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The IRENE-AE9/AP9 Next Generation Radiation Specification Models—Progress Report

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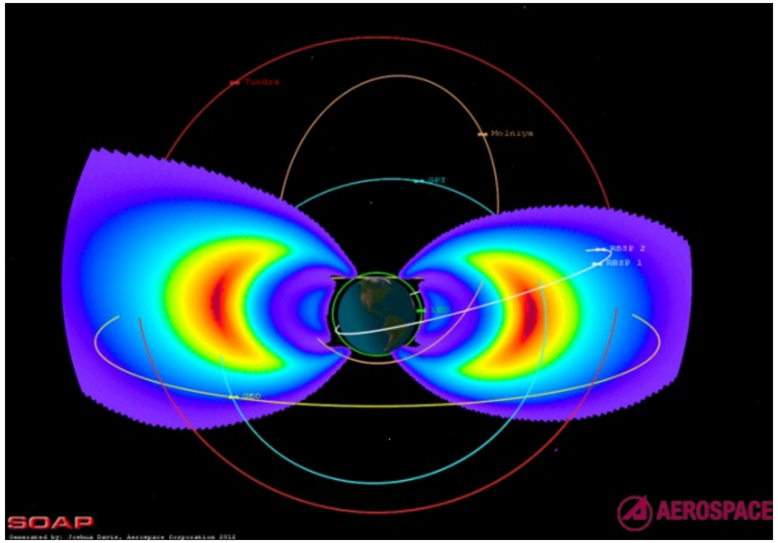
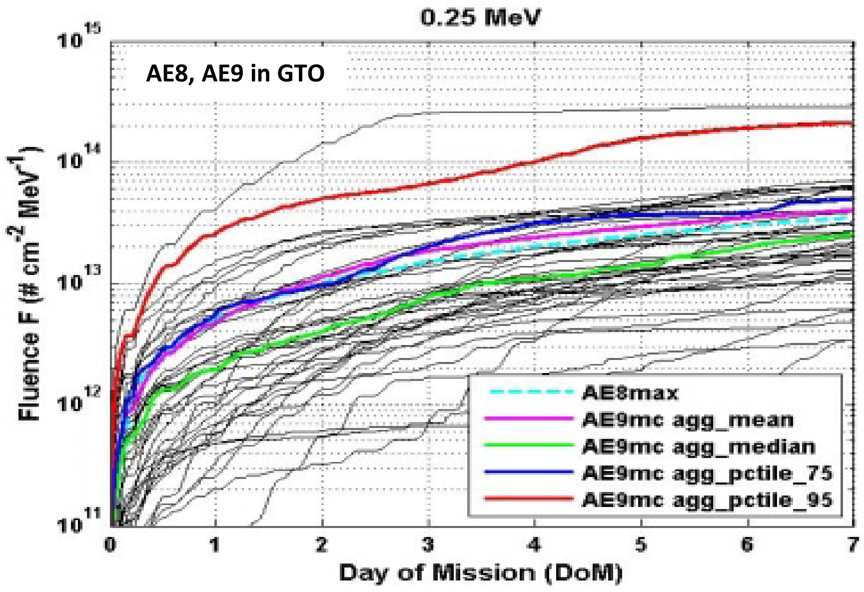
What is IRENE-AE9/AP9?

- IRENE-AE9/AP9 specifies the natural trapped radiation environment for satellite design and mission planning
- It improves on legacy models to meet modern design community needs:
  - Uses 45 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
- V1.00 released in 2012, V1.50 in Dec 2017
  - **V1.57 in release this month**





