AE/AP-9 Radiation Specification Model Development

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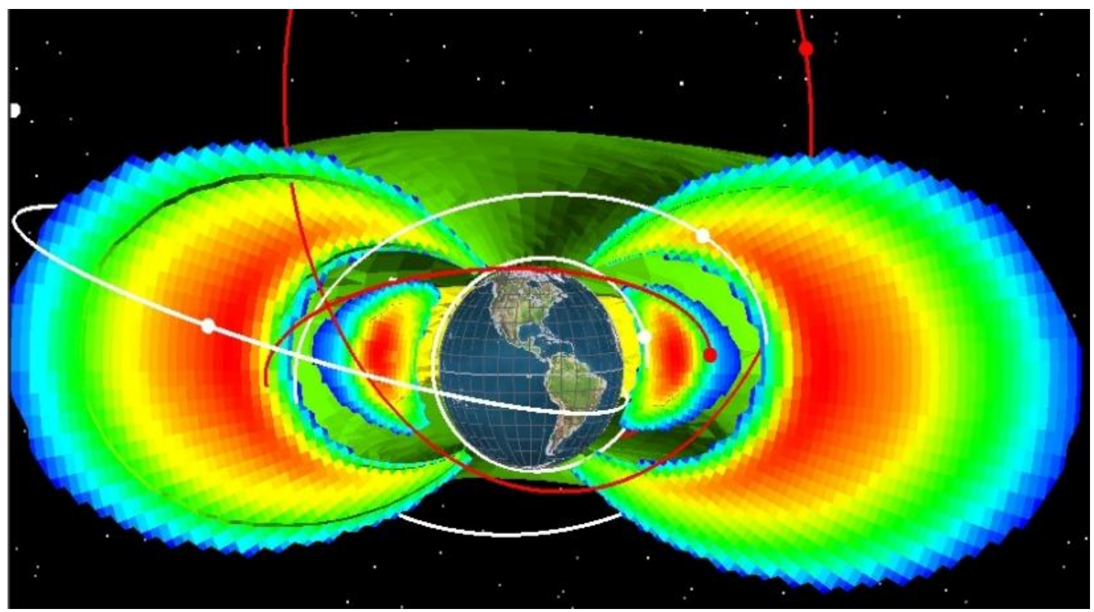

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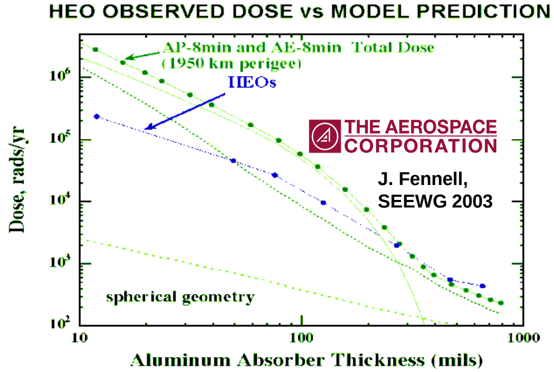
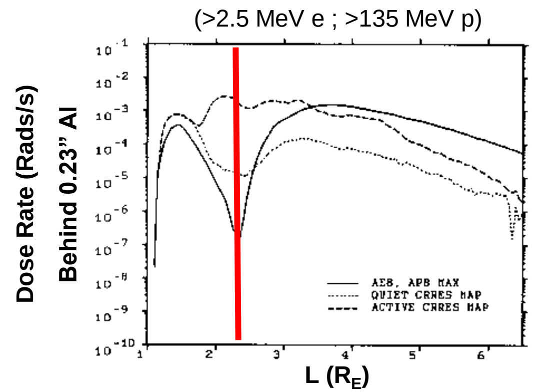
The Need for New Models

Example: Highly Elliptic Orbit (HEO)



HEO dose measurements show that current radiation models (AE8 & AP8) over estimate the dose for thinner shielding

Example: Medium-Earth Orbit (MEO)

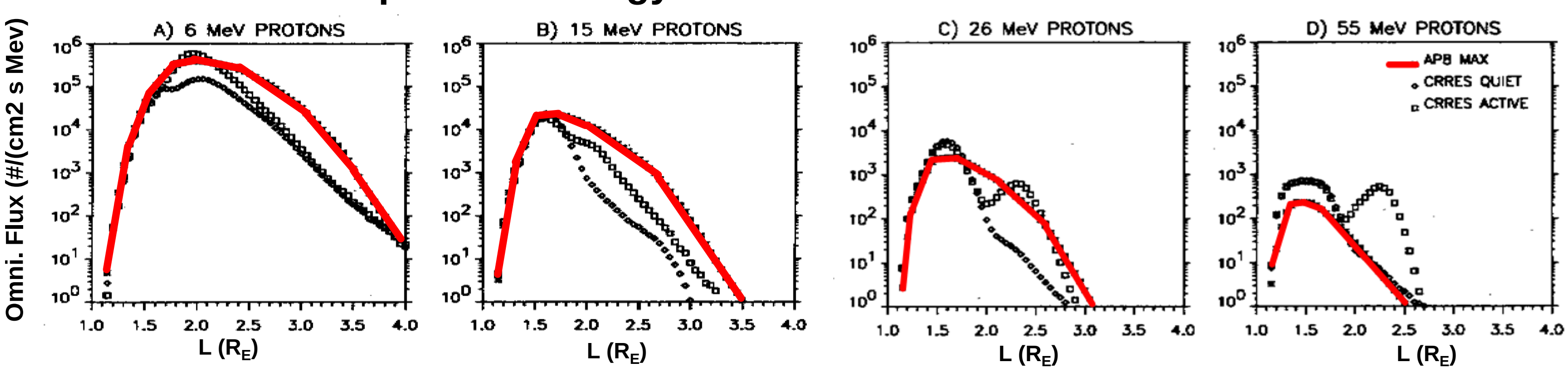


For MEO orbit (L=2.2), #years to reach 100 kRad:

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

AE8 & AP8 under estimate the dose for 0.23'' shielding

Model differences depend on energy:



AP-8/AE-8 inadequate for modern spacecraft design and mission planning

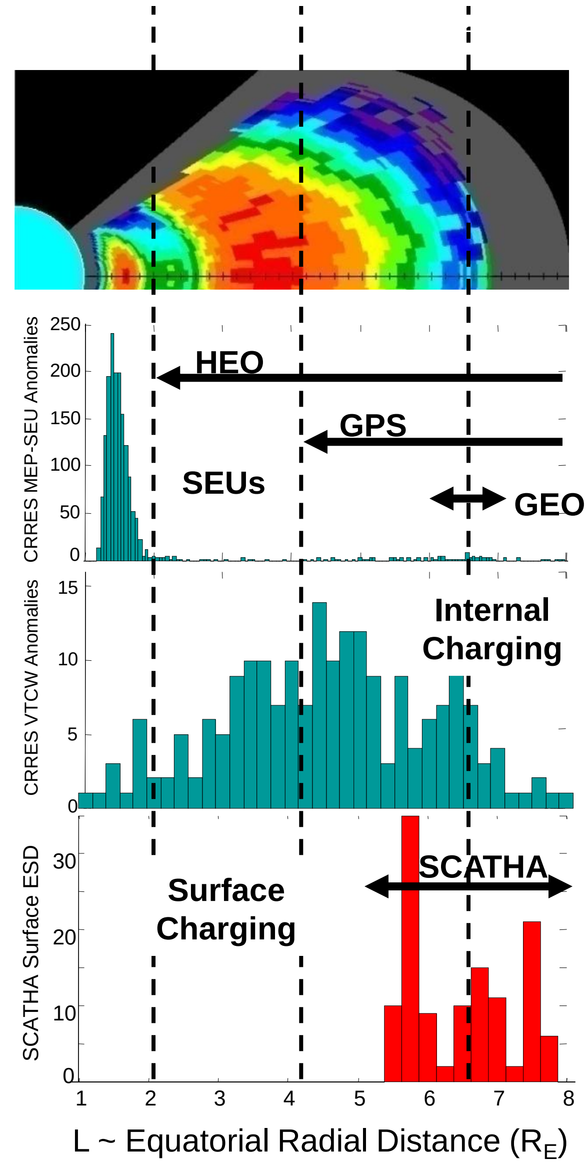
AP9/AE9 Program Objective

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)

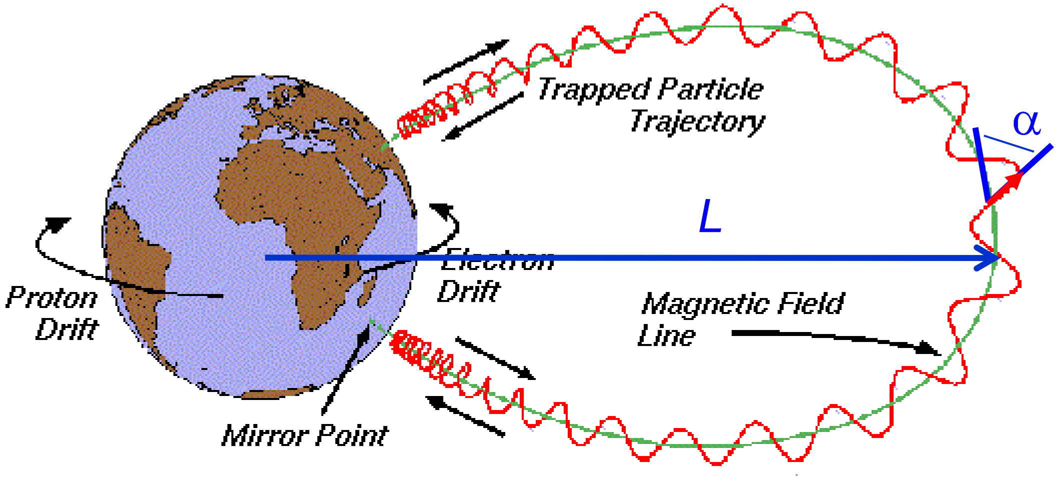
Inputs:

- **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



- **Cartesian coordinates: (*x,v;t*)**
- **Field-Line coordinates: (*E*, L_m, α_0, *MLT*)**
- **Adiabatic invariant coordinates: (*M, K, Φ*)**
- **For AE9/AP9: (*E, K, Φ*)**
  - **IGRF/Olson-Pfitzer 77 Quiet B-field model**
  - **$\log_{10}\Phi - K^{3/4}$ uniform spacing for outer zone**
  - **$\Phi - K^{3/4}$ uniform spacing for inner zone**
  - **Special LEO grid being developed**
    - **Atmospheric density & details of Earths field become important**

Adiabatic invariants

Cyclotron motion:

$$\mu = \frac{p_\perp^2}{2mB} = \frac{p^2 \sin^2 \alpha}{2mB}$$

Bounce motion:

$$K = \int_{s_m}^{s_{m'}} B_m - B(s)\; ds$$

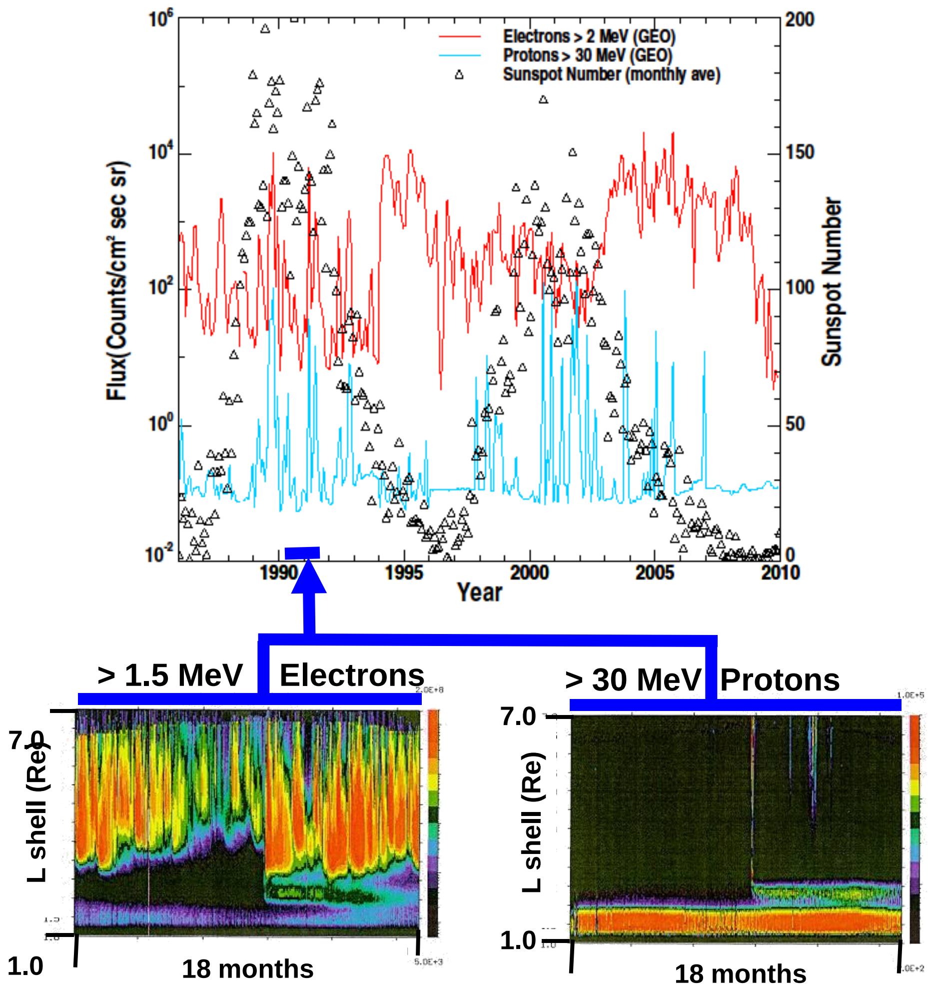
Drift motion:

$$\Phi = \oiint_{S_d} d\vec{a} \bullet \vec{B}$$

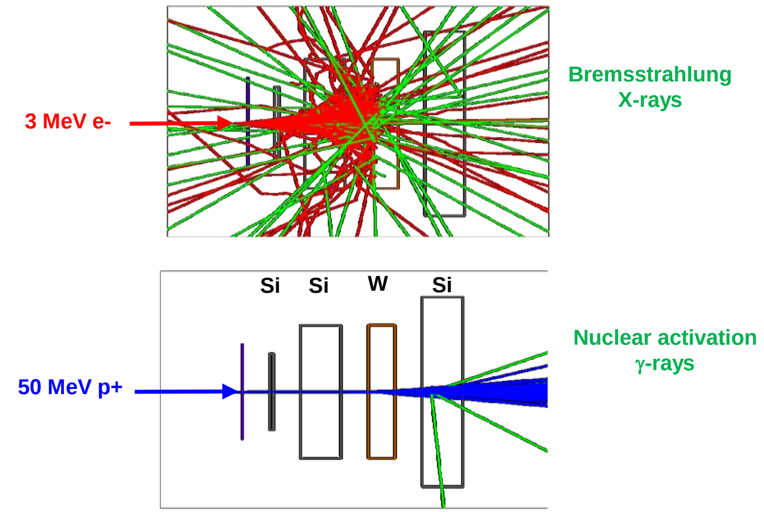
$$L^* = \frac{2\pi M}{\Phi R_E}$$ **“L shell”**

Sources of Uncertainty

Space weather



Particle detectors



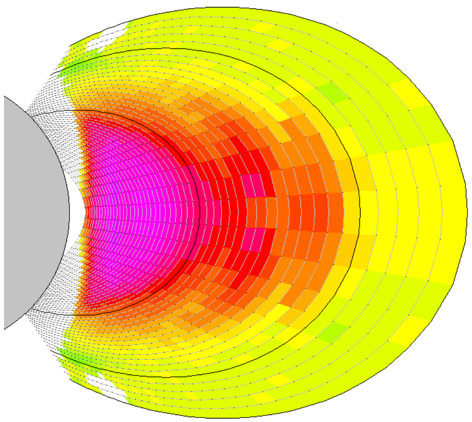
GEANT-4 MC simulation of detector response

- 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



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

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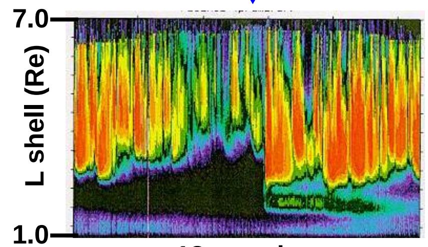
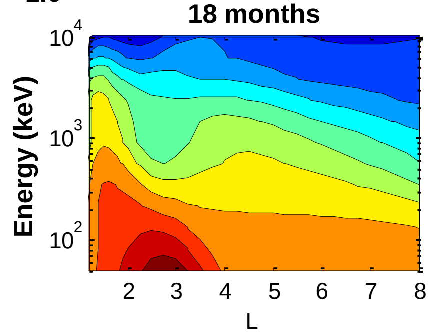
Satellite data & theory



