Space Weather Impacts on Satellites with Emphasis on Launch Vehicles

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CCMC Space Weather Course, NASA KSC
2-4 February 2016
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• Todays presentation will discuss the impact of space weather on satellites with additional emphasis on launch vehicles

• Outline
  – General notes on space environments and effects
  – Environments of importance to satellites, launch vehicles
  – Ionizing radiation effects
  – Spacecraft charging effects
  – Meteors and orbital debris
Outline

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The primary approach for the spacecraft industry to mitigate the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints.

http://www.nap.edu/catalog/12507.html

This technique is rarely 100% successful and space weather will typically end up impacting some aspect of a space mission.

- Some space weather issues are common to all spacecraft, e.g., space situational awareness is one example.
- Specific details of space weather interactions with a spacecraft are often unique because spacecraft systems are unique, there is no “standard” space weather support to mission operations.
# Space Environment Effects

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Effect</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Charging</strong></td>
<td>• Biasing of instrument readings&lt;br&gt;• Power drains&lt;br&gt;• Physical damage</td>
<td>• Dense, cold plasma&lt;br&gt;• Hot plasma</td>
</tr>
<tr>
<td><strong>Deep Dielectric Charging</strong></td>
<td>• Biasing of instrument readings&lt;br&gt;• Electrical discharges causing physical damage</td>
<td>• High-energy electrons</td>
</tr>
<tr>
<td><strong>Structure Impacts</strong></td>
<td>• Structural damage&lt;br&gt;• Decompression</td>
<td>• Micrometeoroids&lt;br&gt;• Orbital debris</td>
</tr>
<tr>
<td><strong>Drag</strong></td>
<td>• Torques&lt;br&gt;• Orbital decay</td>
<td>• Neutral thermosphere</td>
</tr>
<tr>
<td><strong>Total Ionizing Dose (TID)</strong></td>
<td>• Degradation of microelectronics</td>
<td>• Trapped protons&lt;br&gt;• Trapped electrons&lt;br&gt;• Solar protons</td>
</tr>
<tr>
<td><strong>Displacement Damage Dose (DDD)</strong></td>
<td>• Degradation of optical components and some electronics&lt;br&gt;• Degradation of solar cells</td>
<td>• Trapped protons &amp; electrons&lt;br&gt;• Solar protons&lt;br&gt;• Neutrons</td>
</tr>
<tr>
<td><strong>Single-Event Effects (SEE)</strong></td>
<td>• Data corruption&lt;br&gt;• Noise on images&lt;br&gt;• System shutdowns&lt;br&gt;• Electronic component damage</td>
<td>• GCR heavy ions&lt;br&gt;• Solar protons and heavy ions&lt;br&gt;• Trapped protons&lt;br&gt;• Neutrons</td>
</tr>
<tr>
<td><strong>Surface Erosion</strong></td>
<td>• Degradation of thermal, electrical, optical properties&lt;br&gt;• Degradation of structural integrity</td>
<td>• Particle radiation&lt;br&gt;• Ultraviolet&lt;br&gt;• Atomic oxygen&lt;br&gt;• Micrometeoroids Contamination</td>
</tr>
<tr>
<td>Mechanism</td>
<td>Effect</td>
<td>Source</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>--------------------------------------</td>
</tr>
</tbody>
</table>
| Surface Charging                | • Biasing of instrument readings  
• Power drains  
• Physical damage                                                                 | • Dense, cold plasma  
• Hot plasma                                    |
| Deep Dielectric Charging        | • Biasing of instrument readings  
• Electrical discharges causing physical damage                                                                 | • High-energy electrons                          |
| Structure Impacts               | • Structural damage  
• Decompression                                                                 | • Micrometeoroids  
• Orbital debris                                  |
| Drag                             | • Torques  
• Orbital decay                                                                 | • Neutral thermosphere                          |
| Total Ionizing Dose (TID)        | • Degradation of microelectronics                                                                 | • Trapped protons  
• Trapped electrons  
• Solar protons                                      |
| Displacement Damage Dose (DDD)   | • Degradation of optical components and some electronics  
• Degradation of solar cells                                                                 | • Trapped protons & electrons  
• Solar protons  
• Neutrons                                            |
| Single-Event Effects (SEE)       | • Data corruption  
• Noise on images  
• System shutdowns  
• Electronic component damage                                                                 | • GCR heavy ions  
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• Trapped protons  
• Neutrons                                             |
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• Degradation of structural integrity                                                                 | • Particle radiation  
• Ultraviolet  
• Atomic oxygen  
• Micrometeoroids Contamination                         |
# Space Environment Effects

