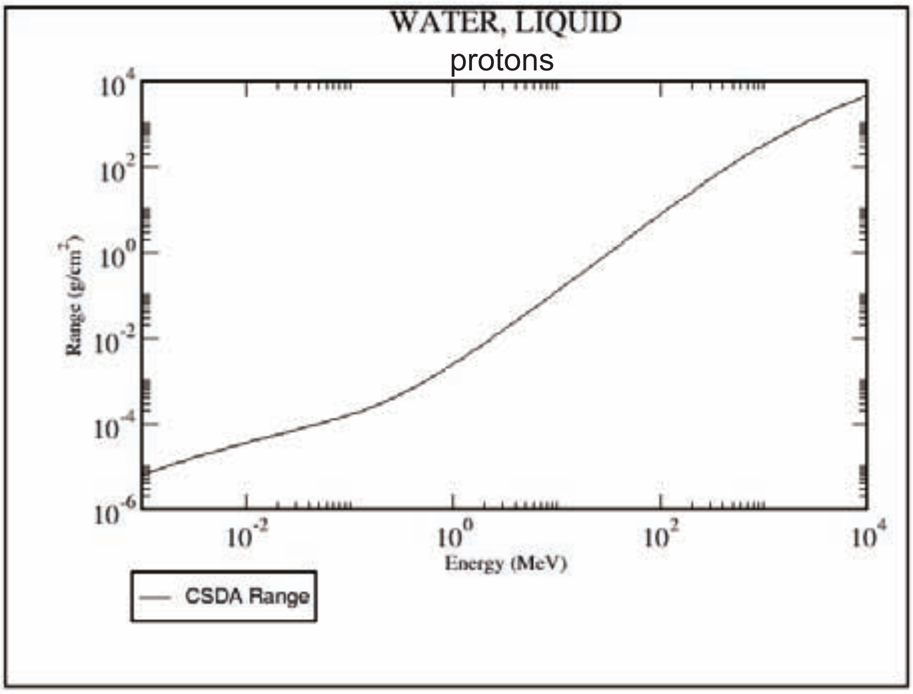
Deep Dielectric Charging – Depth vs Energy – proton example

