Air Force Research Laboratory

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

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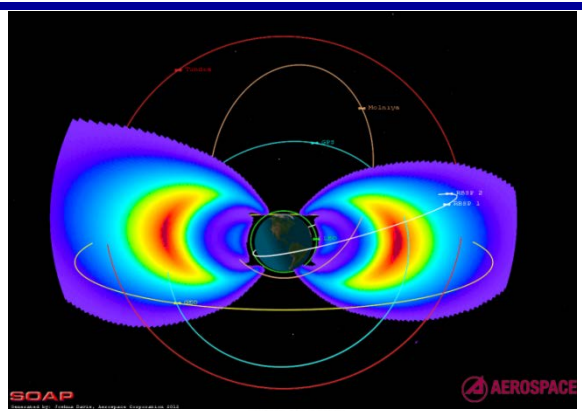
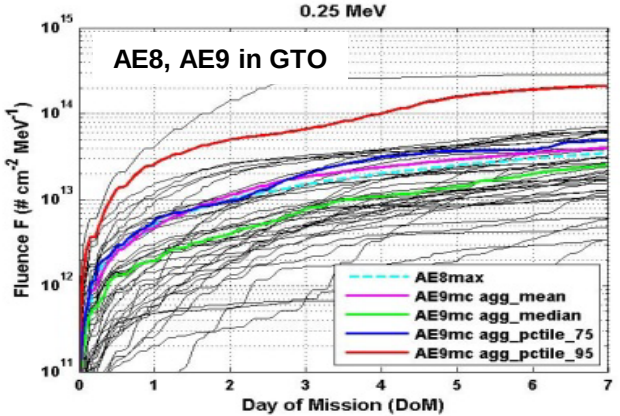
Outline

