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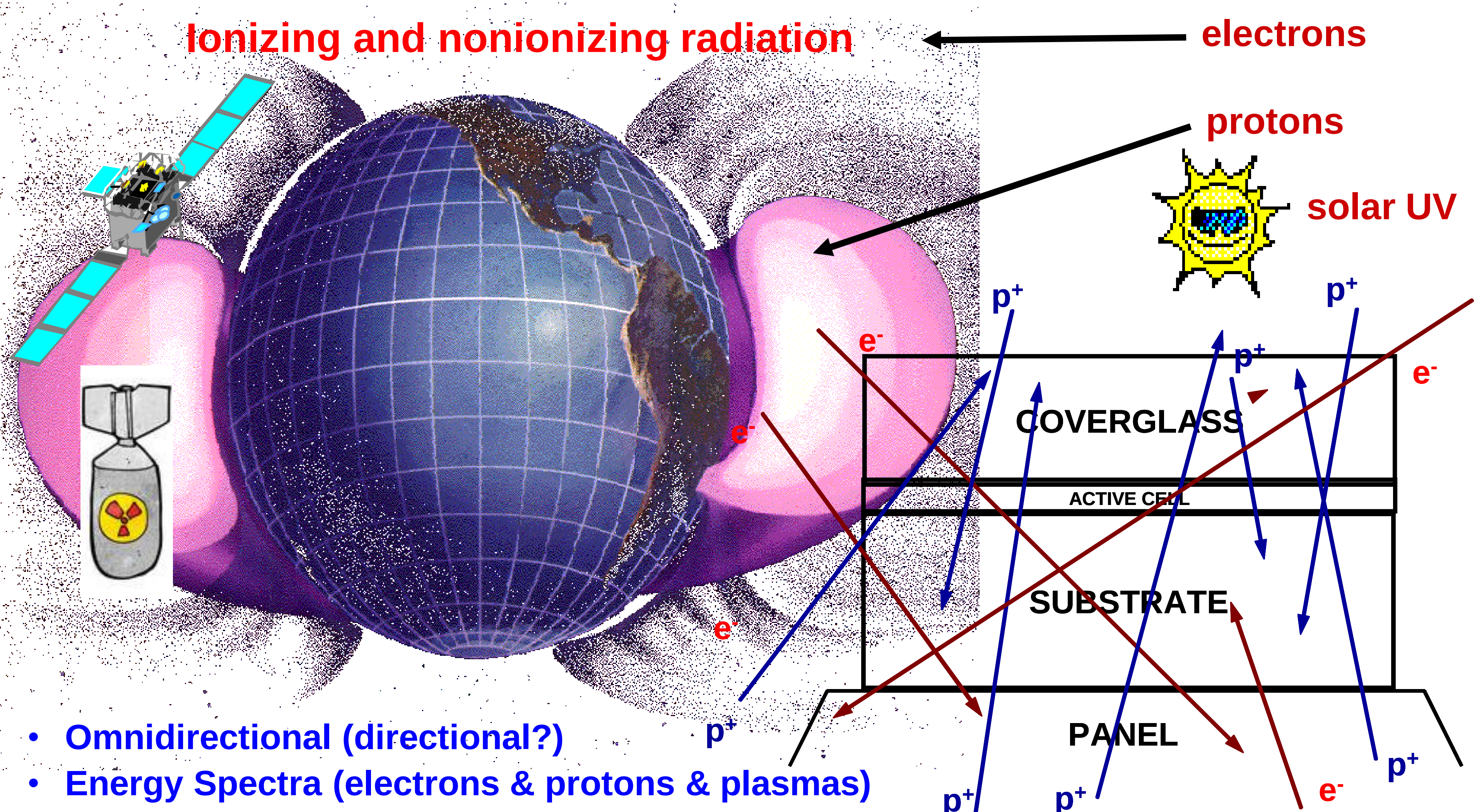
Solar Cell Radiation Environment Analysis Models (SCREAM)

2017 Space Environment Engineering & Science Applications Workshop (SEESAW)

Scott R. Messenger, Ph.D.
Principal Space Survivability Physicist
Scott.messenger@ngc.com
410-993-3976

Space Radiation Environment for Solar Arrays



- Omnidirectional (directional?)
- Energy Spectra (electrons & protons & plasmas)
- Nuclear activation (secondary production)
- Prompt effects (EMP, gammas, neutrons)

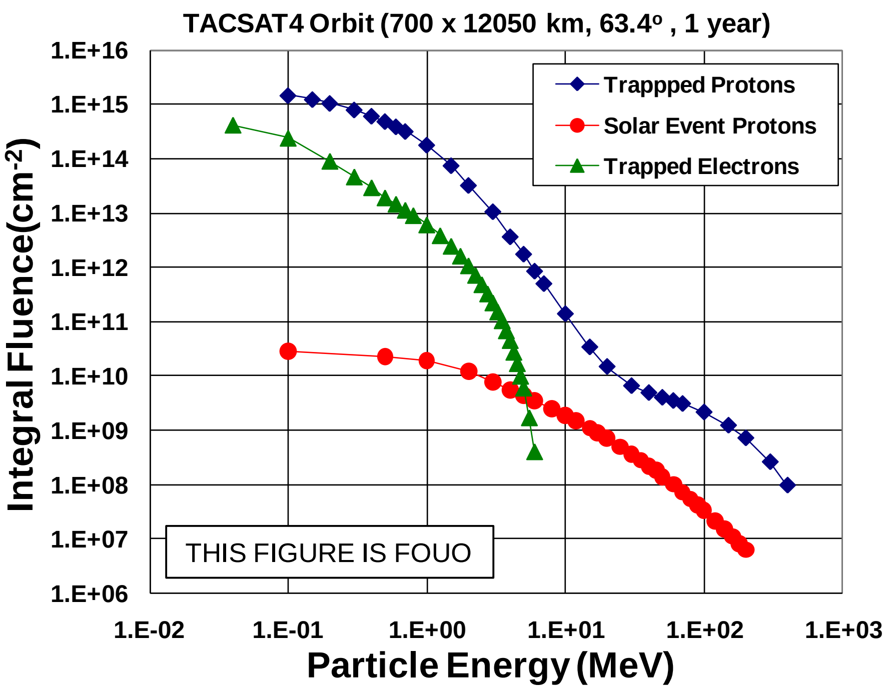
Outline

- Space Solar Cell Modelling
- Displacement Damage Dose (DDD) Model
  - SCREAM
- SCREAM Success Stories
  - TacSat4
  - GPS-IIR SV41
  - Low Thrust Trajectories (DDD accumulation)
- Summary

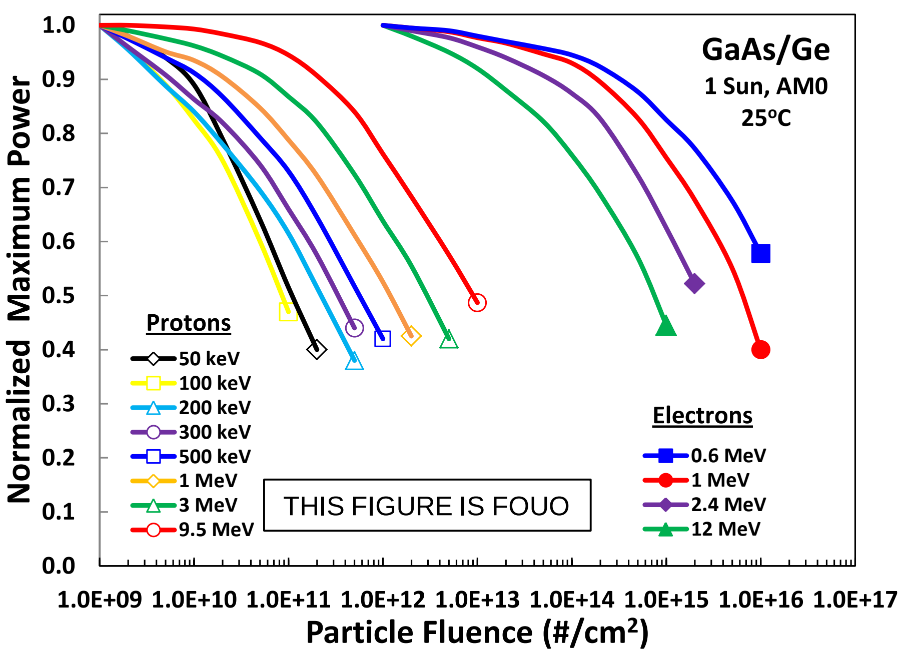
Space Solar Cell Degradation Prediction: The Problem

- To generate ground irradiation data necessary to predict the effect of a space particle energy spectrum on a solar cell
- This is accomplished by reducing the ground data to a characteristic dataset

Electron & Proton Spectra for TacSat4



Electron & Proton Ground Irradiation Data (Single Junction GaAs/Ge, 1991)



Space Solar Cell Degradation Prediction: The Solution(s)

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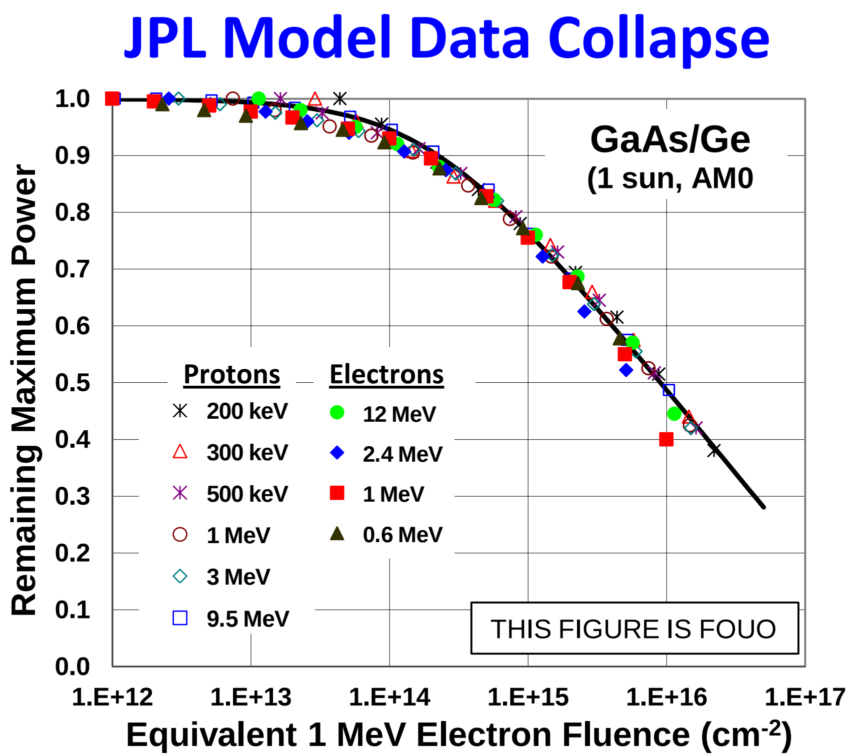
1. JPL method ⇨ RDCs ⇨ equivalent 1 MeV electron fluence & C_{pe}



*The ***heritage*** JPL model is well documented (1970-2000):**

H.Y.Tada and J.R.Carter, Solar Cell Radiation Handbook, JPL Pub. 77-56 (1977) – Green Book (Si)
B.Anspaugh, GaAs Solar Cell Radiation Handbook, JPL Pub. 96-9 (1996) – Blue Book (GaAs)
D.C. Marvin , Assessment of Multijunction Solar Cell Performance in Radiation Environments, TOR-00(1210)-1

Space Solar Cell Degradation Prediction: The Solution(s)

