The AE9/AP9 Radiation and Plasma Environment Models

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Outline

- Background on AE9/AP9/SPM model
- Summary of updates through V1.35
- Version 1.50 update
- Future version plans
- Dedicated web site for model distribution
What is AE9/AP9/SPM?

- AE9/AP9/SPM specifies the natural trapped radiation environment for satellite design and mission planning.
- It improves on legacy models to meet modern design community needs:
  - Uses 37 long duration, high quality data sets.
  - Full energy and spatial coverage—plasma added.
  - Introduces data-based uncertainties and statistics for design margins (e.g., 95th percentile).
  - Dynamic scenarios provide worst case estimates for hazards (e.g., SEEs).
  - Architecture supports routine updates, maintainability, third party applications.
- Version 1.00 released in 2012.
- Version 1.20 released in March 2015.
Coverage and Application

- Expanded energy coverage: keV plasma to GeV protons
- Spatial coverage for all orbit regimes, including tailored coverage for high resolution in LEO
- Model provided with GUI and CmdLine access
- Documentation includes recommended modes for typical use cases

<table>
<thead>
<tr>
<th>Model</th>
<th>AE9</th>
<th>AP9</th>
<th>SPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>e⁻</td>
<td>H⁺</td>
<td>e⁻, H⁺, He⁺, O⁺</td>
</tr>
<tr>
<td>Energies</td>
<td>40 keV—10 MeV</td>
<td>100 keV—2 GeV (V1.20)</td>
<td>1—40 keV (e⁻); 1.15—164 keV (H⁺, He⁺, O⁺)</td>
</tr>
<tr>
<td>Range in L</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>
</tr>
</tbody>
</table>
Data Sets—Temporal Coverage

Incorporates 37 data sets from 1976-2013

- Chosen for high quality and coverage
- 300+ instrument-years of data
- 10x more than AE8+AP8

All solar cycle phases sampled:
- 16 sets >10 yrs
- 26 sets >5 yrs

10x the data of previous models, and still growing!
Version 1.20 – Database Updates

- New data set (first new data to be added):
  - TacSat-4/CEASE proton data—captures new observations of elevated 1-10 MeV protons
  - Additional plasma data: THEMIS/ESA
- New electron templates
  - Improvements for inner zone electrons and for >3 MeV spectra
- New proton templates
  - Incorporate E/K/Φ and E/K/h_{min} profiles observed by Van Allen Probes/Relativistic Proton Spectrometer (RPS)
  - Extend proton energies to 2 GeV
- Low altitude taper
  - Force fast fall-off of flux for h_{min} < 100 km.
  - Cleans up radial scalloping at altitudes below ~1000 km
AP9 V1.20 Validation—SAA

>35 MeV protons
SAA flux profiles are improved in V1.20 as compared to POES observations

Ratio of AP9 V1.20 median to POES data

North-south profile

East-west profile

POES MEPE background
electron contamination
• Fixes Monte Carlo instability in AP9 V1.20
  – (AP9 MC Runs would “explode” after a few years)

• V1.30 updates Monte Carlo tables and algorithms to ensure long run fluence converges to perturbed mean

• Affects AE9 and AP9 Monte Carlo runs

• Mean and Perturbed Mean calculations are unchanged from V1.20 for AE9/AP9/SPM
• Released Jan 2017
• Supports parallelization
  – Uses MPI, supports multiple platforms and parallel environments
  – Use multiple cores on Windows via GUI
  – Use Linux Clusters via Command Line Utility
• Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times
• Better calculation of combined proton and electron dose confidence levels

• All flux and fluence results match V1.30*
  *(with some minor exceptions due to new numerics)*
## Forthcoming Versions

<table>
<thead>
<tr>
<th>Version</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>V1.50 (2017)</td>
<td>New data for electrons, protons</td>
</tr>
<tr>
<td>V1.55 (?) (2017-18)</td>
<td>Kernels for faster effects calculations</td>
</tr>
<tr>
<td>V2.00 (2018-19)</td>
<td>New architecture&lt;br&gt;New modules—solar protons, sample solar cycle&lt;br&gt;New data sets</td>
</tr>
<tr>
<td>V2.50 (?) (2019)</td>
<td>New data sets (DSX, ERG)</td>
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</tbody>
</table>
Changes in AE9/AP9 V1.50