- 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



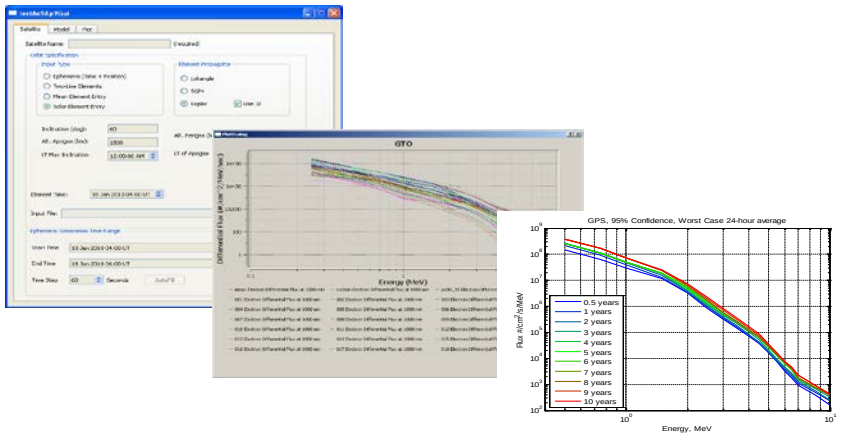


Coverage and Application

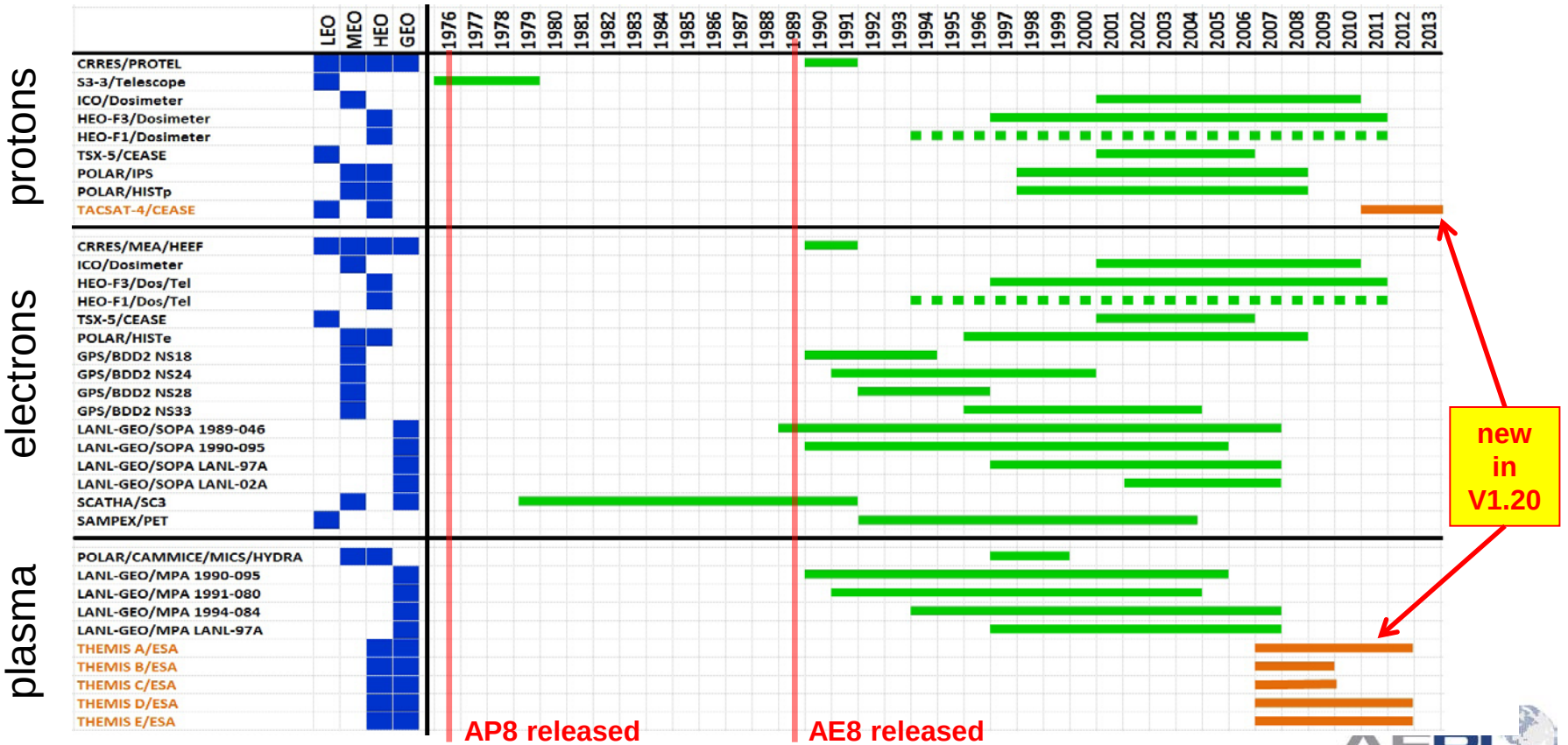
- Expanded energy coverage: keV plasma to GeV protons
- Spatial coverage for all orbit regimes, including tailored coverage for high resolution in LEO

Model	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	$0.98 < L^* < 12.4$	$0.98 < L^* < 12.4$	$2 < L_m < 10$

- Model provided with GUI and CmdLine access
- Documentation includes recommended modes for typical use cases
  - Best practices document with more details is forthcoming

