
Space Weather Week

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Hope to add more…
Provide satellite designers with a definitive model of the trapped energetic particle & plasma environment

- Probability of occurrence (percentile levels) for flux and fluence averaged over different exposure periods
- Broad energy ranges from keV plasma to GeV protons
- Complete spatial coverage with sufficient resolution
- Indications of uncertainty

<table>
<thead>
<tr>
<th>Satellite Hazard</th>
<th>Particle Population</th>
<th>Natural Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Charging</td>
<td>0.01 - 100 keV e⁻</td>
<td>Minutes</td>
</tr>
<tr>
<td>Surface Dose</td>
<td>0.5 - 100 keV e⁻, H⁺, O⁺</td>
<td>Minutes</td>
</tr>
<tr>
<td>Internal Charging</td>
<td>100 keV - 10 MeV e⁻</td>
<td>Hours</td>
</tr>
<tr>
<td>Total Ionizing Dose</td>
<td>&gt;100 keV H⁺, e⁻</td>
<td>Hours</td>
</tr>
<tr>
<td>Single Event Effects</td>
<td>&gt;10 MeV/amu H⁺, Heavy ions</td>
<td>Days</td>
</tr>
<tr>
<td>Displacement Damage</td>
<td>&gt;10 MeV H⁺, Secondary neutrons</td>
<td>Days</td>
</tr>
<tr>
<td>Nuclear Activation</td>
<td>&gt;50 MeV H⁺, Secondary neutrons</td>
<td>Weeks</td>
</tr>
</tbody>
</table>

Space particle populations and hazards
Summary of SEEWG, NASA workshop & AE(P)-9 outreach efforts:

<table>
<thead>
<tr>
<th>Priority</th>
<th>Species</th>
<th>Energy</th>
<th>Location</th>
<th>Sample Period</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Protons</td>
<td>&gt;10 MeV (&gt; 80 MeV)</td>
<td>LEO &amp; MEO</td>
<td>Mission</td>
<td>Dose, SEE, DD, nuclear activation</td>
</tr>
<tr>
<td>2</td>
<td>Electrons</td>
<td>&gt; 1 MeV</td>
<td>LEO, MEO &amp; GEO</td>
<td>5 min, 1 hr, 1 day, 1 week, &amp; mission</td>
<td>Dose, internal charging</td>
</tr>
<tr>
<td>3</td>
<td>Plasma</td>
<td>30 eV – 100 keV (30 eV – 5 keV)</td>
<td>LEO, MEO &amp; GEO</td>
<td>5 min, 1 hr, 1 day, 1 week, &amp; mission</td>
<td>Surface charging &amp; dose</td>
</tr>
<tr>
<td>4</td>
<td>Electrons</td>
<td>100 keV – 1 MeV</td>
<td>MEO &amp; GEO</td>
<td>5 min, 1 hr, 1 day, 1 week, &amp; mission</td>
<td>Internal charging, dose</td>
</tr>
<tr>
<td>5</td>
<td>Protons</td>
<td>1 MeV – 10 MeV (5 – 10 MeV)</td>
<td>LEO, MEO &amp; GEO</td>
<td>Mission</td>
<td>Dose (e.g. solar cells)</td>
</tr>
</tbody>
</table>

(indicates especially desired or deficient region of current models)

**Inputs:**
- Orbital elements, start & end times
- Species & energies of concern (optional: incident direction of interest)

**Outputs:**
- Mean and percentile levels for whole mission or as a function of time for omni- or unidirectional, differential or integral particle fluxes [#/cm² s or #/(cm² s MeV) or #/(cm² s sr MeV)] aggregated over requested sample periods
Adiabatic invariants:

– Cyclotron motion: \[ \mu = \frac{p^2}{2mB} = \frac{p^2 \sin^2 \alpha}{2mb} \]

– Bounce motion: \[ K = \int_{s_m}^{s_m'} [B_m - B(s)] ds \]

– Drift motion: \[ \Phi = \iint_{S_m} da \cdot B \quad \text{and} \quad L^* = \frac{2\pi M}{\Phi R_E} \]

Choose \((E, K, \Phi)\) coordinates

– IGRF/Olson-Pfitzer 77 Quiet B-field model

– Minimizes variation of distribution across magnetic epochs
LEO Coordinate System

- **Version Beta** \((\Phi, K)\) grid inadequate for LEO
  - Not enough loss cone resolution
  - No “longitude” or “altitude” coordinate
    - Invariants destroyed by altitude-dependent density effects
    - Earth’s internal B field changes amplitude & moves around
    - What was once out of the loss-cone may no longer be and vice-versa
    - Drift loss cone electron fluxes cannot be neglected
  - No systematic Solar Cycle Variation

- **Version 1.0** will splice a LEO grid onto the \((\Phi, K)\) grid at ~1000-2000 km
  - Minimum mirror altitude coordinate \(h_{\text{min}}\) to replace \(\Phi\)
  - Capture quasi-trapped fluxes by allowing \(h_{\text{min}} < 0\) (electron drift loss cone)
Sources of Uncertainty

