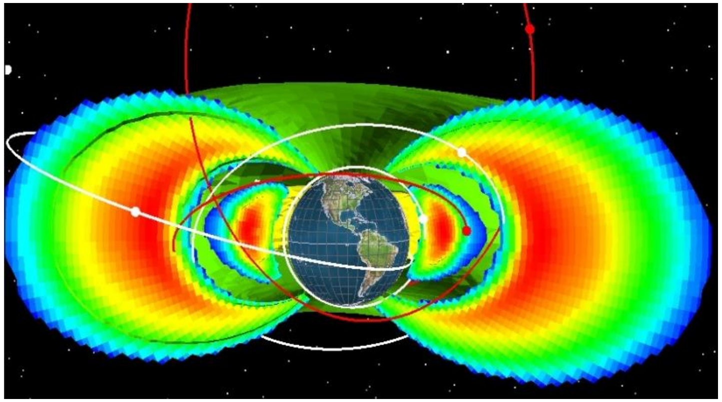
AP-9/AE-9:
New Radiation Specification Models

Space Weather Week

26 Apr 2011



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International Contributors:

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Hope to add more…

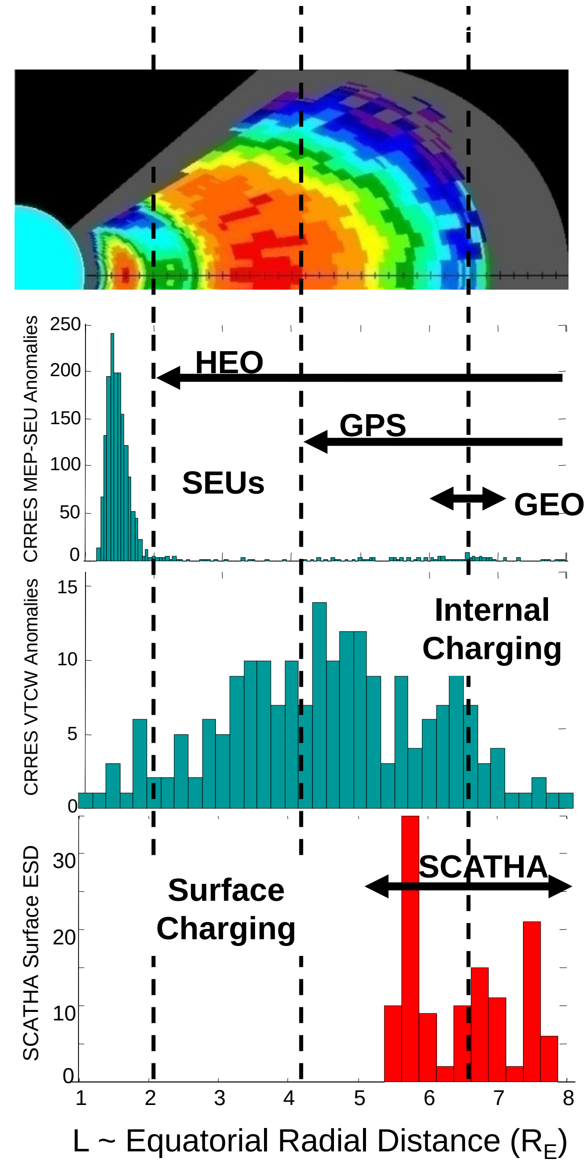
AP9/AE9 Program Objective

Provide satellite designers with a definitive model of the trapped energetic particle & plasma environment

- Probability of occurrence (percentile levels) for flux and fluence averaged over different exposure periods
- Broad energy ranges from keV plasma to GeV protons
- Complete spatial coverage with sufficient resolution
- Indications of uncertainty

Satellite Hazard	Particle Population	Natural Variation
Surface Charging	0.01 - 100 keV e^-	Minutes
Surface Dose	0.5 - 100 keV e^-, H^+, O^+	Minutes
Internal Charging	100 keV - 10 MeV e^-	Hours
Total Ionizing Dose	>100 keV H^+, e^-	Hours
Single Event Effects	>10 MeV/amu H^+, Heavy ions	Days
Displacement Damage	>10 MeV H^+, Secondary neutrons	Days
Nuclear Activation	>50 MeV H^+, Secondary neutrons	Weeks

Space particle populations and hazards



Requirements

Summary of SEEWG, NASA workshop & AE(P)-9 outreach efforts:

Priority	Species	Energy	Location	Sample Period	Effects
1	Protons	>10 MeV (> 80 MeV)	LEO & MEO	Mission	Dose, SEE, DD, nuclear activation
2	Electrons	> 1 MeV	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Dose, internal charging
3	Plasma	30 eV – 100 keV (30 eV – 5 keV)	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Surface charging & dose
4	Electrons	100 keV – 1 MeV	MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Internal charging, dose
5	Protons	1 MeV – 10 MeV (5 – 10 MeV)	LEO, MEO & GEO	Mission	Dose (e.g. solar cells)

(indicates especially desired or deficient region of current models)

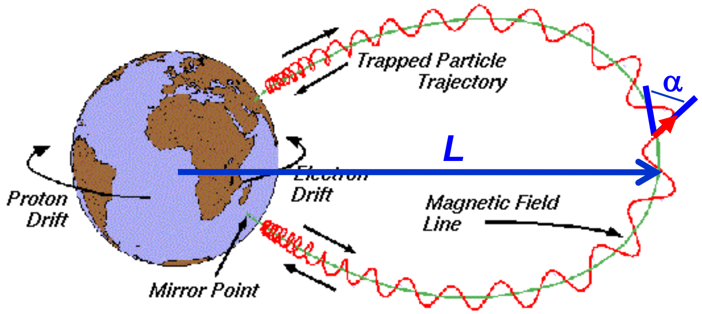
Inputs:

