Surface Charging Analysis of the Radiation Belt Storm Probes (RBSP) and Magnetospheric MultiScale (MMS) Spacecraft

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Spacecraft Surface Charging Analysis

- What surface potentials (chassis and differential) can be expected?
- How will these potentials change with sun direction and spacecraft operations?
- How will these surface potentials influence the measurements?
- Can differential potentials that are high enough to cause discharges occur?
Outline of Discussion

• Missions
  – Radiation Belt Storm Probes (RBSP)
  – Magnetospheric MultiScale (MMS)
• Surface potentials in magnetosphere
  – *Nascap-2k* models
  – Geosynchronous substorm
  – High secondary yield environments
  – Low temperature environments
  – Rotation
• Electric field measurements
  – Large scale potential variations
  – Spacecraft axial asymmetry
  – Contribution of differential potentials
• Conclusions
Missions

- **Radiation Belt Storm Probes (RBSP)**
  - Built by Johns Hopkins University Applied Physics Laboratory for NASA’s Living with a Star program
  - Pair of satellites
  - 2012 launch, two-year mission
  - 700 x 30,600 km, 10° inclination orbit
  - Includes electric field and low energy particle instruments
  - Spin rate of 5 RPM; spin axis 20° off sun-pointing

- **MultiScale Magnetosphere (MMS)**
  - Built by NASA/Goddard Space Flight Center
  - Four satellites in tetrahedral formation
  - 2014 launch, two-year mission
  - 1300 x 70,000 km (1.2 x 12 R_E), 28° inclination orbit; boosted to 1.2 x 25 R_E
  - Includes electric field and low energy particle instruments
  - Spin rate of 3-4 RPM; spin axis 2° from perpendicular to Earth-Sun line
Electrostatic Cleanliness

- **Environments**
  - Tenuous, hot plasma ($\sim 10^6$ m$^{-3}$, $\sim 10^4$ eV) near geosynchronous altitudes during substorms
  - Tenuous, moderate energy plasma ($10^4$ to $10^8$ m$^{-3}$, 1 to $10^4$ eV)
  - Dense, cold plasma ($\sim 10^{12}$ m$^{-3}$, $\sim 0.1$ eV for RBSP; $\sim 10^{10}$ m$^{-3}$; $\sim 1$ eV for MMS) near perigee

- **Surface potentials complicate measurements of electric fields and low energy particle fluxes**
  - Requirement for less than 1 V differential potential $\Rightarrow$ conductivity requirements
  - Almost all surfaces conductive and grounded
  - ITO coated solar cell coverglass
  - No exposed voltages; solar cell sides and interconnects covered
  - MMS has active ion beam to keep potential $\leq +4$ V, ASPOC

- **Region of scientific interest**
  - RBSP: entire orbit because mapping radiation belts
  - MMS: above 9 $R_E$ because interested in reconnection
Nascap-2k Models

- Include insulating surfaces, particle detectors, and the axial and magnetometer booms
- Very thin spin plane booms not in model
  - Introduce numeric difficulties
  - Estimate influence on axial electric field measurements
- MMS deployable truss axial booms modeled with solid booms
  - Use 0.1 m diameter to match capacitance
  - 0.1 m boom is 0.76 transparent to match collecting area
Magnetospheric Spacecraft Surface Charging

- Potential of each surface adjusts until net current is zero
- Absent barrier formation, insulators charge independently from chassis
- Sunlit surfaces positive to re-attract most ejected photoelectrons
  - See poster *Photoemission Driven Charging in Tenuous Plasma*
- For $30 \text{ eV} < \theta_e < 2000 \text{ eV}$, $-I_e + I_{sec} > 0$ for most materials, even shaded insulating surfaces at positive potentials
- Magnetospheric environments:
  - Geosynchronous substorm and other high temperature ($\theta_e > 2000 \text{ eV}$)
  - High secondary yield ($30 \text{ eV} < \theta_e < 2000 \text{ eV}$) (rare for RBSP)
  - Low temperature ($\theta_e < 30 \text{ eV}$)
Geosynchronous Substorm Differential Potentials

- Significant negative chassis charging will not occur in sunlight
- Shaded insulating surfaces may develop kilovolt differential potentials and possibly arc discharges
- Calculations were done for 15 minutes in very severe “NASA Worst Case” environment in sunlight and in eclipse