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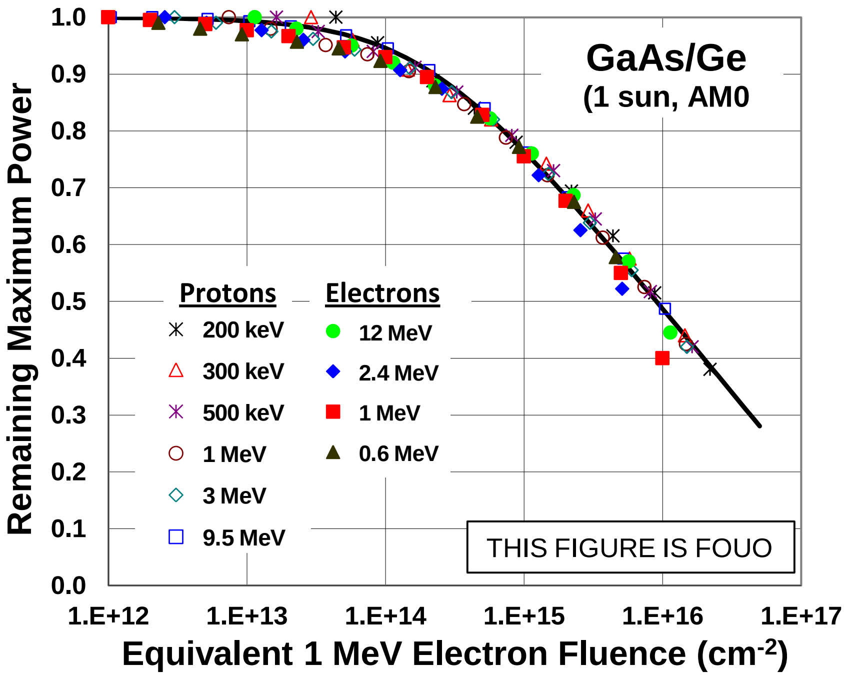
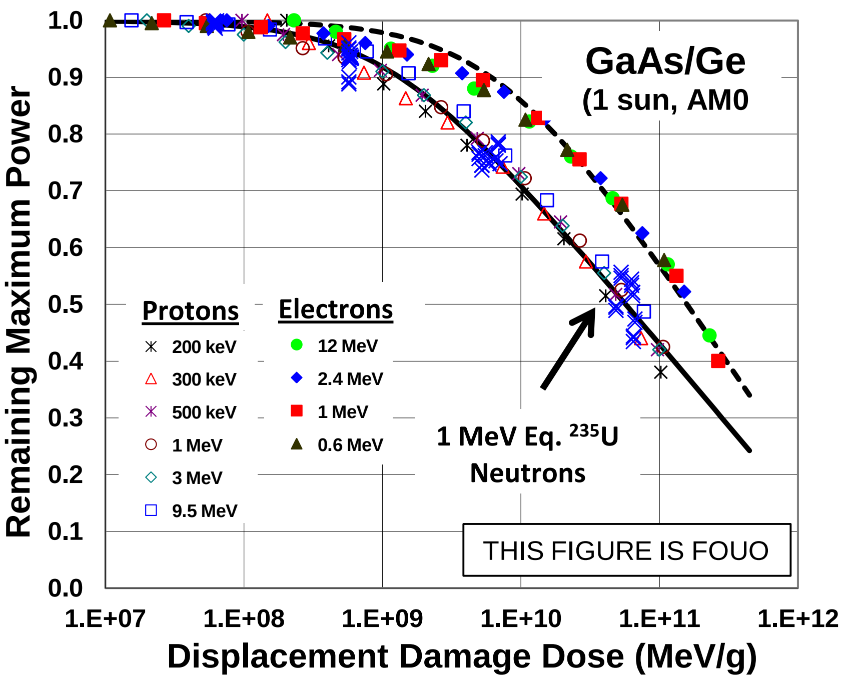
1. JPL method ⇨ RDCs ⇨ equivalent 1 MeV electron fluence & C_{pe}
2. NRL method ⇨ NIEL ⇨ displacement damage dose (DDD)

JPL Model Data Collapse



NRL/DDD Model Data Collapse



*The ***advanced*** **NRL/DDD model is well documented (1994-2012):**

S.R. Messenger, et al., "Modeling solar cell degradation in space: A comparison of the NRL displacement damage dose and JPL equivalent fluence approaches", Prog. Photovolt.: Res. Appl. vol. 9, pp. 103-121, 2001.

S.R. Messenger, et al., "SCREAM: A new code for solar cell degradation prediction using the displacement damage dose approach," 35th IEEE PVSC, 2010, p. 1106.

NRL DDD Method

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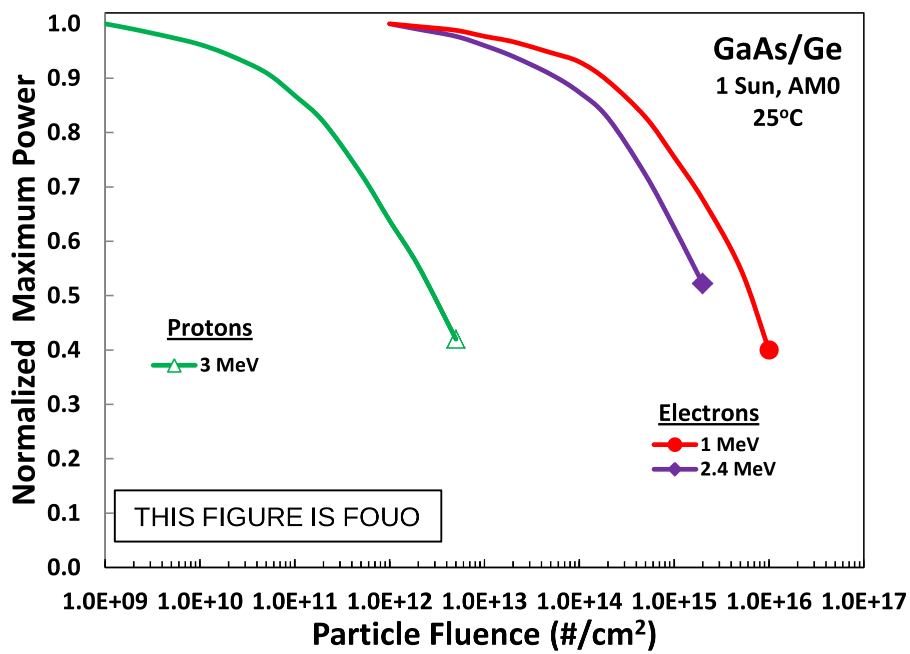
- **Data needed (*AIAA S-111)**
  - **Protons**
    - **E > 1-4 MeV (need uniform DD) (ϕ = 10^{10} to 10^{13} p^+/cm^2)**
  - **Electrons**
    - **E = 1 & >2 MeV (ϕ = 10^{13} to 10^{16} e^-/cm^2)**
- **Advantages**
  - **~3-4X cost reduction in qualification**
  - **Convenient for new tech quals, design tweaks, requals**
- **Disadvantages**
  - **Heritage Heritage Heritage**
  - **Not applicable to protons on thick silicon**

Electron and Proton Ground Data



"Qualification and Quality Requirements for Space Solar Cells" (AIAA S-111A-2014) – JPL and/or DDD models acceptable

Space Solar Cell Modeling: NRL Displacement Damage Dose (DDD)

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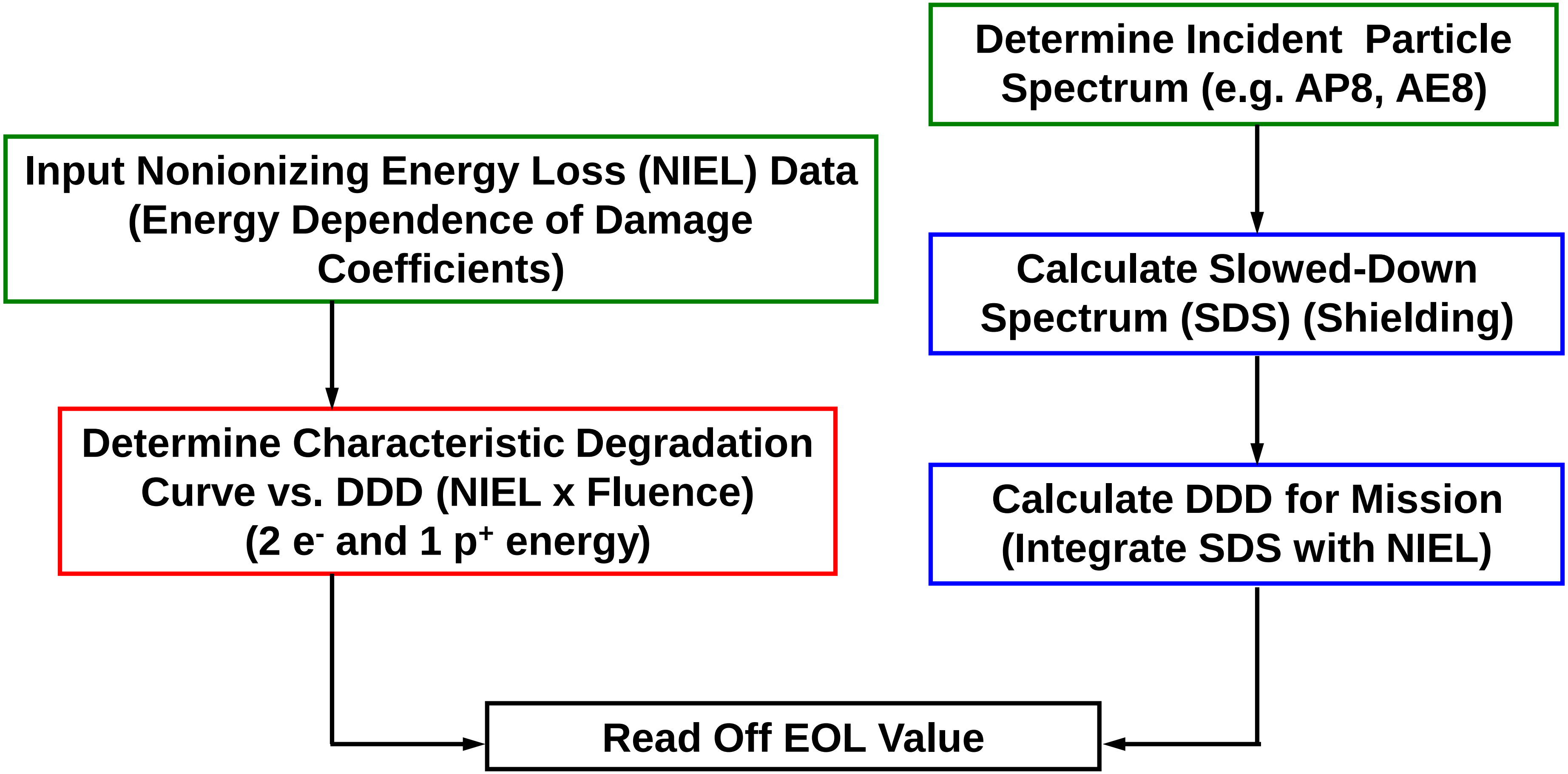
NRL Displacement Damage Dose Model for Solar Cell EOL Calculations



*RED – Measurements *Blue – Calculation *Green – Data input

DDD EOL Prediction Method

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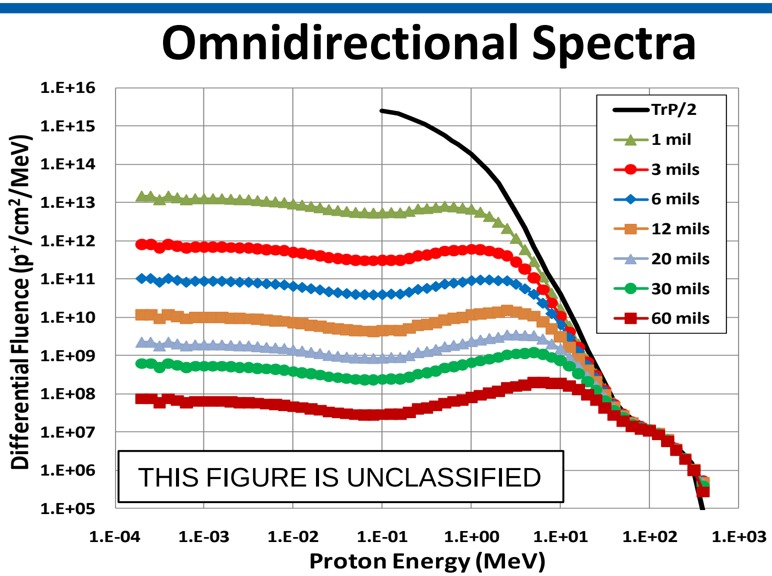
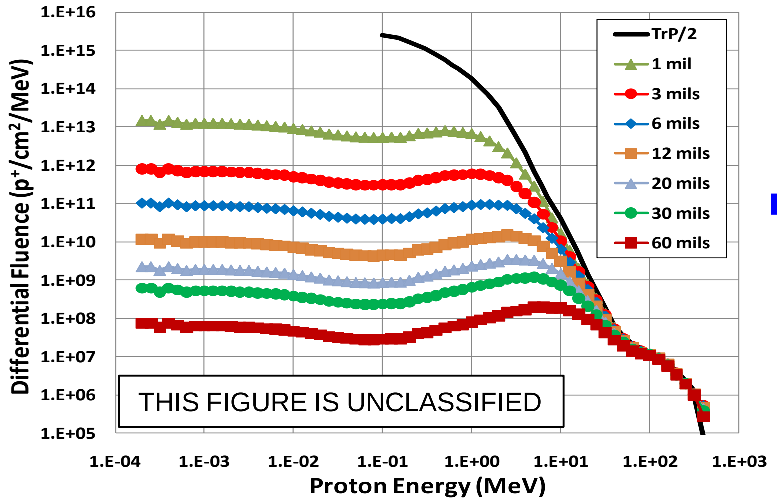
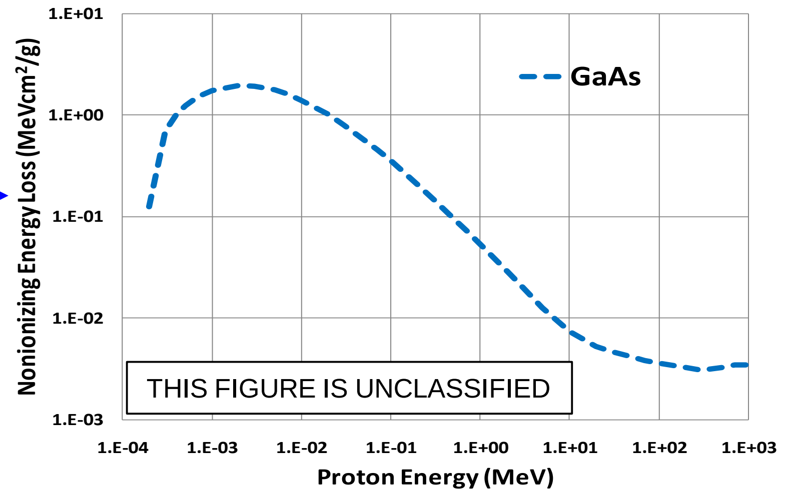