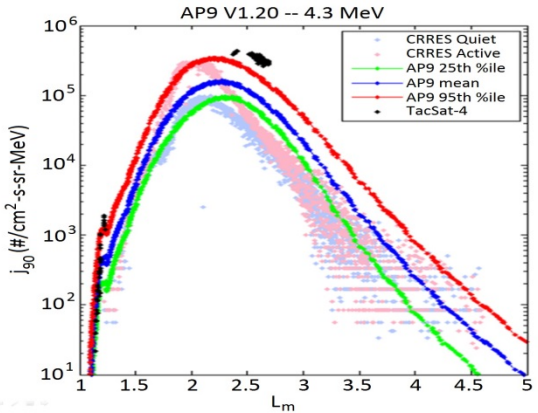


Data Sets—Temporal Coverage

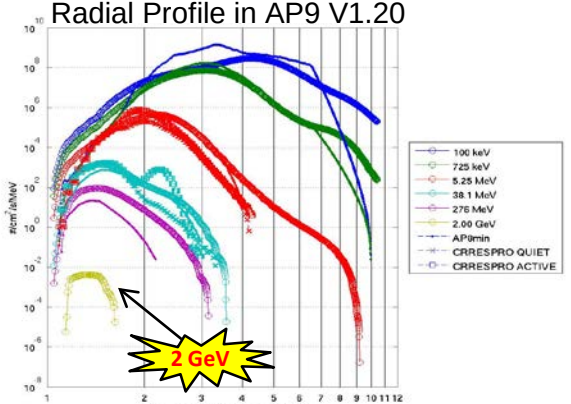


Version 1.20 – Database Updates

- 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



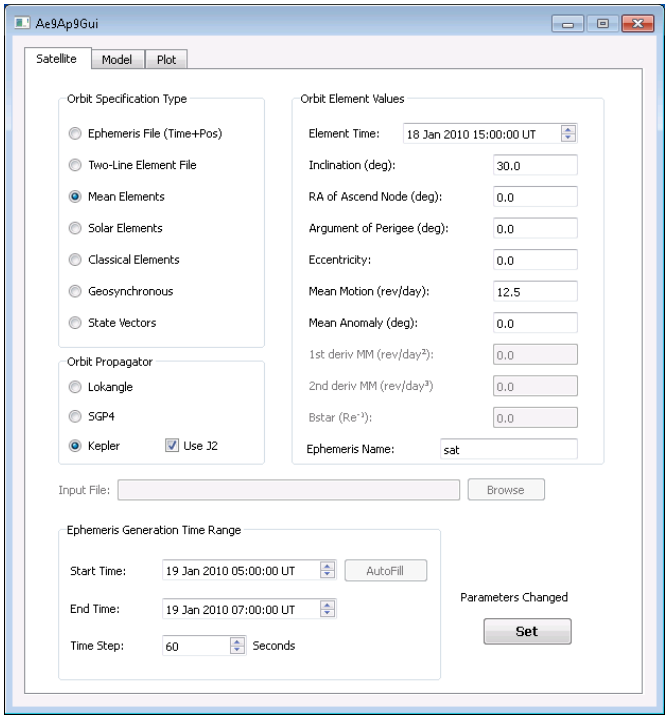
Radial Profile in AP9 V1.20



Radial Distance along +X MAG

V1.20 Feature Updates

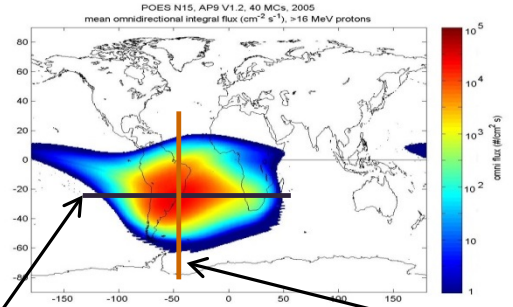
- Feature improvements
  - More options for orbit element input and coordinates
  - Third party developers guide
  - Pitch angle tool—make internal pitch angle calculations accessible to users
  - More options for unidirectional flux queries
  - Easy extraction of adiabatic invariant coordinates
  -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