<table>
<thead>
<tr>
<th></th>
<th>Thickness (mm)</th>
<th>Sun Angle</th>
<th>Sunlit Potential (V)</th>
<th>Eclipse Potential (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMS Chassis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover</td>
<td>0.127</td>
<td>5°, 85°, shaded</td>
<td>+3.2 to -2900</td>
<td>-19,000</td>
</tr>
<tr>
<td>Connector</td>
<td>1.0</td>
<td>85° and shaded</td>
<td>-8000 to -12,000</td>
<td>-19,000</td>
</tr>
<tr>
<td>Foam</td>
<td>1.0</td>
<td>shaded</td>
<td>-12,000</td>
<td>-19,000</td>
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<tr>
<td>Sun Sensor</td>
<td>0.127</td>
<td>20°</td>
<td>+0.5</td>
<td>-22,000</td>
</tr>
<tr>
<td>Shaded Insulator</td>
<td>0.127</td>
<td>shaded</td>
<td>-4500</td>
<td>-22,000</td>
</tr>
<tr>
<td>RBSP Chassis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grout</td>
<td>0.635</td>
<td>20°</td>
<td>+0.4</td>
<td>-23,000</td>
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<tr>
<td>Sun Sensor</td>
<td>0.127</td>
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</table>

- Thick insulators and electrically isolated components of concern
- EMI shielding should be verified for discharges that may occur at the thickest insulators
High Secondary Yield Environments
(30 eV < $\theta_e$ < 2000 eV; MMS Only)

- MMS most often in environments with $-I_e + I_{sec} > 0$, so even shaded surfaces at positive potentials
- Without ASPOC ion beam, chassis potentials ~+40 V in very low density plasma of magnetotail
- Shaded insulators may differentially charge negative to remain near plasma ground
- Insulators may have differential potentials on the order of +10 V and -40 V without ASPOC and +50 V and -2 V with ASPOC
- Results consistent with experience

<table>
<thead>
<tr>
<th></th>
<th>Env 1</th>
<th>Env 2</th>
<th>Env 3</th>
<th>Env 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (eV)</td>
<td>350</td>
<td>2000</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal Current ((\mu\text{A} \text{ m}^{-2}))</td>
<td>80</td>
<td>6.0</td>
<td>0.93</td>
<td>0.008</td>
</tr>
<tr>
<td>Sunlit Chassis with ASPOC off (V)</td>
<td>2.3</td>
<td>3.4</td>
<td>7.6</td>
<td>42</td>
</tr>
<tr>
<td>Eclipse Chassis with ASPOC off (V)</td>
<td>N/A</td>
<td>2.6</td>
<td>N/A</td>
<td>3</td>
</tr>
<tr>
<td>Insulator with Normally Incident Sun (V)</td>
<td>3.3</td>
<td>3.2</td>
<td>14.8</td>
<td>56</td>
</tr>
<tr>
<td>Shaded Insulator (V)</td>
<td>3.1</td>
<td>1.7</td>
<td>3.1</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Low Energy Environments

- Below about 30 eV (depending on the material) few secondary electrons are ejected
- Shaded surfaces charge negative to repel plasma electrons
- Surfaces in wake of plasma flow have enhanced negative charging

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<th>RBSP</th>
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<tr>
<td></td>
<td>Plasma Plume 1</td>
<td>Plasma Plume 2</td>
</tr>
<tr>
<td>Temperature (eV)</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Thermal Current (µA m⁻²)</td>
<td>0.83</td>
<td>0.134</td>
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<tr>
<td>Sunlit Chassis with ASPOC off (V)</td>
<td>2.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Eclipse Chassis with ASPOC off (V)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Directly Sunlit Insulator (V)</td>
<td>1.3</td>
<td>8</td>
</tr>
<tr>
<td>Shaded Insulator (V)</td>
<td>-1.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>Insulator on Side (V)</td>
<td>-1.5 to 1.3</td>
<td>-1.5 to 6.7</td>
</tr>
</tbody>
</table>
Effect of Rotation (MMS)

- When rotation is included, surface potentials of thinner surfaces may not reach equilibrium values
- Electrically isolated and thick layers (Connector) reach equilibrium potential quickly
- Thin layers (Cover) reach equilibrium potential slowly
- Chassis held at 4 V by ASPOC
Electric Field from Surface Potentials