New update—IRENE V1.57.004

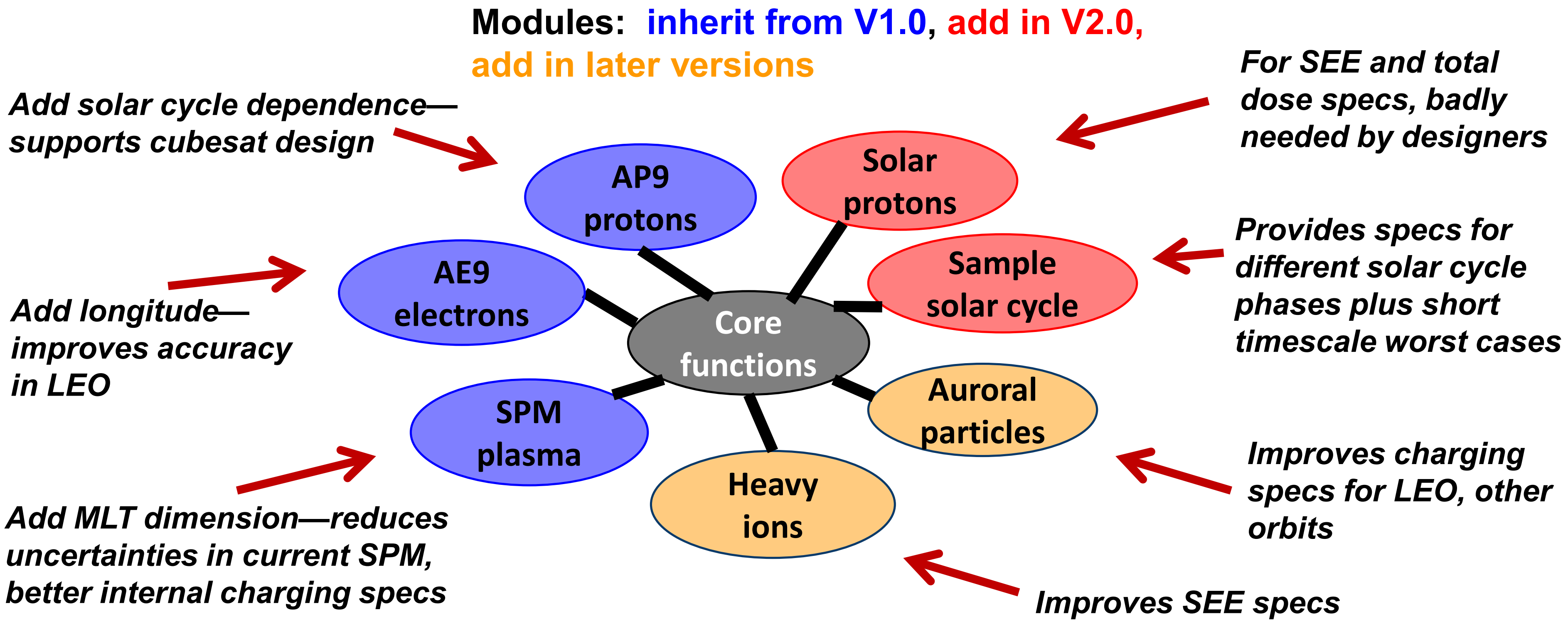
- A new update to IRENE, V1.57.004, will be publicly available in the coming days from the IRENE website: **https://www.vdl.afrl.af.mil/programs/ae9ap9/downloads.php**
- Updates in this version:
  - A new kernel-based calculation of the dose values—provides faster dose calculations than using SHIELDOSE2
  - Accumulation capabilities are expanded
    - Can now define multiple interval lengths
    - Added features to 'Boxcar' and 'Exponential Flux Average' accumulation including logging of 'worst case' values
  - Expanded software API—now includes C and Python model- and application-level API methods
  - Dependencies on third-party libraries updated to more recent versions
  - No updates to flux maps in this release—flux- and fluence-based results match those from V1.50.001

Effects Kernels

- Precomputed kernels convert flux-energy spectrum into linear radiation effects
- Kernels allow use of AE9/AP9 statistical machinery to compute effects at every time step or for every scenario, as needed, before computing confidence levels – removes unneeded conservatism
- Kernels are “fast” to allow calculation of worst case transients by converting every spectrum to its effects
- V1.55-1.57 introduces dose vs. depth kernel derived from SHIELDOSE2
  - SHIELDOSE2 does not give accurate results for depths <0.1 mm (4 mils) Al equivalent
- What we need:
  - Dose-depth kernel for thin depths
  - Covering 2.5 nm – 0.1 mm (10^{-4} – 4 mils) Al equivalent
  - Addresses plasma effects (10 eV – 200 keV)
  - Also includes heavy ion effects (O^+, He^+)

