Methodology of Real-Time Space Radiation Dose Estimates Using Onboard Vehicle Dosimeters

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Motivation

- **Need to Assess Biological Impacts to Astronauts in Real-Time during Solar Energetic Particle (SEP) Events**
- **NASA Real-Time Dose Assessment Guideline**
  - Minimize the Dependence on Physics Transport Codes
  - Maximize Use of Onboard Dosimeter Data
- **The General Approach**
  - I. Optimize Use of Vehicle Dosimeter Measurements to Estimate Body Dose Quantities at Crew Location
  - II. The Body Dose Quantities are Inputs to Acute Radiation Risk Models Used to Assess Biological Impacts
    - Predict incidence/severity of Acute Radiation Syndrome (ARS)
    - Predict incidence/magnitude of Performance Decrement
- **This Real-Time Approach will be Tested on the EM-1 Flight**

Main Objective & Assumptions

- **Focus of this Study**
  - Part I of General Approach to Real-Time Biological Impact Assessment
  - Estimate of SEP Absorbed Dose at Crew Locations Using Measurements at the Dosimeter Locations
- **Main Objective**
  - Evaluate Two Independent Methodologies for Estimating Dose at Crew Locations Using Dosimeter Measurements
- **Assumptions**
  - Dosimeter Measurements are Simulated (HZETRN code)
  - A 15% Standard Deviation is Assumed for Measurement Noise
  - Only Absorbed Dose in Silicon is Estimated at Crew Locations
  - SEP Events Assumed Isotropic

Outline

- **Method 1: Dosimeter Dose-Depth Fit**
  - Description of Method
  - Test Method 1 for EM-1 Dose at Crew Locations from Distribution of SEP Event-Accumulated Doses
- **Method 2: Dosimeter Dose-Database Fit**
  - Description of Method
  - Test Method 2 for EM-1 Dose at Crew Locations from Distribution of SEP Event-Accumulated Doses
- **Down Select to One Operational Method**
- **Assess Operational Methodology for Time-Dependent SEP Events**
- **Summary & Next Steps**

Description of Method 1: Dose-Depth Fit

Dose-Depth Fit: Basic Approach

Fit Power-Law in Depth to Onboard Dosimeter Measurements

$$D(\mathbf{x}_i) = A x_{eff\,(i)}^{-\gamma} = \int D(\mathbf{x}_i, \mathbf{\Omega}(\mathbf{x})) d\mathbf{\Omega}$$

Dose measurement from detectors (i)

Effective depth of detector (i)

Dose delivered to detectors at position $\mathbf{x}_i$ by "*true*" radiation environment along ray paths $\mathbf{\Omega}$

Dose-Depth Fit: Basic Approach

$$D_{(i)} = A x_{eff\,(i)}^{-\gamma}$$

$$x_{eff\,(i)} = \sum_{n=0}^{N} c_n(i)\gamma^n$$

Dose-depth power-law representation requires iterative approach to obtain self-consistent solution of these two equations

Determination of Fit Parameters:

1. Effective depth expansion coefficients for each detector (i):

   $$D_i(xeff) = \int D(\mathbf{x}_\mathrm{i}, \Omega(\mathbf{x}))\,d\Omega$$

   Determine x_{eff} and γ from large database of SEP simulations and fit x_{eff} to polynomial in γ

2. Power-Law Parameters (A, γ):

   Real-time fit to D(i) measurements using Bayesian statistical inversion

The Inverse Problem

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \boldsymbol{\varepsilon}$$

Vector of Measurements — Model of Measurement — Measurement Error

Statement of inverse problem: Find model parameters **x** that "optimally estimate" the measurements **y** to within the measurements error **ε**

Solution of inverse problem: Find model parameters **x,** given the measurements **y,** that maximize the posteriori pdf P(**x**|**y**)

$$P(\mathbf{x} \mid \mathbf{y}) = P(\mathbf{y} \mid \mathbf{x}) P(\mathbf{x}) / P(\mathbf{y})$$

(Bayes' theorem on inverse probabilities)

The Inverse Problem

Assuming Gaussian Statistics

$$-2\ln P(\mathbf{x}\,|\,\mathbf{y}) = (\mathbf{y}-\mathbf{F}(\mathbf{x}))^T\,\tilde{\mathbf{S}}_\varepsilon^{-1}(\mathbf{y}-\mathbf{F}(\mathbf{x})) + (\mathbf{x}-\mathbf{x}_a)^T\,\tilde{\mathbf{S}}_a^{-1}(\mathbf{x}-\mathbf{x}_a) + \text{const.}$$

Measurement noise variance matrix — a-priori — a-priori variance matrix

Define the cost function

$$\Phi(\mathbf{x}) = (\mathbf{y}-\mathbf{F}(\mathbf{x}))^T\,\tilde{\mathbf{S}}_\varepsilon^{-1}(\mathbf{y}-\mathbf{F}(\mathbf{x})) + (\mathbf{x}-\mathbf{x}_a)^T\,\tilde{\mathbf{S}}_a^{-1}(\mathbf{x}-\mathbf{x}_a)$$

Solution: the maximum likelihood solution $\mathbf{x}_s$ to the Bayesian statistical inverse problem satisfies (i.e., minimizes the cost function):

$$\nabla\Phi(\mathbf{x}_s) = 0$$

Optimal Solution of Inverse Problem

Solution Vector:

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \tilde{\mathbf{S}}_i \left[\tilde{\mathbf{K}}_i^T \tilde{\mathbf{S}}_\varepsilon^{-1} \left(\mathbf{y} - \mathbf{F}_i \right) + \tilde{\mathbf{S}}_a^{-1} \left(\mathbf{x}_a - \mathbf{x}_i \right) \right]$$

Solution Covariance Matrix:

$$\tilde{\mathbf{S}}_i = \left[\tilde{\mathbf{S}}_a^{-1} + \tilde{\mathbf{K}}_i^T \tilde{\mathbf{S}}_\varepsilon^{-1} \tilde{\mathbf{K}}_i \right]^{-1}$$

Jacobian Matrix:

$$\tilde{\mathbf{K}}_i \equiv \frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}}$$

Forward Model Approximation:

$$\mathbf{F}(\mathbf{x}) = \mathbf{F}(\mathbf{x}_i) + \frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}} (\mathbf{x} - \mathbf{x}_i) + \ldots$$

