ESD Initiated Failures on High Voltage Satellites

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PVA Anomalies on Recent Satellites

- Tempo 2
  - GEO- launched in March, 1997
  - 10.5KW GeAs/Ge array
  - several strings shorted
    - 2.1 - 2.7A, 100V
    - power loss > 20%
- PanAmSat
  - launched in July, 1997
  - power loss > 20%
- Other satellites with silicon arrays are in orbit
  - slightly different layout
  - only 1 anomaly

ESD Initiated Failures on High Voltage Satellites

- On-orbit Anomalies
- Spacecraft Charging Analysis
- ESD Triggered Failure Mechanism
- Laboratory Results
- Prevention Measures
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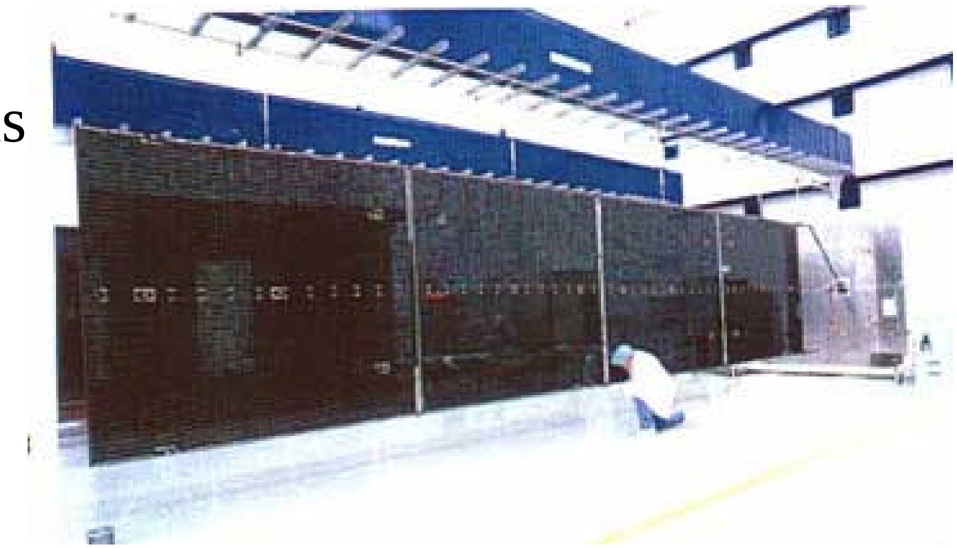

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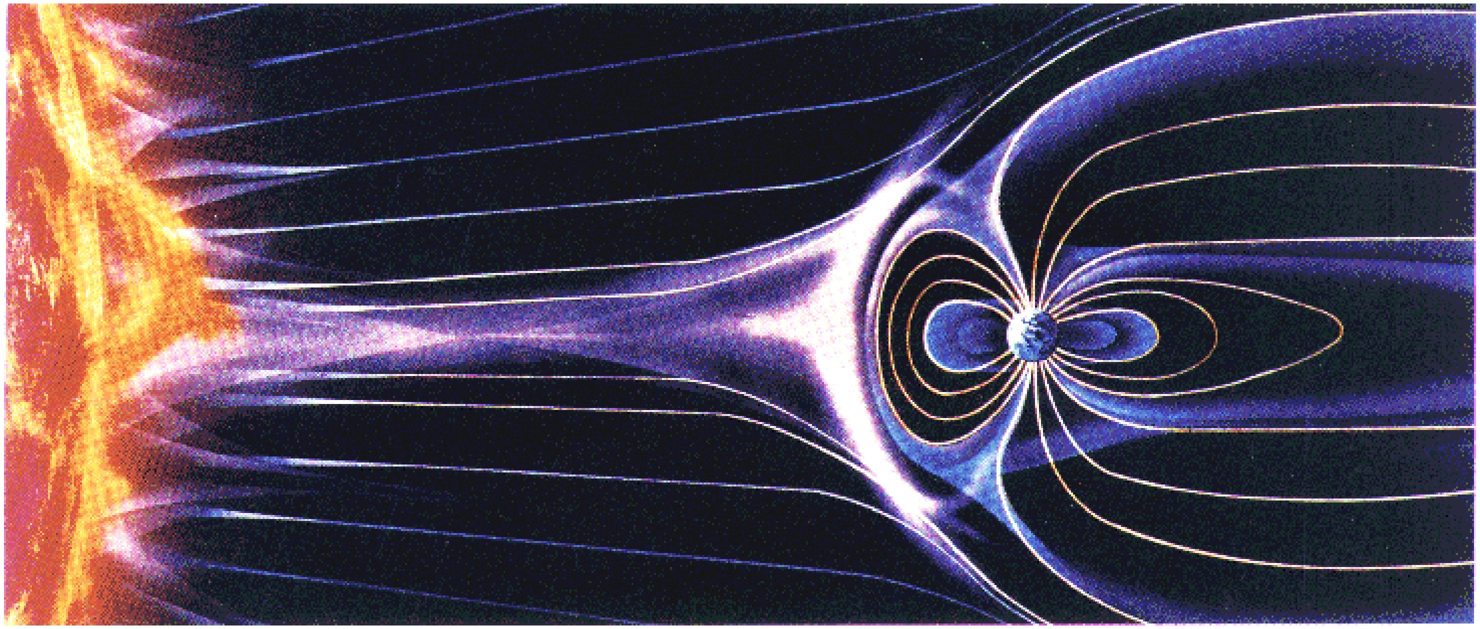
Anomalies are Correlated Magnetospheric Substorms



- Solar activity generates enhanced solar wind
- Interaction with magnetosphere causes substorms
- Substorms cause spacecraft charging

