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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Prepared for:

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

Contract No. FA8802-09-C-0001

Authorized by: National Systems Group

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Assuring Space Mission Success

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Approved by:

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Research & Technology
Imaging Programs Diuvision
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The AE9/AP9 Radiation Specification Development

Paul O’Brien & Tim Guild
Space Science Department, The Aerospace Corporation
Greg Ginet, AFRL/RVBX (MIT Lincoln Lab)
Stu Huston, AFRL/RVBX (Boston College)

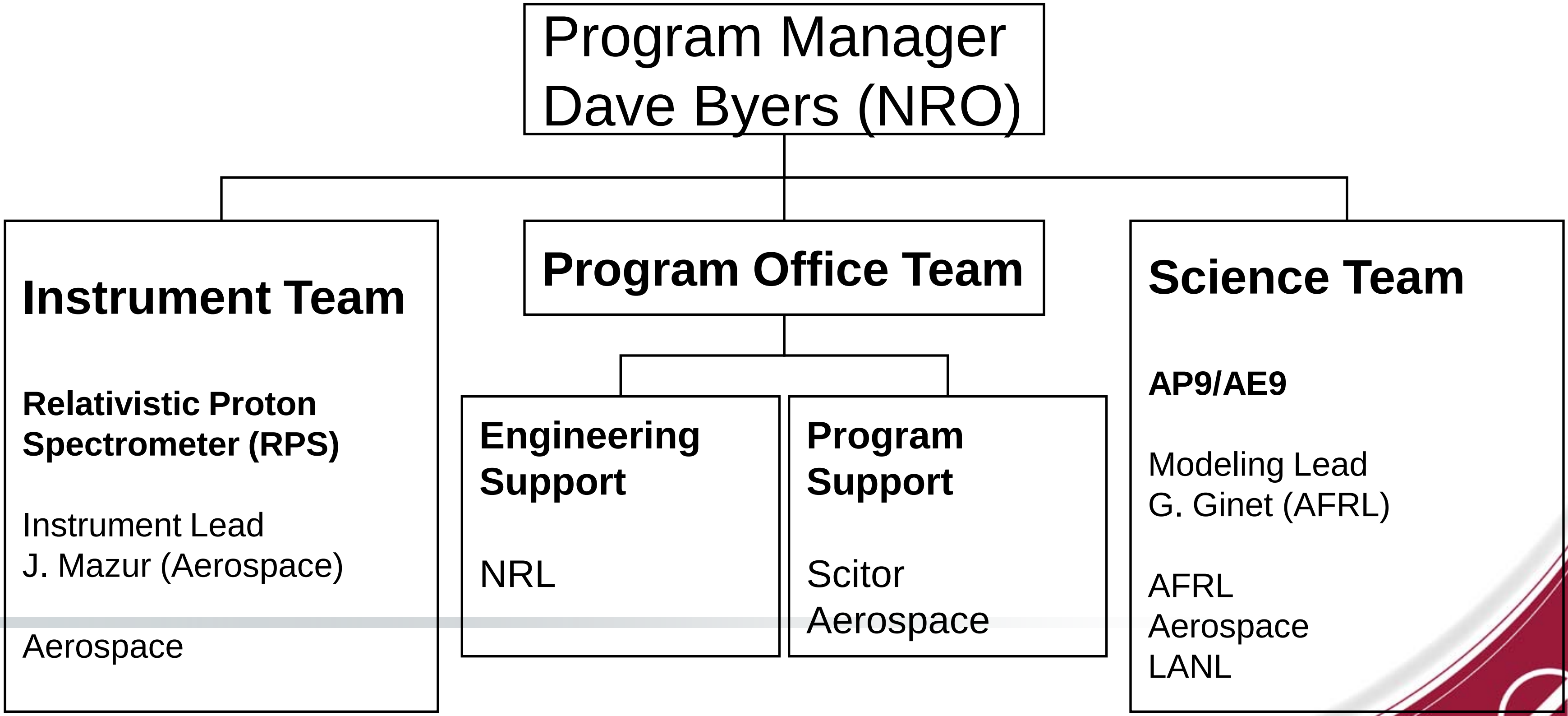
Space Sciences Applications Lab Seminar
July 28th, 2009

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*



Program Manager
Dave Byers (NRO)

Instrument Team

Relativistic Proton Spectrometer (RPS)

Instrument Lead
J. Mazur (Aerospace)

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Program Office Team

Engineering Support

NRL

Program Support

Scitor
Aerospace

Science Team

AP9/AE9

Modeling Lead
G. Ginet (AFRL)

