AE9/AP9/SPM Overview

February 2017

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Integrity ★ Service ★ Excellence

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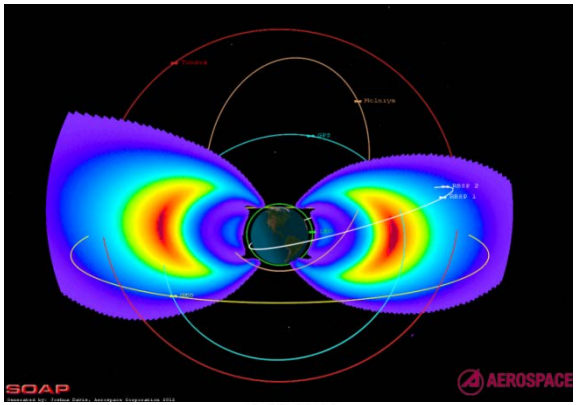
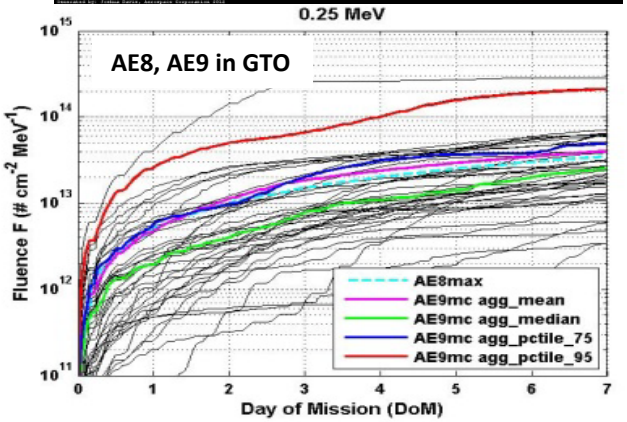
Outline

- Background on AE9/AP9/SPM model
- Summary of updates through V1.35
- 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



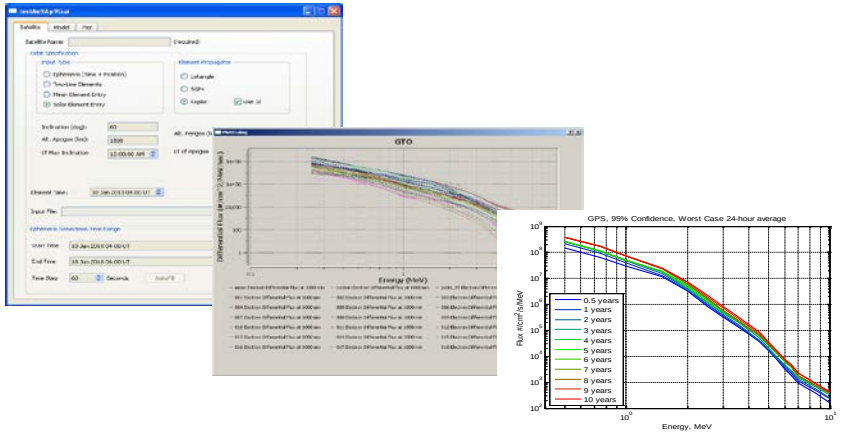


Coverage and Application

- 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

Model	AE9	AP9	SPM
Species	e^-	H^+	e^-, H^+, He^+, O^+
Energies	40 keV—10 MeV	100 keV—2 GeV (V1.20)	1—40 keV (e^-); 1.15—164 keV (H^+, He^+, O^+)
Range in L	$0.98 < L^* < 12.4$	$0.98 < L^* < 12.4$	$2 < L_m < 10$