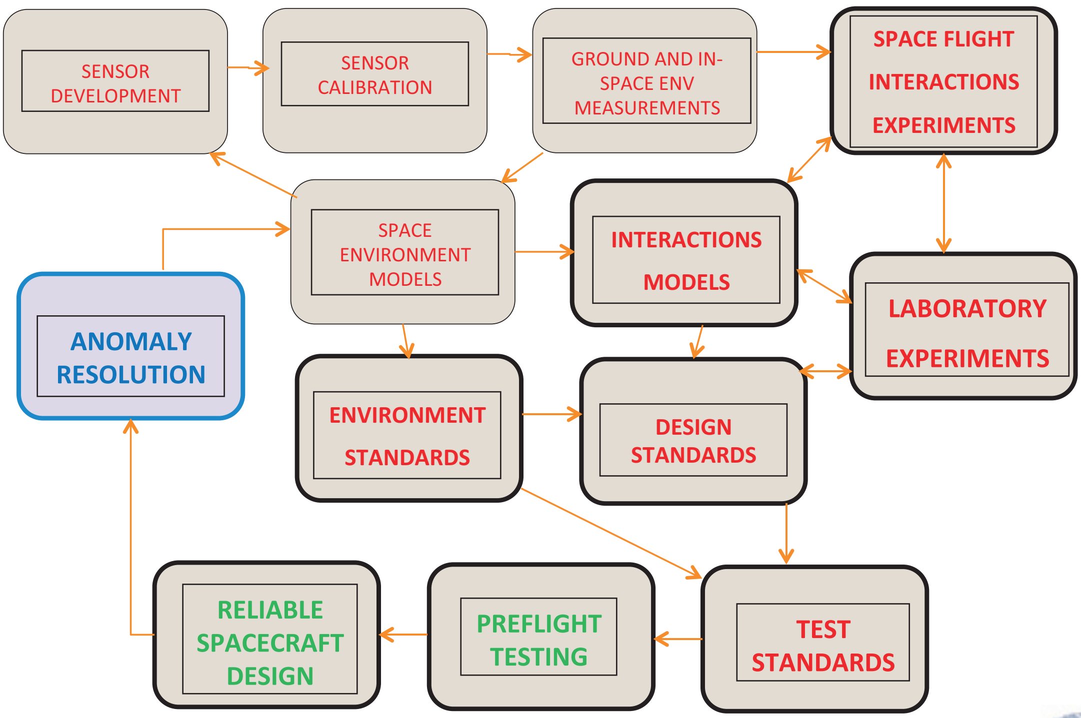


How to Design to Prevent Space Weather Charging-Related Anomalies

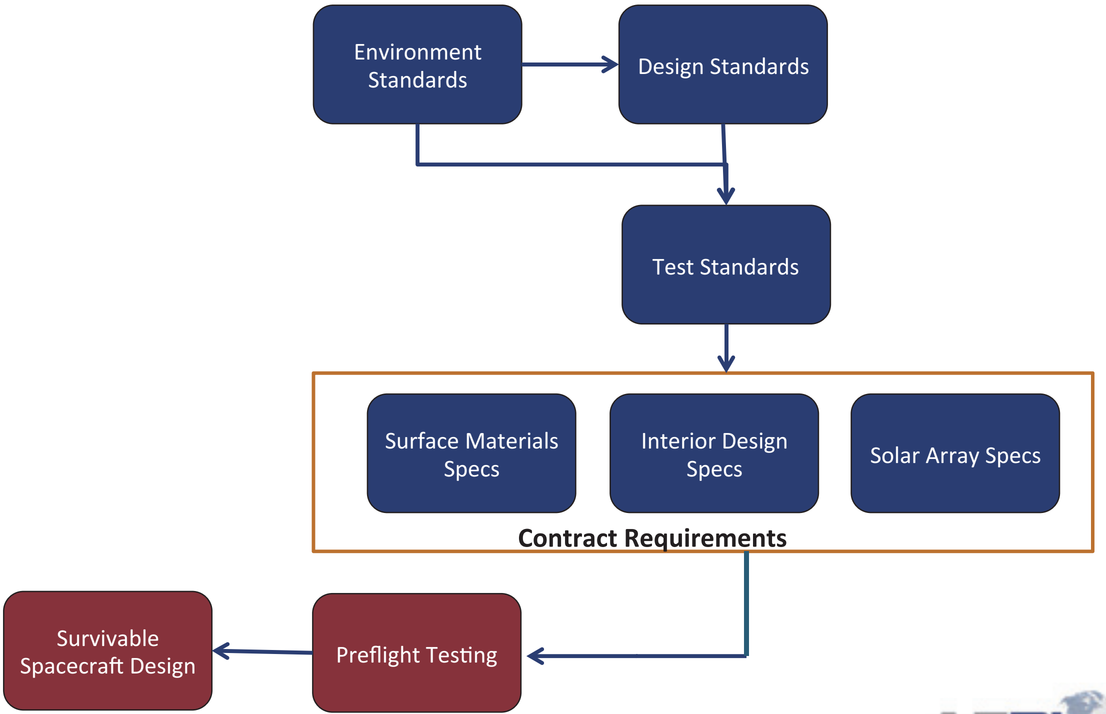
- Harden all vital electronics and place in well-shielded Faraday cage
- Coat all surfaces with grounded conductors
- No ungrounded or unshielded wires or conducting areas (Galaxy 15 failure mechanism, NASA TP-2361)
- Design for more secondary electron emission and less photoemission (per Shu Lai, 2011, “Spacecraft Charging”)
- Design and test arrays to prevent ESDs and sustained arcs (Tempo-2 failure mechanism, NASA-STD-4005, NASA-HDBK-4006, ISO 11221)
- Design spacecraft to prevent deep dielectric discharges (Anik-1 and 2 failure mechanism, NASA-HDBK-4002A)
- **Fly charge monitors and charging mitigation systems**

Building Spacecraft Immune to Arcing

Steps in Developing Spacecraft that are Reliable in the Space Environment



Technology Transfer Flowchart



Standards

- National and International Design Standards
  - JAXA JERG-2-211A – Design Standard, Spacecraft Charging and Discharging
  - ECSS-E-ST-20-06C – Space engineering, Spacecraft charging
  - US MIL-STD-1809 – Space Environment for USAF Space Vehicles
  - NASA TP-2361 – Design Guidelines for Assessing and Controlling Spacecraft Charging Effects
  - NASA-HDBK-4002A – Mitigating In-Space Charging Effects—A Guideline
  - NASA-STD-4005 – Low Earth Orbit Spacecraft Charging Design Standard
  - NASA-HDBK-4006 – Low Earth Orbit Spacecraft Charging Design Handbook
  - ANSI/AIAA S-115 – Low Earth Orbit Spacecraft Charging Design Standard Requirement and Associated Handbook
  - two ISO Standards in process:
    - ISO WD19923 - Space Systems - Spacecraft charging potential estimation in the worst case environments
    - ISO N1100 - Space Systems – Spacecraft Charging – Earth Orbit
- International Testing Standard
  - ISO 11221 – Space systems — Space solar panels — Spacecraft charging induced electrostatic discharge test methods