- Measured field is potential difference between two symmetrically opposite points, $E = \frac{\phi_2 - \phi_1}{\Delta}$
- Dipolar potential of value ±0.5 V

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<th>MMS</th>
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<tr>
<td>Radius of equivalent sphere (m)</td>
<td>0.96</td>
<td>1.4</td>
</tr>
<tr>
<td>Distance to electric field sensor (m)</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Potential at axial electric field sensor (mV)</td>
<td>±13</td>
<td>±4.1</td>
</tr>
<tr>
<td>Spacecraft electric field (mV/m)</td>
<td>2.2</td>
<td>0.26</td>
</tr>
<tr>
<td>Target axial field accuracy (mV/m)</td>
<td>4</td>
<td>1</td>
</tr>
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</table>

- A dipolar field can result from
  - Asymmetric charge on the spacecraft
    - Probably impossible to correct
  - Geometric asymmetry of a uniformly charged spacecraft
- Analytic result for 10-cm radius patch (300 cm²) differentially charged to 50 V (ignores spacecraft capacitance)

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<tr>
<td>Potential at axial electric field sensor (mV)</td>
<td>25</td>
<td>3.3</td>
</tr>
<tr>
<td>Spacecraft electric field (mV/m)</td>
<td>2.1</td>
<td>0.11</td>
</tr>
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Asymmetric Spacecraft Creates Dipolar Field

- **Source of axial asymmetry**
  - RBSP: Solar array panels
  - MMS: Spin plane booms 0.27 m above body center and magnetometer booms below center

- **Correction**
  - RBSP: Axial booms lengths to be adjusted on orbit
  - MMS: Bottom axial boom inset about 10 cm

- **Calculation**
  - Spin plane booms approximated by spheres with same potential and electric field at detector
  - Similar calculation for MMS shows ~25 cm inset needed; remaining field to be corrected for in data analysis
  - Assumes no debye shielding

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**RBSP Axial Electric Field as Function of Top Detector Position for +4 V chassis**

<table>
<thead>
<tr>
<th>Top Boom Length (m)</th>
<th>Without Boom Effect</th>
<th>With Boom Effect</th>
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<tbody>
<tr>
<td>5.5</td>
<td>-20</td>
<td>-15</td>
</tr>
<tr>
<td>5.7</td>
<td>-15</td>
<td>-10</td>
</tr>
<tr>
<td>5.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6.3</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>6.5</td>
<td>20</td>
<td>20</td>
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Insulators Have No Influence on Spin Plane Electric Field Measurements

- Solve Laplace’s equation for RBSP
  - 26.7 cm² shaded insulator at -1 kV; chassis at +0 V
  - Monopole boundary conditions on grid boundary
- Resulting difference at ends of spin plane booms
  - ~0.45 mV/80 m << 0.3 mV/m requirement
  - Results similar for MMS
Axial Booms Reduce Spacecraft-generated Field

- Analytic result for 300 cm$^2$ at 50 V

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- Laplace’s equation with spacecraft geometry gives potentials at axial electric field detectors
  - Calculation includes capacitance of all surfaces
- Spacecraft surfaces
  - Chassis at 0 V
  - RBSP: 0.06 m$^2$ at -50 V
  - MMS: 0.11 m$^2$ at -50 V
- Spacecraft-generated field
  - RBSP: 0.3 mV/m
  - MMS: 0.05 mV/m
- With debye screening, potentials will be smaller
Conclusions

• Computed RBSP and MMS surface potentials and consequences
• RBSP and MMS have a high degree of electrostatic cleanliness
• Surface potentials expected to have acceptable impact on measurements
• Surface potentials controlled by
  – Tenuous plasma => sunlit surfaces float positive
  – Dense plasma and shaded surfaces => negative potentials
  – \(-J_e + J_{sec} > 0\) => shaded surfaces +1 to +2 V
  – Low current => surface potentials never reach equilibrium
• Spacecraft axial asymmetry creates measurable axial field
  – Reduced by different length booms
• Differentially charged insulators create electric field
  – Spacecraft capacitance reduces field
  – \(0.1 \text{ m}^2 \Rightarrow E \ll \text{requirement}\)