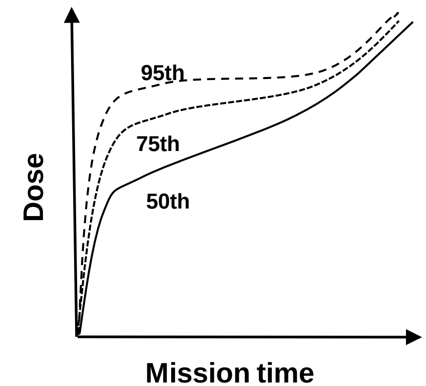


Statistical Monte-Carlo Model

- 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

=

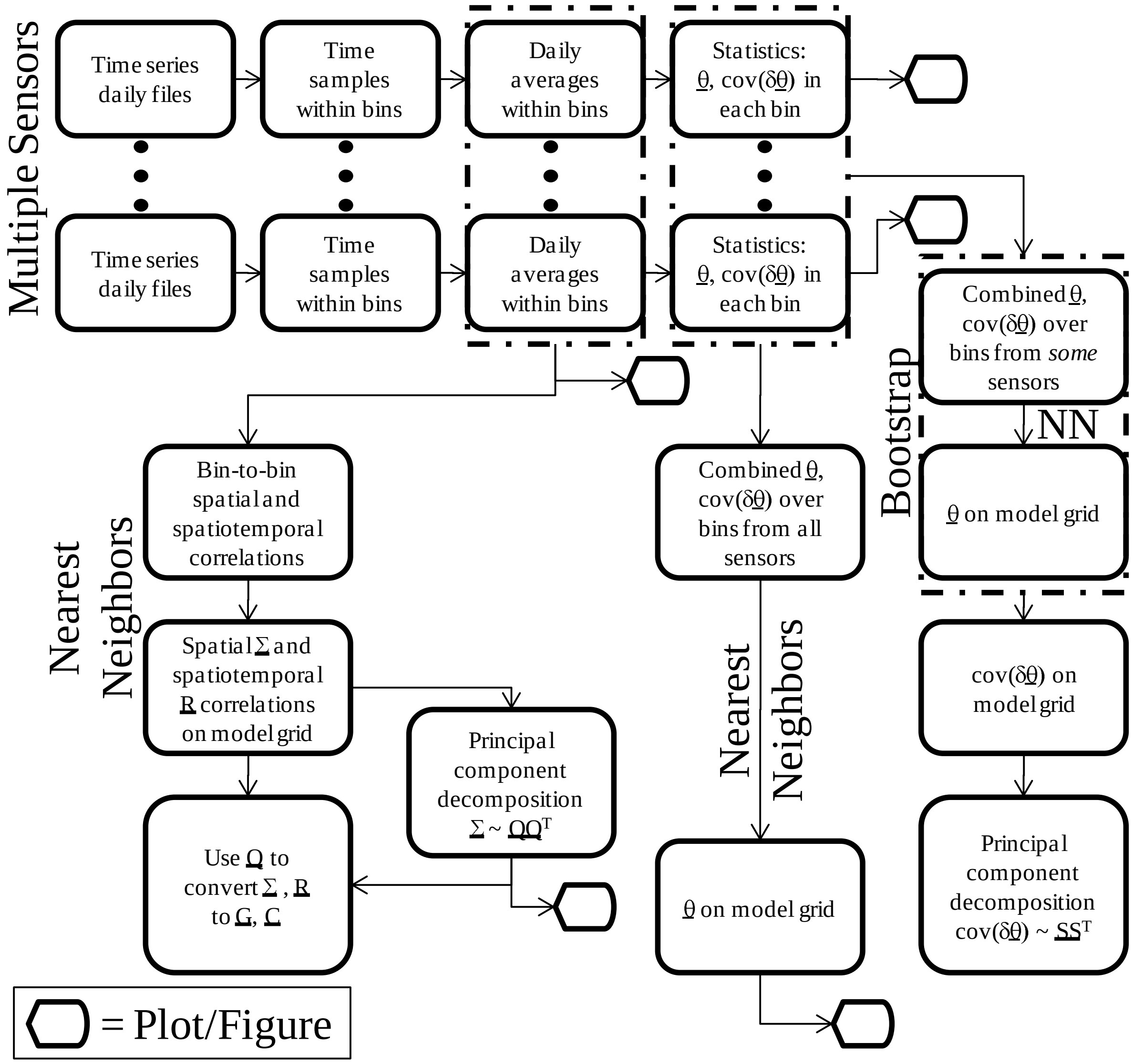
User's orbit



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

Generating the Runtime Tables



Monte-Carlo Quantities

Quantity	Symbol	Size	Purpose
Parameter map	$\theta(E,K,\Phi)$	~50,000 x 2 (will double when we add LEO grid)	Represents transformed 50th and 95th percentile flux on coordinate grid (weather variation)
Parameter Perturbation Transform	$S_\theta(E,K,\Phi)$	~50,000 x 2 x 30 (will double when we add LEO grid)	Represents error covariance matrix for θ (measurement errors). $S_\theta S_\theta^T$ is the error covariance matrix for θ.
Principal Component Matrix	$Q(E,K,\Phi)$	~50,000 x 10 (will double when we add LEO grid)	Represents principal components (q) of spatial variation (spatial correlation). QQ^T is the spatial covariance matrix for normalized flux (z).
Time Evolution Matrix	G	~10 x 10 (V1.0 will have multiple G's)	Represents persistence of principal components (temporal correlation)
Noise Conditioning Matrix	C	~10 x 10	Allocates white noise driver to principal components (Monte Carlo dynamics)
Marginal Distribution Type	N/A	N/A	Weibull (electrons) or Lognormal (protons) used for converting 50th and 95th percentiles into mean or other percentiles

Monte-Carlo Scenarios

Initialization and white noise drivers are different for each scenario to represent unpredictable dynamics

Conversion to flux is different for each scenario to represent measurement uncertainty in the flux maps

Randomly initialize Principal Components (q_0) and flux conversion parameters (θ)

→

Evolve PCs in time
$q_{t+1} = \Sigma G_i q_{t-Ti} + C\eta_{t+1}$

→

Convert PCs to flux: q_t -> z_t -> j_t
(Uses perturbed θ)

↓

Map global flux state to spectrum at spacecraft
$J_t = H_t j_t$

G, C, and the parameters of the conversion from PCs to flux are derived from statistical properties of empirical data and physics-based simulations

The measurement matrix H is derived from the location of the spacecraft and the energies/angles of interest

To obtain percentiles and confidence intervals for a given mission, one runs many scenarios and post-processes the flux time series to compute statistics *on the estimated radiation effects across* scenarios.

Data Sets

Data Set	Orbit/Duration	Measurements
HEO-1	Molniya, L>2, little coverage L<4, 1994 onward	Dosimeter, p+: >80, >160, >320 keV, >20, >40, >55, >66 MeV e- : >130, >230 keV, >1.5, >4, >6.5, >8.5 MeV
HEO-3	Molniya, L>2, 1997 onward	Dosimeter, p+: >80, >160, >320 keV, >5, 16-40, 27-45 MeV e- : >130, >230, >450, >630 keV, >1.5, >3.0 MeV
ICO	45°, 10000 km circular, MEO L>2.5, 2001 onward	Dosimeter, p+: >15, >24, >33, >44, >54 MeV e- : >1.2, >2.2, >4, >6, >8 MeV
TSX-5	67° LEO, 400 x 1700 km, June 2000- Jul 2006	CEASE (dosimeter & telescope), p+: 20 – 100 MeV, 4 int. channels; e- : 0.06 – 4 MeV, 5 int. chanels
CRRES	GTO, L>1.1, contamination issues in inner zone, Jul 1990 – Oct 1991	PROTEL, p+: 1 – 100 MeV, 22 channels HEEF, e-: 0.6 – 6 Mev, 10 channels; MEA(e-): 0.1 – 1.0 MeV LEPA, p+ & e-: 100 ev – 50 KeV
S3-3	97.5° MEO, 236 x 8048 km, 1976-1979	p+: 80 keV – 15.5 MeV (5 ch), > 60 MeV (no GF) e- : 12 keV – 1.6 MeV (12 ch)
GPS	54° , 20000 km, MEO L>4.2, Jan 1990 onwards	BDD/CXD, p+: 5/9 – 60 MeV e- : 0.1/0.2 – 10 MeV
Polar	90° , 1.8 x 9.0 Re, Feb 1996 – Apr 2008	CAMMICE/MICS, p+, O+: 1-200 keV/e HYDRA, p+, e-: 2 eV – 35 keV IES/HISTe, e-: 30 keV – 10 MeV
SCATHA	Near-GEO, 5.5 < L < 7.5, 1979 - 1989	SC3, e-: 0.05 – 4.6 MeV, 11 differential channels
MDS-1	GTO, L>1.1,2002-2003	Electron channels: ~0.5, ~1, ~2 MeV
AZUR	103°, 387 x 3150 km, 1969-1970	12 proton channels, 0.25- 100 MeV
GOES 7,8 & 11	GEO 1986 onwards	SEM, p+: 0.8 – 700 MeV, 10 differential channels >1, >5, >10, >30, >50, > 100 MeV integral channels
SAMPEX	LEO (500 km) 1992.5 onward	PET, p+: up to 400 MeV e- : >0.5, >1, 1-6, 3-16, 10-20 MeV
LANL - GEO	GEO 1985 onwards	MPA/CPA/ESP/SOPA, p+: 0.1 keV – 200 Mev e- : 0.1 keV - > 10 MeV
DSP-21	GEO Aug 2001 onward	CEASE (dosimeter & telescope) p+: 20 – 100 MeV, 4 integral channel e- : 0.06 – 4 MeV, 5 integral channels
TWINS F1	HEO 2006 onwards	Dosimeter, p+: > 8.5, > 16, > 27 MeV; e-: > 0.63, > 1.5, > 3 MeV