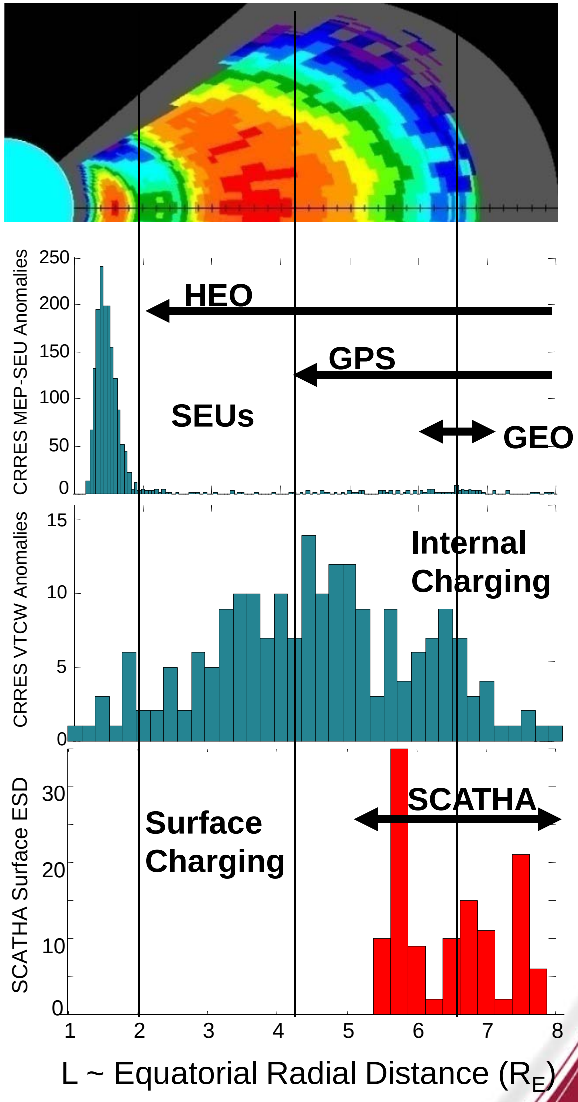
AFRL
Aerospace
LANL

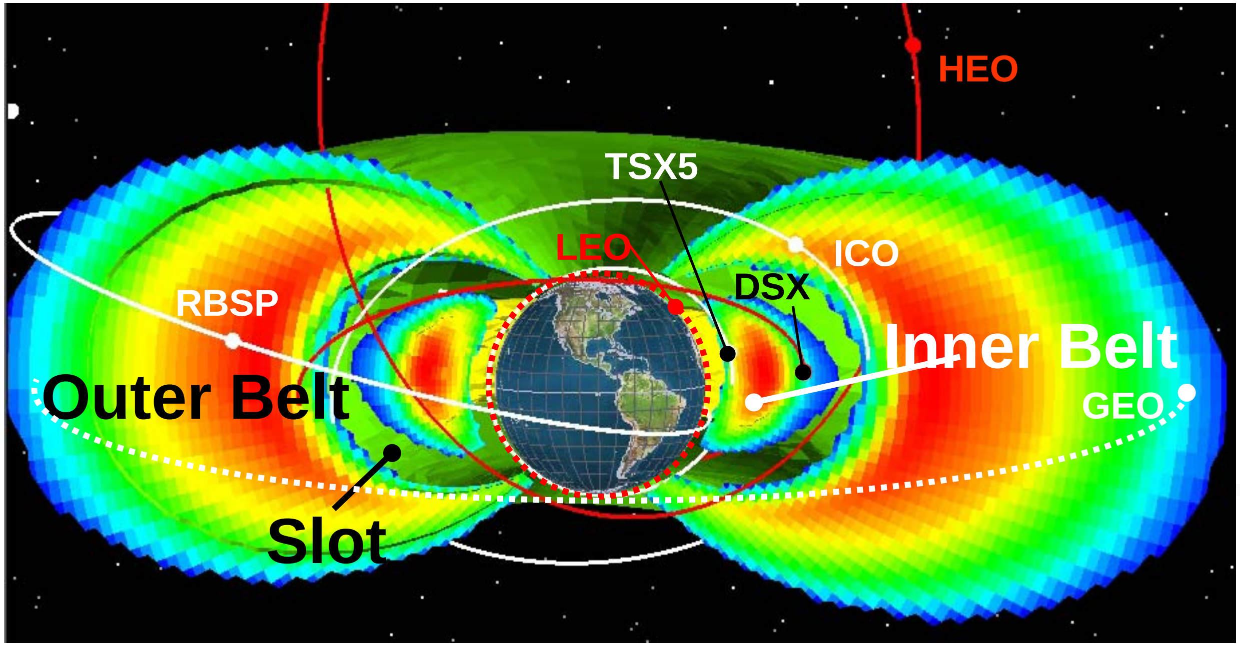
AE9/AP9 Overview

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

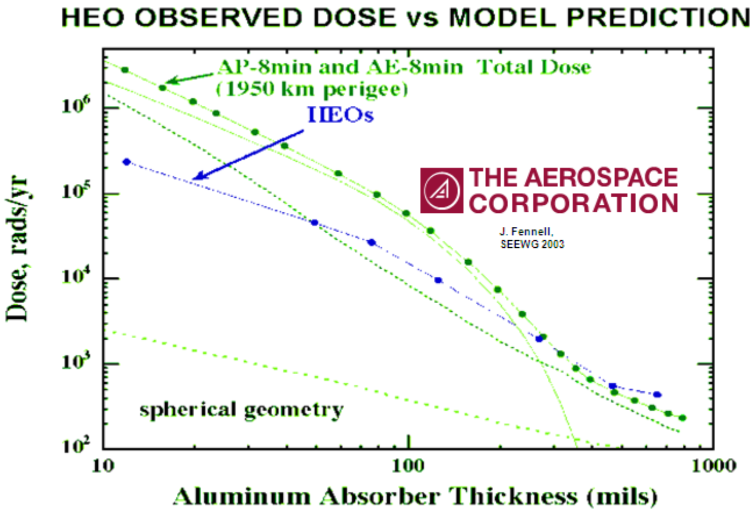
To achieve this objective, AE9/AP9 will have to be fundamentally different from and far more complex than AE8/AP8





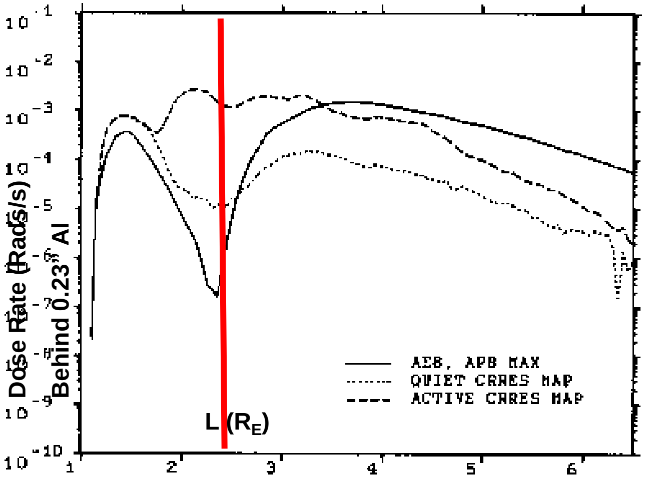
Shortcomings of AE8/AP8

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

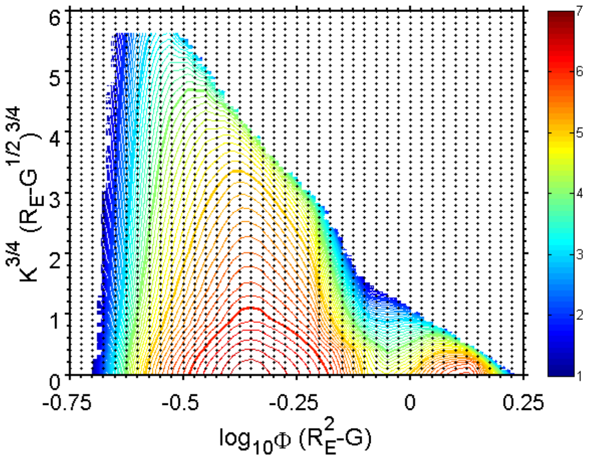
Summary of SEEWG, NASA workshop & AE(P)-9 outreach efforts:

Priority	Species	Energy	Location	Time Variation	Effects
1	Protons	>10 MeV (> 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 (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 statistics	Dose (e.g. solar cells)

(indicates especially desired or deficient region of current models)

AE9/AP9 Implementation

Satellite data

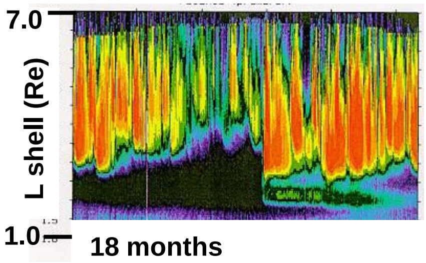


Flux maps

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

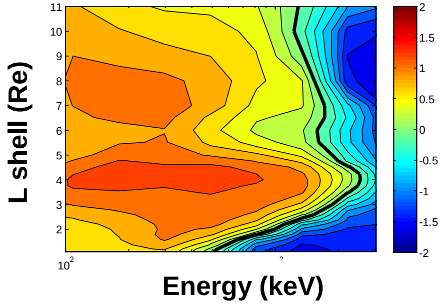
+

Satellite data & physics-based models



18 months

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)

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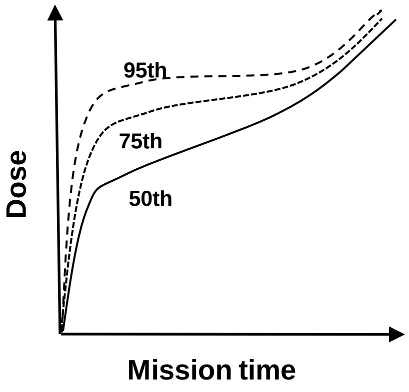
User's orbit & Monte-Carlo simulations



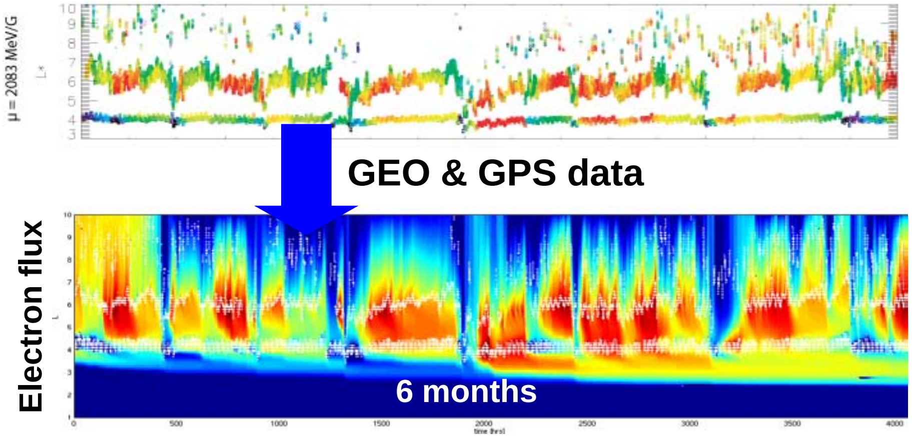
User application

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



LANL DREAM model

- 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

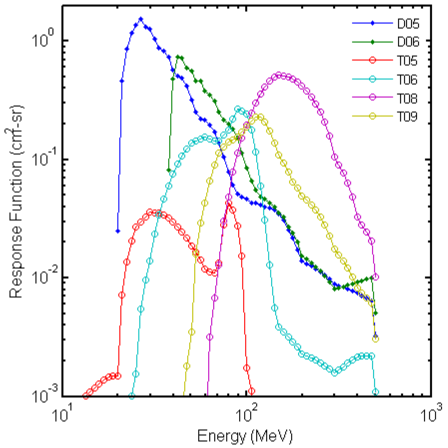
- The requirement to provide statistics (variously called uncertainty, error bars, or confidence intervals) leads to computing probability integrals in a high-dimensional space (easily $>10^5$ variables)
- The only economical way to perform such an integral is to solve it via Monte Carlo methods
- The 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

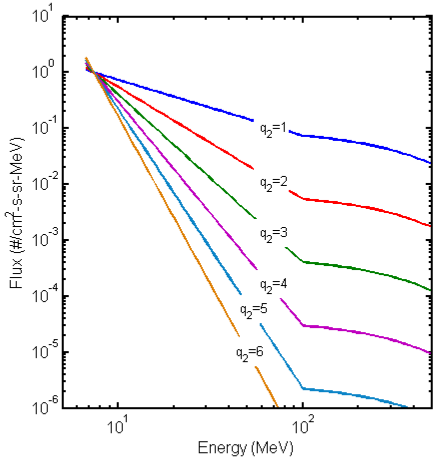
- To exploit certain symmetries in the particle population, the model requires unidirectional differential flux (e.g., #/cm^2/s/sr/MeV)
- We must determine the unidirectional differential flux at a given energy with a given local pitch angle (angle between particle momentum and magnetic field)
- With 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