## Space Environmental Impacts on Space Systems

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ESD-Internal, surface, and indeterminate</td>
<td>54%</td>
<td>31%</td>
<td>10%</td>
</tr>
<tr>
<td>SEU (GCR, SPE, SAA, etc.)</td>
<td>28%</td>
<td>17%</td>
<td>5%</td>
</tr>
<tr>
<td>Radiation Dose</td>
<td>5%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Meteoroids and Orbital Debris</td>
<td>3%</td>
<td>---</td>
<td>5%</td>
</tr>
<tr>
<td>Atomic Oxygen</td>
<td>&lt; 1%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Atmospheric Drag</td>
<td>&lt; 1%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Design</td>
<td>---</td>
<td>---</td>
<td>25%</td>
</tr>
<tr>
<td>Other or Unknown</td>
<td>8%</td>
<td>52%</td>
<td>55%</td>
</tr>
</tbody>
</table>

[McKnight, 2015]
Oct 23: *Genesis* satellite at L1 entered safe mode, normal operations resumed on Nov. 3. *Midori-2 (ADEOS-2)* Earth-observing satellite power system failed, safe mode, telemetry lost (23:55), *spacecraft lost*

Oct 24: *Stardust* comet mission went into safe mode due to read errors; recovered. *Chandra X-ray Observatory* astronomy satellite observations halted due to high radiation levels (09:34EDT), restarted Oct. 25

*GOES-9, 10 and 12* had high bit error rates (9 and 10), magnetic torquers disabled due to geomagnetic activity

Oct 25: *RHESSI* solar satellite had spontaneous CPU reset (10:42)

Oct 26: *SMART-1* had auto shutdown of engine due to increased radiation level in lunar transfer orbit (19:23)

Oct 27: *NOAA-17 AMSU-A1* lost scanner

GOES-8 X-ray sensor turned itself off and could not be recovered

Oct 28-30: Astronauts on *Intl. Space Station* went into service module for radiation protection

Instrument on *Integral* satellite went into safe mode because of increased radiation

*Chandra* observations halted again autonomously, resumed Nov 1
Oct 28:  *DMSP F16* SSIES sensor lost data twice, on Oct. 28 and Nov. 3; recovered. microwave sounder lost oscillator; switched to redundant system

*SIRTF*, in orbit drifting behind Earth, turned off science experiments and went to Earth pointing due to high proton fluxes, 4 days of operations lost

*Microwave Anisotropy Probe* spacecraft star tracker reset and backup tracker autonomously turned on, prime tracker recovered

Oct 29: *Kodama* data relay satellite in GEO; safe mode, signals noisy, recovery unknown

*RHESSI* satellite had 2 more spontaneous resets of CPU (28, 17:40; 29, 03:32).

*CHIPS* satellite computer went offline on Oct. 29 and contact lost with the spacecraft for 18 hr. When contacted the S/C was tumbling; recovered successfully. Offline for a total of 27 hrs.

*X-ray Timing Explorer* science satellite Proportional Counter Assembly (PCA) experienced high voltages and the All Sky Monitor autonomously shut off, both instruments recovered Oct 30 but PCA again shut down. PCA recovery delayed into November.
Oct 28-31: CDS instrument on SOHO spacecraft at L1 commanded into safe mode for 3 days

*Mars Odyssey* spacecraft entered safe mode, MARIE instrument had a temperature red alarm leading it to be powered off (Oct. 28). S/C memory error during downloading on 29 Oct corrected with a cold reboot on Oct. 31

Both *Mars Explorer Rover* spacecraft entered “sun idle” mode due to excessive start tracker events

Oct 29: NASA’s Earth Sciences Mission Office directed all instruments on 5 spacecraft be turned off or safed due to Level 5 storm prediction. Satellites affected include AQUA, Landsat, TERRA, TOMS, and TRMM

Oct 30: *ACE & Wind* solar wind satellites lost plasma observations

Electron sensors of *GOES* satellite in geosynchronous orbit saturated

Nov 2: *Chandra* observations halted again autonomously due to radiation. Resumption of observations delayed for days

Nov. 6: *Polar TIDE* instrument reset itself and high voltage supplies were disabled; recovered within 24 hr.

*Mars Odyssey* spacecraft commanded out of Safe mode; operations nominal.

adapted from Allen and Wilkerson, 2010

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Space Weather and Climatology

- Space climatology:
  - Variability over months to years
  - Space environment effects on both satellites and launch vehicles are best mitigated by good design
  - Effects on launch vehicle will be present regardless of launch date and time

- Space weather:
  - Variability over minutes to days
  - Effects mitigated by design or operational controls
  - Design satellites to withstand mean, extreme space weather events that may occur during time on orbit
  - Launch operations may be deferred to avoid space weather effects during short flight (launch constraint)

North Alabama, 5 Nov 2001 CST (GMT 309-310)
Radiation Belt Energetic Electrons and Protons

TSX-5  410 km x 1750 km x 69°

Dose rate [rad(Si) sec$^{-1}$] averaged over five seconds for the entire TSX-5 mission from two CEASE dosimeter channels measuring mostly (a) >1 MeV electrons and (b) 37–42 MeV protons.