Data Sets—Temporal Coverage

Incorporates 37 data sets from 1976-2013

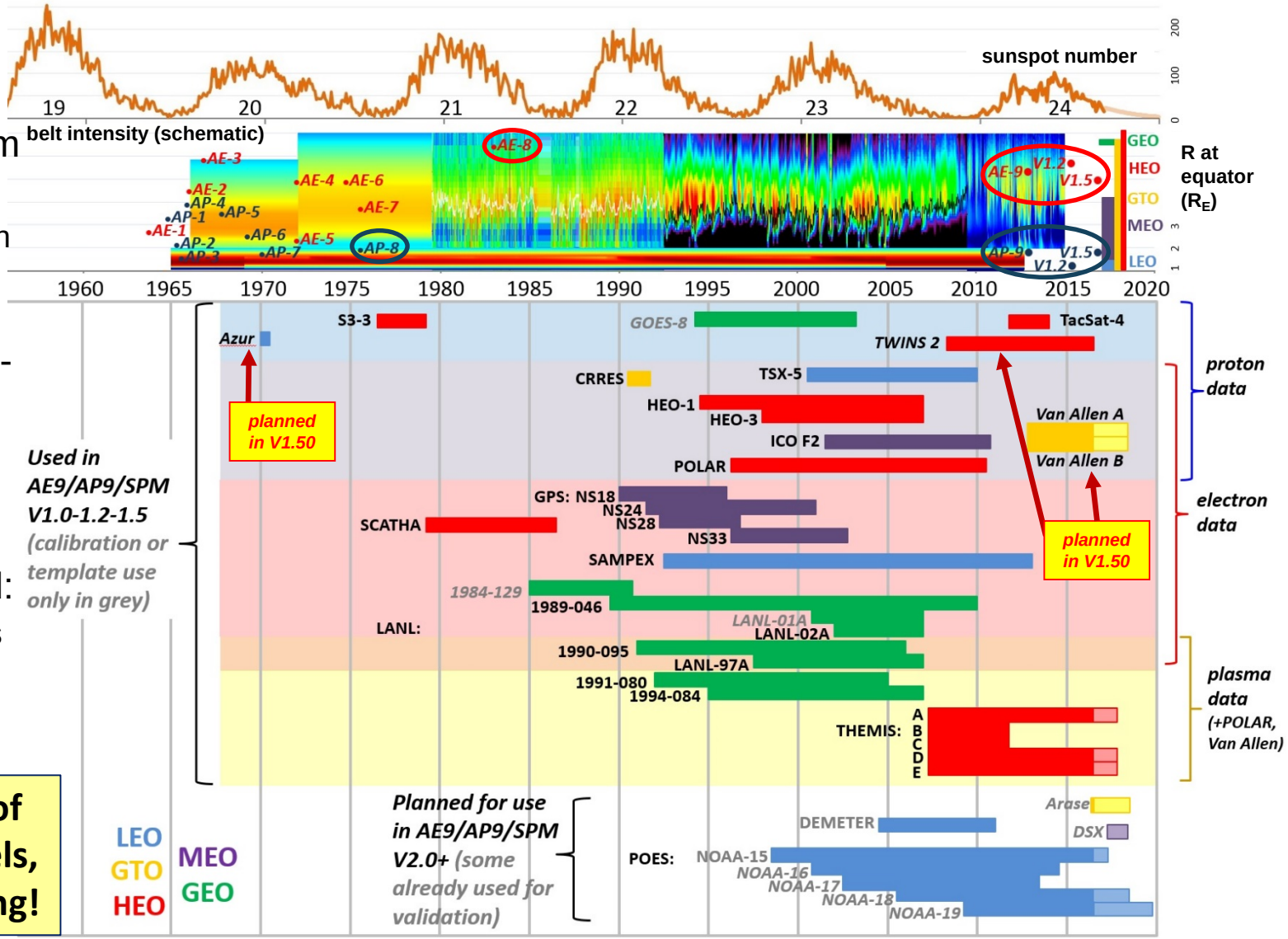
- Chosen for high quality and coverage

300+ instrument-years of data

- 10x more than AE8+AP8

All solar cycle phases sampled:

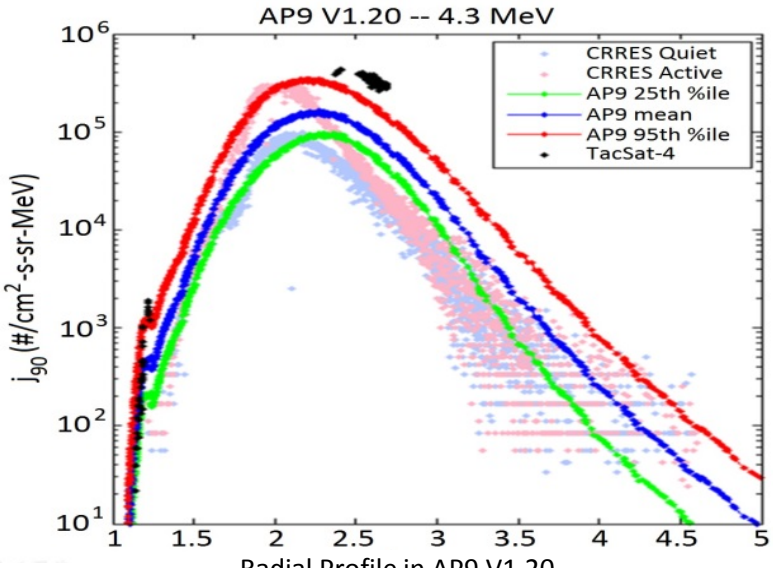
- 16 sets >10 yrs
- 26 sets >5 yrs



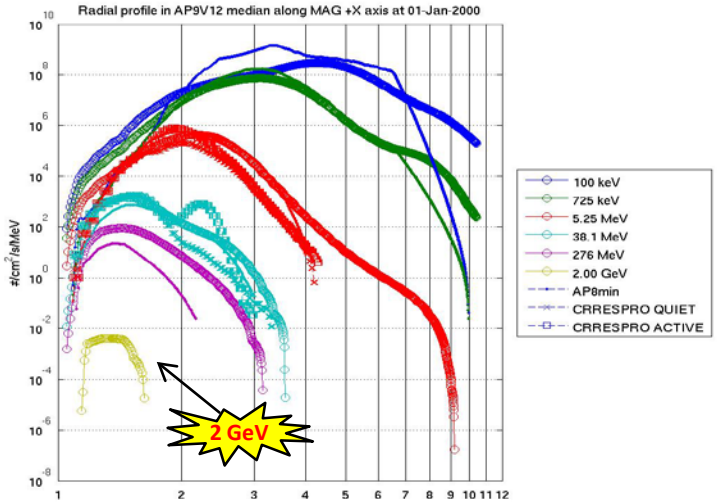
10x the data of previous models, and still growing!