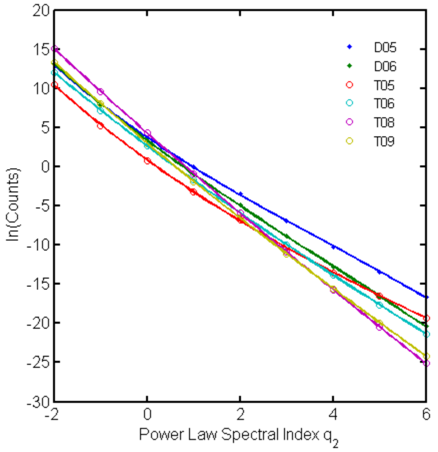
(1) Channel response functions



(2) Assume a spectral shape



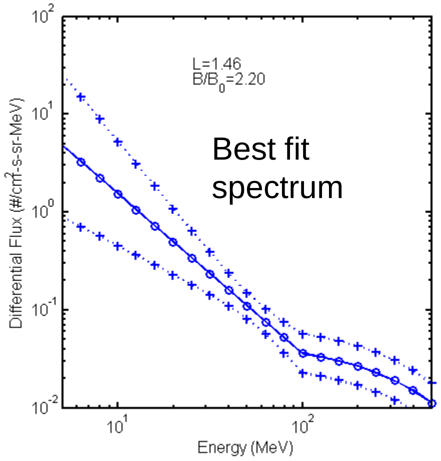
(3) Integrate (1) with (2) to obtain channel response to input spectrum