$$\approx \mathbf{F}_i + \tilde{\mathbf{K}}_i (\mathbf{x} - \mathbf{x}_i)$$

Develop Effective Depth Parameterizations for EM-1 Vehicle

EM-1 Effective Depth

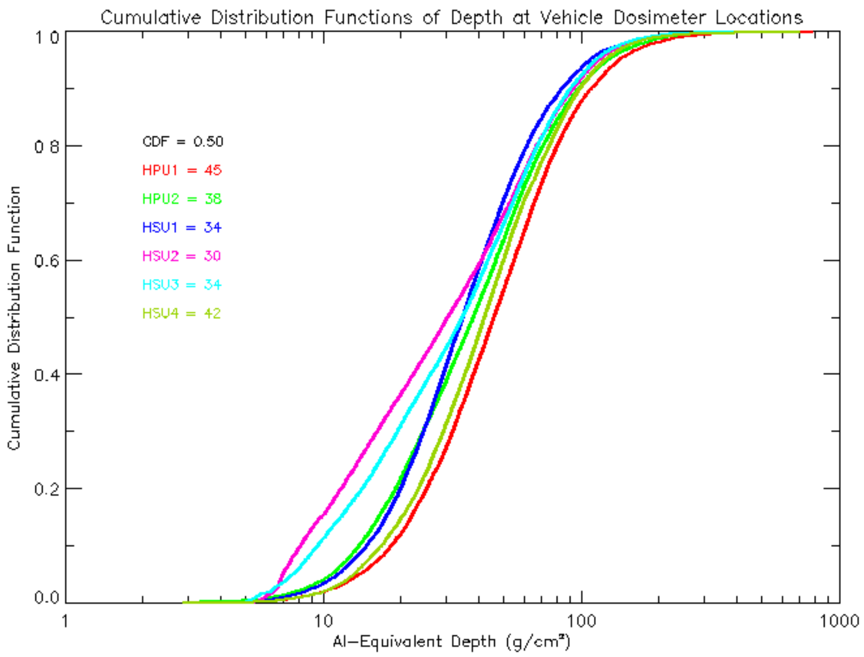
- **Calculate Database of Dose-Depth Curves (**0-100 g/cm^2**) for 65 Historical SEP Events Using HZETRN**
  - SEP/GLE Database (1956-2006): Tylka et al. (38th COSPAR Assembly)
- **Calculate Dose at EM-1 Dosimeter & Crew Locations for the Same 65 Historical SEP Events Using HZETRN**
- **From Dose-Depth Curve, Find Effective Depth that Reproduces Dose at EM-1 Dosimeter & Crew Locations for Each SEP Event**

$$D_i(x_{eff}(\gamma)) = \int D(\mathbf{x}_i, \Omega(\mathbf{x}))d\Omega$$

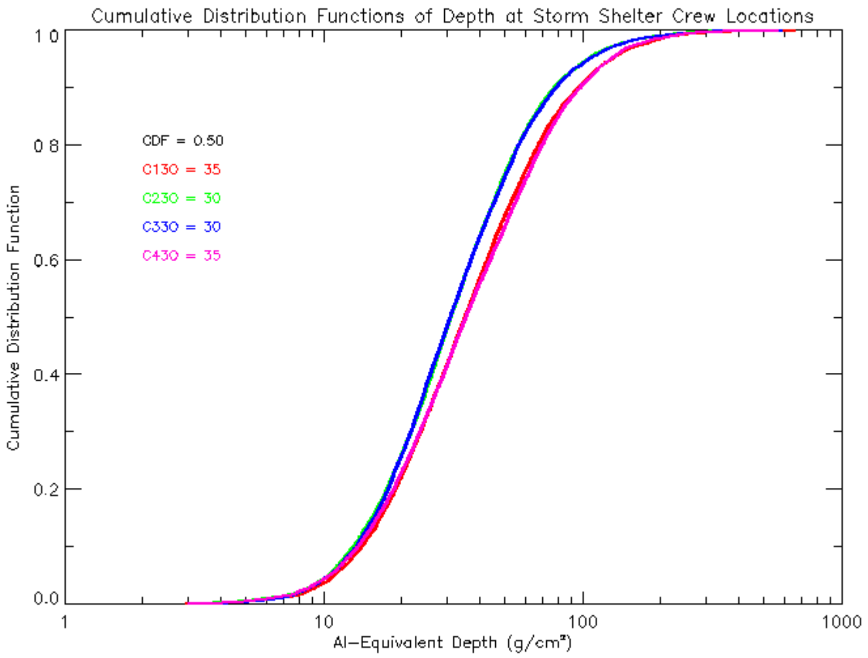
- **Catalogue** (x_{eff}, γ) **for Each SEP Event at the Dosimeter & Crew Locations**
- **Use** (x_{eff}, γ) **Catalogue to Fit Effective Depth** (x_{eff}) **to Polynomial in Power-Law Index (**γ**) for Each Dosimeter & Crew Locations**