- **Orbital elements, start & end times**
- **Species & energies of concern (optional: incident direction of interest)**

Outputs:

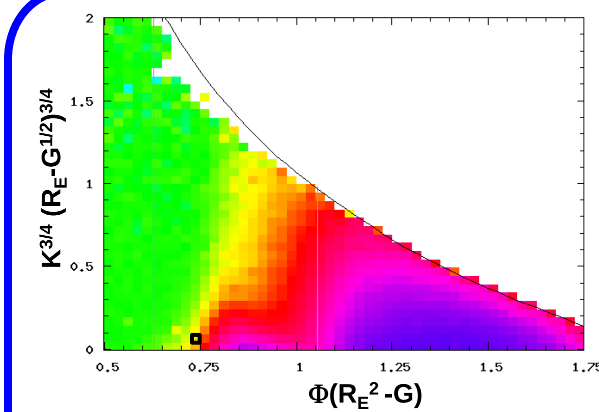
- **Mean and percentile levels for whole mission or as a function of time for omni- or unidirectional, differential or integral particle fluxes [#/(cm^2 s) or #/(cm^2 s MeV) or #/(cm^2 s sr MeV)] aggregated over requested sample periods**

Coordinate System



Adiabatic invariants:

- **Cyclotron motion:** $\mu = \frac{p_\perp^2}{2mB} = \frac{p^2 \sin^2 \alpha}{2mB}$
- **Bounce motion:** $K = \int_{s_m}^{s_{m'}} \left[B_m - B(s) \right] ds$
- **Drift motion:** $\Phi = \iint_{S} \mathbf{da} \cdot \mathbf{B}$ **and** $L^* = \frac{2\pi M}{\Phi R_E}$



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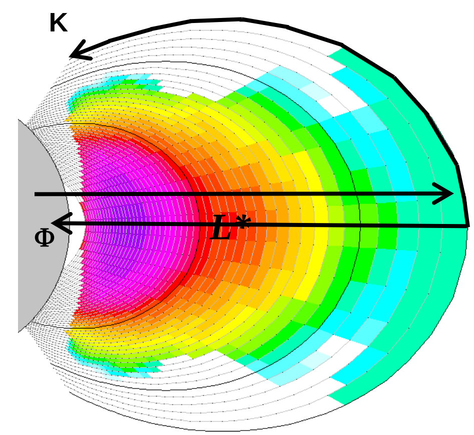
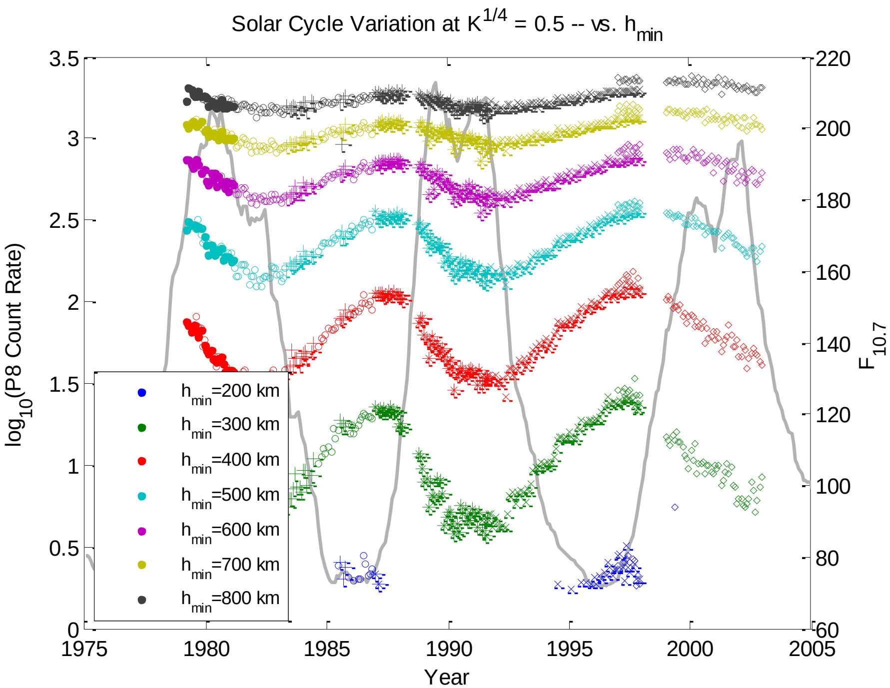


Choose *(E, K, Φ)* coordinates

- **IGRF/Olson-Pfitzer 77 Quiet B-field model**
- **Minimizes variation of distribution across magnetic epochs**

