The AE9/AP9/SPM Radiation Belt and Space Plasma Specification Model

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Outline

• Background on AE9/AP9/SPM model
• Release of V1.30 with new data and features
• New validation results
• 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
- Version 1.30 released in February 2016
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
  - Best practices document with more details is forthcoming

<table>
<thead>
<tr>
<th>Model</th>
<th>AE9</th>
<th>AP9</th>
<th>SPM</th>
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<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; Lm &lt; 10</td>
</tr>
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</table>
Data Sets—Temporal Coverage

- **Protons**
  - CRRES/PROTEK
  - S3-3/Teloscope
  - IGO/Dosimeter
  - HEO-F3/Dosimeter
  - HEO-F1/Dosimeter
  - TSX-5/CEASE
  - POLAR/IPS
  - POLAR/HISTp
  - TACSAT-4/CEASE

- **Electrons**
  - CRRES/MEa/HEEP
  - IGO/Dosimeter
  - HEO-F3/Dos/Tel
  - HEO-F1/Dos/Tel
  - TSX-5/CEASE
  - POLAR/HISTe
  - GPS/BDD2 NS18
  - GPS/BDD2 NS24
  - GPS/BDD2 NS28
  - GPS/BDD2 NS33
  - LANL-GEO/SOPA 1989-046
  - LANL-GEO/SOPA 1990-095
  - LANL-GEO/SOPA LANL-97A
  - LANL-GEO/SOPA LANL-02A
  - SCATHA/SC3
  - SAMPEX/PET

- **Plasma**
  - POLAR/CAMMICE/MICS/HYDRA
  - LANL-GEO/MPA 1990-095
  - LANL-GEO/MPA 1991-090
  - LANL-GEO/MPA 1994-084
  - LANL-GEO/MPA LANL-97A
  - THEMIS A/ESA
  - THEMIS B/ESA
  - THEMIS C/ESA
  - THEMIS D/ESA
  - THEMIS E/ESA

*New in V1.20*

**AP8 released**

**AE8 released**

Distribution A: Approved for public release; distribution unlimited. OPS-16-12518
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 RBSP/Relativistic Proton Spectrometer
  - 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
V1.20 Feature Updates

• Feature improvements
  – More options for orbit element input and coordinates
  – Third party developers guide
  – Pitch angle tool—make internal pitch angle calculations accessible to users
  – More options for unidirectional flux queries
  – Easy extraction of adiabatic invariant coordinates
  – Improved error messages
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
AP9 Validation in LEO

- Review by ESA showed discrepancies among AP9, AP8, and data (including Azur)
- Extensive review by team:
  - We trust data currently in AP9
  - AP9 model accurately represents these data sets
  - We also trust Azur data
  - Most likely explanation: Azur and S3-3 represent two different geophysical states
  - We expect that inclusion of Azur data will decrease AP9 fluxes and increase error bars
  - Need to explain discrepancies and natural variability
AE9 GEO Issue

- AE9 is higher than IGE at GEO, looks like AE8
- One-year average of AE9 V1.20 calibrated LANL data are often well above IGE for same year
- All data were calibrated to CRRES MEA and HEEF
- In some K/L bins data spread is 100x across large energy range (typically larger K, lower pitch angle)
- It is not a simple calibration issue

LANL and IGE for Year 2003

Data spread is ~100x!
AE9 V1.20 Model Comparison

• Inner zone electrons at E>3 MeV are lower in V1.20 than V1.00
  – Result is more consistent with Van Allen Probe results
V1.20 GUI Patches

• GUI crashes when computing more than 5 scenarios
• GUI abandons IntegralPlasma calculation for long runs
• Patched in V1.20.004 release
Version 1.30 – Monte Carlo Fix

• 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
V1.30 Verification vs Matlab Prototype

- All tests completed. Except for Issues noted:
  - Obtained <1% discrepancy on all flux, fluence outputs
  - Obtained < 10% discrepancy on all dose rate, cumulative dose outputs

- Issue 1: Summing percentiles
  - Approximating percentiles of sum with sum of percentiles (same approach used for adding solar protons)
  - Better approach: do sums/integrals before computing percentiles
  - Affects IntegralPlasma utility and GUI plots/output of Proton+Electron Dose
  - Fix will typically reduce 95th percentile confidence limits
  - Resolution: Notify users. Fix in V1.35

- Issue 2: Position/Velocity Coordinates w/ Kepler propagator
  - C++ implementation of Kepler conversion from r,v to elements has a bug; a workaround via Two-Line Elements (TLEs) is used instead
  - Gives 0.2% difference from MATLAB Prototype in satellite locations, leading to larger discrepancies in flux
  - Acceptable: this level of detail is consistent with precision of TLEs, which are the de facto standard
  - Resolution: Notify users.