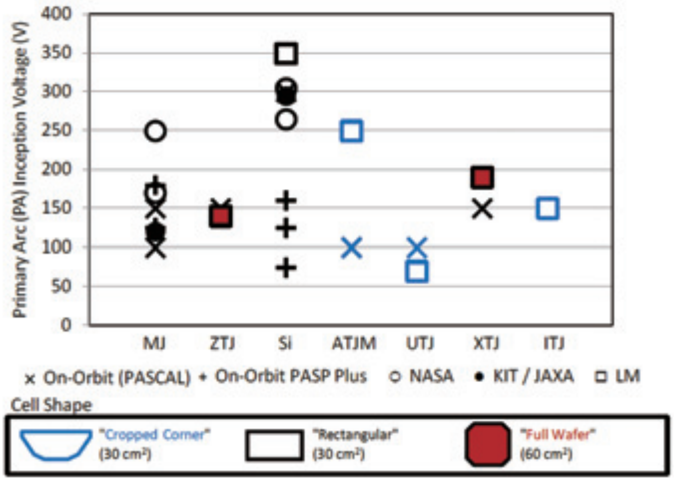
CHARGING - NEWS

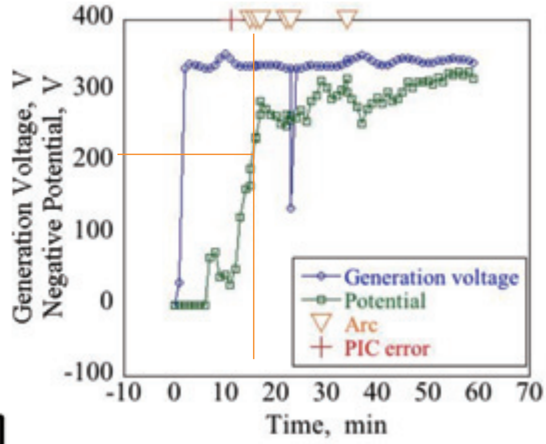
US Air Force Interested in Measuring Space Environment Around AF Spacecraft

- Space Situational Awareness
  - If an anomaly occurs, we must be able to immediately tell whether it was the result of the natural environment (ie spacecraft arcing) or a hostile action
  - Monitor(s) on board spacecraft to measure space environment are the most straight-forward way of telling this
  - Monitors have previously flown on LANL satellites, some INTELSATs, SES and research satellites

LEO Flight Experiments on Arc Thresholds and High Voltage Arrays

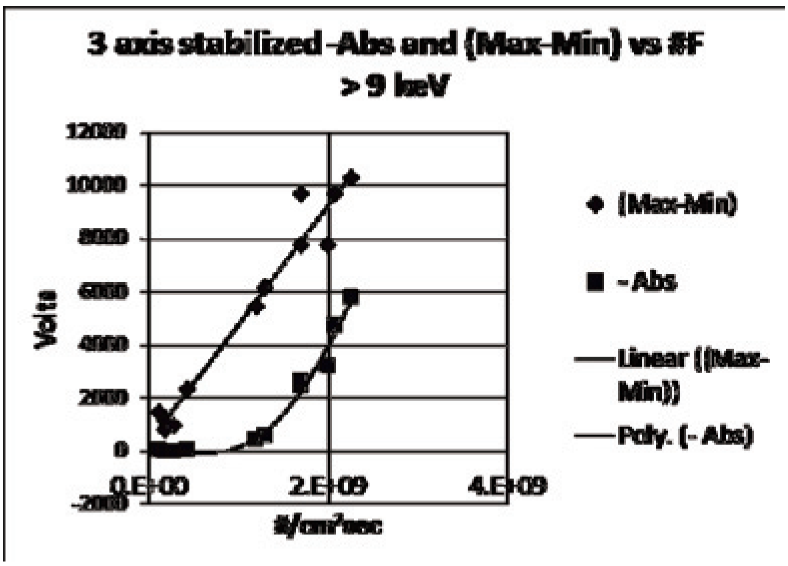
PASCAL on ISS: Threshold ~ 75 V, Triple Junction, cold
PASP-Plus: Threshold ~ 75 V, Silicon, cold
Horyu-II in LEO: Threshold ~ 200 V, Triple Junction, sun





Space System Susceptibility

- What is the GEO "Driver" for Differential Charging?
  - Nascap runs say it is the total electron flux at E> 9 keV
  - Threshold for frame charging similar to "critical electron temperatures" of Dr. Shu Lai