Version Beta

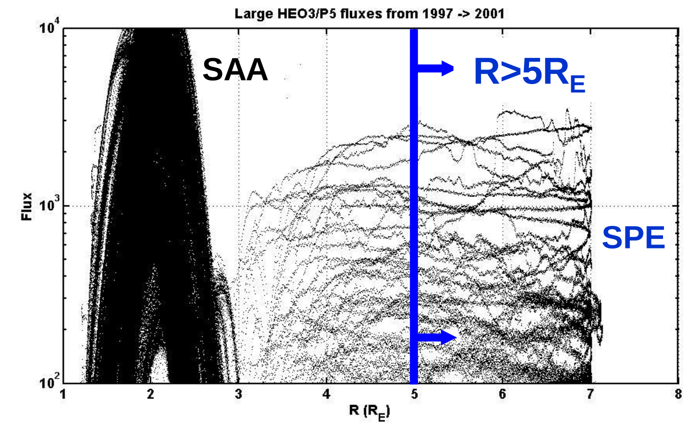
Version 1.0

Version 1.+

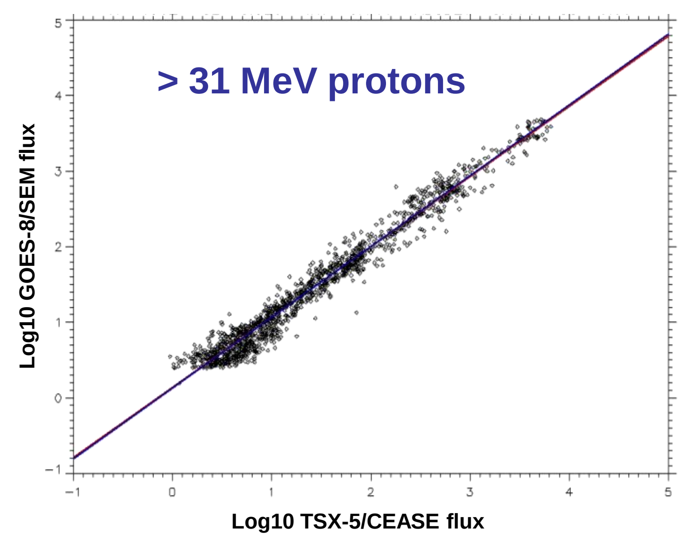
Validation Only

Cross-calibration

- **In-flight detector cross-calibration is used to estimate the measurement uncertainties**
  - **Building first-principle error budgets for detectors is complicated and often impossible**
  - **By looking at the same event cross-calibration can estimate and remove systematic error between detectors given a "standard sensor"**
  - **Residual random error for each detector then becomes the "detector error" used in AP9/AE9 development**
- **For protons (easier):**
  - **Look at simultaneous observations of solar proton events (SPEs) which provide a uniform environment at high latitudes and altitudes**
  - **Standard sensor = GOES**
  - **Chain of cross-cal completed for Version Beta**
- **For electrons (harder):**
  - **No uniform solar "electron event" – need at least Lshell conjunction**
  - **Standard sensor = CRRES/HEEF-MEA**
  - **Cross-cal NOT completed for Version Beta**



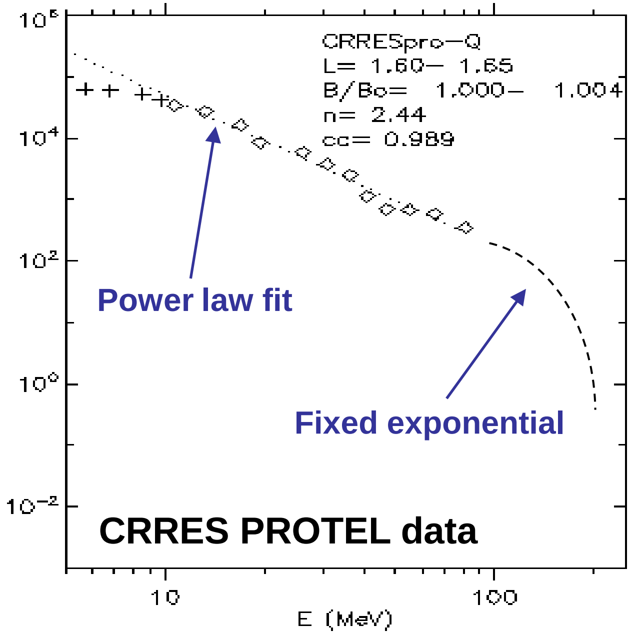
A proton event as seen by a HEO satellite



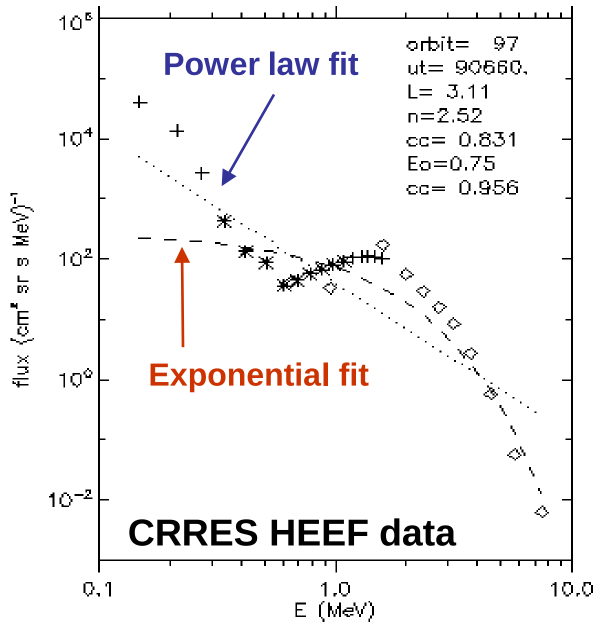
GOES-8/SEM – TSX-5/CEASE data during an SPE

Spectral Inversion

Protons



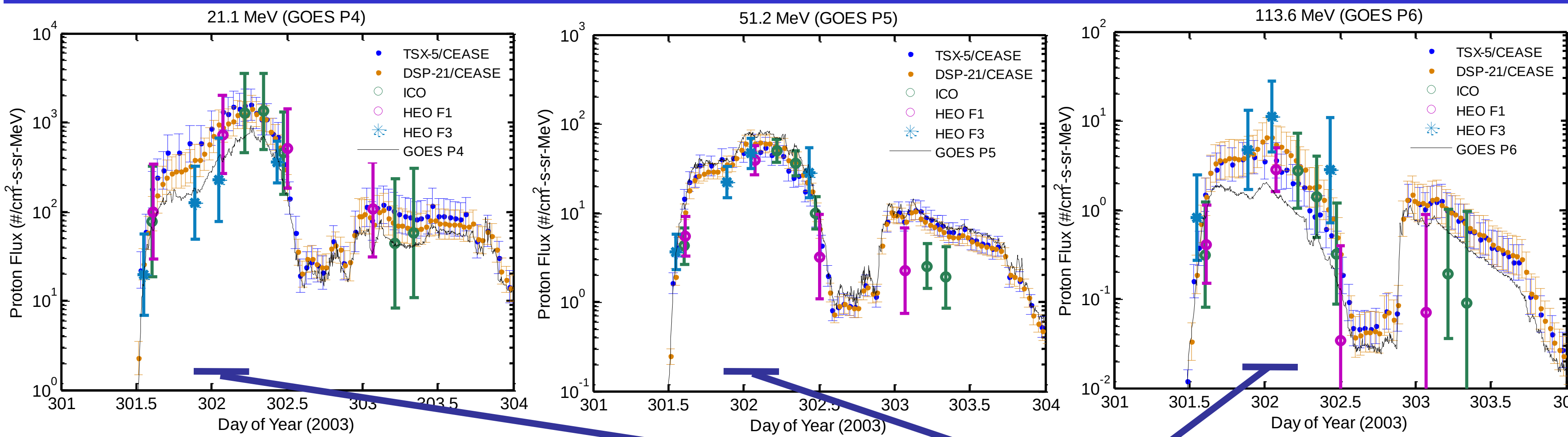
Electrons



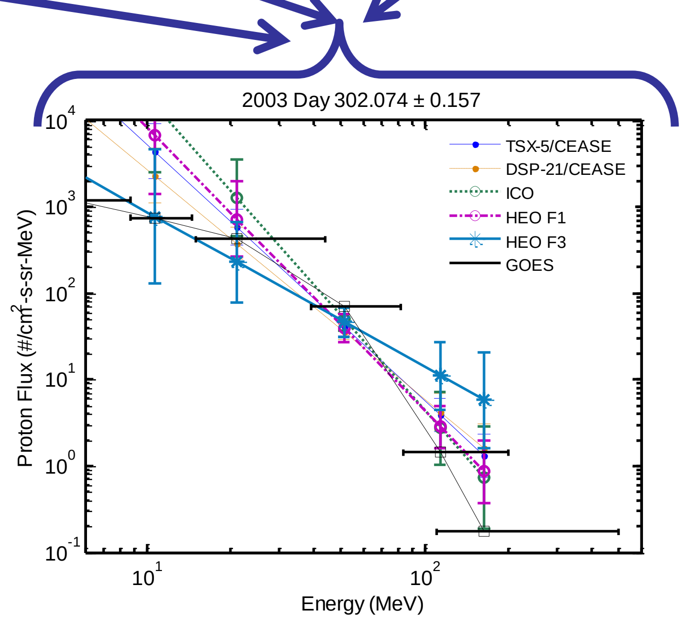
Dosimeter data sets have wide spatial and temporal coverage …but require response models & inversion algorithms to pull out spectra

- **Protons are straight forward,**
  - **Power law between 10 – 100 MeV; fixed rate exponential > 100 MeV (Version Beta)**
  - **Fit to broken power law < 10 MeV (Version 1.0)**
- **Electrons are more complex**
  - **LANL relativistic Maxwellian for GPS data only (Version Beta)**
  - **More sophisticated techniques being developed for Version 1.0**