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



Radial Profile in AP9 V1.20

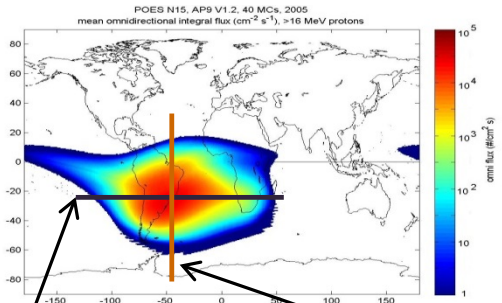


Radial Distance along +X MAG

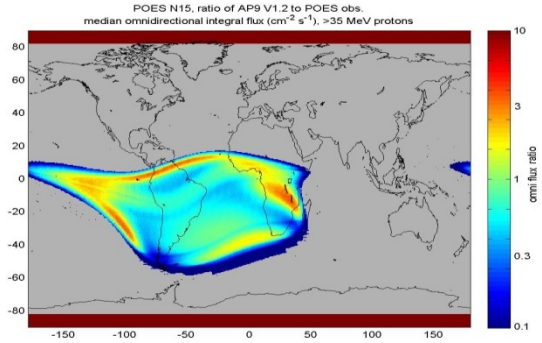
AP9 V1.20 Validation—SAA

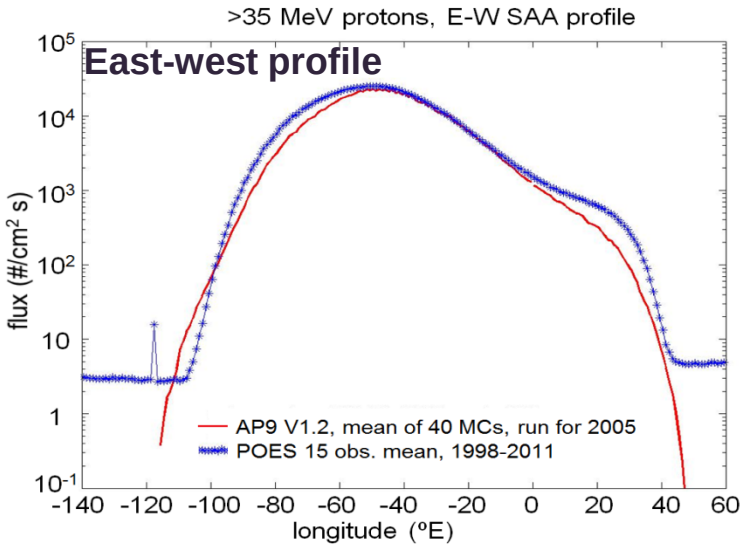
>35 MeV protons

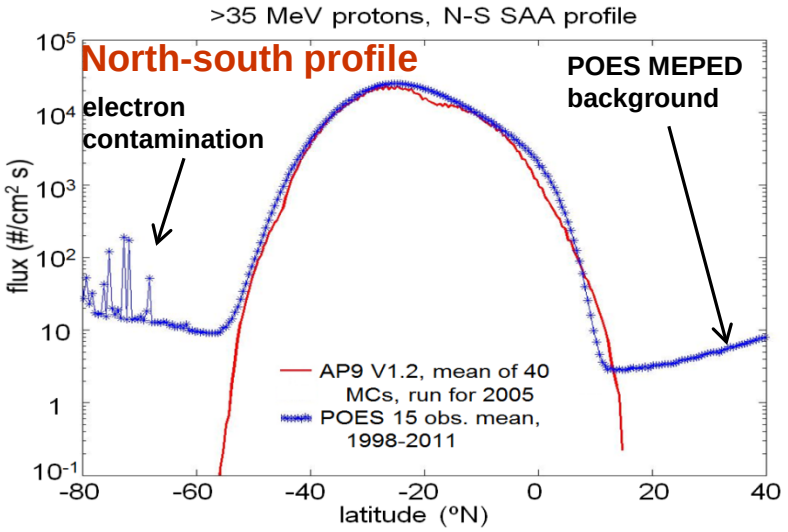
SAA flux profiles are improved in V1.20 as compared to POES observations



Ratio of AP9 V1.20 median to POES data



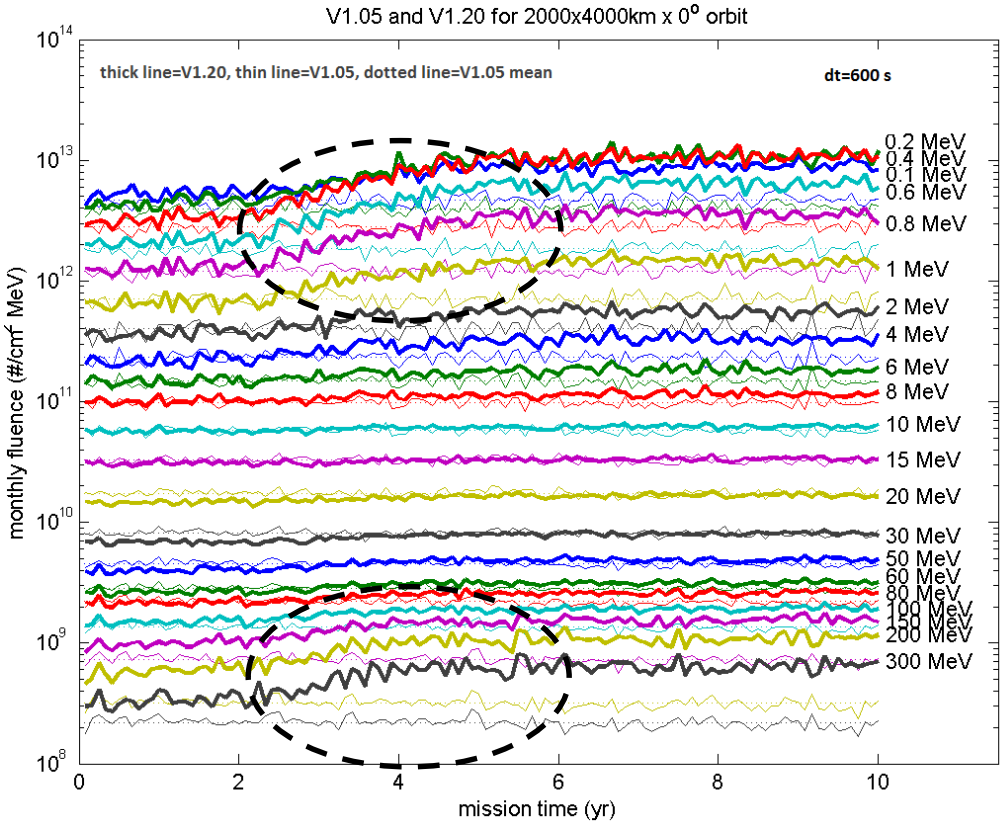




Version 1.30 – Monte Carlo Fix

- 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

- <u>Mean and Perturbed Mean calculations are unchanged from V1.20 for AE9/AP9/SPM</u>