EM-1 Cumulative Depth Distribution

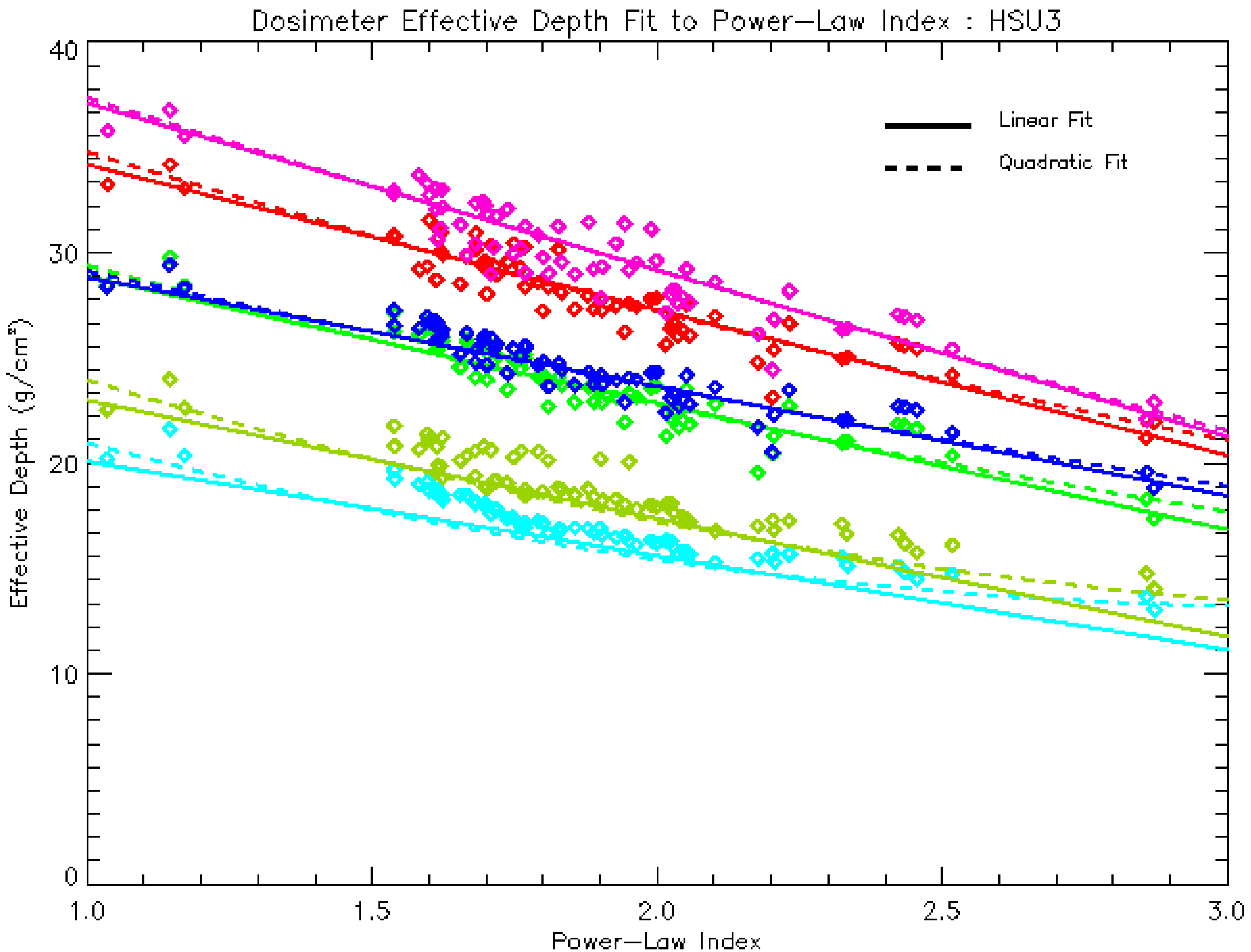
Vehicle Dosimeter Locations



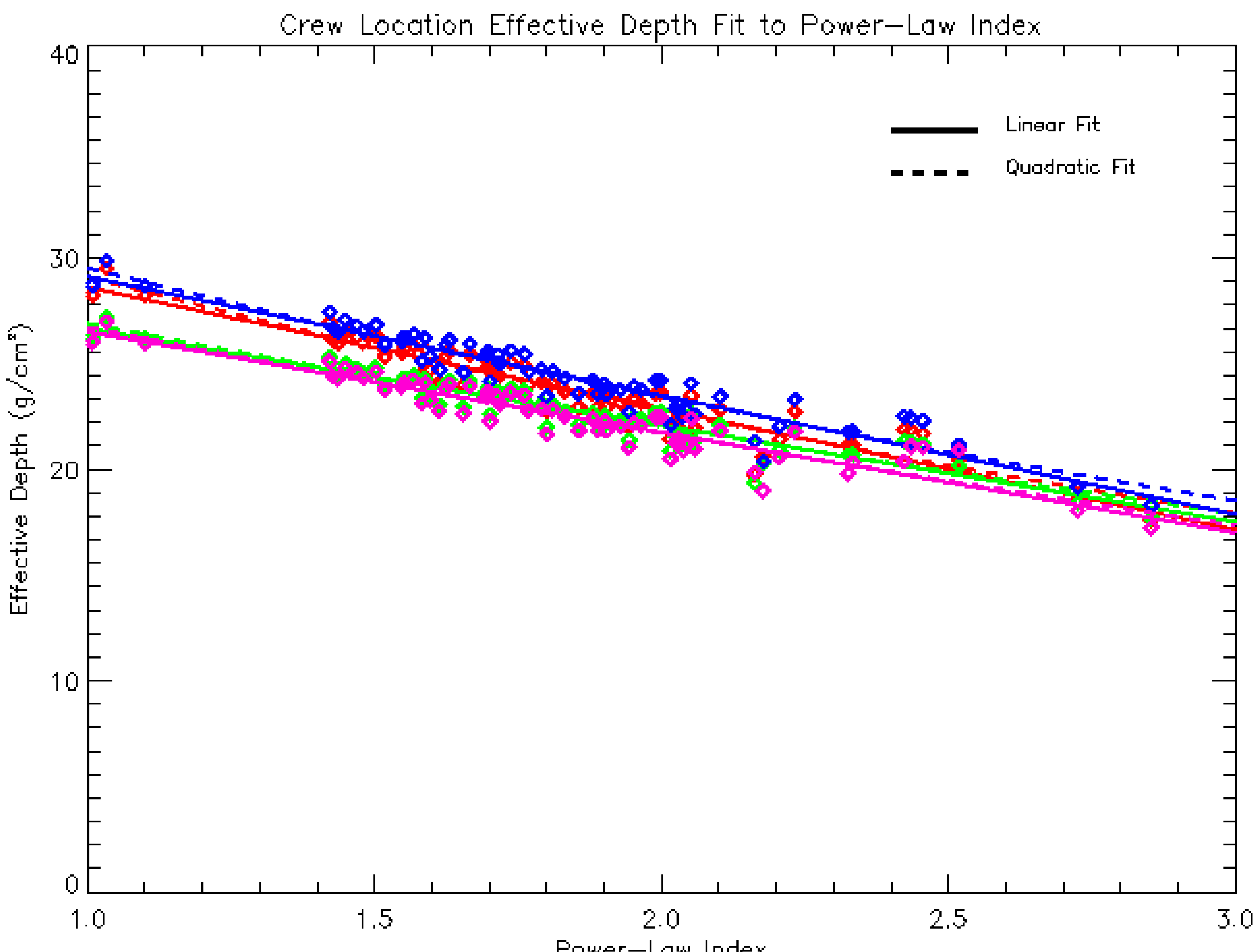
Storm Shelter Crew Locations



Effective Depth: EM-1 Detectors



Effective Depth: EM1 Crew Locations

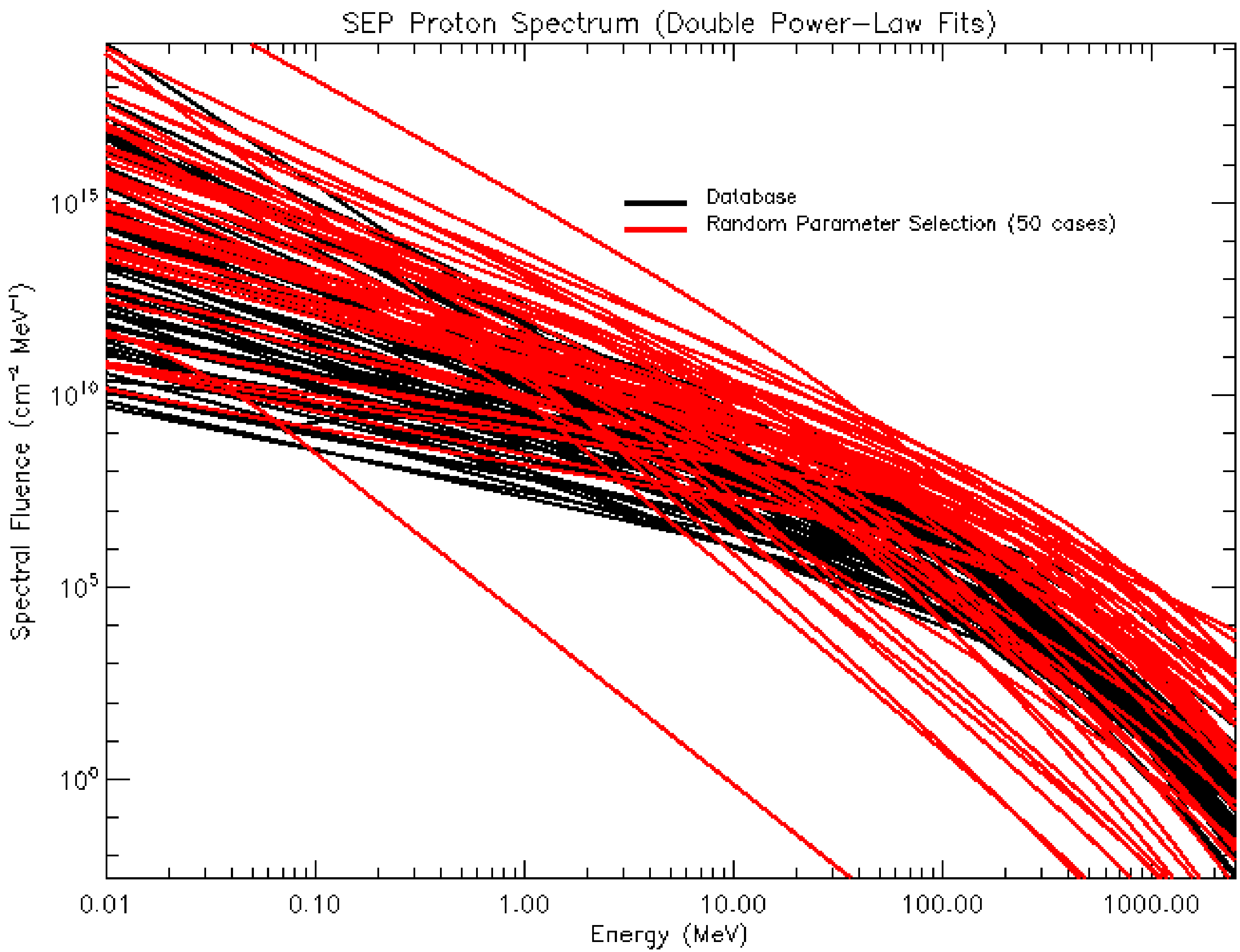


Test Dosimeter Dose-Depth Fit Approach for EM-1 Vehicle

Test Set-Up -1

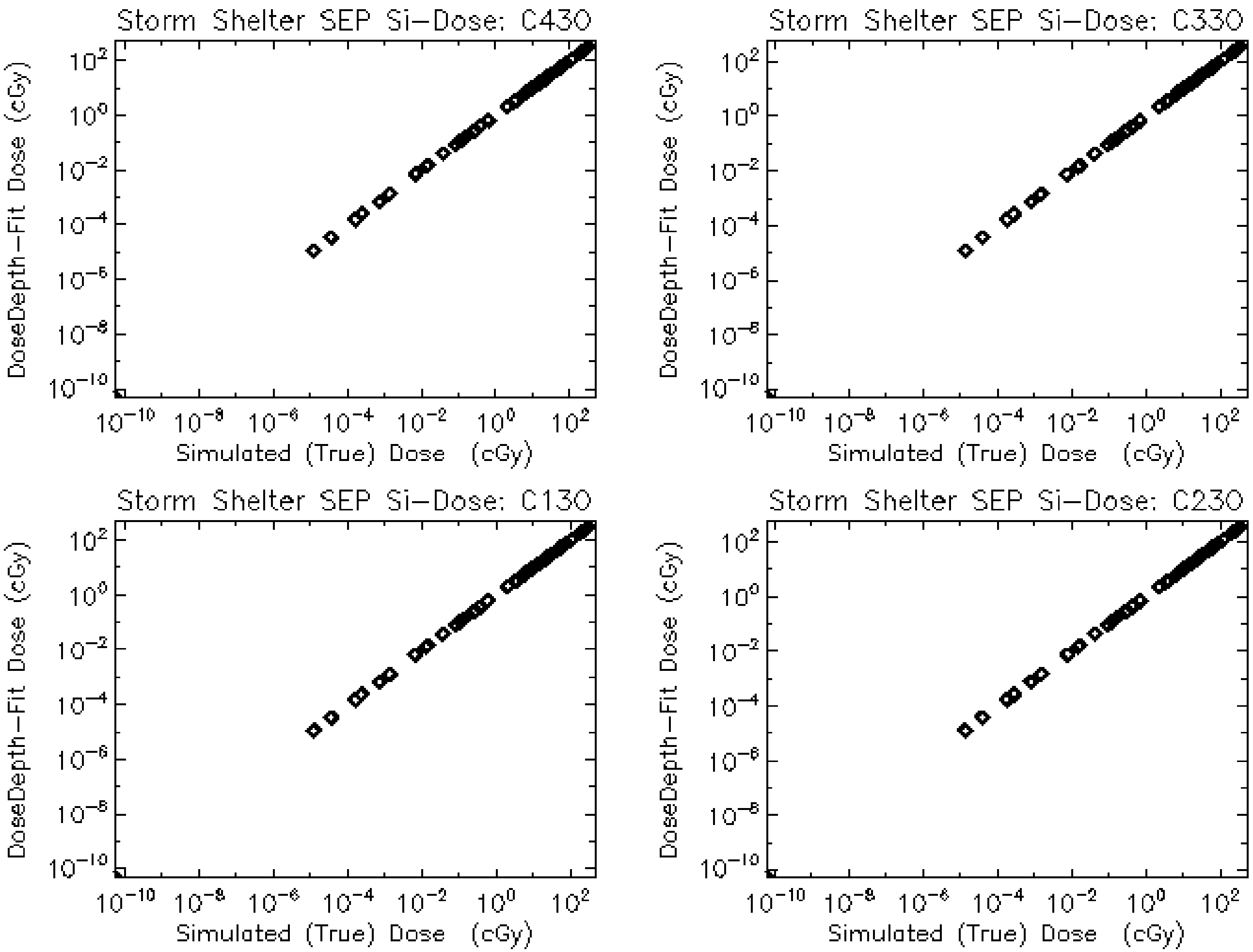
- **Simulate EM-1 Dosimeter Measurements (HZETRN)**
- **Estimate Dose at EM-1 Crew Locations**
  - Use Dose-Depth Fitting Method to Derive Parameters (A, γ) Based on Simulated EM-1 Dosimeter Measurements
  - Estimate Dose at Crew Locations Using Fit Parameters (A, γ) and Effective Depth Parameterization $(D = Ax_{eff}^{-\gamma})$
- **Simulate Dose at EM-1 Crew Locations (HZETRN)**
- **Compare Dose-Depth Fit Estimate of Dose at Crew Location with Simulated Dose (HZETRN)**
- **Simulated SEP Event Test Cases Based on Random Selection of SEP Spectral Parameters**