LEO Coordinate System

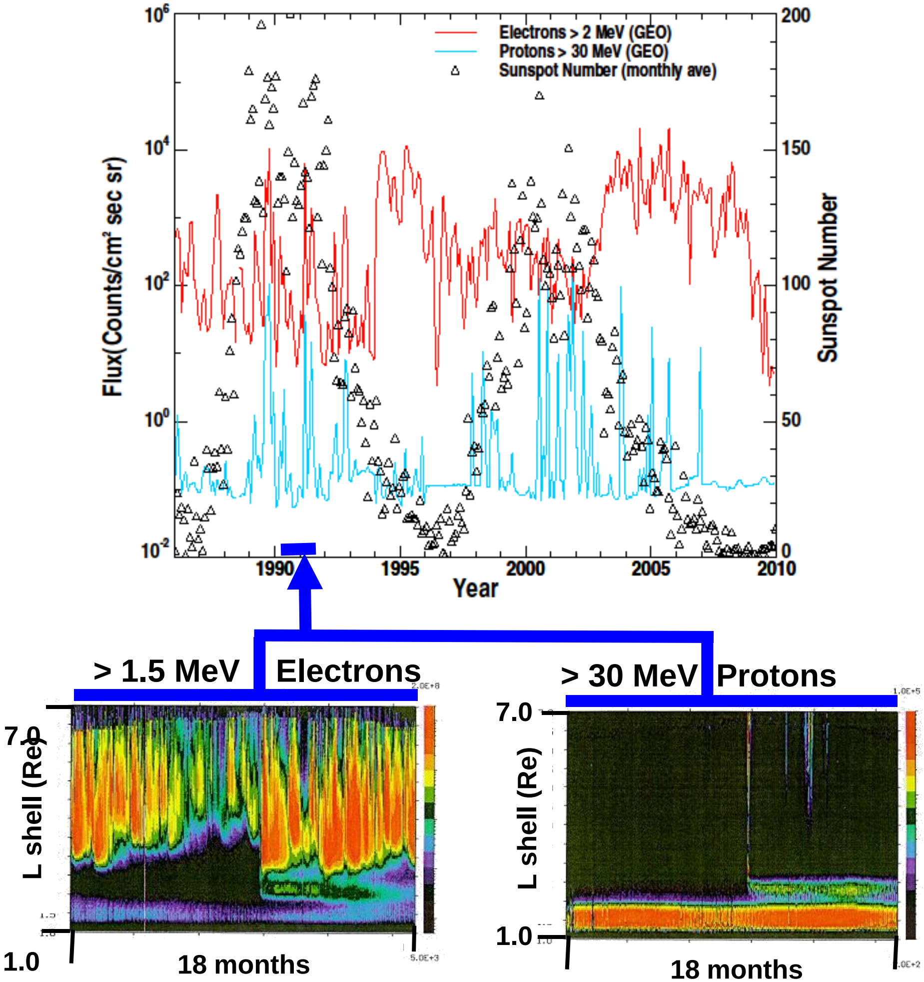
- **Version Beta *(Φ, K)* grid inadequate for LEO**
  - **Not enough loss cone resolution**
  - **No "longitude" or "altitude" coordinate**
    - **Invariants destroyed by altitude-dependent density effects**
    - **Earth's internal B field changes amplitude & moves around**
    - **What was once out of the loss-cone may no longer be and vice-versa**
    - **Drift loss cone electron fluxes cannot be neglected**
  - **No systematic Solar Cycle Variation**



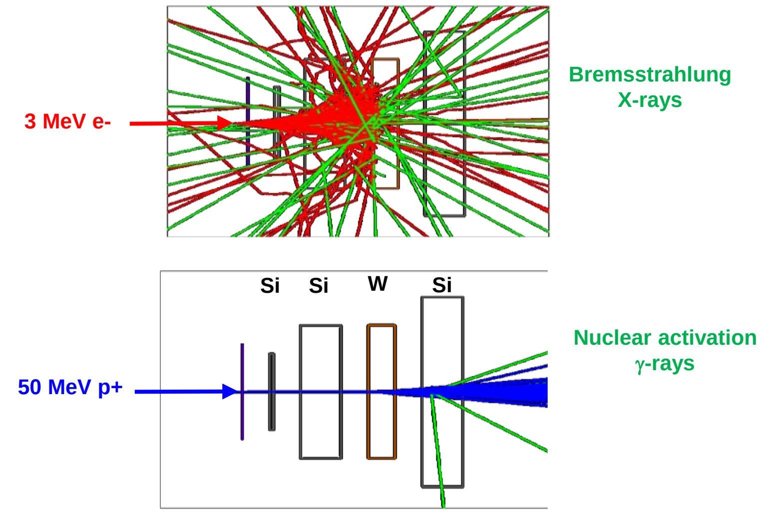
- **Version 1.0 will splice a LEO grid onto the *(Φ, K)* grid at ~1000-2000 km**
  - **Minimum mirror altitude coordinate h_{min} to replace *Φ***
  - **Capture quasi-trapped fluxes by allowing h_{min} < 0 (electron drift loss cone)**

Sources of Uncertainty

Space weather



Particle detectors



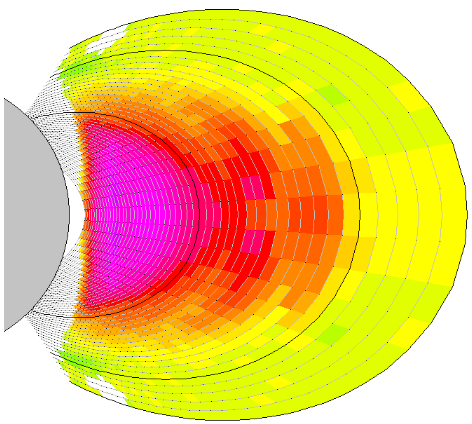
GEANT-4 MC simulation of detector response

