AEROSPACE REPORT NO.
TOR-2009(3905)-8

# The AE9/AP9 Radiation Specification Development

15 September 2009

Paul O'Brien,[1] Tim Guild,[1] Greg Ginet,[2] and Stu Huston[3]

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Chestnut Hill, MA

Prepared for:

National Reconnaissance Office
14675 Lee Rd.
Chantilly, VA 20151-1715

Contract No. FA8802-09-C-0001

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SC-1755(2, 5666, 26, JS)

# The AE9/AP9 Radiation Specification Development

Paul O’Brien & Tim Guild
Space Science Department, The Aerospace Corporation
Greg Ginet, AFRL/RVBX (MIT Lincoln Lab)
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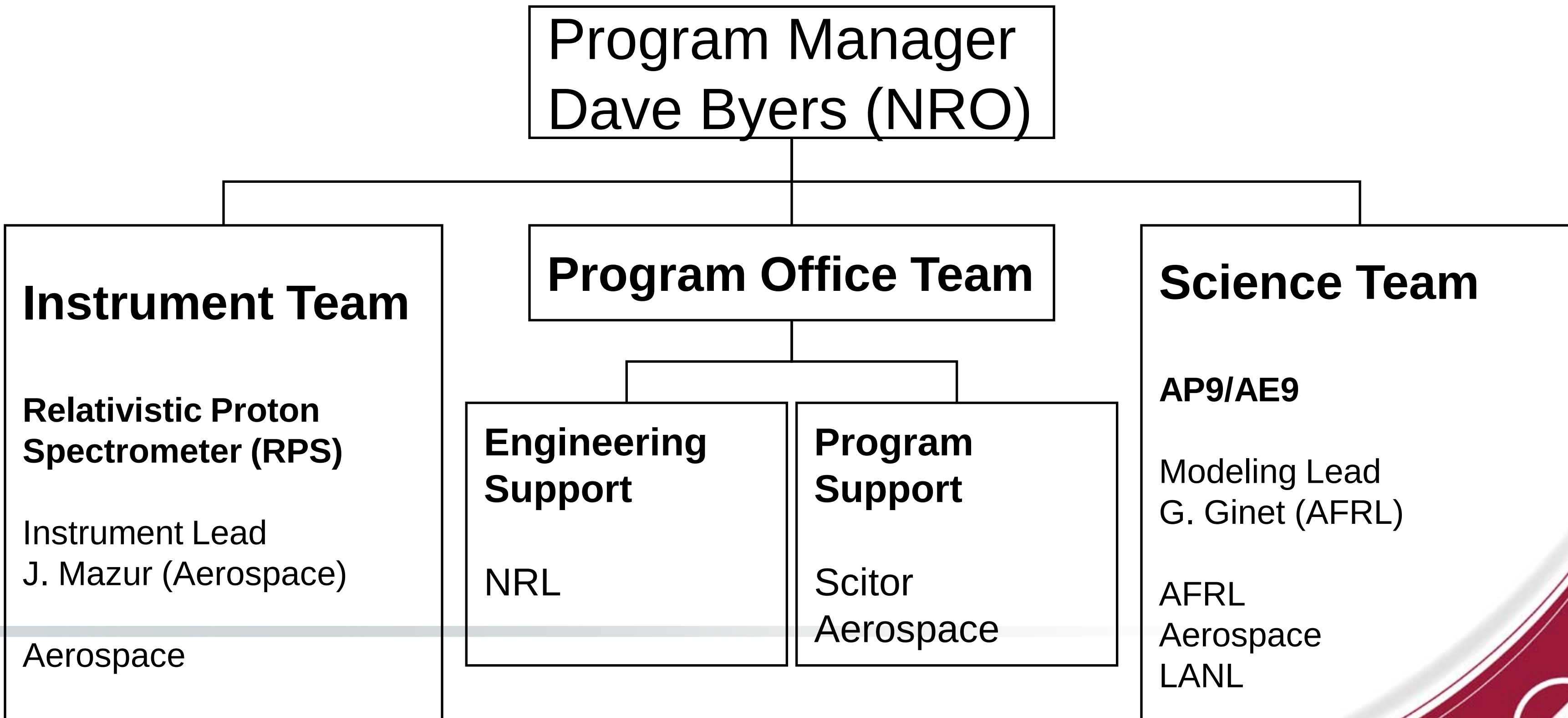
Space Sciences Applications Lab Seminar
July 28th, 2009

# Outline

- Project Overview
- Requirements Review
- Implementation Approach
- Status Update
- Future Plans
- Appendix - Impact of AE9/AP9 on the use of Environmental Effects Codes

# Proton Spectrometer Belt Research Program

- The objective of the PSBR program is to reduce uncertainty in the radiation environment specifications used to design satellites
- The PSBR program consists of two elements
  - *Aerospace's RPS sensor to fly on NASA's RBSP mission*
  - *The AE9/AP9 modeling effort*

