Introduction

Outline

• Spacecraft charging physics
• Charging anomaly, failure mechanisms
• History/examples of spacecraft charging anomalies and failures
• High voltage solar arrays
• Summary

<table>
<thead>
<tr>
<th>Space Environment Impacts on Space Systems</th>
<th>Anomaly Diagnosis</th>
<th>Number</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>ESD-Internal, surface</td>
<td></td>
<td>162</td>
<td>54.1</td>
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<td>and uncategorized</td>
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<tr>
<td>SEU (GCR, SPE, SAA, etc.)</td>
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<td>Radiation dose</td>
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<td>Atomic oxygen</td>
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<td>0.3</td>
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<tr>
<td>Atmospheric drag</td>
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<td>1</td>
<td>0.3</td>
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<td>Other</td>
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<td>8.0</td>
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<tr>
<td>Total</td>
<td></td>
<td>299</td>
<td>100.0%</td>
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</table>

[Koons et al., 2000]
What is Charging?

- The build up of current on or within spacecraft materials. The sum of the currents = 0 at equilibrium.
  - Surface
  - Deep dielectric

\[
\frac{dQ}{dt} = C \frac{dQ}{dt} = \frac{d\sigma}{dt} A = \sum I_k = \\
\text{incident ions} + I_i (V) \\
\text{incident electrons} - I_e (V) \\
\text{backscattered electrons} + I_{bs,e} (V) \\
\text{conduction currents} + I_c (V) \\
\text{secondary electrons due to } I_e + I_{se} (V) \\
\text{secondary electrons due to } I_i + I_{si} (V) \\
\text{photoelectrons} + I_{ph,e} (V) \\
\text{active current sources (beams, thrusters)} + I_b (V)
\]
Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**
  - Due to net charge density on spacecraft surfaces or within insulating materials due to current collection to/from the space environment

- **Electrodynamic (inductive) potentials**
  - Modification of frame potentials without change in net charge on spacecraft
  - Plasma environment not required
  - Examples include
    - EMF generated by motion of conductor through magnetic field
    - Externally applied electric fields

\[
\nabla \cdot D = \nabla \cdot \varepsilon E = \nabla \cdot \varepsilon (-\nabla \phi) = \rho
\]
\[
\nabla^2 \phi = -\frac{\rho}{\varepsilon}
\]
\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot J \quad \text{where } J = J_R + J_C
\]

\[
\begin{align*}
\vec{F} &= q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{Laboratory frame} \\
\vec{F}' &= q\vec{E}' \quad \text{Spacecraft rest frame} \\
\vec{E}' &= \vec{E} + \vec{v} \times \vec{B} \quad \text{Forces equal in both frames!} \\
\varepsilon'_m &= \int_c \vec{E}' \cdot d\vec{S} = \int_c (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S} \\
\Delta \phi' &= \int_c (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S}
\end{align*}
\]

Surface charging
\[
\frac{dQ}{dt} = C \frac{d\phi}{dt} = \sum_k I_k \sim 0 \text{ at equilibrium}
\]

Charging Anomaly and Failure Mechanism

• Accumulation of excess negative charge or inductive redistribution of charge generates potential differences between spacecraft and space (frame potential) or between two points on the spacecraft (differential potential)

• An electrostatic discharge (ESD) results when electric fields associated with potential differences \( E = -\nabla \Phi \) exceed the dielectric breakdown strength of materials allowing charge to flow in an arc

• Damage depends on energy available to arc
  \[ E = \frac{1}{2} CV^2 \]

• Charging anomalies and failures depend on
  – Magnitudes of the induced potentials and strength of the electric fields
  – Material configuration (and capacitance)
  – Electrical properties of the materials
    • Surface and volume resistivity, dielectric constant
    • Secondary and backscattered electron yields, photoemission yields
    • Dielectric breakdown strength

ISS MMOD shield 1.3 μm chromic acid anodized thermal control coating
(T. Schneider/NASA)

PMMA (acrylic) charged by ~2 to 5 MeV electrons
Impact of Charging on Spacecraft

- **Electrostatic discharge (ESD) currents**
  - Compromised function and/or catastrophic destruction of sensitive electronics
  - Solar array string damage (power loss), solar array failures
  - Un-commanded change in system states (phantom commands)
  - Loss of synchronization in timing circuits
  - Spurious mode switching, power-on resets, erroneous sensor signals
  - Telemetry noise, loss of data

- **Electromagnetic interference (EMI)**
  - EMI noise levels in receiver band exceeding receiver sensitivity
  - Communications issues due to excess noise
  - Phantom commands, signals

- **Material damage**
  - ESD damage to mission critical materials including thermal control coatings, re-entry thermal protection systems, optical materials (dielectric coatings, mirror surfaces)
  - Re-attracted photo ionized outgassing materials deposited as surface contaminants