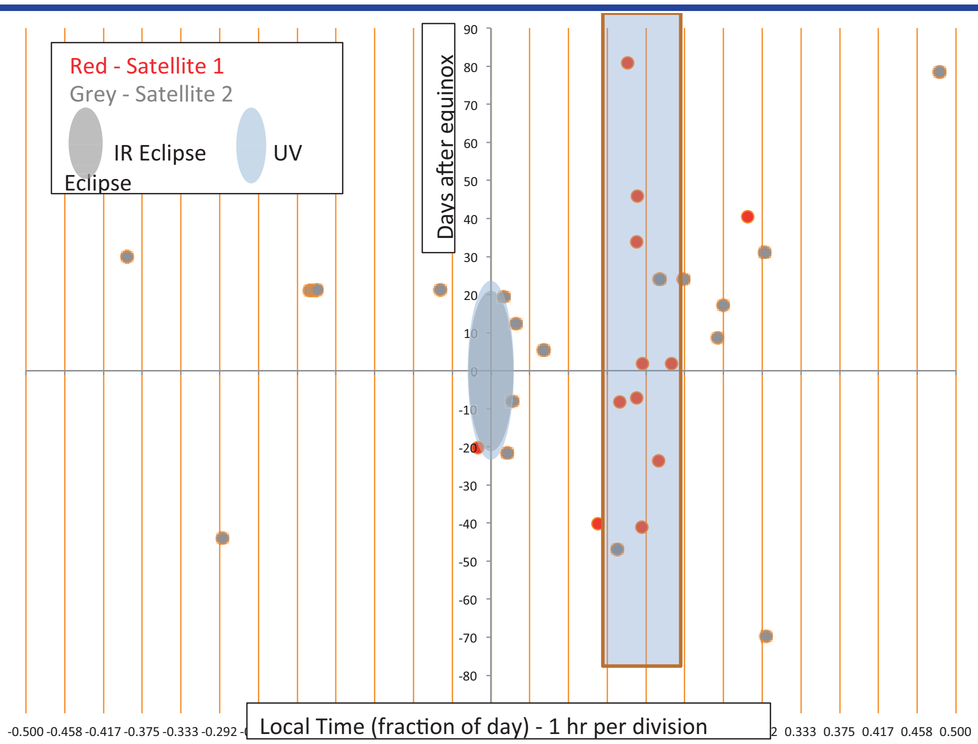


Nascap simulations

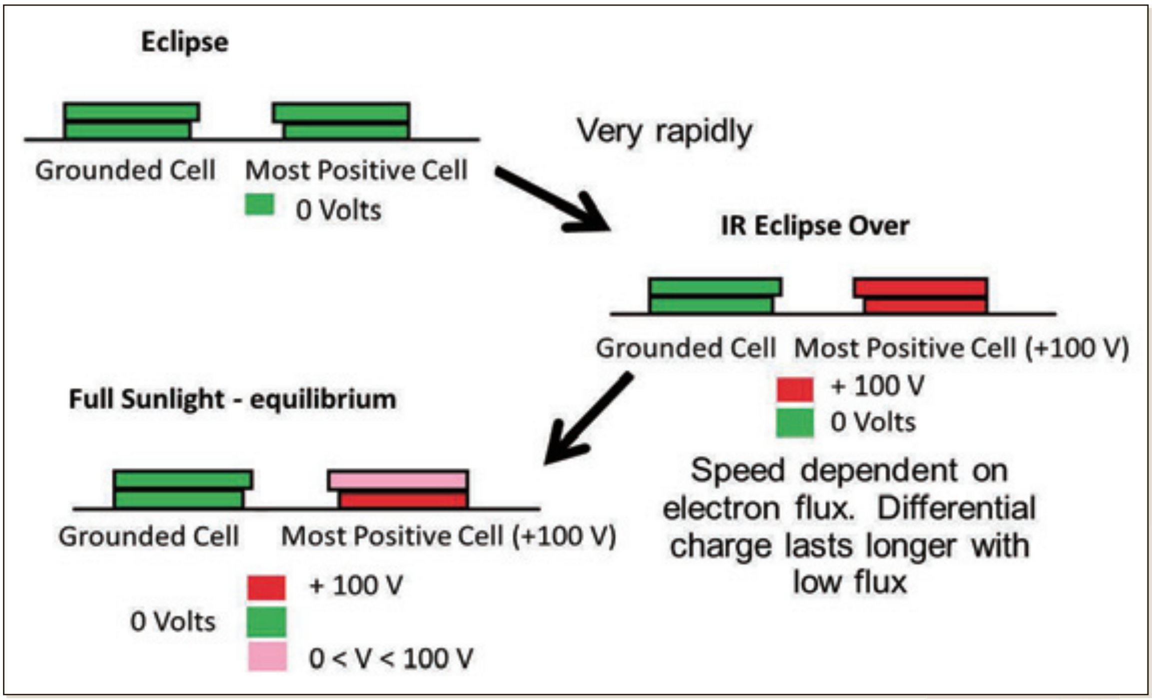
The Importance of Prior States

- Sustained Arcing Events in 1997-2002 showed two preferred states –
  - In sunlight for at least three hours, or
  - Within a few minutes of going into or coming out of eclipse
- Lab Testing in a low flux GEO environment on eclipse exit shows arcing on every exit at 220 V differential bias
- Lab Testing in a LEO environment shows –
  - Arc threshold of 70 V differential bias!
  - Arc rate depends on UV flux over ten minutes prior to differential bias
- It is likely that these arcs were from a grounded cell to an adjacent cell and coverglass at positive potentials. Not the typical arc from a negative cell to its more positive coverglass

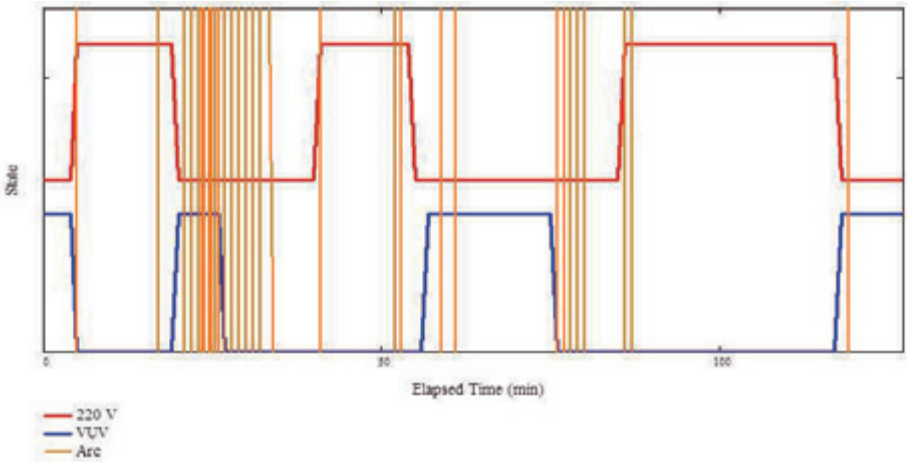
1997-2002 Sustained Arcing Events



1997-2002 Sustained Arcing Events – Possible Scenario

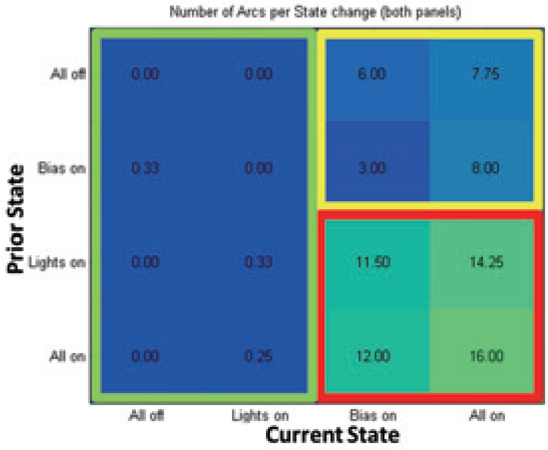


1997-2002 Sustained Arcing Events – GEO Lab Testing



- A low density plasma was created in the Jumbo chamber of the AFRL Spacecraft Charging and Instrument Calibration Lab (SCICL) with a very low flux electron gun at 20 keV
- A VUV source of about 1.4 suns at the sample was used to try to discharge the coverglasses after a 220 V run (probably useless on positive coverglasses)
- The power supply to provide the differential voltage was floated, so the cells would take on their respective potentials regardless of the frame floating potential
- No arcs occurred at ΔV < 220 V – but every time 220 V was turned on the sample arced, as well as many times when UV was switched on

1997-2002 Sustained Arcing Events – LEO Lab Testing



- A high density, low temperature plasma was created in the Jumbo chamber of SCICL with a hollow cathode source (J. Williams)
- As in the GEO test, a VUV source of about 1.4 suns at the sample was used, but now the times of VUV and bias were randomly selected
- The power supply to provide the differential voltage was floated, so the cells would take on their respective potentials regardless of the frame floating potential
- No arcs occurred at ΔV < 70 V – but arc rate at 70 V depended on prior state of VUV illumination

