AE9, AP9 and SPM: New Models of the Trapped Radiation and Space Plasma Environment

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JAXA, Japan
Hope to add more…
Outline

• Introduction
• Architecture & Data
• Application
• Future Plans
• Summary
Energetic Particle & Plasma Hazards

Solar array power decrease due to radiation damage

Single event effects in microelectronics: bit flips, fatal latch-ups

Spacecraft components become radioactive

False stars in star tracker CCDs

Electromagnetic pulse from vehicle discharge

Surface degradation from radiation

Electronics degrade due to total radiation dose

Solar array arc discharge

Induced Voltage

Time
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(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
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
- 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
Popoviciu et al. 2022

Analysis of Remote Sensing Data and Potential Applications in Agriculture

Distribution A. Approved for public release; distribution unlimited.
# Data Sets – Energy Coverage

## Protons

<table>
<thead>
<tr>
<th>Protons</th>
<th>Orbit</th>
<th>Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRRES/PROTEL</td>
<td>LEO</td>
<td>0.10, 0.20, 0.40, 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, 500.0, 600.0, 700.0, 1200.0, 2000.0</td>
</tr>
<tr>
<td>S3-3/Telescope</td>
<td>MEO</td>
<td>---</td>
</tr>
<tr>
<td>ICO/Dosimeter</td>
<td>HEO</td>
<td>---</td>
</tr>
<tr>
<td>HEO-F3/Dosimeter</td>
<td>GEO</td>
<td>---</td>
</tr>
<tr>
<td>TSX5/CEASE</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>POLAR/IPS</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>POLAR/HISTp</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

## Electrons

<table>
<thead>
<tr>
<th>Electrons</th>
<th>Orbit</th>
<th>Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRRES/MEA/HEEF</td>
<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>ICO/Dosimeter</td>
<td>MEO</td>
<td>---</td>
</tr>
<tr>
<td>HEO-F3/Dos/Tel</td>
<td>HEO</td>
<td>---</td>
</tr>
<tr>
<td>HEO-F1/Dos/Tel</td>
<td>GEO</td>
<td>---</td>
</tr>
<tr>
<td>TSX5/CEASE</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>POLAR/HISTe</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>GPS/BDDII</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>LANL GEO/SOPA</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SAMPEX/PET</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SCATHA/SC3</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

## Plasma

<table>
<thead>
<tr>
<th>Plasma</th>
<th>Orbit</th>
<th>Energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLAR/CAMMICE/MICS</td>
<td>LEO</td>
<td>H+, He+, O+</td>
</tr>
<tr>
<td>POLAR/HYDRA</td>
<td>MEO</td>
<td>e-, He+</td>
</tr>
<tr>
<td>LANL GEO/MPA</td>
<td>HEO</td>
<td>e+</td>
</tr>
<tr>
<td>POLAR/HYDRA</td>
<td>GEO</td>
<td>---</td>
</tr>
</tbody>
</table>
Data Sets – Temporal Coverage
Cross-calibration

• In-flight detector cross-calibration is used to estimate the measurement uncertainties
  – Building first-principle error budgets for detectors is complicated and often impossible
  – By looking at the same event cross-calibration can estimate and remove systematic error between detectors given a “standard sensor”
  – Residual random error for each detector then becomes the “detector error” used in AP9/AE9 development

• For protons (easier):
  – Look at simultaneous observations of solar proton events (SPEs) which provide a uniform environment at high latitudes and altitudes
  – Standard sensor = GOES8/SEM

• For electrons (harder):
  – No uniform solar “electron event” – need at least magnetic coordinate conjunction
  – Typical conjunction criteria: $\Delta L^* < 0.1$, $\Delta B/B_0 < 0.1$, $\Delta$UT < 4 hours, 4 < MLT < 8 or 16 < MLT < 20, Kp < 2 last 48 hours
  – Standard sensor = CRRES/HEEF-MEA
Electron Cross-Cal Tree

SCATHA/SC3

CRRES/MEA/HEEF

LANL-GEO/CPA 1981-025
LANL-GEO/CPA 1982-019
LANL-GEO/CPA 1984-037

LANL-GEO/SOPA 1990-095

LANL-GEO/CPEA 1984-129
LANL-GEO/SOPA 1991-080

LANL-GEO/SOPA 1989-046

GPS/BDDII ns18

TSX5/CEASE

GPS/BDDII ns24

SAMPEX/PET

GPS/BDDII ns28

LANL-GEO/SOPA LANL-02A
LANL-GEO/SOPA LANL-01A
LANL-GEO/SOPA LANL-97A
LANL-GEO/SOPA 1994-084

LANL-GEO/SOPA LANL-02A
LANL-GEO/SOPA LANL-01A
LANL-GEO/SOPA LANL-97A
LANL-GEO/SOPA 1994-084

GPS/BDDII ns33

S3-3/MES

POLAR/HISTe

Differential/Integral channels
- cross calibration links
- RMS error only
- cross calibration checks
- other cross calibrations
- AE9 data set

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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

50th & 95 % Flux maps

Flux map – sensor 1 ← Template interpolation ← Statistical reduction
(50th & 95 %)

Flux map – sensor 2

Flux map – sensor N

Flux – map sensor N
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
Software Applications

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

• 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
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</td>
<td>Perturbed Mean</td>
<td>Several orbits or days</td>
<td>AP9+Solar</td>
</tr>
<tr>
<td>(proton fluence)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton SEE</td>
<td>Monte Carlo</td>
<td>Full Mission</td>
<td>AP9+Solar (no SPMH)</td>
</tr>
<tr>
<td>(proton worst case)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Charging</td>
<td>Monte Carlo</td>
<td>Full Mission</td>
<td>AE9 (no SPME)</td>
</tr>
<tr>
<td>(electron worst case)</td>
<td></td>
<td></td>
<td></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
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

10 years

Compare to GOES >2 MeV fluence
AE9/AP9 Compared to AE8/AP8

- AE8 vs. AE9 at 0.3 MeV
- AP8 vs. AP9 at 0.3 MeV
- AE8 vs. AE9 at 1 MeV
- AP8 vs. AP9 at 1 MeV
- AE8 vs. AE9 at 10 MeV
- AP8 vs. AP9 at 10 MeV
- AE8 vs. AE9 at 30 MeV
- AP8 vs. AP9 at 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 (> 100 MeV)
  – No data – spectra are extrapolated
  – 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
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 2012 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. NASA/RBSP, 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.
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
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
• Version 1.0 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

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Backup slides
Coordinate System

- Previous models used $L$, $B/B_o$ coordinate space
- AP-9/AE-9 uses magnetic invariant coordinates: $E$, $K$, $\phi$
  - Uses IGRF/Olson-Pfitzer 77 Quiet B-field model
  - Minimizes variation of distribution across magnetic epochs
- The $K$, $\phi$ grid is spliced with a $K$, $h_{\text{min}}$ grid to cover LEO (below ~1000-2000 km)
  - Provides better loss cone resolution
  - Addresses loss of invariants from interaction with atmosphere in LEO
  - Captures quasi-trapped fluxes in electron drift loss cone by allowing $h_{\text{min}}<0$ (to -500 km)

Use of invariant coordinates plus separate LEO grid provides increased capabilities
To obtain percentiles and confidence intervals for a given mission, one runs many scenarios and post-processes the flux time series to compute statistics on the estimated radiation effects across scenarios.