SEP Spectra for Algorithm Testing



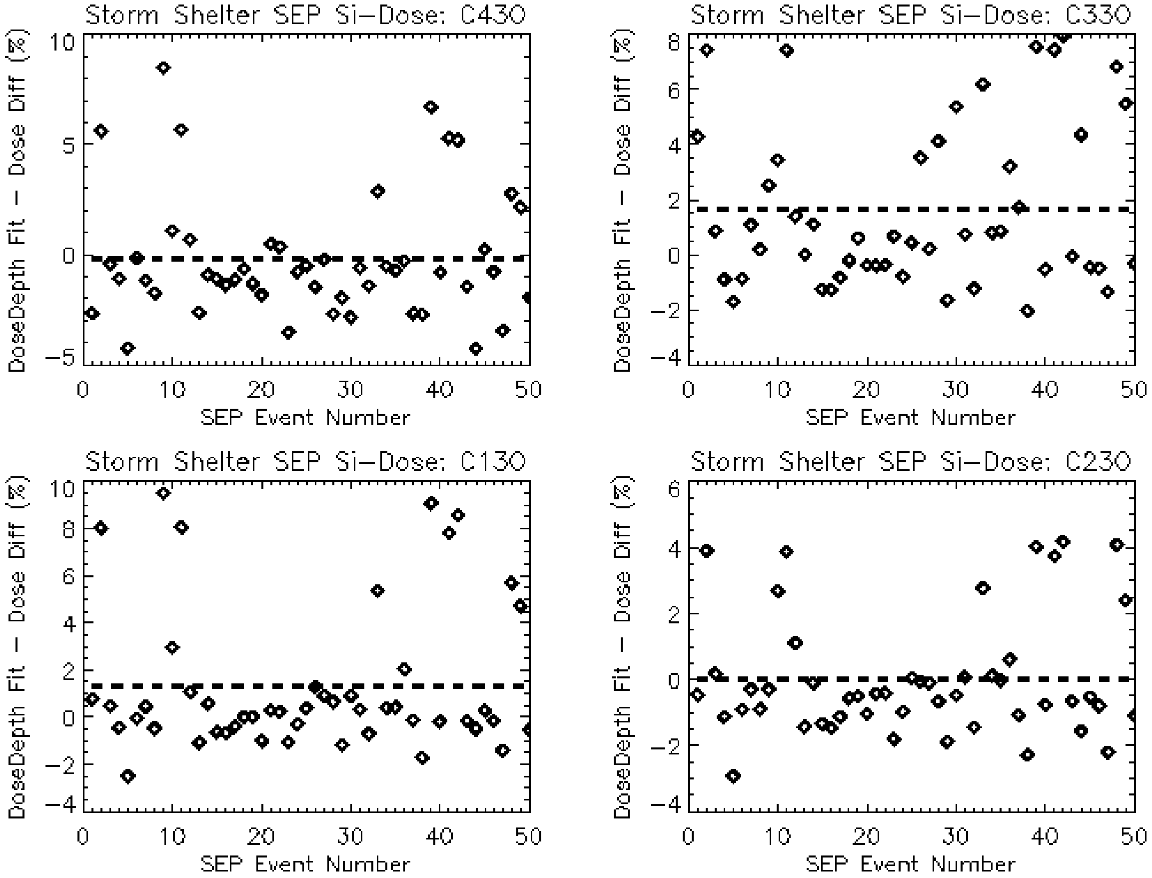
Estimated vs *“True”* Si-Dose

Storm Shelter Crew Locations



Estimated vs "*True*" Si-Dose Diff

Storm Shelter Crew Locations



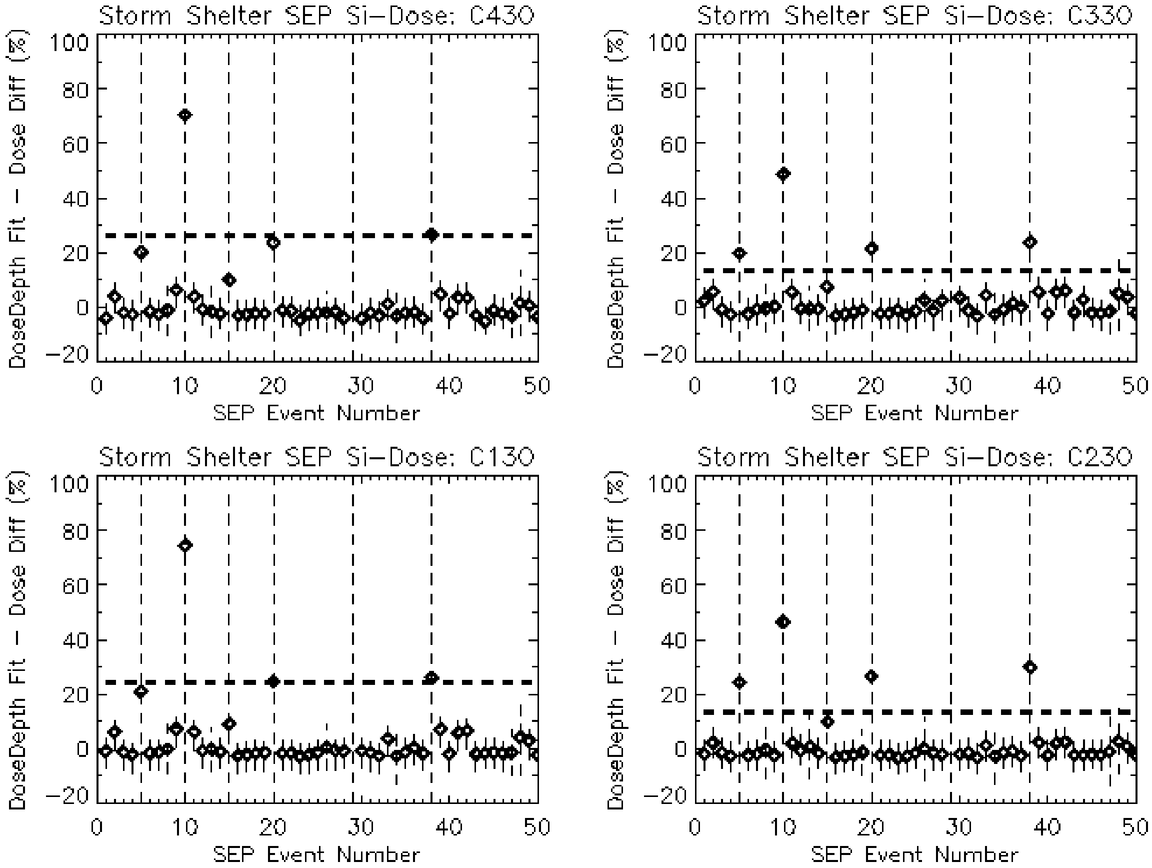
Absolute Average Difference < 3%
Maximum Difference < 10%

Test Set-Up -2

- **Simulate EM-1 Dosimeter Measurements (HZETRN)**
  - Perturb measurements by random noise (15% STD)
  - 50 Random Samples
- **Estimate Dose at EM-1 Crew Locations**
  - Use Dose-Depth Fitting Method to Derive Parameters (A, γ) Based on Simulated EM-1 Dosimeter Measurements
  - Estimate Dose at Crew Locations Using Fit Parameters (A, γ) and Effective Depth Parameterization $(D = Ax_{eff}^{-\gamma})$
- **Simulate Dose at EM-1 Crew Locations (HZETRN)**
- **Compare Dose-Depth Fit Estimate of Dose at Crew Location with Simulated Dose (HZETRN)**
- **Simulated SEP Event Test Cases Based on Random Selection of SEP Spectral Parameters**

Estimated vs "*True*" Si-Dose Diff

Storm Shelter Crew Locations



Absolute Average Difference < 35%
Maximum Difference ~ 1200%

Description of Method 2: Dose-Database Fit

Dose-Database Fit: Basic Approach

1. **Compute Normalized Variance-Weighted Average Measured Dose**

$$\hat{D}_{\text{det}}^{(i)} = \frac{D_{\text{det}}^{(i)}}{\sum_{i=1}^{N_{\text{det}}} \tilde{\mathbf{S}}_{\varepsilon,(ii)}^{-1} D_{\text{det}}^{(i)} \Big/ \sum_{i=1}^{N_{\text{det}}} \tilde{\mathbf{S}}_{\varepsilon,(ii)}^{-1}}$$

2. **Compute Normalized Dose Calculated from the SEP Event Database at the Dosimeter Locations**

$$\hat{D}_{i,j} = \frac{D_{i,j}}{\frac{1}{N_{\text{det}}} \sum_{i=1}^{N_{\text{det}}} D_{i,j}}$$

3. **Find SEP Event that Minimizes the Square Residual Between the Measured & Database Normalized Average Dose**

$$j^* = \min_j \left\{ \sum_{i=1}^{N_{\text{det}}} \left[\hat{D}_{\text{det}}^{(i)} - \hat{D}_{i,j} \right]^2 \right\}$$

