GOES-R Satellites Radiation Belt Electron Calibration

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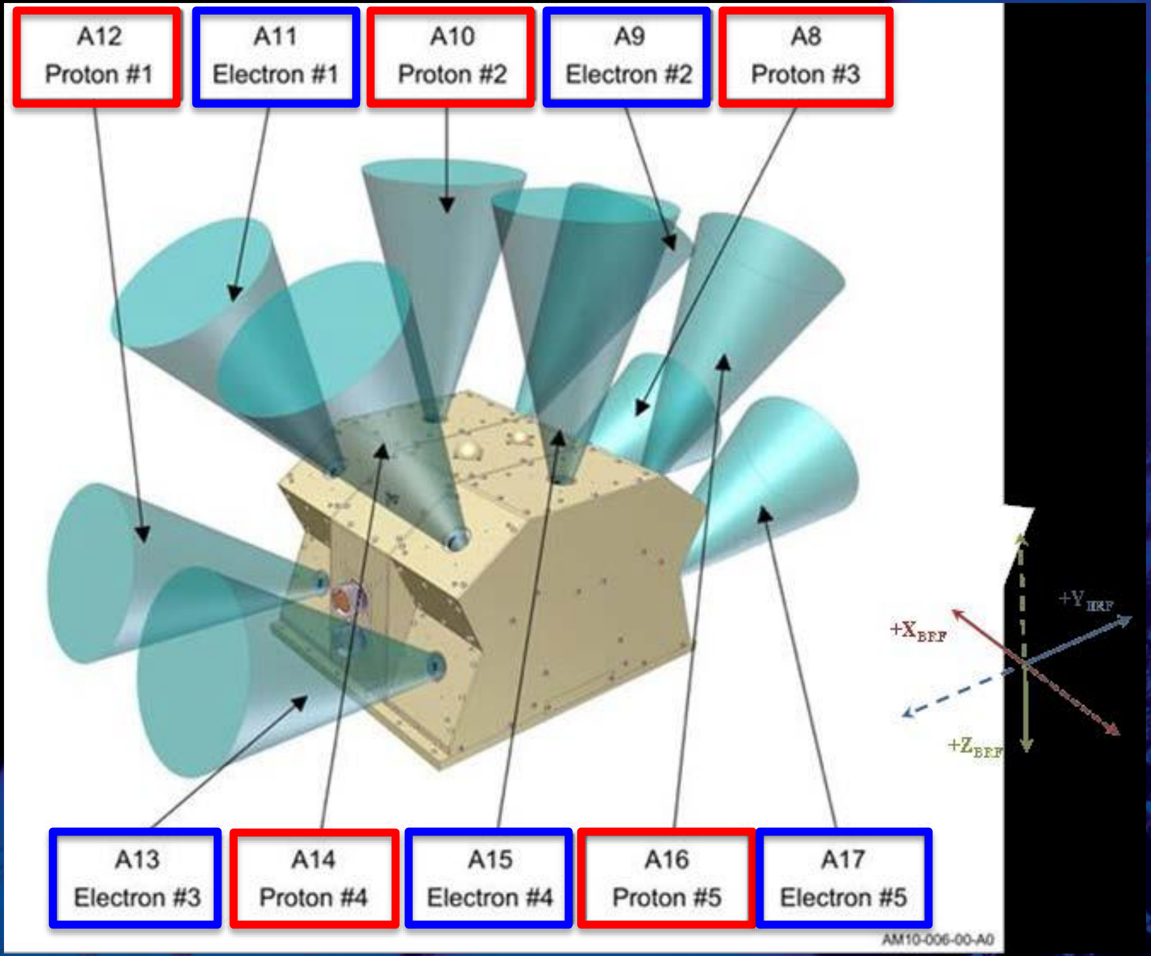
GOES-R Program

- **Satellites launched to date:**
  - **GOES-16 (R): launched 19 November 2016**
    - **GOES-East (75.2ºW) since 18 December 2017**
  - **GOES-17 (S): launched 01 March 2018**
    - **In storage (104.7ºW) since 14 March 2023**
    - **Was GOES-West (137.2ºW) from 12 February 2019 to 3 January 2023**
  - **GOES-18 (T): launched 01 March 2022**
    - **GOES-West (136.8ºW) since 3 January 2023**
- **Each GOES-R-series observatory carries a Space Environment In-Situ Suite (SEISS)**
  - **Radiation belt electrons are measured by the Magnetospheric Particle Sensor – High Energy (MPS-HI)**

Magnetospheric Particle Sensor – High Energy (MPS-HI)