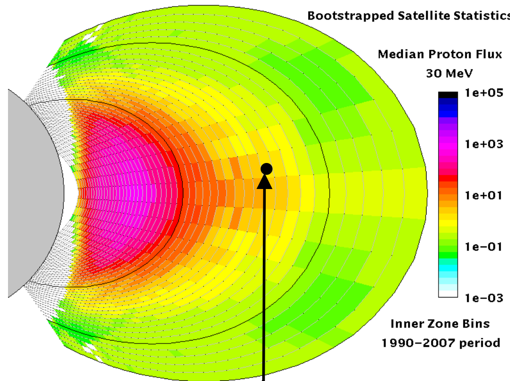
Proton Inversion Validation



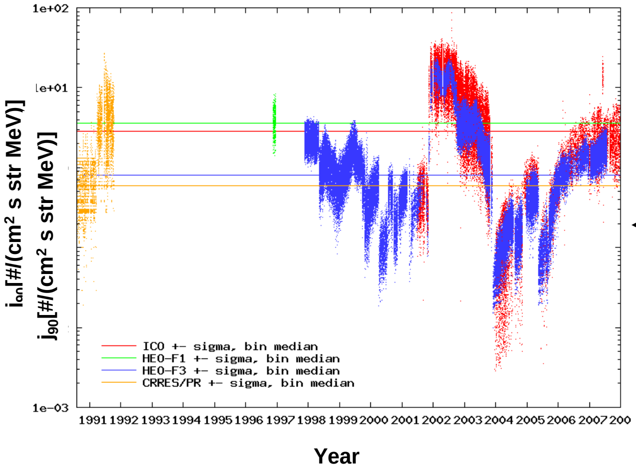
- **Validate proton spectral inversion algorithms during solar proton events**
  - **Invert HEO-F1/Dosimeter, HEO-F3/Dosimeter, ICO/Dosimeter, TSX-5/CEASE and DSP-21/CEASE data**
  - **Compare with GOES detailed spectra**
- **Reasonable agreement given SPEs are not always power laws**
- **Example: Halloween 2003 SPE**



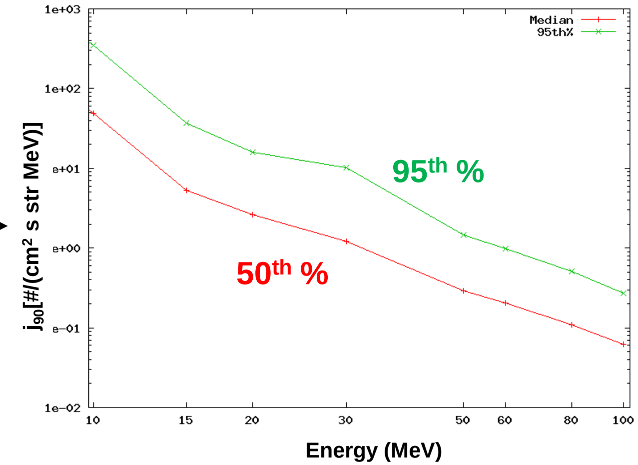
Example: Proton Flux Maps



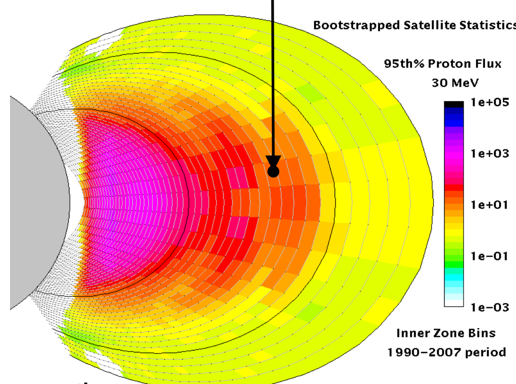
50th %



Time history data



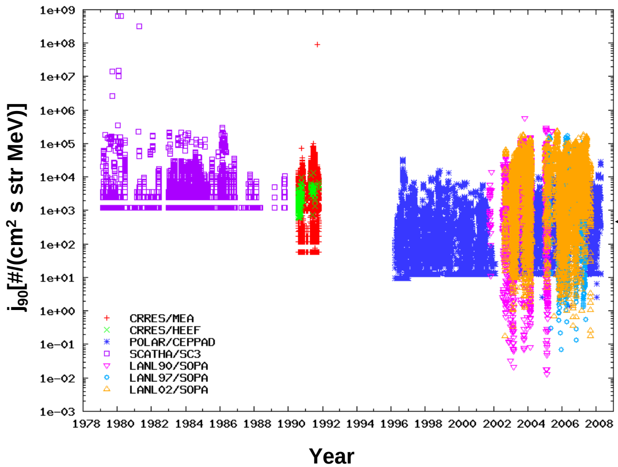
Energy spectra



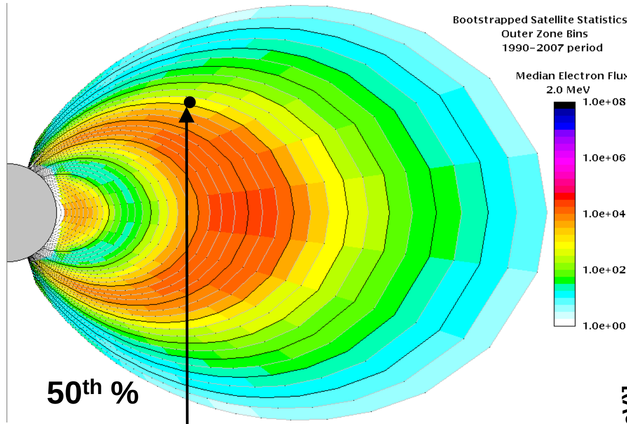
95th %

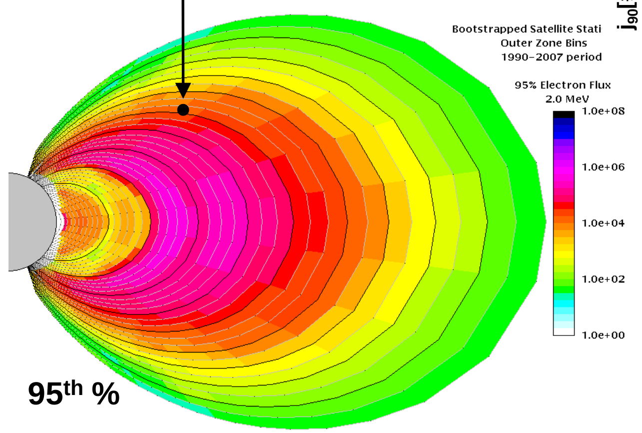
Flux maps (30 MeV)

Example: Electron Flux Maps

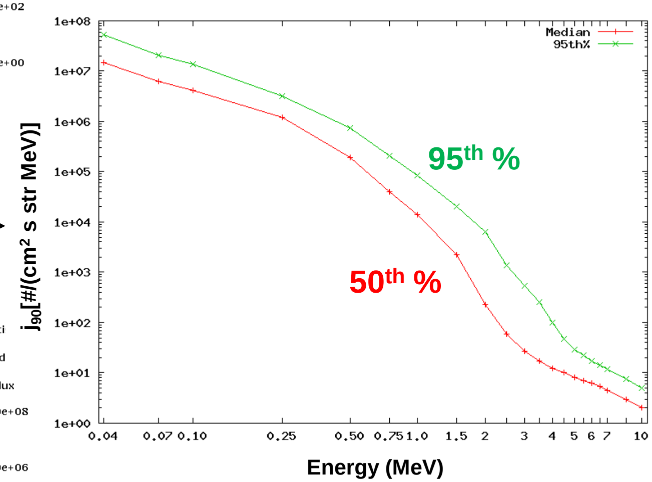


Time history data





Flux maps (2.0 MeV)