- Imperfect electronics (dead time, pile-up)
- Inadequate modeling & calibration
- Contamination & secondary emission
- Limited mission duration

To the spacecraft engineer uncertainty is uncertainty regardless of source

Architecture Overview

Satellite data



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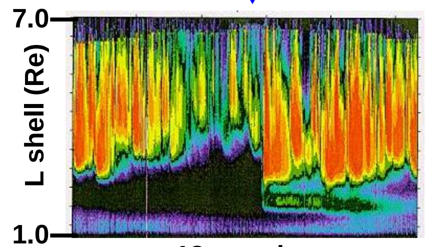
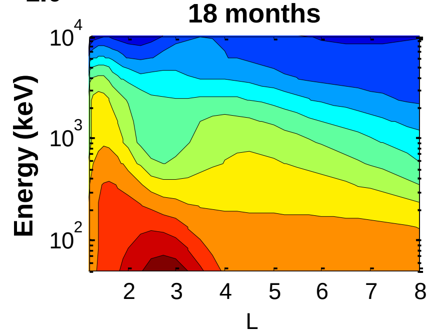
Satellite data & theory





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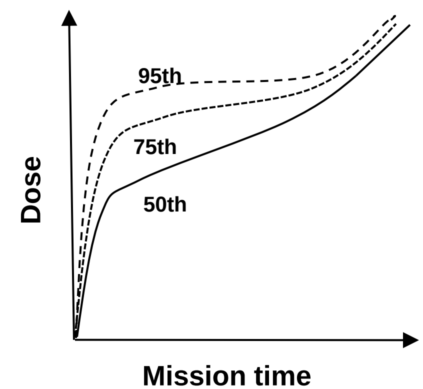
User's orbit



Flux maps

- Derive from empirical data
- 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

Statistical Monte-Carlo Model

- Compute spatial and temporal correlation as spatiotemporal covariance matrices
  - From data (Version Beta & 1.0)
  - Use one-day sampling time (Version Beta)
- Set up 1st order auto-regressive system to evolve perturbed maps in time
  - Covariance matrices gives SWx dynamics
  - Flux maps perturbed with error estimate gives instrument uncertainty

User application

- Runs statistical model N times with different random seeds to get N flux profiles
- Aggregates N profiles to get median, 75th and 90th confidence levels of flux & fluence
- Computes dose rate, dose or other desired quantity derivable from flux

Data Sets

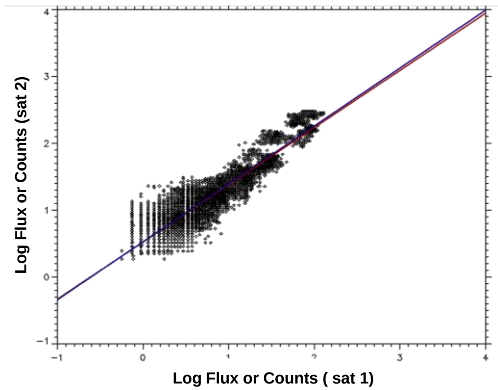
Protons	Orbit				Energy [MeV]																								
	LEO	MEO	HEO	GEO	0.10	0.20	0.40	0.60	0.80	1.00	2.00	4.00	6.00	8.00	10.0	15.0	20.0	30.0	50.0	60.0	80.0	100.0	150.0	200.0	300.0	400.0	700.0	1200.0	2000.0
CRRES/PROTEL	■	■	■	■							■	■	■	■	■	■	■	■	■	■	■								
S3-3/Telescope	■				■	■	■	■	■	■	■																		
ICO/Dosimeter		■													■	■	■	■	■	■	■	■	■	■	■	■			
HEO-F3/Dosimeter			■												■	■	■	■	■	■	■	■	■	■	■	■			
TSX5/CEASE	■															■	■	■	■	■	■	■	■	■	■	■			
POLAR/ISP		■	■		■	■	■	■	■	■																			
POLAR/HISTp		■	■									■	■	■	■														
HEO-F1/Dosimeter			■												■	■	■	■	■	■	■	■	■	■	■	■			

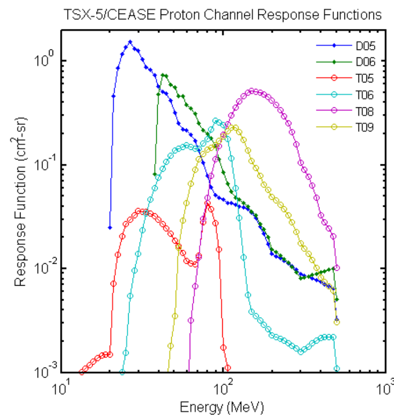
Electrons	Orbit				Energy [MeV]																				
	LEO	MEO	HEO	GEO	0.04	0.07	0.10	0.25	0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	8.50	10.0
CRRES/MEA/HEEF	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
S3-3/MES	■				■	■	■	■	■	■	■	■													
ICO/Dosimeter		■					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
HEO-F3/Dos/Tel			■					■	■	■	■	■	■	■	■										
TSX5/CEASE	■						■	■	■	■	■	■	■	■											
POLAR/HISTe									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
GPS/BDD		■						■	■	■	■	■	■	■	■	■									
LANL GEO/SOPA				■		■	■	■	■	■	■	■													
SCATHA/SC3		■		■		■	■	■	■	■	■	■	■	■	■	■	■	■							
HEO-F1/Dos/Tel			■					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	

