AE9/AP9/SPM: New Models for Radiation Belt and Space Plasma Specification

05 May 2014

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Outline

• Introduction
• Overview of AE9/AP9/SPM
• Model Application
• Validation and Comparisons
• Current & Future Releases
• Summary
AE9/AP9/SPM is a suite of empirical models describing the trapped electron, proton, and plasma in the near earth space environment.

- AE9/AP9/SPM meets the satellite and space instrumentation design community’s need for radiation environment specification model
  - Responsive tool with expanded range of features not available with legacy models
  - Uses the most up-to-date data available
  - Introduces quantitative statistics for use in design efforts
Near-Earth Radiation Environment

- **Inner radiation belt:** protons + electrons
- **Outer radiation belt:** electrons
- **Lines of constant L value:**
  - 8
  - 7
  - 6
  - 5
- **South Atlantic Anomaly (SAA):** lowest altitude extent of inner radiation belt
Need for Accurate Near-Earth Radiation Environment Estimations

- Solar array power decrease
- False stars in star tracker CCDs
- Surface degradation
- EMP from vehicle discharge
- Electronics degradation
- Solar array arc discharge
- Spacecraft components become radioactive
- Single event effects in electronics: bit flips, fatal latch-ups

Energetic protons, electrons and plasma pose a wide range of hazards to spacecraft and components

These hazards are dynamic and sometimes not accurately captured in legacy models

For MEO orbit (L=2.2), years to reach 100 kRad:
- Quiet conditions (NASA AP8, AE8): 88 yrs
- Active conditions (CRRES active): 1.1 yrs

AE8 & AP8 under estimate the dose for 0.23” shielding
AE8 & AP8 electron and proton empirical models are the most widely used of the various legacy models

- These are capable models, but do not meet emerging needs of the design community

- AE8/AP8 lacked the ability to trade actual environmental risks like other system risks
  - AE8/AP8 could never answer questions such as “how much risk can be avoided by doubling the shielding mass?”

- Inaccuracies and lack of indications of uncertainty
  - Creates the necessity of excessive margin in designs

- No plasma specification
  - Unknown surface dose effects

- No natural dynamics
  - Not present are environments for internal charging or worst case proton effects, such as single event effects (SEEs)
AE9/AE9/SPM suite provides advanced capabilities for estimating the natural trapped radiation environment in near-Earth Space for satellite design.

- Unprecedented coverage in energies and particle types addressing major space environmental hazards
- Includes uncertainties and dynamics that have never been available for use in design
  - Data-based statistics quantifying uncertainties from both measurements and space weather variability
  - Estimate design margins (95th percentile rather than arbitrary factors)
- Dynamic scenarios allow users to create worst cases for internal charging, single event effects, and impacts on mission life
### AE9/AP9/SPM Suite Coverage

<table>
<thead>
<tr>
<th>MODEL</th>
<th>AE9</th>
<th>AP9</th>
<th>SPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>$\text{e}^{-}$</td>
<td>$\text{H}^{+}$</td>
<td>$\text{e}^{-}$, $\text{H}^{+}$, $\text{He}^{+}$, $\text{O}^{+}$</td>
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<tr>
<td>L Range</td>
<td>$0.98 &lt; L^* &lt; 12.4$</td>
<td>$0.98 &lt; L^* &lt; 12.4$</td>
<td>$2 &lt; L_m &lt; 10$</td>
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<tr>
<td>Energy Range</td>
<td>40 keV – 10 MeV</td>
<td>100 keV – 400 MeV (V1.0-V1.05) 100 keV – 2 GeV (V1.20)</td>
<td>$\text{e}^{-}$ : 1-40 keV $\text{H}^{+}$, $\text{He}^{+}$, $\text{O}^{+}$: 1.15 – 164 keV</td>
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</tbody>
</table>

