SPENVIS Spacecraft Charging Tools

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Outline

• Introduction
• Overview SPENVIS S/C charging package
  – EQUIPOT: Surface charging of very simple s/c
  – SOLARC: Charging of solar panel
  – DICTAT: Internal charging
  – Environment models and charging data
• S/C charging in Next Generation SPENVIS
Introduction

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\[ J_{\text{net}}(V) = -J_e + J_i + J_{\text{be}} + J_{\text{se}} + J_{\text{si}} + J_{\text{pe}} + J_c \]

\[ C_A \cdot \frac{dV}{dt} = J_{\text{net}}(V) + \sigma \cdot V \]

Equilibrium: \( J_{\text{net}}(V_{eq}) = 0 \)
→ floating potential

secondaries (material dependent)
SPENVIS S/C Charging package

EQUIPOT (EQUilibrium POTential)
G.L. Wrenn & A.J. Sims, 1990
D. Rodgers, 2002 (update)

SOLARC (SOLar ARray interaction Code)
R. Bond, 1990

LEOPOLD (Low Earth Orbit and POLar environments Data)
R. Bond & T. Field, 1990

DICTAT (Dielectric Internal Charging Threat Assessment Tool)
D. Rodgers, 1999

ESPIRE suite (R. Bond, 1990)

GORIZONT/ADIPE & CRRES/LEPA Data bases

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EQUIPOT surface charging code

- No input orbit required
- 1D calculation of equilibrium potential of passive S/C
- No geometry effects
- LEO and GEO environments
- Inclusion of ram/wake effects and sunlight/eclipse status
- Version 1.3 in current SPENVIS
EQUIPOT GEOMETRY

S/C or structure = conducting sphere with radius = 1m
Patch = planar slab
EQUIPOT wake/ram effect at LEO

$V_{\text{ion}} < V_{s/c} < V_e$

→ Ions impact ram surface, $e^-$ everywhere
→ Negatively charged rear surfaces
→ Regions of differential charging

(G.B. Giffin, 1996)
EQUIPOT input (1): s/c environment

- **Spacecraft is in** sunlight
- Sun angle on isolated patch [deg]: 90.0

1. **Spacecraft environment**
   - Environment specification: ECSS worst case model (SCATHA)

2. **Incident distribution**
   - isotropic

3. **Environment type**
   - low altitude
   - high altitude

4. **ECSS worst case model (SCATHA)**
   - NASA guidelines worst case
   - NASA guidelines average GEO environment
   - Meteosat very disturbed
   - Meteosat very quiet
   - user defined

- **Thermal spectra**
  - Electrons
  - Density [cm⁻³], Temperature [eV]
  - 10, 1000

- **Ions**
  - Density [cm⁻³], Temperature [eV]
  - 10, 1000

- **Flux spectra**
  - Electron, Ion mass [amu]
  - Energy [eV], Flux [cm⁻² s⁻¹ e⁻¹]

- **Environmental effects**
  - Ram/wake effects:
  - Spacecraft altitude [km]: 500.0
  - Angle of attack [deg]: 90.0

- **Patch normal**
  - wrt patch normal
EQUIPOT input (2): material properties

Structure: aluminium
- Atomic number: 13
- Photoelectric current [A m⁻²]: 4.0E-5
- SEE yield for 1 keV protons: 0.244
- Proton energy for maximum SEE yield [keV]: 230

SEE formula: 
- Maximum SEE yield for electrons: 0.97
- Electron energy for maximum SEE yield [keV]: 0.3
- Stopping power fit: Katz

R₁ [Å]: 154
n₁: 1.8
R₂ [Å]: 220
n₂: 1.76

Structure: fixed potential
- Potential [V]: 0.0

Intermediate insulator
- Relative permittivity: 3.0
- Thickness [m]: 0.001
- Conductivity [ohm⁻¹ m⁻¹]: 1.0E-15
EQUIPOT outputs

- emission yields vs energy (eV)
- environment parameters vs. energy (eV)
- voltage and current vs. time
EQUIPOT: use and interpretation