Metcalf et al., 2007
Solar Protons and Galactic Cosmic Rays

- **GCR**
  - Anti-correlated with solar cycle
  - Small flux variation
- **SEP**
  - Correlated with solar cycle
  - Large flux variation

http://omniweb.gsfc.nasa.gov/
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**Single Event Effects (SEE)**

**Single event effect (SEE):** current generated by ion passing through the sensitive volume of a biased electronic device changes the device operating state.

**SEE Generated by Heavy Ions (Z=2-92):**
- High linear energy transfer (LET) rate of heavy ions produces ionization along track as ion slows down.
- Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE.
- SEE is caused directly by ionization produced by incident heavy ion particles.

**SEE Generated by Protons (Z=1):**
- Proton LET is too low to generate SEE, but secondary heavy ions are produced in nuclear reactions with nuclei of atoms (usually silicon) inside electronics. Energy is transferred to a target atom fragment or recoil ion with high LET and charge deposited by recoil ion(s) is the direct cause of SEE.
- Only a small fraction of protons are converted to such secondary particles (1 in $10^4$ to $10^5$).
Total Ionizing Dose

• Cumulative ionizing damage due to proton and electron energy deposition in materials
  – Electron, hole pairs responsible for long term effects due to charge trapping at damage sites
  – Modifies electrical characteristics of electronic devices
  – Darkening, damage of materials (optics, fiber optics, dielectric filters)
  – Breaking bonds modifies chemical structure (polymers, epoxy binders)

• Effects in electronics
  – Leakage currents
  – Threshold shifts
  – Timing changes
  – Functional failures

• Shielding partially mitigates the effects by reducing of low energy protons, electrons

![Graph showing voltage during erase function vs. total dose (krad(Si))](image)

LaBel, 2003

1 Gray = 1 Joule/kilogram = 100 rad
1 centiGray = 1 rad
Displacement Damage

- Cumulative non-ionizing damage due to proton, electron, and neutrons
  - Particle impact of displaces ion from lattice position
  - Creates charge trapping sites, modifies electrical behavior of material

- Effects in electronics
  - Accumulation of defect sites result in device degradation
  - Optocouplers, solar cells, imagers (e.g., CCD’s), Linear bipolar devices

- Shielding partially mitigates the effects by reducing low energy protons, electron damage
  - High energy protons, neutrons are difficult to shield

\[ \text{RH1056 op-amp degradation acceptable for gamma ray exposure, fails when exposed to protons} \]

\[ \text{National LM117 output voltage modified by exposure to gamma rays, protons} \]
ESA SOHO Solar Array Degradation

I(t)/I(t=0) - Proton events and solar activity

SOHO Sun-Earth L1

J(> 9 MeV)
J(> 40 MeV)

Year

10^10
10^8
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

p+/(cm^-2.s-1)
F(>15 MeV)
p+/(cm^-2.s-1)
UoSAT-3 Single Event Upsets

University of Surrey Satellite (UoSAT)

[http://www.esa.int/TEC/Space_Environment/SEMQ95T4LZE_0.html]

780 km, 98° inclination
SeaStar Satellite Single Event Upsets (SEU)

- SeaStar satellite
  - 705 km, 98.2° inclination

- Flight Data Recorder SEU counts

- Daily rate is just over 100 SEU per day
  - Slowly decreasing as background GCR flux decreases

- Two periods with enhanced SEU are due to solar proton events
  - 15-16 July 2000
  - 9 November 2000

Katz, 2004
Solar Particle Events, CCD Imagers

SOHO (L1) 14 July 2000 “Bastille Day Event”

10:42 UT 11:16 UT 11:42 UT

GOES8 Proton Flux (5 minute data)

Particale cm^-2 s^-1

Universal Time

Updated 2000 Jul 16 23:56:03 NOAA/SEC Boulder, CO USA
Impact on Science Data Quality

GEOTAIL CPI/HPA

Univ of Iowa

http://www.pi.physics.uiowa.edu/www/cpi/

GOES11 Proton Flux (5 minute data)

Begin: 2003 Oct 8 0000 UTC

Particles cm^-2 s^-1 MeV

Updated 2003 Oct 10 23:56:04 UTC

NOAA/SEC Boulder, CO USA

Updated 2003 Oct 13 23:56:03 UTC

NOAA/SEC Boulder, CO USA
SPE Data Contamination of Geotail CPI/HPA Data

GEOTAIL CPI/HPA

Univ of Iowa

http://www.pi.physics.uiowa.edu/www/cpi/

GOES11 Proton Flux (5 minute data)