- AE9/AP9 covers trapped radiation over full range of orbit regimes
- SPM introduces coverage of plasma energies and species
- AP9 V1.20 will extend energy range up to 2 GeV, based on Van Allen Probe observations
Range of Near-Earth Particle Hazards

**PARTICLE ENERGIES:**

- 1 eV
- 10 eV
- 100 eV
- 1 keV
- 10 keV
- 100 keV
- 1 MeV
- 10 MeV
- 100 MeV
- 1 GeV

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**AE9/AP9/SPM Suite Energy Range Coverage**

(trapped particles only)
The AE9/AP9/SPM suite is based on data sets mostly acquired after development of AE8 and AP8 and covers greater spatial and energy ranges than the prior models:

- Maps of the particle fluxes are created from these data sets.
- Estimates of uncertainties include both measurements uncertainties and space weather variability.

AE9/AP9/SPM incorporates 33 data sets measured by space-based sensors:

- Data sets were selected for accuracy in inner magnetosphere.
- Data during solar proton events were eliminated:
  - resulting maps describe trapped radiation only.
- Cross-calibration was done to a single standard sensor, both eliminating relative biases and providing estimates of measurement uncertainty.
Data Sets
Used for AE9/AP9/SPM

Most data sets used cover min+max solar cycle conditions

Will be used in future versions

AE9/ AP9/ SPM data sources

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## Examples of Future AE9/AP9/SPM Data Sets

### Key:
- **Electron Energies**
- **Proton Energies**
- **Ion Energies**

<table>
<thead>
<tr>
<th>Particle Energies</th>
<th>1 eV</th>
<th>10 eV</th>
<th>100 eV</th>
<th>1 keV</th>
<th>10 keV</th>
<th>100 keV</th>
<th>1 MeV</th>
<th>10 MeV</th>
<th>100 MeV</th>
<th>1 GeV</th>
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<tbody>
<tr>
<td><strong>SWx:</strong> Space Weather Experiment</td>
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<td><strong>WP1x:</strong> Wave Particle Interactions Experiment</td>
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<td><strong>LIPS:</strong> Low Energy Imaging Particle Spectrometer</td>
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<td><strong>HIPS:</strong> High Energy Imaging Particle Spectrometer</td>
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<tr>
<td><strong>HEPS:</strong> High Energy Proton Spectrometer</td>
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<td><strong>CEASE:</strong> Compact Environment Anomaly Sensor</td>
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<tr>
<td><strong>LCI FSH:</strong> Loss Cone Imager, Fixed Sensor Head</td>
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<tr>
<td><strong>LCI HST:</strong> Loss Cone Imager, High Sensitivity Telescope</td>
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<td><strong>CREDANCE:</strong> Cosmic Ray Environment Dosimetry and Charging Experiment</td>
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<td><strong>HOPE:</strong> Helium Oxygen Proton Electron</td>
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<td><strong>MagEIS:</strong> Magnetic Electron Ion Spectrometer</td>
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<tr>
<td><strong>REPT:</strong> Relativistic Electron Proton Telescope</td>
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<tr>
<td><strong>RPS:</strong> Relativistic Proton Spectrometer</td>
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<tr>
<td><strong>RBSPICE:</strong> RBSP Ion Composition Telescope</td>
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AE9/AP9/SPM Creates Flux Maps based on Satellite Data

- Creates maps for median and 95th percentile of distribution function
  - Maps characterizes both nominal and extreme environments
- Includes error maps with instrument uncertainty

Satellite data & theory

Statistical Monte-Carlo Model

- Compute spatial and temporal correlation as spatiotemporal covariance matrices
- Set up Nth-order auto-regressive system to evolve perturbed maps in time

User’s orbit

User application

- Runs statistical model N times with different random seeds to get N flux profiles
- Computes dose rate, dose or other desired quantity derivable from flux for each scenario
- Aggregates N scenarios to get median, 75th and 90th confidence levels on computed quantities
How to Use AE9/AP9