- Rapid assessment of likelihood of charging for surface materials on s/c
- Identification of worst case situations
- Sensitivity study to small changes in environment and surface material properties:
  - estimate of error bars on the results of more complex charging codes
  - indicate where more accurate material data or plasma measurement must be made
- Conclusion:
  \[ |V_{eq}| < 100 \ \text{V} \quad : \quad \text{no serious charging problem} \]
  \[ 100 \leq |V_{eq}| \leq 1000 \ \text{V} \quad : \quad \text{appropriate design modification (after param. change)} \]
  \[ |V_{eq}| > 1000 \ \text{V} \quad : \quad \text{more detailed study is needed} \]
SOLARC Solar Array Analysis Programme

- Fast charging analyses of solar panel attached or not to a structure in LEO and Polar environments
- Version 2.00 in current SPENVIS

equilibrium at LEO dense plasma (from J-F Roussel 2002)
SOLARC input(1): plasma environment

input from e.g. LEOPOLED, IRI2001
SOLARC input(2): s/c configuration

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SOLARC output

Main outputs:

- current collected by the specified solar array and spacecraft surfaces;
- array and structure voltages relative to the ambient plasma potential (i.e. floating voltages);
- plasma current and power loss;
- erosion or sputtering of surfaces caused by energetic ion impingement.
DICTAT Internal charging code

- No input orbit required, but can be an input
- 1-D internal charging code calculating $E$ and $V$ due to penetrating electrons
- Fast, analytical transport equations
- Simulates dielectric + shielding
- Planar or cylindrical geometry
- Built-in FLUMIC environment model or user input
- Use: - Is dielectric safe or not to Electrostatic Discharge (ESD)?
  - If not which countermeasures?
- Version in current SPENVIS: 3.0
DICTAT Code logic

1. High energy electron flux spectrum
2. Electron transport through shielding
3. Current deposition in dielectric
4. Calculate \( E_{\text{max}} \)

- Shielding prop.
- Geometry Slab. coax
- Grounding scheme
- Sample temperature
- Exposure time

- Local environm.: \( T, \) radiation
- Radiation dose in dielectric
- Material props.: \( \sigma, \varepsilon, \) RIC, ...
- Breakdown threshold \( E_b \)

- No ESD
  - \( E_{\text{max}} < E_b \)
  - \( E_{\text{max}} > E_b \)
- ESD
  - Change shielding
  - Change dielectric

Tutorial

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DICTAT input(1): electron flux

**FLUMIC 3.0 omni + isotrop.**

**Only 1st segment**

**INTEGRAL spectrum**
- max. 30 pts
- E: 0.001-10 MeV
- F(E<E_{min}) = const
- F(E>E_{max}) = 0
- F(E_{min}<E<E_{max}): lin.int
- Omni: cm^{-2}s^{-1}sr^{-1}
- Mono: cm^{-2}s^{-1}
DICTAT input(2): geometry & mat. Props.

If omni

298-398 K

**$\varepsilon_r$**

$\sigma(J) = K_p (dD/dt) \Delta$

$\sigma(T) = a \cdot \exp(-bE_A/T)/T$

**$R = 0.55 \cdot E[1-0.9841/(1+3E)]$**

($E < 10$ MeV), $Z \leq 26$

**$E = J \cdot (1 - \exp(-t/\tau))/\sigma$**

$\tau = RC = \varepsilon/\sigma$
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**SPENVIS Spacecraft Charging Tools**

**DICTAT outputs**

**DICTAT v3.0 - Dielectric Internal Charging Threat Assessment Tool**

**Tutorial**

**User inputs were:**

1. Planar geometry
   - Dielectric grounded once at inner surface
   - Shield material: ALUMINIUM
   - Shield thickness: 1.0000E-03 cm
   - Isol. metal material: ALUMINIUM
   - Isol. metal thickness: 0.000 cm
   - Dielectric material: TEFLOX
     - density: 2.17 g/cm^3
     - conductivity: 1.00E-16 / (Ω m)
     - permittivity: 2.15
     - breakdown field: 1.00E+07 V/m
     - E_po: 2.00E-14
     - activation energy: 0.00 eV
   - Delta: 0.70
   - Dielectric thickness: 0.1000 cm
   - Surface charging potential 0.000 volts
   - Temperature: 295.0 K
   - Field of view: 90.0 degrees about normal
   - Flux isotropic
   - Model is FLNIVCS V3.6 19/11/03
   - Fraction of Solar cycle=0.000 Fraction of year=0.000
   - Using t-shell=1.50 and D/b=0.00 with duration 48.0 hours

