Using spacecraft anomalies to evaluate space environment models

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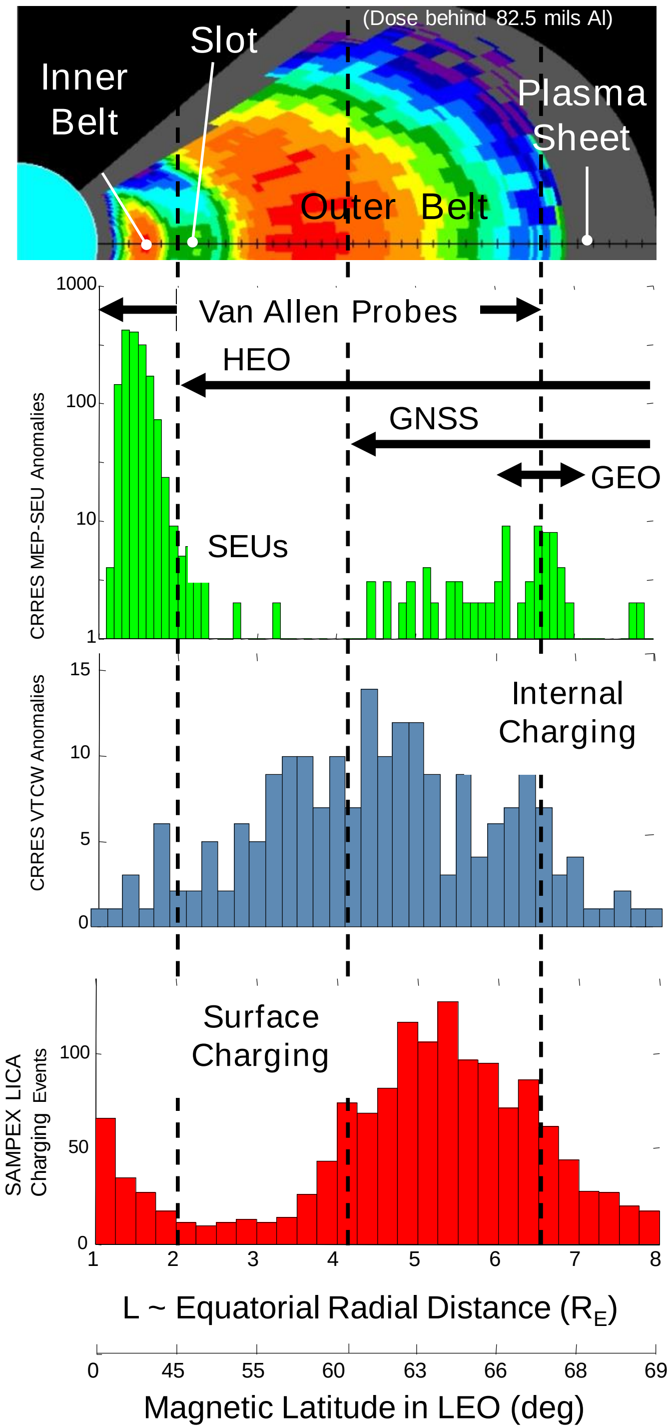
Outline

- Space weather-related satellite anomaly types
- Modeling space weather anomaly risk
- The “green anomalies” metric
- Estimating the impact of model errors on green anomaly rate
- Results for some sample anomalies

