AE9/AP9-IRENE: Overview and Recent Updates

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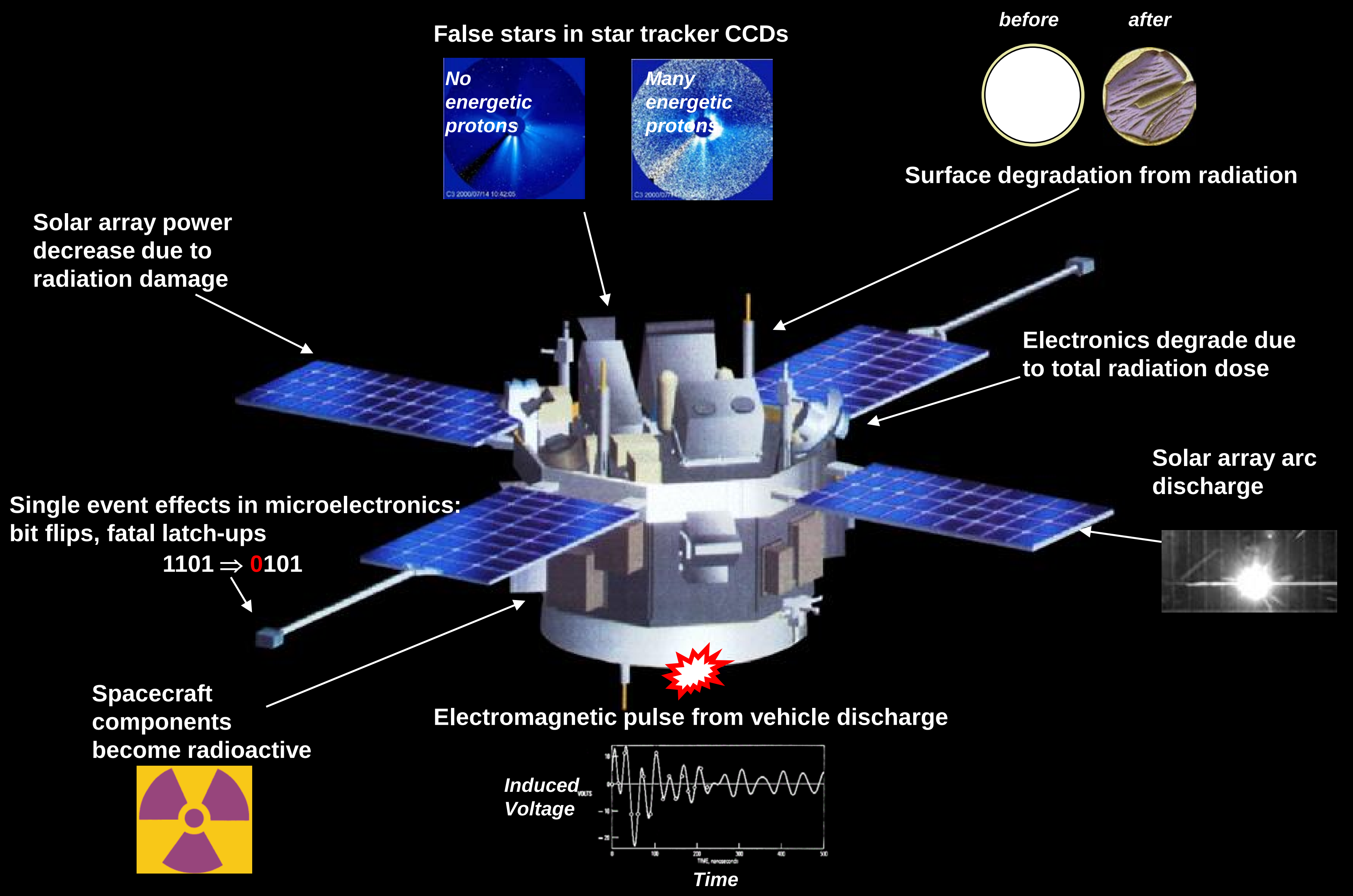
The Aerospace Corporation

Integrity ★ Service ★ Excellence

Outline

- The need for a new radiation model
- AE9/AP9-IRENE: An overview
- The Monte-Carlo framework
- Kernels for SEE rates
- How to make a worst-case specification
- Summary

Energetic Particle & Plasma Hazards

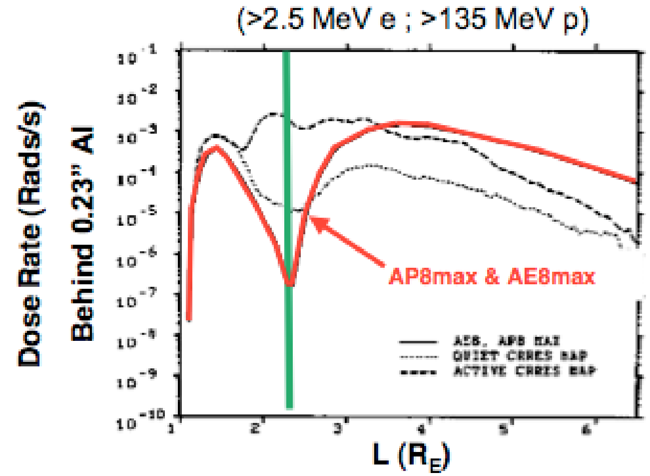


Distribution A: Approved for public release; distribution unlimited.

The Need for AE9/AP9

- Prior to AE9/AP9, the industry standard models were AE8/AP8 which suffered from
  - inaccuracies and lack of indications of uncertainty leading to excess margin
  - no plasma specification with the consequence of unknown surface dose
  - no natural dynamics with the consequence of no internal charging or worst case proton single event effects environments
- AE8/AP8 lacked the ability to trade actual environmental risks like other system risks
- AE8/AP8 could never answer questions such as “how much risk can be avoided by doubling the shielding mass?”

Example: Medium-Earth Orbit (MEO)



For MEO orbit (L=2.2), #years to reach 100 kRad:

- **Quiet conditions (NASA AP8, AE8) : 88 yrs**
- **Active conditions (CRRES active) : 1.1 yrs**

AE8 & AP8 under estimate the dose for 0.23” shielding

System acquisition requires accurate environment specifications without unreasonable or unknown margins.

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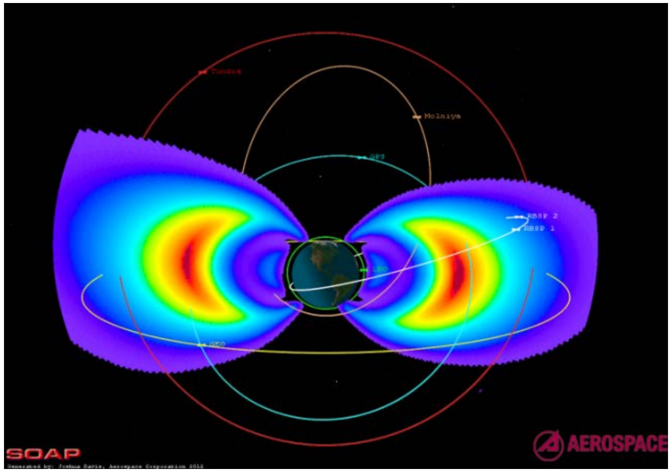
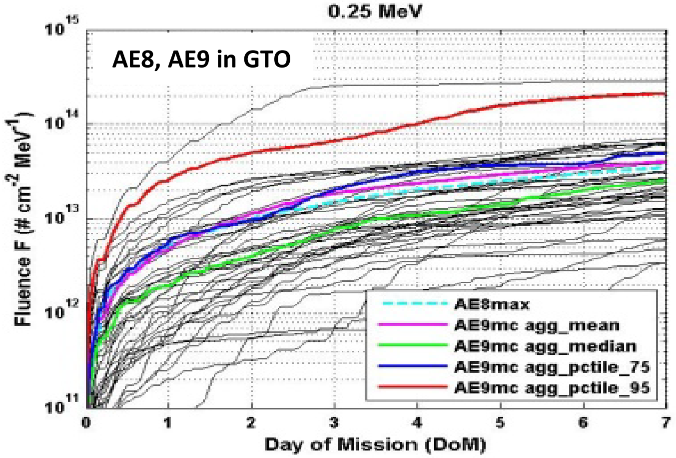
What is AE9/AP9/SPM?

- 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

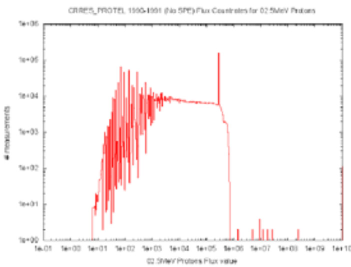


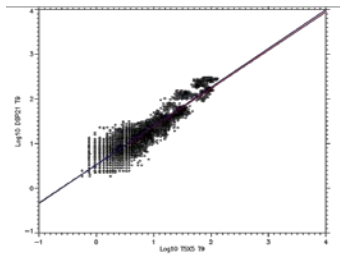


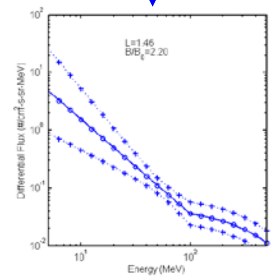
Building Flux Maps

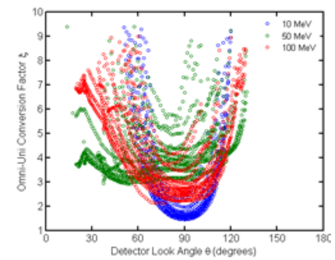
Example for a dosimeter data set

Sensor model



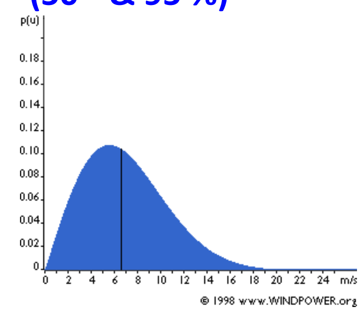




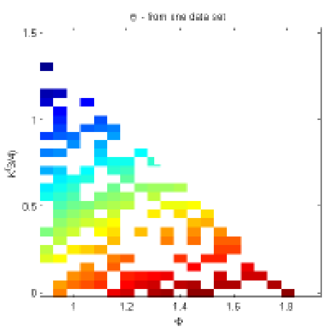


Sensor 1 data → Cleaning → Cross-calibration → Spectral inversion → Angle mapping (j_{90})

Statistical reduction (50^{th} & 95 %)



← Template interpolation ←

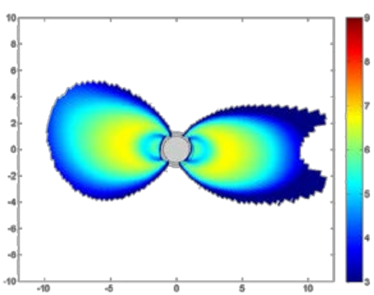


- Flux map – sensor 1
- Flux map – sensor 2
- .
- .
- .
- Flux – map sensor N

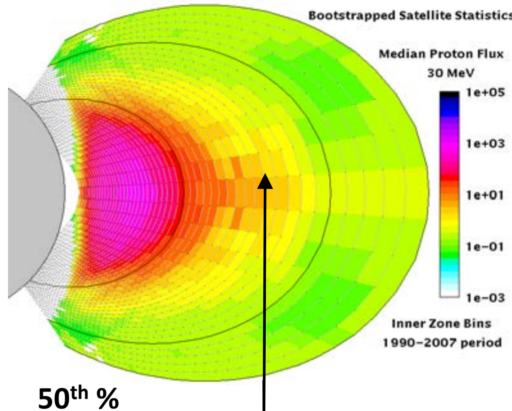
Bootstrap initializing with variances

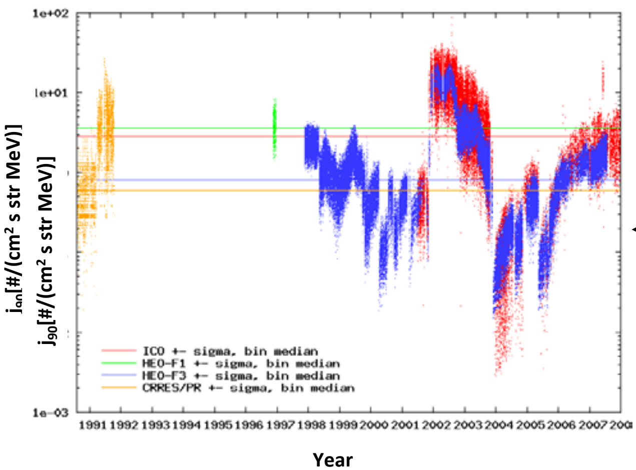
↓

50^{th} & 95 % Flux maps

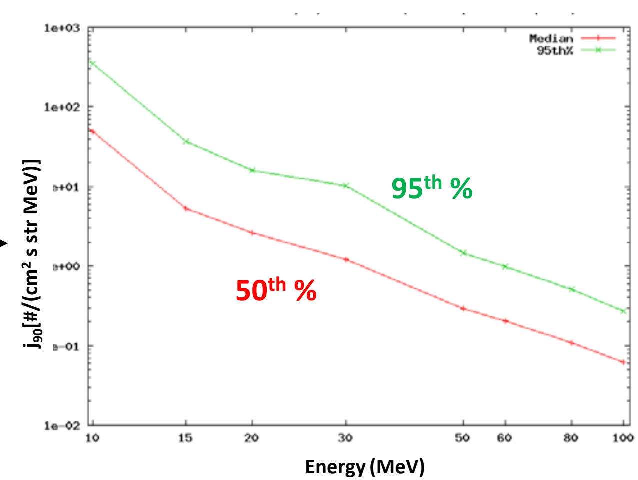


Example: Proton Flux Maps

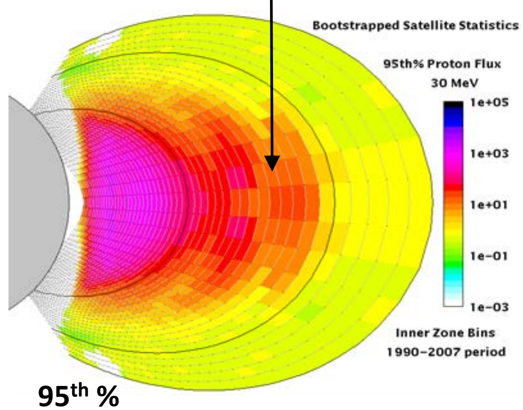




Time history data



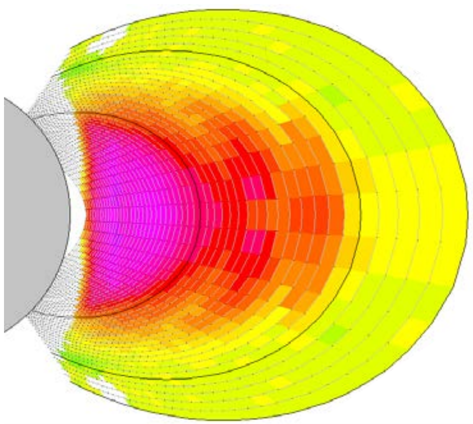
Energy spectra



Flux maps (30 MeV)

Architecture Overview

Satellite data



Flux maps

- Derive from empirical data
  – Systematic data cleaning applied
- Create maps for median and 95th percentile of distribution function
  – Maps characterize nominal and extreme environments
- Include error maps with instrument uncertainty
- Apply interpolation algorithms to fill in the gaps

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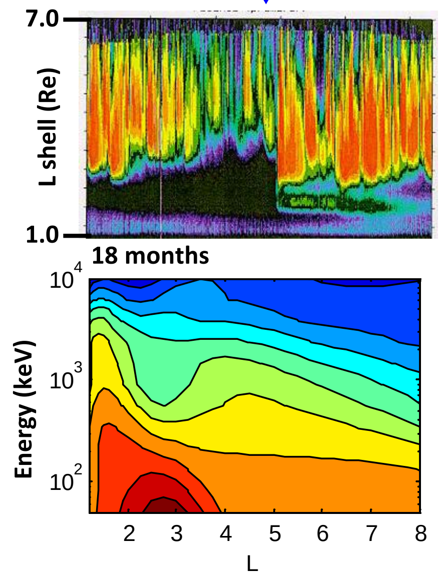
Satellite data & theory



Statistical Monte-Carlo Model

Compute spatial and temporal correlation as spatiotemporal covariance matrices
– From data (V 1.0)
– Use one-day (protons) and 6 hour (electrons) sampling time (V 1.0)

Set up Nth-order auto-regressive system to evolve perturbed maps in time
– Covariance matrices give SWx dynamics
– Flux maps perturbed with error estimate gives instrument uncertainty

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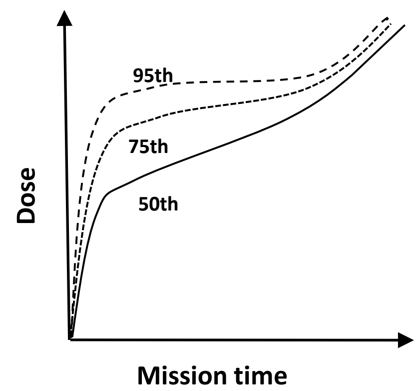
User's orbit



User application

Runs statistical model N times with different random seeds to get N flux profiles

Computes dose rate, dose or other desired quantity derivable from flux for each scenario

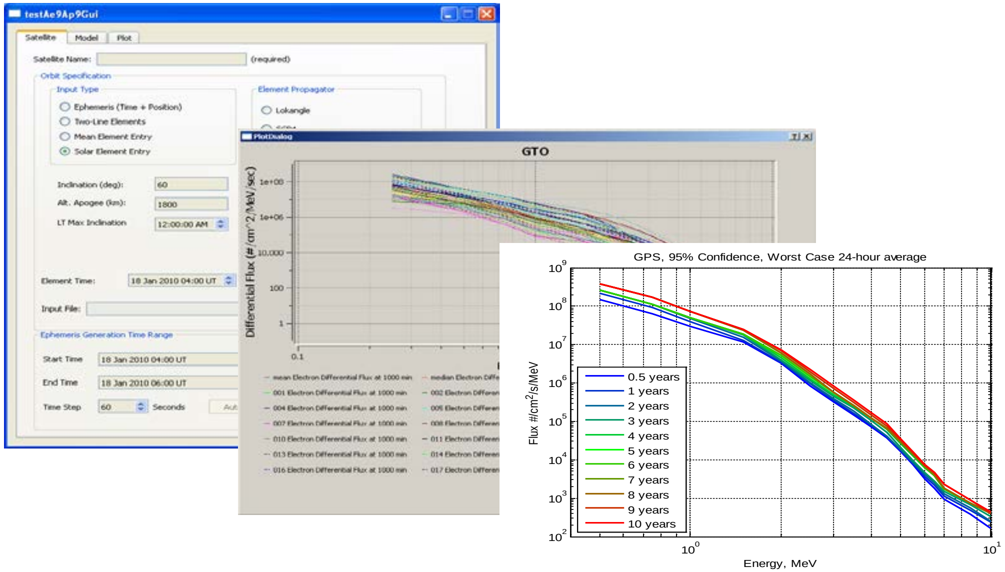
Aggregates N profiles to get median, 75th and 90th confidence levels on computed quantities

AFRL

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 1976-2016

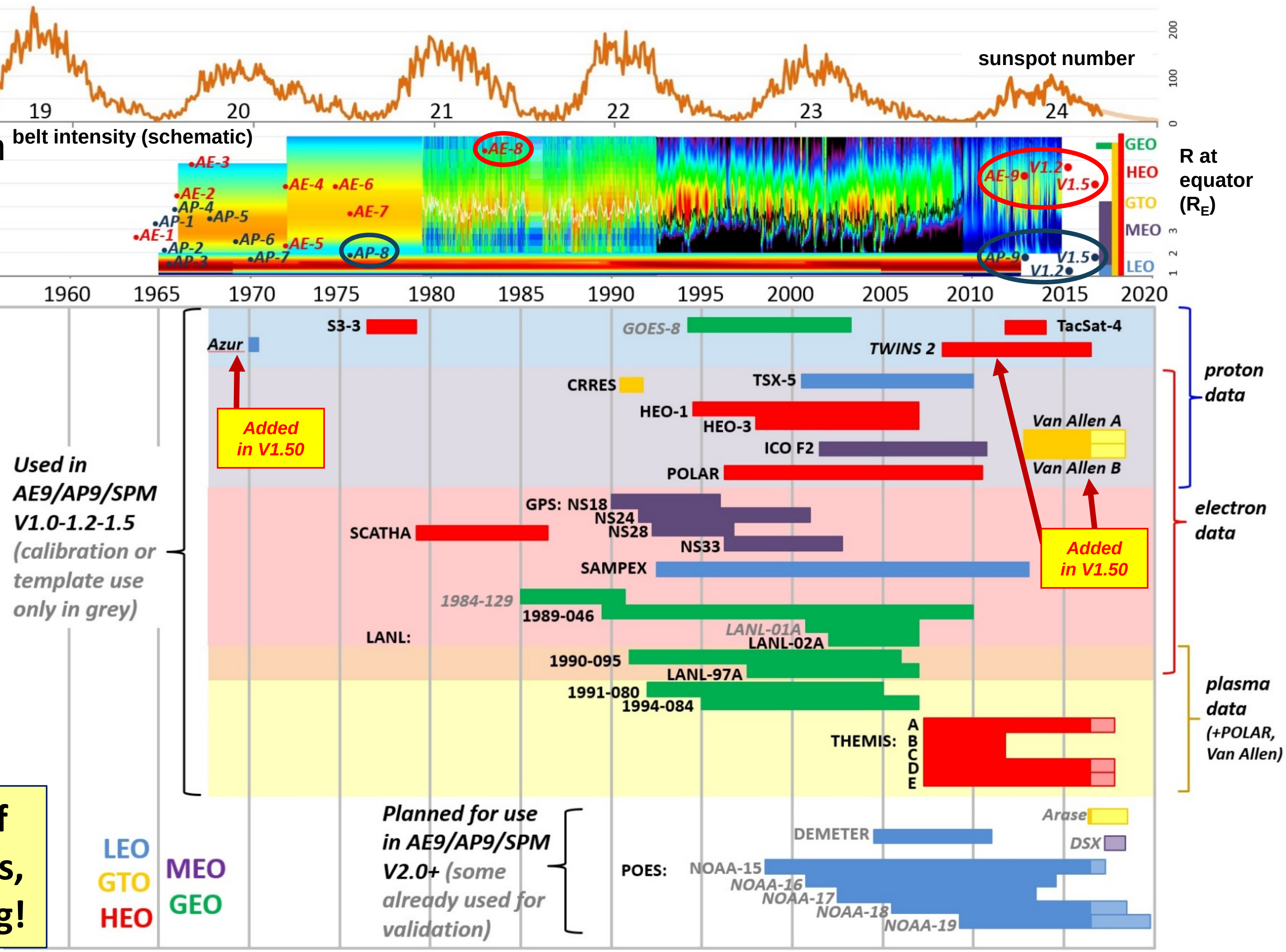
- Chosen for high quality and coverage

300+ instrument-years of data

- 10x more than AE8+AP8

All solar cycle phases sampled:

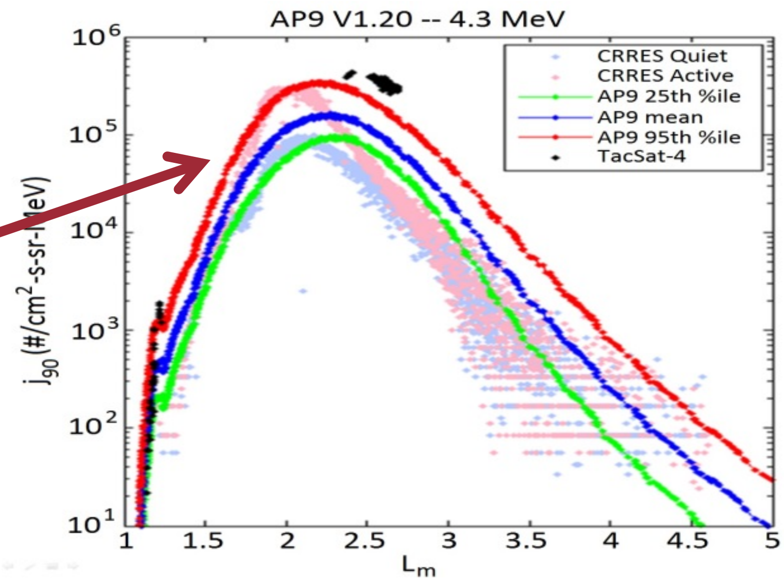
- 16 sets >10 yrs
- 26 sets >5 yrs

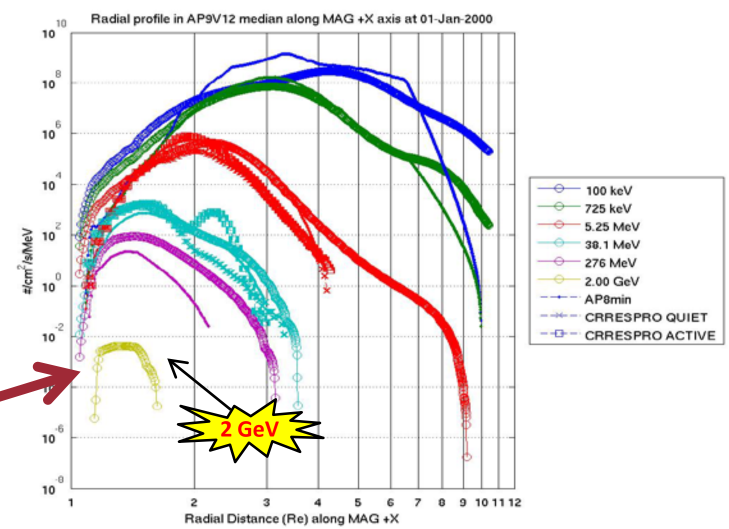


10x the data of previous models, and still growing!

Versions to Date

V1.00 (2012)	Initial release, 31 data sets
V1.20 (2015)	TacSat-4/CEASE proton data THEMIS/ESA plasma data 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 datasets change the flux maps: Van Allen Probes, Azur, HiLET





Upcoming Versions

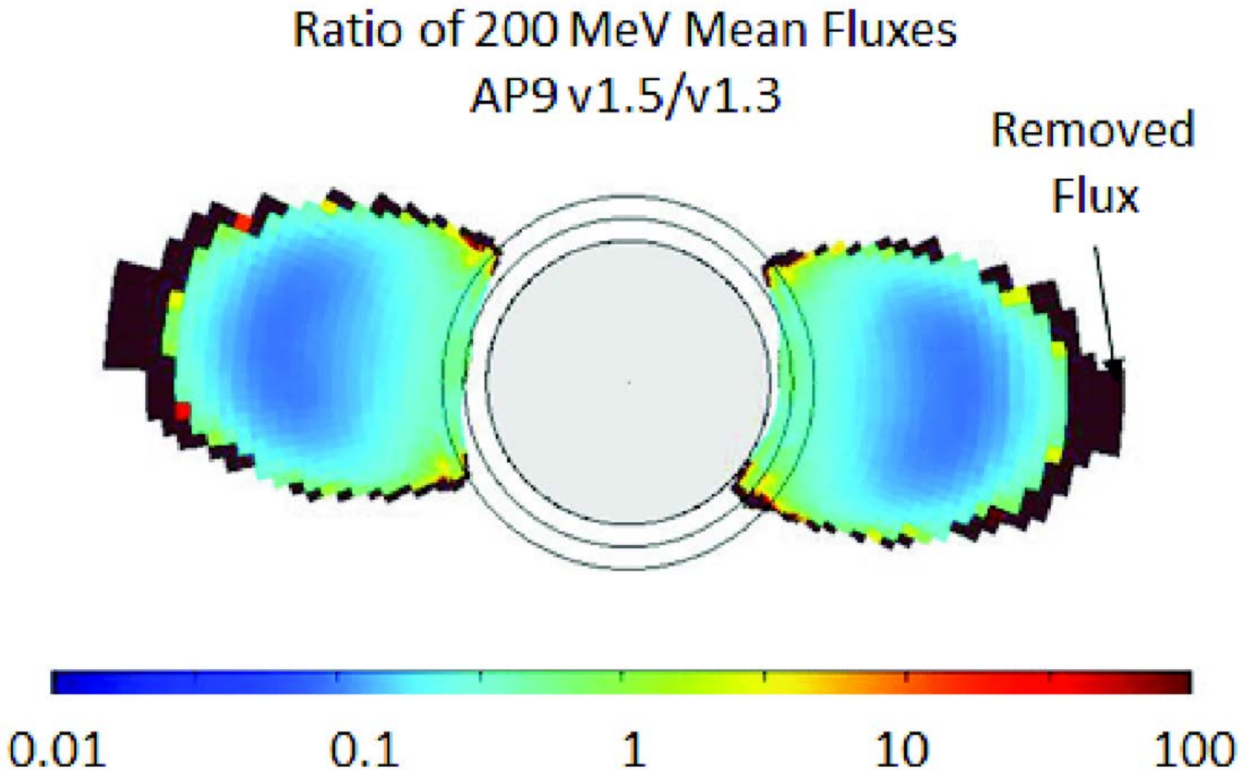
	Features
V1.55 (2018)	Kernels for faster effects calculations
V1.60 (2018)	Additional Van Allen Probes data
V2.00 (~2019)	New architecture New modules—solar protons, sample solar cycle 4-dimensional AE9, AP9, SPM New data sets—POES, int'l.
V2.50(?) (~2020)	New modules New data sets—DSX, Arase

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 will be new accumulator options (e.g., fluence accumulation intervals)**

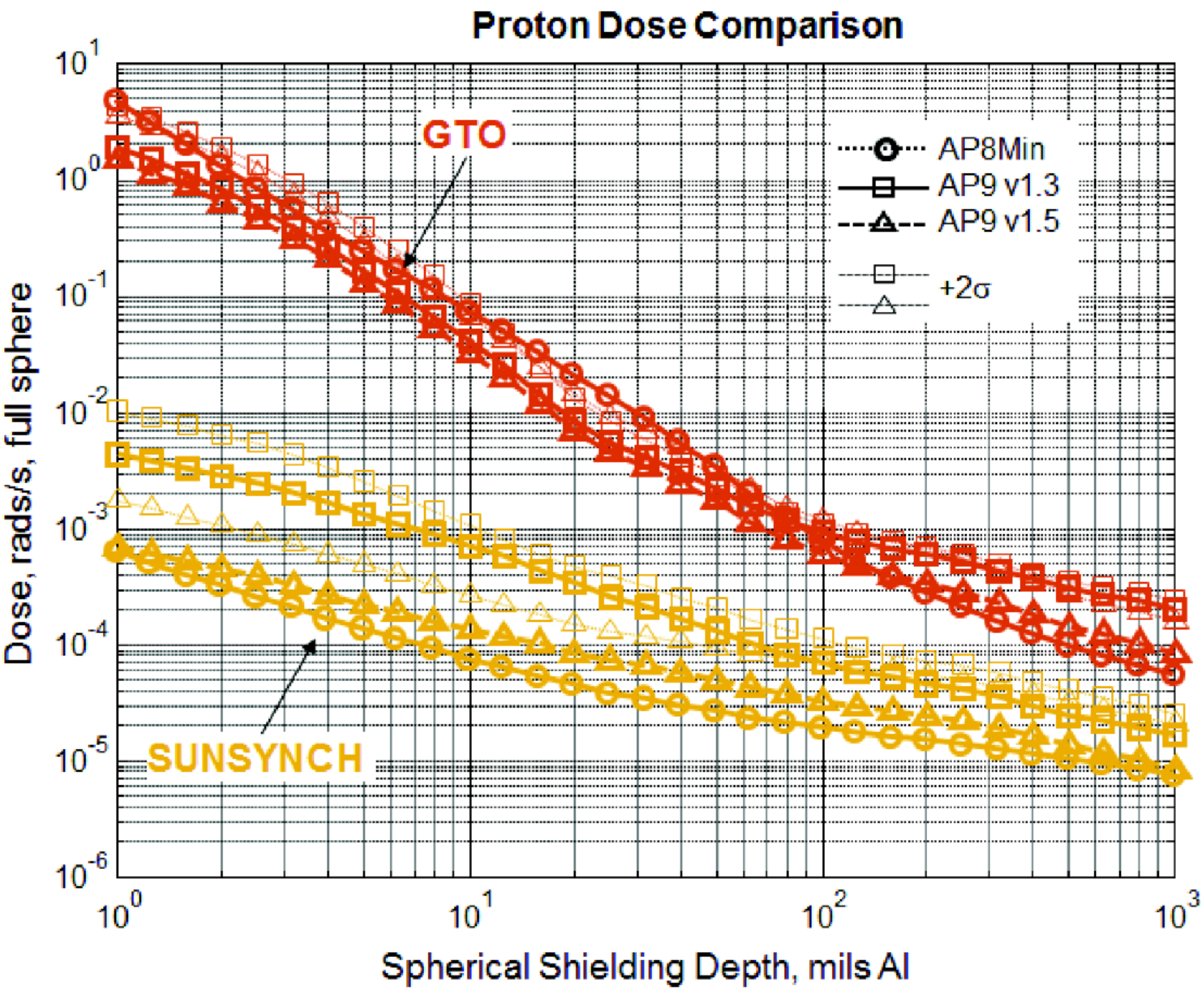
satellite	orbit	time period	instrument	species	energy
Van Allen Probes A & B	GTO (800 x 30600 km, 10°)	Aug 2012 – Dec 2016	RPS (Relativistic Proton Spectrometer)	protons	>58 MeV -- ~2 GeV
			REPT (Relativistic Electron Proton Telescope)	protons	20 – 100 MeV
			MagEIS	electrons	30 keV – 2 MeV
Azur	384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



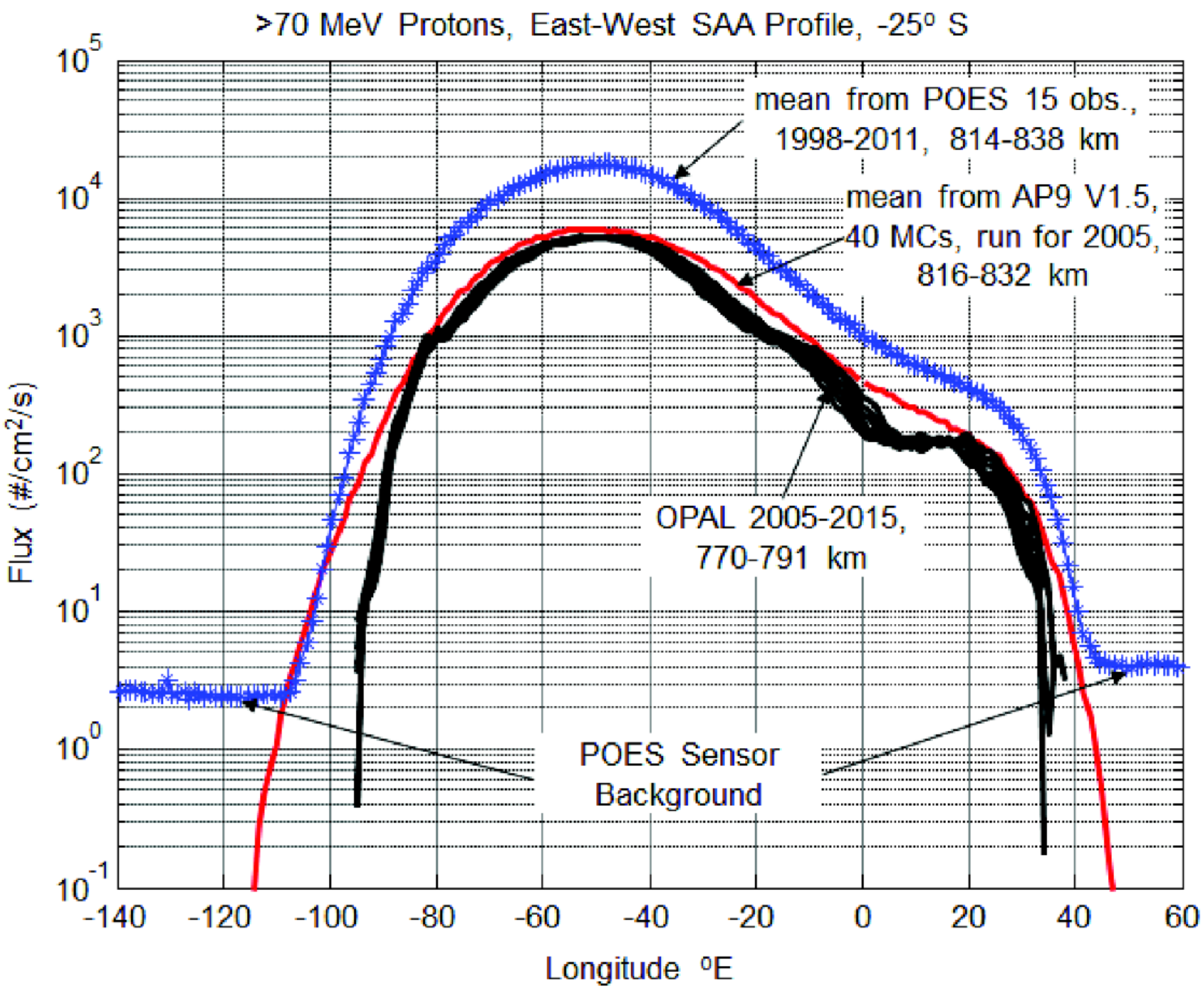
- AP9 adds Azur, HiLET and Van Allen Probes data
- These new data generally bring down the inner zone fluxes
- Especially large changes >150 MeV where RPS data represent the first clean observations in the inner zone up to 2 GeV

V1.50 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

Independent Comparison with Data



- 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

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Run Modes

- **Static Mean/Percentile**
  - Flux maps initialized to mean or percentile values
  - Flux maps remain static throughout run
  - Flux output is always the mean or selected percentile
  - Percentiles are appropriate only for comparing with measurements at a given location
- **Perturbed**
  - Flux maps are initialized with random perturbations
  - Flux maps remain static throughout run
  - Multiple runs provide statistical confidence intervals for cumulative parameters
  - Appropriate for cumulative/integrated quantities (e.g., fluence, TID)
- **Monte Carlo**
  - Flux maps are initialized with random perturbations
  - Flux maps evolve over time
  - Multiple runs provide statistical confidence intervals including worst-case over specified time intervals
  - Needed for estimate of uncertainty in time-varying quantities (e.g., SEE rates, deep dielectric charging)

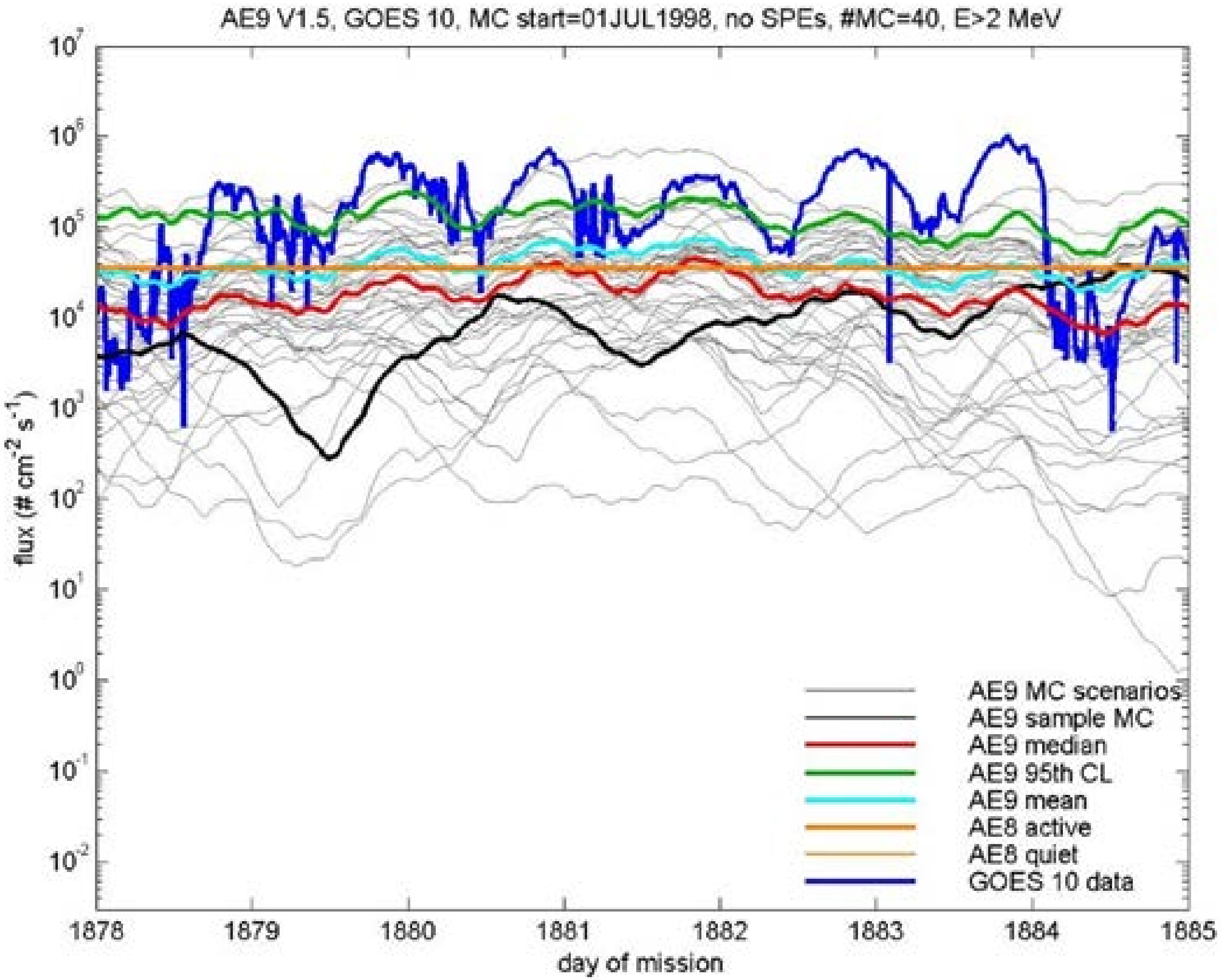
Which Run, for Which Effects?

Spec Type	Type of Run	Duration	Notes
Total Dose	Perturbed Mean	Several orbits or days	SPME+AE9, SPMH+AP9+Solar
Displacement Damage (proton fluence)	Perturbed Mean	Several orbits or days	AP9+Solar
Proton SEE (proton worst case)	Monte Carlo	Full Mission	AP9+Solar
Internal Charging (electron worst case)	Monte Carlo	Full Mission	AE9 (no SPME)

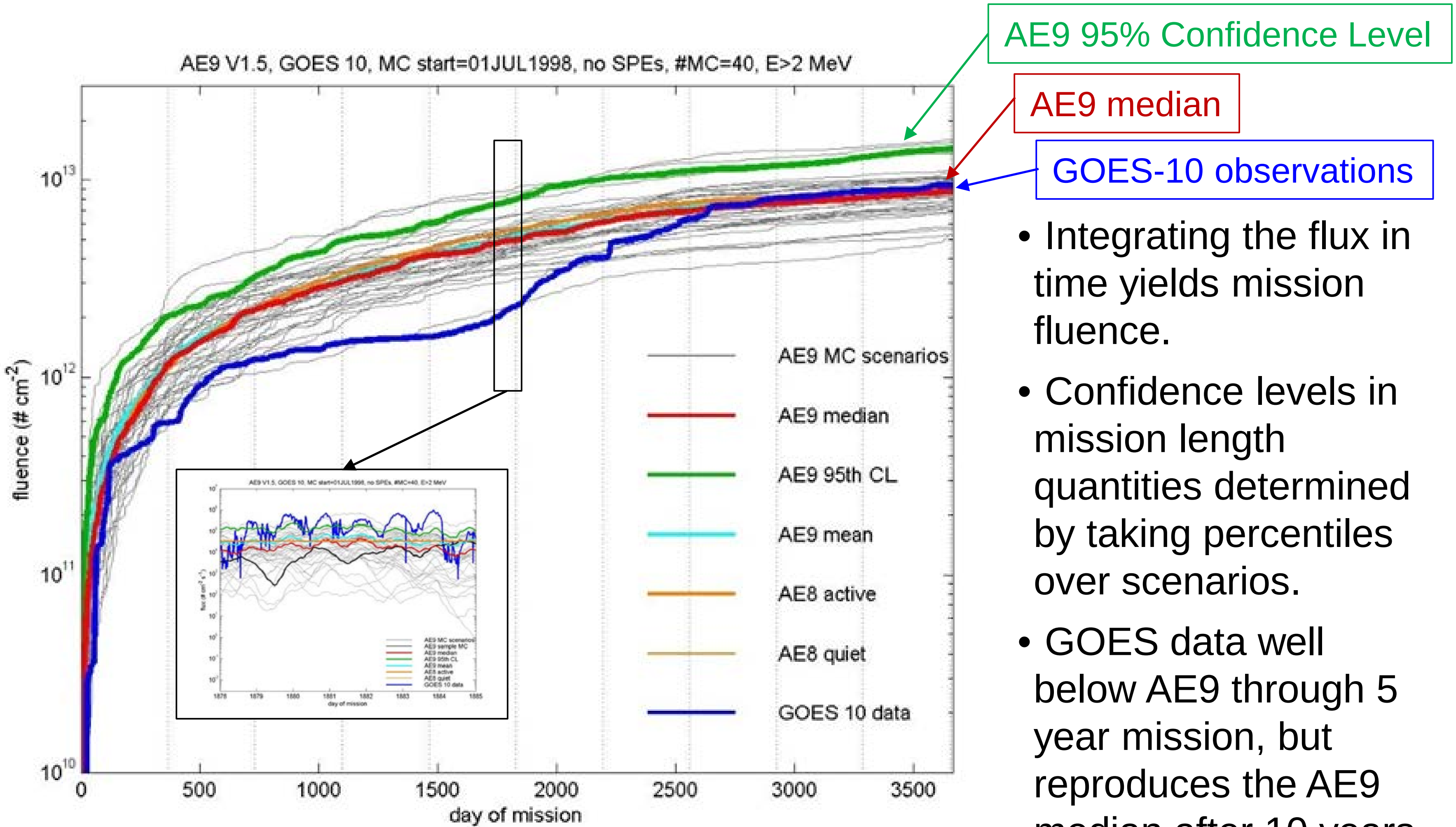
- Run 40 scenarios through either static Perturbed Mean or dynamic Monte Carlo
- Compute statistics by comparing results across scenarios (e.g., in what fraction of scenarios does the design succeed)
- Do not include plasma (SPM*) models in worst case runs

Monte-Carlo AE9 Runs

- Example taken from AE9 to more clearly show space weather captured in Monte-Carlo variation.
- 40 MC scenarios run, in AE9 (electrons) at GEO, shown as gray lines.
- Monte-Carlo variability mimics space weather, albeit statistically.
- We take statistics over scenarios to determine the environment variability.
- Compare the median (20th out of 40 ranked scenarios) with AE8 – only a median description.
- Here we compare with 1 week of GOES >2 MeV electron flux in blue; happened to be an enhanced outer zone.

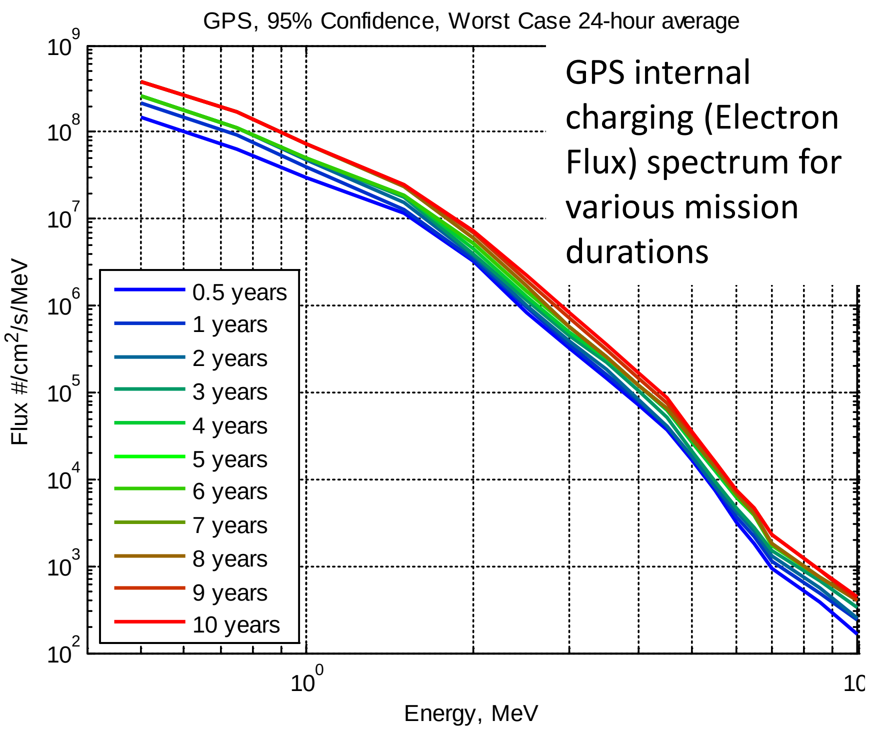


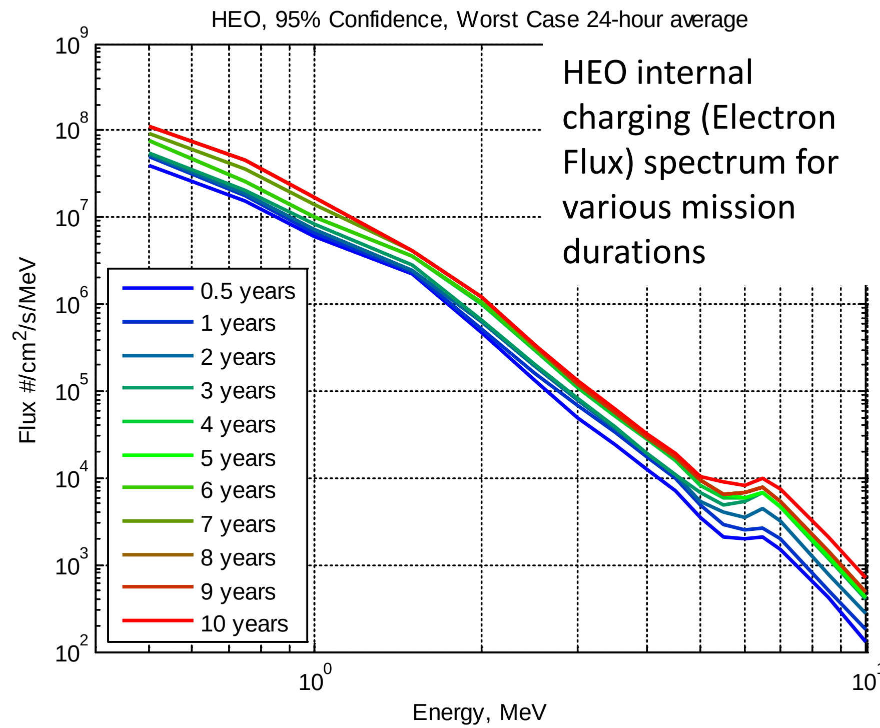
Monte-Carlo AE9 Runs



- Integrating the flux in time yields mission fluence.
- Confidence levels in mission length quantities determined by taking percentiles over scenarios.
- GOES data well below AE9 through 5 year mission, but reproduces the AE9 median after 10 years.

Do You Really Need to Simulate the Whole Mission?





- Yes ☹ (Space Weather!)
- Worst case internal charging flux grows by more than a factor of 2 from a 6 month to a 10 year mission
- The effect is orbit dependent and even larger in LEO

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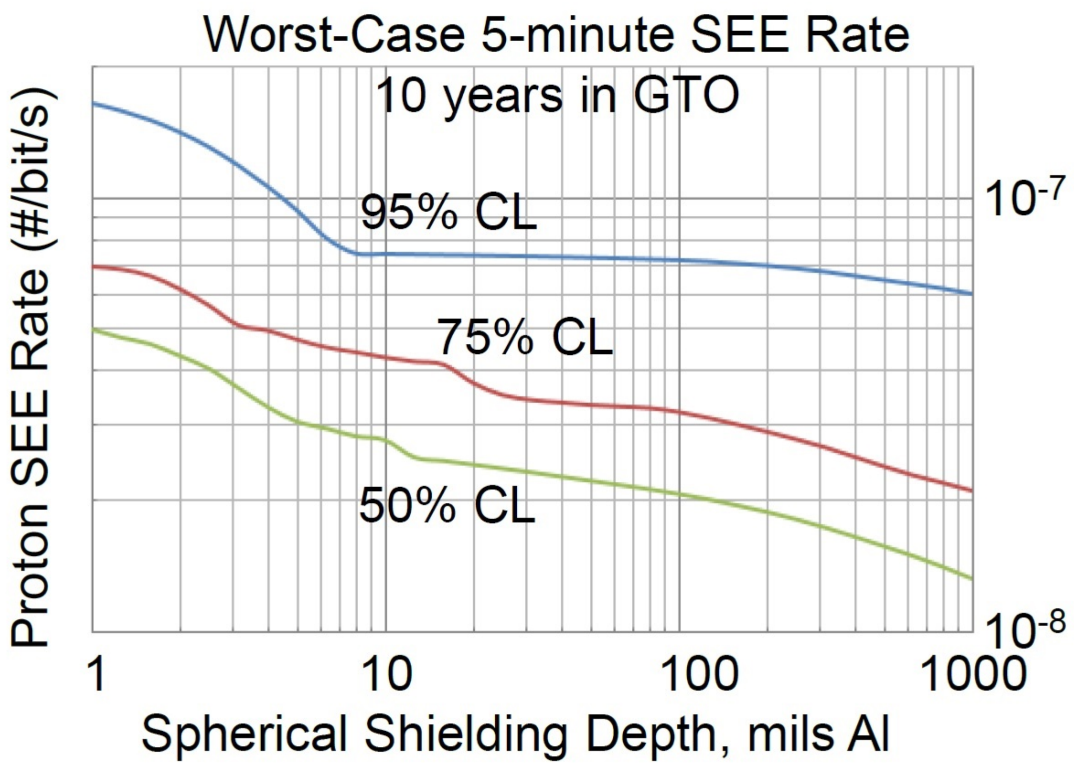
Effects Kernels

- AE9/AP9 natively provides confidence levels on differential or integral flux
- Users want more:
  - It is conservative to compute the 95^{th} % confidence level radiation effect from a 95^{th} percentile spectrum: assumes all energies are at 95^{th} % 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

Value of SEE Kernels

- We can use a kernel to compute the proton SEE rate behind different amounts of shielding (TOR-2015-02707)
- Use the continuous slowing down approximation to define the degraded spectrum behind known amount of Al shielding
- Apply user-defined Weibull or Bendel SEE cross section to compute SEE rate from degraded spectrum
- Again, derive confidence levels over scenarios on the effects, not on the environment then translate to effects.
  - Aggregating effects last removes conservatism
- See O'Brien and Kwan, *IEEE Trans. Nuc. Sci.*, Vol 65, No. 1, p. 457, January 2018.



Can now answer the question:
How much shielding is needed to obtain a desired SEE rate with a desired confidence?

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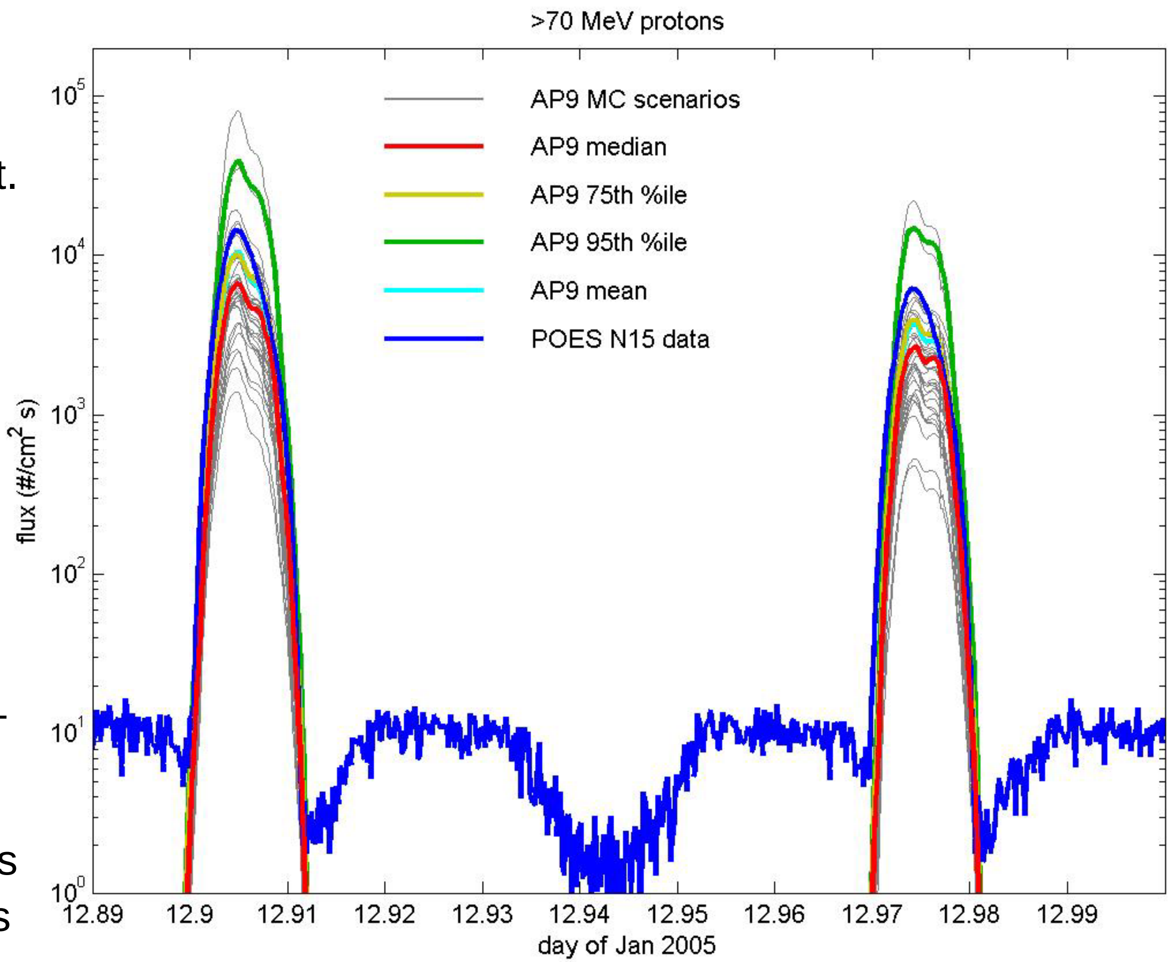
Example: Worst-Case SEE Specification

- **<u>Task</u>:** Compute an appropriately conservative estimate of the short term (e.g. minutes) SEE rate in a proton sensitive device on a LEO spacecraft.
  - **<u>Worst-case</u>:** use Monte-Carlo simulations.
  - **<u>Short term rate</u>:** box-car average fluxes in time
  - **<u>SEE rate</u>:** use the kernel approach to translate short term proton flux to SEE rate
- Here we describe how to run AP9 and post-process the results to obtain a worst-case SEE rate.

Generate AP9 Monte-Carlo Runs

- Run AP9 in Monte-Carlo Mode for the mission duration at the mission orbit.
- Yields 40 mission-long flux time-series at every energy
  - This captures statistically the space weather dynamics sampled at the orbit simulated.
- For each MC scenario, choose the time-interval of interest for the effect.
  - Example: 1-minute boxcar-average fluxes, available with V1.55.
- Now we have 40 time-series of 5-minute-averaged fluxes at all energies.

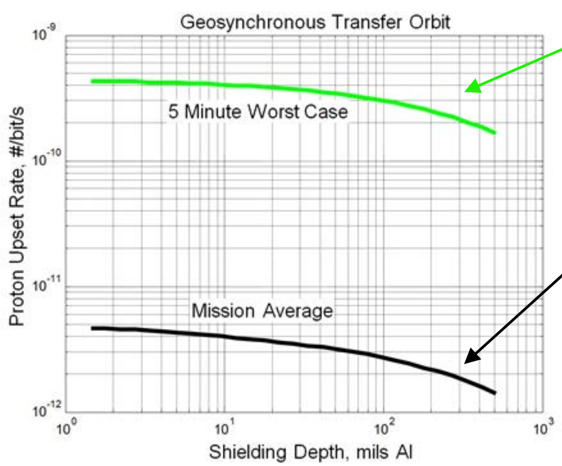


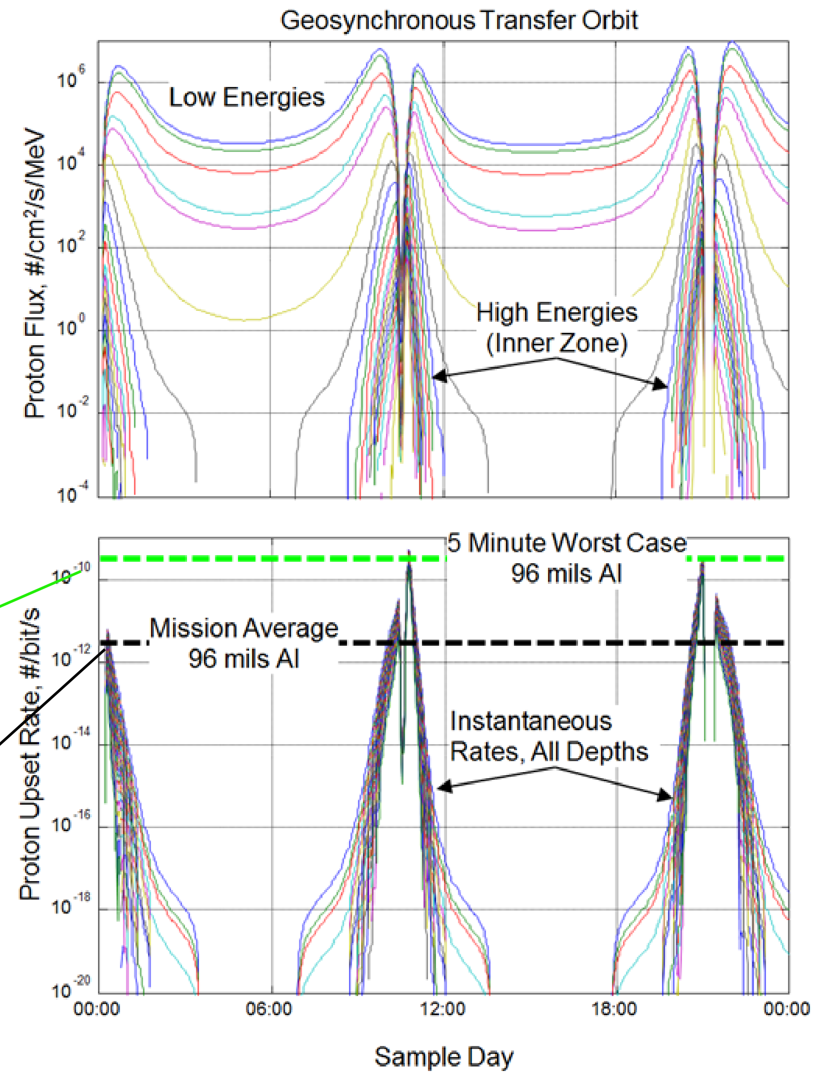
Generating the SEE Kernel

- From test data of the parts in question, determine Bendel or Weibull fit parameters to the upset rate.
- Approximate the shielding thickness and material between space and the part to degrade the external proton spectrum (using CSDA).
- Use the forthcoming utility to generate the kernel for AP9 use.
  - Functionality included in a forthcoming version

Applying the SEE Kernel

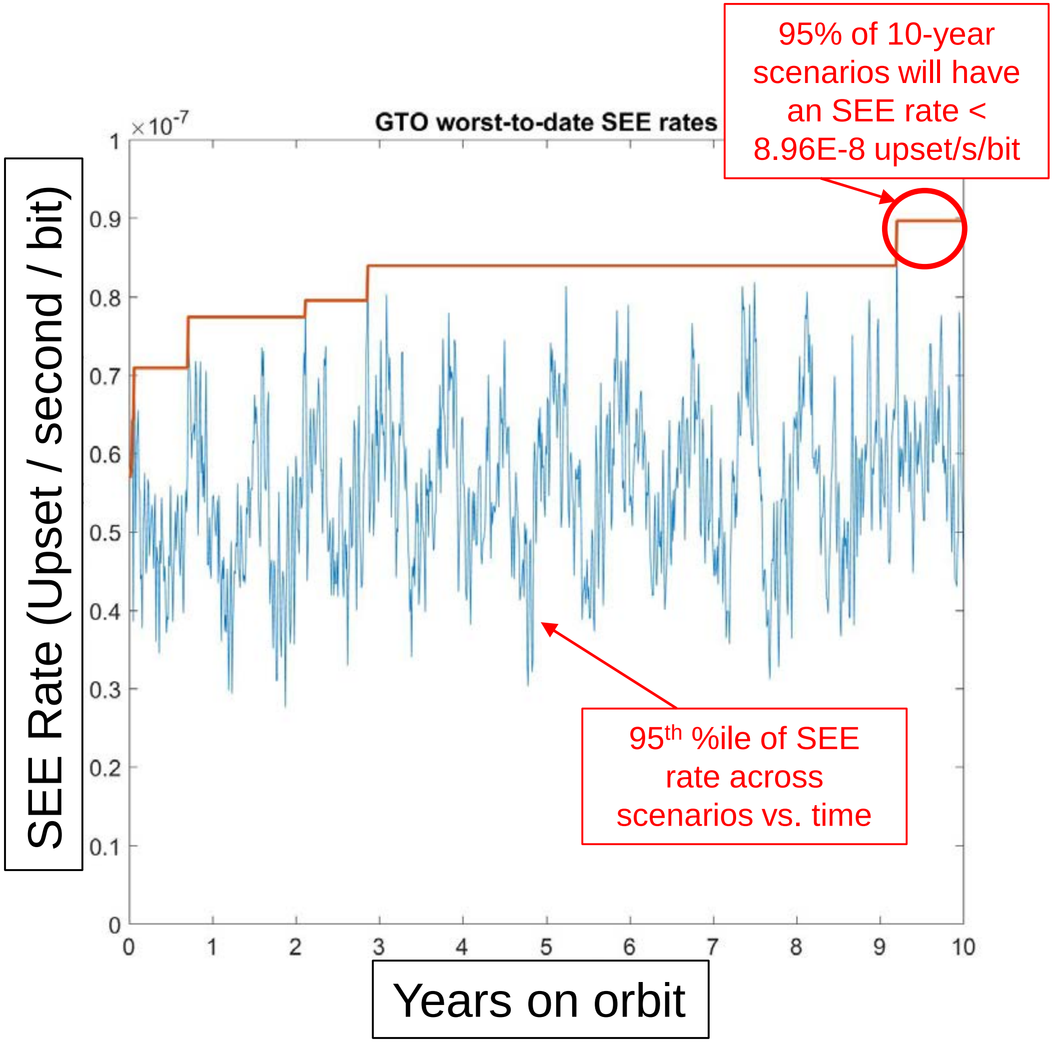
- Pass that 1-minute boxcar average proton flux (top) through the SEE kernel to get SEE rates as a function of shielding depth and mission time (bottom).
- Can calculate instantaneous upset rate, mission-averaged upset rate, or worst-case over time interval in #/bit/sec from the entire mission time-series.





Aggregate over Monte-Carlo Scenarios

- The Monte-Carlo statistical variability will generate space weather perturbations according to the observed likelihood of happening.
  - Rare, large changes will have an increased chance of happening with longer MC simulations (i.e. solar particles trapped in the slot).
- This sampling increases the worst-case SEE rate with longer mission durations.
- To construct worst-case spec:
  - Run MC scenarios for mission duration.
  - Pick off the desired percentile SEE rate at mission duration across all scenarios.
  - Same method for other worst-case specs (e.g., internal charging)



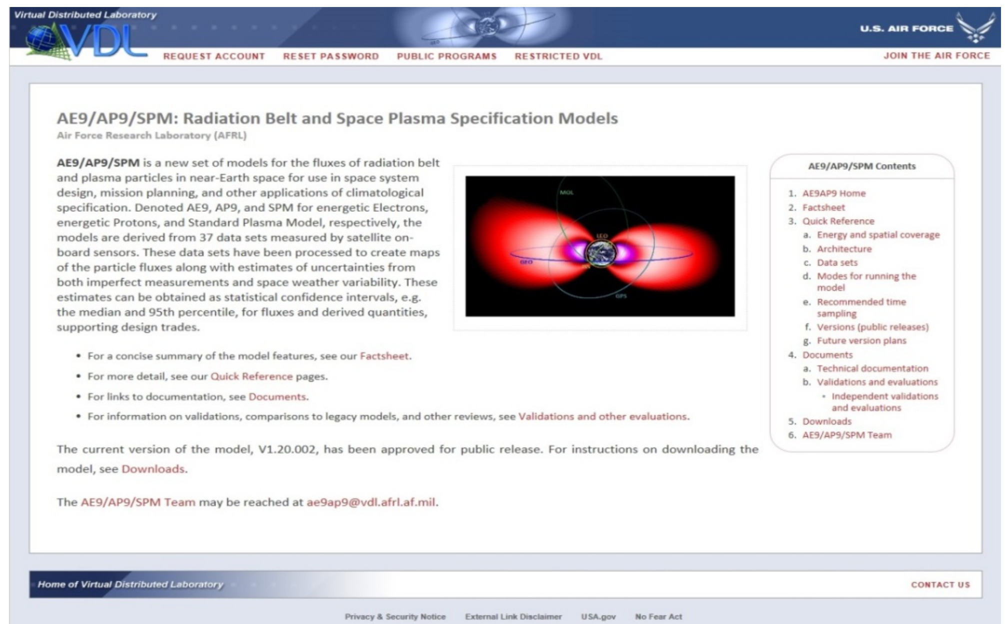
IRENE

- Starting with V1.50, AE9/AP9 now includes international contributions (Azur data)
- To recognize the internationalization of the model, we will begin transition to a new name: International Radiation Environment Near Earth (IRENE)
- AE9/AP9 V1.5 is then also known as AE9/AP9-IRENE
- We will use both names for a few releases, and eventually switch to IRENE only
- In addition to Azur data, ESA is working hard to produce a Monte Carlo solar proton model that we can integrate with AP9

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 demonstrate maintainability
- Future releases will include new data sets and new features, driven by user needs
- <u>Comments, questions, etc. are welcome and encouraged!</u>
- 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
- Model downloads, documentation, news are available at AFRL's Virtual Distributed Laboratory: https://www.vdl.afrl.af.mil/programs/ae9ap9