2. At Equilibrium:
   - Charging current: 1.3153E-11 Amps/cm^2
   - E_max: 1.0000E+07 V/m Voltage=5644 Volts

3. After 48.0 hours:
   - Charging current: 1.3153E-11 Amps/cm^2
   - E_max: 1.0000E+07 V/m Voltage=5644 Volts

4. The dielectric is liable to experience breakdown
   - Maximum field is higher than Breakdown field
   - Maximum current incident on the component
   - Options to make the structure safe:
     - Reduce dielectric thickness to less than 9.00E-02 cm
     - Increase shield thickness to greater than 6.73E-03 cm

**E_max, V_s, J_tot ... vs. time**

**electron spectrum**
Environment and charging data

LEOPOLD:
- Low Earth environment (200-2000 km)
- density, temperature, velocity, flux, ...

<table>
<thead>
<tr>
<th>Altitude: 200.000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental characteristic</td>
</tr>
<tr>
<td>Neutral particle density</td>
</tr>
<tr>
<td>Electron density</td>
</tr>
<tr>
<td>Electron temperature</td>
</tr>
<tr>
<td>Ion temperature</td>
</tr>
<tr>
<td>Average ion mass</td>
</tr>
<tr>
<td>2.9896-26</td>
</tr>
<tr>
<td>Electron thermal velocity</td>
</tr>
<tr>
<td>Ion thermal velocity</td>
</tr>
<tr>
<td>Spacecraft circular velocity</td>
</tr>
<tr>
<td>Electron thermal particle flux</td>
</tr>
<tr>
<td>Ion ram particle flux</td>
</tr>
<tr>
<td>Electron saturation current density</td>
</tr>
<tr>
<td>Ion ram saturation current density</td>
</tr>
<tr>
<td>Debye length</td>
</tr>
<tr>
<td>Mass ratio</td>
</tr>
<tr>
<td>Dimensionless satellite velocity</td>
</tr>
<tr>
<td>Ion kinetic energy</td>
</tr>
<tr>
<td>Mach number</td>
</tr>
<tr>
<td>Mach angle</td>
</tr>
</tbody>
</table>
2 databases with charging events:

- Gorizont 91/2-ADIPE:

- CRRES-LEPA:

<table>
<thead>
<tr>
<th>Date</th>
<th>UT</th>
<th>LT</th>
<th>Data duration</th>
<th>Maximum Potential</th>
<th>Eclipse</th>
<th>Electron charging</th>
<th>Electron potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-NOV-91</td>
<td>14:30-15:00</td>
<td>19:40-20:20</td>
<td>15.86</td>
<td>600</td>
<td>No</td>
<td>Yes</td>
<td>200</td>
</tr>
<tr>
<td>11-MAR-92</td>
<td>17:00-19:30</td>
<td>22:20-00:50</td>
<td>23.54</td>
<td>10000</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>22-MAR-92</td>
<td>18:30-24:00</td>
<td>23:50-05:20</td>
<td>22.79</td>
<td>4000</td>
<td>Yes</td>
<td>Yes</td>
<td>300</td>
</tr>
<tr>
<td>24-MAR-92</td>
<td>16:00-19:30</td>
<td>21:20-00:50</td>
<td>23.32</td>
<td>3000</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>25-MAR-92</td>
<td>18:00-19:00</td>
<td>23:20-00:20</td>
<td>23.04</td>
<td>3000</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>27-MAR-92</td>
<td>22:00-24:00</td>
<td>03:20-05:20</td>
<td>16.04</td>
<td>800</td>
<td>No</td>
<td>Yes</td>
<td>300</td>
</tr>
<tr>
<td>28-MAR-92</td>
<td>22:00-23:30</td>
<td>03:20-04:50</td>
<td>23.40</td>
<td>1000</td>
<td>No</td>
<td>Yes</td>
<td>250</td>
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<tr>
<td>29-MAR-92</td>
<td>20:45-21:45</td>
<td>02:05-03:05</td>
<td>18.31</td>
<td>1000</td>
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<td>No</td>
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<tr>
<td>07-APR-92</td>
<td>16:30-19:15</td>
<td>21:50-00:35</td>
<td>23.22</td>
<td>3000</td>
<td>Yes</td>
<td>No</td>
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</tr>
<tr>
<td>08-APR-92</td>
<td>18:30-19:30</td>
<td>23:50-00:50</td>
<td>23.18</td>
<td>10000</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>24-AUG-92</td>
<td>00:00-02:00</td>
<td>05:20-07:20</td>
<td>28.62</td>
<td>1000</td>
<td>No</td>
<td>Yes</td>
<td>400+900</td>
</tr>
</tbody>
</table>
Electron spectrum: case a