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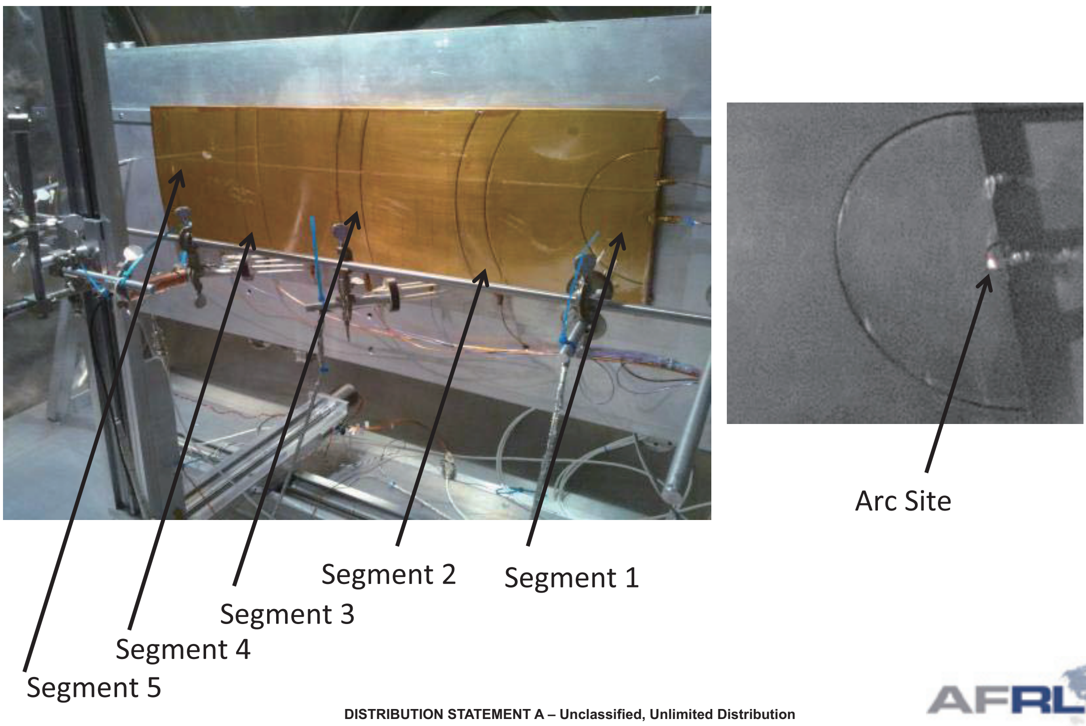
Plasma Propagation Speed



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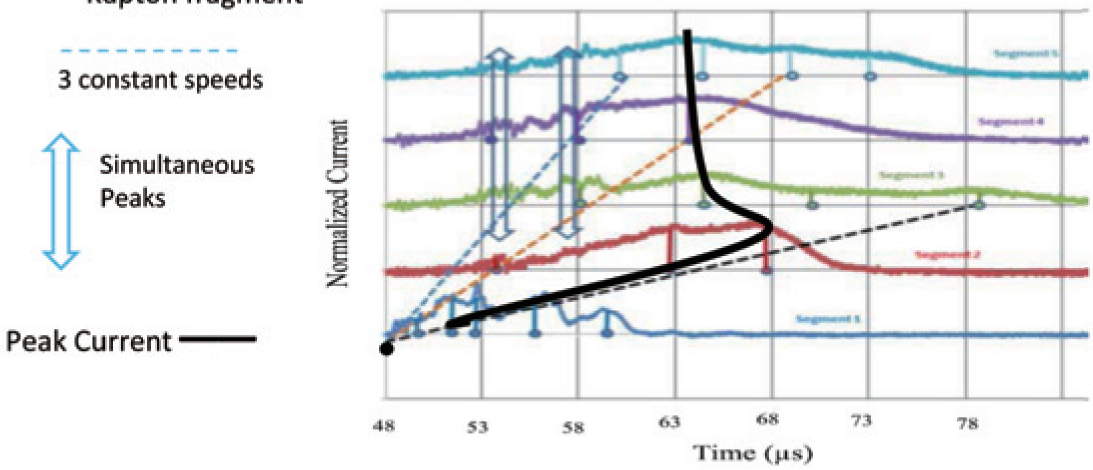
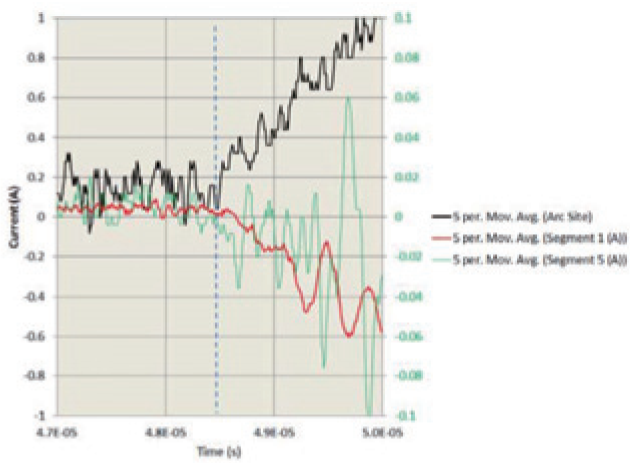
Plasma Propagation Speed