MRD 3.3.6.1.3 Magnetospheric Electrons and Protons: Medium and High Energy



Credit: SEISS-TR-MH074-2 Rev C, Figure 3-1

- Primary purpose: measure radiation belt particle fluxes in the energy range responsible for internal charging
- 5 electron telescopes and 5 proton telescopes
  - 30 deg full-width conical FOVs, centers separated by 35 deg
- Each electron telescope:
  - 10 differential channels, 50 keV – 4 MeV
  - 2 integral channels, >2 MeV and >4 MeV (latter not part of L1b)
- Each proton telescope:
  - 11 differential channels
  - 7 channels, 80 keV – 1 MeV (trapped)
  - 4 channels, 1-12 MeV (solar protons)
- Two dosimeters (250 and 100 mil Al)
  - Distinguish particles depositing < 1 MeV and >1 MeV

Steps of Radiation Belt Electron Calibration

- **Initial Data Calibration**
  - **Dead time correction**
    - Based on Singles channels
    - Product of analog and digital electronics corrections
    - Dead time parameter from instrument calibration, $\tau_a \sim 10^{-7} s$, $\tau_d = 0s$
  - **Bowtie Analysis**
  - **Background removal for channels E9-E11**
- **MPS-HI Telescope Cross-Comparison**
  - **Statistical comparison between telescopes observing the same pitch angles**
- **Cross-Satellite Comparison of Trapped Particles**
  - **Comparison between GOES-R satellites**

Inverse Model: Bowtie Method

Differential Channels

$$G\delta E = \frac{\int_0^\infty j(E)G(E)dE}{j(E_{eff})}$$

Bowtie analysis, differential: cm^2 sr keV

$$j(E_{eff}) = \frac{R}{G\delta E}$$

L1b processing (diagonalized)

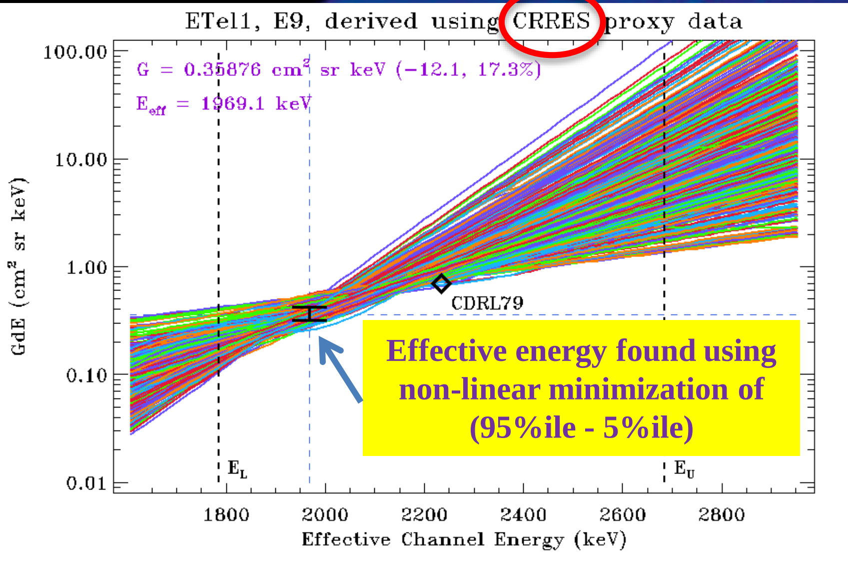
Integral Channel

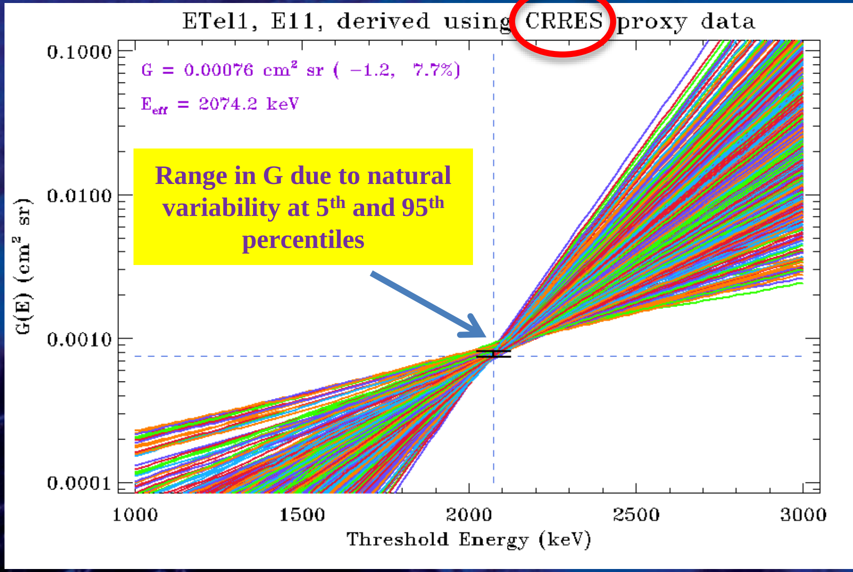
$$G_I(E_L) = \frac{\int_0^\infty j(E)G(E)dE}{\int_{E_L}^\infty j(E)dE}$$