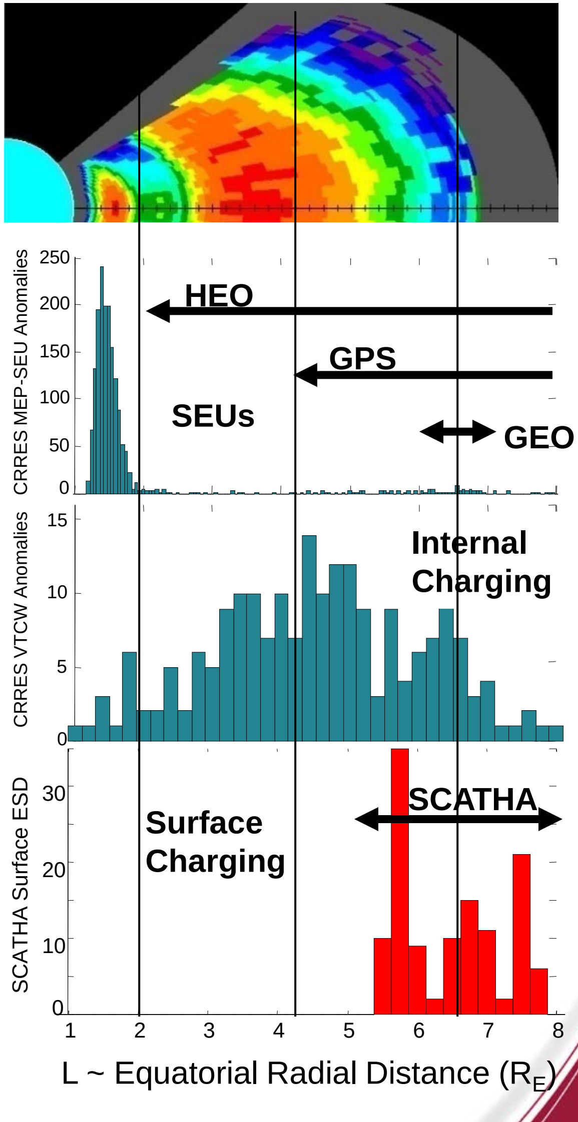


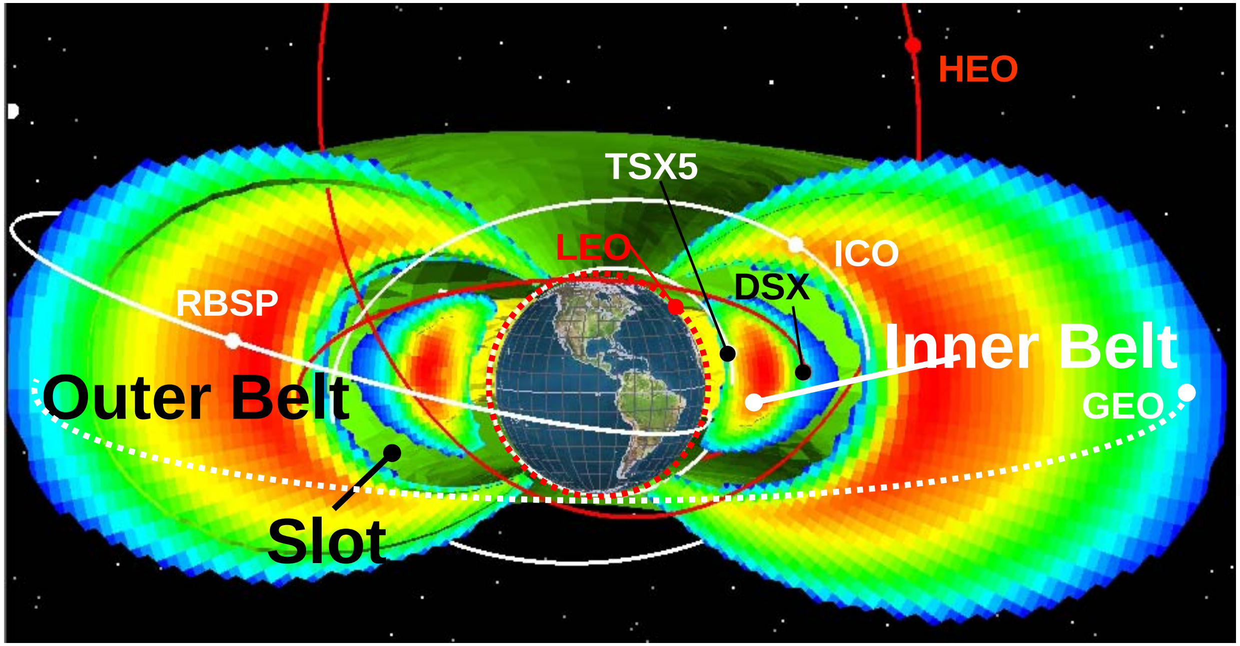
# AE9/AP9 Overview

OBJECTIVE: Provide satellite designers with a definitive model of the trapped energetic particle and plasma environment to include:

- Quantitative accuracy
- Indications of uncertainty
- Flux probability of occurrence and worst cases for different exposure periods
- Broad energy ranges including hot plasma & very energetic protons
- Complete spatial coverage

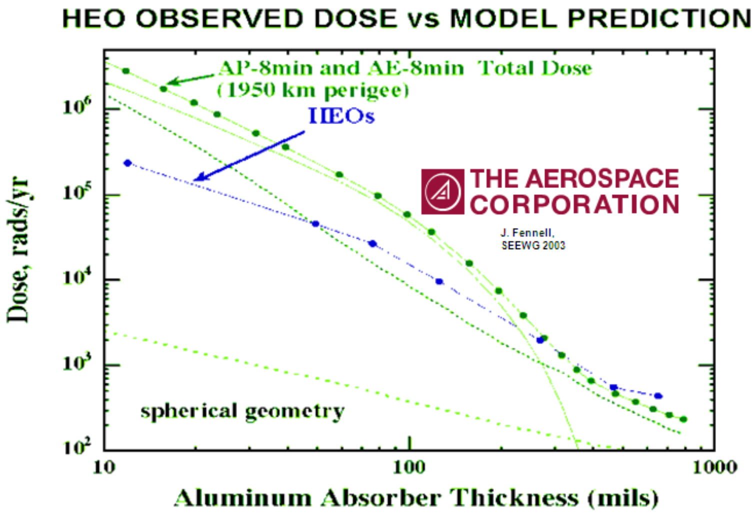
To achieve this objective, AE9/AP9 will have to be fundamentally different from and far more complex than AE8/AP8



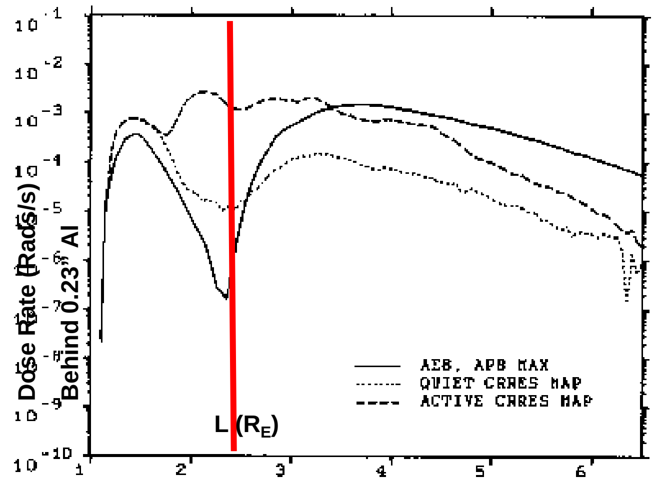
# Shortcomings of AE8/AP8

## 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

THE AE8/AP8 models are inadequate:

- *They are quantitatively wrong by different degrees depending on location, energy, and species*
- *They are incapable of accurately representing the risk associated with environmental dynamics*
- *They contain no indication of the uncertainty due to the limitations of the underlying measurements*

# Requirements

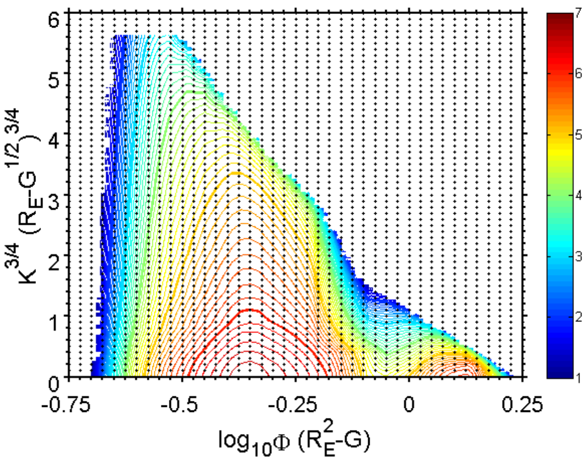
Summary of SEEWG, NASA workshop & AE(P)-9 outreach efforts:

| Priority | Species | Energy | Location | Time Variation | Effects |
|---|---|---|---|---|---|
| 1 | Protons | >10 MeV<br>(> 80 MeV) | LEO & MEO | Mission statistics (i.e. % thresholds) | 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<br>(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<br>(5 – 10 MeV) | LEO, MEO & GEO | Mission statistics | Dose (e.g. solar cells) |

(indicates especially desired or deficient region of current models)

# AE9/AP9 Implementation

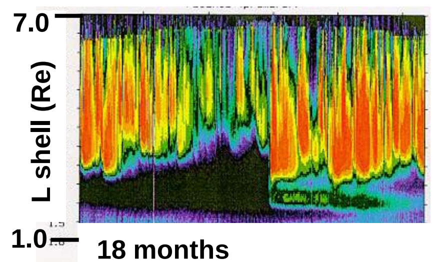
**Satellite data**




## Flux maps

- Median, 95th percentile of statistical distribution at each grid point
- Derived from empirical data
- Interpolation algorithms needed to fill in the gaps

**Satellite data & physics-based models**

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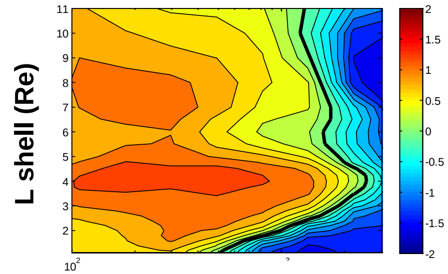
2nd Princ. Comp. (24% Var.)