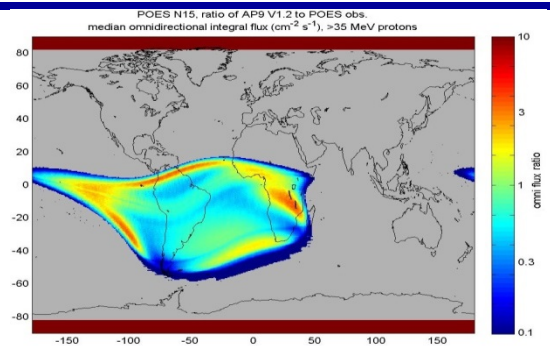
AP9 V1.20 Validation—SAA

>35 MeV protons

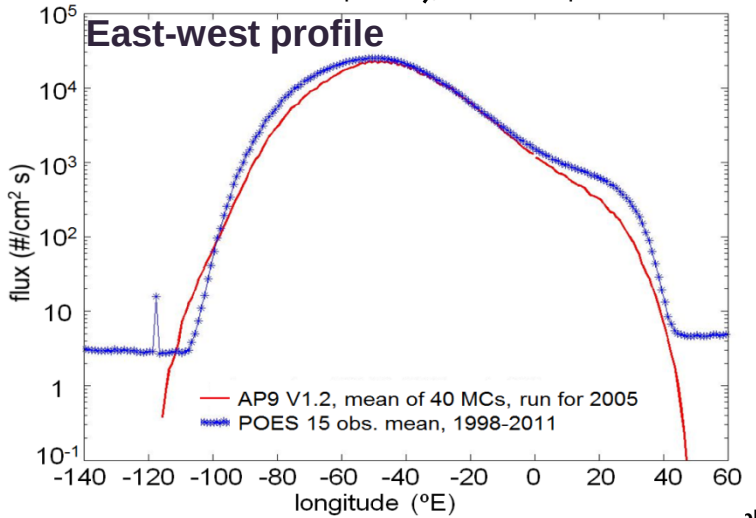
SAA flux profiles are improved in V1.20 as compared to POES observations