Optimal Solution for General LSQ

Define the cost function

$$\Phi(\mathbf{x}) = (\mathbf{y} - \mathbf{F}(\mathbf{x}))^T \tilde{\mathbf{S}}_\varepsilon^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x}))$$

Solution: the maximum likelihood solution $\mathbf{x}_s$ to the Bayesian statistical inverse problem satisfies (i.e., minimizes the cost function):

$$\nabla \Phi(\mathbf{x}_s) = 0$$

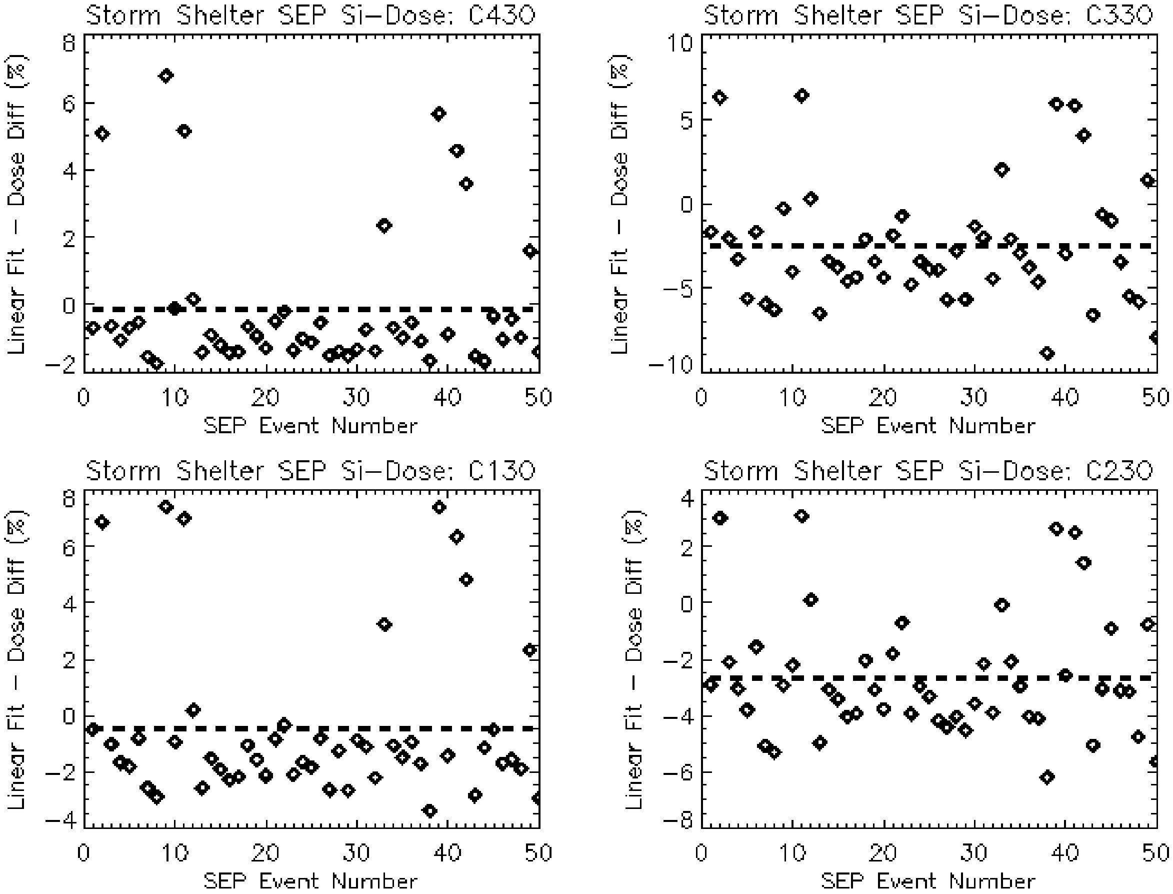
Solution Vector (General LSQ):

$$\mathbf{x}_s = \mathbf{x}_0 + \left(\tilde{\mathbf{K}}^T \tilde{\mathbf{S}}_\varepsilon^{-1} \tilde{\mathbf{K}}\right)^{-1} \left[\tilde{\mathbf{K}}^T \tilde{\mathbf{S}}_\varepsilon^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x}_0))\right]$$