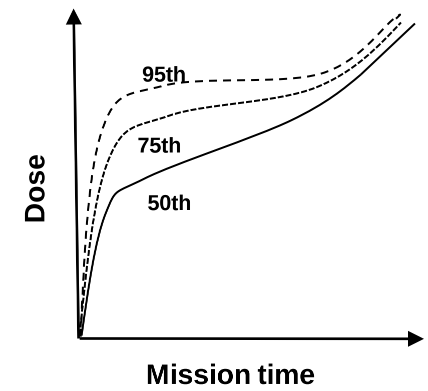

## Space/time covariance

Correlate data in space and time

- From data, if enough (electrons)
- From physics-based models when not enough (protons, plasma)
- Fixed sampling time scale (one day)

=

**User's orbit & Monte-Carlo simulations**



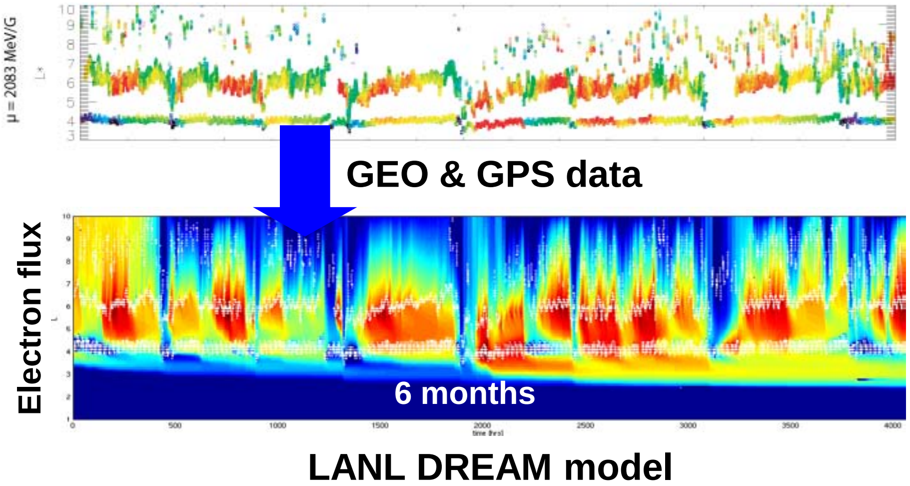

## User application

Flux vs time in "Standard Solar Cycle" or in Monte Carlo scenarios

Compute dose, SEE, charging etc in post-processing

Obtain median, 75th, 90th or other confidence levels

# Standard Solar Cycle




- The “Standard Solar Cycle” is an 11+ year “reanalysis”
- It combines data and numerical physics-based simulation via data assimilation for an entire solar cycle (or more)
- The Standard Solar Cycle is a real, past interval with real magnetic storms and, therefore, realistic time evolution
- Proposed missions can “fly through” the Standard Solar Cycle (by time shifting their launch date into the past)
- For long missions, the Standard Solar Cycle represents a single, highly realistic scenario
- However, it does not provide much in the way of error bars—all solar cycles are different

# Monte Carlo Scenarios

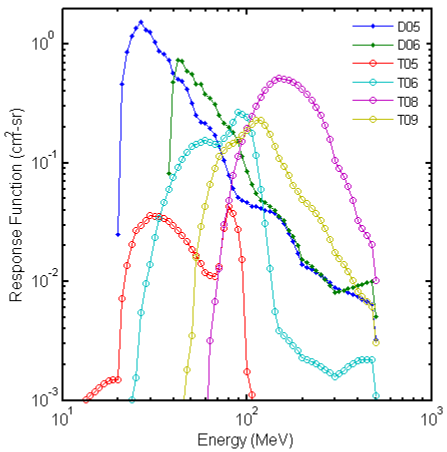
- The requirement to provide statistics (variously called uncertainty, error bars, or confidence intervals) leads to computing probability integrals in a high-dimensional space (easily >$10^5$ variables)
- The only economical way to perform such an integral is to solve it via Monte Carlo methods
- The most straightforward way to implement the Monte Carlo integral is to generate “realistic” mission-length global radiation environment scenarios and “fly” the proposed mission through them
- The Monte Carlo problem is broken down into surrogate (multivariate) time series of a small number (10s) of “principal components” (PCs) of global variation.
- The time evolution is governed by spatiotemporal covariance of fluxes from observations or global simulations
- The time series of these PCs can be converted into a time series of flux at the spacecraft
- From the flux time series, one can compute expected effects (dose, charging, SEE)
- By computing effects for many scenarios, one can obtain confidence intervals on the severity of the effects
- One can then reasonably answer questions like “how much do I reduce my risk of failure if I double my shielding?”

# Spectral/Angular Inversion

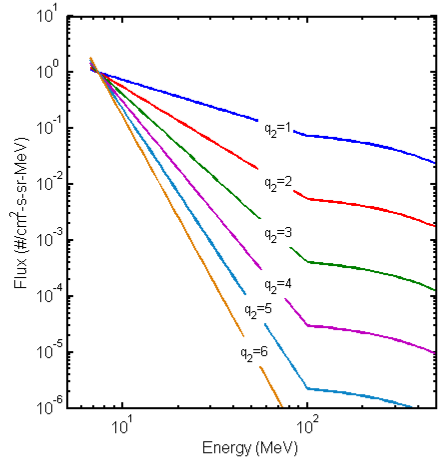
- To exploit certain symmetries in the particle population, the model requires unidirectional differential flux (e.g., #/cm$^2$/s/sr/MeV)
- We must determine the unidirectional differential flux at a given energy with a given local pitch angle (angle between particle momentum and magnetic field)
- With few exceptions, our long-term measurements have poor energy and angular resolution (i.e., most are omnidirectional integral fluxes)
- We have to make some assumptions and perform an inversion (a fit)
- We have developed a handful of ad hoc maximum likelihood algorithms that work "well enough"
- Once we have an acceptable global statistical model, we can use it in turn to improve our inversions for the next version of the model