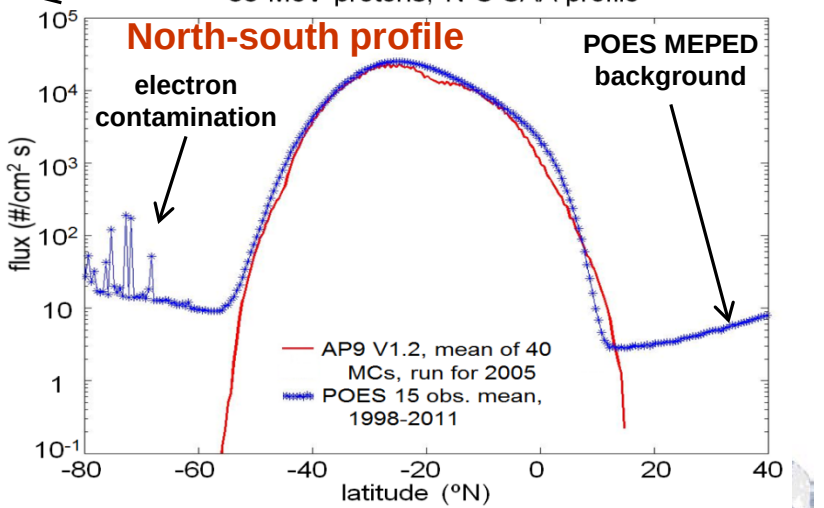
Ratio of AP9 V1.20 median to POES data



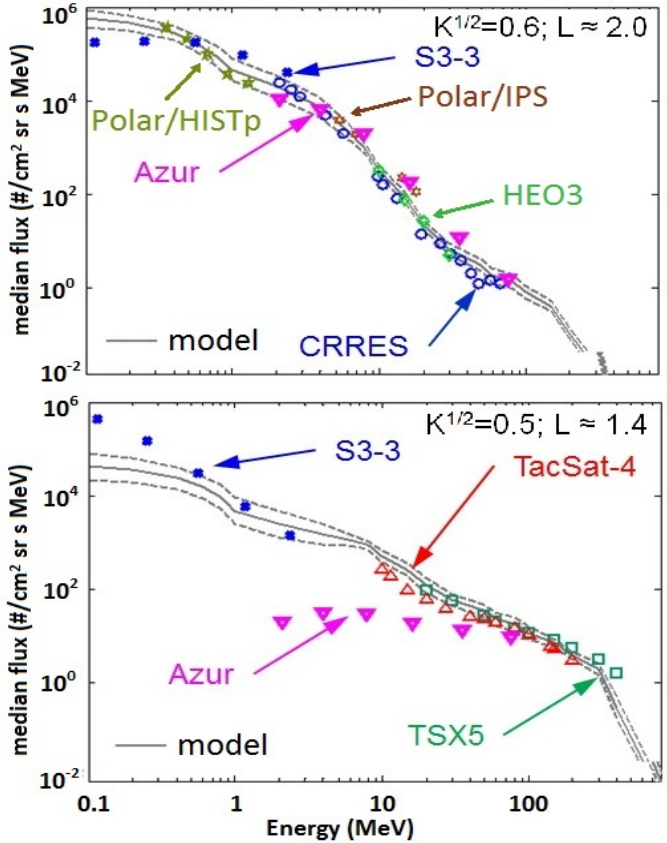
>35 MeV protons, E-W SAA profile



>35 MeV protons, N-S SAA profile



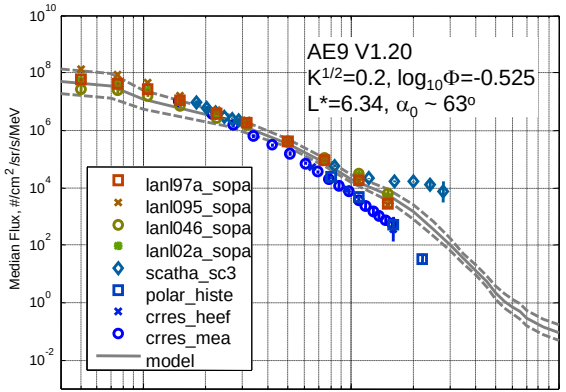
AP9 Validation in LEO



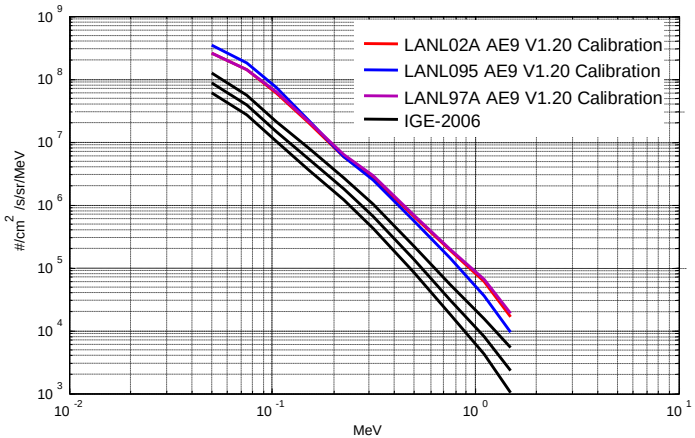
- Review by ESA showed discrepancies among AP9, AP8, and data (including Azur)
- Extensive review by team:
  - We trust data currently in AP9
  - AP9 model accurately represents these data sets
  - We also trust Azur data
  - Most likely explanation: Azur and S3-3 represent two different geophysical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