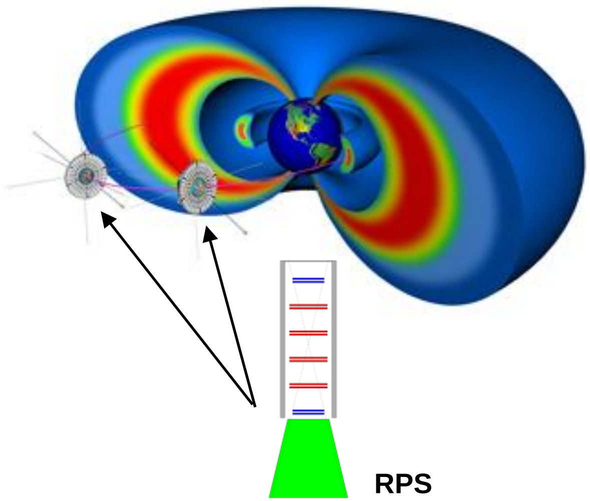


Energy spectra

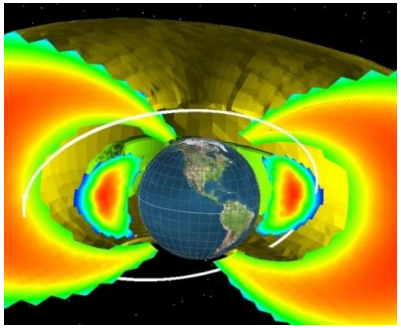
Future Data Sources

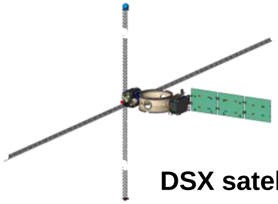
- **Inner zone protons are poorly measured ,**
  - **Specification of energetic protons is #1 satellite design priority**
  - **HEO-1/Dosimeter (1994 – current) – little inner zone coverage**
  - **HEO-3/Dosimeter (1997 – current) – little inner zone coverage**
  - **ICO/Dosimeter (2001 – current) – only slot region coverage**
  - **CRRES/PROTEL (1990-1991) – contamination issues in inner zone**
- **Relativistic Proton Spectrometer (RPS) on NASA Radiation Belt Storm Probes (RBSP)**
  - **Measures protons 50 MeV - 2 GeV**
  - **RPS instruments provided by NRO will be on the 2 RBSP satellites (launch ~ May 2012)**
  - **Other NASA detectors on RBSP in GTO will provide comprehensive coverage of the entire radiation belt regions**
- **Other upcoming data sources:**
  - **AFRL DSX, 6000 x 12000 km, 68° (slot region), comprehensive set of particle detectors including protons 50 MeV – 450 MeV, launch Oct 2012**
  - **TACSAT-4, 700 x 1100 km , 63° (inner belt & slot region), CEASE detector, launch Sep 2010**

RBSP orbits



DSX orbit





DSX satellite

Version Beta Validation

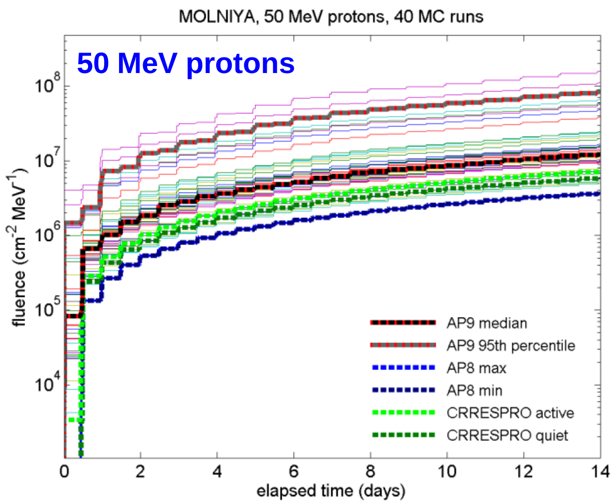
Known issues:

- **Electron data not complete nor cross-calibrated**
  - Error bars fixed at $\delta \ln j = 0.1$
  - Minimal LEO and inner belt data
- **Independent LEO coordinate system not implemented**
  - *(Φ, K)* coordinates not enough below ~1600 km due to neutral density effects & Earth B-field variations
- **Covariance matrices only computed for one-day lag time**
  - Longer time-scale SWx fluctuations not being adequately captured
- **Performance not optimized**
  - LEO: 17 min/(scenario day) at 10 sec resolution -> 103 hrs/(scenario year)
  - MEO: 3.2 min/(scenario day) at 1 min resolution -> 19 hrs/(scenario year)

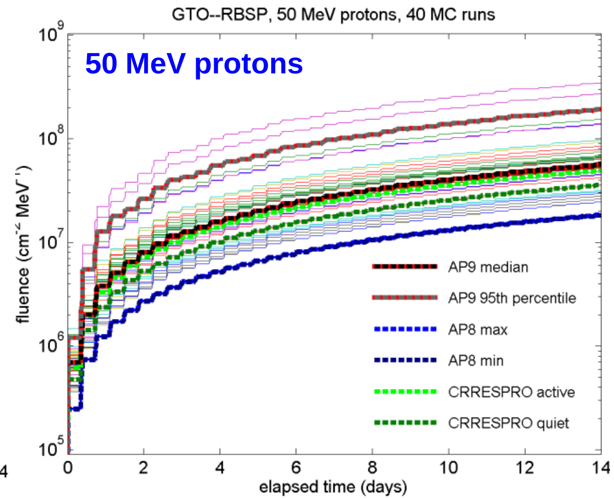
AE9/AP9 Version Beta is for test purposes only - NOT to be used for satellite design or other applications!

Model Comparisons

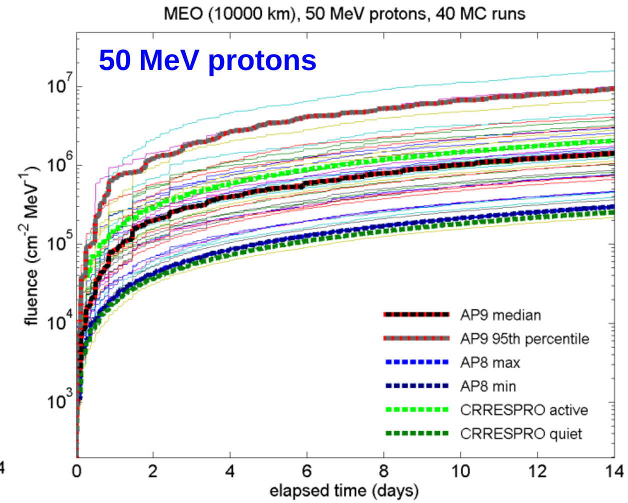
HEO (1475 X 38900 km, 63° incl.)

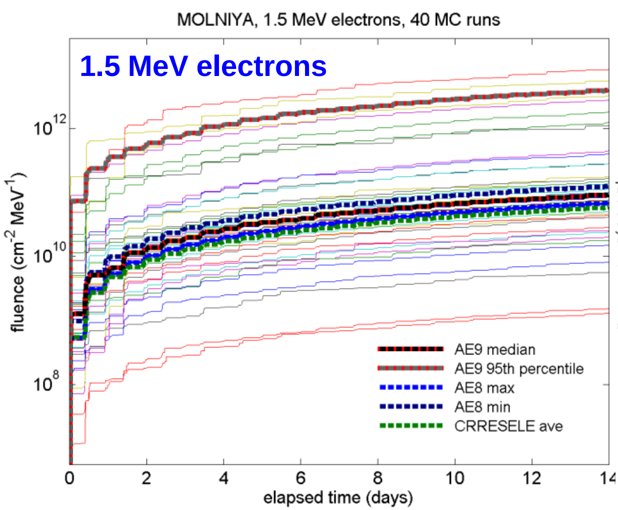


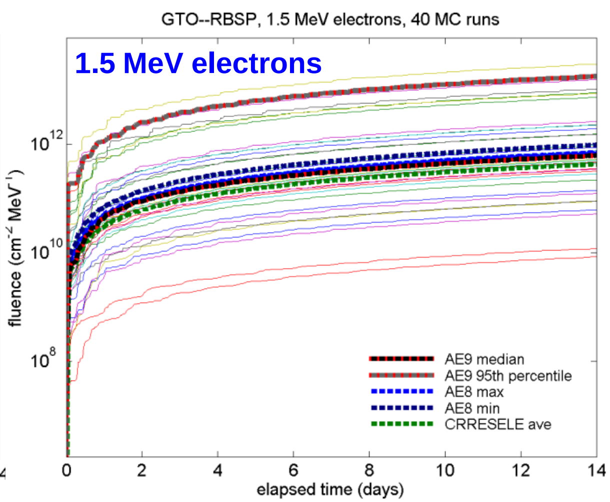
GTO (500 X 30600 km, 10° incl.)

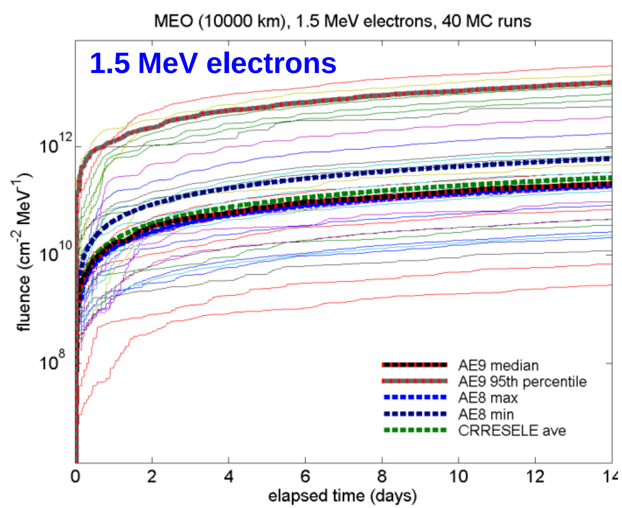


MEO (10000 km circ. , 45° incl.)