Space weather

- Electrons > 2 MeV (GEO)
- Protons > 30 MeV (GEO)
- Sunspot Number (monthly ave)

Particle detectors

- Bremsstrahlung X-rays
- Nuclear activation γ-rays
- GEANT-4 MC simulation of detector response

- Imperfect electronics (dead time, pile-up)
- Inadequate modeling & calibration
- Contamination & secondary emission
- Limited mission duration

To the spacecraft engineer, uncertainty is uncertainty regardless of source.
**Architecture Overview**

**Satellite data**

**Satellite data & theory**

**User’s orbit**

**Flux maps**
- Derive from empirical data
- Create maps for median and 95th percentile of distribution function
  - Maps characterize nominal and extreme environments
- Include error maps with instrument uncertainty
- Apply interpolation algorithms to fill in the gaps

**Statistical Monte-Carlo Model**
- Compute spatial and temporal correlation as spatiotemporal covariance matrices
  - From data (Version Beta & 1.0)
  - Use one-day sampling time (Version Beta)
- Set up 1st order auto-regressive system to evolve perturbed maps in time
  - Covariance matrices gives SWx dynamics
  - Flux maps perturbed with error estimate gives instrument uncertainty

**User application**
- Runs statistical model N times with different random seeds to get N flux profiles
- Aggregates N profiles to get median, 75th and 90th confidence levels of flux & fluence
- Computes dose rate, dose or other desired quantity derivable from flux
# Data Sets

## Protons

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Protons Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO</td>
<td>0.10, 0.20, 0.40, 0.60, 0.80, 1.00, 2.00, 4.00, 6.00, 8.00, 10.0, 15.0, 20.0, 30.0, 50.0, 60.0, 80.0, 100.0, 150.0, 200.0, 300.0, 400.0, 700.0, 1200.0, 2000.0</td>
</tr>
<tr>
<td>MEO</td>
<td></td>
</tr>
<tr>
<td>HEO</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td></td>
</tr>
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## Electrons

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<tr>
<th>Orbit</th>
<th>Electrons Energy [MeV]</th>
</tr>
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<tbody>
<tr>
<td>LEO</td>
<td>0.04, 0.07, 0.10, 0.25, 0.50, 0.75, 1.00, 1.50, 2.00, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00, 5.50, 6.00, 6.50, 7.00, 8.50, 10.0</td>
</tr>
<tr>
<td>MEO</td>
<td></td>
</tr>
<tr>
<td>HEO</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
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## Plasma

<table>
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<tr>
<th>Orbit</th>
<th>Plasma Energy [keV]</th>
</tr>
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<tbody>
<tr>
<td>LEO</td>
<td>0.50, 1.00, 2.00, 4.00, 6.00, 12.00, 20.0, 40.0, 60.0, 80.0, 100.0, 150.0</td>
</tr>
<tr>
<td>MEO</td>
<td></td>
</tr>
<tr>
<td>HEO</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td></td>
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</table>
Building Flux Maps

Low resolution energy & wide angle detector?

Data collection ➔ Cross-calibration ➔ Sensor modeling ➔ Spectral inversion

Binning to model grid ➔ Angle mapping to $j_{90}$
Example: Proton Flux Maps

Time history data

Energy spectra

Flux maps (30 MeV)
Example: Electron Flux Maps

**Time history data**

- **Flux maps (2.0 MeV)**

- **Energy spectra**
  - 50th %
  - 95th %
  - 95th %

**Energy (MeV)**

- 50th %
- 95th %
Model Comparison: GPS Orbit

Electrons > 1 MeV

Comparison of AE9 mean to AE8

AE9 full Monte-Carlo – 40 runs
Data Comparison: GEO electrons
DSP-21/CEASE (Vβ.2)

0.125 MeV
DSP, >0.125 MeV electrons, 40 MC runs

0.55 MeV
DSP, >0.55 MeV electrons, 40 MC runs

1.25 MeV
DSP, >1.25 MeV electrons, 40 MC runs

10 year runs, 40 MC scenarios, 1 – 5 min time step
Summary

• AE-9/AP-9 will improve upon AE-8/AP-8 to address modern space system design needs
  – More coverage in energy, time & location for \textit{trapped} energetic particles & plasma
  – Includes estimates of instrument error & space weather statistical fluctuations

• Version Beta.3 now in limited distribution
  – Provides mean and Monte-Carlo scenarios of flux along arbitrary orbits
  – Dose calculations provided with ShieldDose utility
  – Includes historical AP8/AE8, CRRES and CAMMICE/MICS models
  – \textbf{NOT TO BE USED FOR SATELLITE DESIGN OR SCIENTIFIC STUDIES}

• Version 1.0 due in Fall 2011
  – Can be used for satellite design and science
  – Will be open distribution
  – Standard solar-cycle in Version 1.0+, release date TBD

• Version 2 will include much needed new data sets
  – Relativistic Proton Spectrometer and other instruments on NASA Radiation Belt Storm Probes giving complete radiation belt coverage (launch in ~2012)
  – Instruments on DSX will provide slot region coverage (launch ~2012)
  – Due two years after RBSP launch