Version 1.35

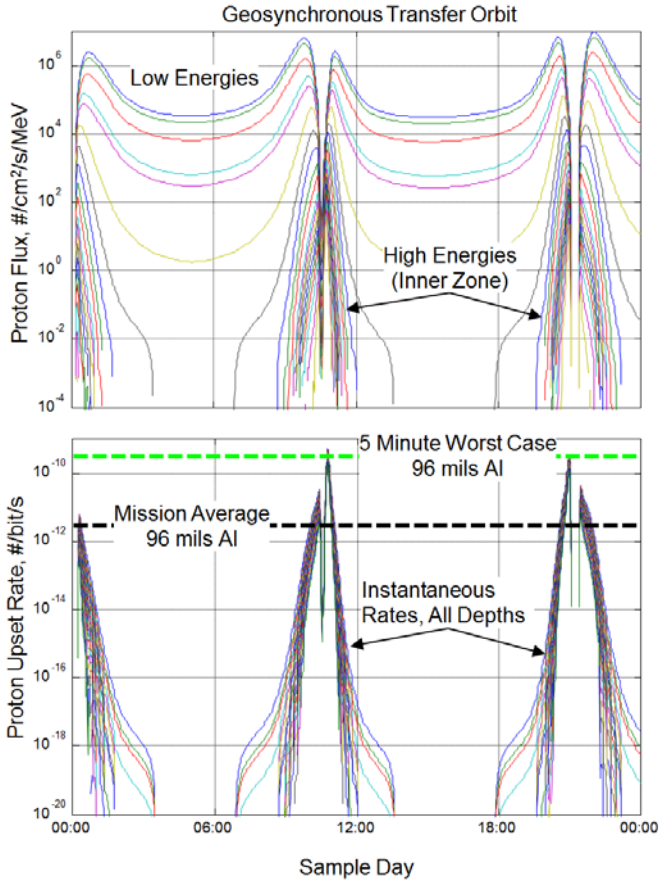
- Released Jan 2017
- Supports parallelization
  - Uses MPI, supports multiple platforms and parallel environments
  - Use multiple cores on Windows via GUI
  - Use Linux Clusters via Command Line Utility
- Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for 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

V1.50 (2017)	New data for electrons, protons (next talk)
V1.55(?) (2017)	Kernels for faster effects calculations
V2.00 (2018)	New architecture New modules—solar protons, sample solar cycle New data sets
V2.50(?) (2019)	New data sets (DSX, ERG)

Kernel-Based Effects Calculation



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

Example: Proton SEE rate calculation

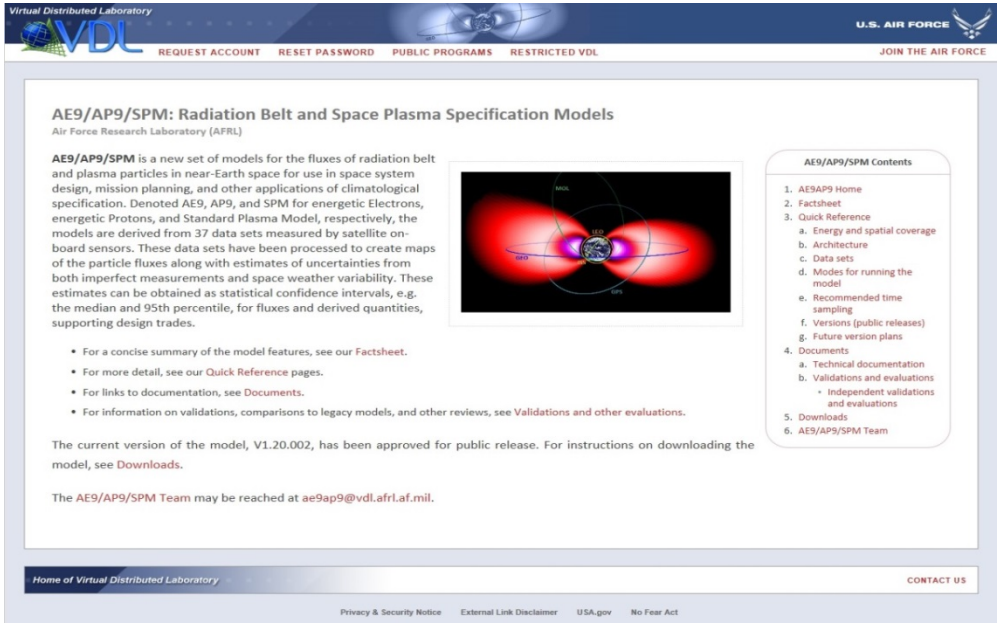
- User provides Weibull or Bendel Parameters and desired shielding depths
- Utility computes "kernel" that transforms proton flux to SEE rate behind shielding
- Model will be able to output
  - Instantaneous SEE rate
  - Mission average SEE rate
  - Worst case SEE rate on desired timescale

