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

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Hope to add more…
Outline

• Introduction & Background
• Architecture & Data
• Application
• Comparisons with AE8/AP8 and Data
• Future Plans
• Summary
Energetic Particle & Plasma Hazards

- Solar array power decrease due to radiation damage
- False stars in star tracker CCDs
  - No energetic protons
  - Many energetic protons
- Electronics degrade due to total radiation dose
- Single event effects in microelectronics: bit flips, fatal latch-ups
  - $1101 \Rightarrow 0101$
- Spacecraft components become radioactive
- Electromagnetic pulse from vehicle discharge
- Solar array arc discharge
- Surface degradation from radiation

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The Need for AE9/AP9

- Prior to AE9/AP9, the industry standard models were AE8/AP8 which suffered from
  - inaccuracies and lack of indications of uncertainty leading to excess margin
  - no plasma specification with the consequence of unknown surface dose
  - no natural dynamics with the consequence of no internal charging or worst case proton single event effects environments

- 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?”

Example: Medium-Earth Orbit (MEO)

System acquisition requires accurate environment specifications without unreasonable or unknown margins.
### Requirements

**Summary of SEEWG, NASA workshop & AE/AP-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>
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<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 [#/cm²s) or #/(cm²s MeV) or #/(cm²s sr MeV)] aggregated over requested sample periods
What is AE9/AP9?

- AE9/AP9 specifies the natural trapped radiation environment for satellite design
- Its unprecedented coverage in particles and energies address the major space environmental hazards
- AE9/AP9 includes uncertainties and dynamics that have never been available for use in design
  - The uncertainty allows users to estimate design margins (95 percentile rather than arbitrary factors)
  - Dynamic scenarios allow users to create worst cases for internal charging, single event effects, and assess mission life
- “Turn-Key” system for ingesting new data sets ensures that the model can be updated easily
- The model architecture and its datasets are superior to AE8/AP8 in every way
- V1.0 released 20 January 2012 to US Government and Contractors
- V1.0 cleared for public release on 5 September 2012 (Current version is 1.04)
Architecture Overview

**Satellite data**

**Satellite data & theory**

**User’s orbit**

**Flux maps**
- Derive from empirical data
  - Systematic data cleaning applied
- 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 (V 1.0)
  - Use one-day (protons) and 6 hour (electrons) sampling time (V 1.0)
- Set up Nth-order auto-regressive system to evolve perturbed maps in time
  - Covariance matrices give SWx dynamics
  - Flux maps perturbed with error estimate give instrument uncertainty

**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
## Data Sets – Energy Coverage

### Protons

<table>
<thead>
<tr>
<th>Orbit</th>
<th>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>
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<tr>
<td>MEO</td>
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<tr>
<td>HEO</td>
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<td>GEO</td>
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### Electrons

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Energy [MeV]</th>
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<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, 7.50, 8.50, 10.0</td>
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<tr>
<td>MEO</td>
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<td>HEO</td>
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<td>GEO</td>
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### Plasma

<table>
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<th>Orbit</th>
<th>Energy [keV]</th>
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<tbody>
<tr>
<td>LEO</td>
<td>H+, He+, O+</td>
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<tr>
<td>MEO</td>
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<tr>
<td>HEO</td>
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<tr>
<td>GEO</td>
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</tbody>
</table>

### Other Data Sets

- CRRES/PROTEL
- S3-3/Telescope
- ICO/Dosimeter
- HEO-F3/Dosimeter
- HEO-F1/Dosimeter
- TSX5/CEASE
- POLAR/IPS
- POLAR/HISTp
- POLAR/CAMMICE/MICS
- POLAR/HYDRA
- LANL GEO/MPA
- SAMPEX/PET
- SCATHA/SC3
- LANL GEO/SOPA

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## Data Sets – Temporal Coverage

<table>
<thead>
<tr>
<th>Data Set</th>
<th>LEO</th>
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<th>HEO</th>
<th>GEO</th>
<th>Temporal Coverage</th>
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<td>S3-3/Telescope</td>
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<td>ICO/Dosimeter</td>
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<td>TSX-S/CEASE</td>
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</table>

- **AP-8 released**: 1989
- **AE-8 released**: 1990
Coordinate System

- **Primary coordinates are** $E, K, \Phi$
  - IGRF/Olson-Pfitzer ’77 Quiet B-field model
  - Minimizes variation of distribution across magnetic epochs