NASCAP Analysis
Plasma Environment

- Plasma Parameters

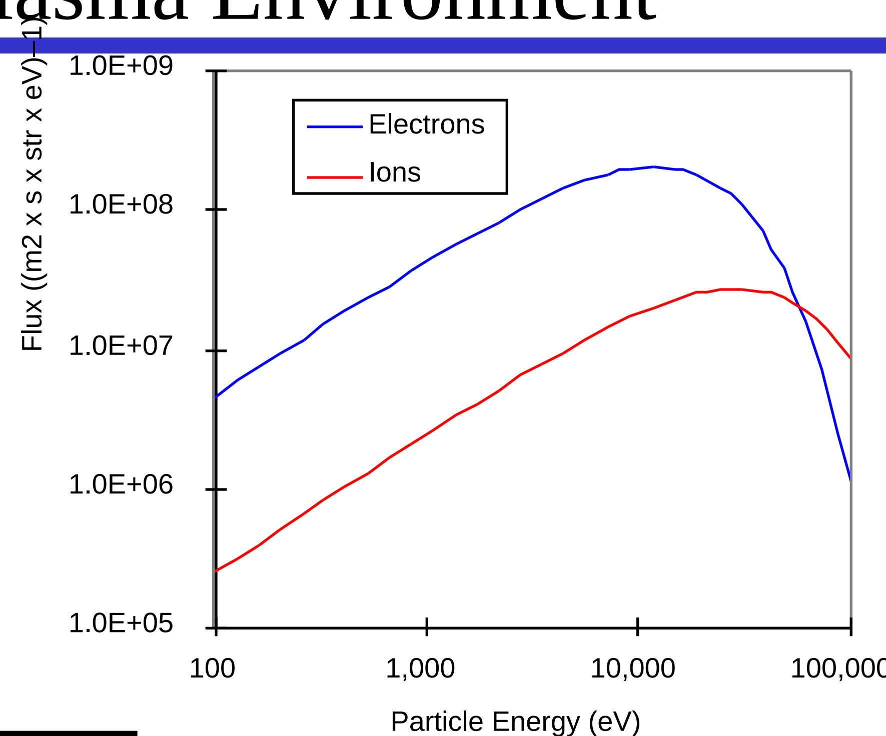
  $n_e = 1.12 \times 10^6\ m^{-3}$

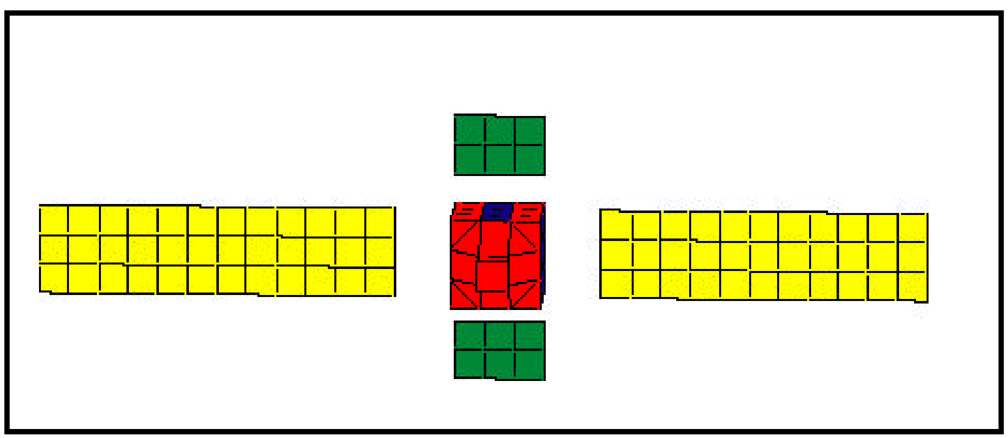
  $T_e = 12\ keV$

  $n_i = 2.36 \times 10^5\ m^{-3}$

  $T_i = 29.5\ keV$

- Orientation to the sun





Environment from:
Design Guidelines for Assessing and Controlling Spacecraft Charging
NASA TP 2361, 1984

Spacecraft Chassis Charges in Sunlight

	Number of Cells	Average Area (m^2)	Current Density ($\mu A\ m^{-2}$)	Current (μA)
Shaded	97	0.72	–1.6	–112
Illuminated	33	0.69	3.4	60
			Net Current	**–52** μA