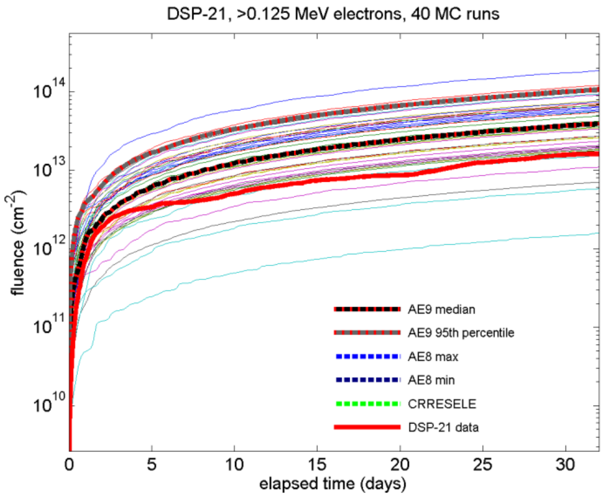




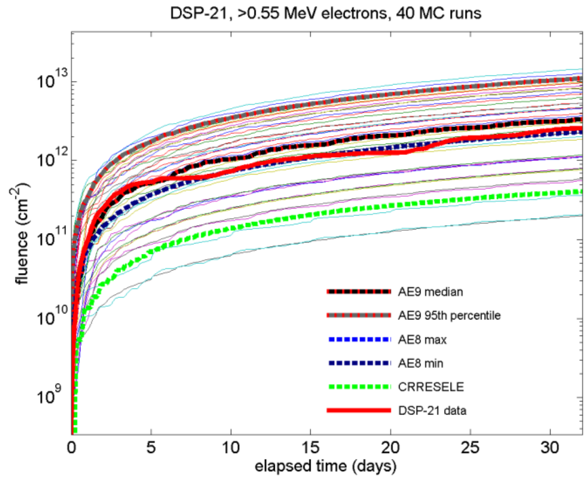
2 week runs, 40 MC scenarios, 1 – 5 min time step