- $(K, \Phi)$ grid is 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

- **Version 1.0 splices in a LEO grid onto the $(\Phi, K)$ grid at 1000 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)
  - $\min(h_{\text{min}})$ set to – 500 km
Building Flux Maps

Example for a dosimeter data set

Sensor 1 data → Cleaning → Cross-calibration → Spectral inversion → Angle mapping ($j_{90}$)

- Bootstrap initializing with variances
  - $50^{th}$ & $95\%$ Flux maps

- Flux map – sensor 1
- Flux map – sensor 2
- Flux – map sensor N

Sensor model

- Statistical reduction ($50^{th}$ & $95\%$ Flux maps)
- Template interpolation
Example: Proton Flux Maps

Time history data

Energy spectra

Flux maps (30 MeV)
Gallery of Mean Flux Maps

AE9 1 MeV

AP9 10 MeV

SPMH 36 keV

SPMO 40 keV

SPMHE 40 keV

SPME 40 keV

GEOC coordinates
• Primary product: AP9/AE9 “flyin()” routine modeled after ONERA/IRBEM Library
  – C++ code with command line operations
  – Input: ephemeris
  – Runs single Monte-Carlo scenario
  – Output: flux values along orbit
    • Unidirectional or Omnidirectional
    • Differential or Integral
    • Mean (no instrument error or SWx)
    • Perturbed Mean (no SWx)
    • Full Monte-Carlo
  – Wrappers available for C and Fortran
  – Source available for other third party applications on request (will be available on the web after public release clearance)
Software Applications (2)

• However… an application tool is provided to demonstrate completed capability
  – Accessible by command line or GUI interface
  – Contains orbit propagator, Monte-Carlo aggregator and SHIELDOSE-2 dose estimation applications
  – Contains historical models AE8, AP8, CRRESELE, CRRESPRO and CAMMICE/MICS
  – Provides simple plot and text file outputs
• We expect other developers to create new software tools incorporating the model
AP9/AE9 Code Stack

GUI input and outputs
– User-friendly access to AE-9/AP-9 with nominal graphical outputs

High-level Utility Layer
– Command line C++ interface to utilities for producing mission statistics
– Provides access to orbit propagator and other models (e.g. AP8/AE8, CRRES)
– Aggregates results of many MC scenarios (flux, fluence, mean, percentiles)
– Provides dose rate and dose for user-specified thicknesses (ShieldDose-2)

Application Layer
– Simple C++ interface to single Monte-Carlo scenario “flyin()” routines

AP9/AE9 Model Layer
– Main workhorse; manages DB-access, coordinate transforms and Monte Carlo cycles; error matrix manipulations

Low-level Utility Layer
– DB-access, Magfield, GSL/Boost
Run Modes

- **Static Mean/Percentile**
  - Flux maps initialized to mean or percentile values
  - Flux maps remain static throughout run
  - Flux output is always the mean or selected percentile
  - Percentiles are appropriate only for comparing with measurements at a given location

- **Perturbed Mean/Percentile**
  - Flux maps are initialized with random perturbations
  - Flux maps remain static throughout run
  - Multiple runs provide confidence intervals based on model uncertainties
  - Appropriate for cumulative/integrated quantities (e.g., fluence, TID)

- **Monte Carlo**
  - Flux maps are initialized with random perturbations
  - Flux maps evolve over time
  - Multiple runs provide confidence intervals including space weather (e.g., worst-case over specified time intervals)
  - Needed for estimate of uncertainty in time-varying quantities (e.g., SEE rates, deep dielectric charging)
What Type of Run

<table>
<thead>
<tr>
<th>Spec Type</th>
<th>Type of Run</th>
<th>Duration</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Dose</td>
<td>Perturbed Mean</td>
<td>Several orbits or days</td>
<td>SPME+AE9, SPMH+AP9+Solar</td>
</tr>
<tr>
<td>Displacement Damage (proton fluence)</td>
<td>Perturbed Mean</td>
<td>Several orbits or days</td>
<td>AP9+Solar</td>
</tr>
<tr>
<td>Proton SEE (proton worst case)</td>
<td>Monte Carlo</td>
<td>Full Mission</td>
<td>AP9+Solar</td>
</tr>
<tr>
<td>Internal Charging (electron worst case)</td>
<td>Monte Carlo</td>
<td>Full Mission</td>
<td>AE9 (no SPME)</td>
</tr>
</tbody>
</table>