# Spectral Inversion Example

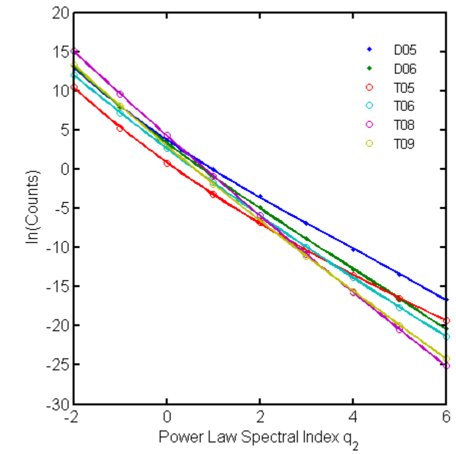
(1) Channel response functions




(2) Assume a spectral shape



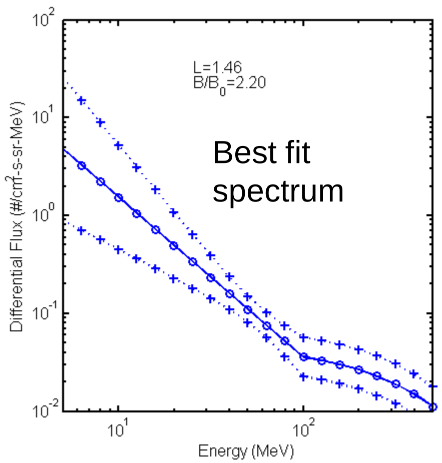

(3) Integrate (1) with (2) to obtain channel response to input spectrum

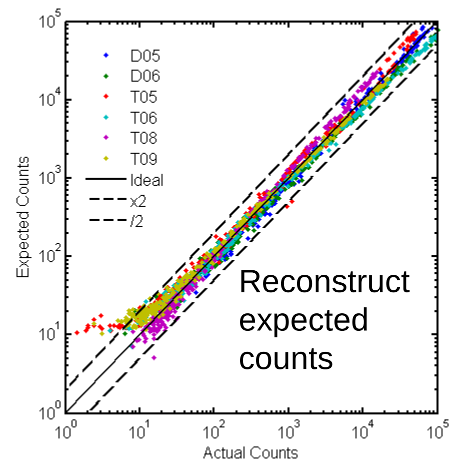



(4) Vector of Observed Counts

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{bmatrix}$$

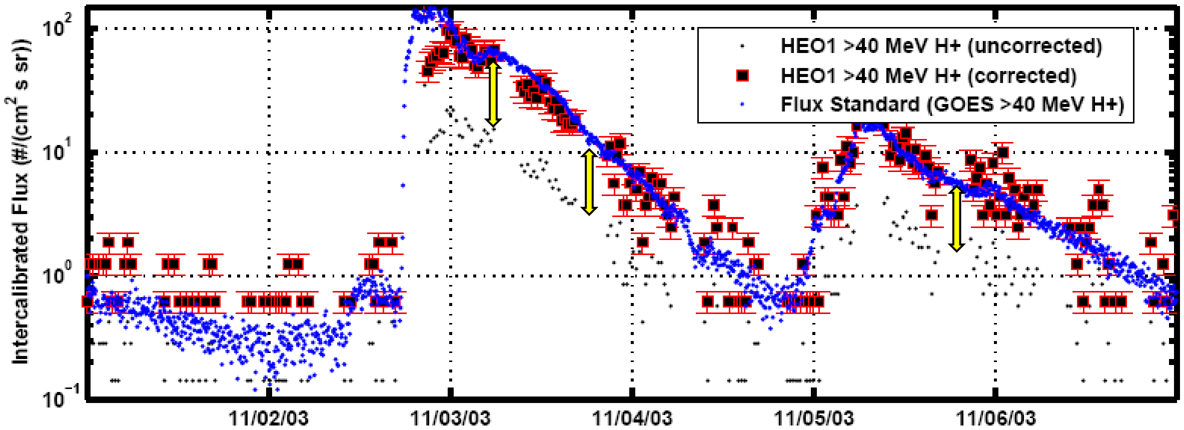
Optimization routine finds "best" q1, q2 to fit observed counts



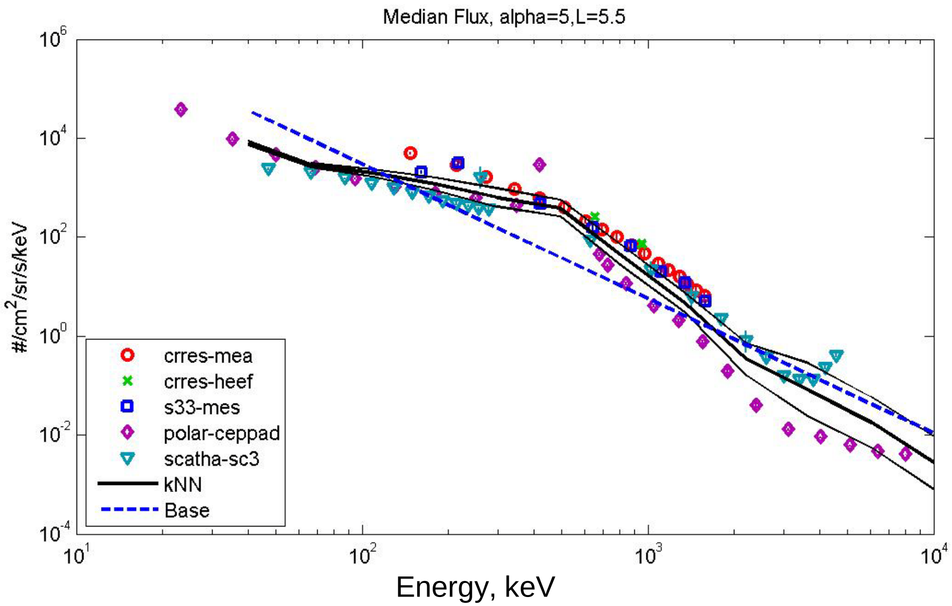



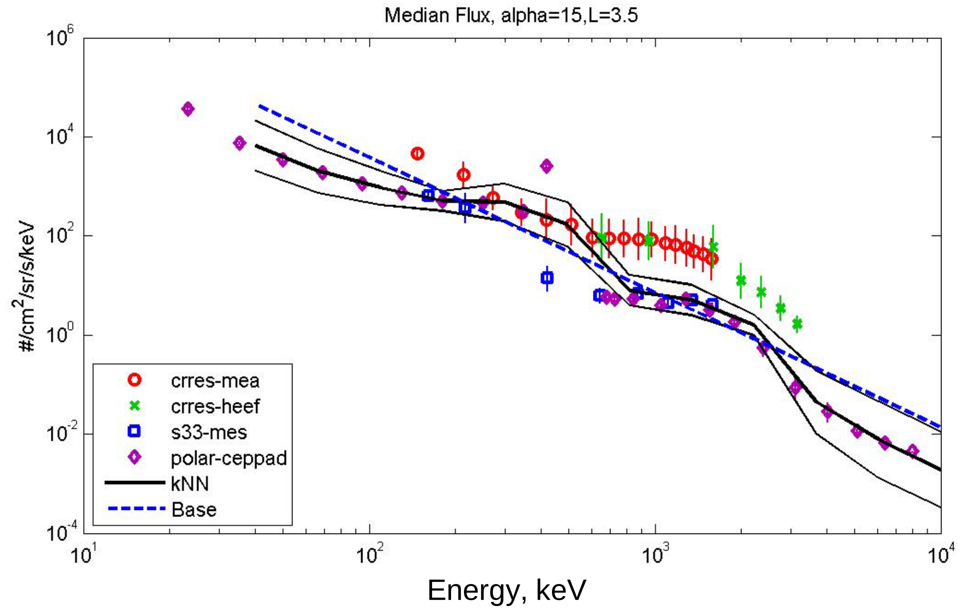
# Intercalibration

- Many of the measurements we employ were performed by “sensors of opportunity” that were designed and calibrated in keeping with their own mission objectives. Therefore, the pre-flight calibrations which we would find most useful usually were not performed
  - *Such calibrations were beyond the scope of these missions*
  - *We employ “on-orbit intercalibration” as a work-around*
  - *For Protons, the “gold standard” is GOES*
  - *For Electrons, it’s CRRES*
- The example below shows HEO-1 data corrected to match GOES during a solar particle event
- The calibration process estimates (and removes) the systematic error
- The correction process also estimates the size of the residual random error
- The residual error is propagated into the AE9/AP9 model