Test Dosimeter Dose-Database Fit Approach for EM-1 Vehicle

Estimated vs *"True"* Si-Dose Diff

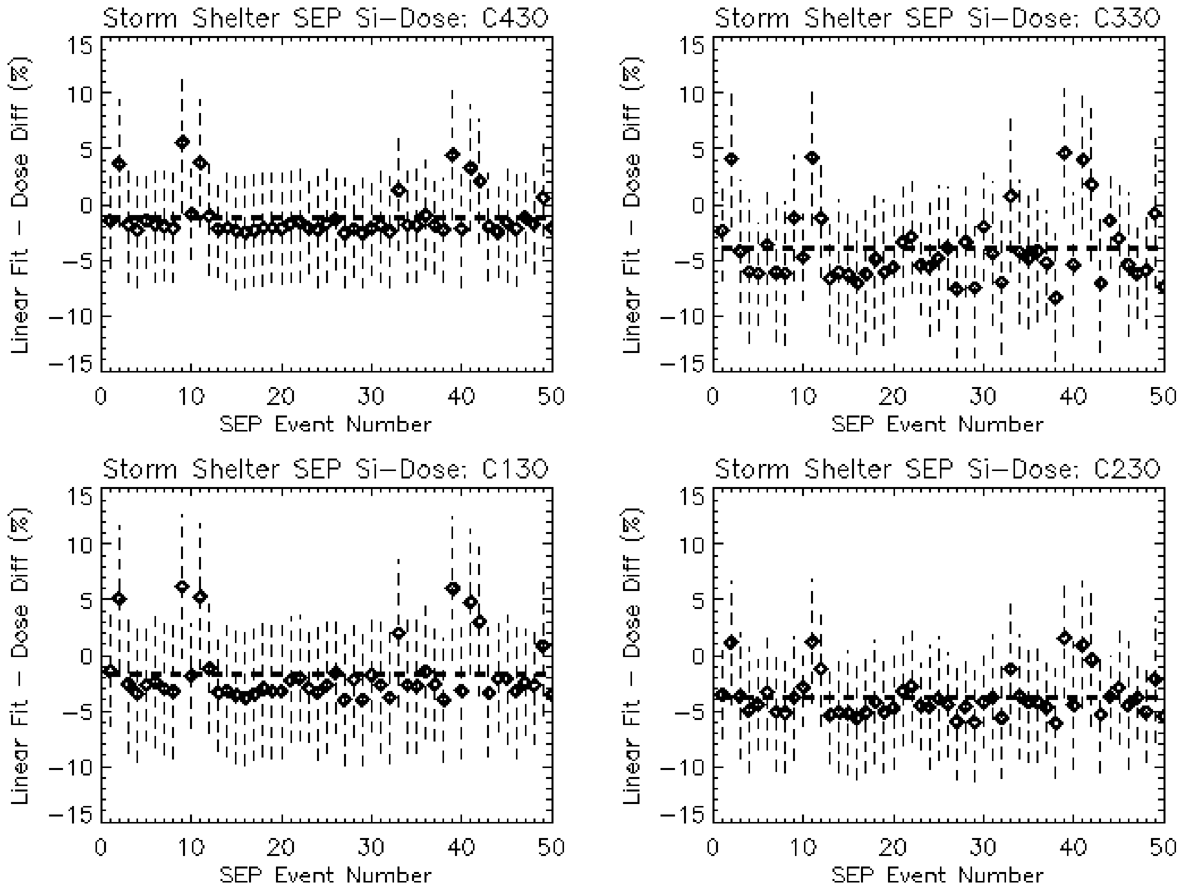
Storm Shelter Crew Locations



Absolute Average Difference < 4%
Maximum Difference ~ 10%

Estimated vs *"True"* Si-Dose Diff

Storm Shelter Crew Locations



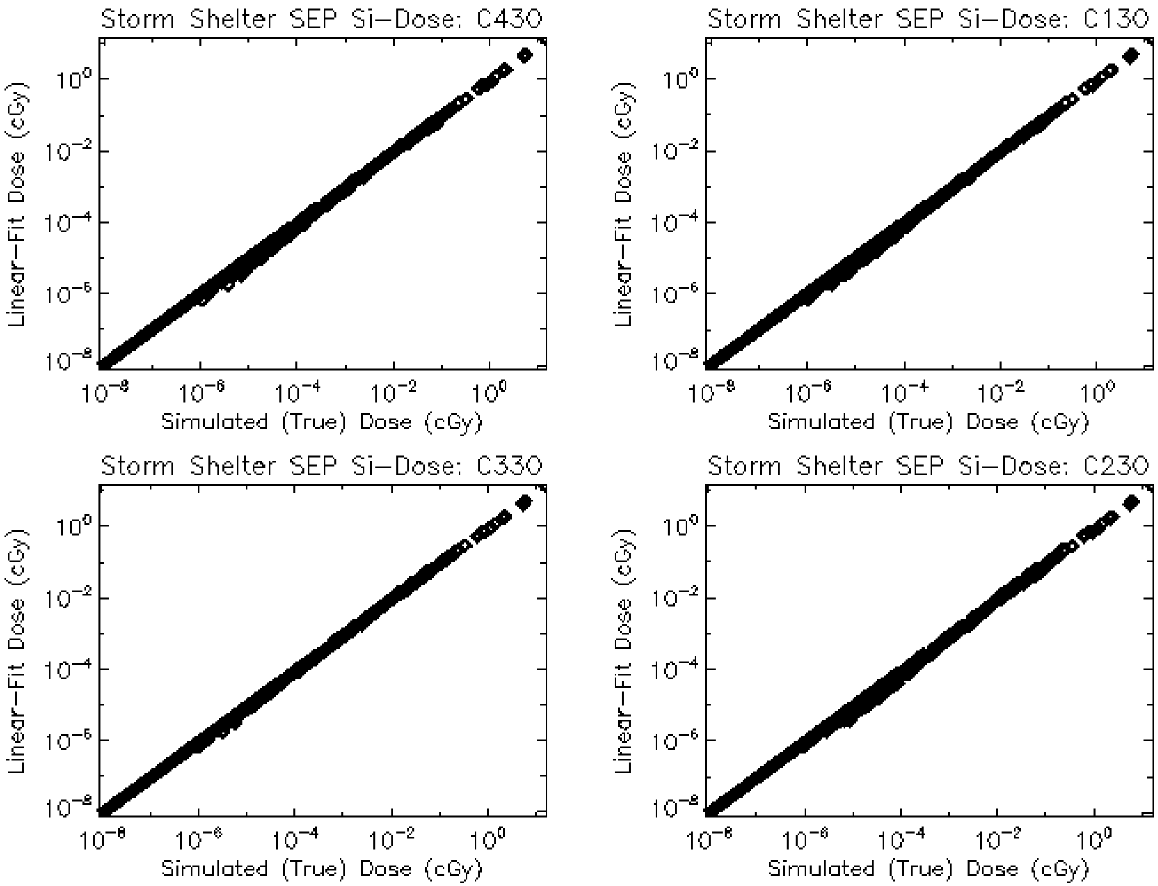
Absolute Average Difference < 7%
Maximum Difference ~ 10%

SEP Database with Time Evolution

- **Down Select to Dose-Database Fit Approach as Operational Approach**
  - More robust (less sensitive to noise perturbations in dosimeter measurements) compared to Dose-Depth Approach
  - Straightforward Approach to get Body Dose Quantities
- **Test Dosimeter Dose-Database Fit Approach for EM-1 Vehicle Using Time-Dependent SEP Event Database**
  - Database Based on IMP-8/GME Measurements (Jim Adams)
  - 479 SEP Events (1973-2001)
  - ~190,000 30-Minute Time Intervals