- Run 40 scenarios through either static Perturbed Mean or dynamic Monte Carlo
- Compute statistics by comparing results across scenarios (e.g., in what fraction of scenarios does the design succeed)
- Do not include plasma (SPM*) models in worst case runs
AE9/AP9 Use Example: LEO Dipper

- A rarely-used mission orbit (150 x 1500 km, 83° inclination) required an analysis of trades between two hazardous environments:
  - Perigee dips at ~150 km yield intense atomic oxygen erosion of exposed polymers
  - Higher apogees expose the vehicle to radiation dose and SEE hazards from the inner Van Allen belt protons

- AE9/AP9 places the mission in the context of normal (blue) or extreme (red) radiation environments

- The AE9/AP9 environment percentiles informed the program of the margin they will have for EEE parts selection

AE9/AP9 allows new concepts to trade space environment hazards against other mission constraints.
MODEL & DATA COMPARISONS
Example—AP9 in LEO

Mean Spectra

Monte Carlo Spectra

20 MeV time series

36 MeV map

AP9 model vs. POES data
Example—AE9 in GEO

Mean Spectra

Monte Carlo Spectra

2 MeV time series

Compare to GOES >2 MeV fluence

10 years
AE9/AP9 Compared to AE8/AP8

Compared to AE8/AP8:

0.3 MeV

1 MeV

3 MeV

30 MeV
AE9-to-AE8 flux ratio

0.3 MeV

1 MeV
AP9-to-AP8 flux ratio

1 MeV

30 MeV
Known Issues—V1.0

• No reliable data for inner zone electrons at lower energy (<~ 600 keV)
  – Spectral and spatial extrapolation can lead to large deviations (e.g., comparison to POES and DEMETER data)
  – No worse than AE8

• No data for high energy protons (> 200 MeV)
  – No data – spectra are extrapolated based on physical models
  – The primary reason for flying the Relativistic Proton Spectrometer (RPS) on the Van Allen Probes

• SPMO (plasma oxygen) and SPME (plasma electron) have small errors which do not reflect the uncertainty in the measurements
  – Not much data (one instrument) with uncorrelated errors
  – Spectral smoothness was imposed at the expense of clamping the error bar

• Error in the primary variables $\theta_1$ (log 50th percentile) and $\theta_2$ (log 95th-50th percentile) capped at factor of 100 (electrons) and 10 (protons)
  – Large variations in these quantities can quickly lead to obviously unrealistic variations in fluxes derived from our assumed non-Gaussian distributions
  – Does not limit representation of space weather variation which is captured in $\theta_2$ (95th %)

RBSP/Van Allen Probe data will be incorporated into V2.0 and should address many of the V1.0 deficiencies
International Collaboration

• Boulder workshop October 2012
  – Proposed AE9/AP9/SPM as an ISO standard
  – Initiated participation from ESA, Russia, Japan
• Santorini Workshop June 2013
• Azur data
  – Obtained data set from Daniel Heynderickx
  – Will be incorporated into next release
• SPENVIS
• We invite additional collaboration
  – New data sets
  – Additional applications & functionality
• International collaboration on updates after V2.0, (as with IGRF, IRI)
• A new name?
  – SPARC -- Space Plasma And Radiation Climatology
  – IRENE -- International Radiation Environment Near Earth
  – ???
Recent AE9/AP9 Improvements

**CmdLineAe9Ap9 Program**
- Support more ShieldDose2 options
- Improved Linux compiler optimization settings
- Documented command-line options
- Multiple file limit resolved
- MJD conversion fixed

**User’s Guide Document**
- Additional information provided for
  - ShieldDose2 model parameters
  - Legacy model ‘advanced’ options
  - Model performance tuning
  - Orbit definition parameters
  - Coordinate system details
  - Modified Julian Date conversions

**Graphical User Interface**
- Clarified labels & error messages
- Added more ‘tooltip’ information
- Various GUI behavior fixes

**New Utility Programs**
- **PlasmaIntegral**
  - Adjusts Plasma integral flux calculations (for non-GUI runs)
- **CoordsAe9Ap9**
  - Calculates ‘Adiabatic Invariant’ coordinates from satellite ephemeris
Comparison of AE8/AP8 (legacy) models to external implementations