- Data
- Double Maxwellian fit
- SCATHA Worst case

<table>
<thead>
<tr>
<th>Case a</th>
<th>Cold electrons</th>
<th>Hot electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-MAR-1992</td>
<td>( n_e ) (cm(^{-3}))</td>
<td>( T_e ) (keV)</td>
</tr>
<tr>
<td>16:18:52</td>
<td>1.368</td>
<td>0.216</td>
</tr>
<tr>
<td>Double Maxwellian Fit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCATHA Worst case</td>
<td>0.200</td>
<td>0.400</td>
</tr>
</tbody>
</table>
S/C charging in SPENVIS-NG

- DICTAT 4.0 (Jupiter)
- New/upgraded environment models
- Interfaces to charging tools from the “Energetic Electron Shielding, Charging and Radiation Effects and Margins” project
- Extension of database with charging events
- **Suggestions from YOU**
Bibliography

- **LEOPOLD:**

- **SOLARC:**

- **EQUIPOT:**

- **DICTAT:**

- Spacecraft Charging Standard (ECSS-E-ST-20-06C)
- Space engineering – Space environment (ECSS-E-10-04A)
Local time distribution of occurrences of static discharges, based on 122 reported events.
Radial extent shows relative number of events in each sector.
After Lam and Hruska, 1991, J. Spacecraft and Rockets
## Environment spectra

<table>
<thead>
<tr>
<th>Description</th>
<th>Thermal electron spectra</th>
<th>Thermal ion spectra</th>
<th>Electron flux spectrum</th>
<th>Ion flux spectra</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low altitude environments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRI at solar minimum, in winter, at 800 km, plus 10 kR aurora</td>
<td>1</td>
<td>3</td>
<td>yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>IRI at solar maximum, in summer, at 800 km, plus 10 kR aurora</td>
<td>1</td>
<td>3</td>
<td>yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Maxwellians for 1,000 km plus aurora</td>
<td>1</td>
<td>3</td>
<td>yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Auroral type spectra from DMSP</td>
<td>1</td>
<td>1</td>
<td>yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cold Maxwellians for ram test</td>
<td>1</td>
<td>1</td>
<td>no</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Test spectra and Maxwellians</td>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cold Single Maxwellian and Fontheim electrons</td>
<td>1</td>
<td>1</td>
<td>yes</td>
<td>none</td>
<td>Fonsheim et al., 1982</td>
</tr>
<tr>
<td>High altitude environments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECSS worst case model (SCATHA)</td>
<td>2</td>
<td>2</td>
<td>no</td>
<td>none</td>
<td>Gussenhoven and Mullen, 1983</td>
</tr>
<tr>
<td>NASA guidelines worst case</td>
<td>2</td>
<td>2</td>
<td>no</td>
<td>none</td>
<td>Mullen and Gussenhoven, 1982</td>
</tr>
<tr>
<td>NASA guidelines average GEO environment</td>
<td>2</td>
<td>2</td>
<td>no</td>
<td>none</td>
<td>Purvis et al., 1984</td>
</tr>
<tr>
<td>Meteosat very disturbed</td>
<td>none</td>
<td>none</td>
<td>yes</td>
<td>1</td>
<td>Wrenn and Johnstone, 1987</td>
</tr>
<tr>
<td>Meteosat very quiet</td>
<td>none</td>
<td>none</td>
<td>yes</td>
<td>1</td>
<td>Wrenn and Johnstone, 1987</td>
</tr>
</tbody>
</table>
Charging mechanism

- Incident Electrons
- Incident Ions
- Sunlight
- SHEATH
- Photo-emission
- Surface Charging
- Deep Dielectric Charging
- Conduction
- Back-scattered Electrons
- Reflected
- Isolated Conductor
- Structure 'GROUND' $V_0$
Earth regimes of concern for on-orbit surface (a) and internal (b) charging
(R.W. Evans et al., 1989)
Absolute charging (~s)

\[ V = V^+ + V^- \]

Differential charging (~min)

\[ V = V^+ + V^- = \text{array voltage} \]
FLUMIC 3.0

INNER BELT (L<2.5 R$_E$)