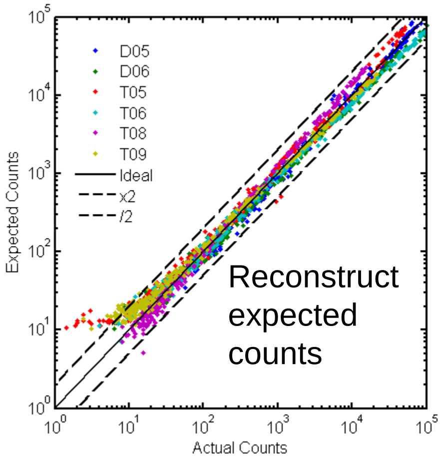
(4) Vector of Observed Counts

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

Optimization routine finds “best” q1, q2 to fit observed counts



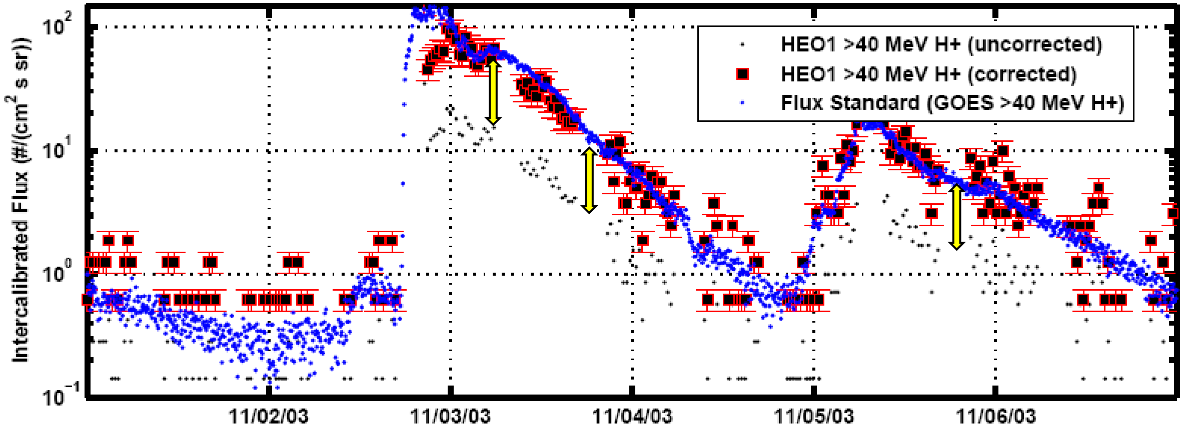
Best fit spectrum



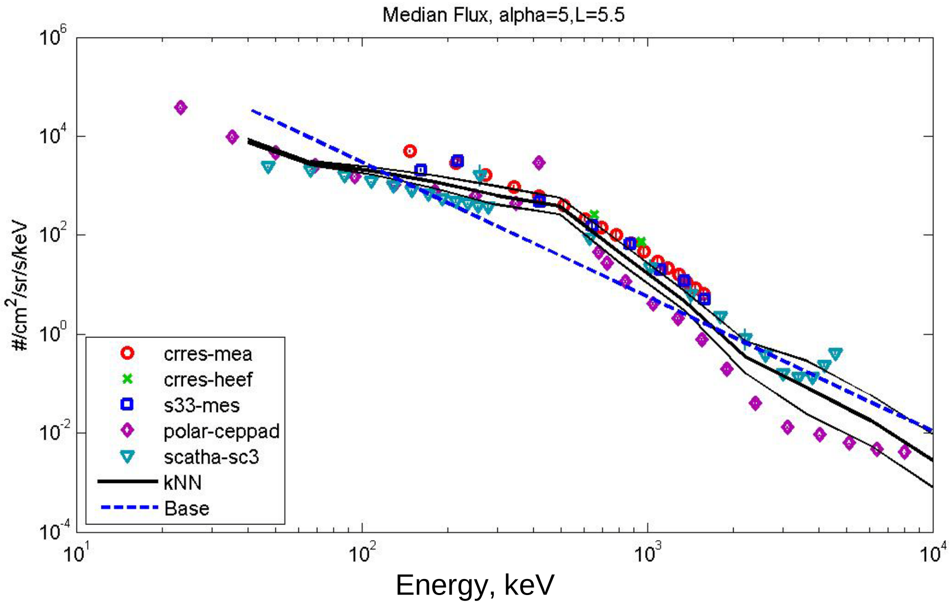
Reconstruct expected counts

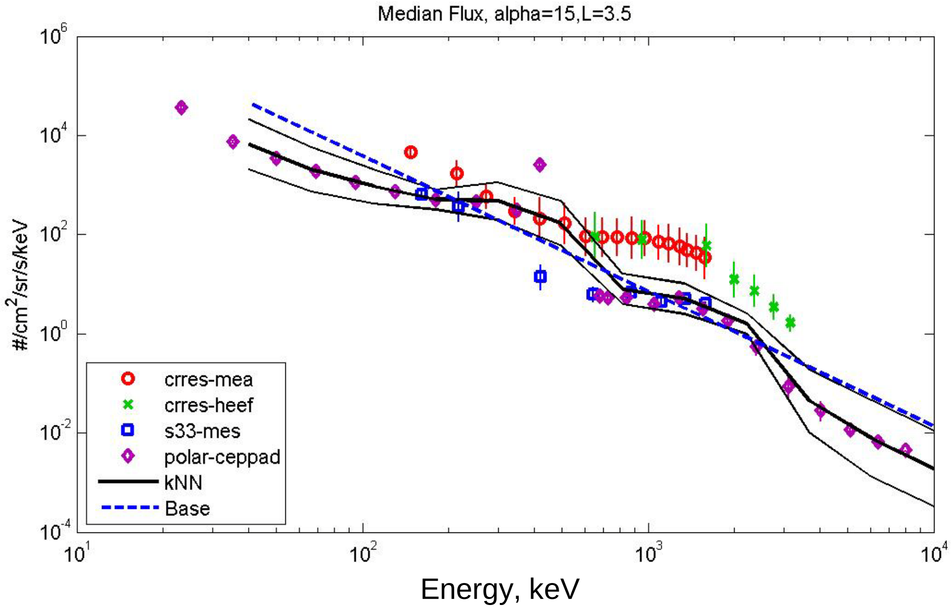
Intercalibration

- 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



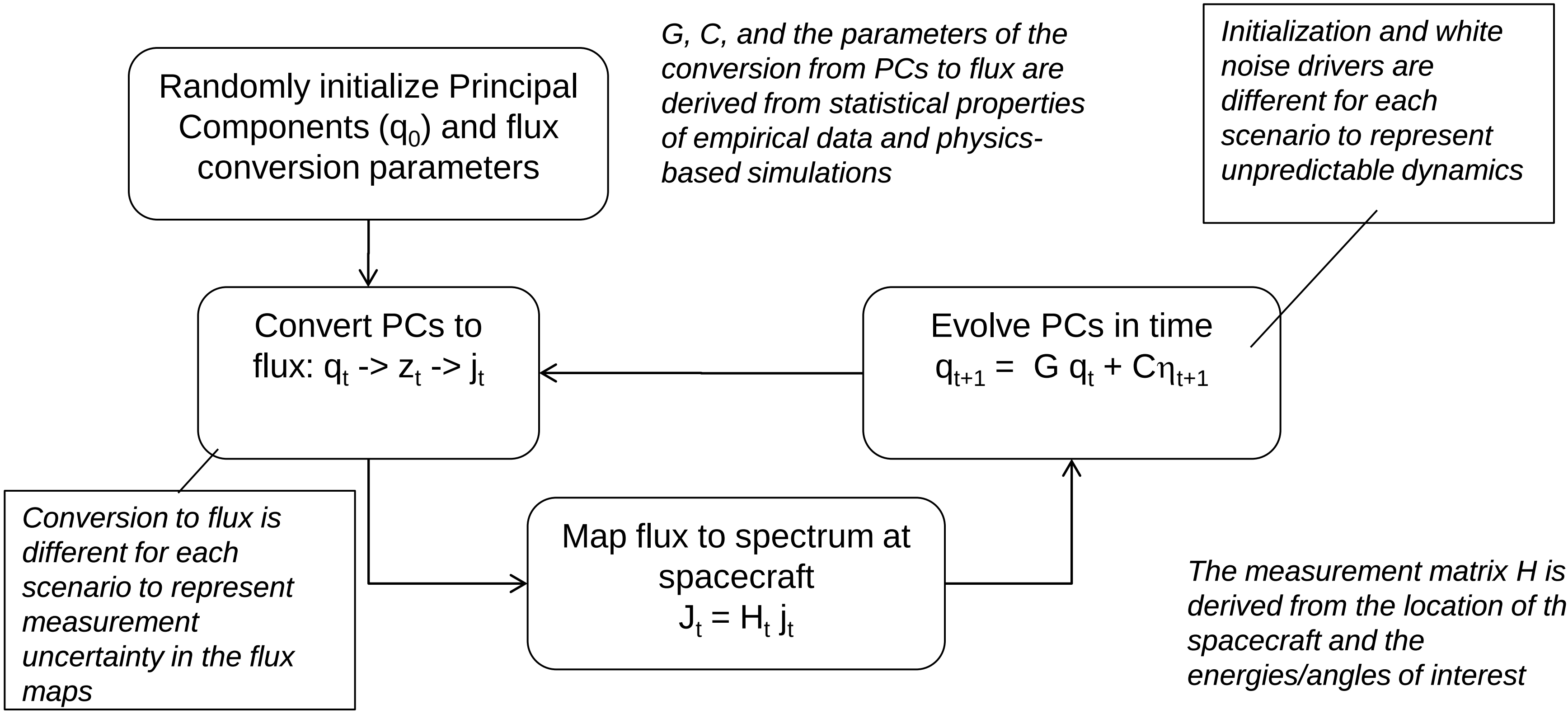
Measurement error and Binning





- 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



Randomly initialize Principal Components (q_0) and flux conversion parameters

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

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

Convert PCs to flux: $q_t \rightarrow z_t \rightarrow j_t$

Evolve PCs in time $q_{t+1} = G q_t + C\eta_{t+1}$

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

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

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

- 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* <u>*across*</u> 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*