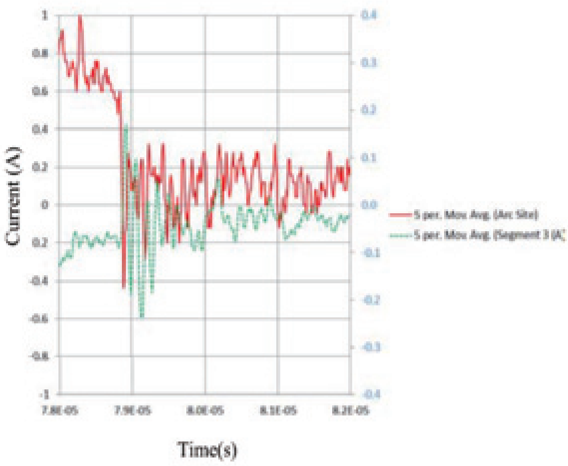
- Tracking separate peaks in current shows:
  - Three or more plasma components with ~ constant speeds
  - Peak in current at a given distance is **not** indicative of plasma speed of any component (below, peak current doubles back!)
  - Possible species (from relative speeds) may be aluminum, carbon, and a Kapton fragment



Plasma Propagation Speed

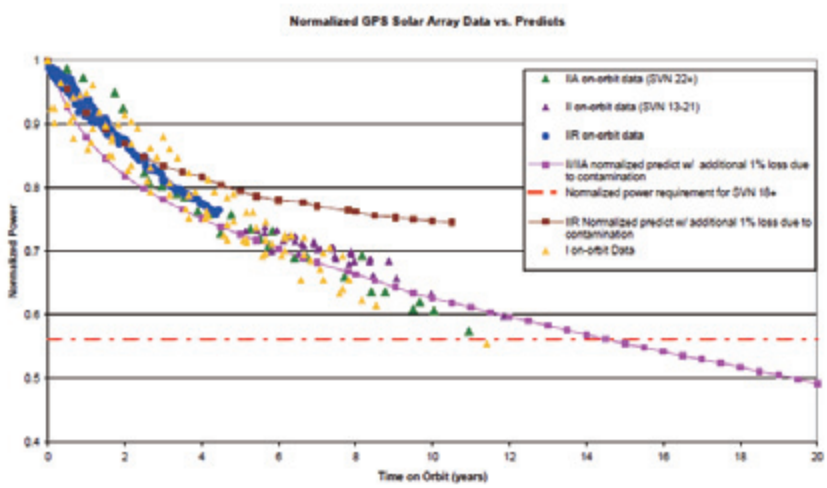
- Simultaneous onset and end of arc current at all distances from arc-site shows that conditions at arc-site determine arc plasma collection everywhere
- Abruptness of end of arc current (< 10 nanoseconds) precludes plasma propagation explanations (such as "fast electrons")





Arcing-Contamination as Source of GPS Satellite Power Degradation

- GPS satellites undergo unexplained power degradation in excess of that from radiation of perhaps 1.5% per year
- Likely source is contamination on solar arrays – flight sensor shows contamination
- Elimination of probable contamination source did not help
- Engineering solution to preserve EOL power was oversizing arrays by 25%