- AP9 and AE9: new data from NASA's Van Allen Probes mission
- AP9: data added from Azur and TWINS 2
- AP9 and AE9: other revisions to flux maps (addressing gradients and other aspects of data set merging)
- Limited feature changes with this release—most significant will be new accumulator options (e.g., fluence accumulation intervals)

<table>
<thead>
<tr>
<th>satellite</th>
<th>orbit</th>
<th>time period</th>
<th>instrument</th>
<th>species</th>
<th>energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Allen Probes A &amp; B</td>
<td>GTO (800 x 30600 km, 10°)</td>
<td>Aug 2012 – Dec 2016</td>
<td>RPS (Relativistic Proton Spectrometer)</td>
<td>protons</td>
<td>&gt;58 MeV -- ~2 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>REPT (Relativistic Electron Proton Telescope)</td>
<td>protons</td>
<td>20 – 100 MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>electrons</td>
<td>1.5 – 30 MeV</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 keV – 7 MeV</td>
</tr>
<tr>
<td>Azur</td>
<td>384 x 3145 km, 103°</td>
<td>Nov 1969 – Mar 1970</td>
<td>EI-88 telescope</td>
<td>protons</td>
<td>1.5 – 104 MeV</td>
</tr>
<tr>
<td>TWINS 2</td>
<td>Molniya (1000 x 39500 km, 63°)</td>
<td>Apr 2008 – Nov 2016</td>
<td>HiLET</td>
<td>protons</td>
<td>6 – 30 MeV</td>
</tr>
</tbody>
</table>
V1.50 Changes – AP9 Flux Maps

- AP9 adds Azur, HiLET and Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Especially large changes >150 MeV where RPS data represent the first clean observations in the inner zone up to 2 GeV
V1.50 Changes – AP9 Dose

- Similar dose in HEO orbit
- Lower dose in GTO for depths >30 mils
- Lower dose in LEO for all depths
- Larger error bars in all orbits
AE9v 1.5 / AE9v 1.3

- AE9 adds Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Some localized higher fluxes
V1.50 Changes – AE9 in LEO

- Fluxes are higher <300 keV for both 1000 km orbits
- Fluxes are a bit higher at all energies in 800 km orbit
- Error bars are larger
• Starting with V1.50, AE9/AP9 now includes international contributions (Azur data)

• To recognize the internationalization of the model, we will begin transition to a new name: **International Radiation Environment Near Earth (IRENE)**

• AE9/AP9 v1.5 is then also known as AE9/AP9-IRENE

• We will use both names for a few releases, and eventually switch to IRENE only

• In addition to Azur data, ESA is working hard to produce a Monte Carlo solar proton model that we can integrate with AP9
Kernel-Based Effects Calculation

- Proton SEE rate calculation, proton displacement damage, electron internal charging currents, etc.

**Example: Proton SEE rate calculation**
- User provides Weibull or Bendel Parameters and desired shielding depths
- Utility computes “kernel” that transforms proton flux to SEE rate behind shielding
- Model will be able to output
  - Instantaneous SEE rate
  - Mission average SEE rate
  - Worst case SEE rate on desired timescale
Major feature changes:
- Sample solar cycle—introduces a full solar cycle reanalysis as a flythrough option
- New module frameworks for e.g. plasma species correlations, SPM stitching with AE9/AP9, auroral electrons, additional coordinates for MLT variation in SPM
- AP9 improvements: solar cycle variation in LEO, east-west effect
- Incorporate untrapped solar protons with statistics

New data
- Van Allen Probes/RPS, MagEIS & REPT protons and electrons
- PAMELA protons—addresses high energy proton spectra
- Other international data sets: possibilities include Cluster/RAPID-IIMS, ESA SREMs, CORONAS, NINA, Akebono/EXOS-D, SAC-C, Jason2, PROBA-V/EPT
AE9/AP9 Website

• We have launched a dedicated web site for the AE9/AP9 project hosted by AFRL’s Virtual Distributed Laboratory: https://www.vdl.afrl.af.mil/programs/ae9ap9

• The latest version of the model may be downloaded from this site after creating an account

• Summaries and model documentation are also available (no account needed)