Simplified Initial Charging Model

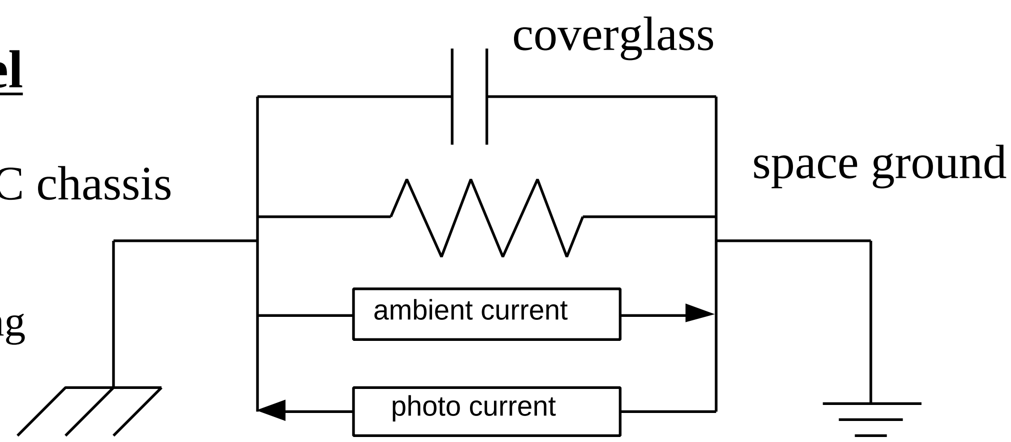
cover glass surface at space ground

no potential barriers

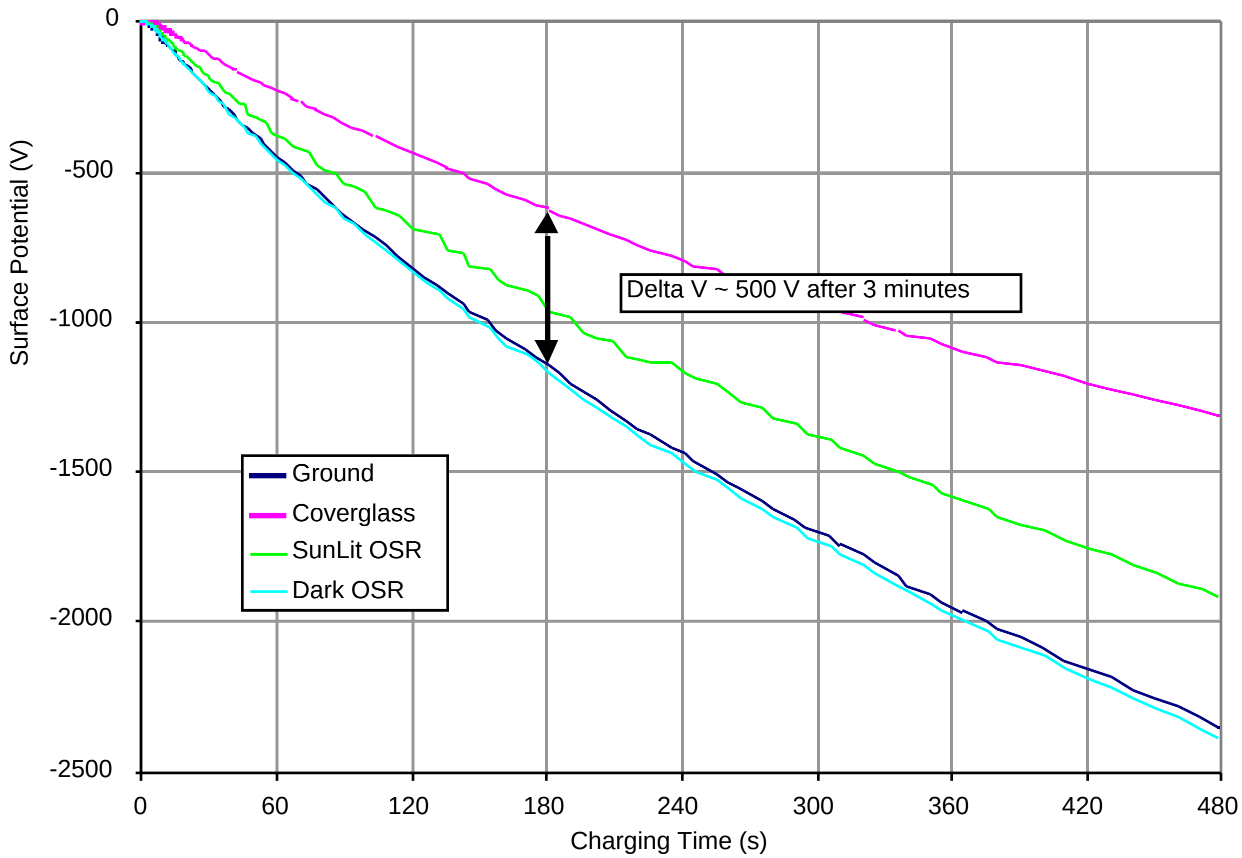
cover glass capacitance dominant

currents to S/C chassis from conducting surfaces

coverglass resistivity

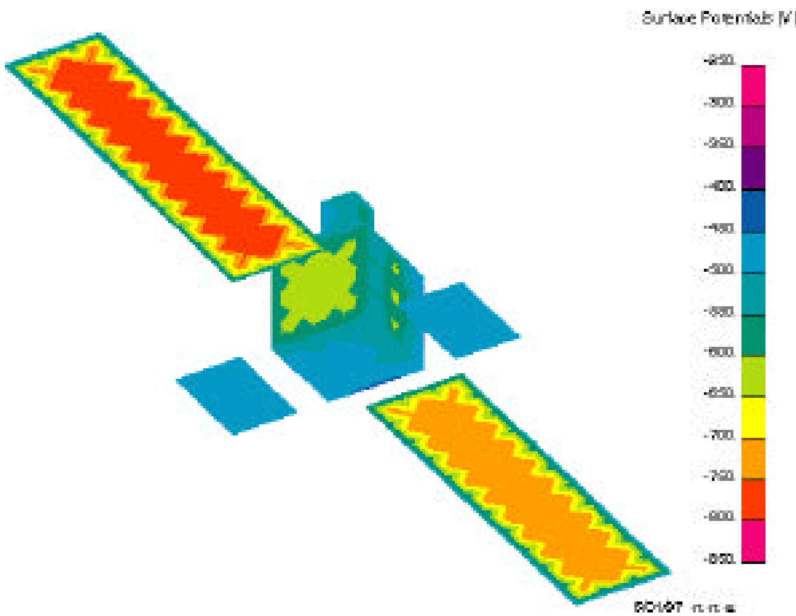


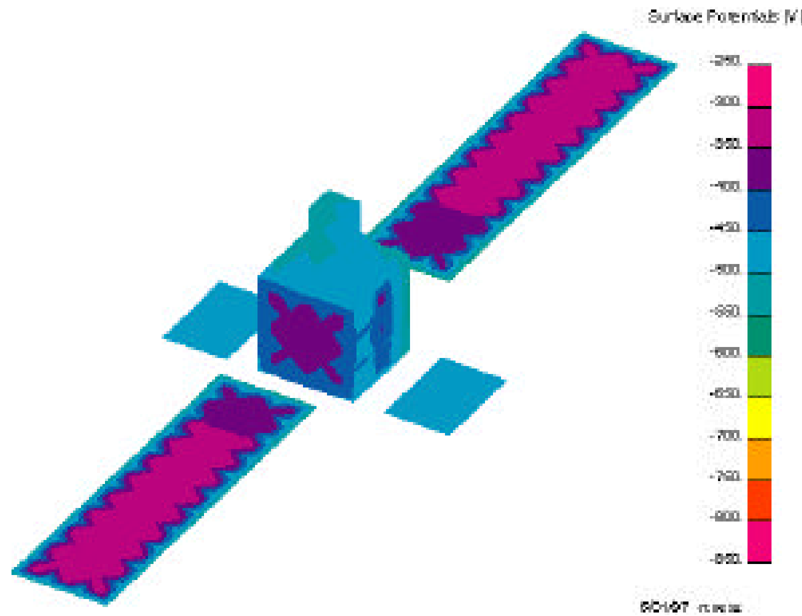
Time History of Potential Development



- S/C chassis charging causes solar cell coverslips to charge
- Differential charging rate ~ 3 V/s