Begin: 2003 Oct 28 0000 UTC

Particles cm⁻² s⁻¹ sr⁻¹

Updated 2003 Oct 30 23:56:03 UTC

NOAA/SEC Boulder, CO USA

Updated 2003 Nov 2 23:56:05 UTC

NOAA/SEC Boulder, CO USA
### Chandra X-Ray Observatory
### Solar Cycle 24 Radiation Interventions

<table>
<thead>
<tr>
<th>Event*</th>
<th>Start</th>
<th>End</th>
<th>Lost Science time</th>
<th>Auto/Manual</th>
<th>Cause (HRC/EPHIN/ACE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (+1)</td>
<td></td>
<td>2011</td>
<td>406 ks (113 hr)</td>
<td>2/1</td>
<td>2/0/1</td>
</tr>
<tr>
<td>1**</td>
<td>Jun 7 15:23 UT</td>
<td>Jun 8 12:50 UT</td>
<td>74.9 (20.8)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>2</td>
<td>Aug 4 07:03</td>
<td>Aug 7 10:25</td>
<td>270.4 (75.1)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>4</td>
<td>Oct 26 11:40</td>
<td>Oct 28 12:33</td>
<td>154 (42.8)</td>
<td>Auto</td>
<td>Command Telemetry Unit (SEU)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2012</td>
<td>1,246 ks (346 hr)</td>
<td>7/3</td>
<td>5/2/3</td>
</tr>
<tr>
<td>5</td>
<td>Jan 23 06:00</td>
<td>Jan 26 08:27</td>
<td>192.1 (53.4)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>6</td>
<td>Jan 27 19:39</td>
<td>Jan 30 02:20</td>
<td>163.4 (45.4)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>7</td>
<td>Feb 27 03:24</td>
<td>Feb 27 20:23</td>
<td>61 (16.9)</td>
<td>Manual</td>
<td>ACE P3’ (soft)</td>
</tr>
<tr>
<td>8</td>
<td>Mar 7 05:30</td>
<td>Mar 13 05:14</td>
<td>440 (122.2)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>10</td>
<td>May 17 02:18</td>
<td>May 18 04:52</td>
<td>93.8 (26.1)</td>
<td>Auto</td>
<td>E1300 (hard)</td>
</tr>
<tr>
<td>11</td>
<td>Jul 12 19:59</td>
<td>Jul 14 00:09</td>
<td>61.7 (17.1)</td>
<td>Auto</td>
<td>E1300 (hard)</td>
</tr>
<tr>
<td>12</td>
<td>Jul 14 21:08</td>
<td>Jul 16 05:16</td>
<td>80.1 (22.3)</td>
<td>Manual</td>
<td>ACE P3’ (soft)</td>
</tr>
<tr>
<td>13</td>
<td>Jul 19 11:44</td>
<td>Jul 20 04:09</td>
<td>56.5 (15.7)</td>
<td>Auto</td>
<td>HRC (hard)</td>
</tr>
<tr>
<td>14</td>
<td>Sep 3 12:57</td>
<td>Sep 4 12:41</td>
<td>44.5 (12.4)</td>
<td>Manual</td>
<td>ACE P3’ (soft)</td>
</tr>
<tr>
<td>3</td>
<td>2013 Q2</td>
<td></td>
<td>283 ks (78 hr)</td>
<td>1/2</td>
<td>0/0/1</td>
</tr>
<tr>
<td>15</td>
<td>Mar 17 12:32</td>
<td>Mar 19 05:58</td>
<td>105.7 (29.4)</td>
<td>Manual</td>
<td>ACE P3’ (soft)</td>
</tr>
<tr>
<td>16</td>
<td>May 22 14:49</td>
<td>May 24 12:22</td>
<td>123.6 (34.3)</td>
<td>Auto</td>
<td>ACIS (hard)</td>
</tr>
<tr>
<td>17</td>
<td>May 24 20:41</td>
<td>May 25 11:56</td>
<td>54.0 (15.0)</td>
<td>Manual</td>
<td>ACE P3’ (soft)</td>
</tr>
</tbody>
</table>


** First radiation interruption since 2006 December 13
Auto ACIS, Manual ACE P3’

Start: 22, 24 May

M5.0 flare
~1200 km/s CME
Peak ~13:32 UT

IP Shock at L1
~17:35 UT

G15 MP2 110-170 keV
G15 P1 0.7 - 4 MeV
G15 P2 4 - 9 MeV
G15 P5 38 - 82 MeV
G15 P > 10 MeV
G15 P > 50 MeV
G15 P >100 MeV

ACE P3’ 115-195 keV
Radioactive Sources and Launch Vehicle TID

- Radioactive thermoelectric generators (RTG) used for space power sources produce greater TID in launch vehicle avionics than would be seen during flight from natural SPE, GCR, and trapped radiation sources.


- TID depends on how long the RTG will be in proximity of the launch vehicle avionics.