DDD EOL Prediction Method

Omnidirectional Spectra



Nonionizing Energy Loss (2006)



DDD EOL Prediction Method

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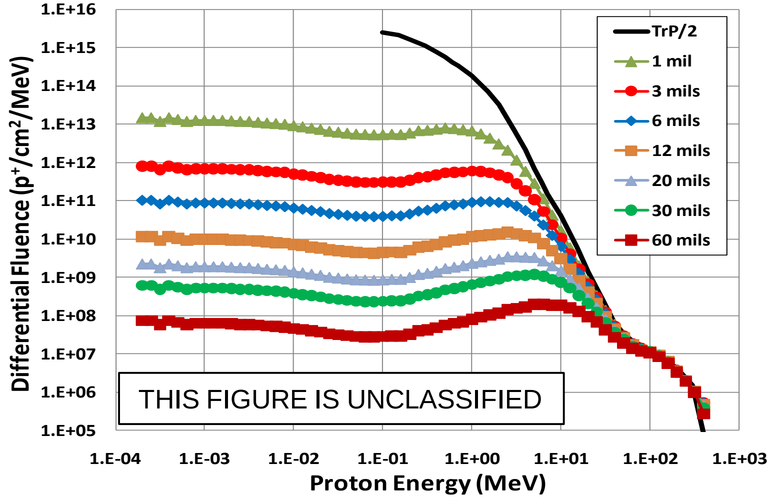
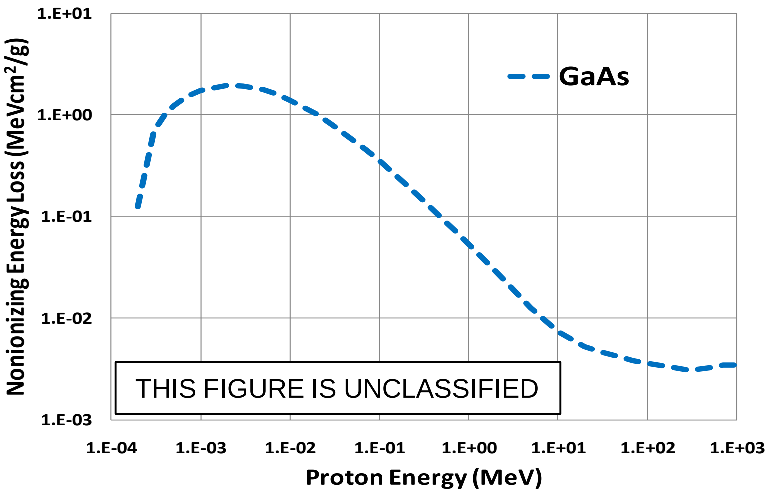
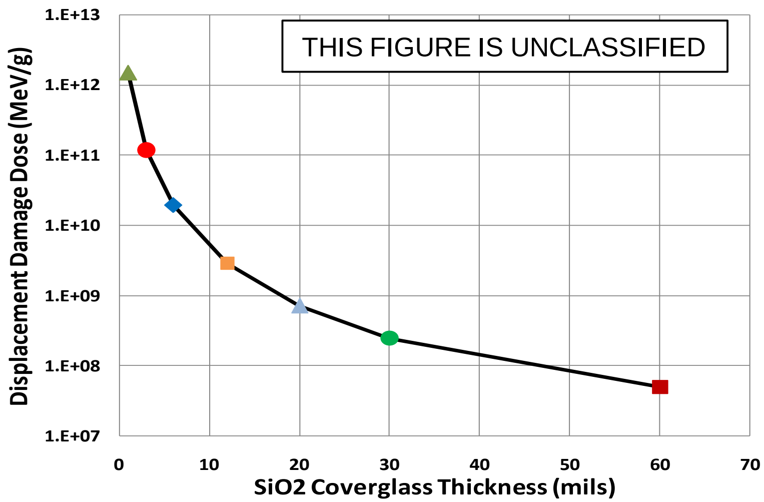
Omnidirectional Spectra



Nonionizing Energy Loss (2006)



Total Mission DDD



DDD EOL Prediction Method

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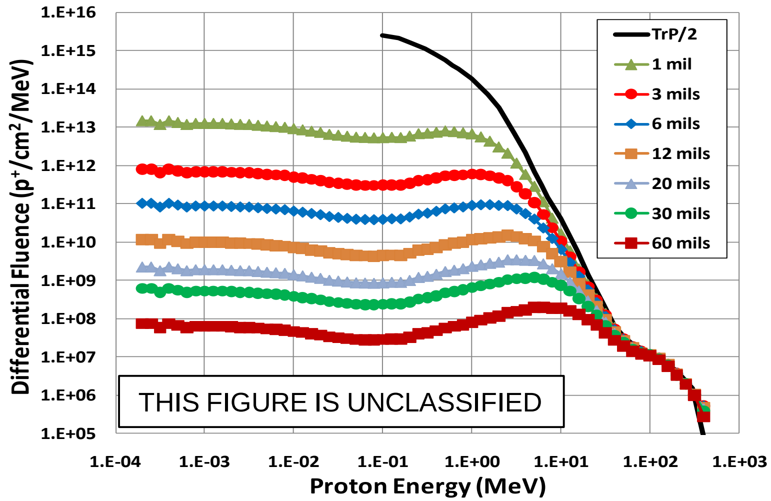
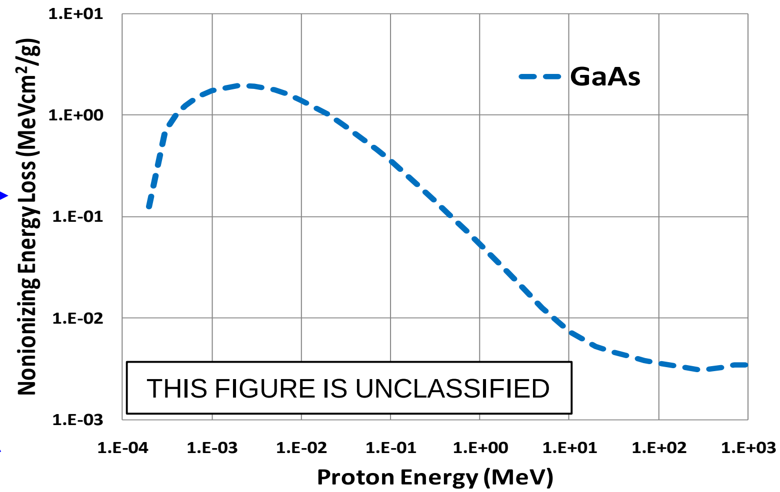
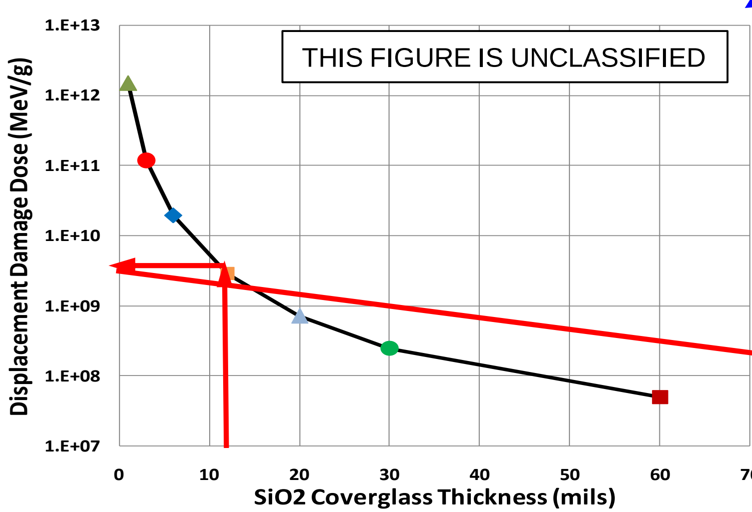
Omnidirectional Spectra



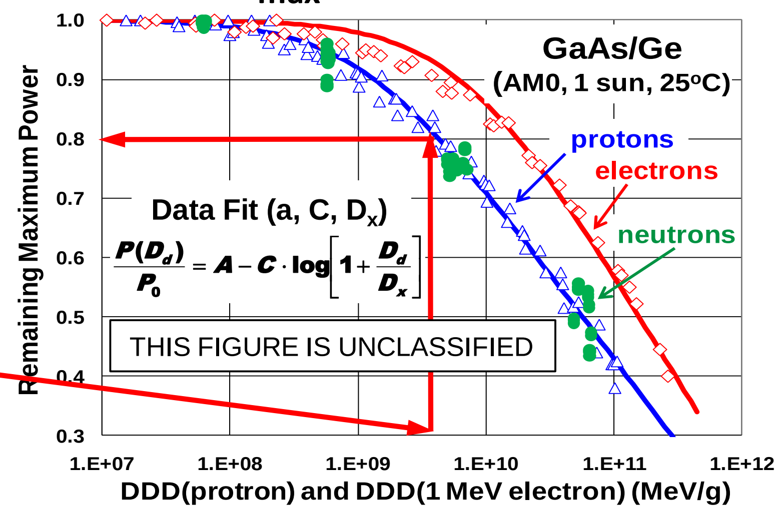
Nonionizing Energy Loss (2006)



Total Mission DDD



P_{max} Degradation



SCREAM (Solar Cell Radiation Environment Analysis Models)

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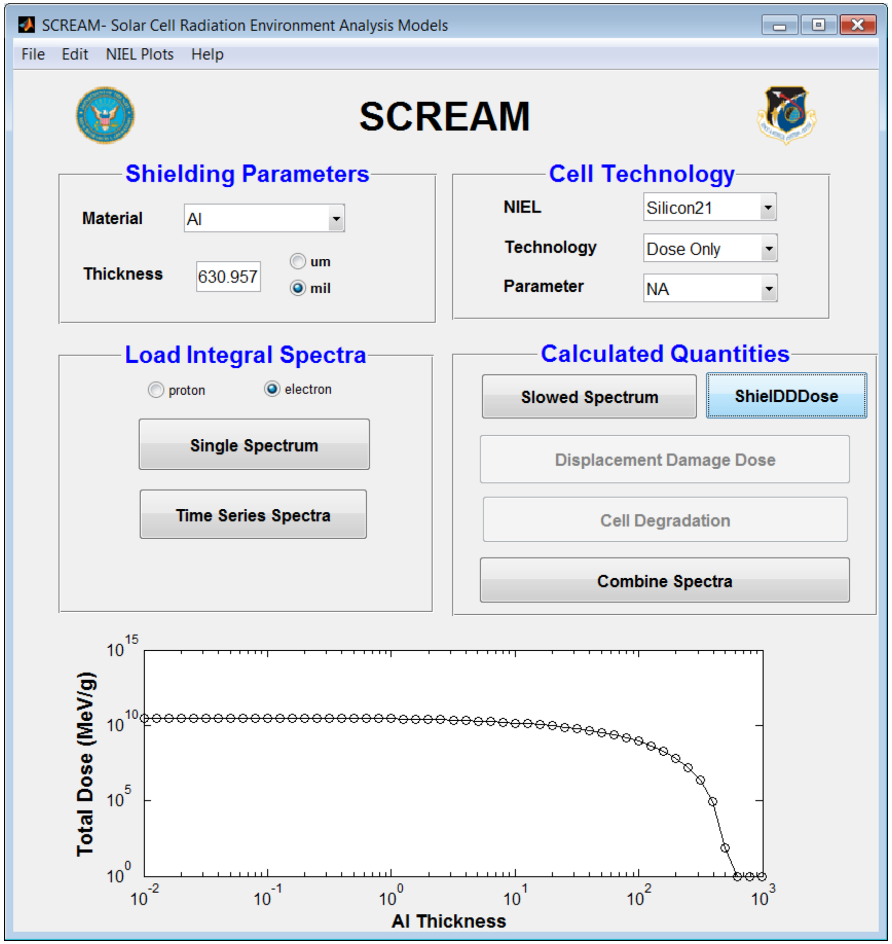
- Excel file driven menus as inputs
  - Input integral radiation spectra
    - Single & multi-spectra, electron and proton
  - Shielding material
  - Nonionizing energy loss (NIEL)
  - Multilayer shielding
  - Parametric degradation coefficients (GaAs, ITJ, UTJ, ATJ, Si-electrons, user)
- Output
  - Slowed-down radiation spectra
  - End-of-life (EOL) predictions
  - DDD only options ("ShielDDDose")
  - Trajectory capability through "Time Series Spectra" input option