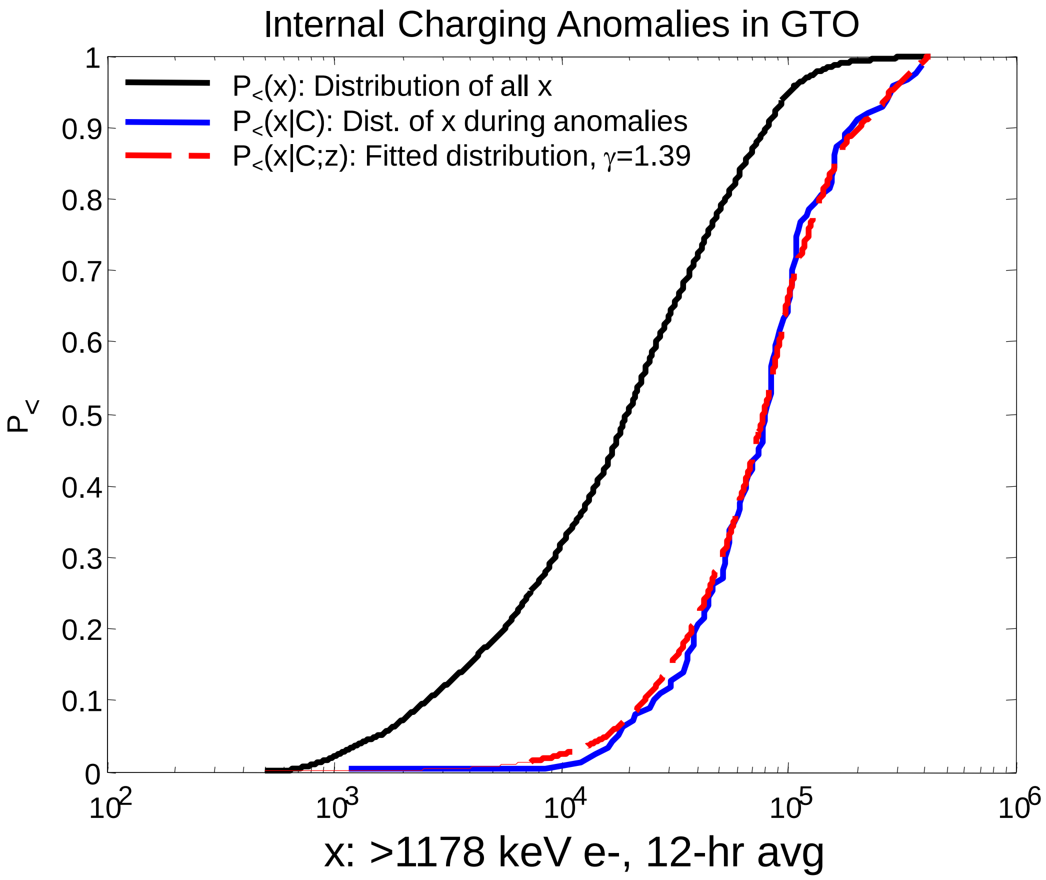
Space weather-related satellite anomaly types



- **Event Total Dose (ETD)** occurs primarily in orbits that rarely see trapped protons in the 1-20 MeV range (e.g., GEO, GPS) because these are the orbits for which solar particle events and transient belts make up a majority of the proton dose (including displacement damage).
- **Single Event Effects (SEE)** tend to occur in the inner (proton) belt and at higher L shells when a solar particle event is in progress.
- **Internal charging (IC)** and resulting electrostatic discharges (ESD) occur over a broad range of L values corresponding to the outer belt, where penetrating electron fluxes are high.
- **Surface charging (SC)** and resulting ESD occur when the spacecraft or surface potential is elevated: at 2000-0800 local time in the plasma sheet and in regions of intense field-aligned currents. It has also been observed, but not explained, at very low L.

Modeling space weather anomaly risk - I

- Multiple anomaly investigations have established that the anomaly rate can be described with a power-law:
  - *$r(x) \sim x^{\gamma}$*
  - *x = particle flux, dose rate, current, etc., suitably time averaged.*
  - *γ = empirically determined parameter*
- A fitting procedure allows us to select an appropriate *x* and estimate γ when we have reasonably long-term measurements and a statistical sample (>~5) of similar anomalies
- See, e.g., *O'Brien* 2009, *Space Weather*