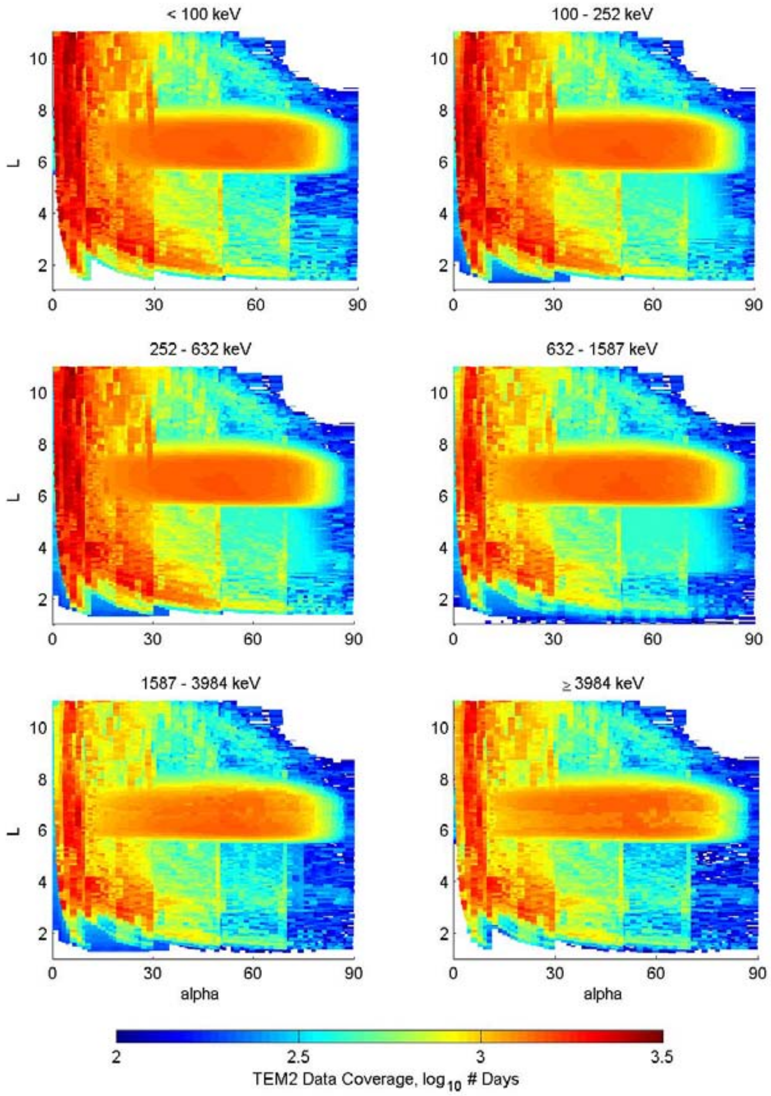
AE9/AP9 Status

- 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

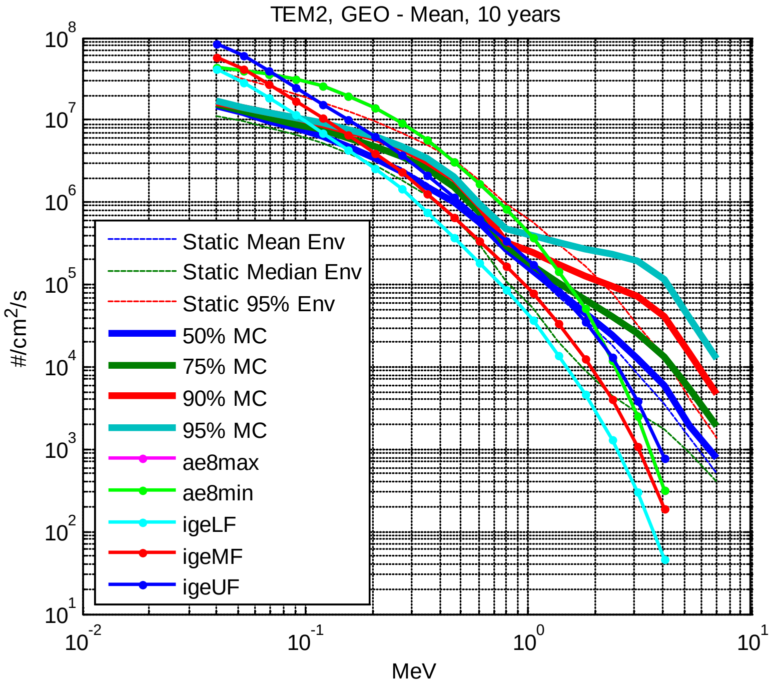
- A statistical electron model (TEM-2c) was constructed from Polar, SCATHA, CRRES, and S3-3 data (TEM-2a had only CRRES and S3-3)
- Most statistical manipulations are not model-specific, so we can use the exact same “ngrs” code for AE9/AP9
- The model describes flux in E, α_{eq}, L_m coordinates in the Olson-Pfitzer Quiet field model (AE9 will use E/K/Φ)
- 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:
  - *50th, 95th 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, 1st-order autoregressive process on principal components