SCREAM is available by request in CD format

***Contact: Dr. Scott R. Messenger (NGC)**

SCREAM Success Stories

- TacSat4 (HEO: 700 km x 12,050 km, 63.4º)
  - Used onboard dosimetry (CEASE-II) and solar cell experiment to explain anomalously large solar array degradation rates
  - SCREAM used CEASE-II data to corroborate solar cell experiment (full IV) data and re-project mission lifetime
- GPS-IIR SV41 (MEO: 20,200 km, 55º)
  - GPS has been plagued with anomalous solar array degradation since onset (many mitigation paths successful, but anomaly continues)
  - SCREAM used LANL BDD Detector data to help understand damage mechanisms and eliminate displacement damage as the anomaly
- Low-Thrust Trajectory Orbit to GEO (LT2GEO)
  - Low-thrust trajectories are extreme mass & cost cutting measures
    - Spacecraft subjected to extreme proton belts
  - SCREAM can simply analyze accumulated DDD to optimize LT trajectory

TacSat4 (HEO: 700 km x 12,050 km, 63.4º)

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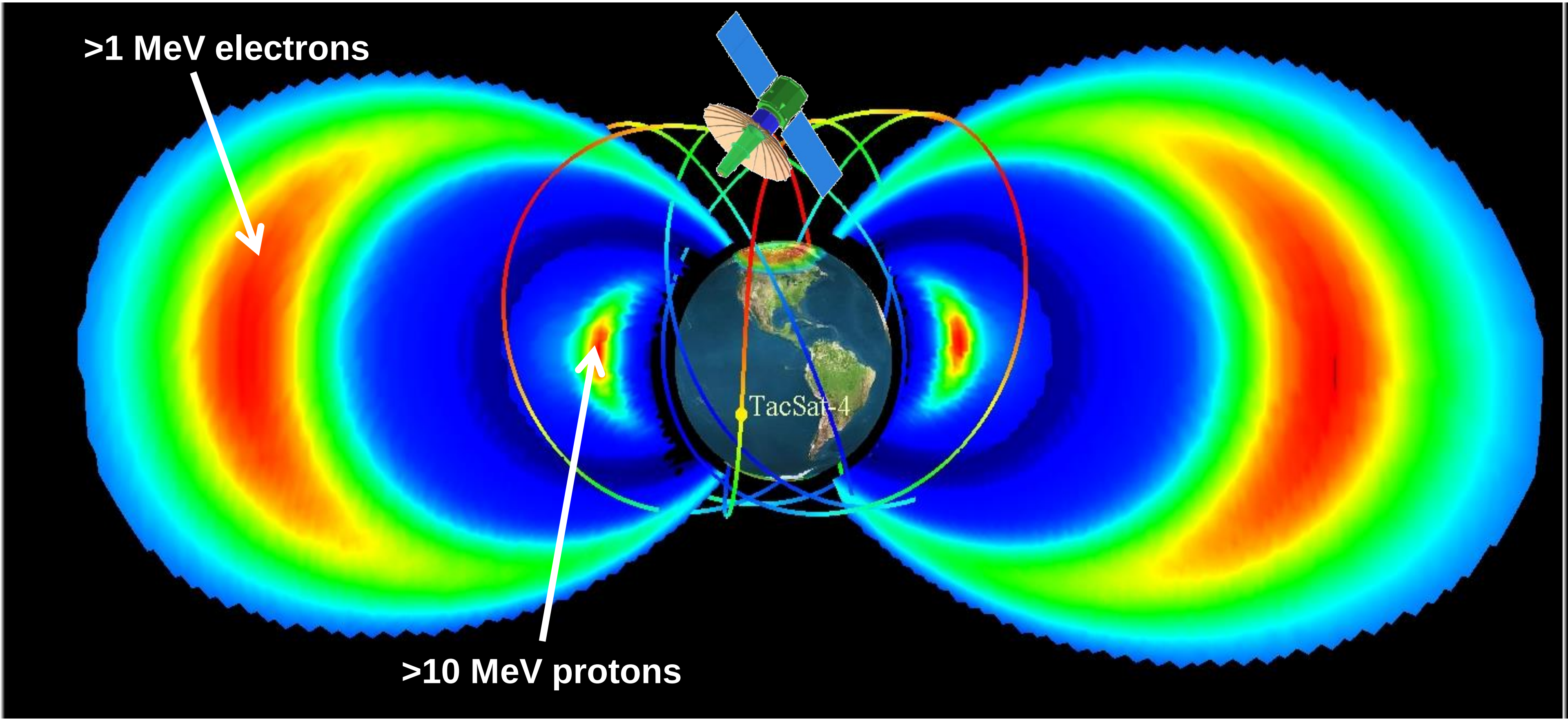
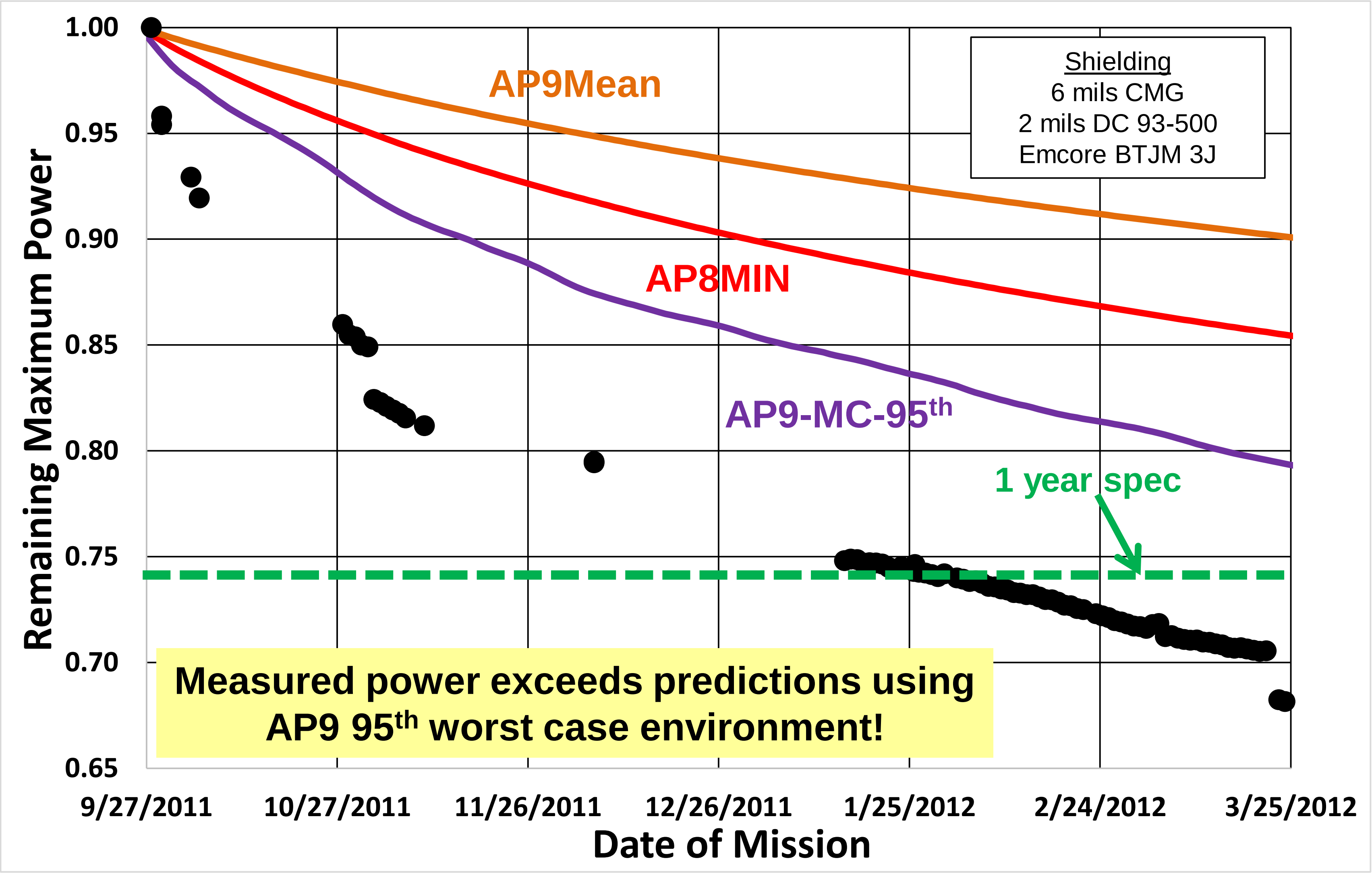
- NRL satellite launched 27 Sept. 2011 (Kodiak, AK)



*** Graphic created using AFGEOSPACE (V2.5)**

TacSat4 (HEO: 700 km x 12,050 km, 63.4º) – Trapped Protons Dominant

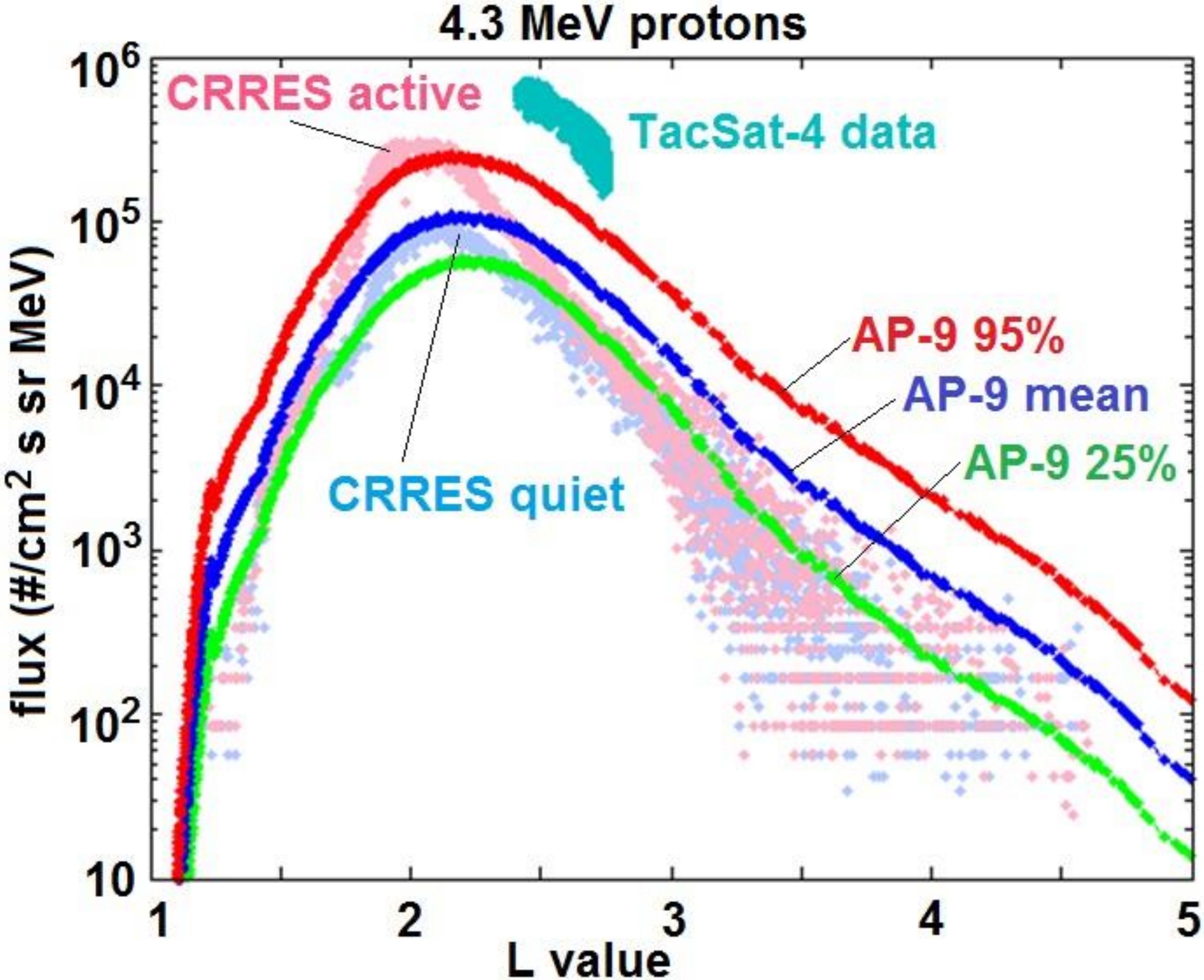
- **Maximum Power Degradation on Emcore ATJ Solar Cell**



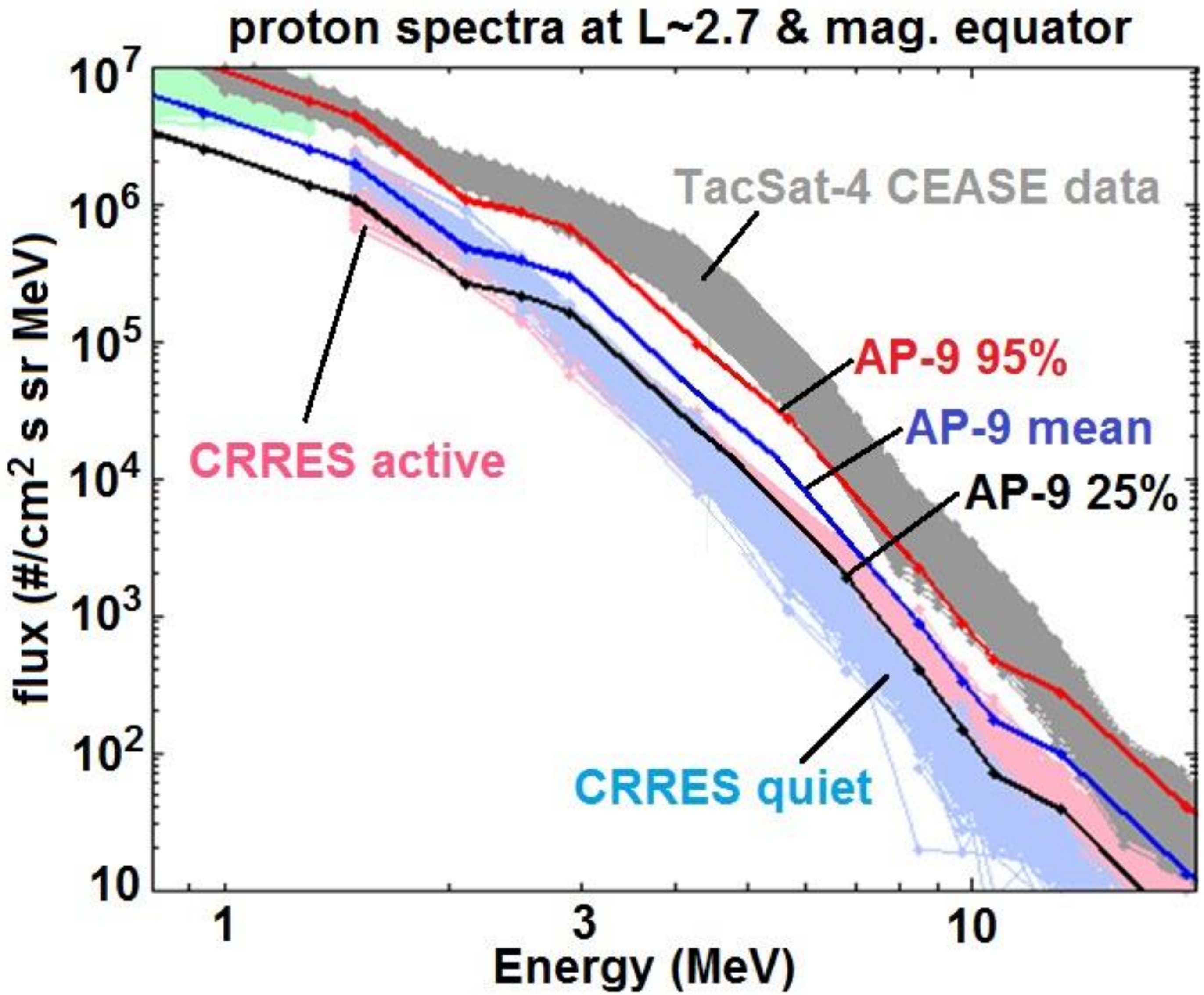
TacSat4 (HEO: 700 km x 12,050 km, 63.4º) – Trapped Protons Dominant

- **Two additional payloads on-board**
  - AFRL: CEASE-II dosimeter package
    - Several dosimeters (particle fluence, TID, SEE, SC)
    - 0.7-80 MeV protons & 0.05-3 MeV electrons
  - NRL: Two solar cell experiments yielding full IV curves
    - SCE#1: SolAero BTJM (3J w/ 6 mil CMG coverglass)

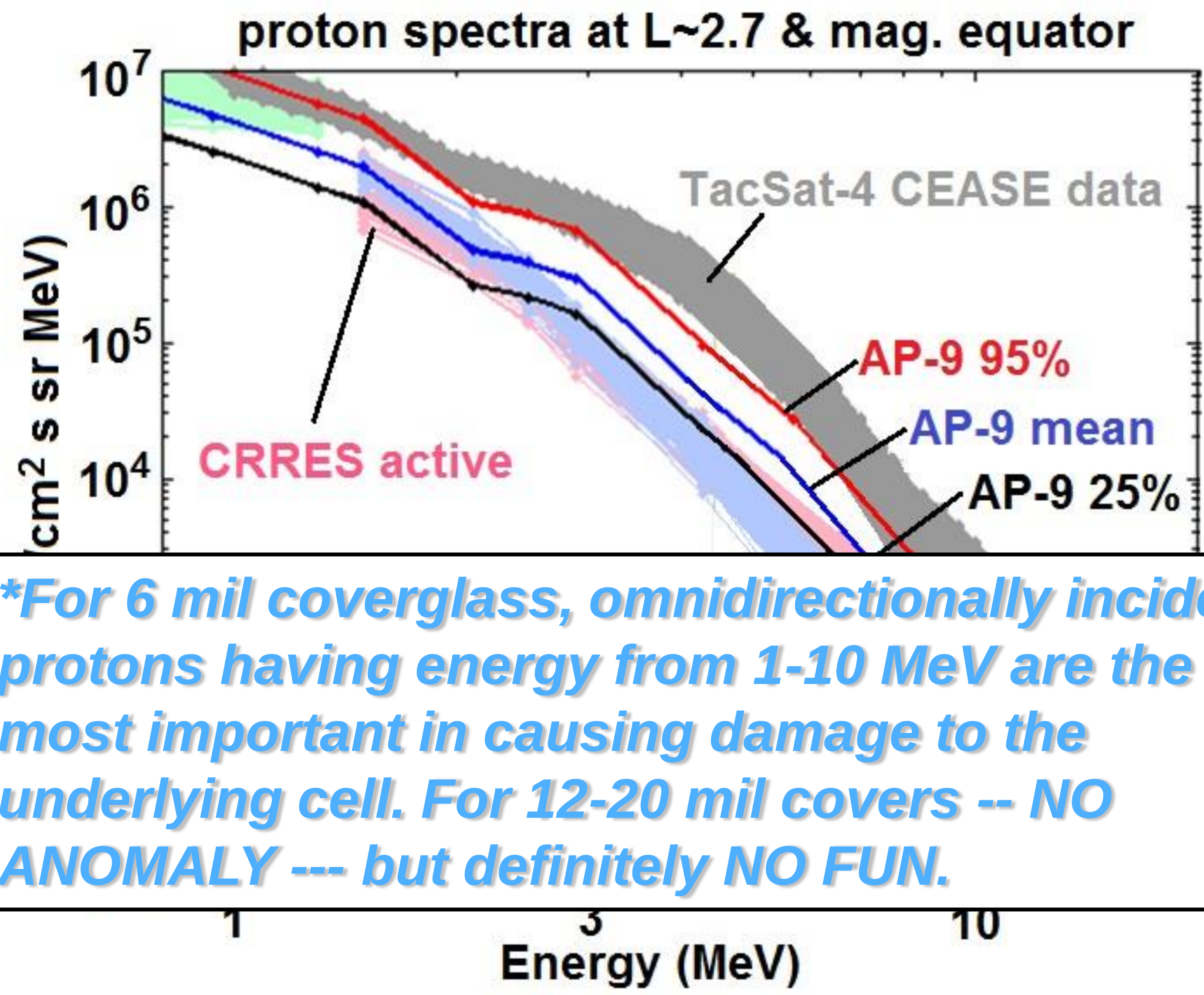
CEASE Proton Energy Comparisons



CEASE Proton Energy Comparisons



CEASE Proton Energy Comparisons



***For 6 mil coverglass, omnidirectionally incident protons having energy from 1-10 MeV are the most important in causing damage to the underlying cell. For 12-20 mil covers -- NO ANOMALY --- but definitely NO FUN.**

TacSat4 (HEO: 700 km x 12,050 km, 63.4º) – Trapped Protons Dominant

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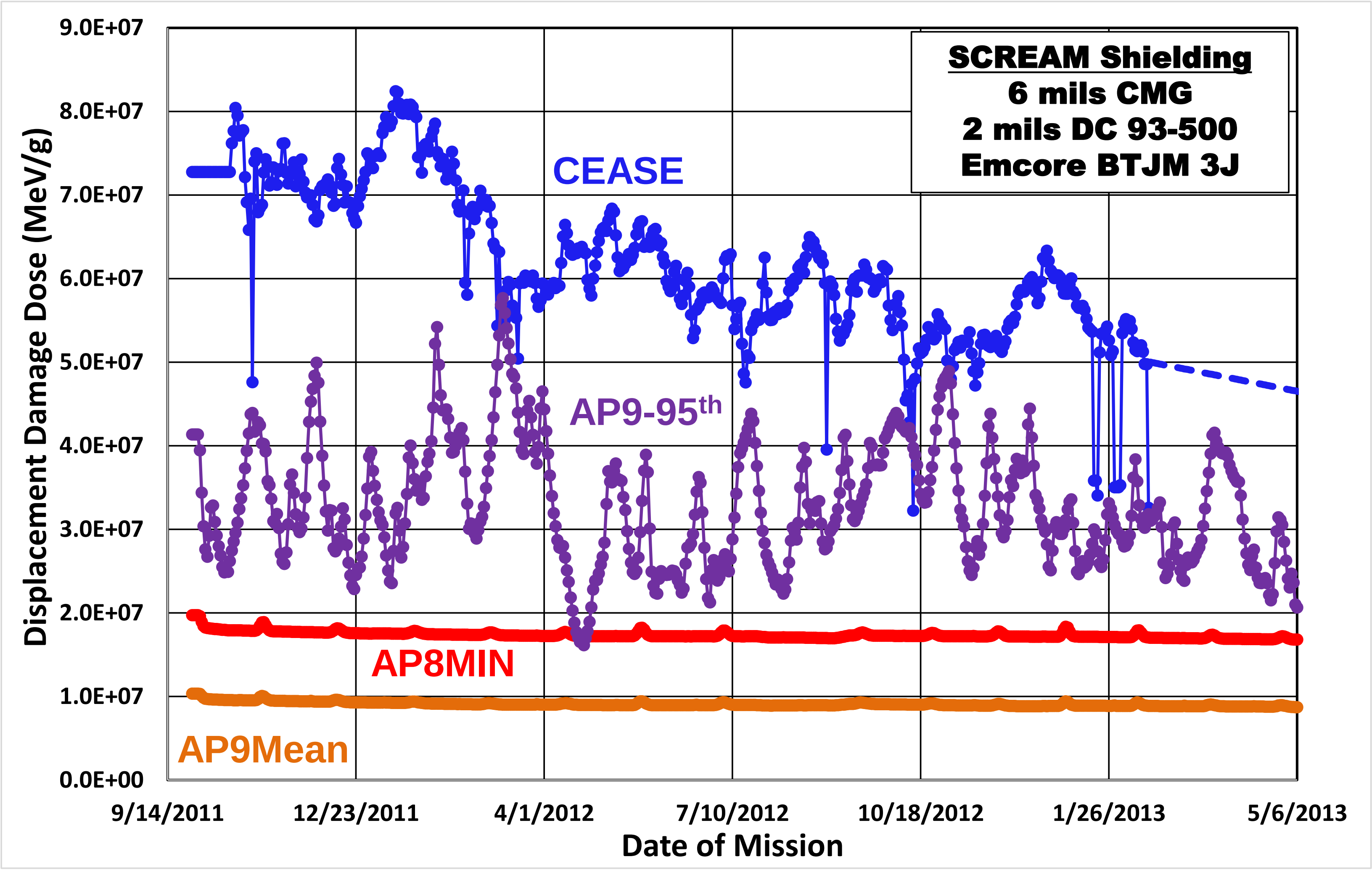
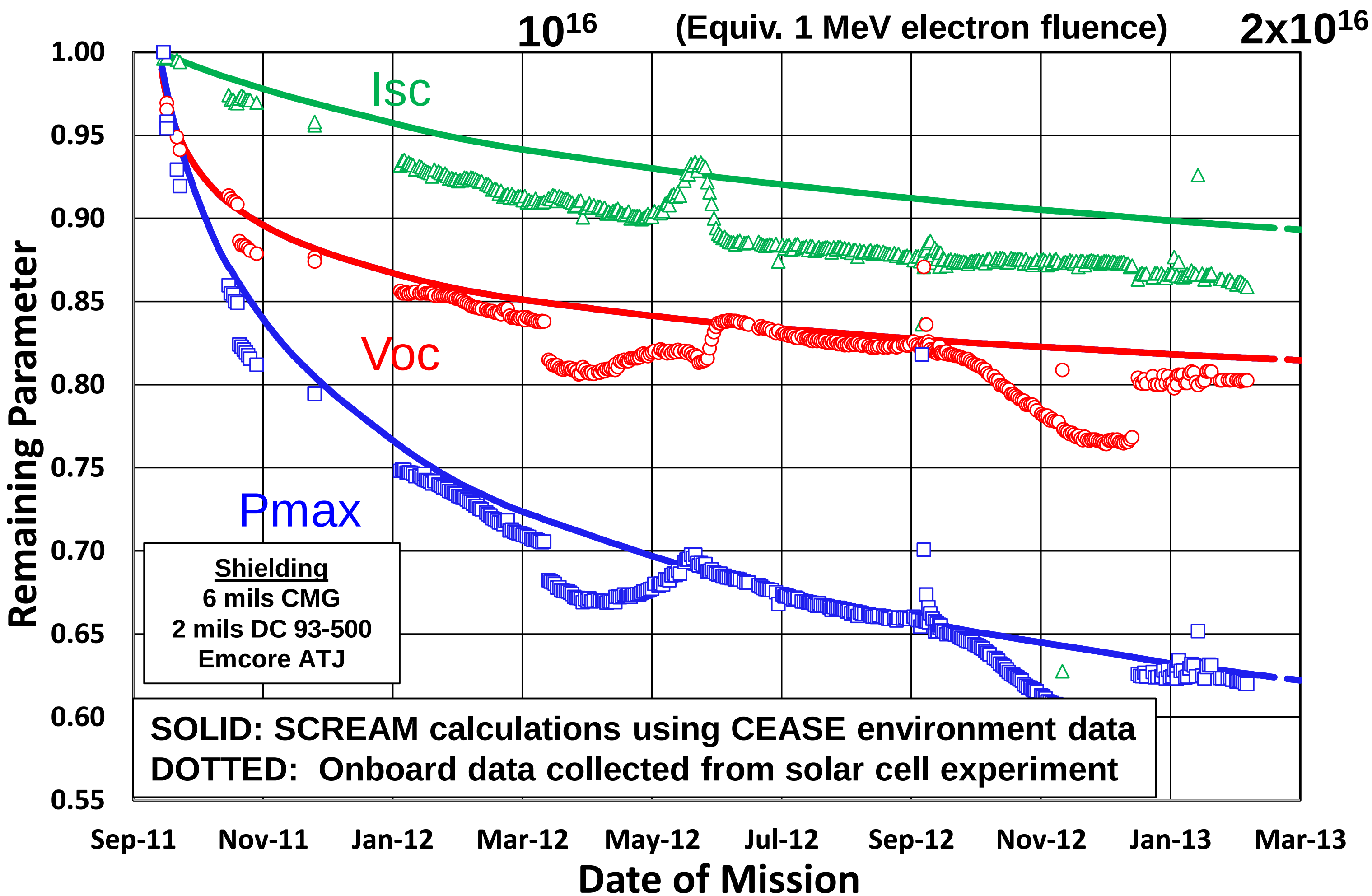
- **SCREAM: Environment data through 6 mil CMG & 2 mil adhesive**