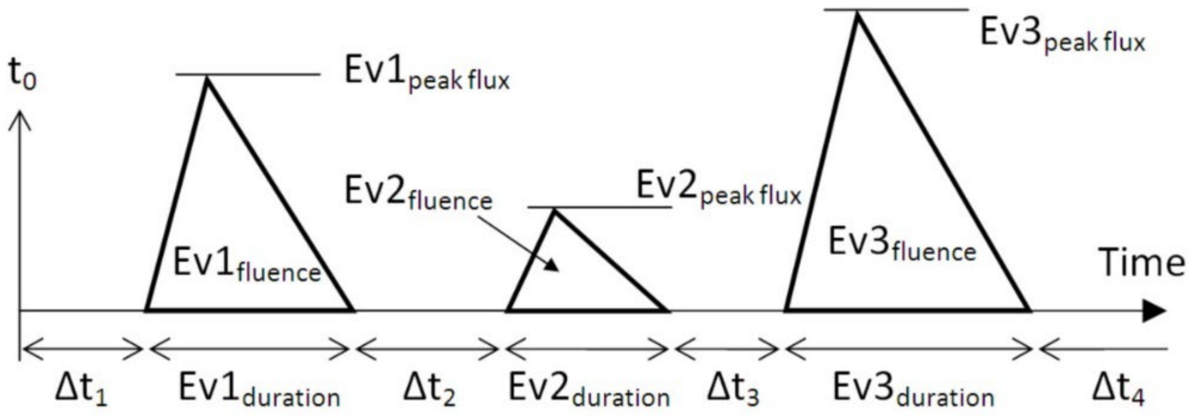
Version 2.0 Modules

- The module architecture is a generalization/combination of existing pieces
  - K-h_{min}/K-Phi stitching (runtime)
  - SPM/AX9 stitching (post-processing → runtime)
  - ESA framework for combining trapped + solar + GCR (post-processing → runtime)



Integrating Solar Protons

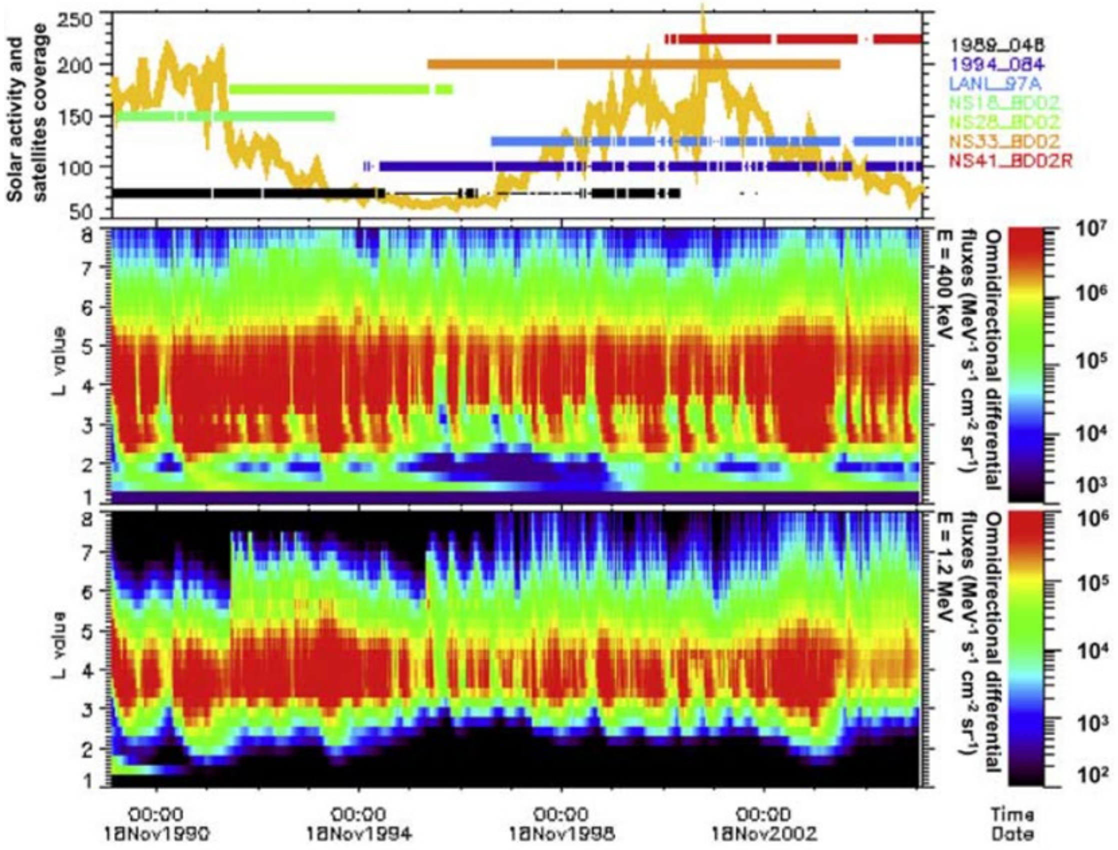
- Solar protons contribute to proton effects AP9:
  - Total Ionizing Dose
  - Displacement Damage
  - Single Event Effects