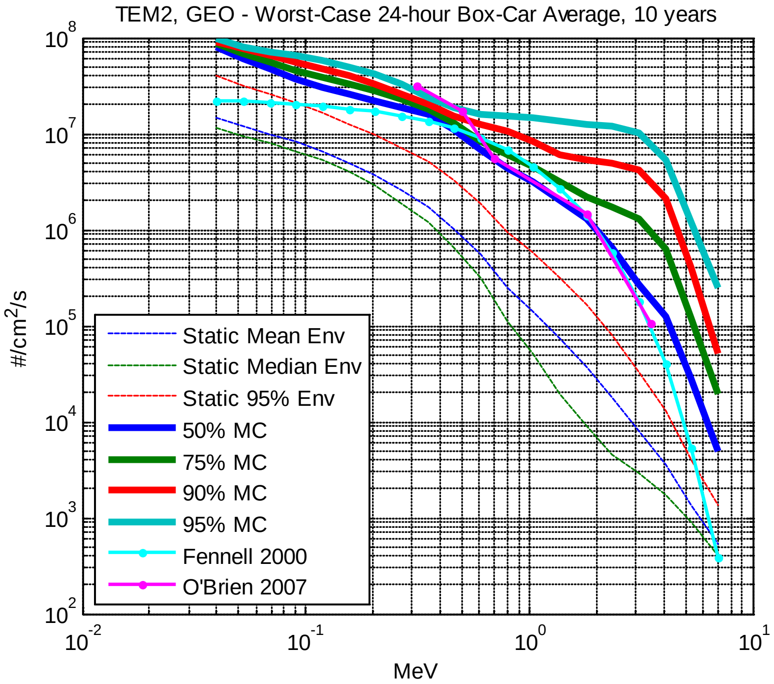
TEM-2 Data Coverage



- 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

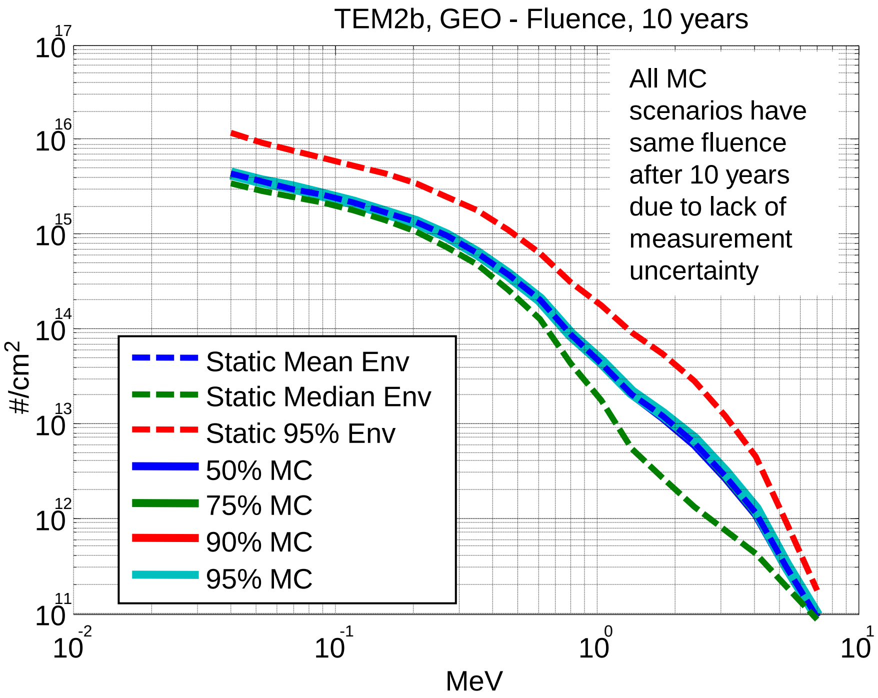
TEM-2 Examples



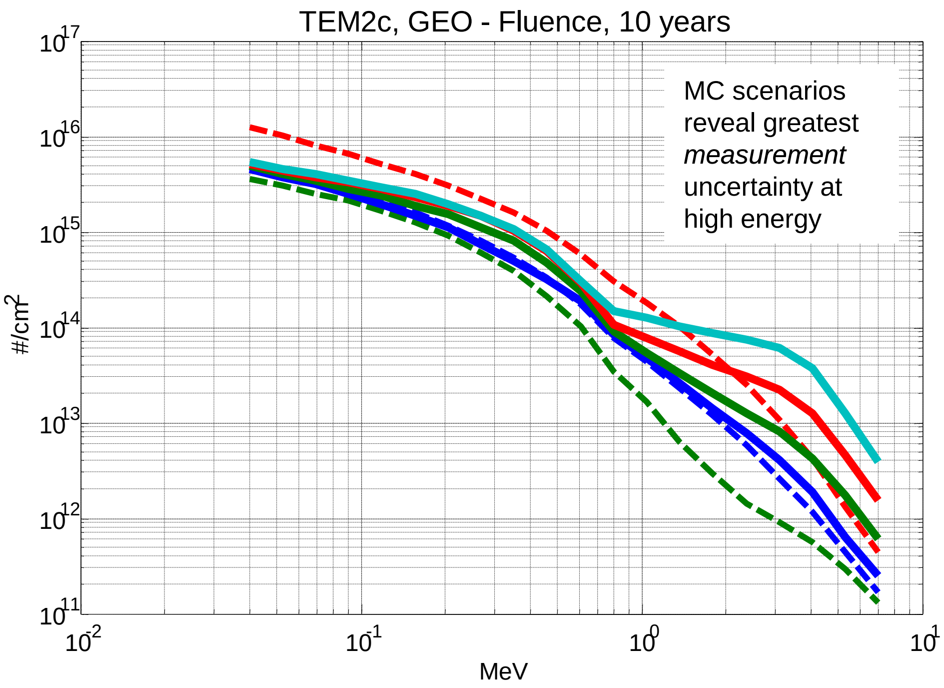


- Below 100 keV, TEM-2 estimates lower mean fluxes then IGE (POLE) and AE8. Above 1 MeV, the reverse is true
- The median worst case for TEM-2 is comparable to O’Brien 2007. However, TEM-2 suggests that above 1 MeV, the measurement error has a very large impact on the worst case
- NOTE: No GEO data were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

A Note on “Measurement Error”



All MC scenarios have same fluence after 10 years due to lack of measurement uncertainty



MC scenarios reveal greatest *measurement* uncertainty at high energy

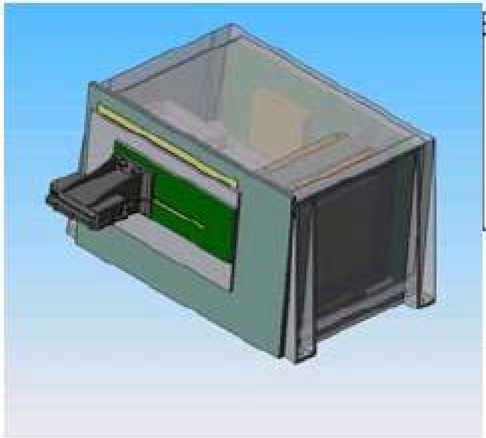
- When one improperly accounts for measurement error, all the Monte Carlo scenarios give the same fluence for long-term missions (E.g., TEM2b on left)
- The proper long-term mission fluence should have a spread due to underlying measurement error: incomplete calibration, insufficient statistics, unknown 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.