Modeling space weather anomaly risk - II

Hazard	Example Hazard Indicator	Typical Time Averaging (hours)	Typical exponent (γ)
Surface Charging	>10 keV electron flux Electron temperature Field-aligned current intensity	NONE	1-4
Internal Charging	>1 MeV electron flux Current beneath 100 mils Al shielding Dose rate (outer zone) below 100 mils Al	1-72	0.7-2
Event Total Dose	>5 MeV proton flux Dose rate below 5 mils Al	12-72	1
Single Event Effects	>30 MeV proton flux >30 MeV cm^2/mg flux	NONE	0.5-2

x = trailing time average of the hazard indicator

Green anomalies

- Operators typically interact with stoplight charts that use a red-yellow-green color scheme
- “Green anomalies” refers to anomalies that occur when the environment is “green”
- We define “green” conditions as having *x* below the 75th percentile
- Given *p(x)*, the statistical distribution of *x,* and the exponent γ, we can estimate what fraction of anomalies occur when x is in the lower 75th percentile, i.e., when the environment is “green”

Computing the green anomaly rate

- The fraction of anomalies under green conditions is given by:

$$G = \frac{\int_0^{x_{75}} x^\gamma \, p(x) dx}{\int_0^\infty x^\gamma p(x) dx}$$

- Where x_{75} is the 75th percentile of x for surface and internal charging
- For single event effects and event total dose, x_{75} is the 75th percentile of x during solar particle event times only

- Larger γ leads to smaller *G*
- A fatter tail in *p(x)* leads to smaller *G*

Estimating the impact of model errors on green anomaly rate

- Now we add multiplicative random noise to *x*

$$y = x \exp[\sigma\eta] = xF^{\eta},\ \eta \sim N(0,1)$$

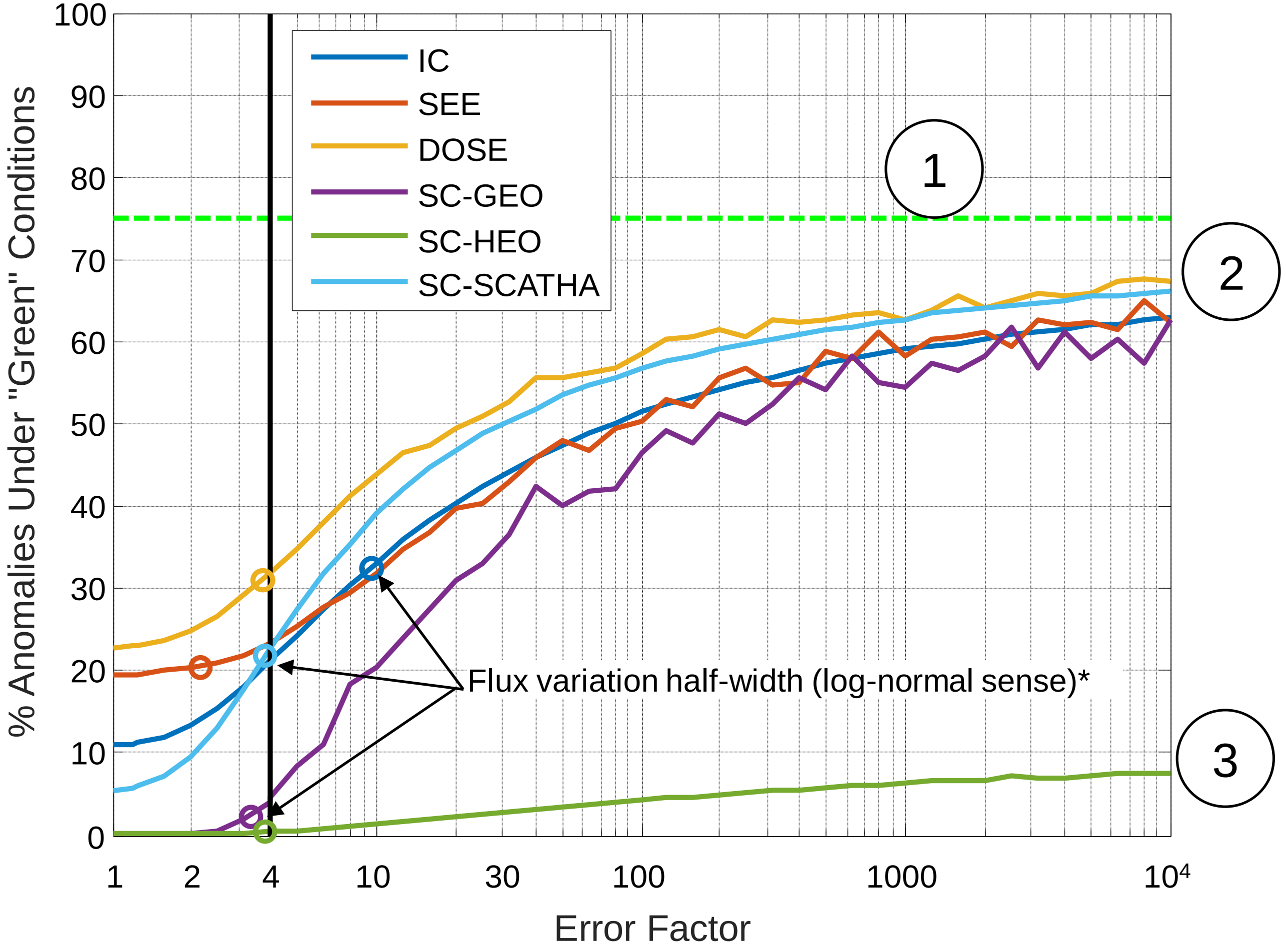
- The random noise η is drawn from a Gaussian with zero mean and unit variance
- *F* is the error factor, and can be thought of as the half-width at half-max of the error distribution
- Interpretation of *F*: ~95% of the time, truth will fall within F^2 of the observation/model
- Example: if *F*=4 (i.e., 4x error), then 95% of the time, the truth falls within a factor of *16* of the observation/model
- The green anomaly fraction for noisy data is given by:

$$G = \frac{\int_0^{y_{75}} x^{\gamma}\, p(y) dy}{\int_0^{\infty} x^{\gamma} p(y) dy} = \frac{\int_0^{y_{75}} \int_{-\infty}^{+\infty} y^{\gamma}\, F^{-\eta\gamma} p(y) N(\eta) d\eta dy}{\int_0^{\infty} \int_{-\infty}^{+\infty} y^{\gamma} F^{-\eta\gamma}\, p(y) N(\eta) d\eta dy} \approx \frac{\sum_{y<y_{75}} x_i^{\gamma}}{\sum x_i^{\gamma}}$$

- Important: compute 75th percentile y_{75} from noise-added data

Results - I

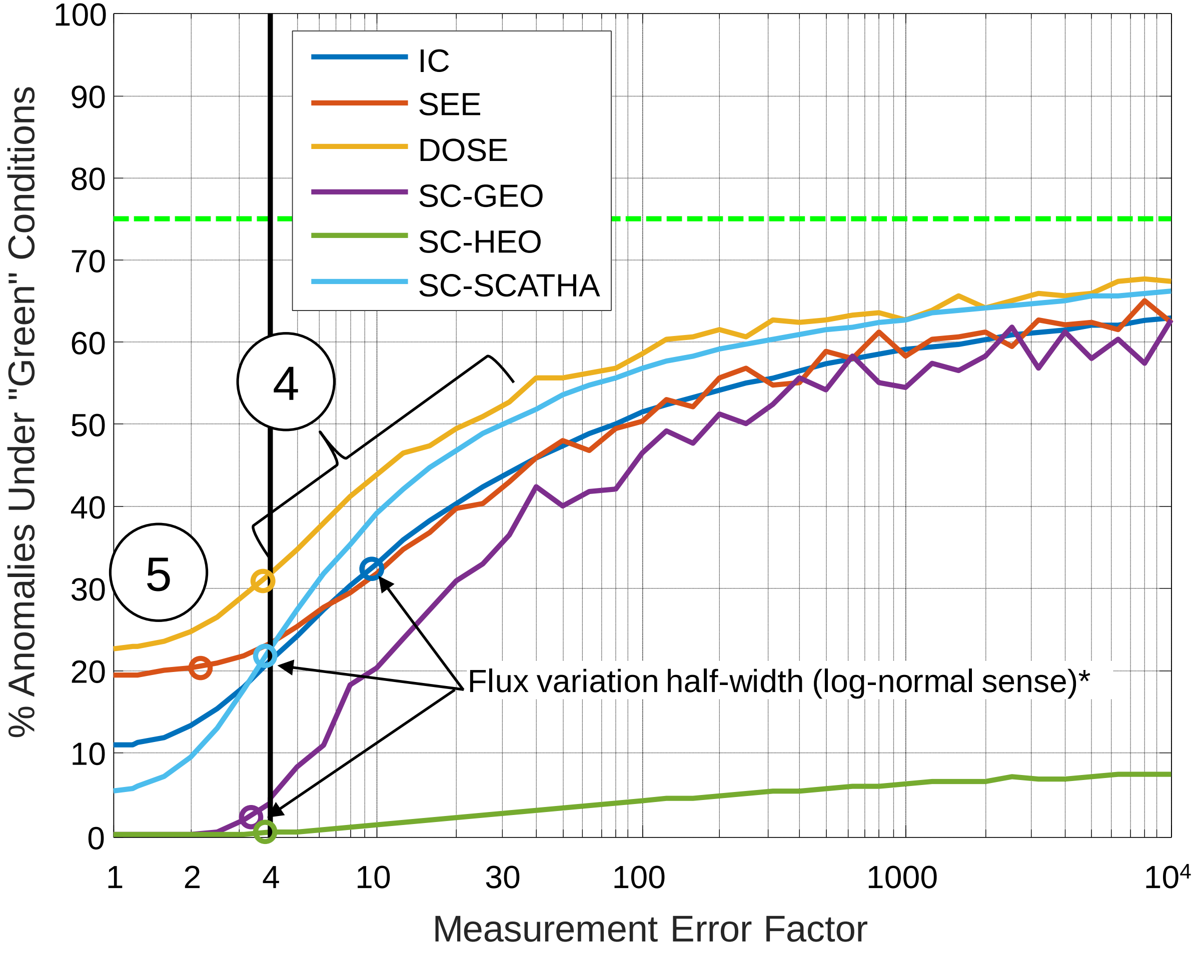
1. For infinite error, we expect the IC and SC curves to saturate at 75%, while the SEE and DOSE curves should saturate well above that
2. We see that even large errors, 10^4, do not erase all utility
3. The HEO case shows that there is no truly universal rule-of-thumb for how much error is tolerable. *It depends*



*Flux variation half-width (log-normal sense) = "1-sigma" value of multiplicative flux variation. E.g., for a value of 10, ~2/3 of the flux values fall within a factor of 10 of the median flux.

Results - II

4. The greatest return on improvement appears to be obtained when cutting the error down from ~30x to ~4x
5. There is often no improvement reducing error less than 2x



*Flux variation half-width (log-normal sense) = “1-sigma” value of multiplicative flux variation. E.g., for a value of 10, ~2/3 of the flux values fall within a factor of 10 of the median flux.

Conclusions

- Even very large multiplicative errors do not erase all of a model’s value for anomaly attribution, at least for the “green anomalies” metrics
- The greatest value for improvement occurs when decreasing the error from ~30x to ~4x

Caveats

- *There are going to be exceptions (e.g., HEO surface charging)*
- *Confounding parameters (e.g., temperature, materials, attitude) also affect how model error impacts anomaly analysis*