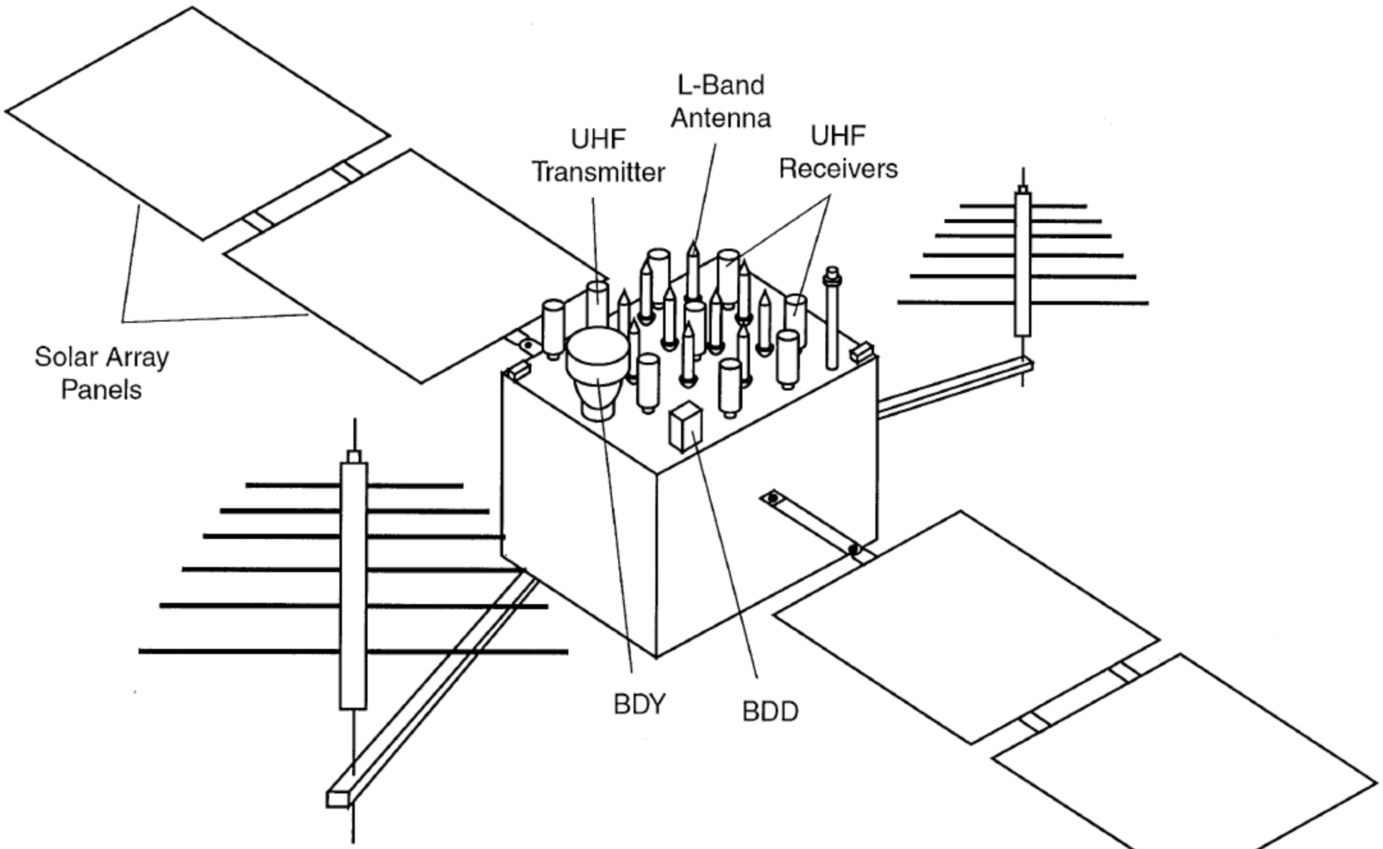
TacSat4 (HEO: 700 km x 12,050 km, 63.4º) – Trapped Protons Dominant

- **SCREAM: DDD results applied to SolAero ATJ solar cell technology**



GPS-IIR (MEO: 20,200 km, 55^o)

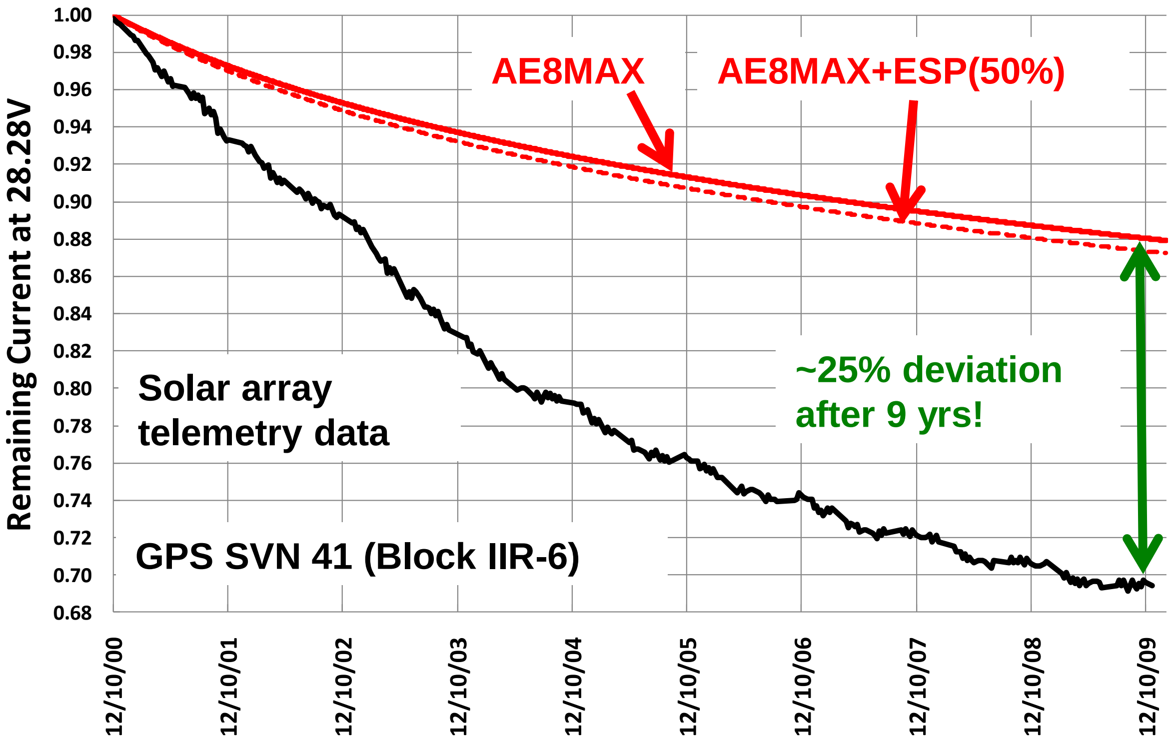
- **SVN41 Launched 10 Nov 2000**



***NIM A 482, 653 (2002)**

GPS-IIR (MEO: 20,200 km, 55º) – Trapped Electrons Dominant

- **GPS spacecraft have shown anomalous silicon solar array degradation throughout [>30] year existence (Marvin, 1988)**



- **Many possibilities posed (coatings, coverglass, contamination, ESD, radiation environment related) but none confirmed**
- **GPS III plans on using oversized arrays to maintain necessary EOL levels**

GPS-IIR (MEO: 20,200 km, 55^o) – Trapped Electrons Dominant

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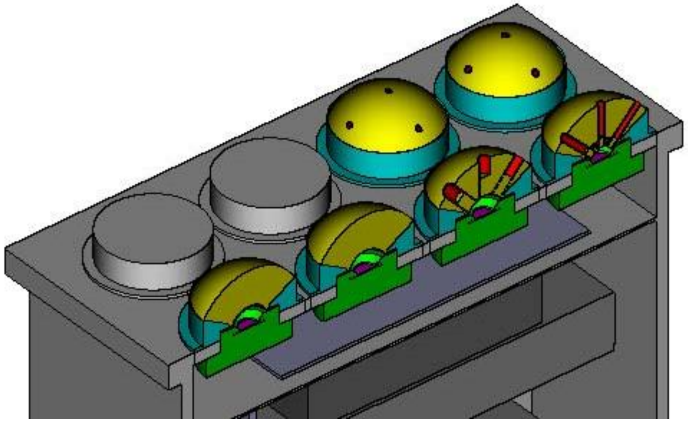
- **LANL Burst Dosimeter Detector (BDD) onboard SVN41**
  - Ion-implanted Si detectors behind varying shielding levels
  - Gives electron fluences for E>0.04 to >10 MeV
  - Gives proton fluences for E>0.05 to >6 MeV
  - Daily fluence and energy spectra supplied by LANL



*LA-UR-10-04234, LA-UR-08-2816

GPS-IIR (MEO: 20,200 km, 55º) – Trapped Electrons Dominant

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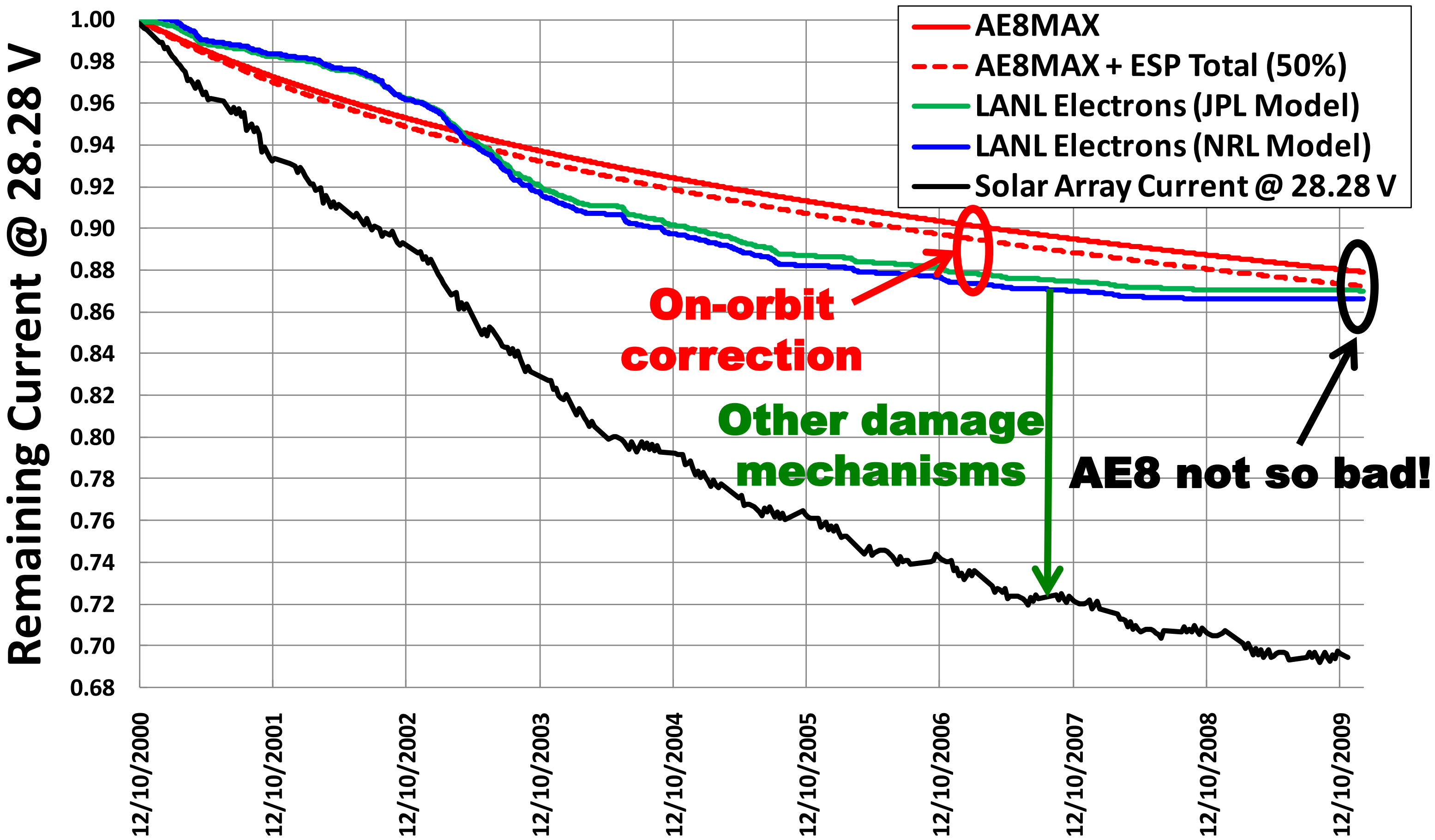
- SCREAM used BDD data to determine expected Si solar cell degradation behind 12 mil CMX coverglass