- Statistical laws disallow adding 95th percentiles from AP9 and a solar model to obtain a combined 95th percentile
  - The statistical distributions must be combined before computing percentiles
  - Combination must include dynamics for Single Event Effects
- We are working with ESA to resolve this problem
  - Developing a Monte-Carlo method for solar protons
  - We will combine that with a geomagnetic cutoff model to limit solar proton access
  - This will enhance mean, perturbed mean, and Monte Carlo runs of AP9

Sample Solar Cycle

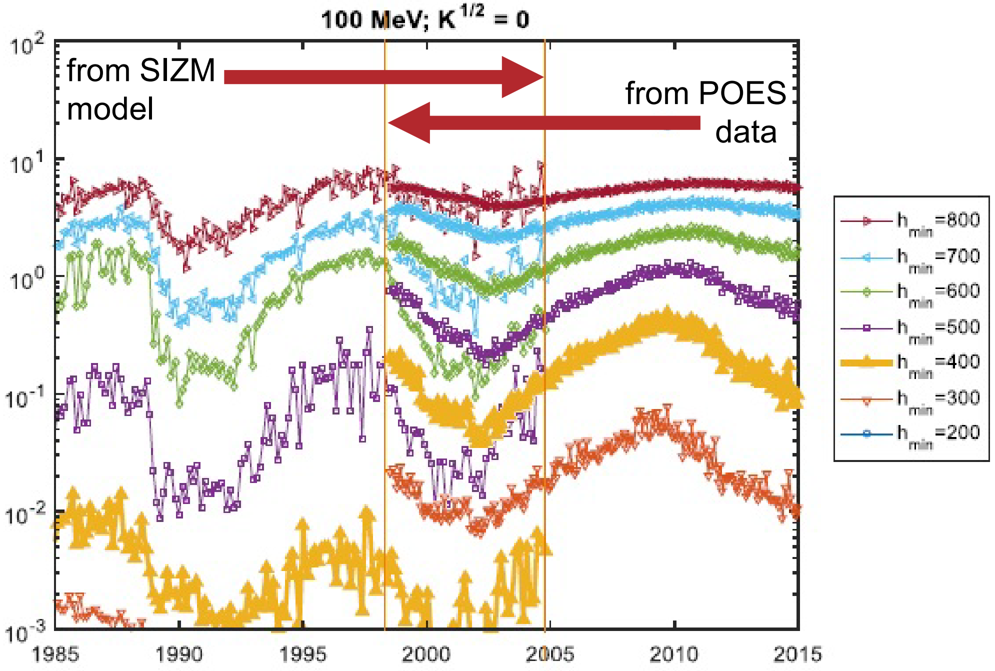
- Capture dynamics of realistic 11+ year solar cycle via data assimilative reanalysis
- “Fly through” this simulated dynamic environment as a check on Monte Carlo results
- Use the sample solar cycle to improve correlation matrices that drive Monte Carlo dynamics
- Use the sample solar cycle to help “fill in” flux maps where observations are missing
- What we need:
  - 10 eV – 10 MeV electrons
  - 10 eV – 1 GeV protons
  - 10 eV – 200 keV He+, O+
  - Data assimilative
  - At least 11 years
  - Prefer one giant simulation with all the above
  - Simulations addressing a subset can still inform correlation models and templates