Version 2.00

- 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
- Int'l. collaborators aboard and new model name:
  IRENE: **I**nternational **R**adiation **E**nvironment **N**ear **E**arth

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



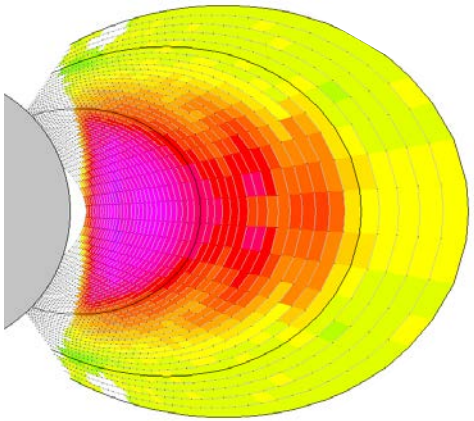
Summary

- AE9/AP9/SPM provides radiation environment specification to meet the needs of modern designers
- Successive releases (Version 1.35 this year) 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):
  - Bob Johnston, Air Force Research Laboratory, AFRL.RVBXR.AE9.AP9.Org.Mbx@us.af.mil
  - 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**

Backups

AE9/AP9 Architecture

Satellite data



Flux maps

- Derive from empirical data
- Apply methods to fill in gaps
- Create maps of nominal and extreme environments
- Capture instrument uncertainty in error maps

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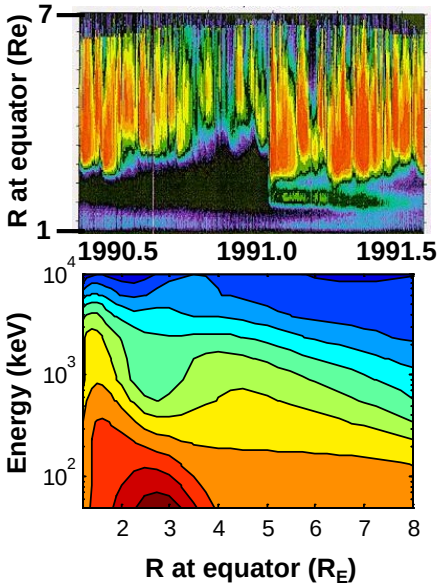
Satellite data & theory



Statistical Monte-Carlo Model

- Compute spatial-temporal correlations
- Set up to evolve perturbed maps in time
- Covariance matrices give SWx dynamics
- Flux maps perturbed with error estimates give instrument uncertainty