NASCAP Calculated Surface Potentials



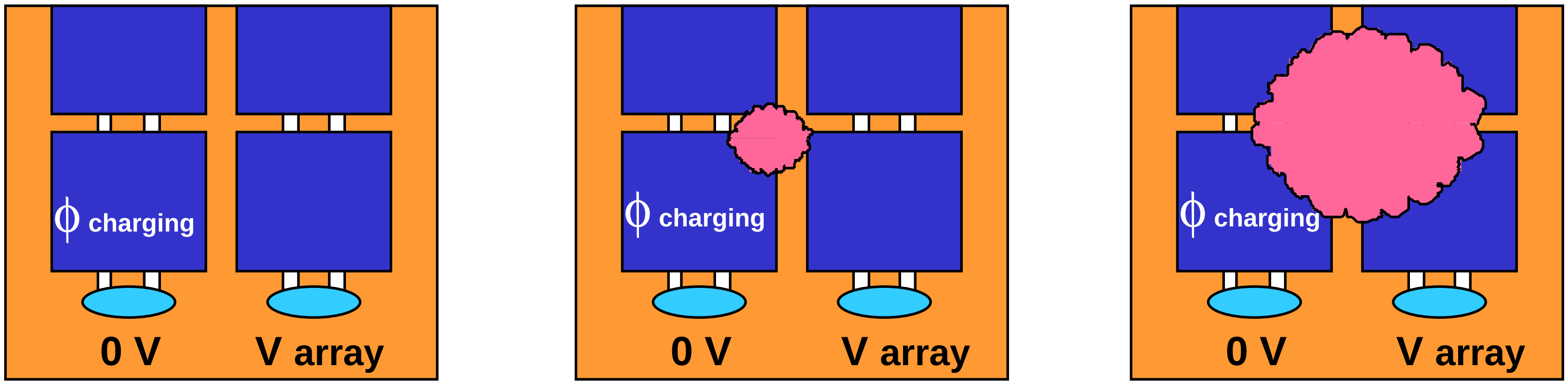


Dark surfaces develop large, negative potentials

Sunlit surfaces have smaller potentials

Differential potentials smaller on inboard panels

Discharge Scenario

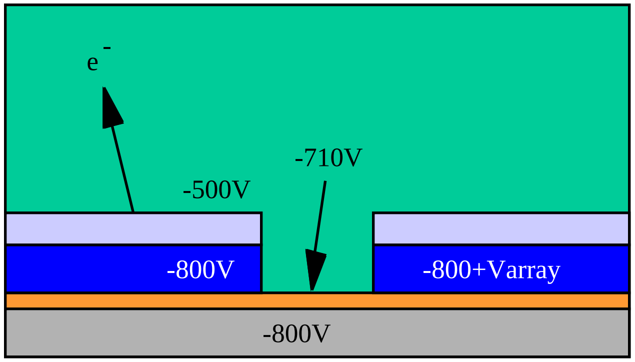


Solar Cell - Coverslip E field > 4 x 10^5 V/m	Small Discharge Starts in Gap Between Cells Discharge Generates a Plasma Cloud	Plasma Cloud Provides Low Impedance Path Across String

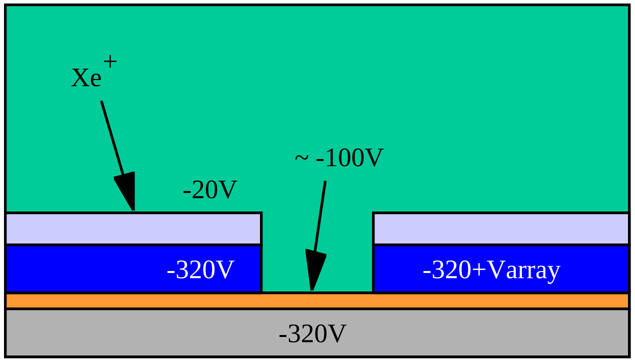
- Spacecraft charging provides trigger arc (~300V)
- Solar array string provides the power for surface flashover
- Sustained surface flashover pyrolizes the kapton
- Permanent low impedance path across string

Design of Chamber Tests

- Goals: test if cells arc and if predicted arc currents couple to array circuit
  - develop same local potential structure as in GEO
  - test if calculated potential differences cause arrays arcing
  - keep chamber plasma currents negligible compared with any arc current
- Charging current densities changes charging time scale
  - GEO - photo electrons ~ 1 nA/cm2
  - Lab - Xe ions ~ 100 nA/cm2
- Lab simulates solar array gap differential potentials except near Kapton