• Future news and releases will be announced through the website
• AE9/AP9/SPM provides radiation environment specification to meet the needs of modern designers
• Successive releases demonstrate maintainability
• Future releases will include new data sets and new features, driven by user needs
• **Comments, questions, etc. are welcome and encouraged!**
• Please send feedback, requests for model or documentation, etc., to (copy all):
  – Paul O’Brien, Aerospace Corporation, paul.obrien@aero.org
• Model downloads, documentation, news are available at AFRL’s Virtual Distributed Laboratory: [https://www.vdl.afrl.af.mil/programs/ae9ap9](https://www.vdl.afrl.af.mil/programs/ae9ap9)
Backups
RPS at LEO

- For Sun Synch LEO (800 km)
  - RPS flux is slightly higher than AP9 up to 200 MeV
  - AP9 dose is about 25% less than RPS

- For High LEO (1000 km x 60°)
  - RPS and AP9 are in good agreement for flux and dose
Possible transient peaks in REPT data at $L^*=1.9-2.5$

REPT results generally consistent with AP9 V1.3
Azur Protons

- Review by ESA showed discrepancies among AP9, AP8, and data (including Azur).
- We extensively reviewed this issue, concluding:
  - Data currently in AP9 are reliable
  - AP9 model accurately represents these data sets
  - Azur data are also reliable
  - Most likely explanation: Azur represents a different climatological state than other data
  - Azur is ~4 months of data near solar max—used in developing AP8 MAX
- At largest L values (L~6), MagEIS climatology is similar to AE9
- MagEIS fluxes are lower at L~4 for E=100s of keV
  - This is likely due to lower-than-average activity state during Van Allen mission
What AE9/AP9 does

- AE9/AP9 is a statistical climatological model

- Most legacy models were static lookup tables of mean flux (compare to mean mode of AE9/AP9)

- Individual Monte Carlo scenarios in AE9/AP9 vary over time with perturbations reflecting both measurement uncertainty and climate variation

- Statistics from many MC scenarios thus give data-based confidence intervals
What AE9/AP9 doesn’t do

- AE9/AP9 does not vary with solar cycle phase—instead, the confidence intervals span the range of solar cycle states
  - It won’t provide results for a selected solar cycle state
  - It probably won’t match a data set from a portion of a solar cycle
- A given quality data set should lie within the range of AE9/AP9 statistics
- Legacy AE8/AP8 give a static answer for each of available activity levels—e.g. AP8 Min/Max
## Issues and Limitations

<table>
<thead>
<tr>
<th>model/ regime</th>
<th>issue in V1.3</th>
<th>expected improvements in V1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP9 in LEO, inner zone</td>
<td>Large uncertainties for E&gt;~100 MeV, leading to unrealistically large margins</td>
<td>Expected to be significantly addressed by including RPS data</td>
</tr>
<tr>
<td>AP9 and AE9 in LEO</td>
<td>Significant uncertainties in particle flux gradients for altitudes &lt;800 km</td>
<td>Should be improved in V1.5 with additional data and with modified templates to address gradients in merged flux maps; further improvement should come with solar cycle dependence of LEO protons in V2.0</td>
</tr>
<tr>
<td>AP9 in LEO</td>
<td>Large uncertainties for E&lt;20 MeV due to variability in satellite sensor data and sparse data coverage</td>
<td>Some improvement expected from inclusion of Azur and TWINS 2 data</td>
</tr>
<tr>
<td>AE9 in LEO, inner zone</td>
<td>Large uncertainties for all energies due to lack of observations uncontaminated by protons; Van Allen Probes have seen long periods with no electrons with E&gt;700 keV, and past measurements are ambiguous</td>
<td>Unknown if state during Van Allen mission is temporary or nominal; addition of Van Allen data should reduce median</td>
</tr>
<tr>
<td>AE9 in GEO</td>
<td>Fluxes are higher than IGE-2006 despite both models using LANL data</td>
<td>May be a difference in LANL data set versions used or a difference in intercalibrations; will seek to resolve by V1.5</td>
</tr>
<tr>
<td>AE9 and AP9, all regimes</td>
<td>No solar cycle dependence, particularly relevant to LEO protons and outer zone electrons; statistics span solar cycle states but a particular state can’t be queried</td>
<td>Will not be addressed in V1.5, although some data sets such as Azur should improve the range of solar cycle states represented; plan to address in V2.0 with solar cycle modulation of LEO protons and with the sample solar cycle</td>
</tr>
</tbody>
</table>