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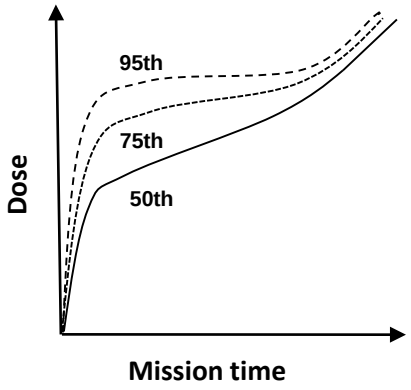
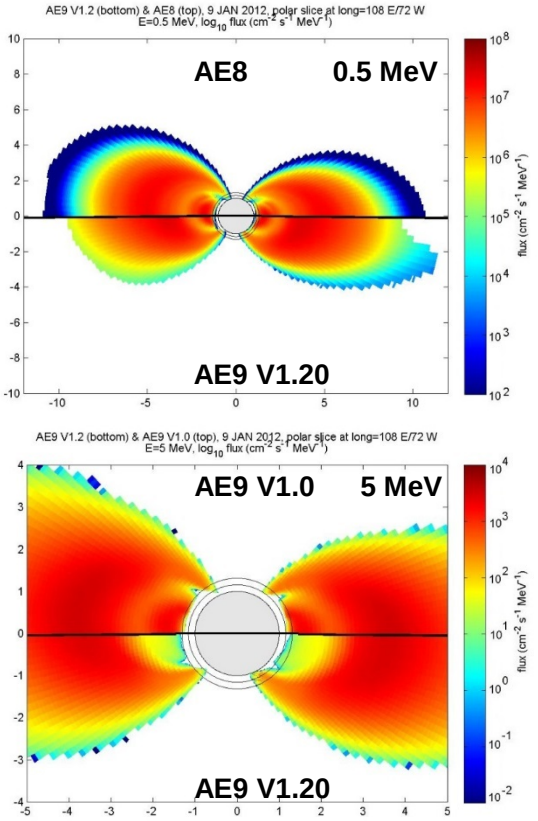
User's orbit

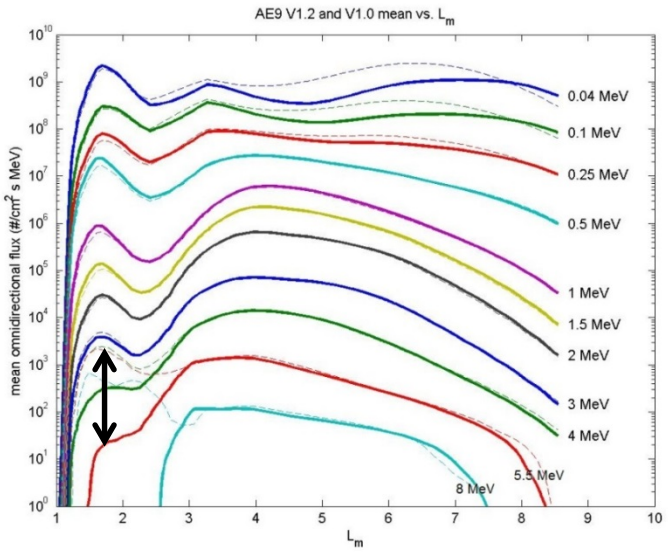


User application

- Aggregate across multiple randomized runs to get confidence levels
- Computes flux, fluence, dose rate, dose

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

Issues Noted by ESA

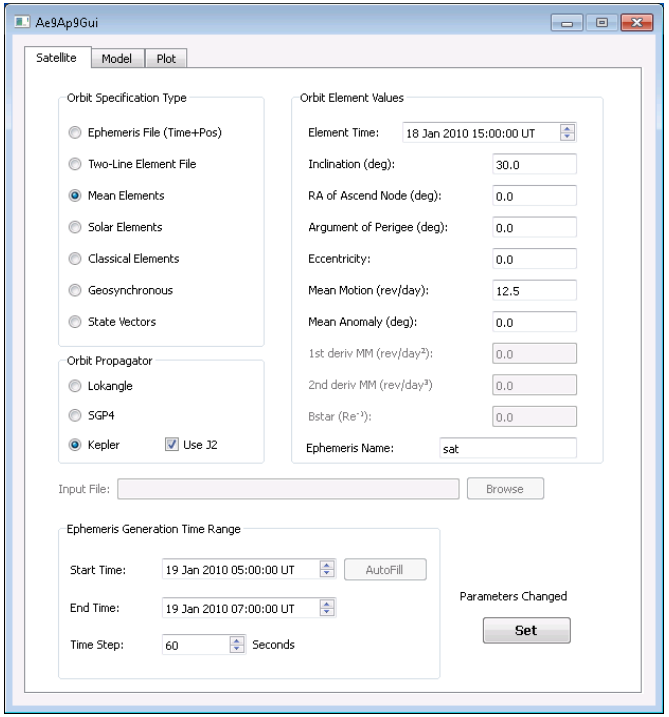
Issues identified by D. Heynderickx in V1.05 *