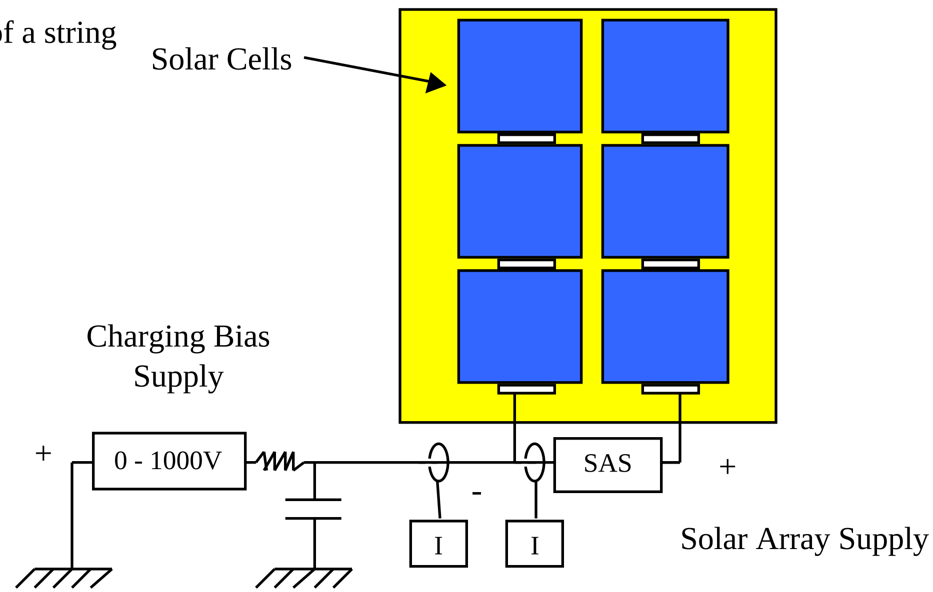
GEO



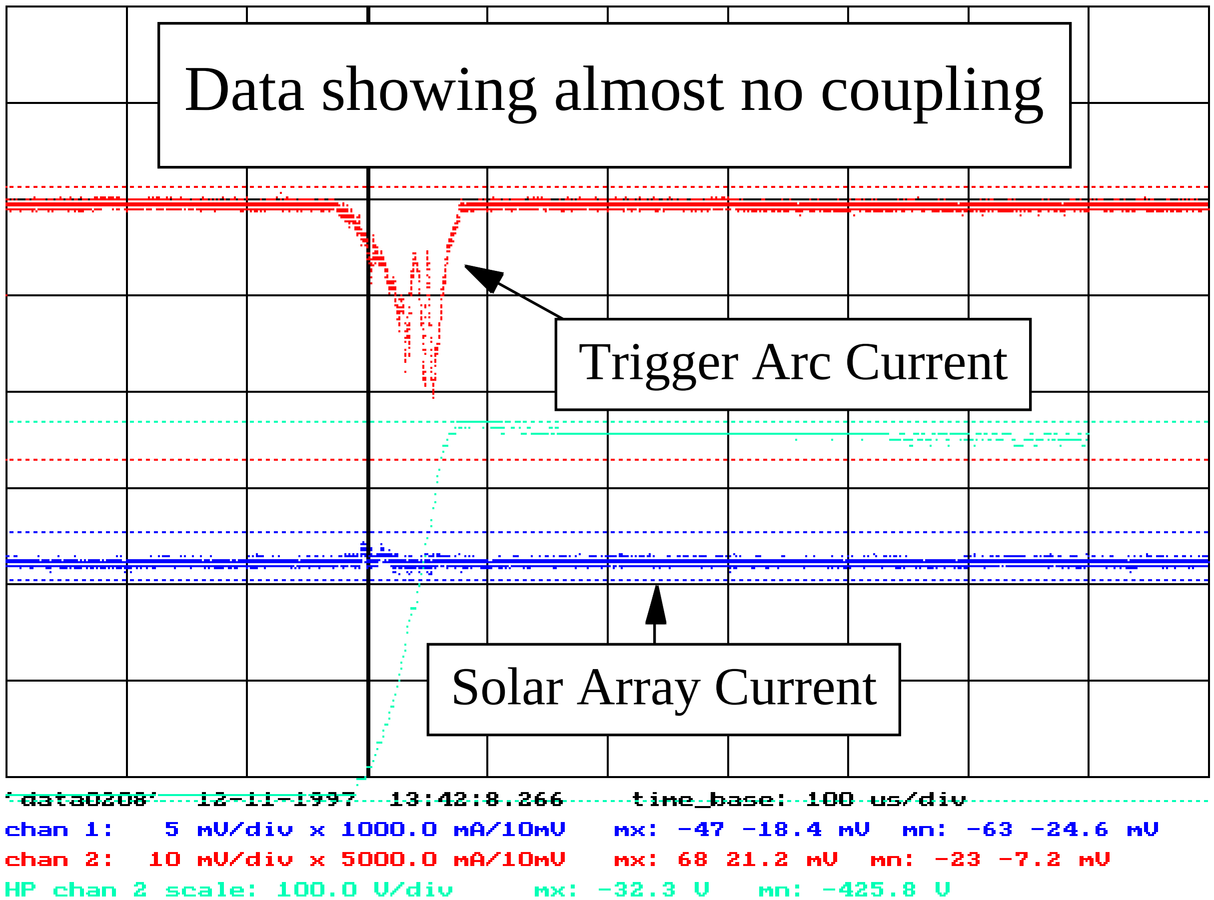
Lab

Tests at NASA/LeRC

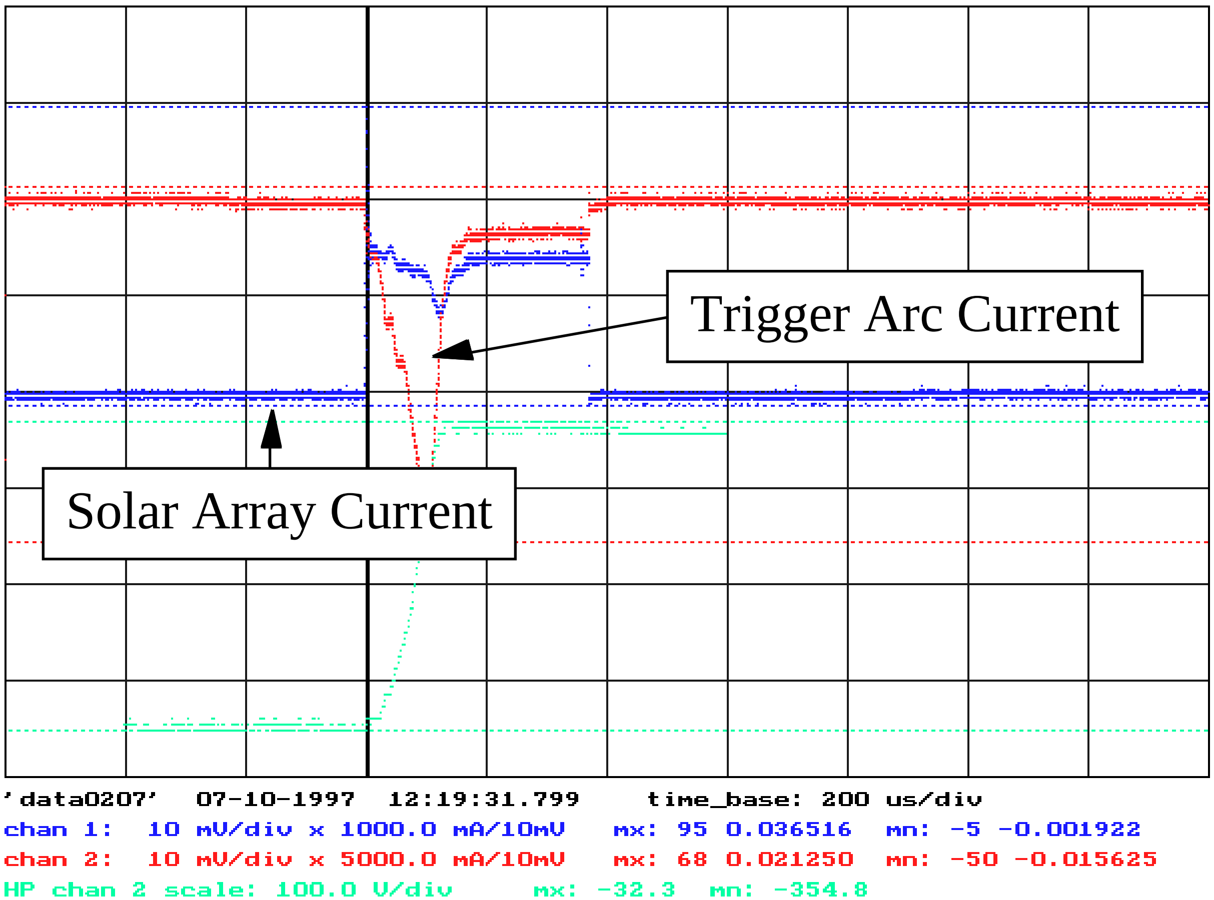
- Chamber Environment
  - Low density, ionosphere like plasma density ~ 10^{11} m^{-3}
  - Pressure < 10^{-6} Torr
- Solar Array Supply (SAS)
  - Purpose: Simulate the current generation capabilities of a string
- Charging Bias Supply (CBS)
  - Purpose: Simulate the sunlight charging of the array
  - Parameters: 0 – 1000V
    - capacitor to simulate wing capacitance
    - positive terminal attached to tank ground
    - 10KΩ current limiting resistor
- Diagnostics
  - Current on the SAS supply
  - Current on the CBS supply
  - Low level TV with time stamp
  - Transient pulse monitor
- Test Procedure
  - Step from –200V to –1000V in 50V steps
  - Dwell the order of an hour at each step to allow differential to develop