Model Run Parameters
- Ax8 in CmdlineAe9Ap9, IRBEM and SPENVIS
- CRRES satellite orbit (GTO)
- Fixed Epoch & Shift SAA options ‘on’
- 28 Feb 2005 (arbitrary), 24 hours, $\Delta t=120$ sec

Comparison Results
- Most model results *nearly* matching
  - Different magnetic field models used
- Integral Flux results match
- Differential Flux results near match
  - Differences due to calculation method
- ShieldDose2 results mostly match
  - Slight offset due to Diff Flux differences

Full report documents all findings
Future Versions

- One major pitfall of AE8/AP8 was the cessation of updates derived from new space environment data and industry feedback
- To insure that AE9/AP9 remains up to date and responsive to program evolution, the following actions must occur in 2013 to 2015:
  1. Complete full documentation of V1.0 and release underlying database
  2. Add these industry-requested capabilities: solar cycle dependence of LEO protons; a “sample solar cycle”; local time dependence of plasmas; longitude dependence of LEO electrons
  3. Ensure ongoing collection of new data to fill holes, improve accuracy, and reduce uncertainty (e.g. Van Allen Probes, with emphasis on inner belt protons; AFRL/DSX; TacSat-4, foreign and domestic environment datasets)
  4. Establish mechanism for annual updates to result in V2 in 2015
- NOAA/NGDC has offered to coordinate 5-year updates after 2015
  - NGDC hosted an international collaboration workshop for AE9/AP9 in October 2012

Keeping the model alive will insure that it stays in step with concerns in program acquisition and lessons from space system flight experience.
Version 1.1

- We recently identified an error affecting some cross calibrations in AE9
  - Incorrect data set version was used in CRRES to LANL-GEO cross calibration
- Result affects relative calibration of LANL-GEO/SOPA datasets, along with error estimates for LANL-GEO/SOPA, CRRES, and POLAR datasets
- Effect is likely small:
  - GEO flux ~20% greater for E>1 MeV
  - GEO flux ~20-50% less for E<0.5 MeV
  - Plot illustrates estimated effect on GEO spectra
- Expected public release in July 2013
Version 1.2

• New data set (first new data to be added):
  – TacSat-4/CEASE proton data—captures new of elevated 1-10 MeV protons
  – Additional plasma data, TBD but likely THEMIS/ESA

• New electron templates
  – Improvements for inner zone electrons and for MeV spectra

• Feature improvements
  – More options for orbit element input and coordinates
  – Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times
  – Allow selection of time period for calculation of fluence—supports different time periods for different effects
  – Mac OSX build

• Expected public release in January 2014
Version 1.5

• New data:
  – Protons: Azur, Van Allen/MagEIS & REPT
  – Electrons: DEMETER/IDP, Van Allen/MagEIS & REPT
  – Plasma: SCATHA/SC8, AMPTE/CCE & CHEM

• New features
  – Parallelization capability for runs on clusters—needed to speed up long runs
  – Pitch angle tool—make internal pitch angle calculations accessible to users

• Expected public release in October 2014

• International collaborators on board—with new model name
Version 2.0

• Major feature changes:
  – Standard 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
  – Improved algorithms for faster run times

• New data
  – Van Allen/MagEIS & REPT protons and electrons
  – PAMELA protons—addresses high energy proton spectra
  – Other international data sets: possibilities include Cluster/RAPID-IIMS, ESA SREMds, CORONAS, NINA, Akebono/EXOS-D, SAC-C, Jason2

• Expected public release in December 2015
• Subsequent releases will include new data
  – DSX/SWx, ERG
Summary

• AE9/AP9 improves upon AE8/AP8 to address modern space system design needs
  – More coverage in energy, time & location for trapped energetic particles & plasma
  – Includes estimates of instrument error & space weather statistical fluctuations
  – Designed to be updateable as new data sets become available

• Version 1.04 is now available to the public


• Updates are in the works
  – Improvements to the user utilities (no change to underlying environments)
  – Improvements to the model environments (new data)
  – Additional capabilities (new features, new models)

• For future versions collaborative development is the goal
  – Being proposed as part of new ISO standard
  – Discussions have begun on collaboration with international partners
Points of Contact

• 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:
• V1.0 code will eventually be available on the NASA SET website
  – In the meantime contact Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu
Thank You