- Issue 3: Magnetic (adiabatic) coordinates output file shows small differences
  - Coordinates file outputs not being computed via same definitions as internal to model runs
  - Acceptable: magnetic coordinates are a diagnostic output, not part of satellite design spec
  - Resolution: Notify users. Fix in V1.35

- Issue 4: Uniform versus Gaussian perturbations to flux maps
  - V1.30.001 uses old algorithm (Gaussian) to perturb flux maps
  - Team believes new algorithm (Uniform) is better, and that’s what’s in our documentation
  - Fix will typically reduce 95th percentile confidence limits
  - Resolution: Notify users. Fix in next major release (V1.5)

- Notice to users sent 13 May 2016
## Next Versions

<table>
<thead>
<tr>
<th>Version</th>
<th>Details</th>
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| V1.35 (2016) | Permits parallelization across scenarios, improving run times  
• Useful for long mission MC runs  
• No change to model outputs from V1.30  
• Variable input cadence allowed in ephemeris files |
| V1.50 (2017) | New data: electrons, protons, and plasma  
New features: effects, more control of output cadence |
Version 1.35 – Coming Soon

- **Parallelization**
  - Uses MPI, supports multiple platforms and parallel environments
  - Use multiple cores on Windows via GUI
  - Use Linux Clusters via Command Line Utility

- More output options to reduce disk usage, improve performance

- Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times

- All flux, fluence and dose results will match V1.30
Version 1.5

• New data:
  – Protons: Azur, Van Allen/MagEIS & REPT, RPS, POES
  – Electrons: Van Allen/MagEIS & REPT
  – Plasma: SCATHA/SC8, AMPTE/CCE-CHEM, Van Allen/HOPE

• New features
  – Introduce kernel-based methods for fast dose/effects calculations
  – Allow selection of time period for calculation of fluence—supports different time periods for different effects
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
Version 2.0

• 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

• Subsequent releases will include new data: DSX/SWx, ERG

• Int’l. collaborators aboard and new model name: IRENE: International Radiation Environment Near Earth
• 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
Issues Noted by ESA

Issues identified by D. Heynderickx in V1.05 *

<table>
<thead>
<tr>
<th>model/ regime</th>
<th>issue</th>
<th>assessment</th>
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<tbody>
<tr>
<td>AP9 in LEO</td>
<td>SAA is too big/has wrong shape (fluxes do not fall off fast enough at SAA edges)</td>
<td>Known V1.05 issue, has been significantly addressed in V1.20</td>
</tr>
<tr>
<td>AP9 in LEO</td>
<td>Fluxes are higher than Azur data for E&lt;10 MeV; altitude gradients are different</td>
<td>Azur data is lower than other data sets, particularly S3-3 at these energies; don’t yet know if this is climatological or instrumental</td>
</tr>
<tr>
<td>AP9 in LEO</td>
<td>Energy spectra is more like a power law, not an exponential as in AP8 and data sets</td>
<td>AP9 template spectra are exponential; spectra in given flux map bins may be power law or exponential; still investigating</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; still investigating</td>
</tr>
</tbody>
</table>

* Not a comprehensive list—these were selected as more significant issues, other reported issues will be checked as well
International Collaboration Notes

• AFRL is investigating CRADA and other options:
  – Some AFRL agreements are with other countries’ defense departments, which doesn’t work in the case of ESA
  – CRADA may be a better option, still checking on this

• Anticipate including AZUR data in V1.5
  – What kind of review does ESA need to do before we can release V1.5?
  – As yet, AFRL does not have a formal agreement with ESA
  – AFRL will have to approve V1.5 for public release before sharing with ESA
  – After ESA approves V1.5, release to public
  – Same issue will apply to future releases

• Anticipate including ESA Solar Proton Model in future version
  – Expect AE9/AP9 team to re-implement solar proton model in C++
  – What verification does ESA want that C++ version is correct?
  – Suggested way forward:
    • ESA provides document describing model along with model parameters/data files
    • ESA provides verification cases to ensure close match of C++ version w/ ESA version
    • Optionally, ESA provides model source code for lower-level diagnosis of discrepancies
Summary

• AE9/AP9/SPM provides radiation environment specification to meet the needs of modern designers
• Release of Version 1.30 this year demonstrates 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
Thank You