- LV provider specifies TID limit at location of LV avionics for combined exposure period of pre-launch processing and launch window operations, examples:
  - Pluto New Horizons: two 30 day periods separated by one year (60 days total)
  - Mars Science Laboratory: 44 days

- US production of Pu-238 fuel has restarted so future RTG missions will be possible and perhaps more common than in recent years.
RTG Radiation Fields

- Pu-238 fuel decays emitting 4 to 6 MeV \( \alpha \)-particles, range of \( \alpha \)-particle is very short and easily stopped in fuel and container. No radiation issue for LV avionics

- Neutrons from spontaneous and induced fission and \((\alpha, n)\) reactions with low Z isotopes will penetrate fuel, housing to produce a radiation field surrounding the device (=DD)

- Pu-236 (trace impurity) radioactive decay products in Pu-238 fuel generate gamma-rays with energies to few MeV (=TID)
  - Ingrowth of impurity daughter products increases gamma-ray flux over time
  - Radiation threat due to penetrating gamma-rays increases over time since fuel was processed

- Verifying LV TID requirements requires measured radiation fields from **flight** RTG
  - Gamma intensity depends on age and purity of fuel
  - Don’t let payload provider use design environments for TID verification!

Figure 4.9-7 Contour Plot of One Year TID Levels of a Single, 8-module MMRTG (TBR)

Figure 4.9-8 Contour Plot of One Year Displacement Damage Dose (in Equivalent 1 MeV neutrons/cm² Fluence from a Single, 8-module MMRTG) (TBR)

[Europa Clipper Mission, ERD (draft) Brinza, 2014]
Delta IV/GPS IIF-5: Launch Delay

- Cape Canaveral Air Force Station Delta IV launch operations on 20-21 February 2014 briefly delayed due to concern over solar proton event
- All system consoles reported GO at T-4 min hold except for Space Weather who reported a violation of launch criteria
- Launch teams determined the proton flux levels were very close to acceptable limit, represented no danger to LV, and decided Space Weather was GO
- Launch successful at end of window
  Window: 21 Feb, 01:40 UT – 01:59 UT
  Launch: 21 Feb, 01:59 UT

http://www.spaceflight101.net/delta-iv-gps-iif5-launch.html
Delta IV/GPS IIF-5: Launch Delay

ULA Delta IV
GPS IIF-5
21 Feb, 01:59 UTC
Orbital Sciences Corporation Antares launch of Cygnus resupply vehicle to ISS from Wallops scheduled 8 January 2014 delayed 24 hours due to solar proton event

Launch Delay of ISS Commercial Resupply Mission

SpaceX, Falcon 9
Thiacom 6 satellite
6 Jan, 22:06 UT

Orbital ATK, Antares
Cygnus (ISS cargo resupply)
1st window: 8 Jan, 18:32 UT, launch delayed
2nd window: 9 Jan, 18:07 UT, launched

Updated 2014 Jan 7 23:56:02 UTC
NOAA/SWPC Boulder, CO USA
Kodiak Star scheduled for September 2001 launch from Kodiak Launch Complex (Alaska) on Athena (Lockheed Martin) rocket

Launch criteria: \( J(>10 \text{ MeV}) < 10 \text{ particles/cm}^2\text{-s-sr} \)

16 Sep: launch operations start, launch approved for 21 Sep
21 Sep: scrub due to terrestrial weather
22 Sep: scrub due to range tracking radar hardware problems, next attempt deferred to 24 Sep
24 Sep: scrub due to solar proton event
25 Sep: scrub due to solar proton event, next attempt deferred to 27 Sep
27 Sep: scrub due to solar proton event, terrestrial weather, next attempt deferred to 29 Sep
29 Sep: attempt begins with radar issues and proton flux out of limits; radar problem is corrected
30 Sep: proton flux decreases to less than constraint value allowing launch at 02:40 UT on 30 Sep

\[ J(>10 \text{ MeV}) = 10 \text{ pfu} \]

http://www.spaceflightnow.com/athena/kodiakstar/status.html
Sardonia and Madura, 2002
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  – **Spacecraft charging effects**
  – Meteors and orbital debris
Surface charging

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

Internal (deep dielectric) charging

\[ \nabla \cdot D = \nabla \cdot \varepsilon E = \nabla \cdot \varepsilon (\nabla \phi) = \rho \]

\[ \nabla^2 \phi = -\frac{\rho}{\varepsilon} \]

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot J \quad \text{where } J = J_R + J_C \]

Inductive potentials

\[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{Laboratory frame} \]

\[ \vec{F}' = q\vec{E}' \quad \text{Spacecraft rest frame} \]

\[ \vec{E}' = \vec{E} + \vec{v} \times \vec{B} \quad \text{Forces equal in both frames!} \]

\[ \varepsilon_m = \oint_C \vec{E}' \cdot d\vec{S} = \oint_C (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S} \]

\[ \Delta \phi' = \oint_C (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{S} \]