- Displacement damage eliminated from secondary damage mechanism
- Other damage mechanism causing anomaly

GPS-IIR (MEO: 20,200km, 55°) – Trapped Electrons Dominant

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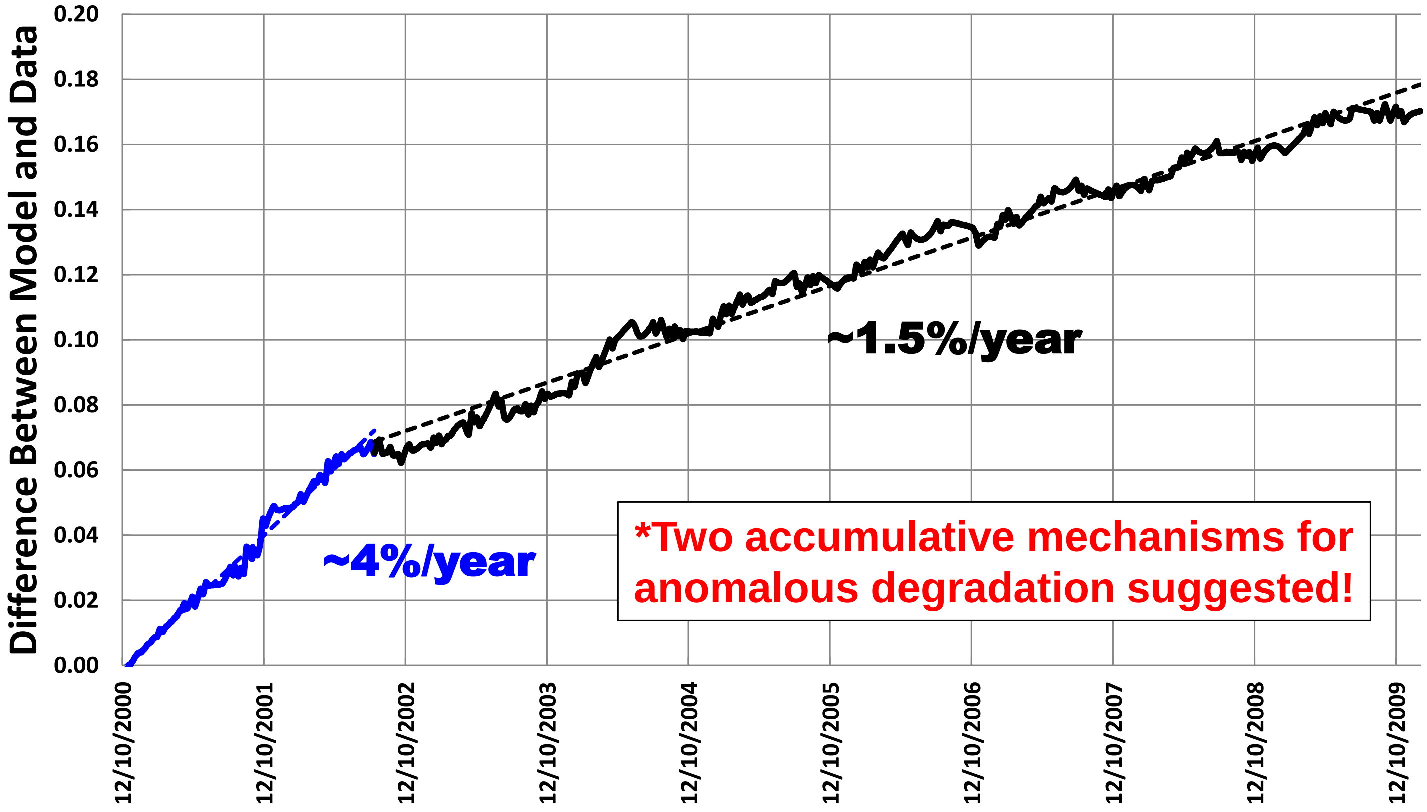
- **Analytical determination between expected (SCREAM) and measured showed interesting trends (IEEE Trans. Nucl. Sci. 58, p.3188 (2011))**
  - **Fast rate (4%/yr): contamination, UV, photo-fixing --- AR coating/conductive oxide?**
  - **Slow rate (1.5%/yr): trapped electrons --- coverglass damage, ESD (Ferguson et al. 2015)?**



Low-Thrust Trajectory to GEO (LT2GEO)

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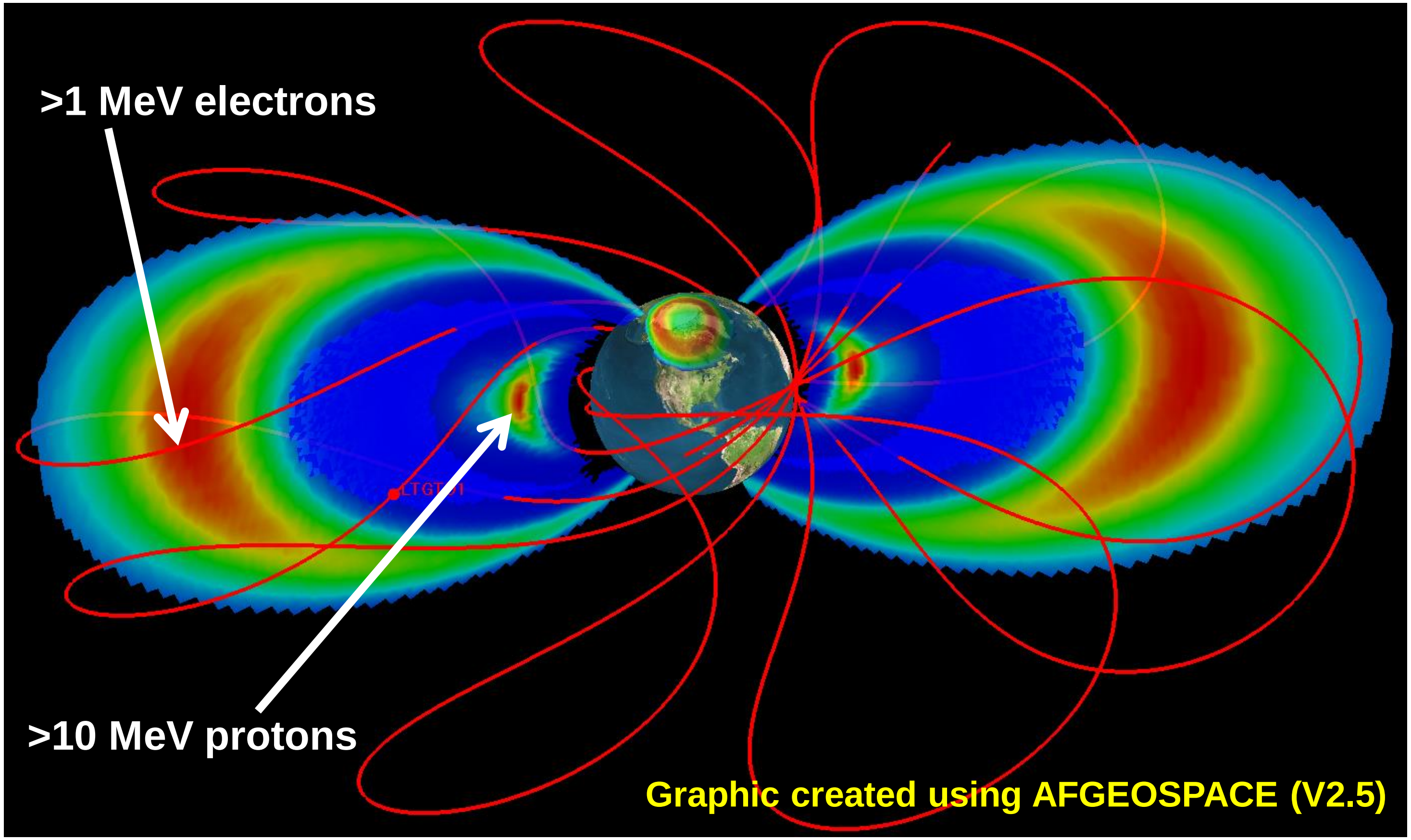

- Reduced Launch Costs
- Increased Payload

Trade Off

- Delayed GEO operations
- More Radiation Exposure

Low-Thrust Trajectory to GEO (LT2GEO)

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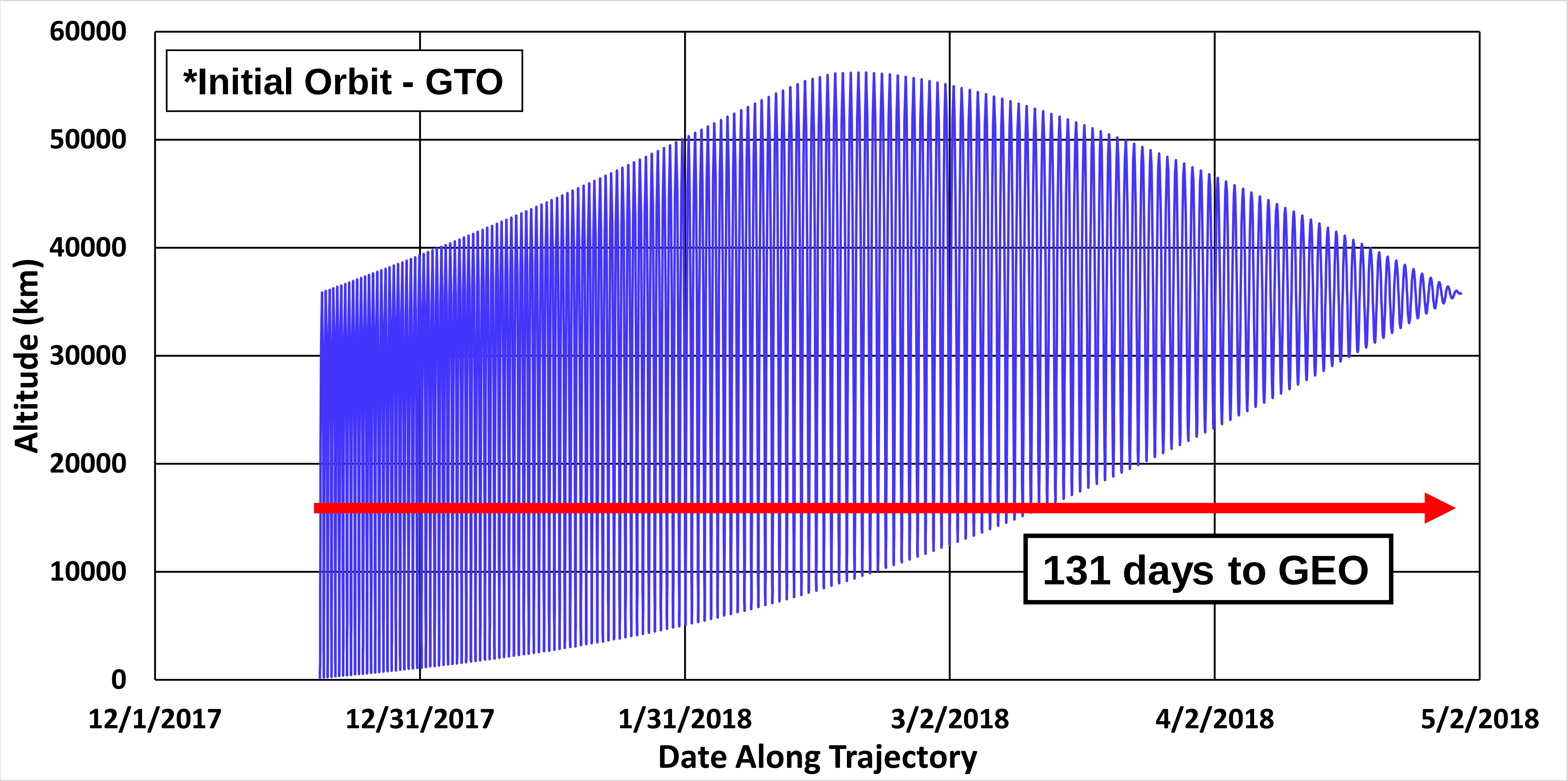
“Minimum-Time” Low-Thrust Trajectory