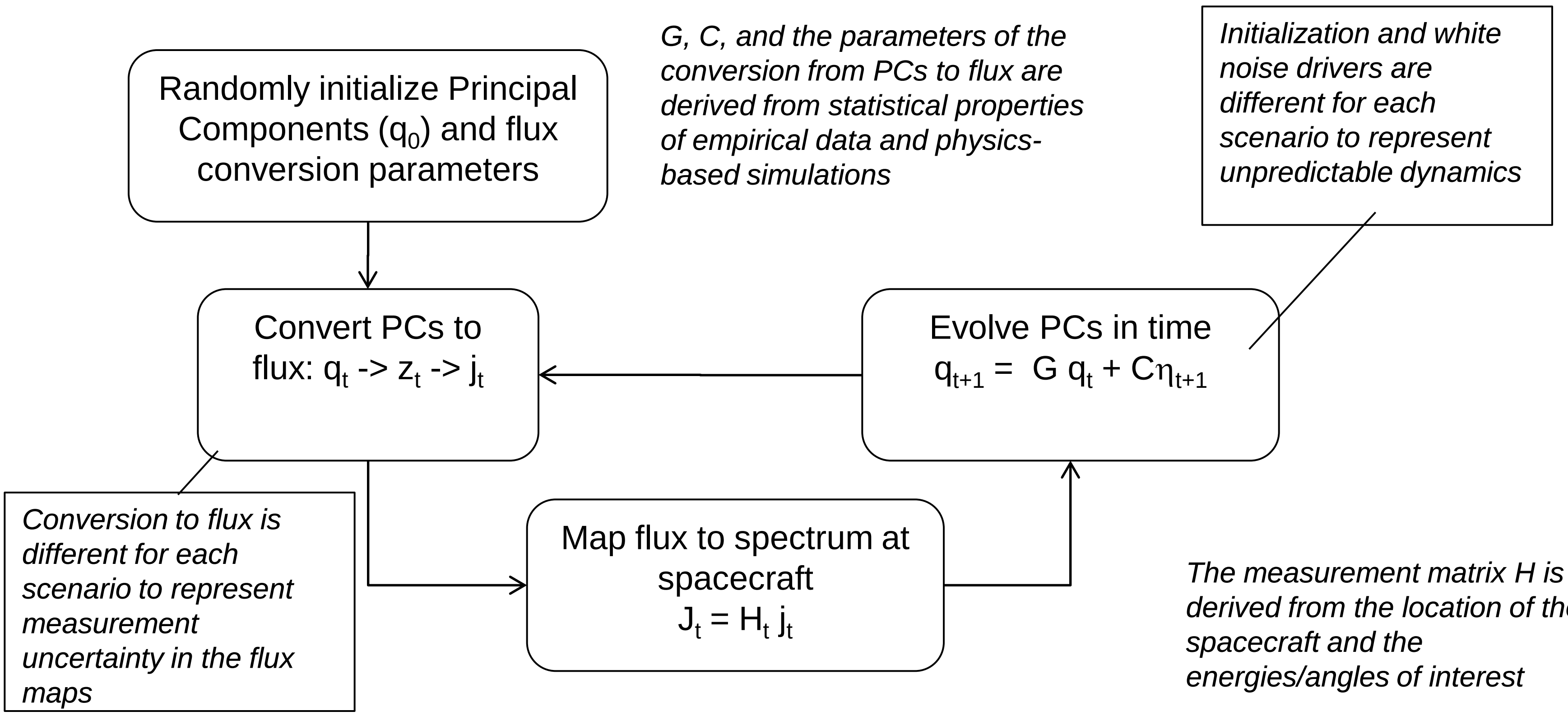
# Measurement error and Binning




- When data from different missions is binned together, sometimes it all agrees pretty well, sometimes it doesn't
- Polar tends to dominate the statistics because of its long duration
- We resolve the inconsistency using a nearest-neighbors interpolation onto a standard grid – we interpolate the *deviation* from a simple "base" model.
- We bootstrap that interpolation over different combinations of instruments to obtain an error estimate for the interpolated flux
- This error estimate is then used to generate the perturbations to the flux map for each Monte Carlo scenario

# Monte Carlo Architecture




- This flow chart represents a single scenario, which provides a flux spectrum time series at the spacecraft for the whole mission.
- To obtain percentiles and confidence intervals, one post-processes the flux time series and computes statistics *on the estimated radiation effects* *across* scenarios.

# A note on coordinates

- For compatibility with simulation codes, we'll use E/K/Φ coordinates
- For the Monte Carlo scenarios, we use Olson-Pfitzer Quiet (OPQ)
- For the standard solar cycle, we use whatever field model the reanalysis used
- Directly computing L* or Φ is too slow for use in a user application
  - *Our nominal worst case is a 10 year LEO mission that requires an L* value every 10 seconds. This would take weeks using a traditional L* algorithm*
  - *LANL developed a fast L* neural network for a recent Tsyganenko model for GEO*
  - *We have developed a neural network for OPQ for the whole radiation belt*