Surface Charging Current Balance

Time dependent current balance

\[
\frac{dQ}{dt} = \frac{d\sigma}{dt} A = C \frac{dV}{dt} = \sum I_k = 0 \quad \text{at equilibrium}
\]

Currents

\[
\frac{dQ}{dt} = \sum I_k =
\]

+ \( I_{i}(V) \) incident ions

- \( I_{e}(V) \) incident electrons

+ \( I_{bs,e}(V) \) backscattered electrons

+ \( I_{c}(V) \) conduction currents

+ \( I_{se}(V) \) secondary electrons due to \( I_{e} \)

+ \( I_{si}(V) \) secondary electrons due to \( I_{i} \)

+ \( I_{ph,e}(V) \) photoelectrons

+ \( I_{b}(V) \) active current sources (beams, thrusters)
Secondary Electron Yields

Charging is suppressed when SEY > 1

\[
\frac{dQ}{dt} = \sum_k I_k = + I_i - I_e + I_{se} + I_{ph,e}
\]

\[
= + I_i - I_e (1 - \delta) + I_{ph,e}
\]

Sternglass, 1954

\[
\delta_e(E, \theta) = \delta_{e,\text{max}} \frac{E}{E_{\text{max}}} \exp(2 - 2 \sqrt{\frac{E}{E_{\text{max}}}}) \exp[2(1 - \cos \theta)]
\]

Katz et al., 1977; Whipple, 1981

\[
\delta_e(E, \theta) = \frac{1.114 \delta_{e,\text{max}}}{\cos \theta} \left[ \frac{E}{E_{\text{max}}} \right]^{-0.35} \left\{ 1 - \exp \left[ -2.28 \cos \theta \left( \frac{E_{\text{max}}}{E} \right)^{1.35} \right] \right\}
\]

\[\delta_m, E_m \text{ from Hasting and Garrett, 1996}\]
Photoemission Yields

- Photoemission is an important factor in controlling surface charging

<table>
<thead>
<tr>
<th>Material</th>
<th>Saturation Photocurrent Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>4.2 nA/cm$^2$</td>
</tr>
<tr>
<td>Au</td>
<td>2.9 nA/cm$^2$</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>2.0 nA/cm$^2$</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.4 nA/cm$^2$</td>
</tr>
</tbody>
</table>

[from Garrett, 1981]

All potentials in event | Maximum Potential | 1-10 nA/cm$^2$

[Grard, 1973]

[Minow et al., 2014]
“Ion Line” Charging Signature, $\phi_{s/c} < 0$

- Low energy background ions accelerated by spacecraft potential show up as sharp “line” of high ion flux in single channel

\[ E = E_0 + q\Phi \]

- Assume initial energy $E_0 \sim 0$ with single charge ions ($O^+, H^+$) and read potential (volts) directly from ion line energy (eV)

- Accuracy of potential measurement set by energy width and separation of the energy channels used to infer the potential

-646 volts
Van Allen Probe-A (GTO)
Los Alamos GEO Spacecraft

LANL 1989-046  6 June 1990

no charging

LANL 1989-046  23 March 1990

~ 8 kV in eclipse
~ 1 kV post midnight

During periods of significant hot plasma injection, spacecraft may become significantly charged relative to background plasma.
Surface charging anomalies typically occur in midnight to dawn local time sector where hot electrons are injected during geomagnetic substorms.

Record ATS-6 charging event $\Phi \sim -19$ kV
Auroral charging is controlled by
- Energy of primary electrons and secondary electron yields
- Density of ambient plasma (to balance auroral electron collection)

Examples of low Earth orbit charging in the auroral zone include
- DMSP ~830 km, 98 deg -10’s V > Φ > -1500 V
- Freja 590 km x 1763 km, 63 deg -10’s V > Φ > -3000 V
DMSP F16: -1000 V Charging Event
Fontheim Distribution

**Ambient background**
- n = 1.0e10 \(1/m^3\)
- Te = 0.2 \(eV\)

**Maxwellian**
- \(J_{max} = 4.0e-6 \ A/m^2\)
- \(T_e = 3.0e3 \ eV\)

**Gaussian (beam)**
- \(J_{gau} = 0.9e-4 \ A/m^2\)
- \(E_{gau} = 10.0e3 \ eV\) beam energy
- \(d_{gau} = 4.0e3 \ eV\) beam width

**Power Law**
- \(J_{pwr} = 3.0e-7 \ A/m^2\)
- \(\alpha = 1.15\) exponent
- \(E_1 = 50.0 \ eV\), first energy
- \(E_2 = 1.0e5 \ eV\), second energy

\[
\text{Flux} (E) = \frac{e}{\sqrt{2\pi\theta m_e}} \frac{E}{\theta} \exp\left(-\frac{E}{\theta}\right) + \pi \zeta_{max} E \exp\left(-\frac{E}{\theta_{max}}\right) + \pi \zeta_{gauss} E \exp\left(-\frac{(E_{gauss} - E)^2}{\Delta}\right) + \pi \zeta_{power} E^{-\alpha}
\]