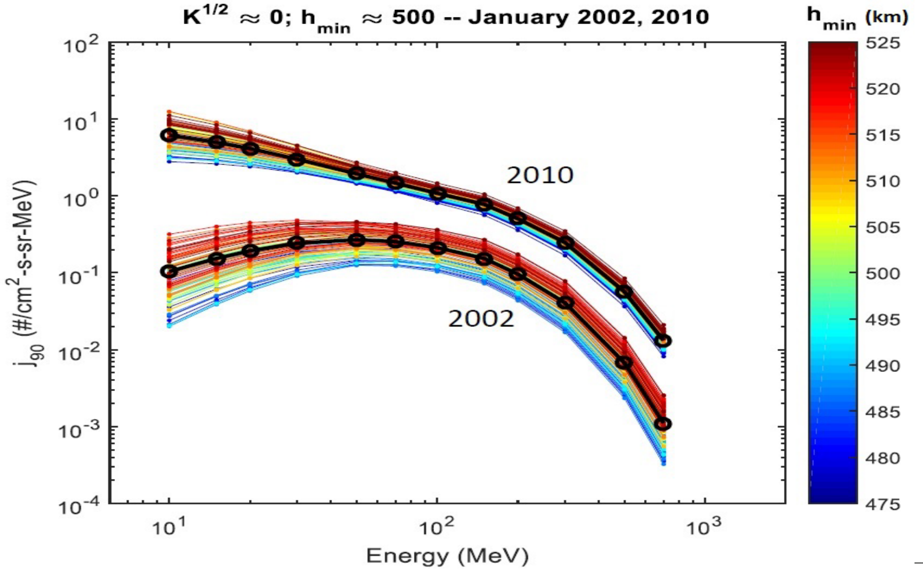


From Maget et al., Space Weather, 2007

Solar Cycle Variation of LEO Protons

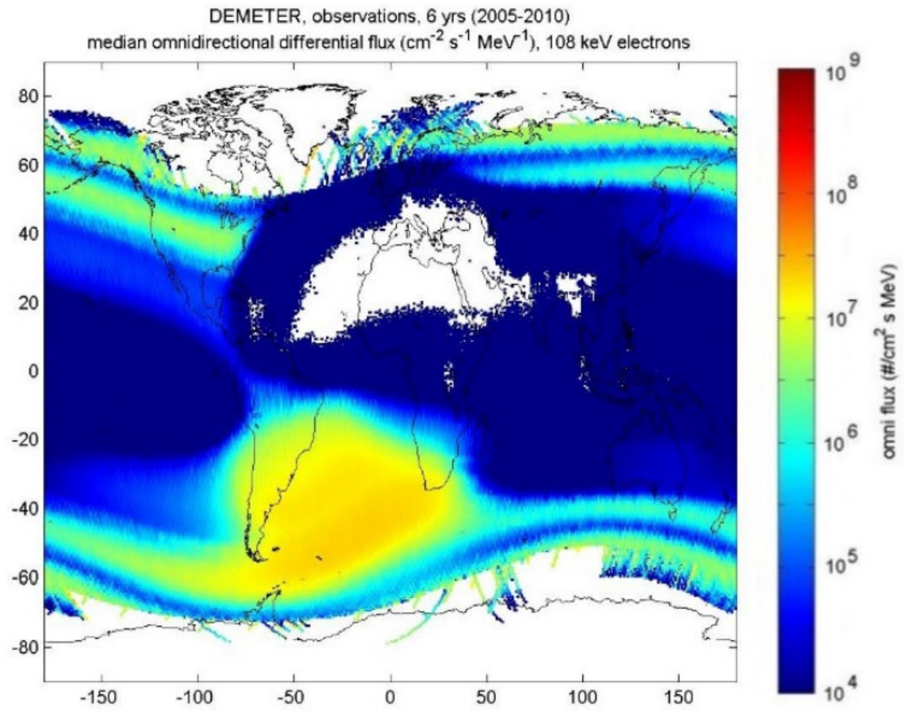
- No solar cycle dependence in AE9/AP9 currently
  - Statistics capture ranges across all solar cycle phases
- Users needs solar cycle dependence for trapped protons
  - Design for short duration LEO missions
  - Supports use of AP9 for nowcast estimates
- Work progressing towards solar cycle modulation of AP9:
  - Use stochastic model for future phase/intensity of solar cycle drivers of LEO protons
  - Use models (Selesnick Inner Zone Model) and data (POES SEM-2) to relate drivers to energy- and location-dependent variability
  - Use results to modulate AP9 flux maps (representing all data sets)
- What we need:
  - More information on altitude gradients
  - LEO data sets, energy & pitch angle resolved, at least ~20 years duration