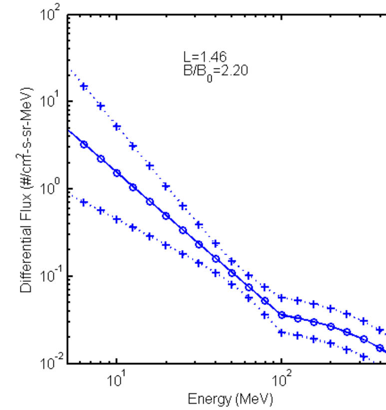
Plasma	Orbit				Energy [keV]											
	LEO	MEO	HEO	GEO	0.50	1.00	2.00	4.00	6.00	12.00	20.0	40.0	60.0	80.0	100.0	150.0
POLAR/CAMMICE		■	■		■	■	■	■	■	■	■	■	■	■	■	■
LANL GEO/MPA				■		■	■	■	■	■	■	■	■			

Building Flux Maps

Low resolution energy & wide angle detector?







Data collection → **Cross-calibration** → **Sensor modeling** → **Spectral inversion**

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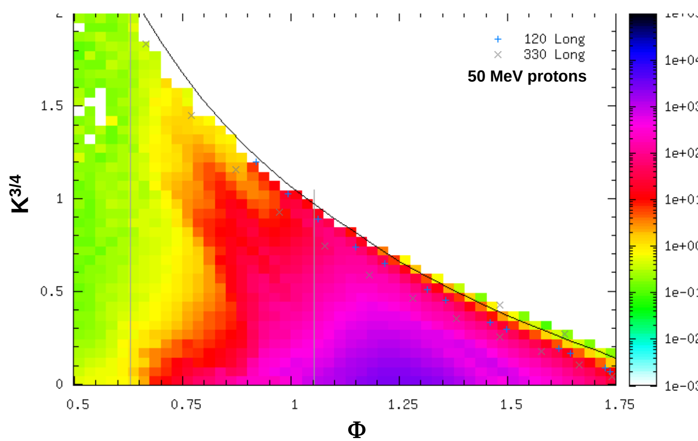
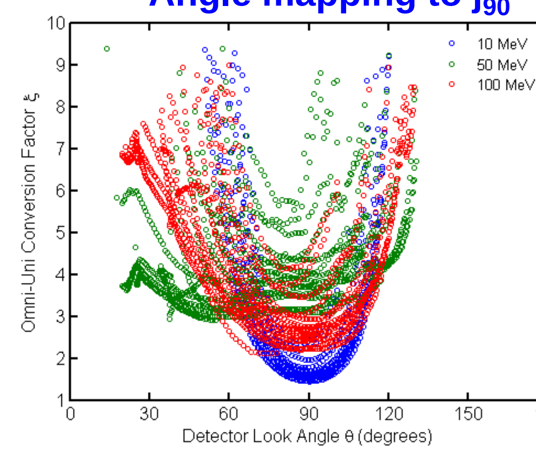
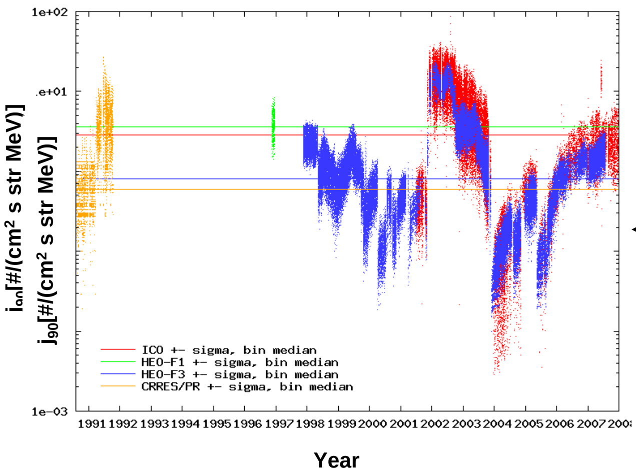
Angle mapping to j_{90} ← **Binning to model grid**