Low-Thrust Trajectory to GEO (LT2GEO)

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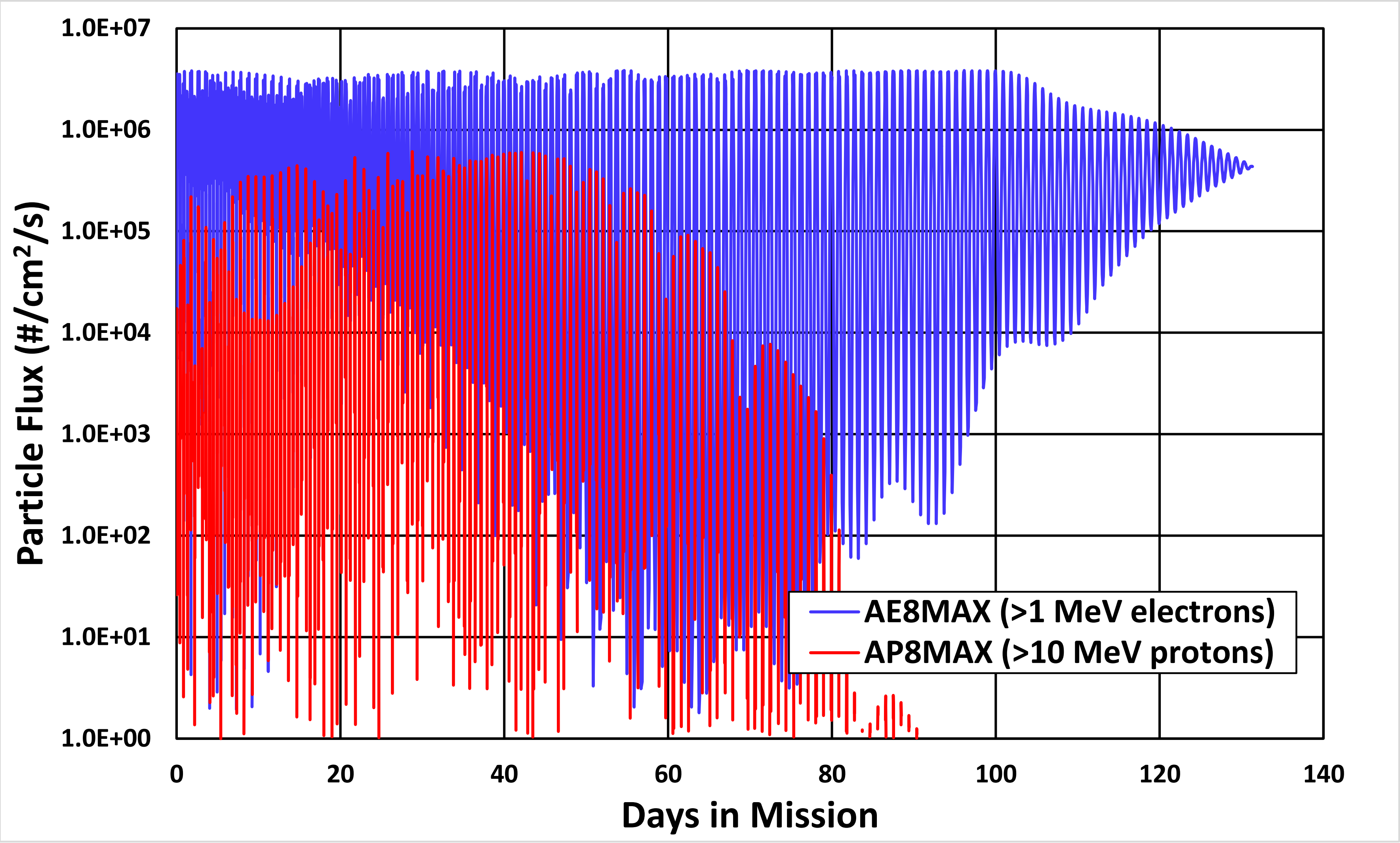
Electron & Proton Fluxes Along Trajectory (AE8MAX/AP8MAX)



Low-Thrust Trajectory to GEO (LT2GEO) – Trapped Protons Dominant

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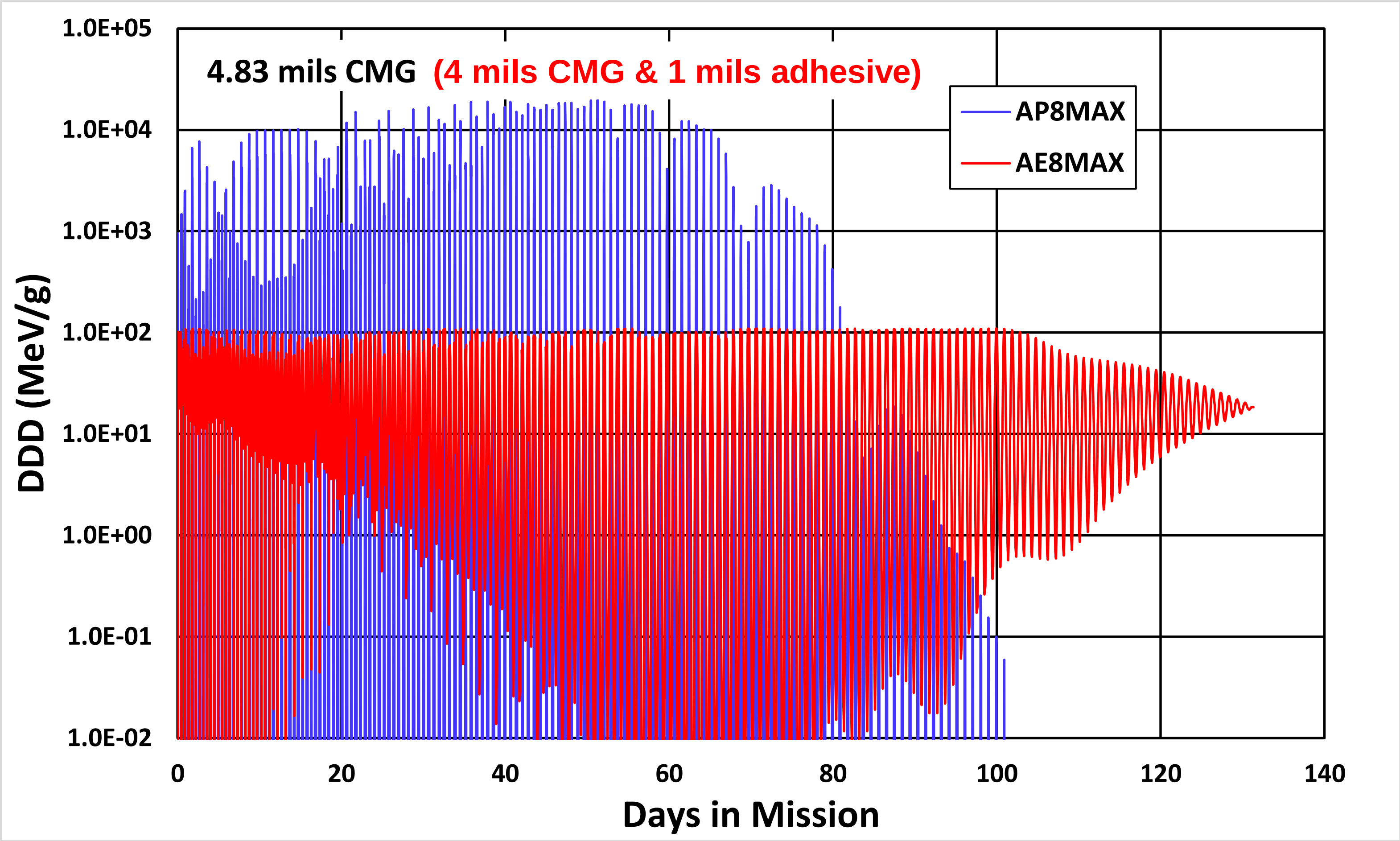
DDD Along Trajectory (AE8MAX/AP8MAX)



* Trapped protons dominate the DDD for the LT2GEO transfer

Low-Thrust Trajectory to GEO (LT2GEO) – Trapped Protons Dominant

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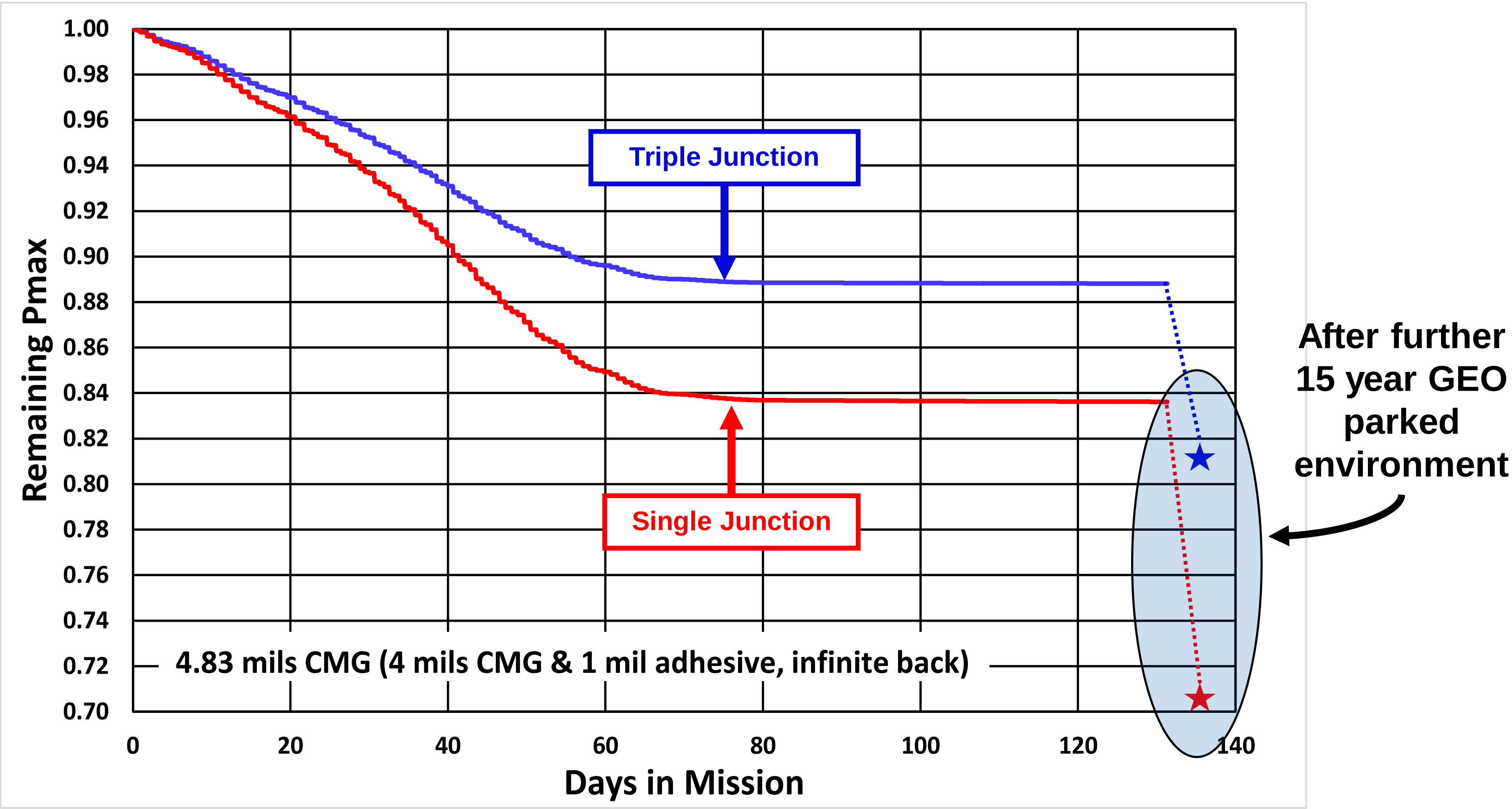
Solar Cell Degradation (AP8MAX/AE8MAX)



***The LT2GEO transfer significantly degrades both 1J and 3J solar cells**

Summary

- SCREAM employs the DDD model for solar cell degradation
  - Slab geometry (2π)
- Bonus Capabilities
  - Multi-layered shielding
  - Time series spectra (on-orbit data, trade studies)
  - ShielDDDose (Depth-DDD curves)
- Applications
  - Easy interpretation of dosimeter data onboard spacecraft for ORS
    - TacSat4 – helped understand extra radiation to project mission lifetime
    - GPS – eliminated DDD effects in solar cell to push efforts elsewhere
    - LT2GEO – aids in better solar array designs in present low-cost needs
  - Not only for solar cells (LEDs, laser diodes, CCDs, etc.)
    - Any ground data for which a parametric vs. DDD curve can be created

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