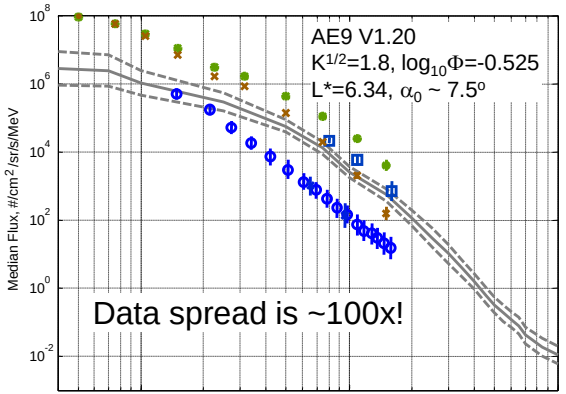
AE9 GEO Issue

- **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**

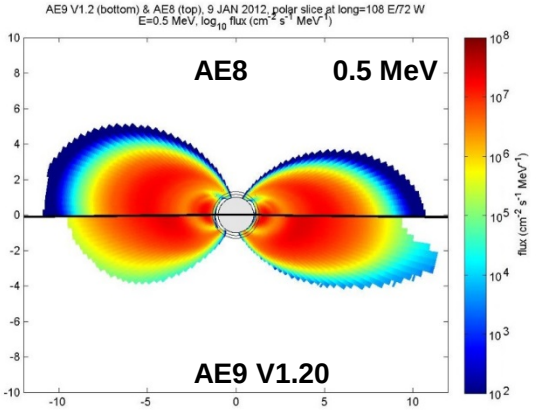


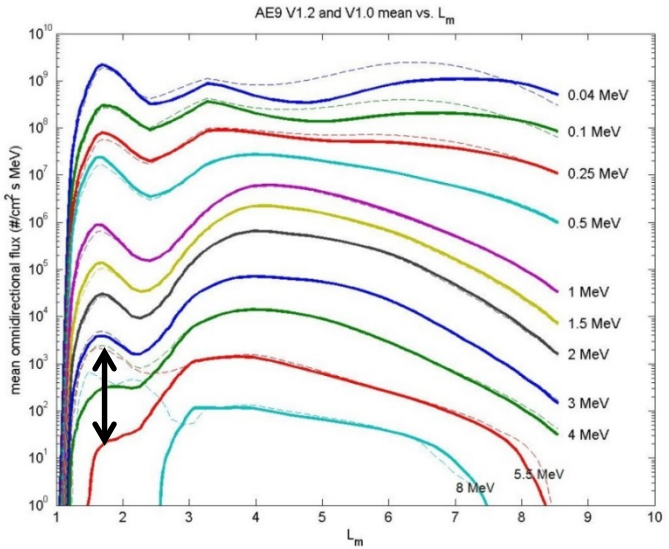
LANL and IGE for Year 2003





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**

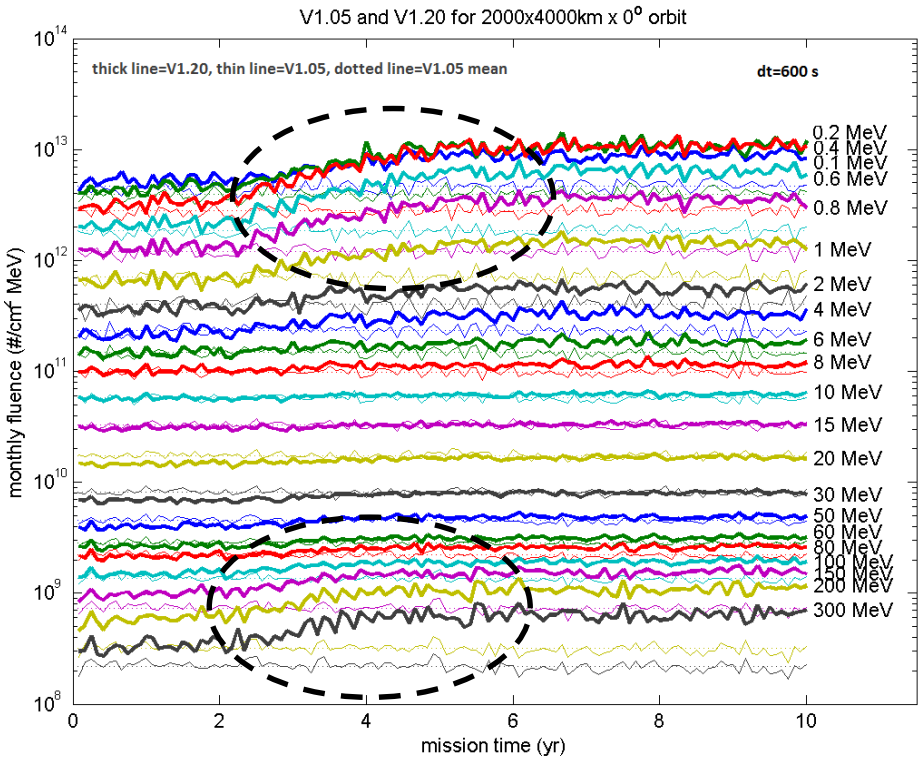
V1.20 GUI Patches

- 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

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



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

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

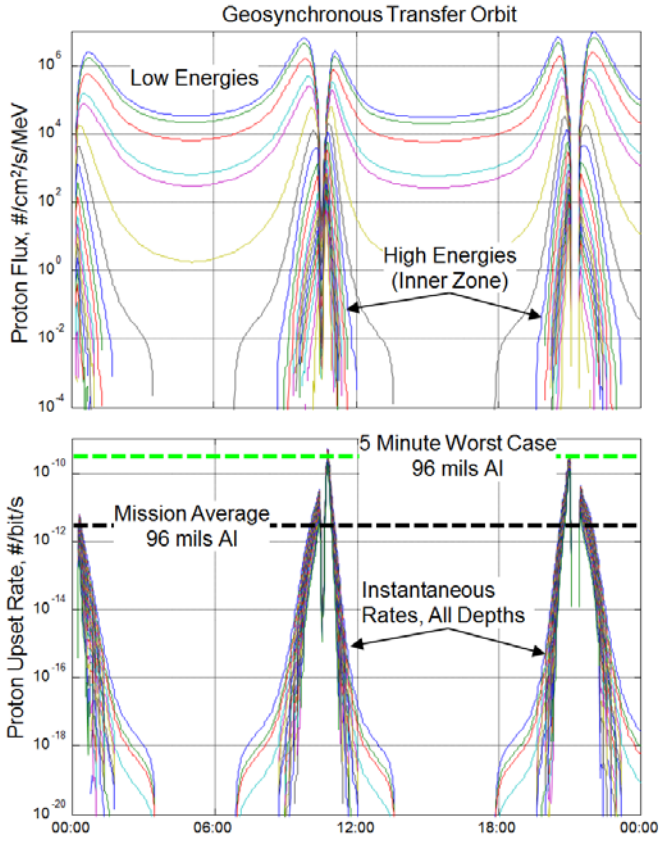
- Parallelization
  - Uses MPI, supports multiple platforms and parallel environments
  - Use multiple cores on Windows via GUI
  - Use Linux Clusters via Command Line Utility
- More output options to reduce disk usage, improve performance
- Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times