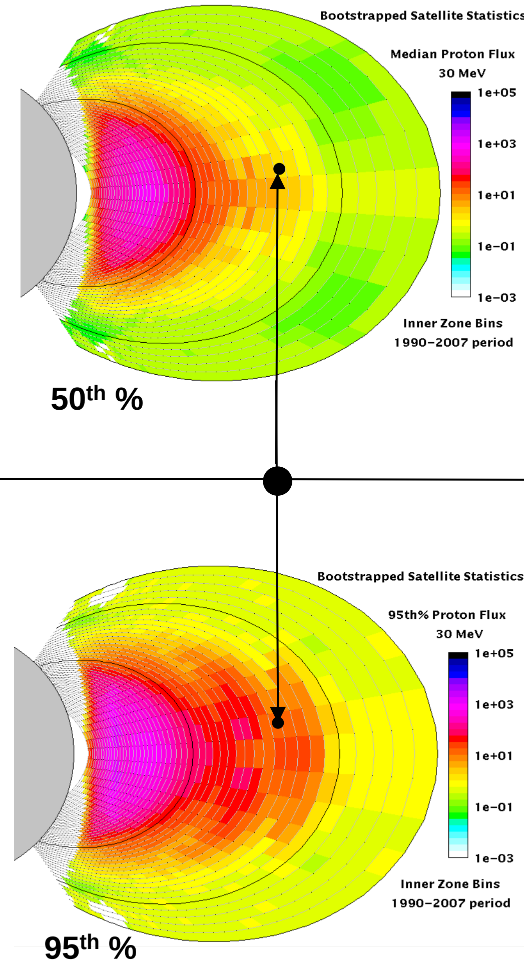




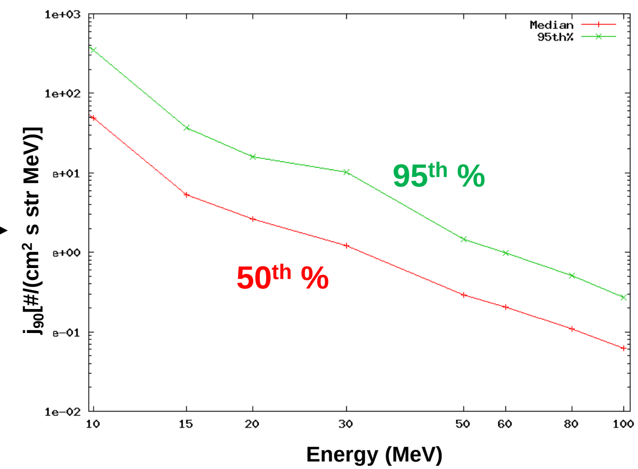
Example: Proton Flux Maps



Time history data

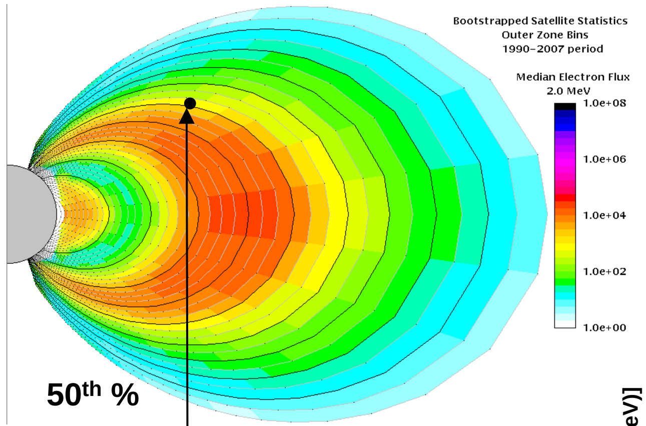


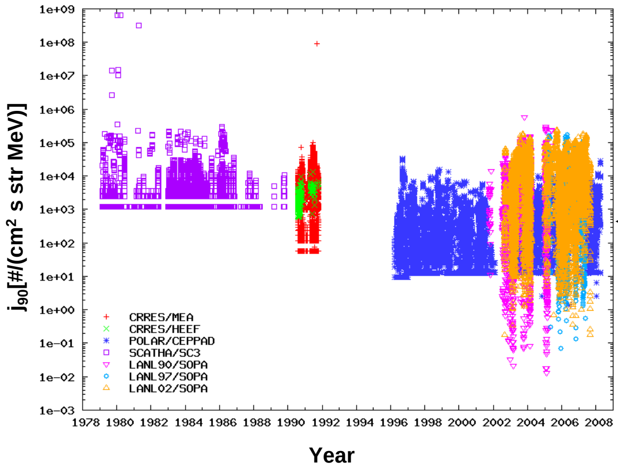
Flux maps (30 MeV)