[Davis et al., 2011]
Auroral Charging Conditions

Necessary conditions for high-level (≥100 V) auroral charging*

- No sunlight (or ionosphere below spacecraft in darkness)
- Intense electron flux >$10^8$ e/cm$^2$-s-sr at energies of 10’s keV
- Low ambient plasma density (<$10^4$ #/cm$^3$)


[Anderson, 2012]
Inverted V, Broadband Aurora
Launch Vehicle Surface Charging

- Charging time scales of \(~\text{seconds}\)
- Insulating materials on spacecraft surface increases threat of differential charging
- Are sensitive electronics located near the insulation materials?
- Will RF noise interfere with critical upcomm/downcomm transmissions?
- Will launch trajectory encounter regions of auroral charging threat?
- Will the encounter be in sunlight or darkness?

Anderson, 2012
Potential variations due to (a) $vxB.L$ (b) eclipse exit solar array (c) auroral charging
26 March 2008 -- Auroral Charging

~17 volts

ISS/FPMU 2008/03/26 (2008/086)

>30 keV electrons, 0 deg

26 Mar 2008 07:30 – 08:00 UT

[adapted from Craven et al., 2009]
9 March 2012

ISS crew imagery

\[ \Phi_{s/c} \]

\[ N_e \]

ISS030e131739
2012/03/09 15:52:06

mlat

12.0 12.4 12.8
Internal (Deep Dielectric) Charging

- High energy (>100 keV) electrons penetrate spacecraft walls and accumulate in dielectrics or isolated conductors
- Threat environment is energetic electrons with sufficient flux to charge circuit boards, cable insulation, and ungrounded metal faster than charge can dissipate
- Accumulating charge density generates electric fields in excess of breakdown strength resulting in electrostatic discharge
- System impact is material damage, discharge currents inside of spacecraft Faraday cage on or near critical circuitry, and RF noise

PMMA (acrylic) charged by ~2 to 5 MeV electrons
GOES Solar Cycle 21 Internal Charging Anomalies (GEO)

smoothed sunspot number

Day in solar rotation period


Black: GOES phantom commands

2-day fluence (F2) > 2 MeV electrons

Red: \[ F2 \geq 10^9 \text{ e}^-/\text{cm}^2\cdot\text{sr} \]
Amber: \[ 10^9 > F2 \geq 10^8 \text{ e}^-/\text{cm}^2\cdot\text{sr} \]
Green: \[ F2 < 10^8 \text{ e}^-/\text{cm}^2\cdot\text{sr} \]
White: no data

[adapted from Wrenn et al. 2002]
Launch Vehicle Internal Charging

- Charging time scales of ~hours to days (or even months), typically low threat for launch vehicles
- Multiple GTO phasing orbits or complete radiation belt transits should be evaluated as special cases
- Insulation on exposed or lightly shielded signal and power cables?
- Cryotank insulation, paints, decals?
- Are sensitive electronics located near the insulation materials?
- Will RF noise interfere with critical upcomm/downcomm transmissions?

[NASA-HDBK-4002a]
ESD Threat Threshold “Rule-of-Thumb”

10-hr fluence: \(2 \times 10^9 \text{ e/cm}^2\) \(2 \times 10^{10} \text{ e/cm}^2\)

Figure 7—IESD Hazard Levels versus Electron Flux (Various Units) (1)Frederickson (1992)
Trans-lunar and trans-Earth injection trajectories transit the radiation belts
TLI/TEI orbits are similar to the geostationary transfer orbit environments encountered by CRRES
- CRRES T~10 hours
  10 hours in radiation belt
- TLI/TEI T~8 days
  ≤4 hours in radiation belt

Basis of Fennell et al. [2000]
preliminary lunar phasing orbit bulk charging environment specification

- CRRESELE Ap dependent (a-c), worst case (d) orbit averaged environments
- Fennell et al. 2000 (e) lunar transfer orbit charging environment derived from directly from CRRES data analysis
Example: Orion Radiation Belt Transit

- NASA-HDBK-4002A recommended thresholds evaluated for flight periods of 2, 4, and 8 hours.

- SLS/Orion Design Specification for Natural Environments (DSNE) internal charging spec is an orbit averaged flux, needs to be multiplied by exposure period to evaluate internal charging threat.

- DSNE specifies no less than 4 hours.

- Design environment exceeds Internal charging threshold for energies less than a few MeV.

- Credible threat for internal charging requires additional analysis, testing.