model/ regime	issue	assessment
AP9 in LEO	SAA is too big/has wrong shape (fluxes do not fall off fast enough at SAA edges)	Known V1.05 issue, has been significantly addressed in V1.20
AP9 in LEO	Fluxes are higher than Azur data for E≤10 MeV; altitude gradients are different	Azur data is lower than other data sets, particularly S3-3 at these energies; don't yet know if this is climatological or instrumental
AP9 in LEO	Energy spectra is more like a power law, not an exponential as in AP8 and data sets	AP9 template spectra are exponential; spectra in given flux map bins may be power law or exponential; still investigating
AE9 in GEO	Fluxes are higher than IGE-2006 despite both models using LANL data	May be a difference in LANL data set versions used; still investigating

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

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



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**

Solar Cycle Variability (V2.00)

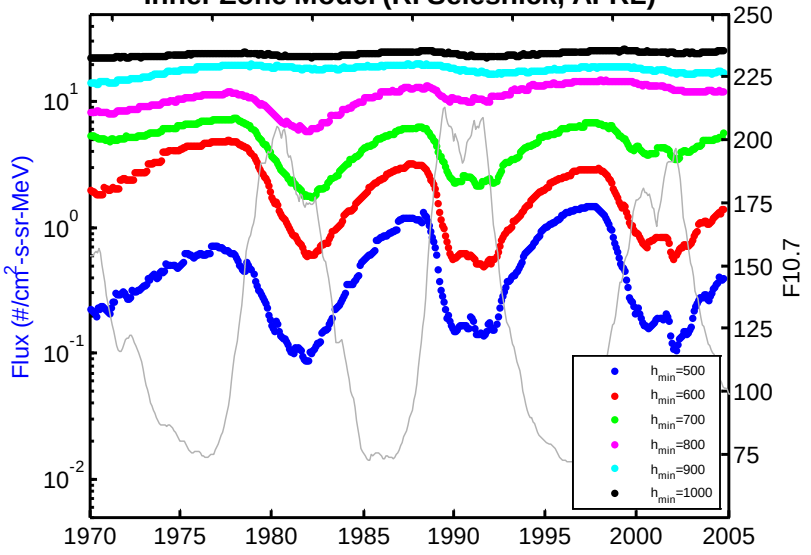
Capture variation of LEO protons with solar cycle phase:

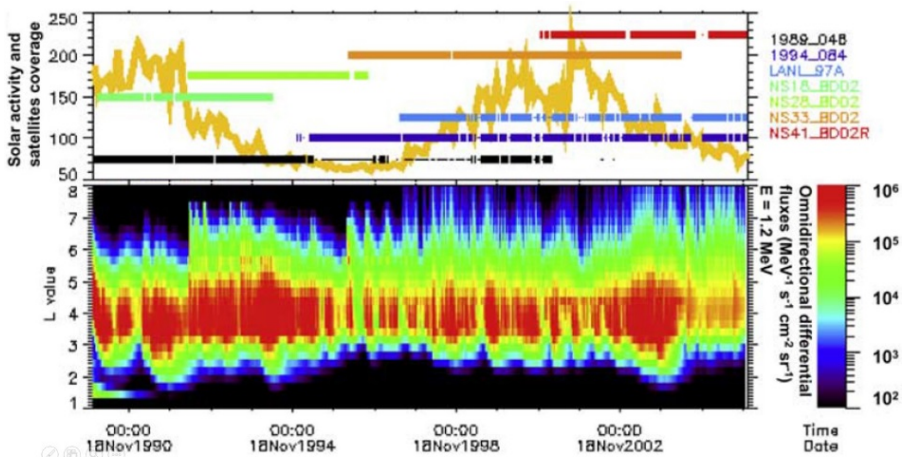
- Use SIZM model + POES data
- Allow flux maps to vary with F10.7 Monte Carlo scenarios
- Capability is needed for short duration missions—e.g. LEO CubeSats

Capture realistic solar cycle dynamics:

- Use data assimilative historical reanalysis of a whole solar cycle
- Import into new module-based architecture
- Provides realistic short-term variability for internal charging hazards

LEO 100 MeV protons from Selesnick Inner Zone Model (R. Selesnick, AFRL)





Outer zone electrons from DREAM reanalysis (LANL)