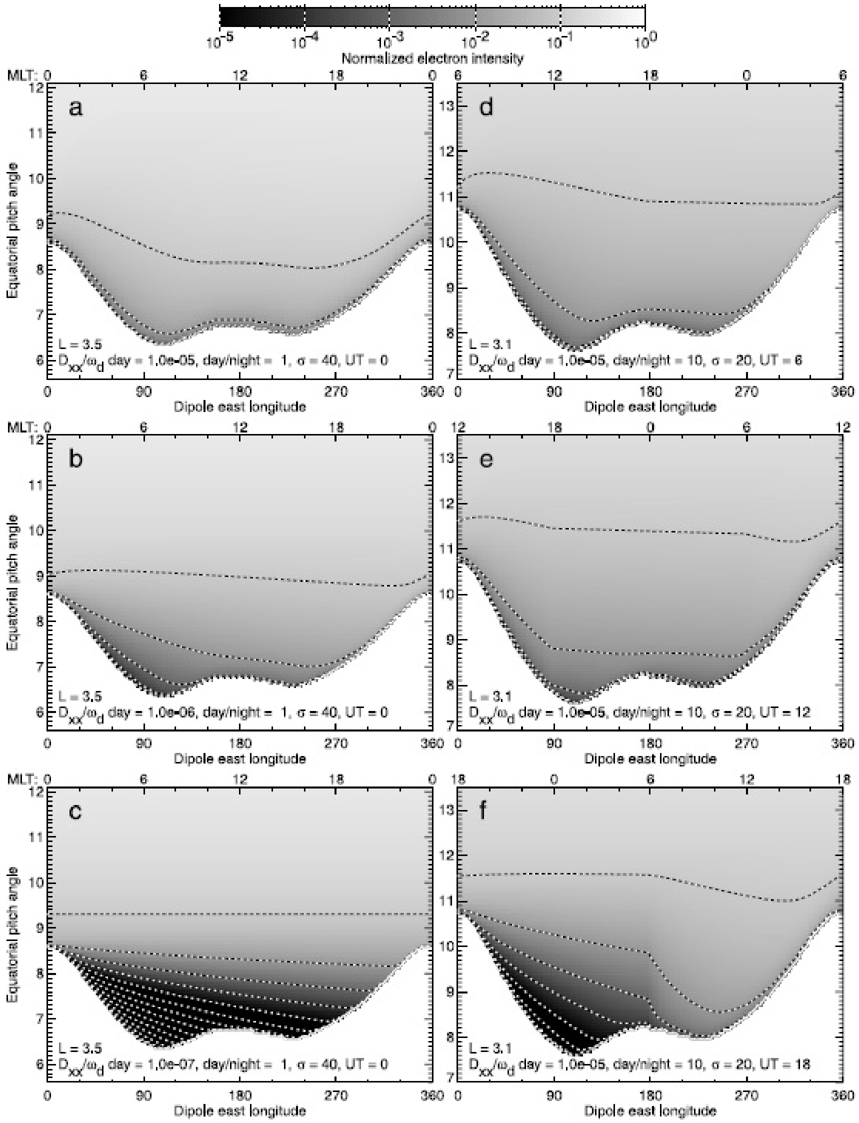
Fast, Compact LEO Electron Coordinates

- Intended to capture drift loss cone structure
- Must account for longitude structure, may also need to account for MLT dependence
- Must run quickly – no run-time drift shell tracing; use neural networks or other speed-ups instead
- Demonstrate on LEO data set like DEMETER or POES



Low-Altitude Electron Gradients

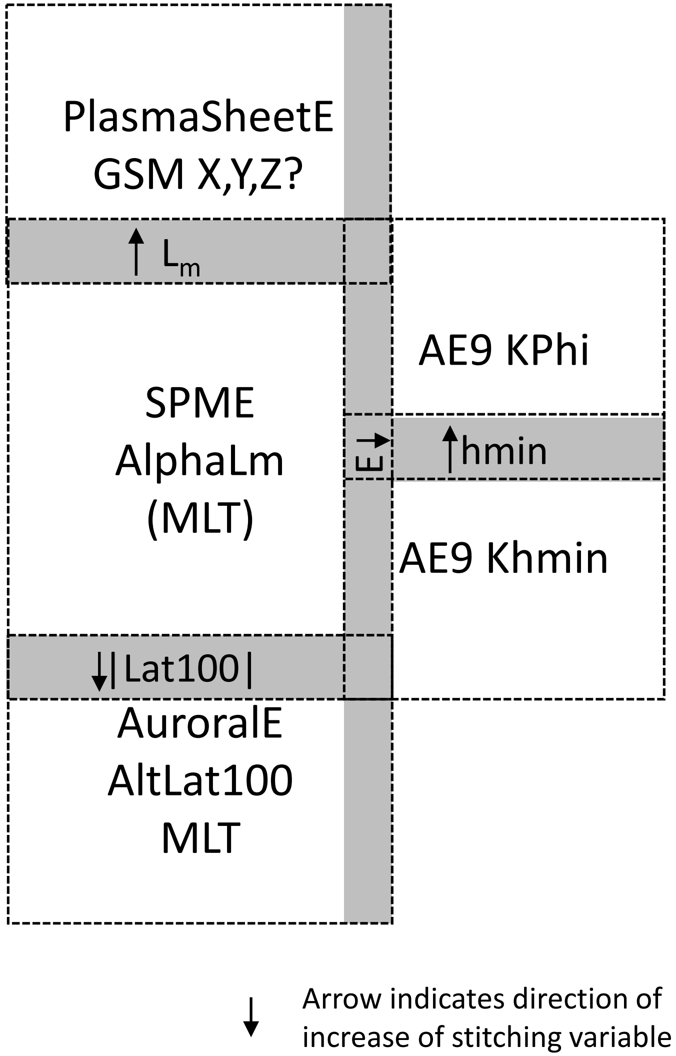
- At plasma and radiation belt energies, we do not have a great ability to model the altitude gradient below ~1000 km.
- This is due in part to paucity of data, which could be remedied with DEMETER and other LEO data sources
- We expect a modeling component, e.g., the Selesnick drift-scattering model, will be needed.
- What we need:
  - Model providing a realistic description of LEO electron variability as a function of energy 10 eV to 10 MeV (especially 10 keV to 10 MeV) and location, 100-1000 km
  - Could be done with a 1-year simulation, or simulation of several storm periods plus a few quiet periods.
  - Intended use: building LEO electron templates.