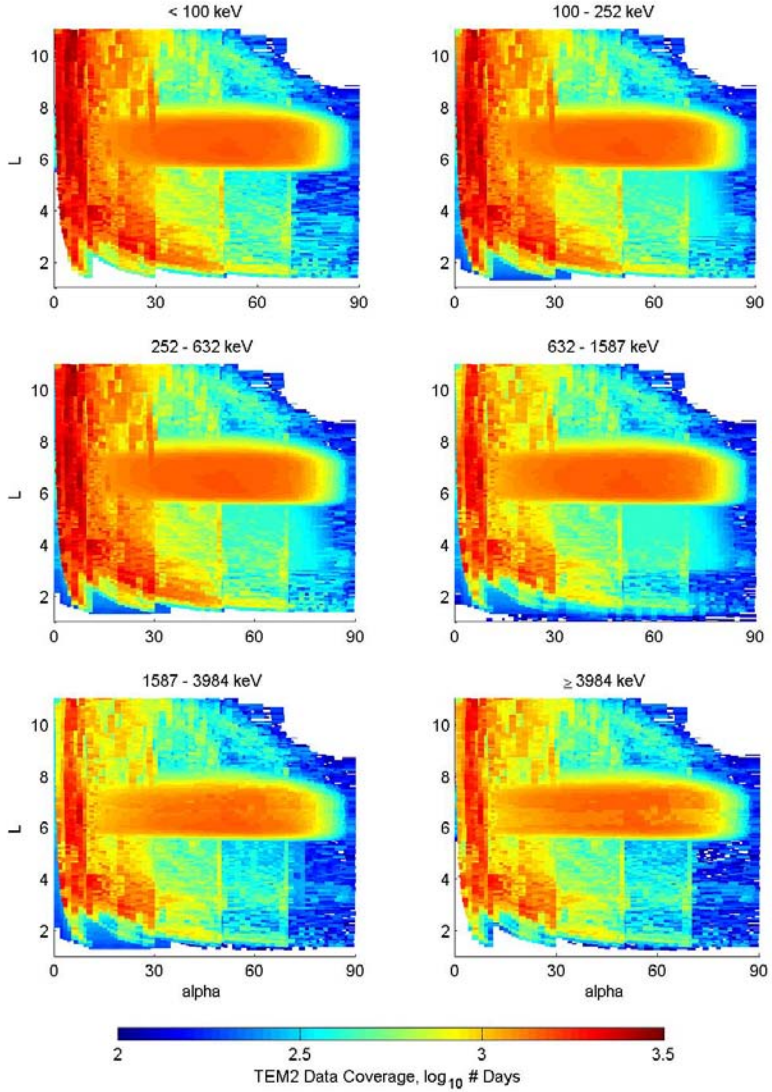
# AE9/AP9 Status

- Spectral and angular inversion algorithms selected and implemented for AE9/AP9 beta release
- Fast "L*" algorithms developed—final integration underway
- GPS, LANL-GEO, HEO, ICO, TSX-5 data nearly ready for ingest
- TEM-2 & TPM-2 Monte Carlo algorithms implemented in Matlab
  - *TEM-2 derived from: S3-3, SCATHA, CRRES, Polar*
  - *TPM-2 derived from: SIZM (Selesnick Inner Zone Model)*
  - *Improved data tables can be utilized without changes to code*
- Standard solar cycle
  - *Example electron standard solar cycles exist but have not been implemented as part of AE9/AP9 beta (TEM-2 Reanalysis, DREAM, Salammbo)*
  - *Proton standard solar cycle will be built from SIZM or Salammbo*

# Trapped Electron Model 2 Overview

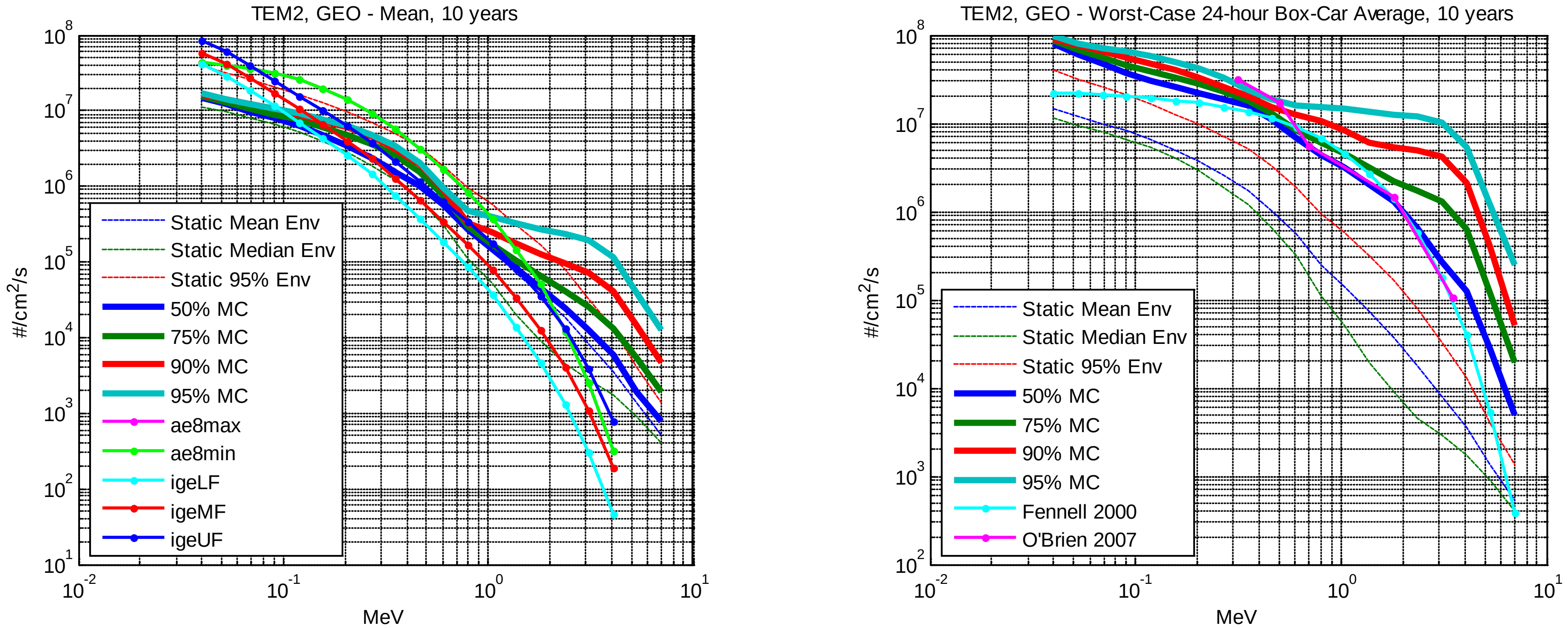
- A statistical electron model (TEM-2c) was constructed from Polar, SCATHA, CRRES, and S3-3 data (TEM-2a had only CRRES and S3-3)
- Most statistical manipulations are not model-specific, so we can use the exact same “ngrs” code for AE9/AP9
- The model describes flux in E, $\alpha_{eq}$, $L_m$ coordinates in the Olson-Pfitzer Quiet field model (AE9 will use E/K/$\Phi$)
- The model preserves:
  - *Statistical variation of flux at each grid point*
  - *Uncertainty in flux map (measurement error, sample size limitations)*
  - *Spatial covariance of flux (what’s a reasonable spectrum or L profile?)*
  - *Spatiotemporal covariance on 1 day timescale (how does the belt evolve?)*
- The model contains:
  - *$50^{th}$, $95^{th}$ percentile flux map on grid*
  - *Error & error covariance on flux map*
  - *Assumes Weibull distribution at each grid point*
  - *Spatial and spatio-temporal covariance:*
    - Retains 11 principal components of spatial variation
    - Matrices for multivariate, $1^{st}$-order autoregressive process on principal components

# TEM-2 Data Coverage



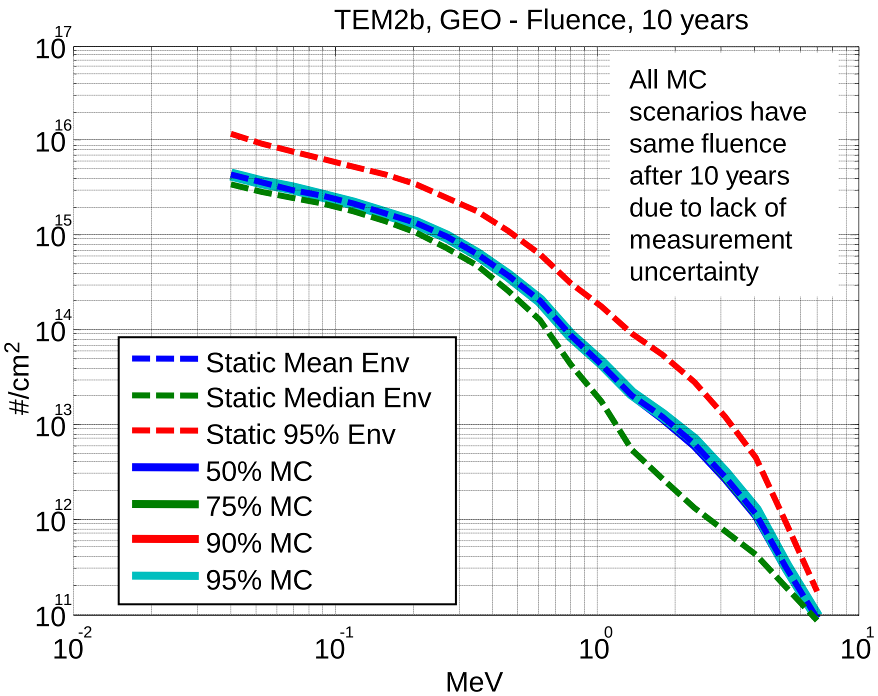

- TEM-2 combines S3-3, SCATHA, CRRES, and Polar data
- It has poor coverage at high equatorial pitch angle
- The wide horizontal band near L~7 is SCATHA data
- The vertical striations are an as-yet-resolved artifact in the Polar data
- Only the CRRES and S3-3 data have been quality controlled to remove regions of high background