- **Other**
  - Compromised science instrument, sensor function
    » Modified “Ion line” charging signature in ion spectrum
    » Photoelectron contamination in electron spectrum
  - Parasitic currents and solar array power loss (LEO)
<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Year(s)</th>
<th>Orbit</th>
<th>Impact*</th>
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<tbody>
<tr>
<td>DSCS II</td>
<td>1973</td>
<td>GEO</td>
<td>LOM</td>
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<td>Voyager 1</td>
<td>1979</td>
<td>Jupiter</td>
<td>Anom</td>
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<td>SCATHA</td>
<td>1982</td>
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<td>Anom</td>
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<td>GOES 4</td>
<td>1982</td>
<td>GEO</td>
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<td>AUSSAT-A1, -A2, -A3</td>
<td>1986-1990</td>
<td>GEO</td>
<td>Anom</td>
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<td>FLTSATCOM 6071</td>
<td>1987</td>
<td>GEO</td>
<td>Anom</td>
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<td>GOES 7</td>
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<td>Anom/SF</td>
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<td>Feng Yun 1A</td>
<td>1988</td>
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<td>Anom/LOM</td>
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<td>MARECS A</td>
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<td>Anik E1</td>
<td>1991</td>
<td>GEO</td>
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<td>Anik E2</td>
<td>1991</td>
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<td>1995</td>
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<td>SAMPEX</td>
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<table>
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<th>Spacecraft</th>
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<th>Orbit</th>
<th>Impact*</th>
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<tr>
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<td>DMSP F13</td>
<td>1995</td>
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<td>Anom</td>
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<td>TSS-1R</td>
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<td>TDRS F-3,F-4</td>
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<td>INSAT 2</td>
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<td>PAS-6</td>
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<td>Feng Yun 1C</td>
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<td>Anom</td>
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<td>Echostar 129</td>
<td>2011</td>
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<td>Suomi NPP</td>
<td>2011-2014</td>
<td>LEO</td>
<td>Anom</td>
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</table>

*Anom=anomaly, LOM=Loss of mission, SF=system failure

Spacecraft Anomalies and Failures Workshop, 24 July 2014
Charging Failures are Expensive!

- Launch Failure: 40.3%
- Power: 31.0%
- Payload: 10.5%
- Propulsion: 9.3%
- T&C / Data handling: 4.6%
- Other: 2.8%
- ACS incl computer: 1.4%

Space Weather Claims:
- Anik E1: USD 142.5m
- Telstar 401: USD 132.0m

Total claims (1994 – 2013) = USD 12,640m [Wade, 2014]
GEO Charging Examples

- GEO surface charging potentials to 1 to 10 kV
- Surface charging most common in midnight through dawn sector
- Internal charging independent of local time

Record ATS-6 charging event $\Phi \sim -19$ kV
GOES Solar Cycle 21 Internal Charging Anomalies

Black: GOES phantom commands
2-day fluence (F2) > 2 MeV electrons

Red: F2 ≥ 10^9 e^-/cm^2-sr
Amber: 10^9 > F2 ≥ 10^8 e^-/cm^2-sr
Green: F2 < 10^8 e^-/cm^2-sr
White: no data

[from Wrenn et al. 2002 ]
High Inclination LEO Charging Examples

- Polar surface charging potentials to 1 or 2 kV
- Surface charging caused by 10’s keV auroral electrons limited to high latitudes

[Minow et al, 2014]
Solar Array Arcing

• Charging issues for low voltage PVA systems are typically limited to extreme LEO auroral and GEO charging environments

• High voltage systems are at risk for ESD due to plasma currents collected on exposed high voltage components, arcing through insulators

• Two types of solar array arcs:
  – Trigger arcs: fast, transient arc
    • Damage limited to local capacitance
    • EMI noise
  – Sustained arcs: long duration, continuous arcs
    • Solar array currents feed power into arc site producing significant damage to cell strings
    • Can lead to total loss of array

ESA EURECA solar array sustained arc damage (ESA)

Sustained arc

Cho, 2014
http://laplace.ele.kyutech.ac.jp/mengu/400V.htm
Mitigation Strategies

• Follow good EMC, grounding/bonding and charging design practices
  – Ground conductive materials to assure an equipotential (eliminate differential charging)
  – Use static dissipative materials when conductors cannot be used

• Analyze spacecraft configuration in charging environment
  – Nascap-2k, In. cam, NUMIT

• Test insulating materials with electron beams at relevant energy (10's keV) and current (~1-10 nA/cm²) to determine if (a) arcing will occur and (b) if it will result in damage
Anomaly Investigations

- Complete anomaly investigation requires
  - Information on environment at time of anomaly
  - Information on spacecraft configuration (material properties, shielding thickness, grounding/bonding details)
  - System vulnerabilities to ESD

- Orbit and environment assessment through analysis of charged particle data during anomaly timeframe
  - Best if your satellite has plasma, particle detectors
  - Data from other sources including nearby satellites if necessary

Material
Z=6, A=11.5
d=2.5 cm
\( \sigma \sim 1 \times 10^{-17} \text{ S/m} \)
\( \kappa = 2.00 \)
\( \rho = 1.0 \text{ g/cm}^3 \)
Common Cause Charging, Radiation Anomalies

- Charging and radiation anomalies can be generated by the same environments.

- Chandra X-ray Observatory star tracker anomalies in spring 2010 were caused by outer radiation belt energetic electron enhancements.

- The same environment resulted in the Galaxy 15 ESD anomaly on 5 April 2010.

- High flux of penetrating MeV electrons impacts well shielded CCD imager, results in charging threat.
Summary

• Charging can cause significant damage to spacecraft resulting in loss of mission, loss of functionality, loss of money

• Complicated physical process that is dependent on spacecraft configuration, material selection, and orbit (environment)

• Failures and anomalies include
  – Destruction of sensitive electronics
  – Solar array string damage
  – Phantom commands
  – Telemetry noise, loss of data
  – ESD damage to mission critical materials
  – Re-attracted photo ionized outgassing materials deposited as surface contaminants
  – Compromised science instruments, sensor function
  – Parasitic currents and solar array power loss

• Build spacecraft to withstand or avoid charging
  – Characterize charging environment
  – Modeling spacecraft response to charging environment
  – Testing components in relevant charging environments

• Anomaly investigation