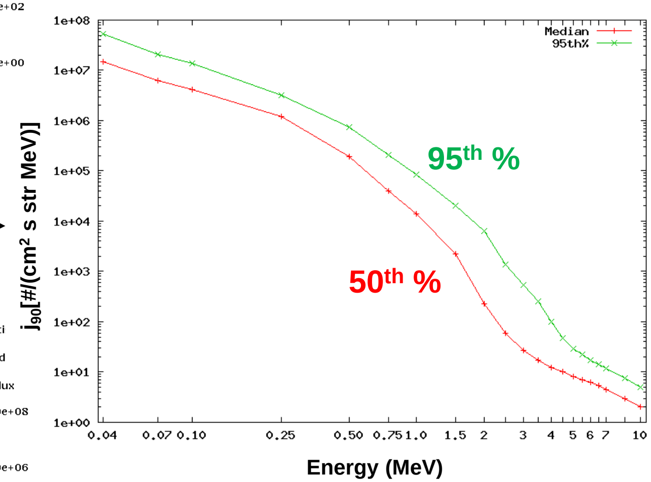
Energy spectra

Example: Electron Flux Maps

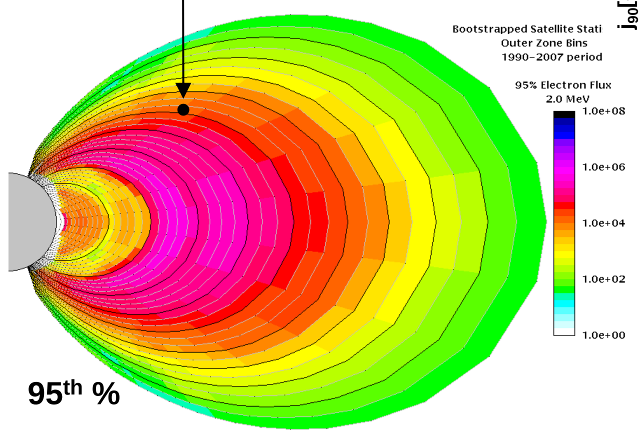




Time history data



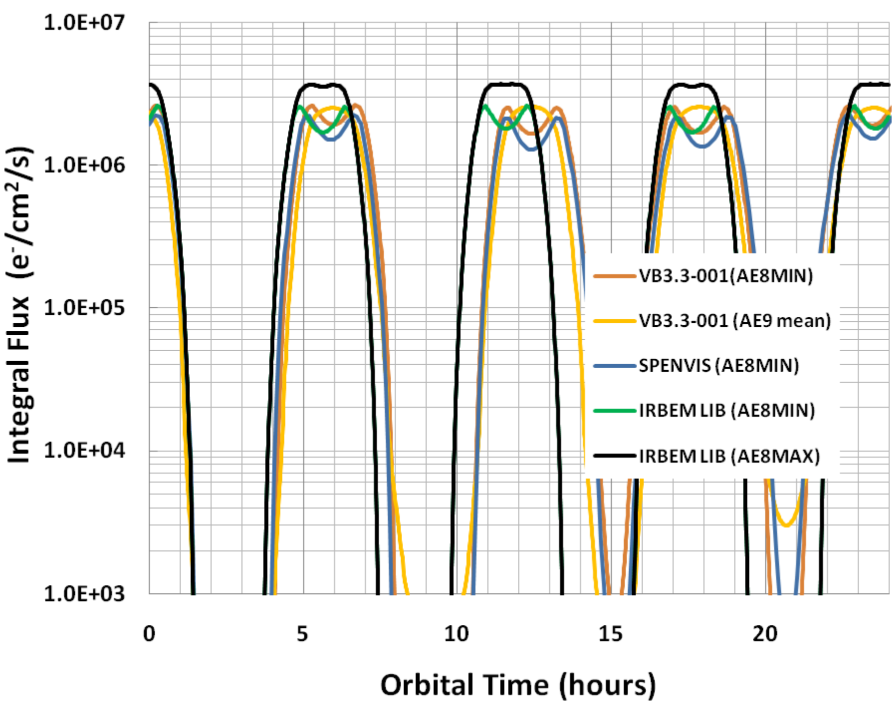
Energy spectra



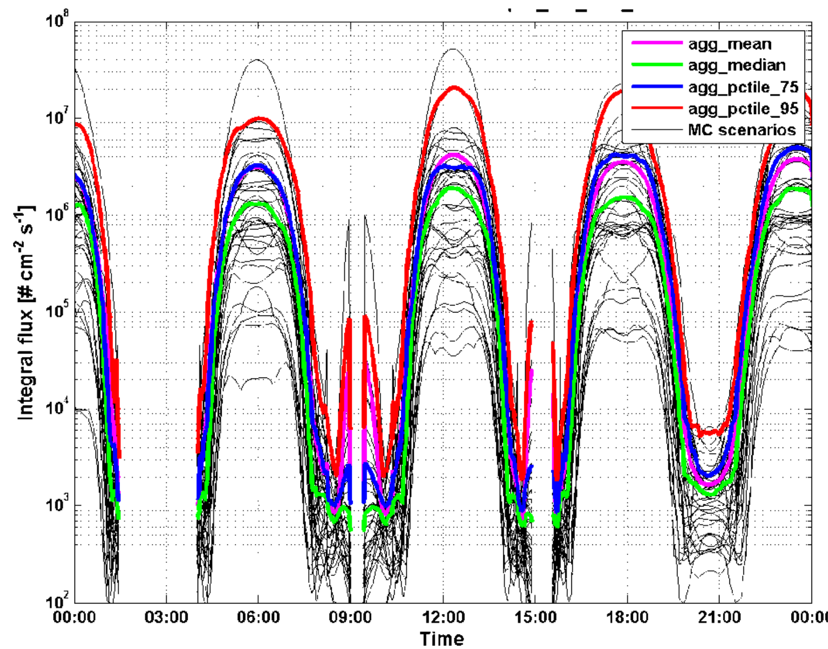
Flux maps (2.0 MeV)

Model Comparison: GPS Orbit

Electrons > 1 MeV



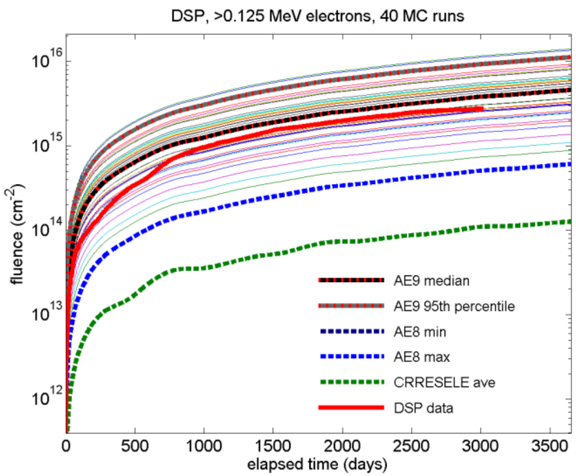
Comparison of AE9 mean to AE8



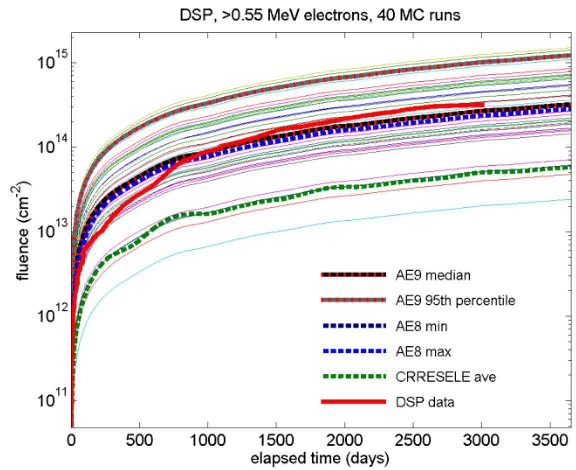
AE9 full Monte-Carlo – 40 runs

Data Comparison: GEO electrons DSP-21/CEASE (Vβ.2)