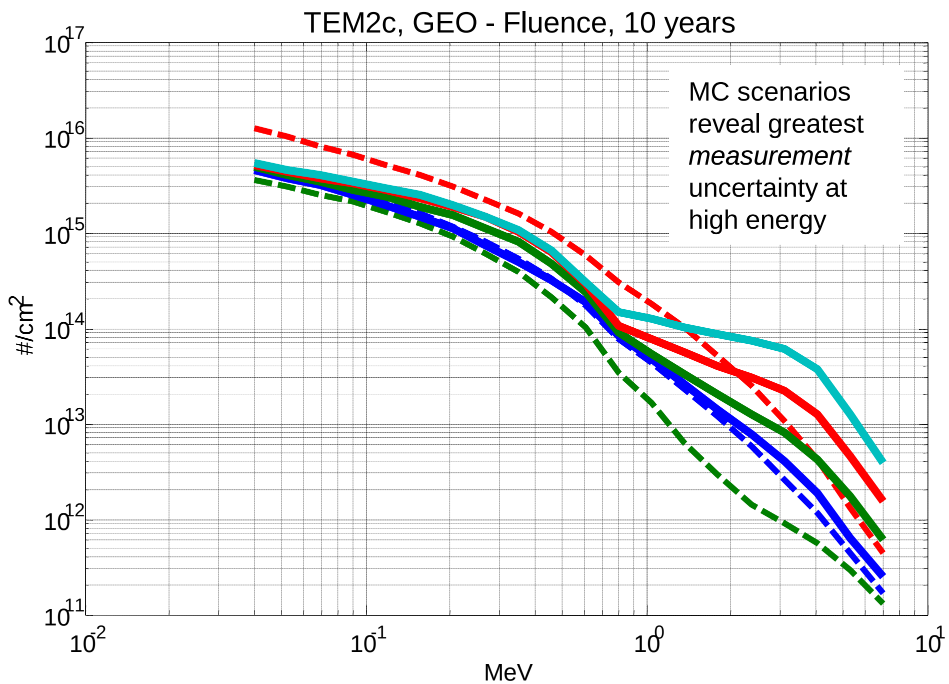
# TEM-2 Examples




- Below 100 keV, TEM-2 estimates lower mean fluxes then IGE (POLE) and AE8. Above 1 MeV, the reverse is true
- The median worst case for TEM-2 is comparable to O’Brien 2007. However, TEM-2 suggests that above 1 MeV, the measurement error has a very large impact on the worst case
- NOTE: No GEO data were used in the creation of TEM-2, so there’s no reason (yet) to doubt the old specs

# A Note on “Measurement Error”



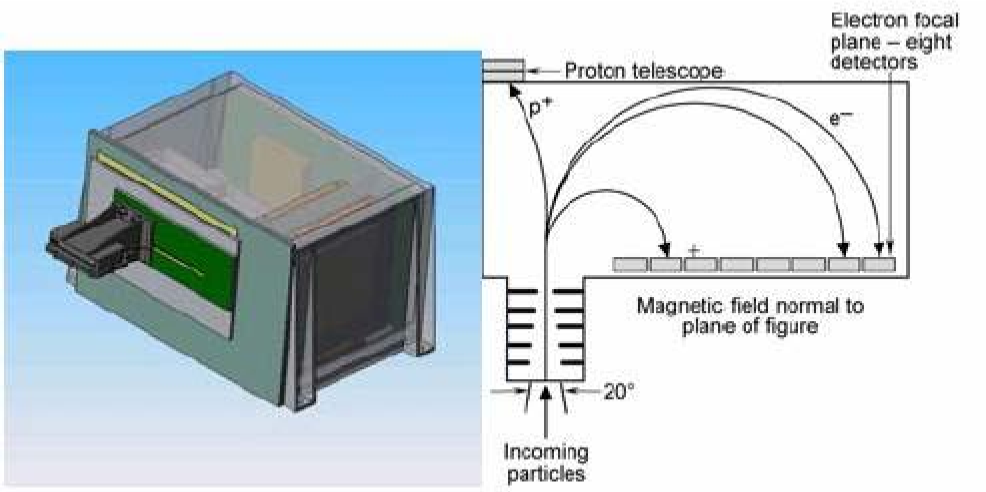

- When one improperly accounts for measurement error, all the Monte Carlo scenarios give the same fluence for long-term missions (E.g., TEM2b on left)
- The proper long-term mission fluence should have a spread due to underlying measurement error: incomplete calibration, insufficient statistics, unknown background (e.g., TEM2c on right)
- We achieve this in AE9/AP9 by perturbing the statistical flux map for each scenario—the perturbations are derived from an estimate of the measurement error.
- In AE9/AP9 even long scenarios (for which dynamics average out in the fluence) will still have a statistical spread due to uncertainty in the original measurements.

# Future Plans

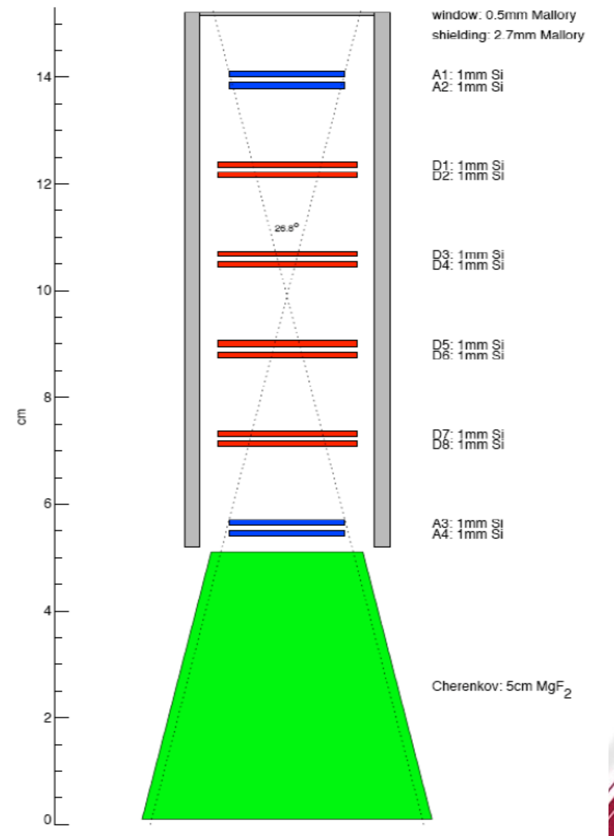
- Beta release in early CY2010
  - *Improves on TEM-2 and TPM-2 with more data*
  - *New average plasma environment model (Polar CAMMICE/MICS)*
  - *TEM-2 converted to E/K/$\Phi$ coordinates*
  - *Not certified for use in satellite design*
  - *Demonstrates Monte Carlo component to obtain feedback from engineers and scientists: Does this do what you need?*
- Version 1.0 release mid CY2011
  - *Ingest all remaining data*
  - *Improve intercalibration and background removal*
  - *Implement Standard Solar Cycle*
  - *Introduce "LEO" grid for improved accuracy at low altitude*
  - *Introduce "East-West" effect*
- Version 2.0 release ~1 year after RBSP launch
  - *Include RBSP, DSX, and TACSAT-4 data*
  - *Include ORBITALS and other international data if available*
  - *Continue to extend, expand Standard Solar Cycle*
  - *RBSP launch is scheduled for May 2012*
- RBSP is nominally a 2 year mission with a maximum life of 4 years