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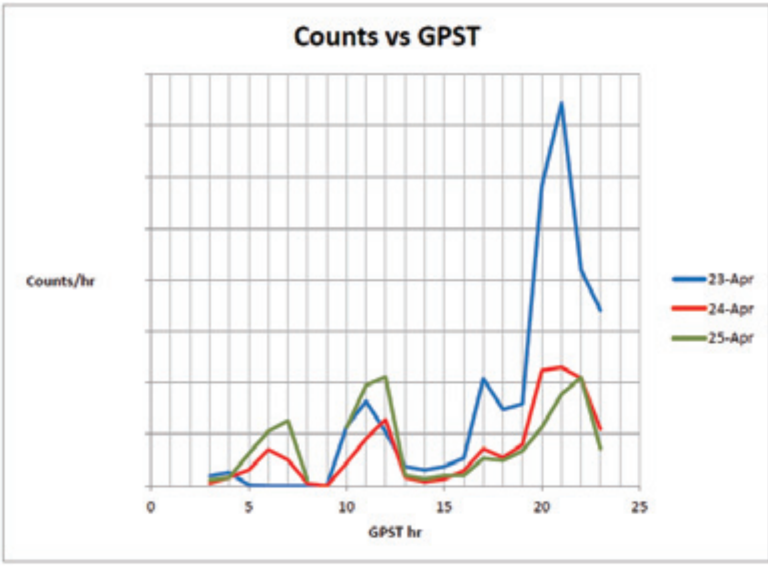
GPS Arcing as Source of Power Degradation

- GPS satellites have USNDS detectors – nuclear detonation monitors
- Many undispersed signals point to arcing on-board spacecraft
- 3 days data from 2014 shown below



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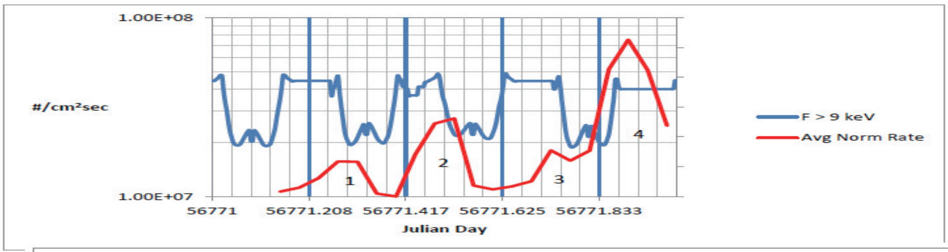
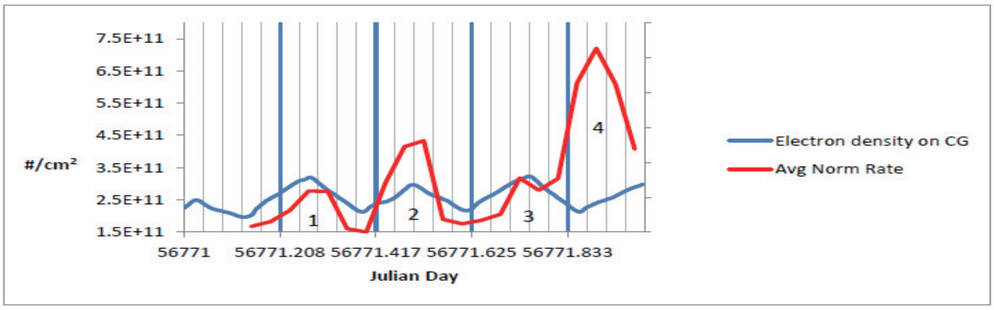
GPS Arcing as Source of Power Degradation

- AE9/AP9 environment of 10-30 keV electrons highly correlated with USNDS event rate – indicative of surface arcing
- Time delay (2.67 hrs) consistent with resistivity of glass – solar arrays?





GPS Arcing as Source of Power Degradation

- **Apparent arc threshold of ~ 2000 V**
- **Number of "arcs" consistent with contamination rates**
- **Observing campaign in progress to see if arcs can be seen by ground-based optical and radio telescopes**
- **If confirmed, arc mitigation may involve higher conductivity coverglasses, may allow 20% smaller solar arrays with no more spurious USNDS signals**

Conclusions

- Spacecraft Charging can lead to arcing and arc-related damage, contamination, EMI
- Charging may be on the surface (< 100 keV electrons) or deeper in dielectrics (> 200 keV electrons)
- In all cases, surface charging is determined by the Current Balance Equation
- Photoemission and secondary electron emission may produce differential charging
- Many electrical properties of surface materials are important in charging calculations. Best models are full 3-D
- Surface charging is mainly dependent on fluxes of electrons above E = 9 keV
- Arcing is due to high electric fields from differential charging
- Primary arcs may sometimes lead to sustained arcs, with disastrous results
- Mitigation techniques are those that reduce electric fields at potential arc-sites
- Arc voltage thresholds in GEO are greater than those in LEO
- Arcs (and sustained arcs) in GEO typically occur within a few hours of midnight, on the morning side of the orbit
- Prior states of UV illumination can change arc rates and thresholds
- Array voltages between cells can lower arc voltage thresholds
- Plasma propagation speed variations may reflect different arc-plasma components
- GPS satellite power degradation may be due to arc-caused contamination