Bowtie analysis, integral: cm^2 sr

$$J(E > E_L) = \frac{R}{G_I}$$

L1b processing





Boudouridis, A., Rodriguez, J. V., Kress, B. T., Dichter, B. K., & Onsager, T. G. (2020). Development of a bowtie inversion technique for real-time processing of the GOES-16/-17 SEISS MPS-HI electron channels. Space Weather, 18, e2019SW002403. https://doi.org/10.1029/2019SW002403

Backgrounds Trending: Methodology

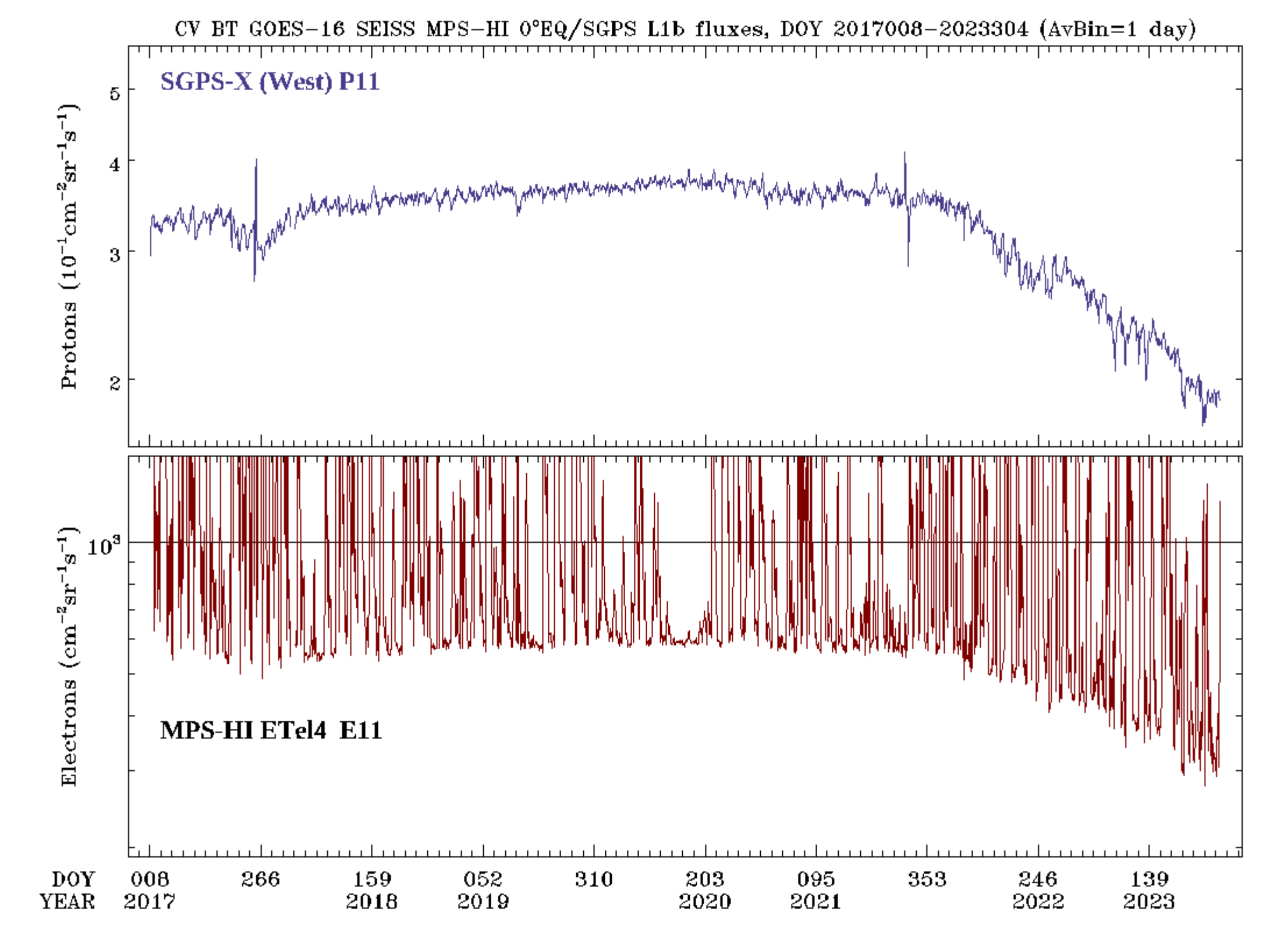
GOES-18 MPS-HI E9-E11 Revised Background Removal