# Aerospace Sensors for NASA's RBSP Mission

## Magnetic Spectrometer: Relativistic Electrons




## Relativistic Proton Spectrometer




- NASA is funding development of MagEIS, which measures MeV electrons and ions (PI: Bern Blake)
- NRO is funding development of RPS, which measures 0.1-1 GeV protons (PI: Joe Mazur)

# Appendix - Impact of AE9/AP9 on the use of Environmental Effects Codes

Preliminary – 7/30/2009

Paul O'Brien
The Aerospace Corporation

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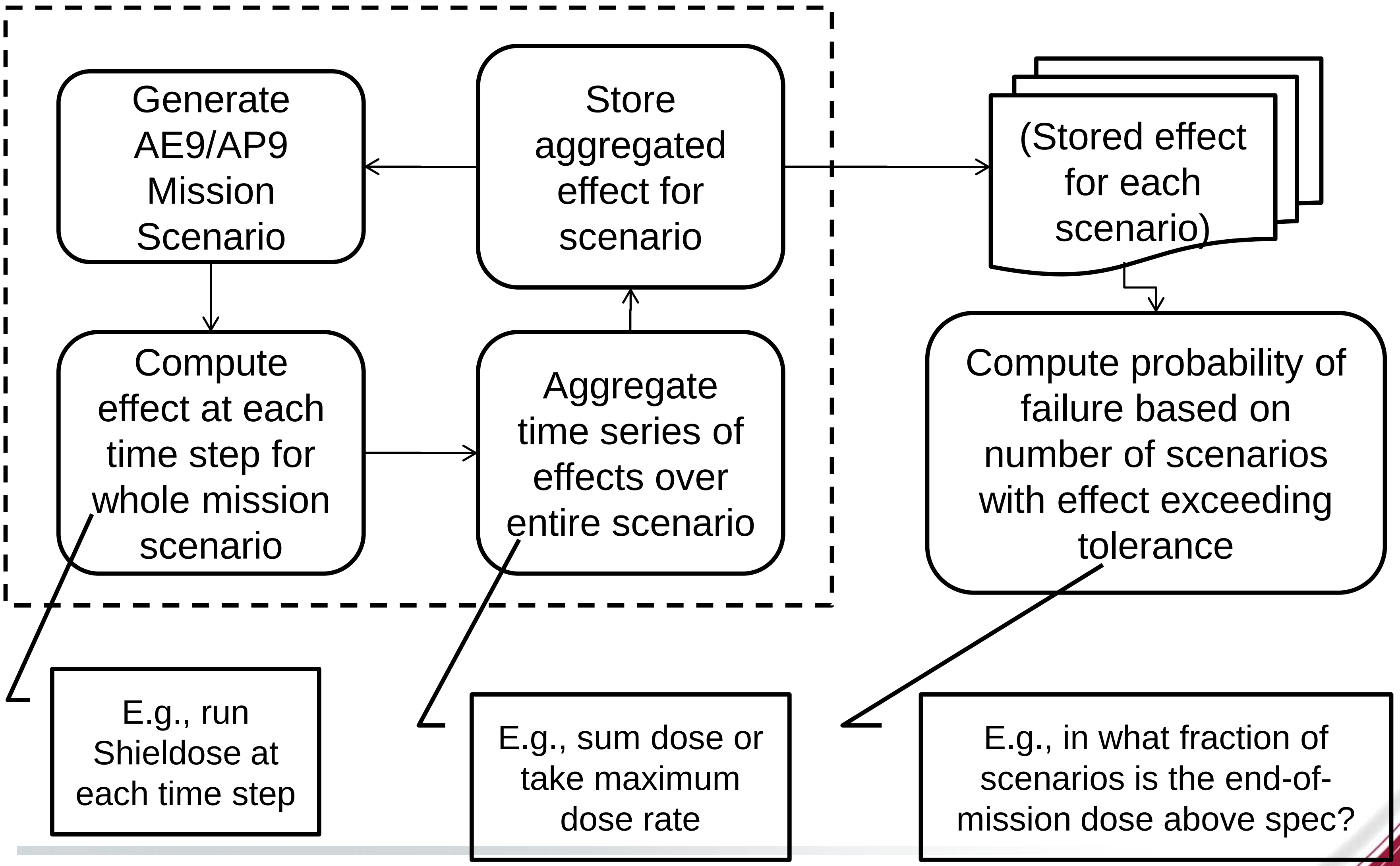
# Types of Linear Effects Calculations

- Most effects are linear functions of the environment
- There are three main types of linear effects
  - *Instantaneous rate effects (SEEs, surface charging)*
  - *Short-term accumulation effects (internal charging, annealing)*
  - *Whole-mission cumulative effects (total dose, displacement damage)*
- Effects codes available today essentially treat all of these effects as being derivable from a single, exact, static flux spectrum
  - *This is an effective, quick-and-dirty approach, and it will still be possible using AE9/AP9*
  - *However, it usually violates certain statistical principals such that it results in a "conservative" estimate with an unknown degree of margin*
  - *If one wants to understand the likelihood of failure, one must take a more sophisticated approach…*

# Effects Codes in the AE9/AP9 Environment



# Linear Effects in Equation Form

Instantaneous Rate Effect: Does *y(t)* exceed threshold $y_0$ at any time during the scenario?

$$y(t) = \sum_s \int \sigma_s(E,\alpha,\beta)\, j_s(E,\alpha,\beta,t)\, dE\, d\alpha\, d\beta$$

Short-Term Accumulation Effect : Does *y(t)* exceed threshold $y_0$ at any time during the scenario?

$$y(t) = \sum_s \int \sigma_s(E,\alpha,\beta) h(\tau)\, j_s(E,\alpha,\beta,t-\tau)\, dE\, d\alpha\, d\beta\, d\tau$$

Whole-Mission Cumulative Effect : Does *y* exceed threshold $y_0$ at the end of the scenario?

$$y = \sum_s \int \sigma_s(E,\alpha,\beta)\, j_s(E,\alpha,\beta,t)\, dE\, d\alpha\, d\beta\, dt$$

$\sigma$ is a cross section that depends on species (s), energy (E), and angle ($\alpha$,$\beta$); $h(\tau)$ is a moving average filter that represents a recovery process (e.g., charge bleed-off); *j* is particle flux from a scenario.