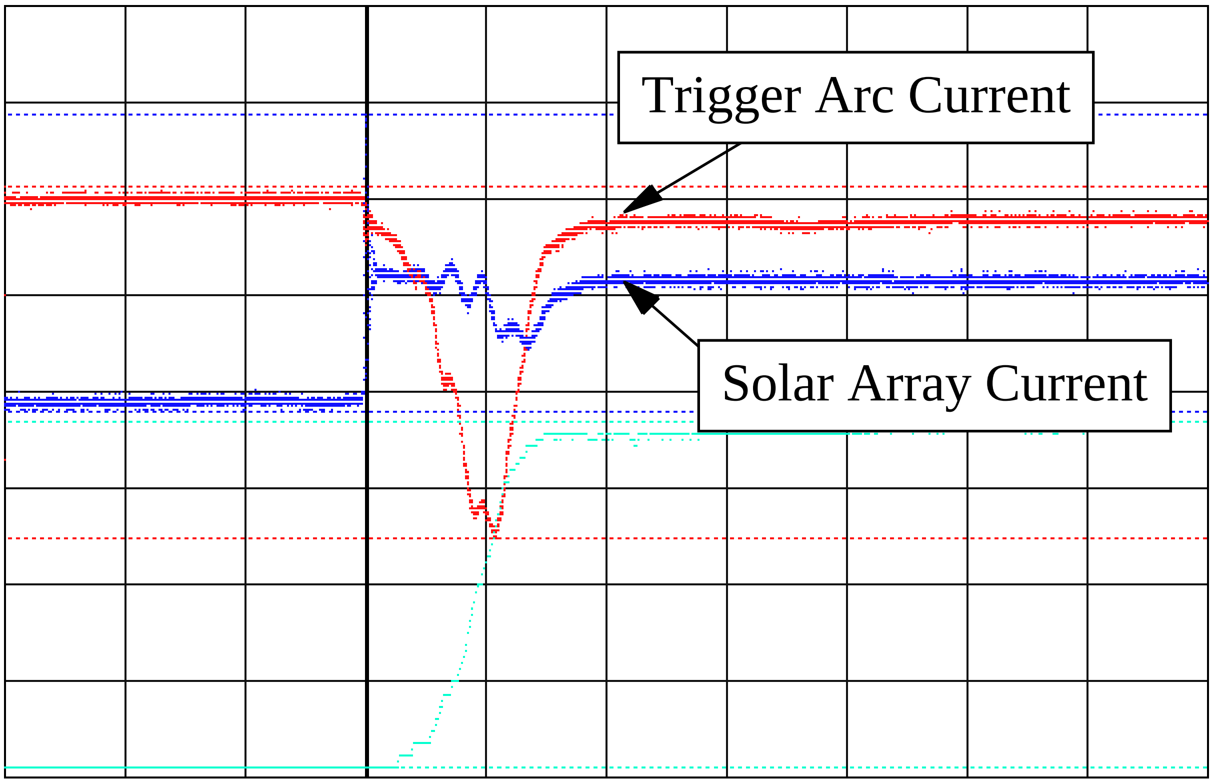
Example Test Data



Example Test Data - Array Arc Extinguishes



Example Test Data - Array Sustained Discharge



'data0410' 06-10-1997 14:16:4.973 time_base: 100 us/div
chan 1: 10 mV/div x 1000.0 mA/10mV mx: 92 28.7 mV mn: -7 -2.2 mV
chan 2: 10 mV/div x 5000.0 mA/10mV mx: 68 21.2 mV mn: -49 -15.3 mV
HP chan 2 scale: 100.0 V/div mx: -32.3 V mn: -393.5 V

Quantitative Model Identifies Critical Parameters

- Spacecraft Charging
  - Ratio of dark to sunlit conducting areas
  - Environment electron temperature & density
  - Coverglass thickness & resistivity
- Trigger Arc
  - Panel capacitance & voltage threshold for arcing
  - Plasma generation efficiency
  - Plume expansion velocity
- Solar Array Coupling Current
  - Geometry
  - Potential
- Cell to Cell Breakdown
  - Plasma plume coupling current
  - String current
  - Cell voltage