Data Comparison: GEO electrons DSP-21/CEASE

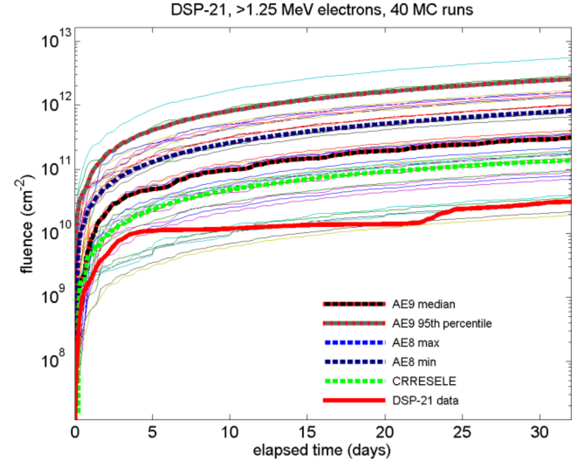
0.125 MeV

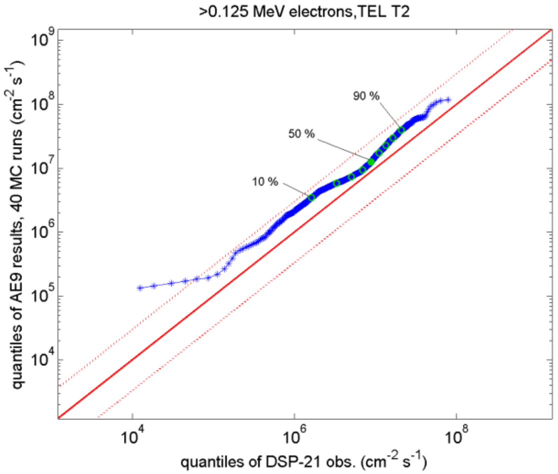


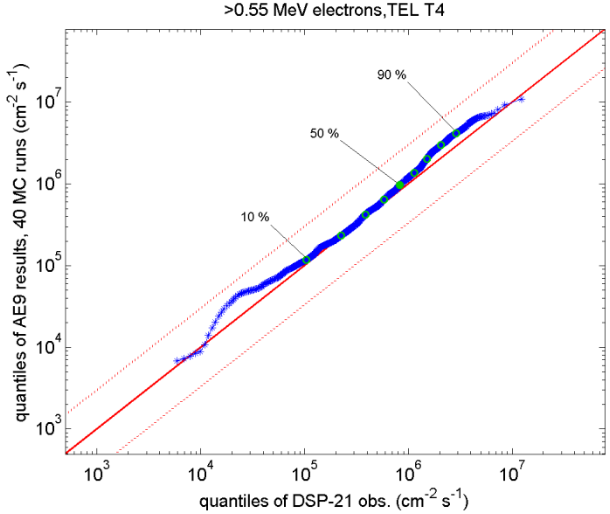
0.55 MeV

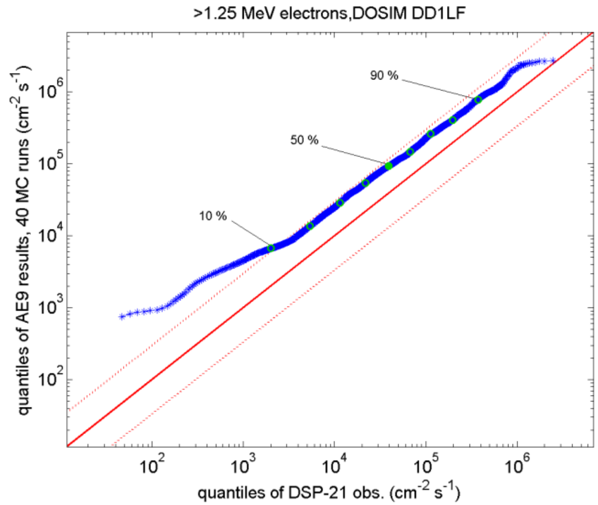


1.25 MeV

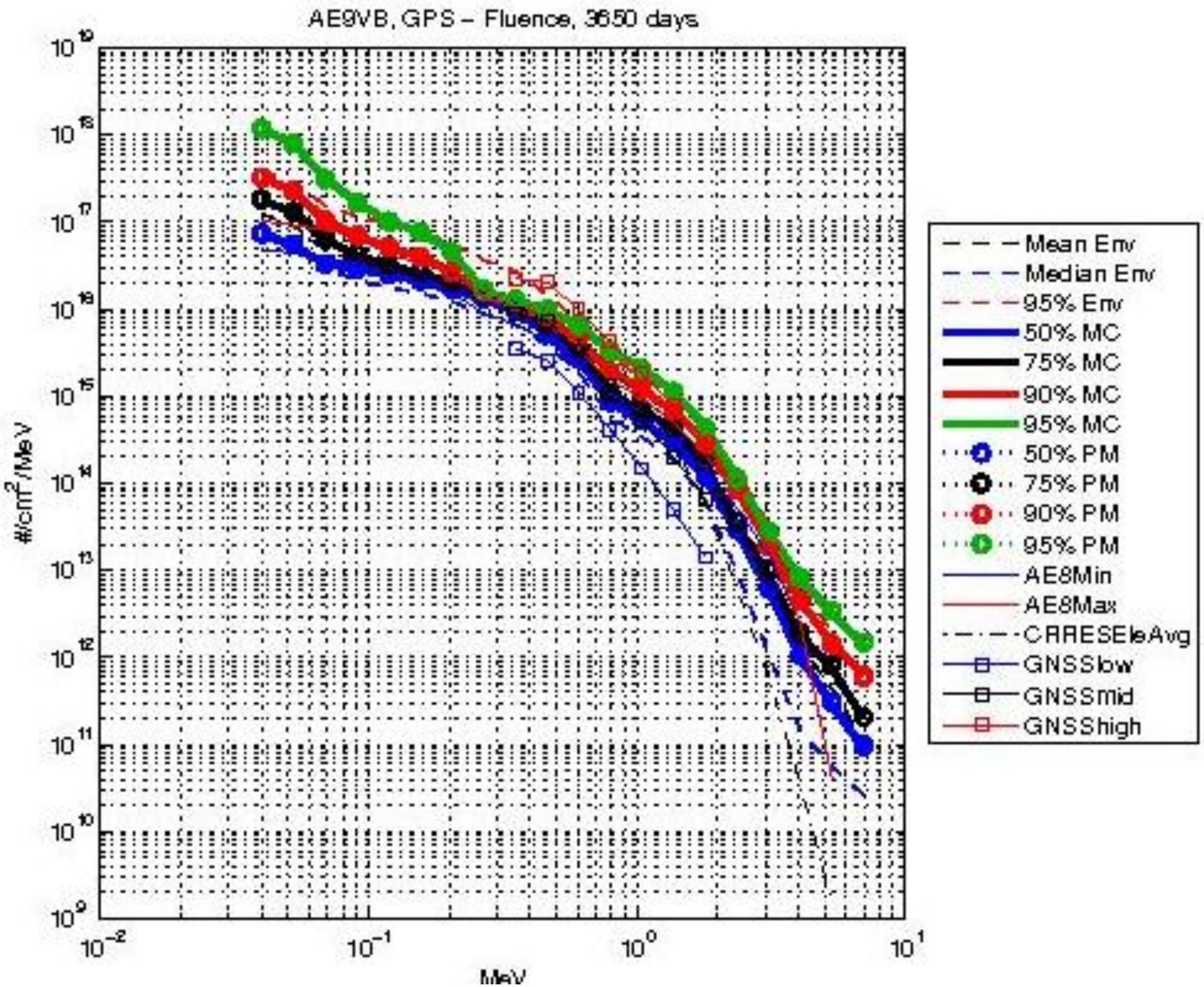






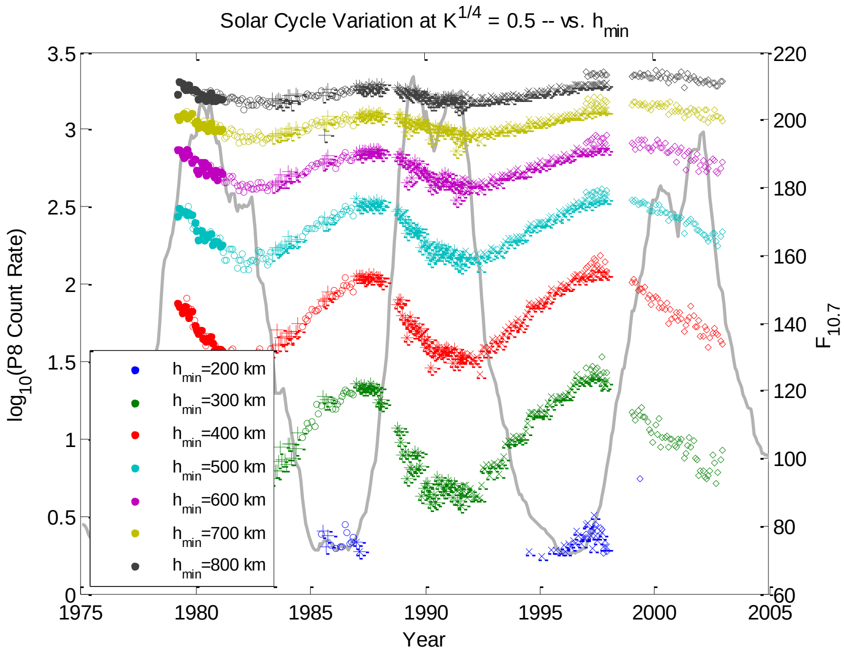


Model Comparison: GPS Orbit



LEO Coordinate System

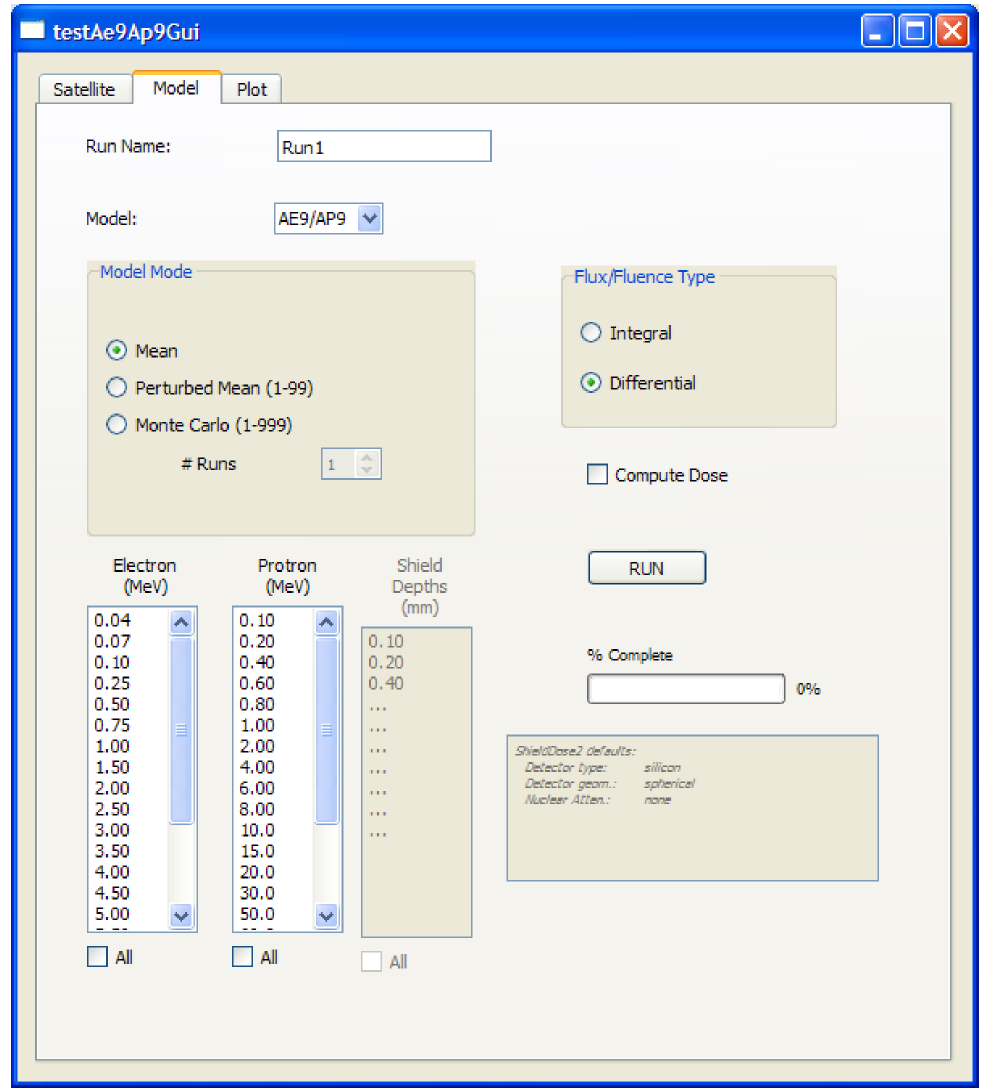
- Version Beta *(Φ, K)* grid inadequate for LEO
  - Not enough loss cone resolution
  - No "longitude" or "altitude" coordinate
    - Invariants destroyed by altitude-dependent density effects
    - Earth's internal B field changes amplitude & moves around
    - What was once out of the loss-cone may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



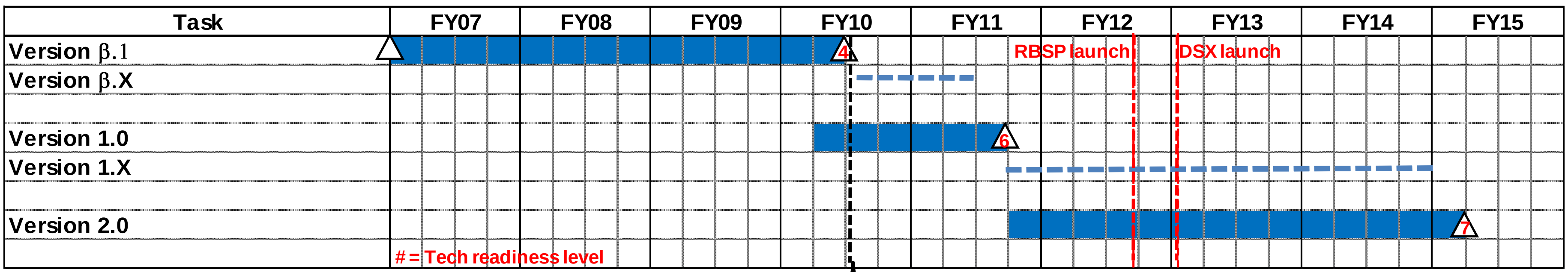
- Version 1.0 will splice a LEO grid onto the *(Φ, K)* grid at ~1000-2000 km
  - Minimum mirror altitude coordinate h_{min} to replace *Φ*
  - Capture quasi-trapped fluxes by allowing h_{min} < 0 (electron drift loss cone)
- Version 1.+ will go further
  - Either the coordinates or the flux maps will have to depend on F10.7. A stochastic F10.7 model (extended from Xapsos et al. 2002) has been developed to add atmospheric variability to the Monte Carlo scenarios.
  - Postponing longitude coordinate (electron drift loss cone) to Version 1.+

Software Applications

- **Primary product: AP9/AE9 “flyin()” routine modeled after ONERA/IRBEM library**
  - **C++ code with command line operations and demo GUI**
  - **Open source available for other third party applications (e.g. STK, Space Radiation, SPENVIS)**
  - **Runs *single* Monte-Carlo scenario**
  - **Input: ephemeris**
  - **Output: flux values along orbit**
    - **Mean (no instrument error or SWx)**
    - **Perturbed Mean (no SWx)**
    - **Full Monte-Carlo**
- **Effects (dose, charging) must be modeled by third-party tools**
    - **Shieldose and running averages are provided in command line app and GUI for demonstration purposes**



Schedule



Version Beta.1 – command line AP9/AE9 – available April 2010

Version Beta.2 – with GUI available May 2010

Version Beta.3 – with minor updates available September 2010

The Beta Version can only be released to US Govt. and Contractors.

Version 1.0 and beyond will be released to the public, including source code.

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 available now to US Govt. and Contractors
  - Energetic protons (> 1 MeV) and electrons (> 1 MeV) highest priority
  - Provides mean and monte carlo scenarios of flux along arbitrary orbits
  - Dose calculations provided with ShieldDose utility
  - Version Beta.3 (August 2010) will include POLAR/CAMMICE/MICS average plasma model
- Version 1 due in 3Q FY11
  - Detailed LEO coordinate system to resolve loss cones & atmospheric density effects
  - Spectral inversion applied to ICO, HEO, TSX-5 and GPS electron data sets
  - CAMMICE/MICS + LANL/MPA average plasma model with uncertainties
  - Expanded data sets, with electron cross-cal
  - Standard solar cycle in Version 1.+, 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