Estimated vs “True” Si-Dose

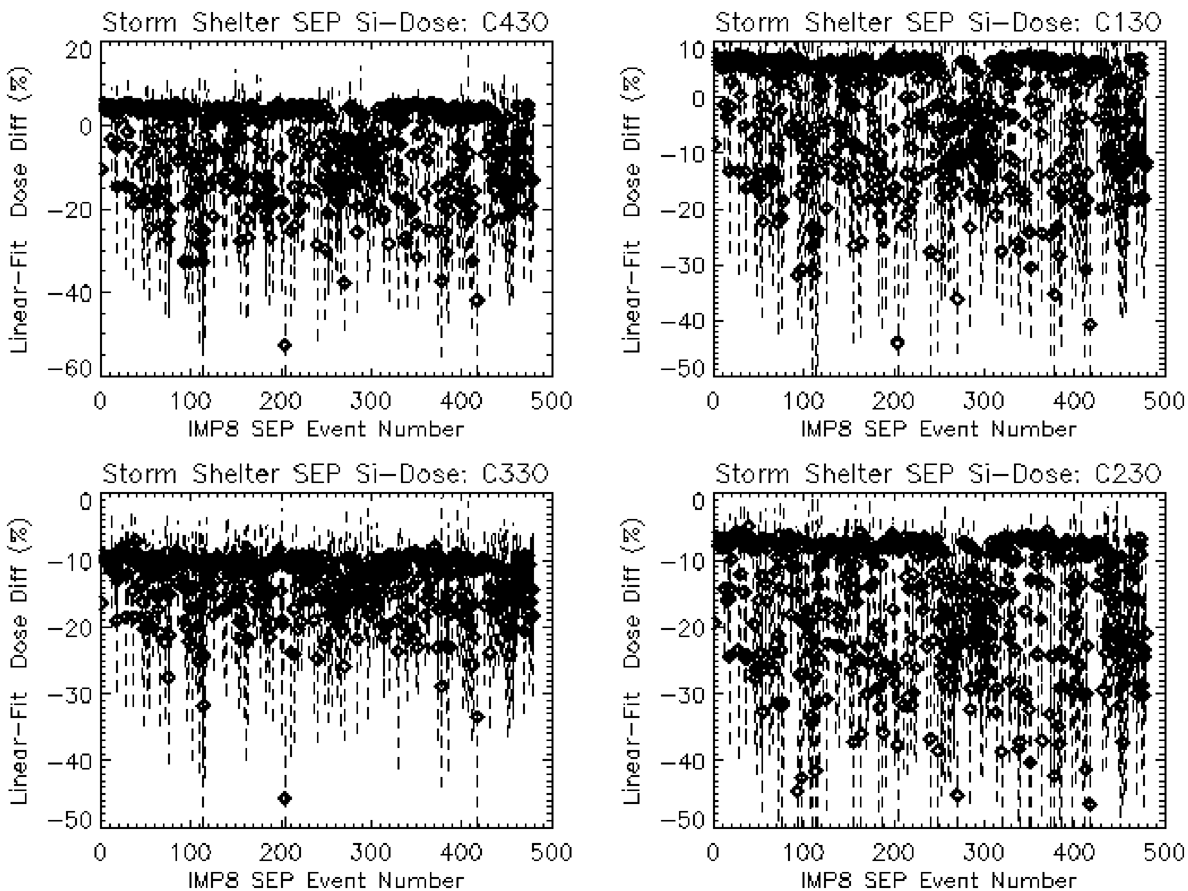
Storm Shelter Crew Locations



Event Accumulated Dose

Estimated vs "True" Si-Dose Diff

Storm Shelter Crew Locations

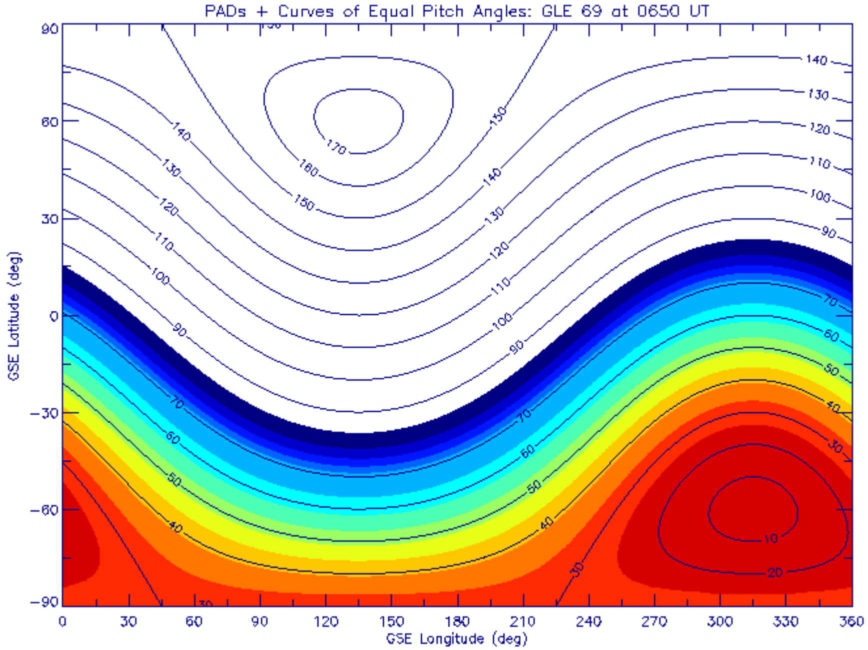


Error bars are STD Over Event Sub-Intervals

Absolute Average Difference < 20%
Maximum Difference ~ 80%

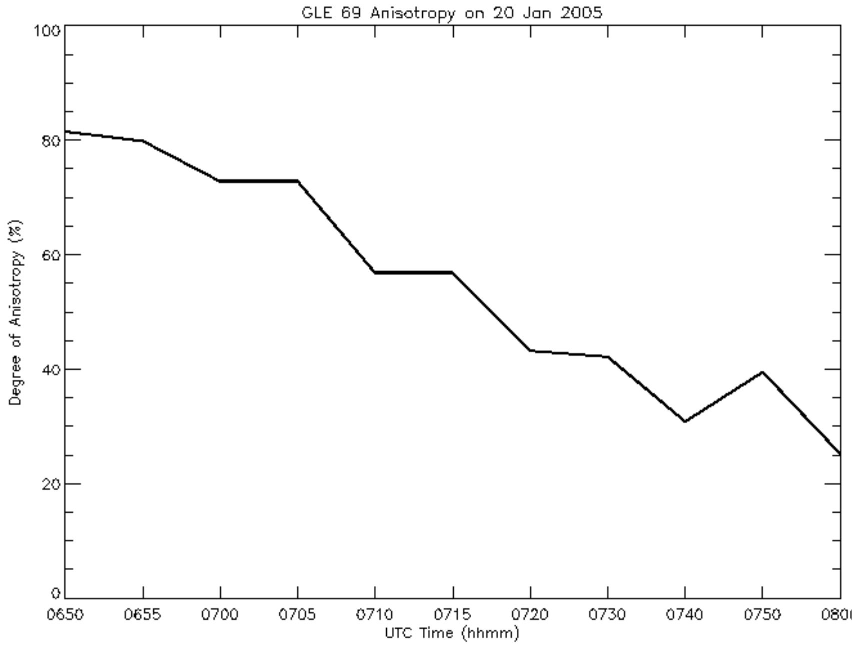
Example SEP Anisotropy: GLE69

Pitch Angle Distribution About Arrival Direction in GSE Coordinates: 06:50 UT



Highly collimated proton beam during initial phase of GLE

Degree of Anisotropy



Anisotropy persists at ~10-30% for more than 12 hours after peak flux

GLE69 Parameterization: *Bombardieri et al., Astrophys. J.,* ***682****, 1315-1327, 2008*

Summary

- **Comparisons of the Two Methods With (simulated) "*True*" Dose (Si) at Crew Locations**
  - No Noise Added to Simulated Dose Measurements
    - Maximum Absolute Difference for Single Event $\leq 10\%$
    - Average Absolute Difference over all Events $< 4\%$
  - Noise Added to Simulated Measurements
    - No Appreciable Change in Robustness and Reliability of Dose-Database Method (same error characteristics as above)
    - Dose-Depth Method can Fail Badly in Estimating the Dose
- **Down Select To the Dose-Database Method as the Real-Time Approach for Estimating Crew Dose from Dosimetry Measurements**
  - Proven to be more Robust for Realistic Measurements
  - Body Dose can be Obtained Straightforwardly from the Optimal SEP Database Index (j*) and the Dosimeter Measurement Fit Parameters
  - Database can be Expanded to Include Anisotropic Effects

Next Steps

- **Expand Database of Dose-Database Method**
  - Include Anisotropic Effects
  - Include Wider Range of SEP Spectral Shapes Using the IMP-8 Time-Dependent Event Database
  - Include Body Dose Quantities and Integrate Dose Output with Acute Radiation Risk Models
- **Re-evaluate Updates to Dose-Database Method**

Backup Slides

Solution Diagnostics

Estimated Relative Parameter Error:

$$\text{Relative Parameter Error}\left(\%\right) = 100 * \mathbf{x}_i \,/\, \sqrt{\tilde{\mathbf{S}}_{ii}}$$

Limited value (even misleading); doesn't account for correlated errors

Convergence Test and Quality Control:

$$\Delta \mathbf{x}^T \tilde{\mathbf{S}} \Delta \mathbf{x} \,/\, n_{\mathbf{x}} \;\square\; 1$$

Includes correlated errors

Goodness Test:

$$P\left(\chi^2 \geq \chi^2_{\text{obs}}\right) = 1 - erf\left(\chi^2_{\text{obs}} \,/\, \sqrt{2}\right)$$

$$\chi^2 : \text{ Reduced chi-square}$$

Probability close to one means the optimally estimated parameters fit the measurements better than any other set of parameters