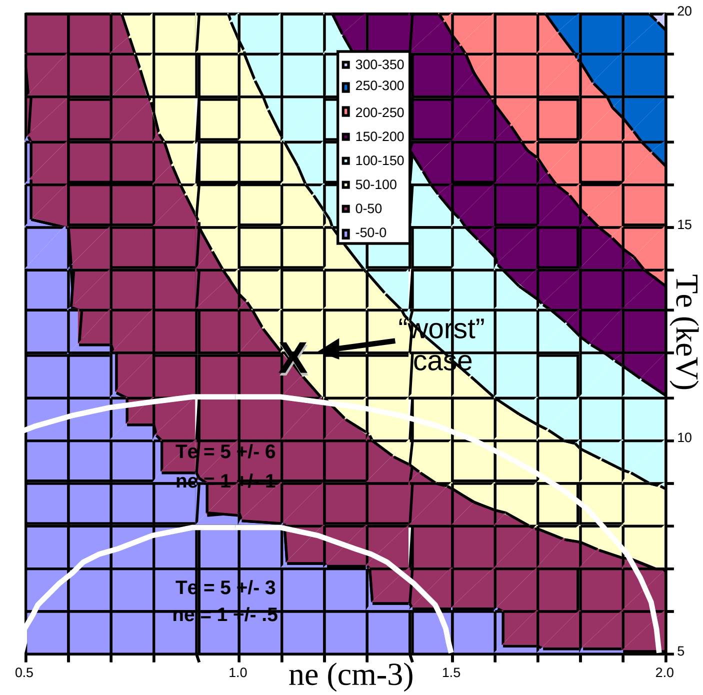
Spacecraft Charging Sensitivity

- Environment
  - electron temperature
  - electron density
- Satellite construction
  - surface materials
  - photo emitting surfaces
- Solar cell coverglass resistivity

Resistivity	Ohm cm	1.0E+13	1.0E+14	1.0E+15	1.0E+16	1.0E+17
	Ohm m	1.0E+11	1.0E+12	1.0E+13	1.0E+14	1.0E+15
Thickness	m	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04
Resistance	Ohms m2	1.0E+07	1.0E+08	1.0E+09	1.0E+10	1.0E+11
Current	Amp/m2	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
Voltage	Volts	1.0E+01	1.0E+02	1.0E+03	1.0E+04	1.0E+05

Voltage drop across a 100µm solar cell coverglass over the published range of resistivities.

Sensitivity of charging current to the environment



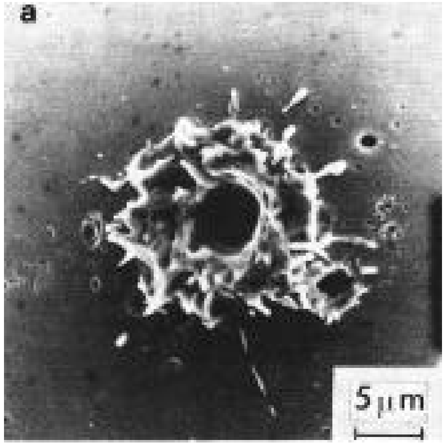
Charging current in micro Amperes

Solar Array Arc Mechanisms

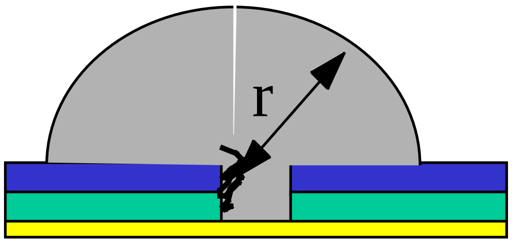
- Trigger arcs are vacuum arcs
  - Fowler - Norheim pre breakdown emission
  - electric field enhanced emission (EFEE)
  - cathode spot - plasma ejection
- Plasma plume expansion
  - velocity
  - potentials
  - currents
- Anode effects
  - energy density
  - distance

Vacuum Arc Formation

- Fowler - Nordheim electron emission
  - requires local electric field enhancement
  - emission must increase field - secondary yield > 1
  - conductivity decreases field
- Cathode spot formation
  - current density
  - resistive heating
  - gas / molecular fragment release
- Quasi neutral plasma expansion
  - higher density than any orbital environment
  - similar properties for all arcs



Trigger Arc Plasma Plume Model



- Arc between cell and coverglass generates a spherically expanding plasma
- Ion generation proportional to arc power $$I_i \approx \frac{IV}{500}$$
- Expansion velocity ~3x10^{4}m/s $$n_i = \frac{I_i}{e v_i 4\pi r^2}$$
- Classical electron-ion scattering $$\sigma = \varepsilon_0 \omega_p^2 / \upsilon_{ei}$$
- Plasma potential from Ohm's law $$V(r) = \int_{r_0}^{r} \frac{I_e}{\sigma 2\pi r^2} dr$$

Trigger Arc Current Magnitude

- Discharge generates charge neutral plasma
- Coverglass with $\Delta\phi$ of 320 V, 6.25 m^2

$$C = \frac{\varepsilon_o \kappa A}{d} \approx 1.8\,\mu F$$

$$Q = C\,\Delta\phi \approx 5.6\times 10^{-4}\ coulombs$$

$$E = \tfrac{1}{2} C\,\Delta\phi^2 \approx 0.1\ \ joules$$

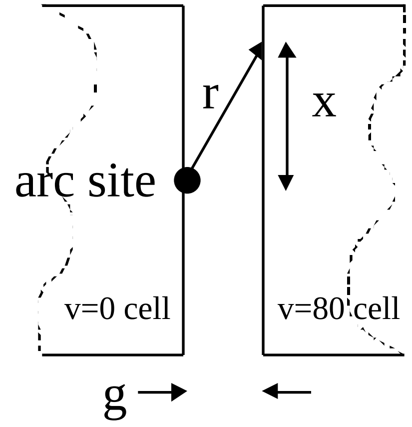
$$\tau \approx \frac{\ell}{v} \approx \frac{1.25}{3\times 10^4} \approx 40\,\mu s$$