From Selesnick et al., JGR, 2003

Statistical Alternative to Weibull-LogNormal Dichotomoy

- Currently AE9 uses Weibull distributions with 2 parameters, while all other models use LogNormal
- This creates statistical discontinuities, which we can, at best, stitch together at run time
- We would prefer a new framework that allows a smooth transition between Weibull and Log-Normal
- Note that the model tracks uncertainty on the statistical parameters via error covariance
  - A naïve table of N percentiles will have N(N+1)/2 error parameters at every grid point
  - Table-of-percentiles approach with a simplified error covariance might work
  - Alternately, a new analytical framework that somehow merges Weibull and LogNormal could work
- Performance is an issue, both in terms of number of parameters and speed of computation



Progress - Architecture

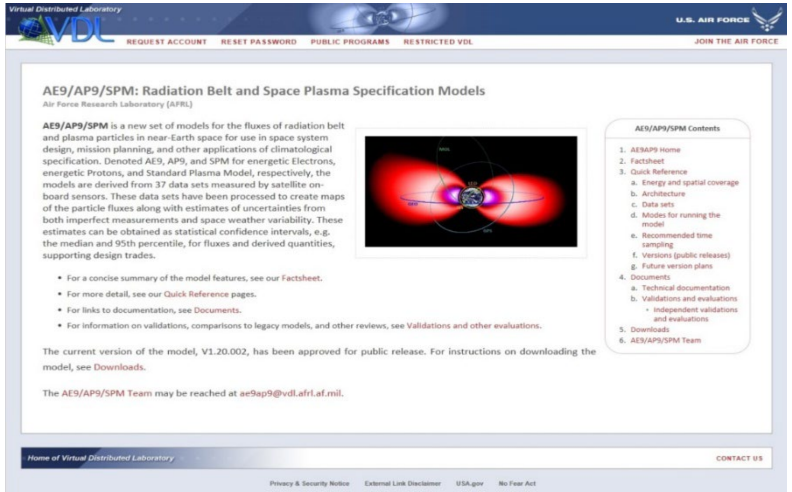
Capability	Status	Notes
Static AE9, AP9, SPMH, SPME Modules	Prototyped	US/Aerospace
Monte Carlo AE9/AP9 Modules	Research	US/Aerospace
Monte Carlo Solar H+	Prototyped	ESA/SPARC
Monte Carlo Solar Ions	Research	ESA/SPARC
Solar Cycle Dependence LEO Protons	Research	US/Huston
Sample Solar Cycle	Datasets Needed	Candidates identified
LEO Electrons Drift Loss Cone	Planned	Need Help
Effects Kernels	Partially Implemented	Dose implemented
Weibull-LogNormal Conflict	Research	ESA/SPARC + Aerospace

Progress – Data Sets

Data Set	Status	Notes
Updated Van Allen	Awaiting Phase F Releases	Add HOPE, RBSPICE, improved MagEIS, REPT, RPS
PROBA V EPT	Ready for cross-cal	Need to make data sharing agreement
PAMELA	First tranche ready	ESA+NASA funded recovery from INFN flood
SREM (multiple vehicles)	Ready for inclusion	Available from ESA, only requires coordination
AMPTE/CCE	Investigating	Need a small project to update/clean data archive
DSX	Taking data	New data source
ARASE	Taking data	New data source
Long duration sims	Making progress	Obtained VERB, partial BAS. Need H+, plasma.

Conclusion

- IRENE-AE9/AP9 continues to be maintained and upgraded as a comprehensive radiation environment design standard
  - Future releases will include new data sets and new features, driven by user needs
  - We seek models and data from the community to further these improvements
- **Comments, questions, etc. are welcome and encouraged!**
- Please send questions, 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, The Aerospace Corporation, paul.obrien@aero.org



- Current model downloads, documentation, news are available at AFRL's Virtual Distributed Laboratory: **https://www.vdl.afrl.af.mil/programs/ae9ap9**

