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

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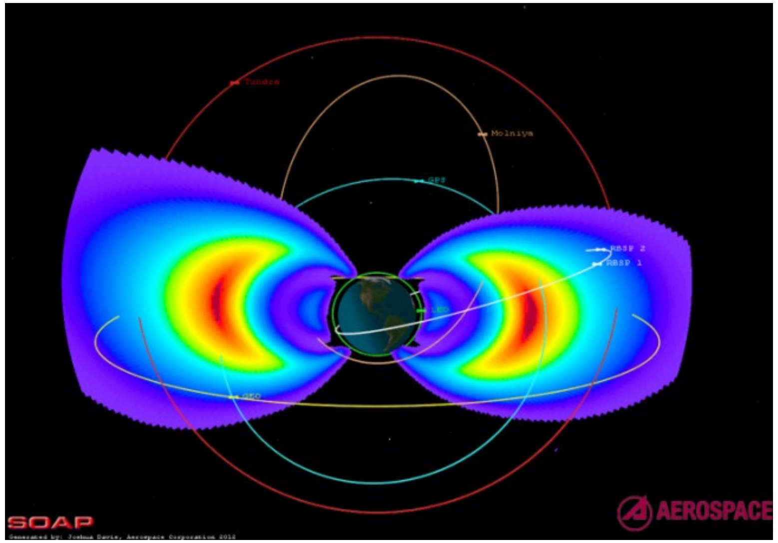
T. P. O'BRIEN[1], W. R. JOHNSTON[2], S. L. HUSTON[3], T. B. GUILD[1], Y.-J. SU[2], C. J. ROTH[3], R. A. QUINN[3], AND J. CHARRON[3]
[1]The Aerospace Corp., Chantilly, VA, USA
[2]Space Vehicles Directorate, AFRL, Kirtland AFB, NM, USA
[3]Atmospheric and Environmental Research, Inc., Lexington, MA, USA

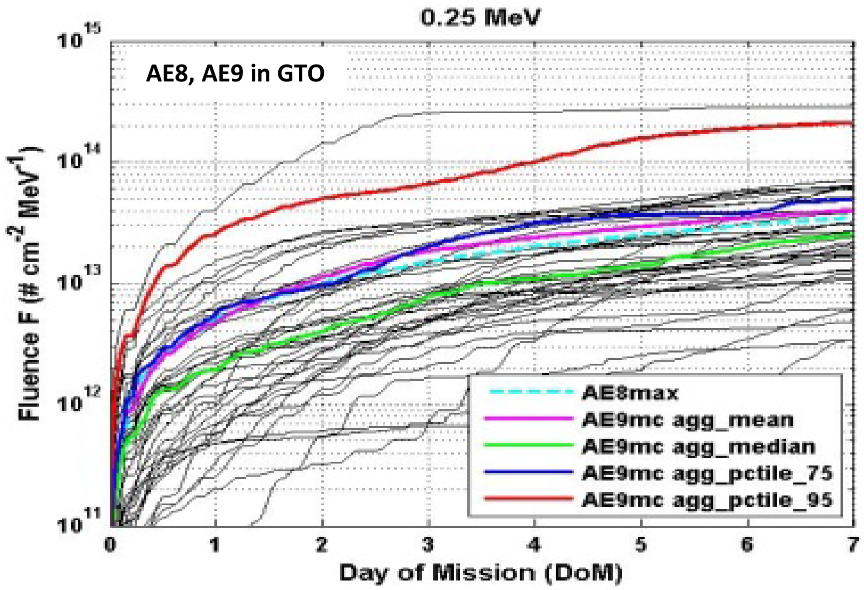
Outline

- Background on AE9/AP9-IRENE
- 2.0 Architecture
- Elements and Progress
- Conclusion

What is AE9/AP9-IRENE?

- AE9/AP9-IRENE 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, V1.56 in August 2020
  - Latest public release: V1.50 in December 2017



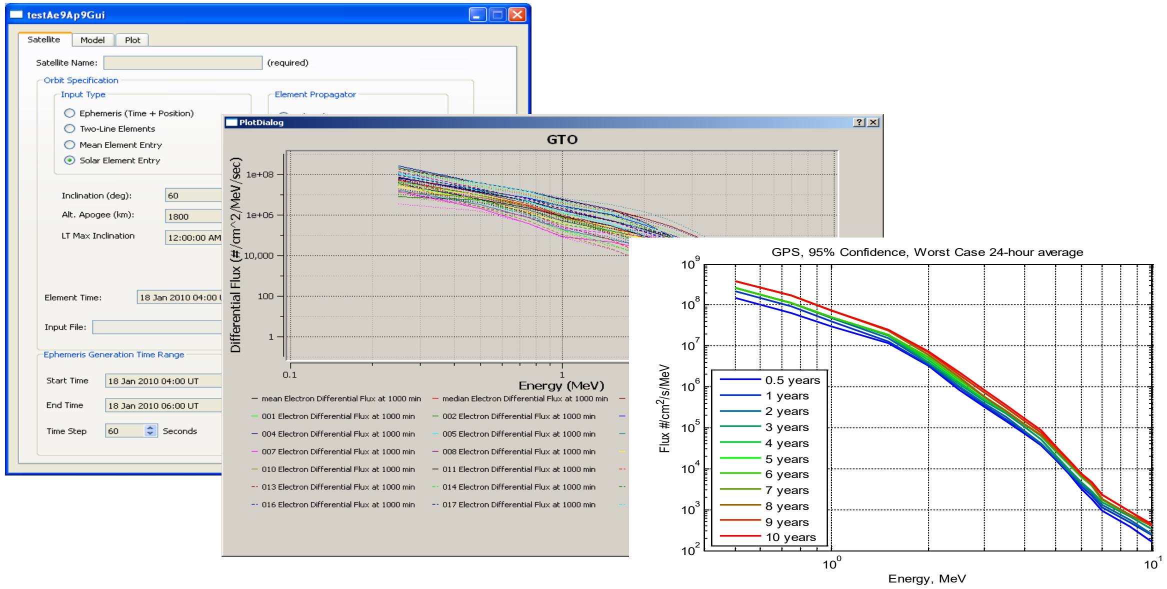


Coverage and Application

- 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 Command Line access
- Documentation includes recommended modes for typical use cases



Data Sets—Temporal Coverage

Incorporates 45 data sets from 1976-2016

- Chosen for high quality and coverage

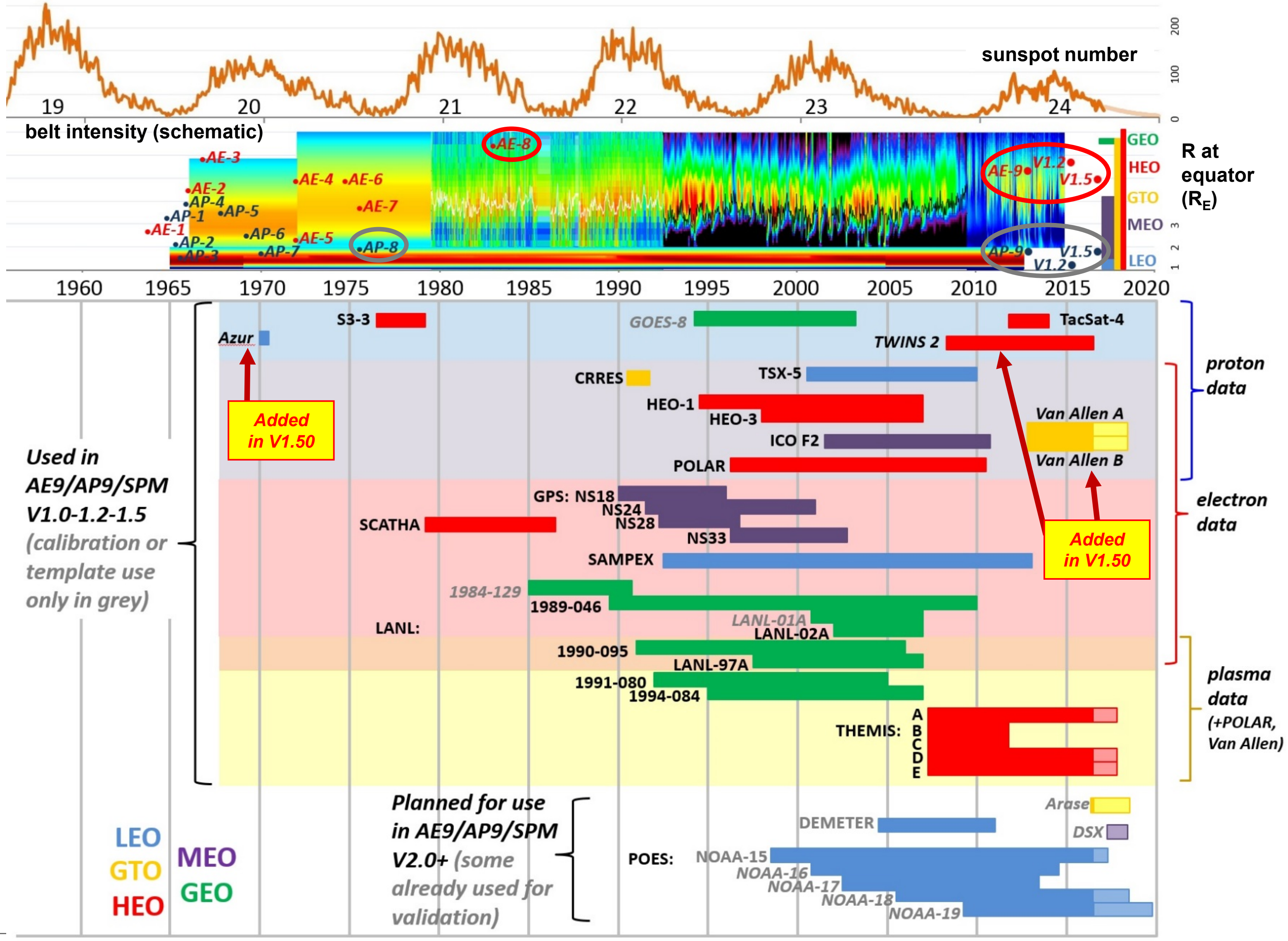
300+ instrument-years of data

- 10x more than AE8+AP8

All solar cycle phases sampled:

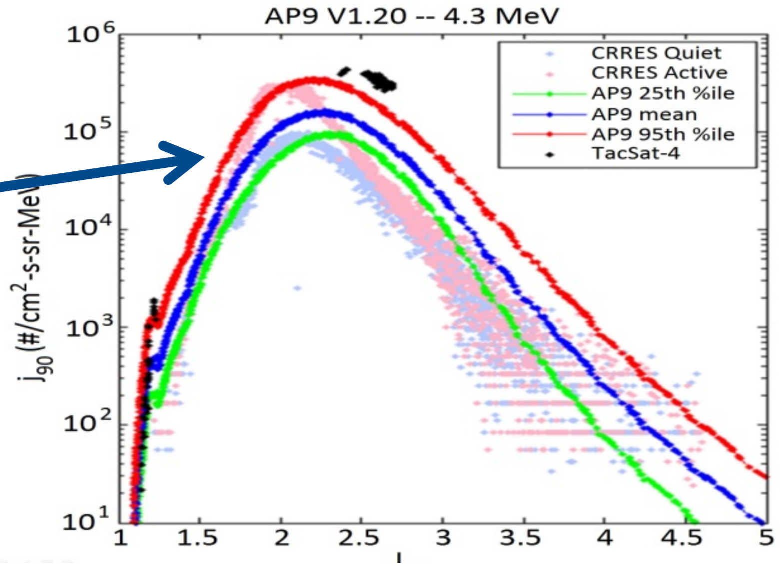
- 16 sets >10 yrs
- 26 sets >5 yrs

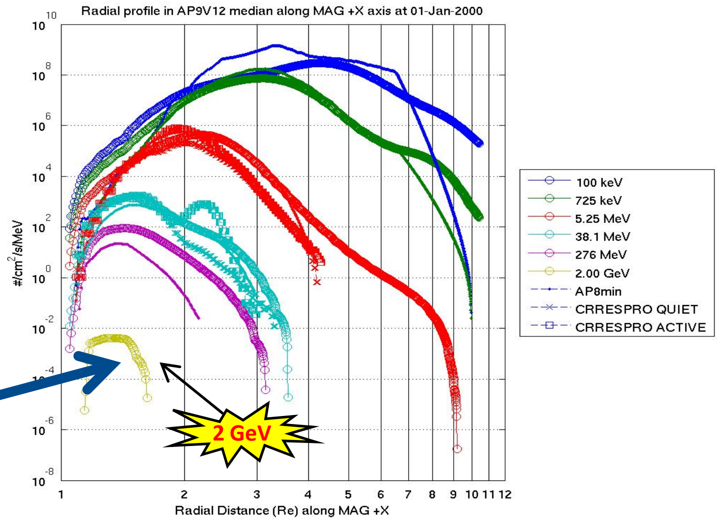
10x the data of previous models, and still growing!



Versions to Date

V1.00 (2012)	Initial release, 31 data sets
V1.20 (2015)	TacSat-4/CEASE proton data THEMIS/ESA plasma data Van Allen Probe influence to AE9 and AP9 changes more I/O options added IGRF 2015
V1.30 (2016)	Fixed instability in V1.20 AP9, AE9 Monte Carlo mode
V1.35 (2017)	Support for parallelized processing
V1.50 (2017)	New data sets for electrons, protons: Van Allen Probes, Azur, HiLET





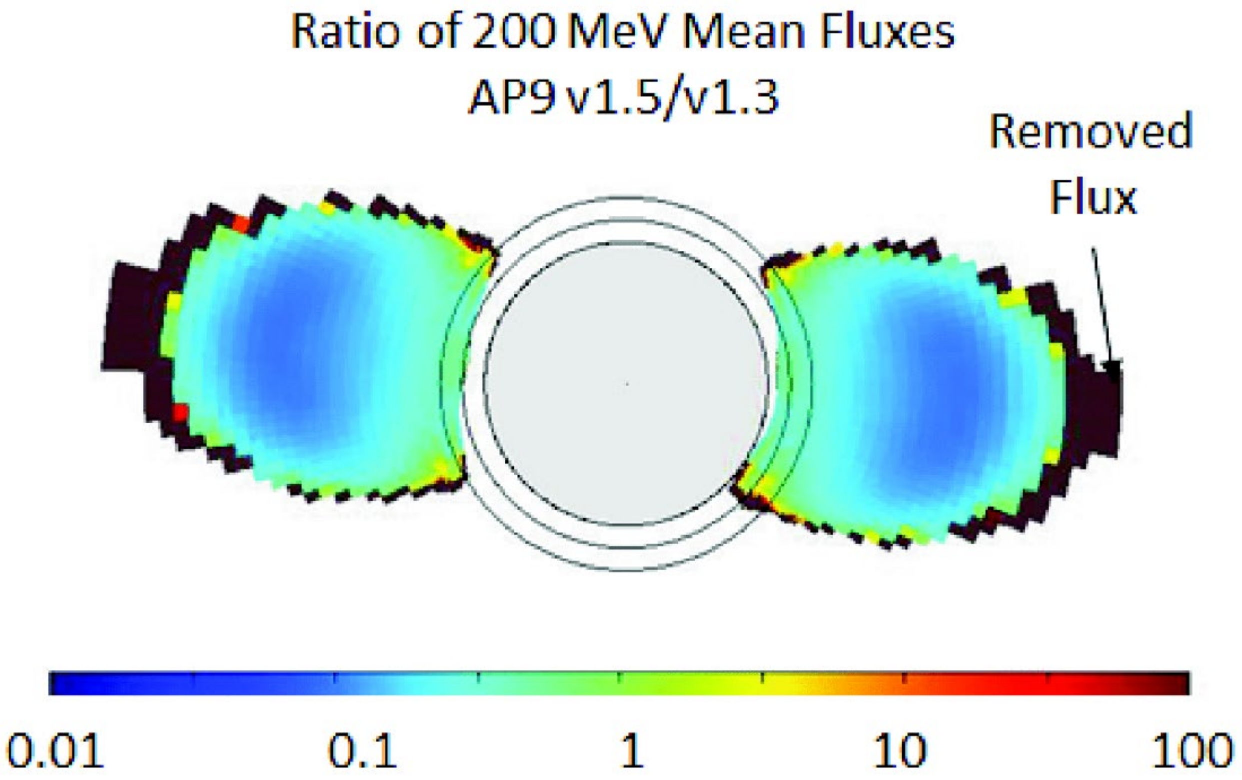
Changes in AE9/AP9 V1.50

- AP9 and AE9: new data from NASA's Van Allen Probes mission
- AP9: data added from Azur and TWINS 2
- AP9 and AE9: other revisions to flux maps (addressing gradients and other aspects of data set merging)
- Limited feature changes with this release—most significant are new accumulator options (e.g., fluence accumulation intervals)

- Begin transition to new name: International Radiation Environment Near Earth (IRENE), reflecting international participation (e.g., Azur data)

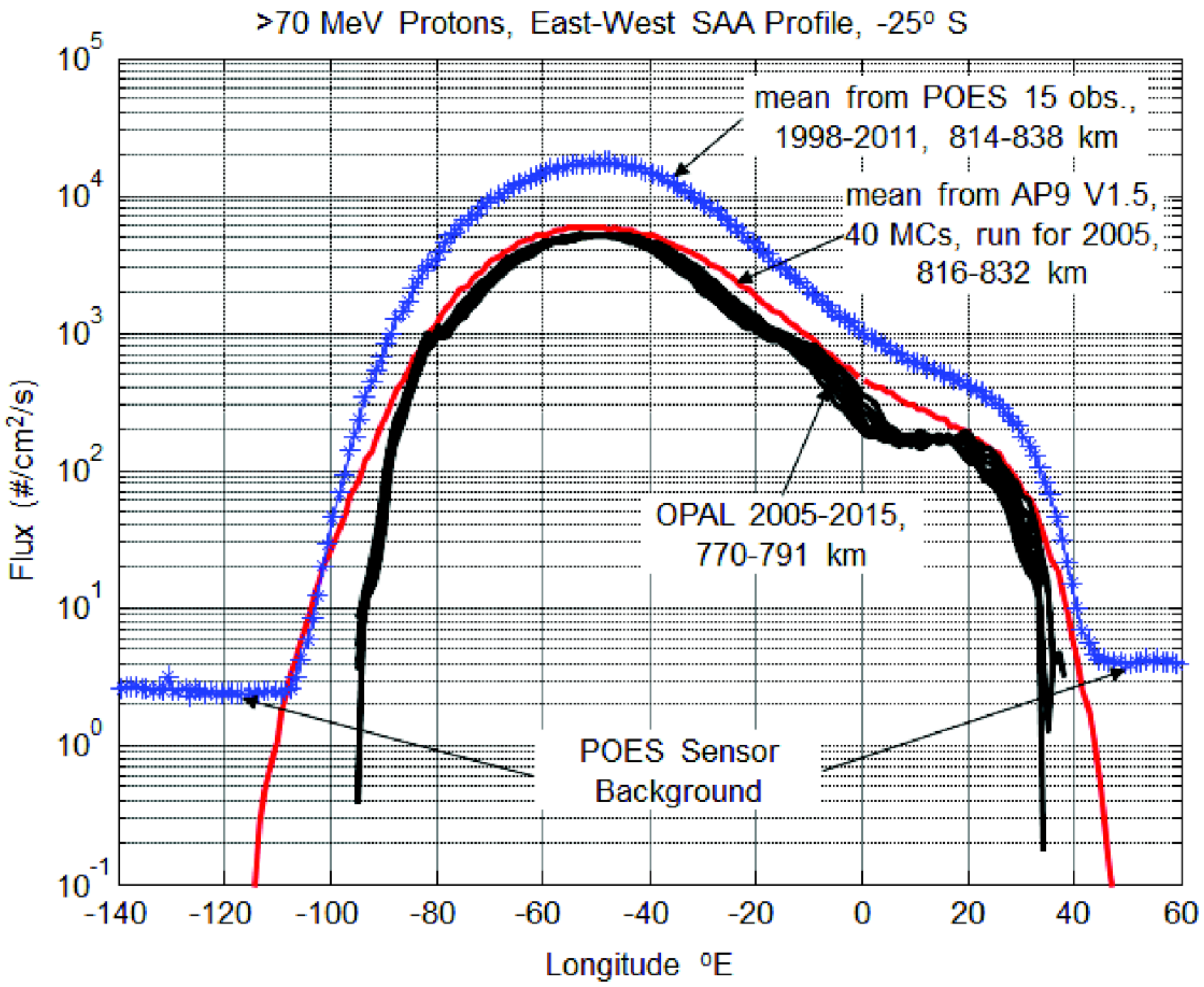
satellite	orbit	time period	instrument	species	energy
Van Allen Probes A & B	GTO (800 x 30600 km, 10°)	Aug 2012 – Dec 2016	RPS (Relativistic Proton Spectrometer)	protons	>58 MeV -- ~2 GeV
			REPT (Relativistic Electron Proton Telescope)	protons	20 – 100 MeV
			MagEIS	electrons	30 keV – 2 MeV
Azur	384 x 3145 km, 103°	Nov 1969 – Mar 1970	EI-88 telescope	protons	1.5 – 104 MeV
TWINS 2	Molniya (1000 x 39500 km, 63°)	Apr 2008 – Nov 2016	HiLET	protons	6 – 30 MeV

V1.50 Changes – AP9 Flux Maps



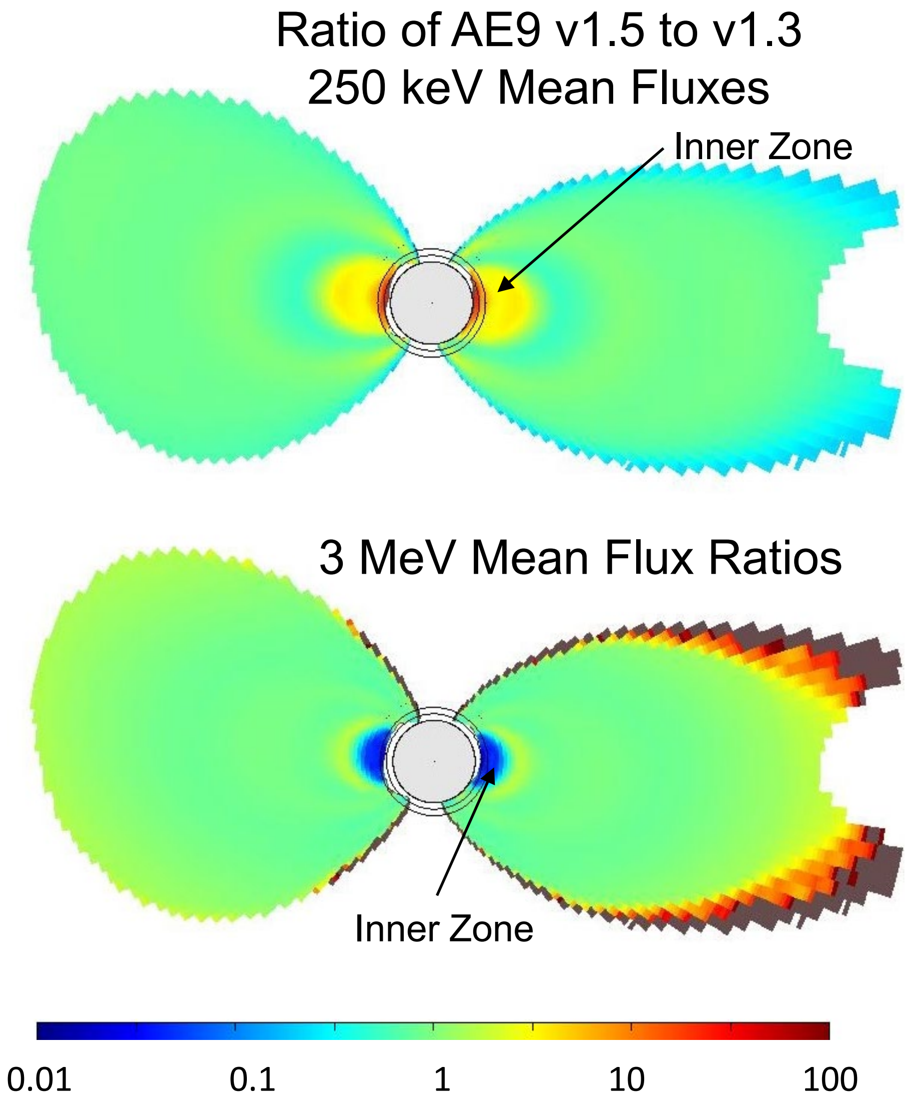
- AP9 adds Azur, HiLET and Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Especially large changes >150 MeV where RPS data represent the first clean observations in the inner zone up to 2 GeV

V1.50 AP9 Validation



- Use a "sequestered" dataset for verification: POES in LEO
- V1.50 is ~2.5-3.5x lower than POES SEM channels with historical flux conversion factors
- V1.50 is comparable to the ONERA/OPAL model, which uses new flux conversion factors for POES/SEM
- Shape of SAA profile is generally consistent between AP9 and data

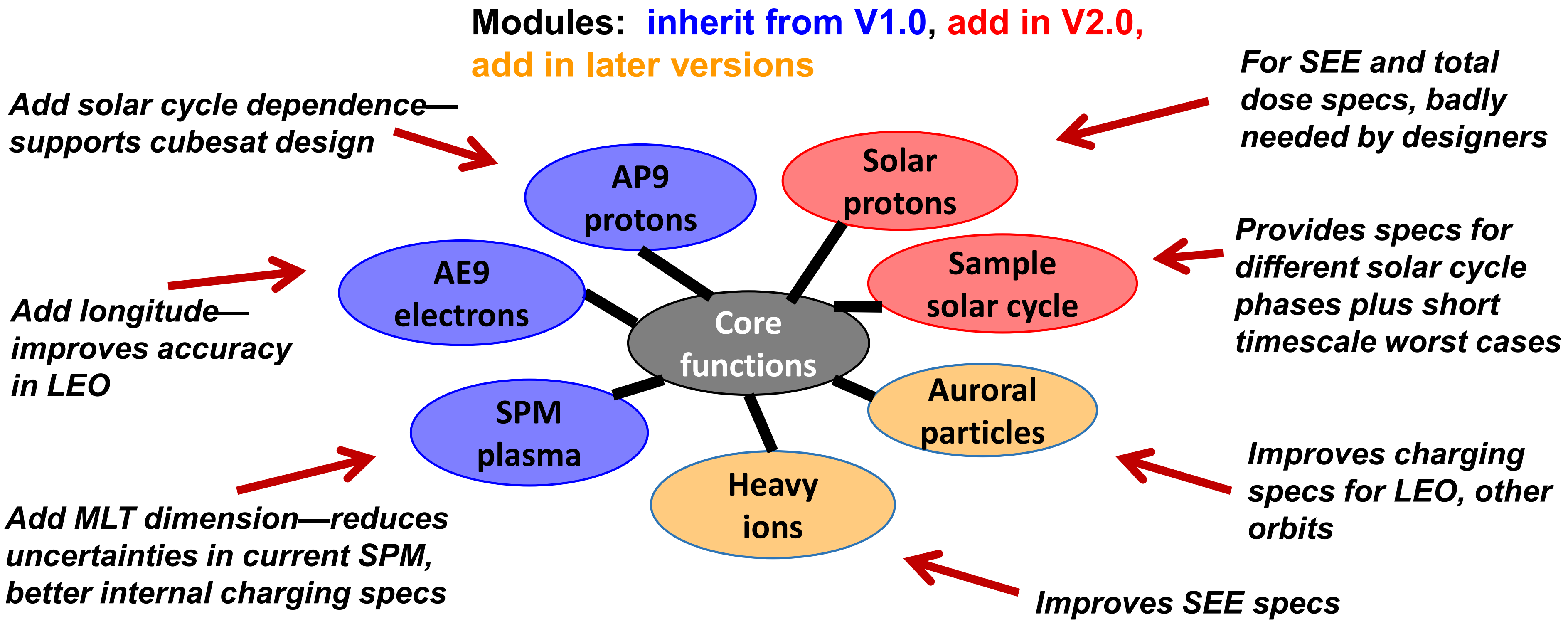
V1.50 Changes – AE9 Flux Maps



- AE9 adds Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Some localized higher fluxes

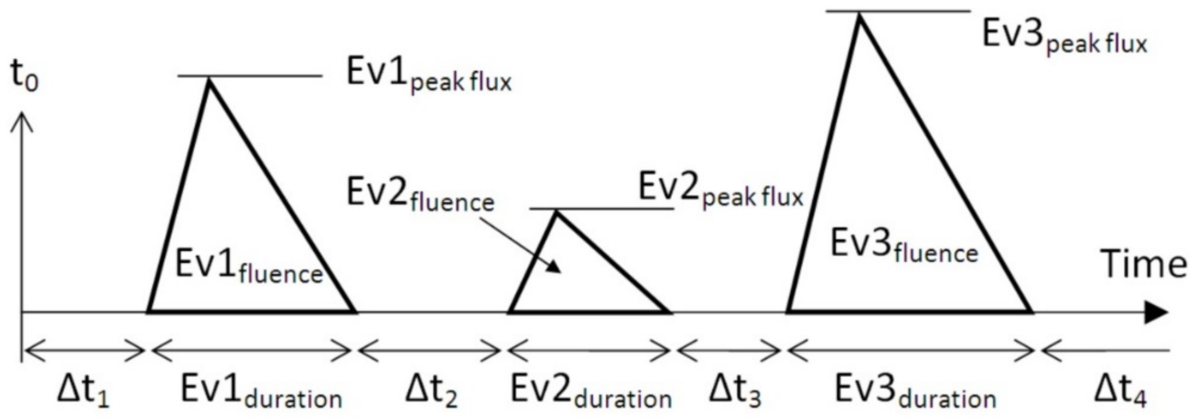
Version 2.0 Modules

- 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

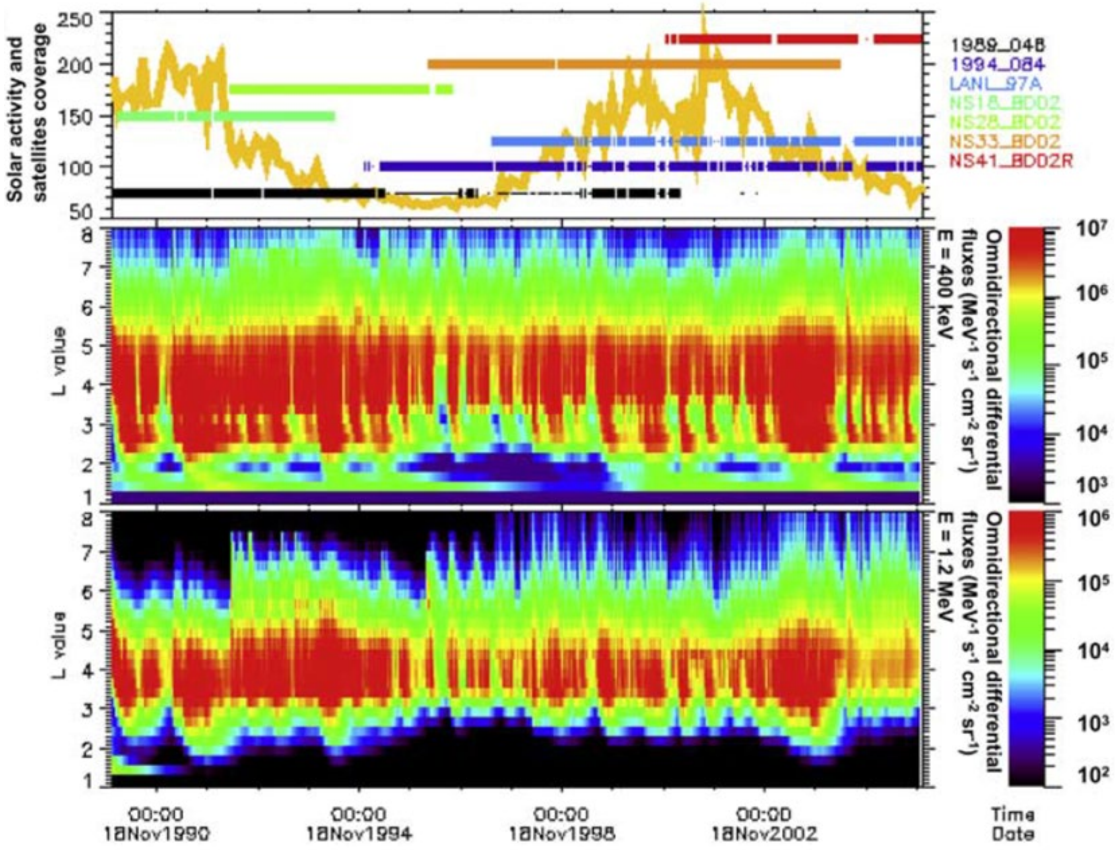
- Solar protons contribute to proton effects AP9:
  - Total Ionizing Dose
  - Displacement Damage
  - Single Event Effects



- 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

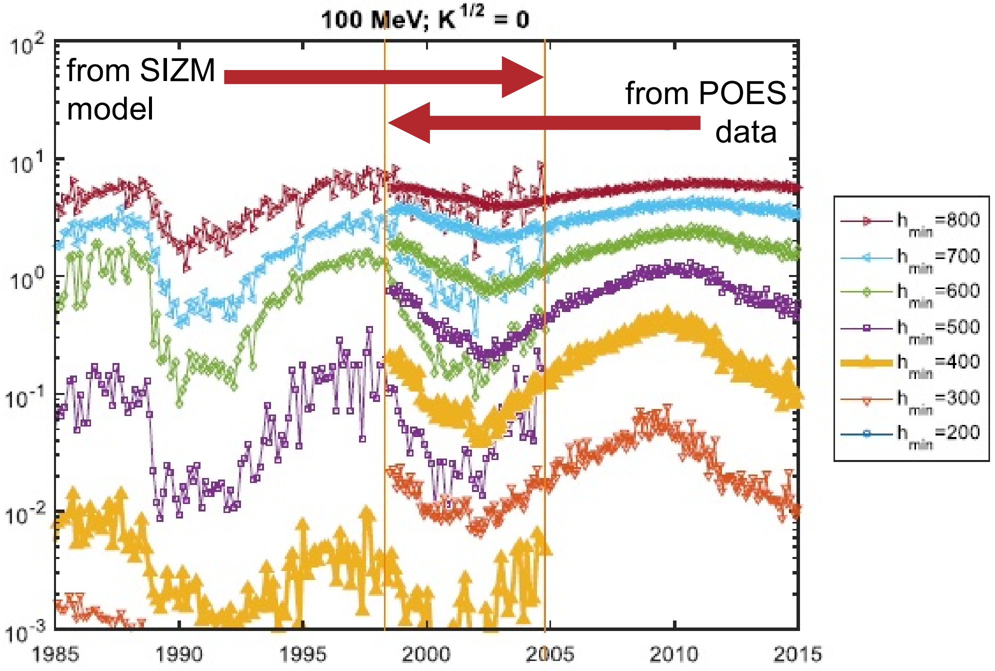
- Capture dynamics of realistic 11+ year solar cycle via data assimilative reanalysis
- “Fly through” this simulated dynamic environment as a check on Monte Carlo results
- Use the sample solar cycle to improve correlation matrices that drive Monte Carlo dynamics
- Use the sample solar cycle to help “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

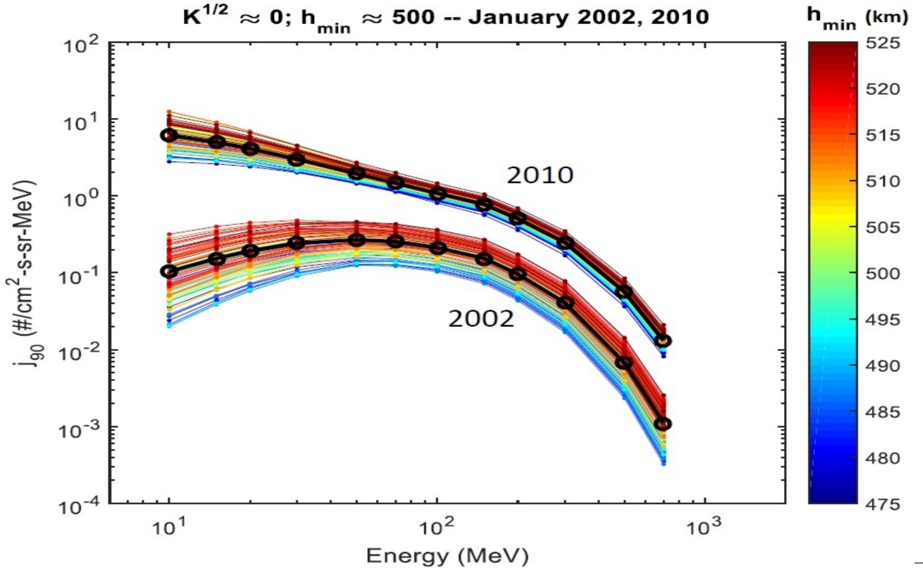


From Maget et al., Space Weather, 2007

Solar Cycle Variation of LEO Protons

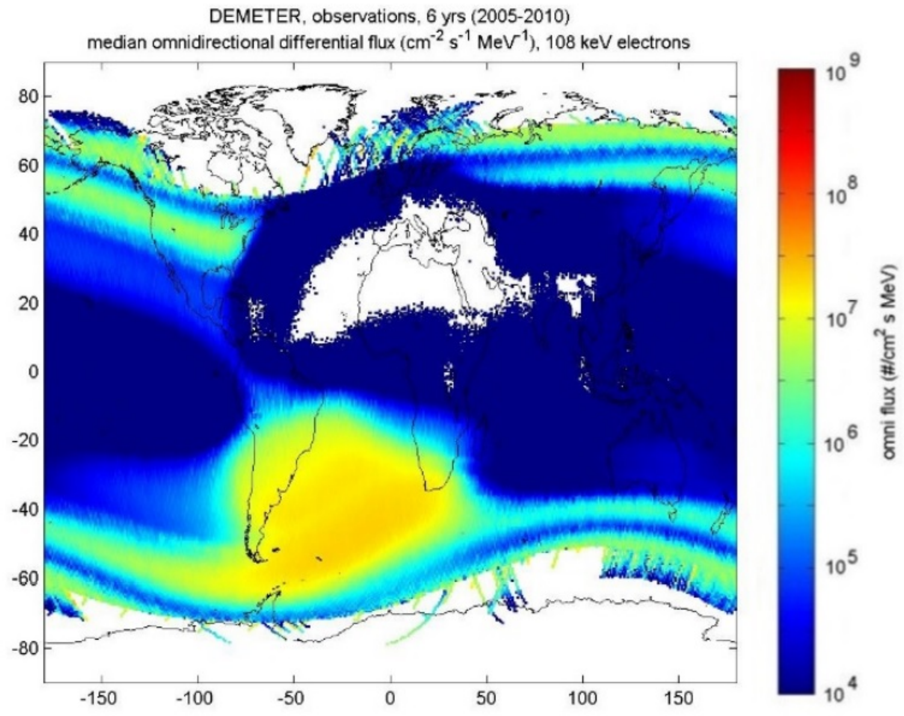
- No solar cycle dependence in AE9/AP9 currently
  - Statistics capture ranges across all solar cycle phases
- Users needs solar cycle dependence for trapped protons
  - Design for short duration LEO missions
  - Supports use of AP9 for nowcast estimates
- Work progressing towards solar cycle modulation 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





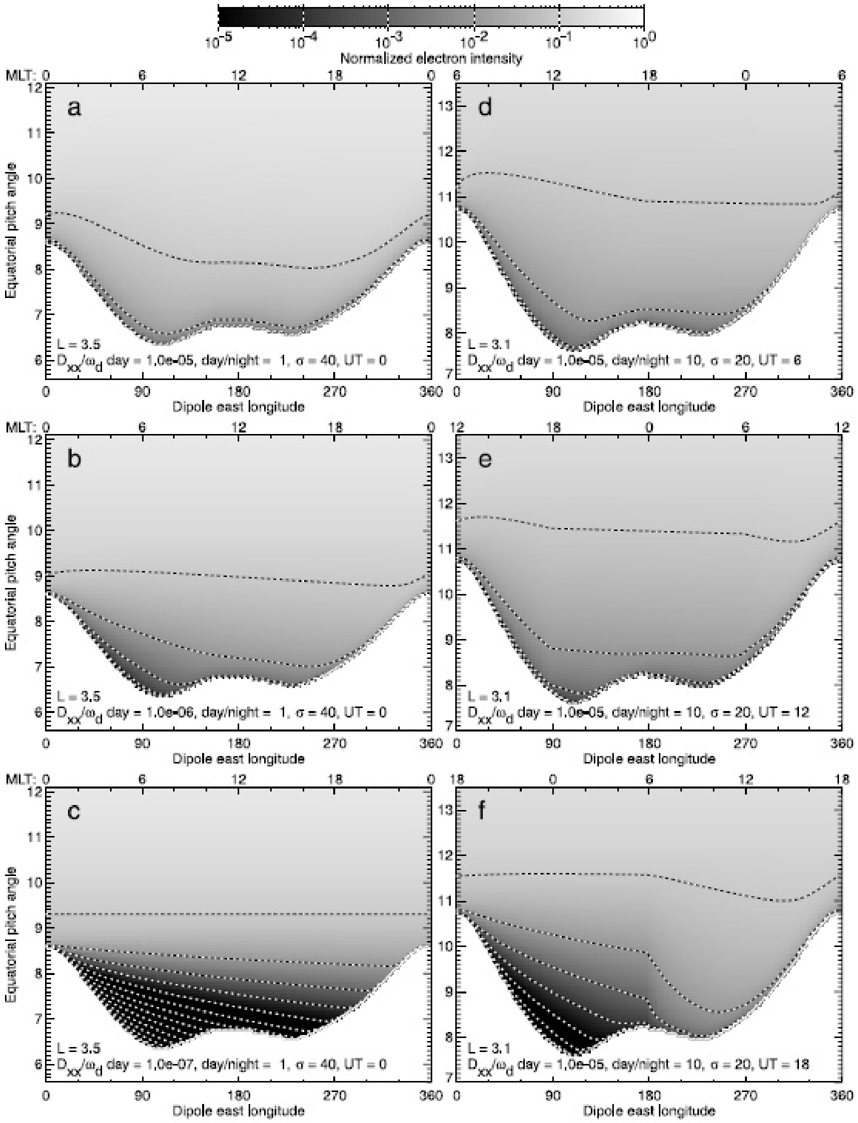
Fast, Compact LEO Electron Coordinates

- 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

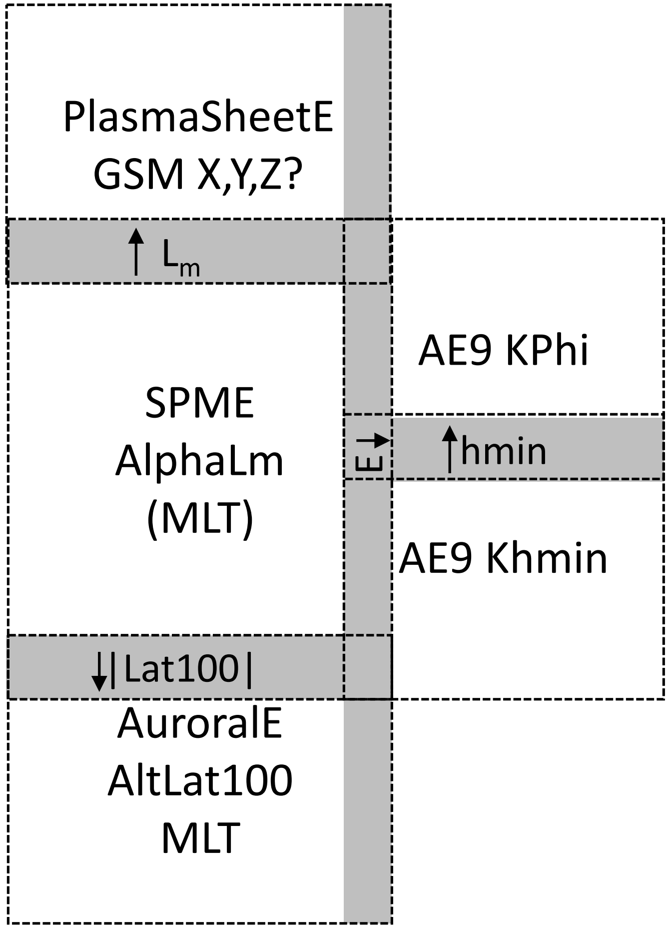
- At plasma and radiation belt energies, we do not have a great ability to model the altitude gradient below ~1000 km
- This is due in part to paucity of data, which could be remedied with DEMETER and other LEO data sources
- We expect a modeling component, e.g., the Selesnick drift-scattering model, 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



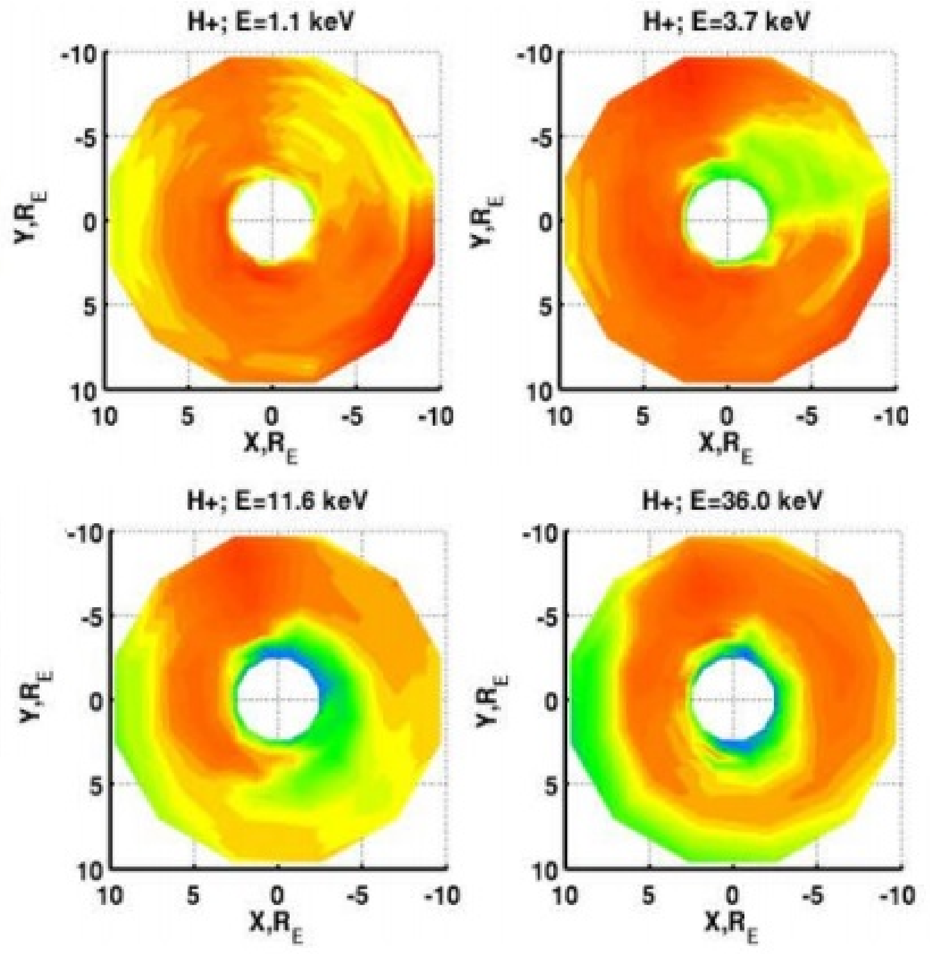
Arrow indicates direction of increase of stitching variable

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 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^+)

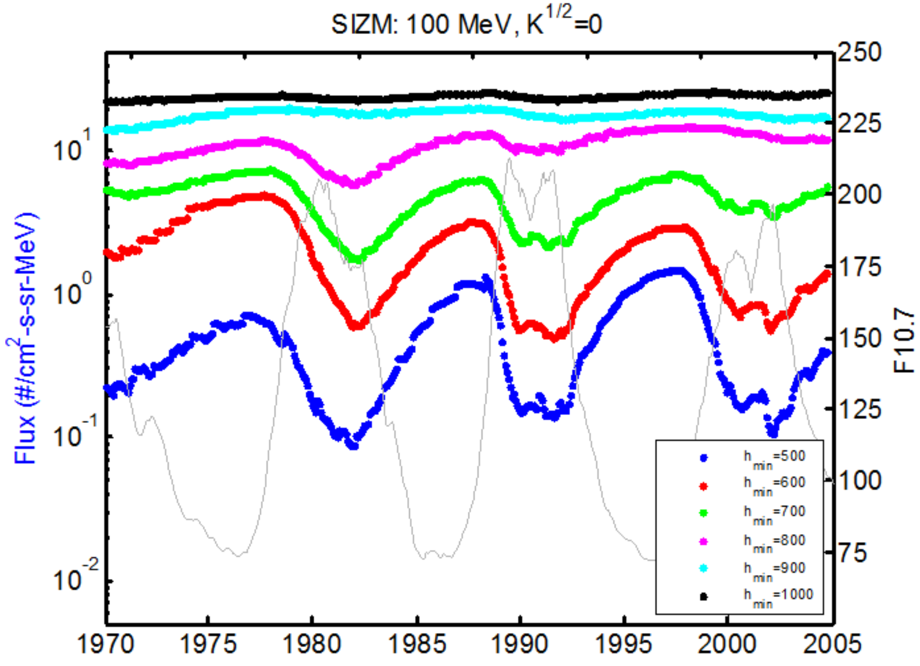
Data Set Needs—Plasma

- Space Plasma Model (SPM) does not currently include MLT dependence
- What we need:
  - Reprocessed or new data sets with MLT coverage
  - Electrons, protons, He^+, O^+
  - 10 eV – 100 keV
- AMPTE/CCE data set is an example of a desired data set
  - GTO orbit, ~5 yrs of data
  - Energy coverage 1.5 – 300 keV/e



Data Set Needs—General

- Additional data sets for all particle populations are needed for:
  - Addressing known spatial/energy regimes with limited coverage
- Planned addition of solar cycle dependence requires data sets for:
  - Informing/validating solar cycle variability
  - Informing/validating low altitude gradients
- What we need:
  - Low altitude, energy- and angle-resolved data sets
  - Long duration (11 years or more) for solar cycle variation



From Selesnick et al., JGR,

Progress - Architecture

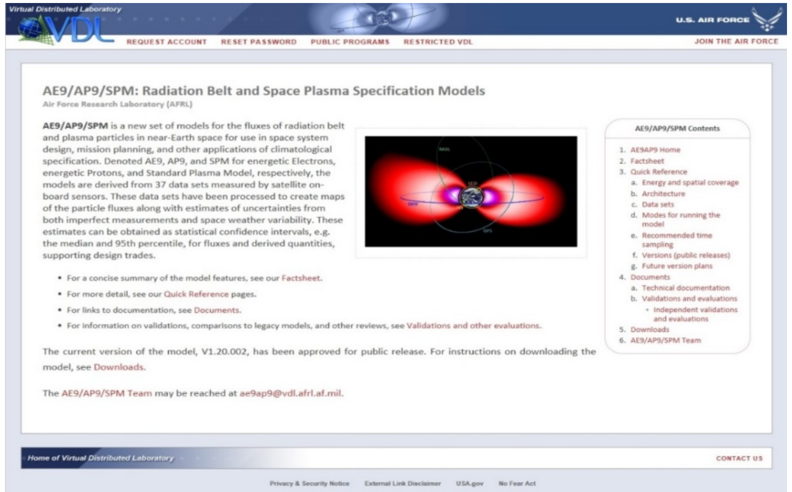
Capability	Status	Notes
Static AE9, AP9, SPMH, SPME Modules	Prototyped	US/Aerospace
Monte Carlo AE9/AP9 Modules	Research	US/Aerospace
Monte Carlo Solar H+	Prototyped	ESA/SPARC
Monte Carlo Solar Ions	Research	ESA/SPARC
Solar Cycle Dependence LEO Protons	Research	US/Huston
Sample Solar Cycle	Datasets Needed	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

- AE9/AP9-IRENE 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**