- <u>All flux, fluence and dose results will match V1.30</u>

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**

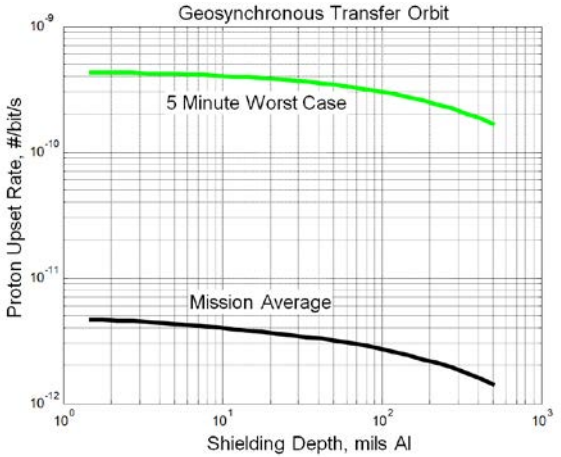
Kernel-Based Effects Calculation



- 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

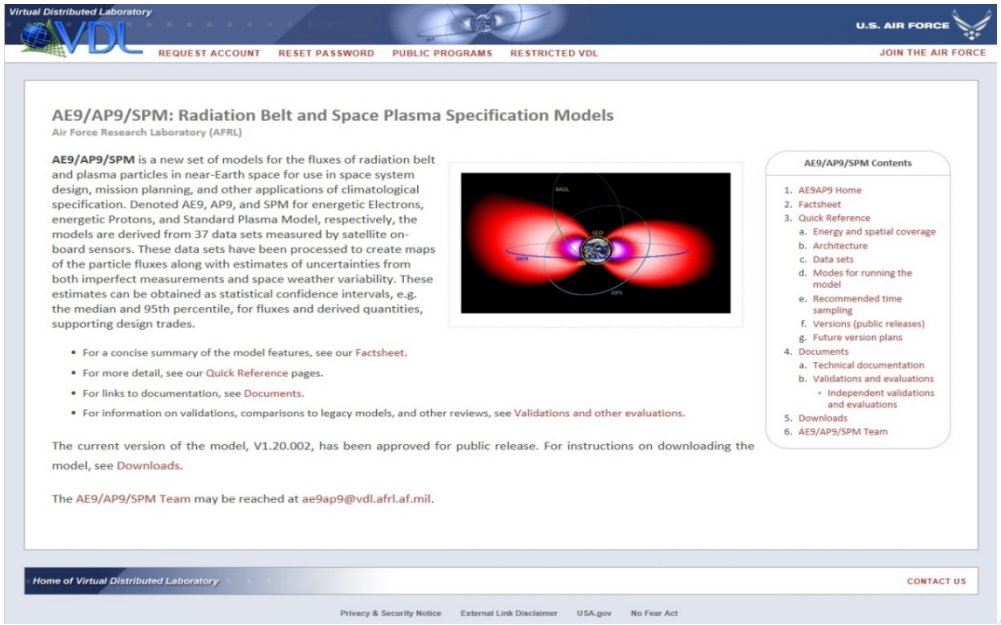


Version 2.0

- 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**: **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



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*

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):
  - 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**

Thank You