• Model provided with GUI and CmdLine access

• Specify input and options:
  • orbital elements or ephemeris
  • coordinate system
  • model(s) to use—AE9/AP9/SPM, legacy models
  • mode—e.g. mean or Monte Carlo scenarios

• Model provides requested quantities
  • fluxes, fluences, doses

• Results for appropriate modes include statistics (e.g. median and 95th percentile) for risk assessment
Model Comparison and Validation

Model comparisons and validations conducted:

- AE9/AP9/SPM results compared to legacy models including AE8/AP8
- AE9/AP9 results validated against independent LEO, HEO, GEO data sets
- Implementations of AE8/AP8 and SHIELDOSE within AE9/AP9 tool validated against results from SPENVIS and IRBEM
AE9/AP9 Compared to AE8/AP8

protons (30 MeV)

electrons (2 MeV)
AP9 Validation—POES 15 (LEO)

POES 15 observations, >36 MeV protons

AP9 median results, >36 MeV protons
AE9 Validation—GOES 10 (GEO)
AE9/AP9 Fluence and Dose Estimates, LEO (800 km)

Proton Mean Spectra - LEO2

Total Dose (Semi-Infinite Slab) - LEO2, AE9+AP9

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AE9/AP9/SPM Fluence Estimates, GEO

AE9, AE8, and SPME fluence vs. energy, GEO orbit, 1 year

- AE9 Monte Carlo, 95th %ile
- AE9 Monte Carlo, mean
- AE9 Monte Carlo, median
- AE8 max
- SPME pert mean, 95th %ile
- SPME pert mean, mean
- SPME pert mean, median

fluence (#/cm² MeV yr)

Energy (MeV)

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AE9/AP9 Dose Estimates, GTO

dose, GTO, 1 day

- AE9 median
- AE9 95th %ile
- AP9 median
- AP9 95th %ile
- AP8 max
- AE8 max

shielding depth (mm Al)
dose (rad S/day)
AE9/AP9/SPM
Current Version and Future Plans

• V1.0 released in 2012, current version V1.05 released in 2013
• AE9/AP9 proposed as an ISO standard trapped radiation model
• V1.2 features
  – New data: TacSat-4 protons, THEMIS plasma
  – New features: more orbit element/coordinate options, pitch angle tool
• V1.5 features
  – Parallelization capability for runs on clusters—needed to speed up long runs
  – New kernel-based effects calculation
  – New data: Van Allen Probe & Azur protons, Van Allen Probe & DEMETER electrons, SCATHA & AMPTE plasma
  – International collaborators on board and new model name: IRENE — International Radiation Environment Near Earth
• V2.0 and later features
  – Sample solar cycle flythrough option
  – New modules
  – New data: PAMELA, DSX/SWx, ERG
Kernel-Based Effects Calculation

- V1.5 will include AE9/AP9 capability to use independently-calculated radiation effects for faster effects results in the AE9/AP9 environment:
  - User precomputes desired effect vs. depth/particle/energy for a particular material/geometry/component, using independent particle simulation code
  - Results are formatted as a “kernel” for import into AE9/AP9/SPM
  - AE9/AP9/SPM environment plus effects kernel yields rapid calculations of specific effects

- Sample kernel for single event effects is in development
- Provides ability to rapidly obtain AE9/AP9 environment effects for specific components

Summary

• AE9/AP9/SPM meets the design community’s need for state-of-the-art radiation environment specification
  – More coverage in energy and location
  – Introduces statistics describing uncertainties and environment variability

• Plans are in place for future updates in both data and features
  – Architecture supports updates with new data
  – Future features will expanded capabilities, addressing additional hazards and more options for applying model results to design
Contact Information

- Comments, questions, etc. are welcome and encouraged!
- Please send feedback to (copy all):
  - Paul O’Brien, Aerospace Corporation, paul.obrien@aero.org
  - Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu
- Information and discussion forum available on NASA SET website:
- The model will eventually be available for web download
  - In the meantime contact Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu