AE9/AP9-IRENE space radiation climatology model

NOVEMBER 7, 2018

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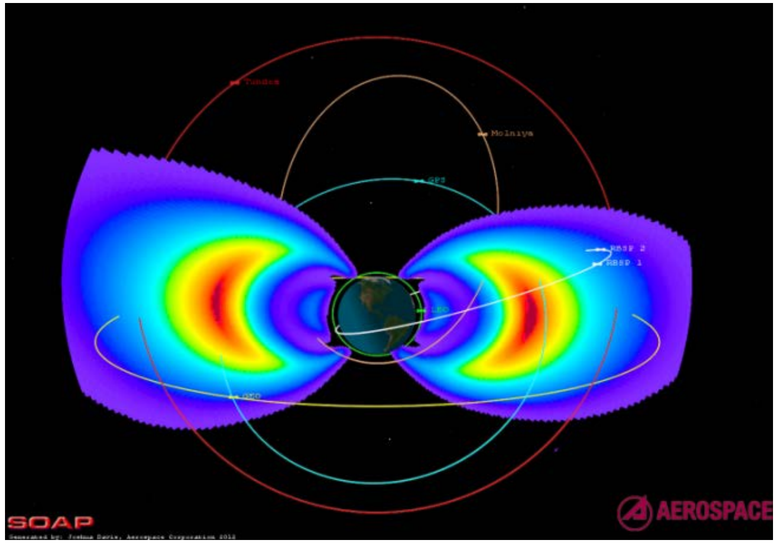
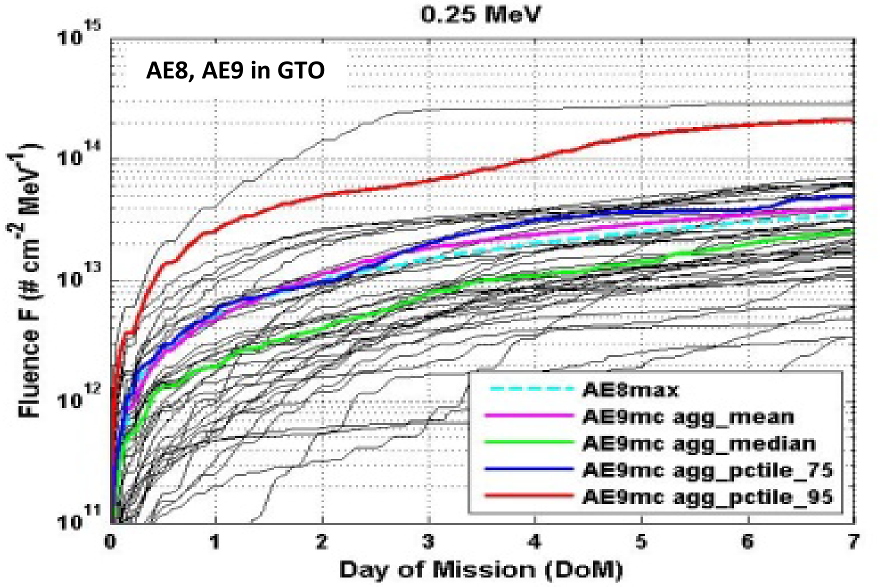
Outline

- Background on AE9/AP9/SPM model
- Version 1.50—new data
- Version 1.55—kernels
- Plans for future versions
- 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
- Version 1.00 released in 2012



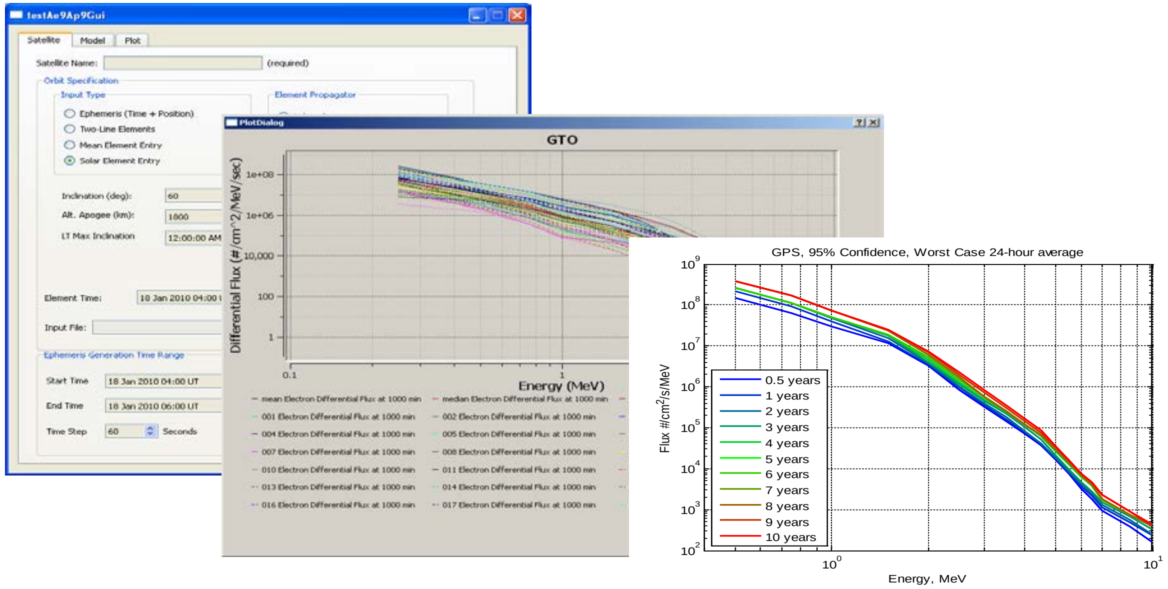


Coverage and Application

- 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

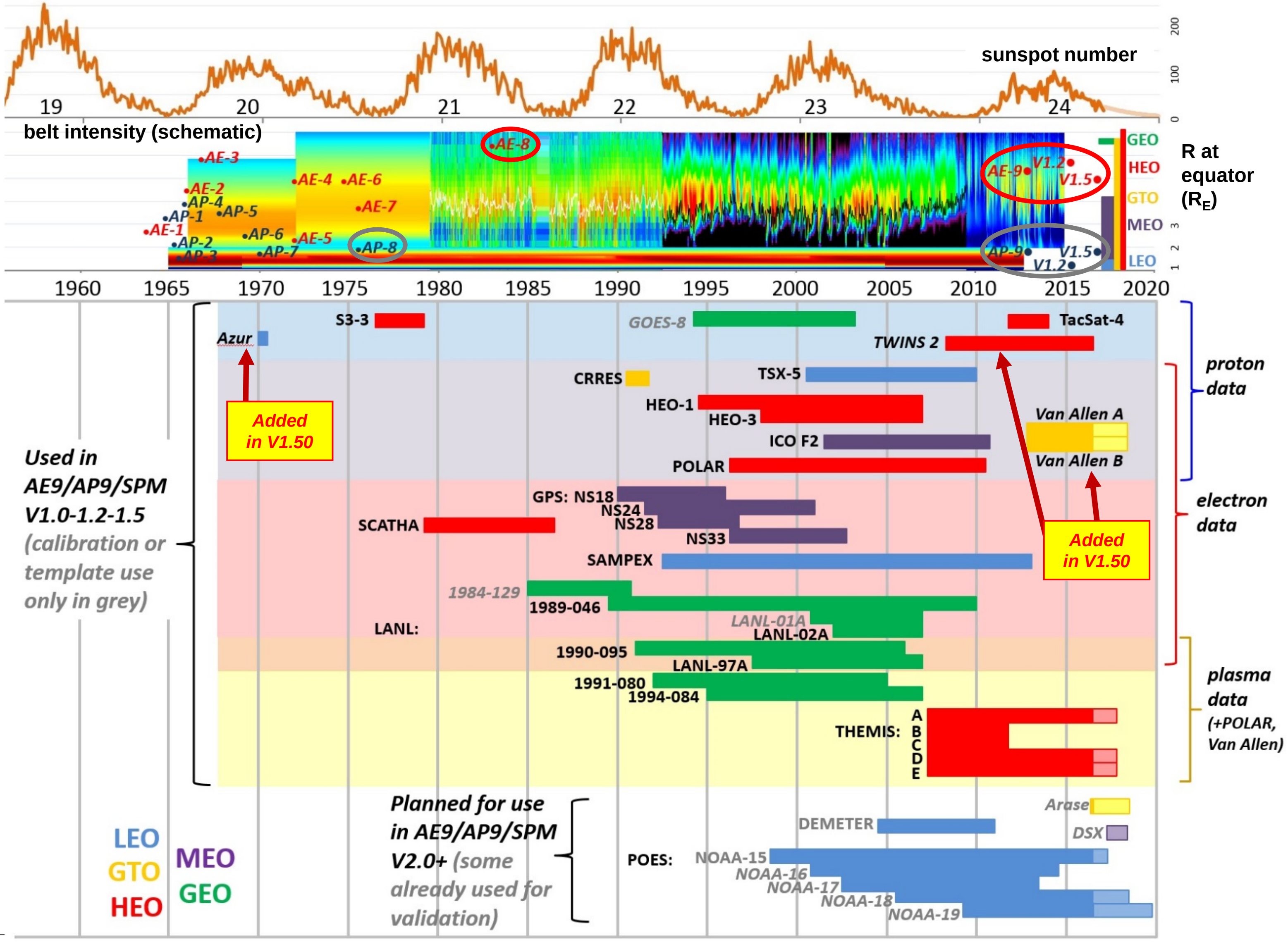
300+ instrument-years of data

- 10x more than AE8+AP8

All solar cycle phases sampled:

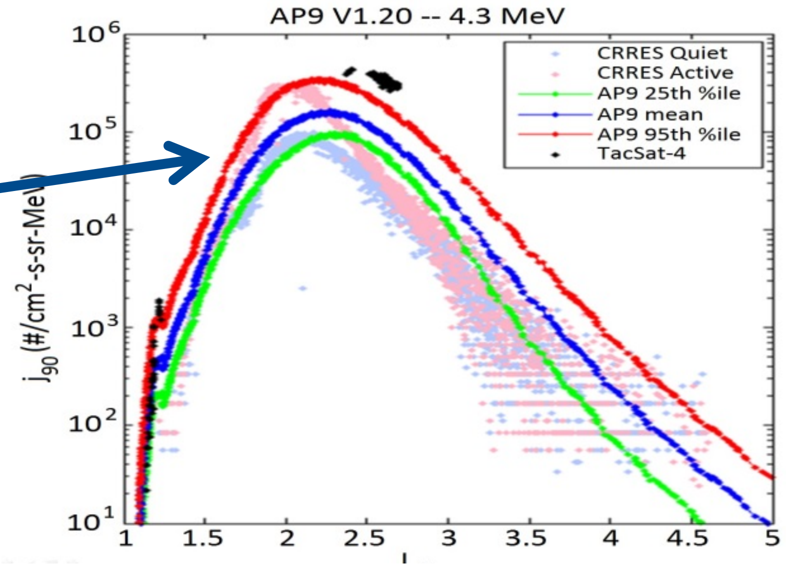
- 16 sets >10 yrs
- 26 sets >5 yrs

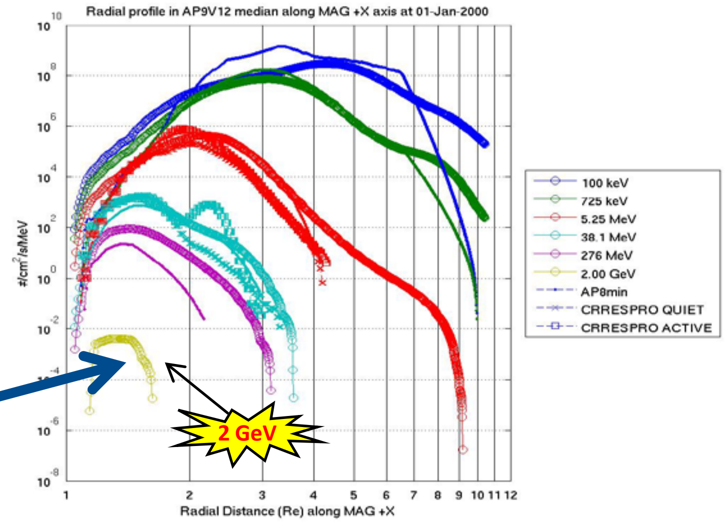
10x the data of previous models, and still growing!



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





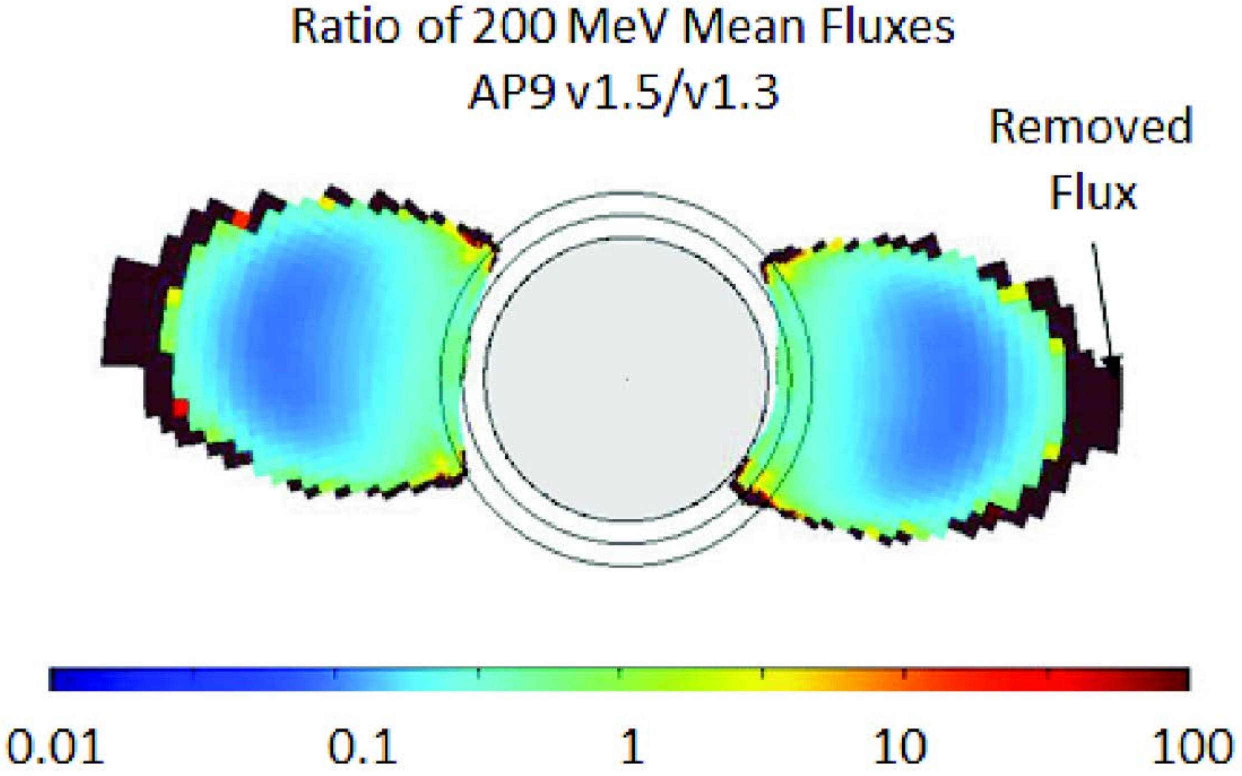
Changes in AE9/AP9 V1.50

- 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)

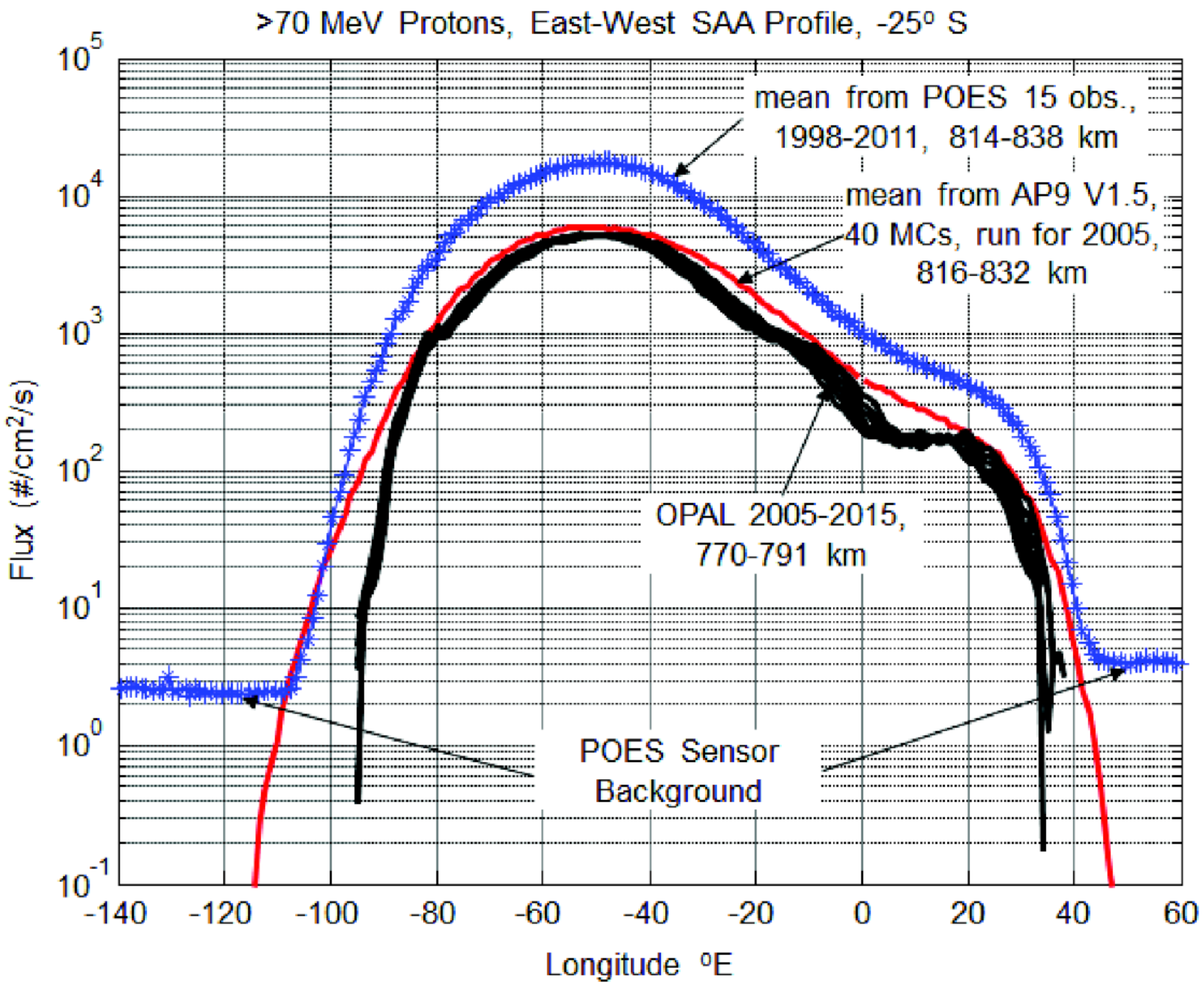
satellite	orbit	time period	instrument	species	energy
Van Allen Probes A & B	GTO (800 x 30600 km, 10°)	Aug 2012 – Dec 2016	RPS (Relativistic Proton Spectrometer)	protons	>58 MeV -- ~2 GeV
			REPT (Relativistic Electron Proton Telescope)	protons	20 – 100 MeV
			MagEIS	electrons	30 keV – 2 MeV
Azur	384 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



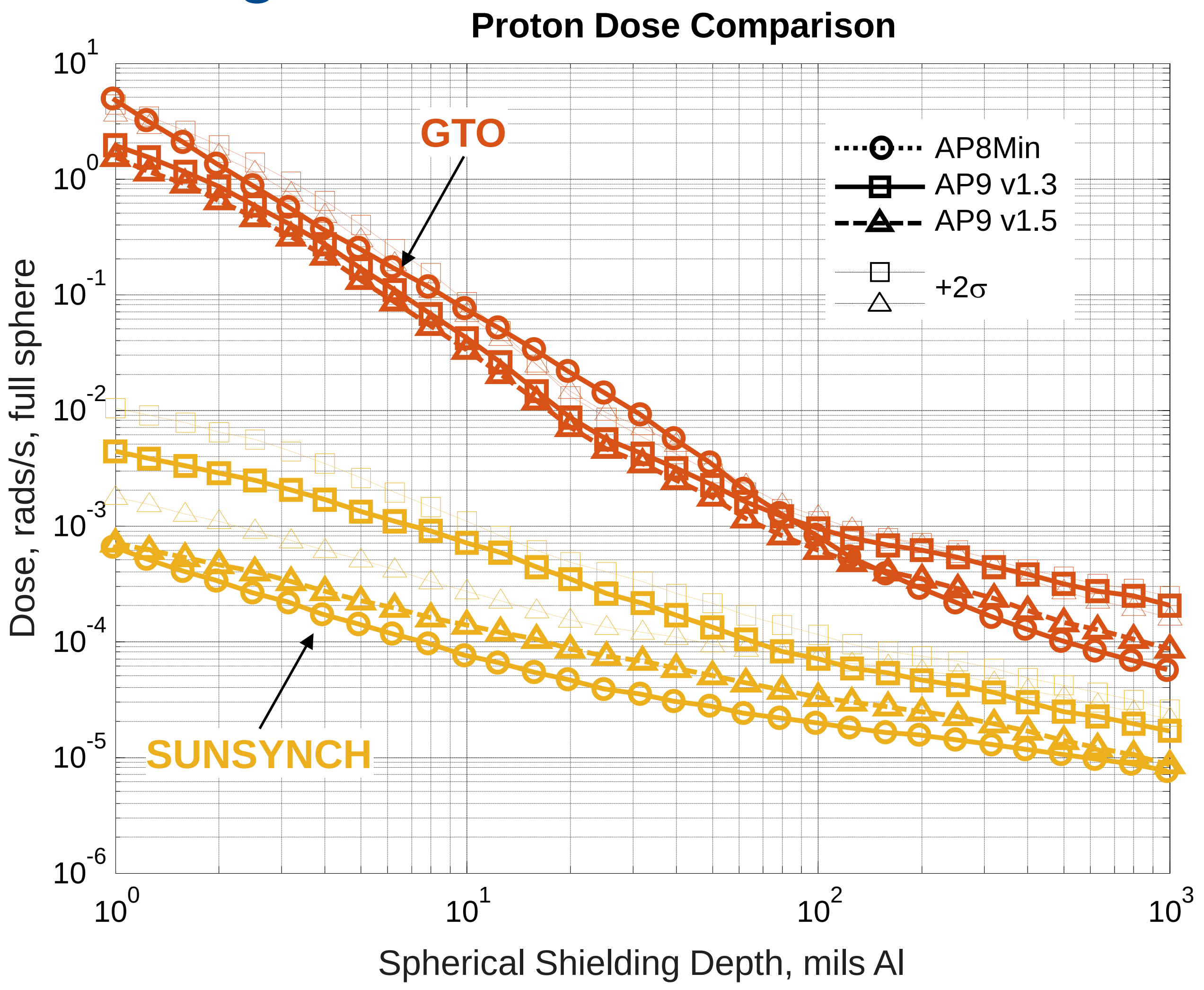
- AP9 adds Azur, HiLET and Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Especially large changes >150 MeV where RPS data represent the first clean observations in the inner zone up to 2 GeV

V1.50 AP9 Validation



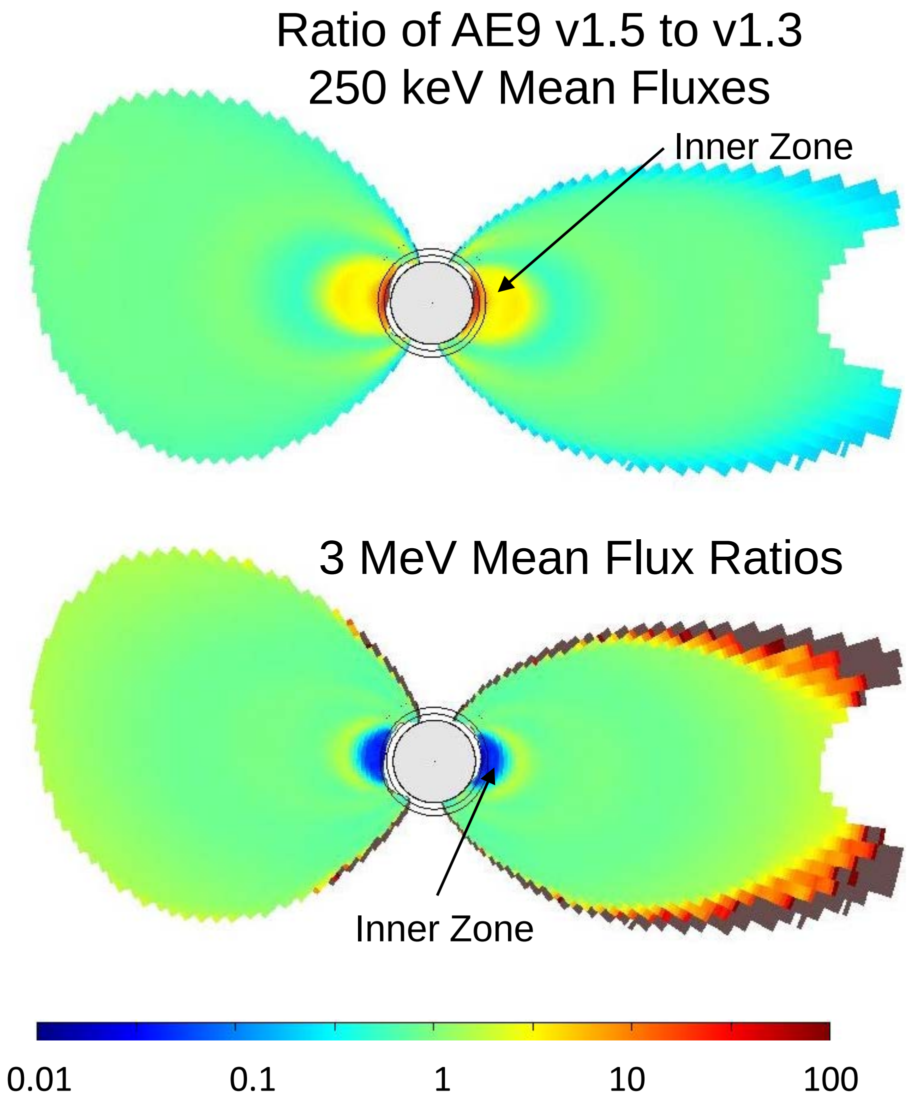
- Use a "sequestered" dataset for verification: POES in LEO.
- V1.50 is ~2.5-3.5x lower than POES SEM channels with historical flux conversion factors.
- V1.50 is comparable to the ONERA/OPAL model, which uses new flux conversion factors for POES/SEM.
- Shape of SAA profile is generally consistent between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

V1.50 Changes – AP9 Dose



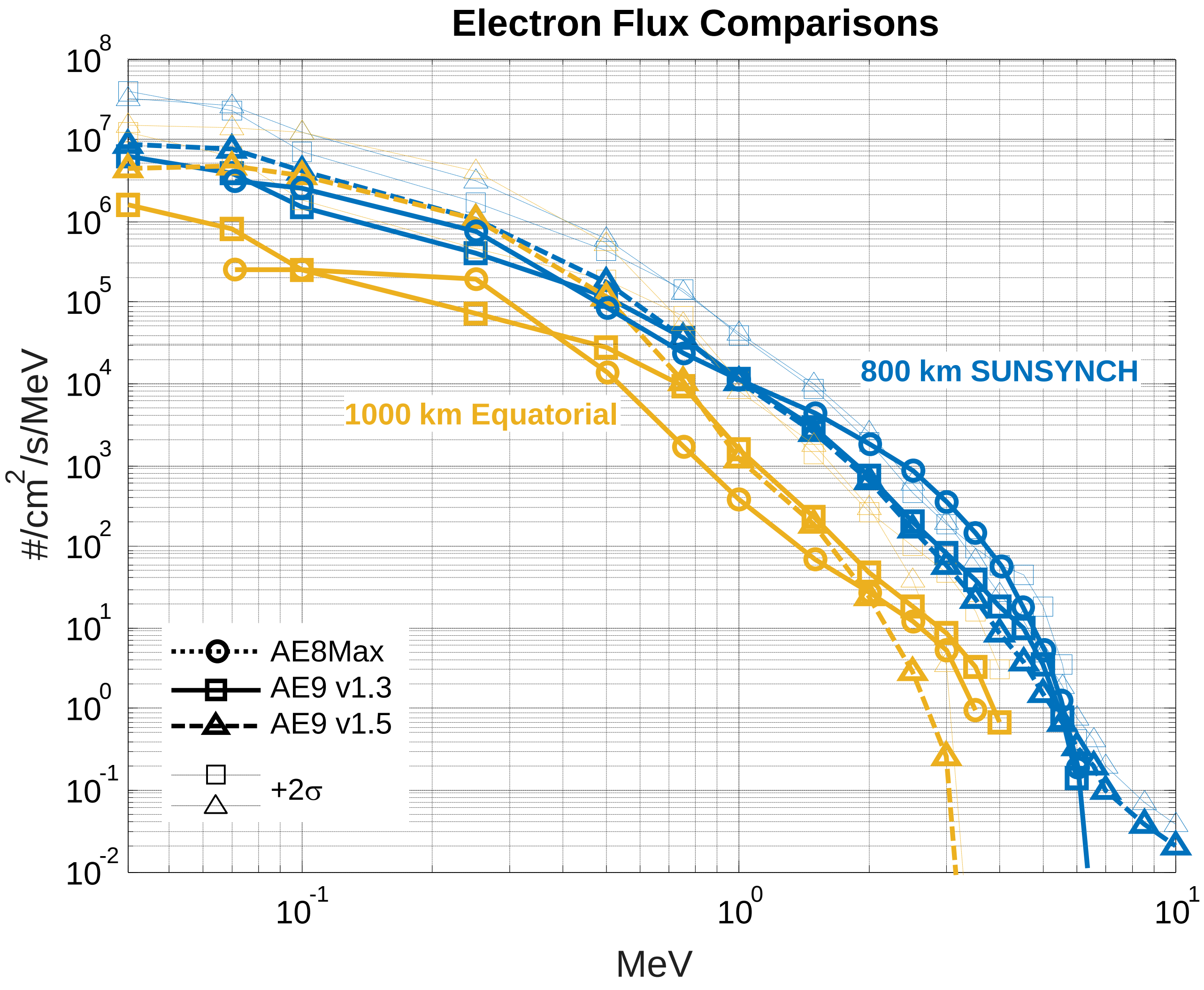
- Lower dose in all orbits
- Most pronounced in LEO at all depths and in GTO at thicker depths
- In some places, larger error bars raise 95% CL even though mean flux is lower

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

V1.50 Changes – AE9 in LEO

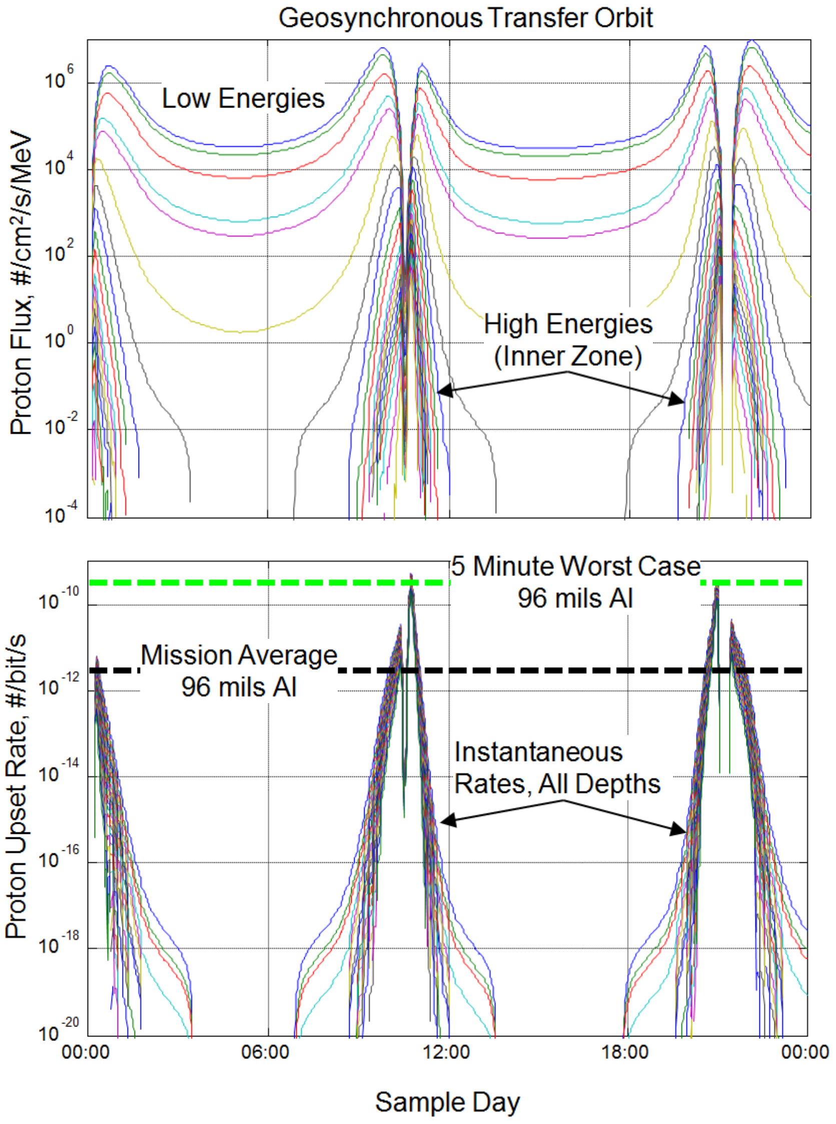


- Fluxes are higher at <800 keV for 1000 km orbits
- Upper error bars are larger for both orbits

Forthcoming Versions

Version	Features
V1.55 (late 2018)	Kernels for faster effects calculations
V1.60 (2019)	Additional Van Allen Probes data
V2.00 (~2020)	New architecture New modules—solar protons, sample solar cycle 4-dimensional AE9, AP9, SPM New data sets—POES, int'l.
V2.50(?) (~2021)	New modules New data sets—DSX, Arase

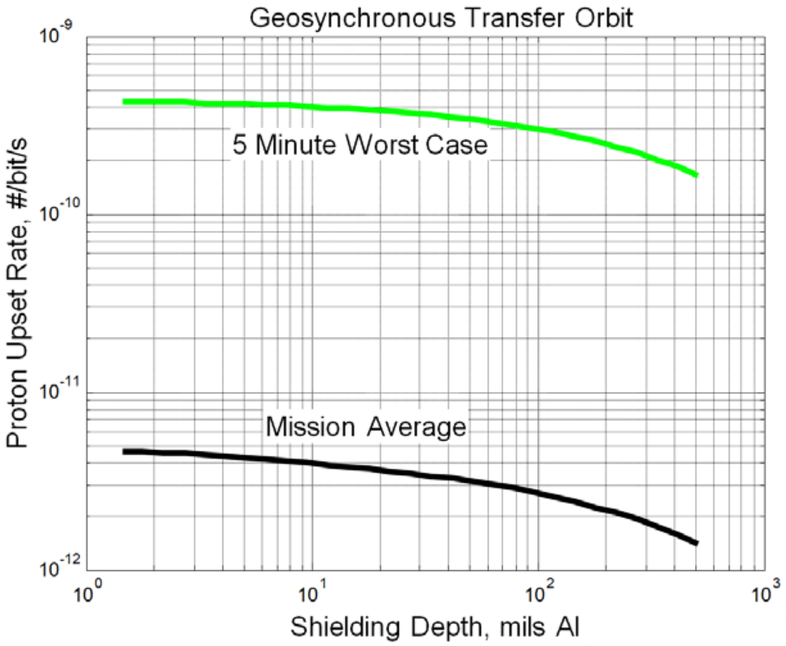
Kernel-Based Effects Calculation



- 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

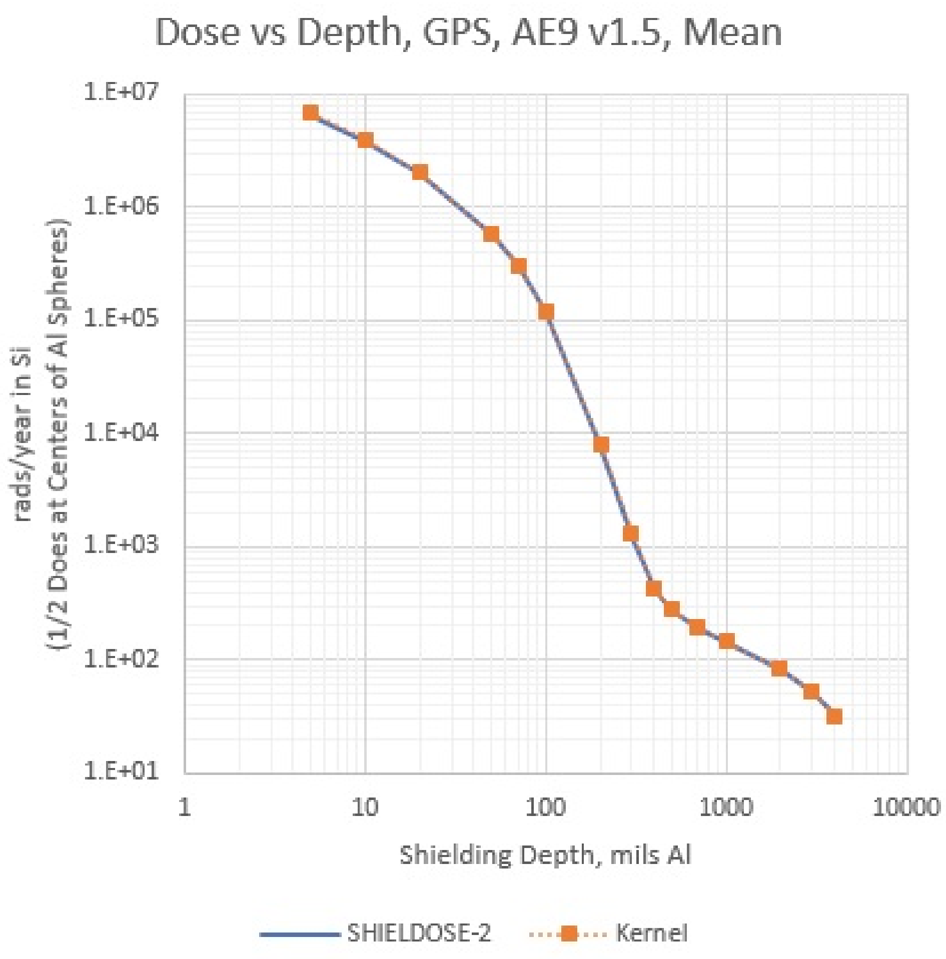


Effects Kernels

- AE9/AP9 natively provides confidence levels on differential or integral flux
- Users want more:
  - It is conservative to compute the 95th % confidence level radiation effect from a 95th percentile spectrum: assumes all energies are at 95th % level simultaneously
  - Users want other radiation effects that have become de facto standards
- 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 allow AE9/AP9 to compute several radiation effects:
  - Dose vs depth
  - Displacement damage due to protons
  - Single Event Effects due to protons
  - Charging current behind shielding
- Kernels are "fast" to allow calculation of worst case transients by converting every spectrum to its effects
- User can provide their own kernels for custom shielding, materials

V1.55 Update – Dose Kernel

- Release 2018
  - US Government & Contractors: November 2018
  - General Public: December 2018
- Changes
  - This is a feature update only
  - Flux maps are not changed –specs generated with v1.55 will be essentially identical to v1.50
- Dose-Depth Kernels
  - All SHIELDOSE-2 target materials and geometries are now supported via kernels
  - Kernels reproduce SHIELDOSE-2 results to within ~10% or better
  - Kernels run as much as 2-10 times faster, e.g., for daily dose outputs on a 1-year run at GEO

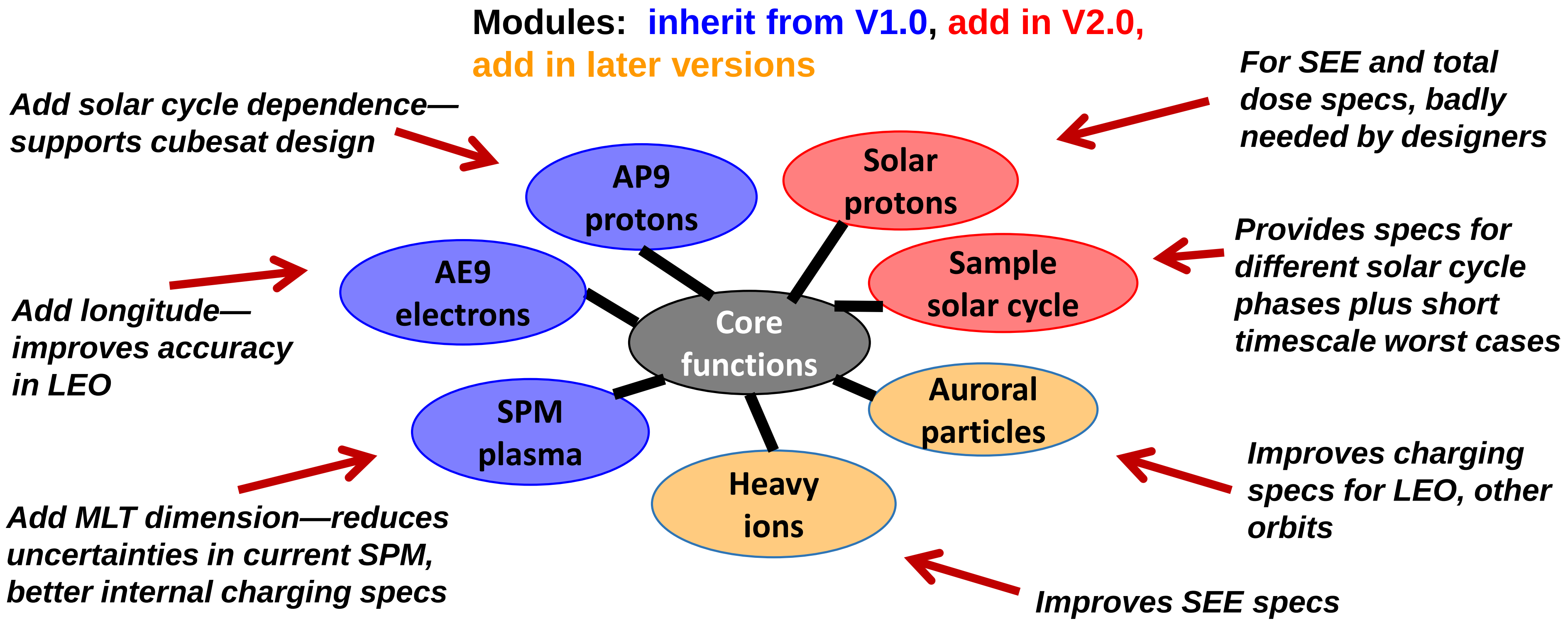


Version 2.00

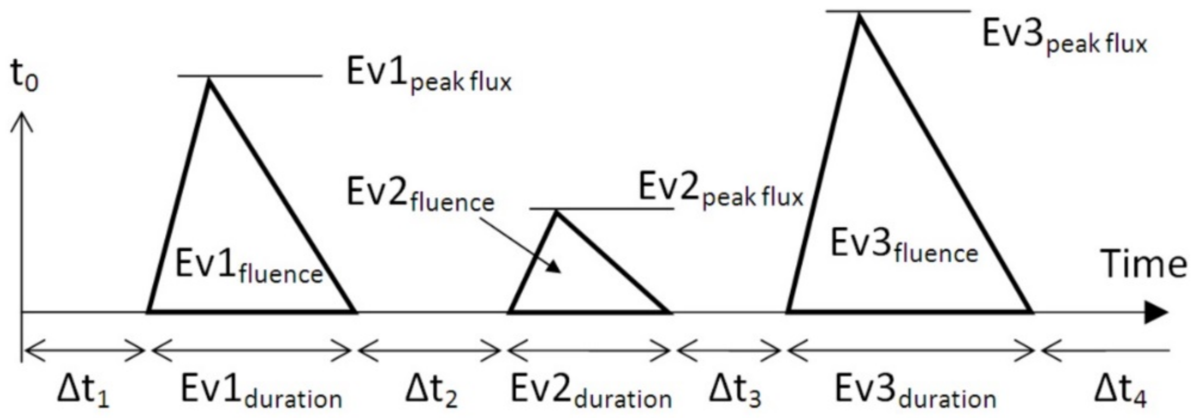
- Major feature changes:
  - Incorporate untrapped solar protons with statistics
  - New module frameworks for e.g. plasma species correlations, SPM stitching with AE9/AP9, auroral electrons, additional coordinates for MLT variation in SPM
  - Sample solar cycle—introduces a full solar cycle reanalysis as a flythrough option
  - AP9 improvements: solar cycle variation in LEO, east-west effect
- New data
  - Van Allen Probes/RPS, MagEIS & REPT protons and electrons (this is additional to Van Allen Probes data already added in V1.50)
  - 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

Version 2.0 Modules

- The module architecture is a generalization/combination of existing pieces
  - Khmin/KPhi stitching (runtime)
  - SPM/AX9 stitching (post-processing → runtime)
  - ESA framework for combining trapped + solar + GCR (post-processing → runtime)



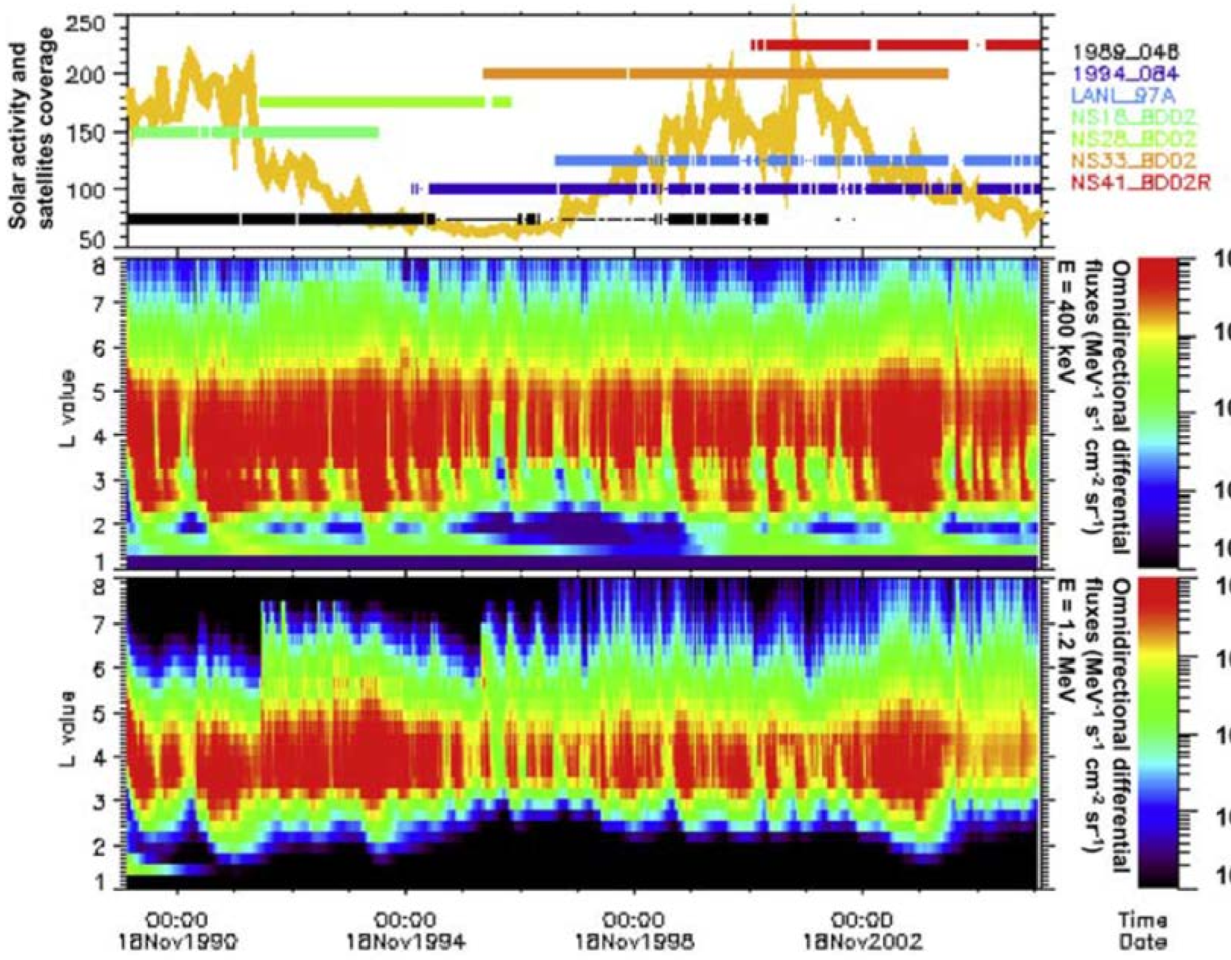
Integrating Solar Protons



- 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



From Maget et al., Space Weather, 2007

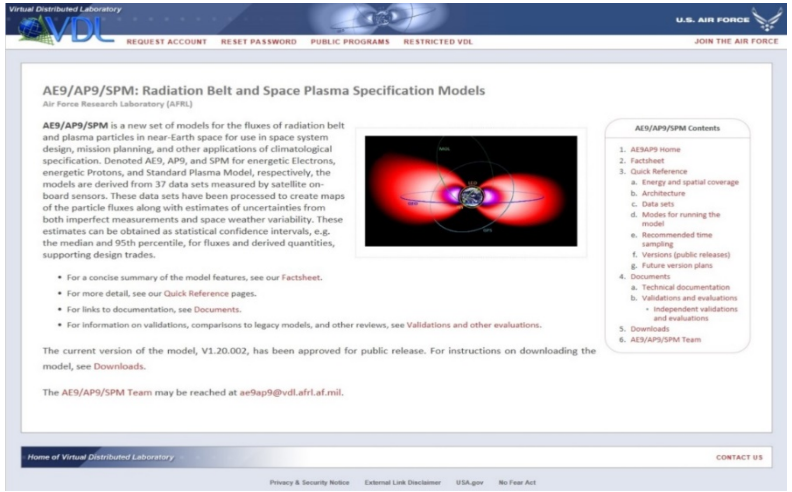
Additional Data in Coming Versions

- Van Allen Probes--plasma, add'l. protons, electrons
- Arase—protons, electrons, plasma
- DSX—protons, electrons, plasma
- PAMELA—high energy protons
- AMPTE—plasma
- Other international data sets
- possibilities include Cluster/RAPID-IIMS, ESA SREMs, CORONAS, NINA, Akebono/EXOS-D, SAC-C, Jason2

- Module changes will add more information, have new data needs
  - plasma MLT dependence
  - new modules such as auroral particles
- Plan to use physics-based and assimilative models to support improvements in flux maps
  - merging data sets, extrapolations, spatial-temporal correlations
  - address low-altitude gradients

Conclusion

- AE9/AP9/SPM provides radiation environment specification to meet the needs of modern designers
- Successive releases 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, 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**