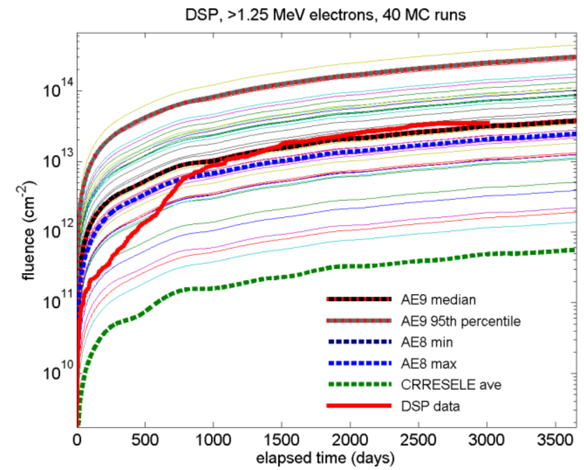
0.125 MeV

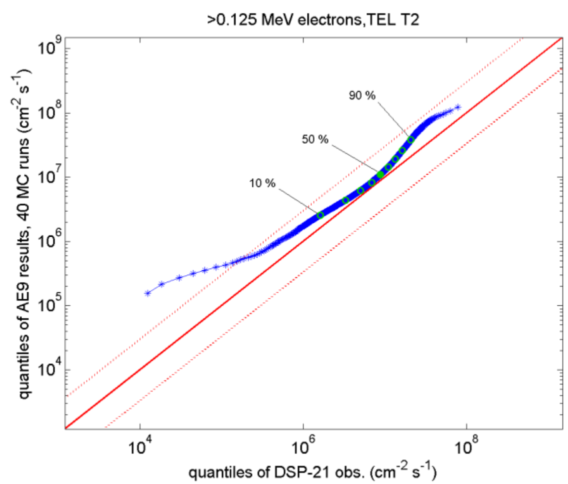


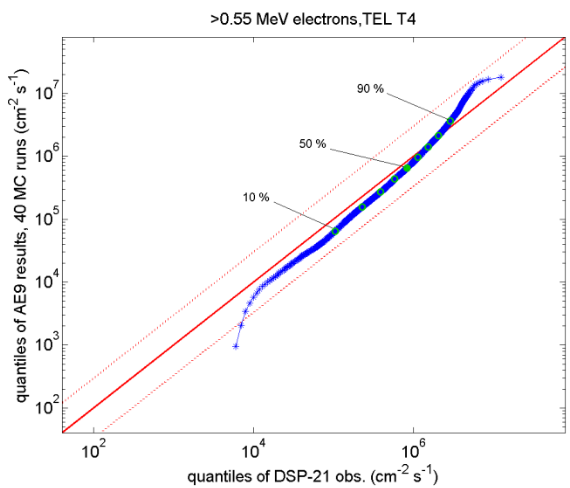
0.55 MeV

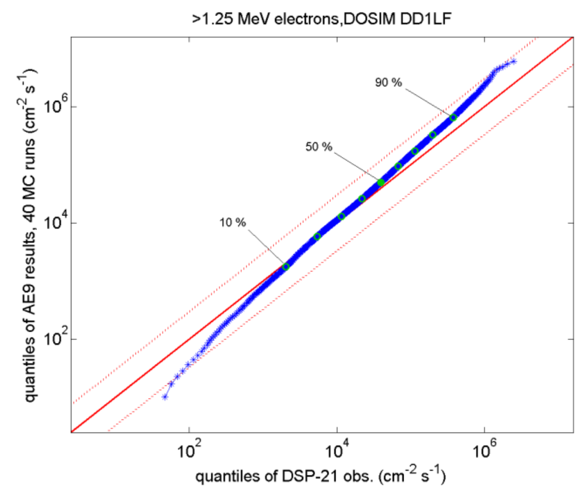


1.25 MeV









10 year runs, 40 MC scenarios, 1 – 5 min time step

Summary

- AE-9/AP-9 will improve upon AE-8/AP-8 to address modern space system design needs
  - More coverage in energy, time & location for *trapped* energetic particles & plasma
  - Includes estimates of instrument error & space weather statistical fluctuations
- Version Beta.3 now in limited distribution
  - Provides mean and Monte-Carlo scenarios of flux along arbitrary orbits
  - Dose calculations provided with ShieldDose utility
  - Includes historical AP8/AE8, CRRES and CAMMICE/MICS models
  - NOT TO BE USED FOR SATELLITE DESIGN OR SCIENTIFIC STUDIES
- Version 1.0 due in Fall 2011
  - Can be used for satellite design and science
  - Will be open distribution
  - Standard solar-cycle in Version 1.0+, release date TBD
- Version 2 will include much needed new data sets
  - Relativistic Proton Spectrometer and other instruments on NASA Radiation Belt Storm Probes giving complete radiation belt coverage (launch in ~2012)
  - Instruments on DSX will provide slot region coverage (launch ~2012)
  - Due two years after RBSP launch