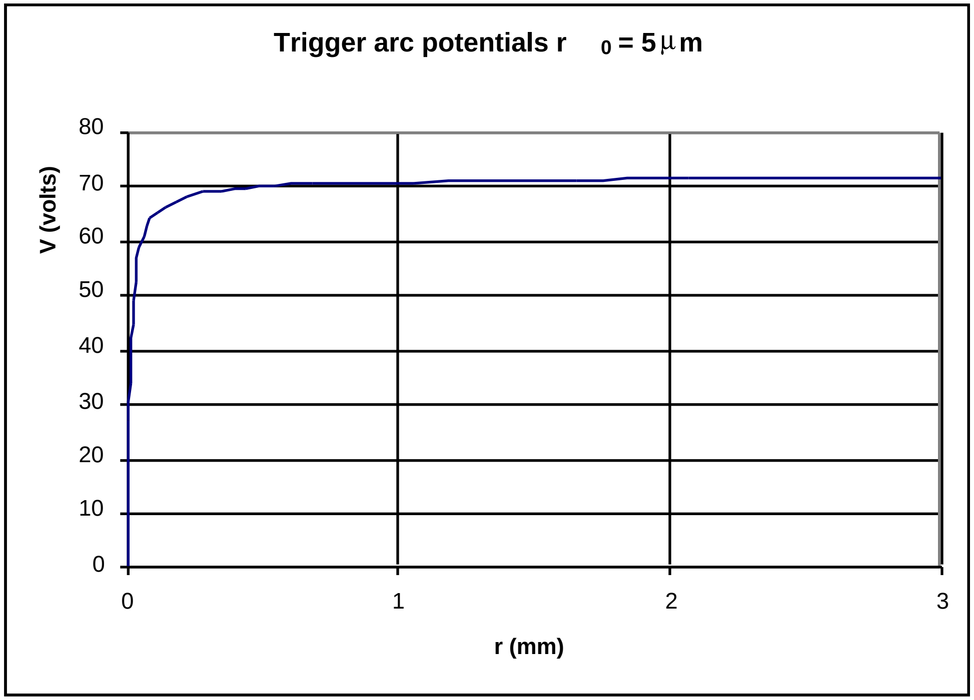
$$I \approx \frac{Q}{\tau} \approx 13\,A$$

- Peak discharge current ~13 A

Trigger Arc Cell to Cell Currents

- Plasma electron thermal current
- Cell voltage vs. plasma potential
- Sheath effects at high voltage





$$I_{max} = \int_{-\infty}^{\infty} h \frac{j_e(1)}{g^2 + x^2} dx = \pi \frac{h\, j_e(1)}{g}$$

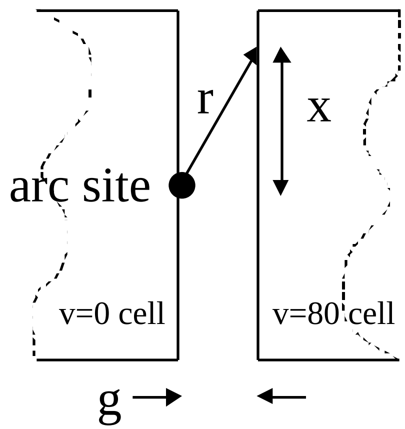
I_i (A)	V(r=1mm)
0.1	127
1	99
10	72
100	44

Modifications Reduce Cell to Cell Currents

- Effect of RTV

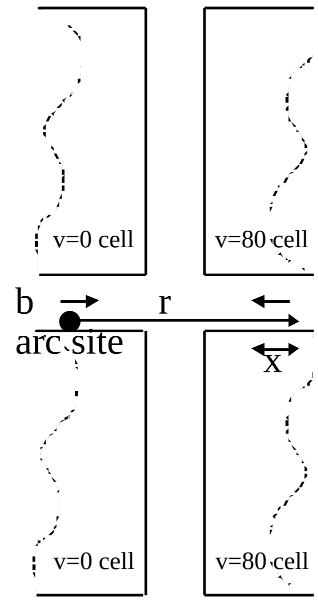
original

$$I_{\max} = 2.6\,A$$



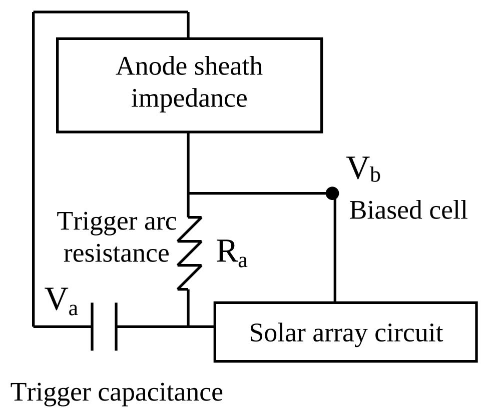
modified

$$I_{\max} = 0.5\,A$$



- Effect of lowering cell to cell potentials

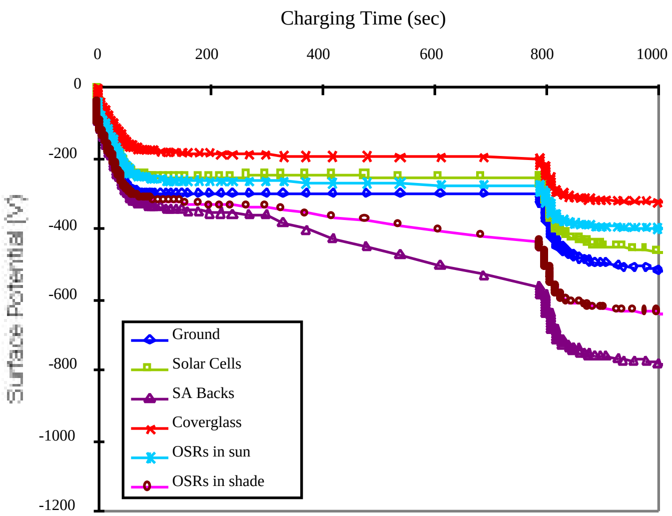
$$I = \min\left(I_s, \quad I_s \exp\left(\frac{V_b - I_a R_a}{T_e} \right) \right)$$



ESD Initiated Failures on High Voltage Satellites

- Trigger arc is a classical vacuum arc
  - S/C potentials cause arcs - GEO or LEO
  - generates expanding plasma plume
  - plume density >> orbital or lab environments
- NASA/LeRC laboratory tests support model
  - solar cells arc
  - arcs trigger array discharges
  - parameters in range of calculations
- Array modifications can stop secondary arcs
  - reduce voltage to cut both current and power to neighboring cells
  - reduce currents to below damage threshold
  - RTV in gap to decrease coupling currents

Analysis Identified Gaps in Present Knowledge



- NASCAP inadequacies
  - charging algorithm has difficulties
  - limited geometry & poor resolution
- Material properties uncertainties
  - predict too little charging
  - effect of space environment
- Solar array arc model deficiencies
  - discharge mechanisms and thresholds
  - current scaling, including array dimensions
  - coupling as a function of voltage, current, and geometry

Need Laboratory Test Procedures Validated by Flight Experiment