<table>
<thead>
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<th>Energy (MeV)</th>
<th>Integral Flux (1/cm^2-sec)</th>
<th>2-hr Integral Fluence (1/cm^2)</th>
<th>4-hr Integral Fluence (1/cm^2)</th>
<th>8-hr Integral Fluence (1/cm^2)</th>
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</tbody>
</table>
NUMIT ("numerical integration") 1D Geometry

\[ \nabla \cdot D = \rho \\
D = \varepsilon E, \quad \varepsilon = \kappa \varepsilon_0 \\
\frac{\partial \rho}{\partial t} = -\nabla \cdot J \\
J = J_R + J_C = J_R + \sigma E \\
\sigma_{\text{radiation}} = k \left( \frac{d\gamma}{dt} \right)^\alpha \\
0.5 < \alpha < 1.0 \]

Siemen (S) = 1/Ω

<table>
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<tr>
<th>Parameter</th>
<th>Material</th>
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<th>2</th>
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<td>1x10^{-17}</td>
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<td>\alpha</td>
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<td>Thickness (cm)</td>
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</tbody>
</table>
Lunar Transit Environments Summary

Orbit:
250 km x 379,867 km
n degree inclination
n = 0°, 30°, 60°

Environment:
AE-8 solar max
Lunar Transit (Extreme) Environments Summary

Orbit:
250 km x 379,867 km
n degree inclination
n = 0°, 30°, 60°

Environment:
10x AE-8 solar max
Lunar Transit

- 30 deg inc
- AE-8 max
- Material 1
  \( \sigma \sim 10^{-15} \text{ S/m} \)
  \( \tau \sim 256 \text{ second} \)

Materials at fixed inclination 30 deg

Siemen (S) = 1/\( \Omega \)
- 30 deg inc
- AE-8 max
- Material 2
  \( \sigma \sim 10^{-17} \text{ S/m} \)
  \( \tau \sim 2.5 \text{ hours} \)

Materials at fixed inclination 30 deg
Lunar Transit

- 30 deg inc
- AE-8 max
- Material 3
  \( \sigma \sim 10^{-19} \text{ S/m} \)
  \( \tau \sim 31 \text{ days} \)

Materials at fixed inclination 30 deg
Lunar Transit Summary

- Maximum electric field magnitudes

![Graphs showing electric field magnitudes for Material 1, Material 2, and Material 3. Each graph plots the logarithm of the electric field magnitude (E/V m) against time (days), with data points labeled at 0 deg, 30 deg, and 60 deg.](image)
• 30 deg inc
• AE-8 max
• Material 4
  $\sigma \sim 10^{-18}$ S/m
  $\tau \sim 50$ hours

Materials at fixed inclination 30 deg

epoxy-fiberglass
  $k_p \sim 0$

[Rodgers et al., 2003]
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max
- $10 \times L \geq 2$
- Material 1
  - $\sigma \sim 10^{-15} \text{ S/m}$
  - $\tau \sim 256 \text{ seconds}$

Materials at fixed inclination 30 deg
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max
- $10x \ L \geq 2$
- Material 2
  - $\sigma \sim 10^{-17} \text{ S/m}$
  - $\tau \sim 2.5 \text{ days}$
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max
- 10x L ≥ 2
- Material 3
  \[ \sigma \sim 10^{-19} \, \text{S/m} \]
  \[ \tau \sim 31 \, \text{days} \]
• 30 deg inc
• AE-8 max
10x L ≥ 2
• Material 4
σ ~ 10^{-18} S/m
τ ~ 50 hours

Materials at fixed inclination 30 deg

k = 0
Lunar Transit (Extreme Environments)

- 30 deg inc
- AE-8 max
- $10 \times L \geq 2$
- Material 5
  $\sigma \sim 10^{-15} \text{ S/m}$
  $\tau \sim 256 \text{ seconds}$

Materials at fixed inclination 30 deg

Ambient
$T \sim 300K$
• 30 deg inc
• AE-8 max
  10x L ≥ 2
• Material 6
  $\sigma \sim 10^{-18}$ S/m
  $\tau \sim 256$ seconds

**Materials at fixed inclination 30 deg**

**Cryogenic**

$T \sim 100K$
• Todays presentation will discuss the impact of space weather on satellites with additional emphasis on launch vehicles

• Outline
  – General notes on space environments and effects
  – Environments of importance to satellites, launch vehicles
  – Ionizing radiation effects
  – Spacecraft charging effects
  – Meteors and orbital debris
Meteors and Orbital Debris

- Meteor and orbital debris impact on spacecraft and launch vehicles represent a small but potentially catastrophic risk.

- Other than large trackable debris items, the untrackable debris environment represents a “climatology” threat that is best mitigated by good design.

- Primary meteor threat is sporadic background, mitigated by design.

- Meteor showers and storms may exceed the sporadic rates and could be avoided by LV if necessary by scheduling launch to avoid high flux environment.

[B. Cooke, NASA Meteoroid Environment Office]
Questions?