$>1$MeV Flux versus L profile

$F(>1$MeV,L) = 4.0 \times 10^{(2.12+4.54/L-0.05)/2-4.56/(L-0.05)/3)}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$

Spectrum

$F(>E)=F(>1$MeV) x exp(-(1-E)/E$_0)$

where $E_0 = 0.14$ MeV

B/B0

For $L < 3$ Flux = Flux(equatorial) x $10^{(a(B/B0)-1)}$

where $a = -0.4559 L+1.4385$ for L$\geq 1.75$

and $a = 36.1/(\sinh((L-1)x10)+0.7)$ for L$<1.75$

For $L \geq 3$ the formula of Vette [14] is used, as in AE8

OUTER BELT (L>2.5 R$_E$)

$>2$MeV Flux at L=6.6 R$_E$

The peak integral flux above 2 MeV at L=6.6 is taken to be $8 \times 10^9$ m$^{-2}$ s$^{-1}$ sr$^{-1}$.

Solar Cycle

$F(>E) = 8 \times 10^9 \times \{0.625-0.375 \sin[2\pi(fsc-0.7)]\}+0.125 \sin[4\pi(fsc-0.15)]$

where $fsc$ is the solar cycle phase starting at solar minimum.

Season

$F(>E) = 8 \times 10^9 \times \{0.625-0.375 \cos[4\pi (fsc+0.03)]\}+0.125 \cos[2\pi (fsc+0.03)]$

where $fsc$ is the fraction of year starting from 1st January.

Spectrum

$F(>E)=F(>2$MeV) x exp((2-E)/E$_0)$

where $E_0 = 0.25$ for $F(>2$MeV) $< 10^7$ m$^{-2}$ s$^{-1}$ sr$^{-1}$

and $E_0 = 0.25 \times 0.11((\log(F(>2$MeV)) - 7)$ for $F(>2$MeV) $> 10^7$ m$^{-2}$ s$^{-1}$ sr$^{-1}$.

$E_0$ in the outer belt is the subject of ongoing study and so this aspect of the model may be updated before the model is finalised.

Flux versus L profile

$F(>E,L) = F(>E,6.6) \times 10^{tanh(0.6(L-2.5))/cosh(1.5(L-4.3))}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$

where $F(>E,6.6) = F(foy,fsc) \times \exp([-2\times E]/E_0)$.

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Table 1. Summary of databases used for FLUMIC

<table>
<thead>
<tr>
<th>Database</th>
<th>Orbit</th>
<th>GTO with inclination of 7°</th>
</tr>
</thead>
<tbody>
<tr>
<td>REM</td>
<td>Data</td>
<td>Electron flux in three channels, 1-2.2 MeV, 2.2-4.6 MeV and 4.6-10 MeV</td>
</tr>
<tr>
<td>GOES</td>
<td>Data</td>
<td>Geostationary, with longitude around 75° and 135°</td>
</tr>
<tr>
<td>Data duration</td>
<td>More than a solar cycle</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Electron flux in two channels, &gt;0.6 MeV and &gt;2 MeV</td>
<td></td>
</tr>
<tr>
<td>SURF</td>
<td>Data</td>
<td>GTO, with inclination of 7°</td>
</tr>
<tr>
<td>Data duration</td>
<td>12 days, after which communication with the spacecraft was lost</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Electron current behind two levels of shielding, corresponding approximately to 1 MeV and 1.7 MeV</td>
<td></td>
</tr>
</tbody>
</table>

---

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DICTAT geometry
Algorithm for breakdown solution

1. The code first determines the critical current necessary to exactly reach the threshold field, based on Adamec's and Calderwood's [1975] equation (9) and stored values of the radiation-induced conductivity.
2. The ratio by which the actual current exceeds the critical current is found.
3. The existing shield thickness is multiplied by this ratio to give a second value of the shield thickness.
4. With this shield thickness, a second equilibrium electric field is found.
5. If the new electric field is not within 0.5% of the breakdown threshold, a third thickness is created based on a linear extrapolation or interpolation from the first two points.
6. If the electric field resulting from this thickness is not acceptably close to the breakdown threshold, a fourth point is created, based on linear extrapolation from the second and third points.
7. This process is continued until convergence is achieved and the final value is multiplied by 0.99 to ensure the result is between 1.5 and 0.5% below breakdown.