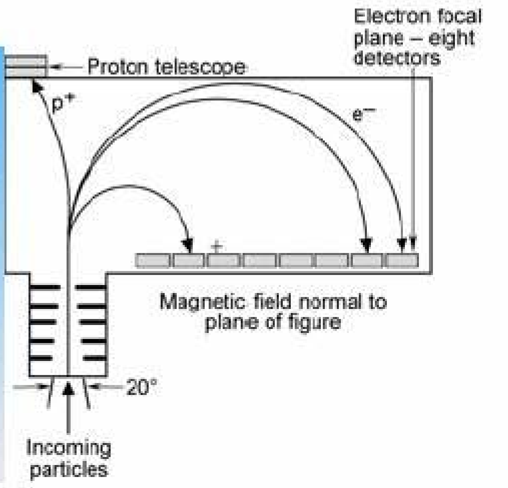
Future Plans

- 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/Φ 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

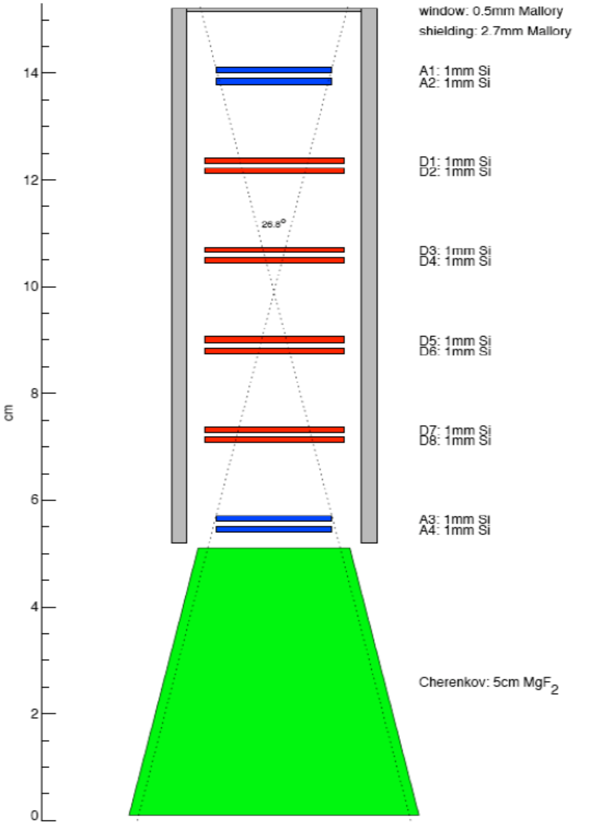
Aerospace Sensors for NASA’s RBSP Mission

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

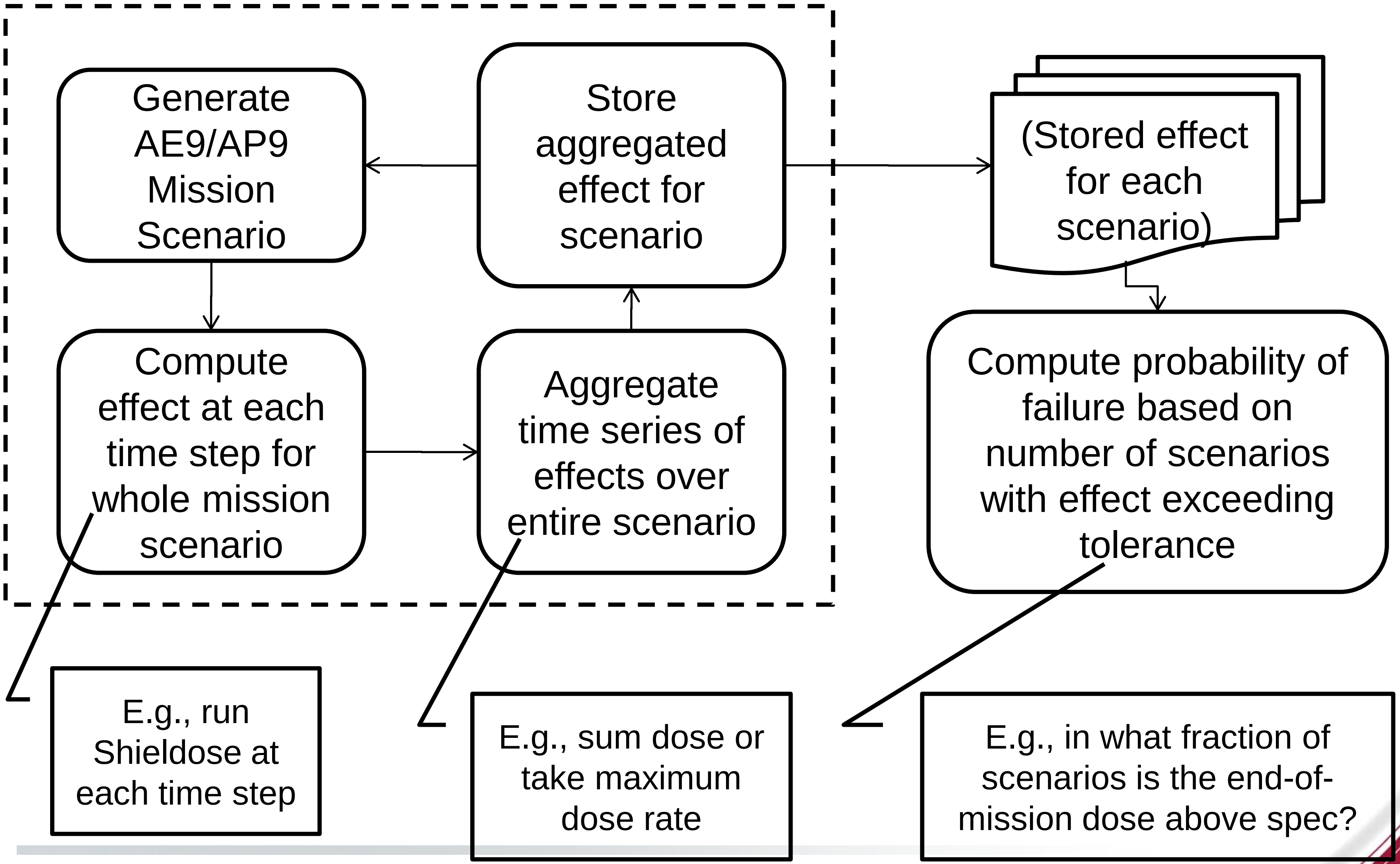
Preliminary – 7/30/2009

Paul O’Brien
The Aerospace Corporation

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



Generate AE9/AP9 Mission Scenario

Compute effect at each time step for whole mission scenario

Aggregate time series of effects over entire scenario

Store aggregated effect for scenario

(Stored effect for each scenario)

Compute probability of failure based on number of scenarios with effect exceeding tolerance

E.g., run Shieldose at each time step

E.g., sum dose or take maximum dose rate

E.g., in what fraction of scenarios is the end-of-mission dose above spec?

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?

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

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