The baseline algorithm is inadequate to correct for the observed slowly-varying background due presumably to Galactic Cosmic Ray (GCR) protons. The background removal coefficients were corrected so as to better account for the GCR proton contamination. This involves a number of observations and assumptions (demonstrated for MPS-HI E11 (> 2 MeV) channel):

- **The first assumption is that the MPS-HI backgrounds are due to the GCRs.**
- **Solar and Galactic Proton Sensor (SGPS) P11 channel is the best single measure of GCR fluxes. Use the −X sensor (looking east)**
- $M_{ELE}(i, E11) = N_{ELE}^{true}(i, E11) - C_{ELE}^{obc}(i, E11) = N_{ELE}^{true}(i, E11) - \gamma(i, E11) F_{SGPS-X_{P11}}$
- **The coefficient γ is calculated separately for each telescope.**
- **Assuming that SGPS-X P11 can track the GCR background well, we can average the SGPS-X P11 fluxes and the background fluxes in E11 due to the GCRs, yielding**

$$\gamma(i, E11) = \overline{C_{ELE}^{obc}(i, E11)} \Big/ \overline{F_{SGPS-X_{P11}}} = G_{P11} \, \overline{C_{ELE}^{obc}(i, E11)} \Big/ \overline{C_{P11}}$$

Backgrounds Trending: Connection to Galactic Cosmic Rays

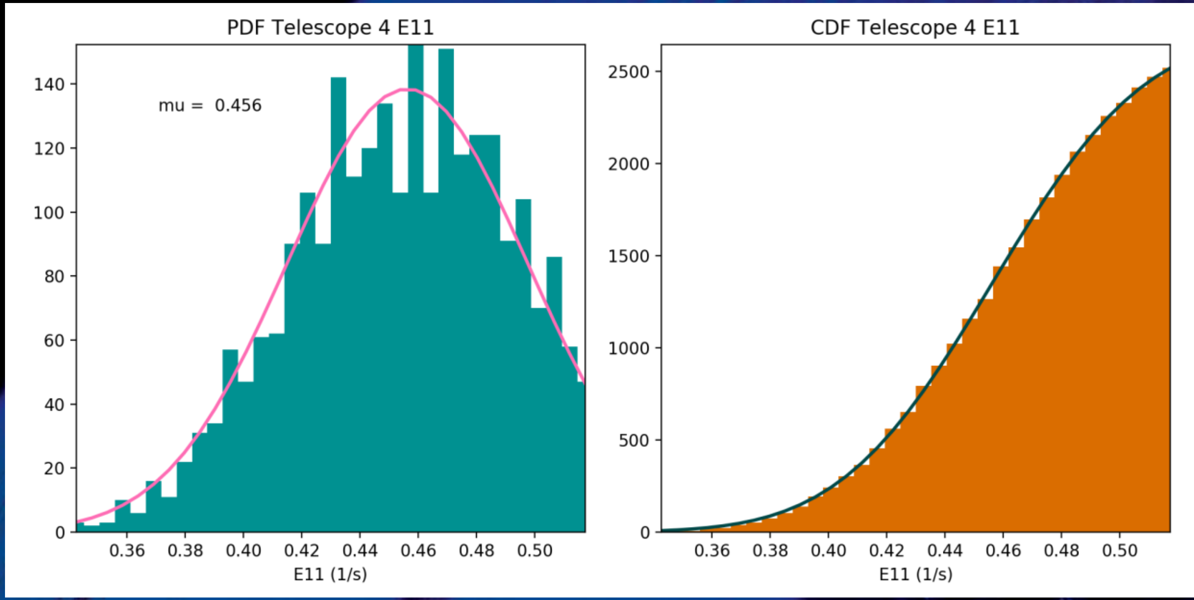


- GOES-16 entire mission plot 01/08/2017-10/31/2023
- Bowtie analysis for MPS-HI E11 is included but the backgrounds are not removed
- SGPS-X P11 flux is decreasing over time
- MPS-HI E11 backgrounds are also decreasing

Backgrounds Trending: Methodology

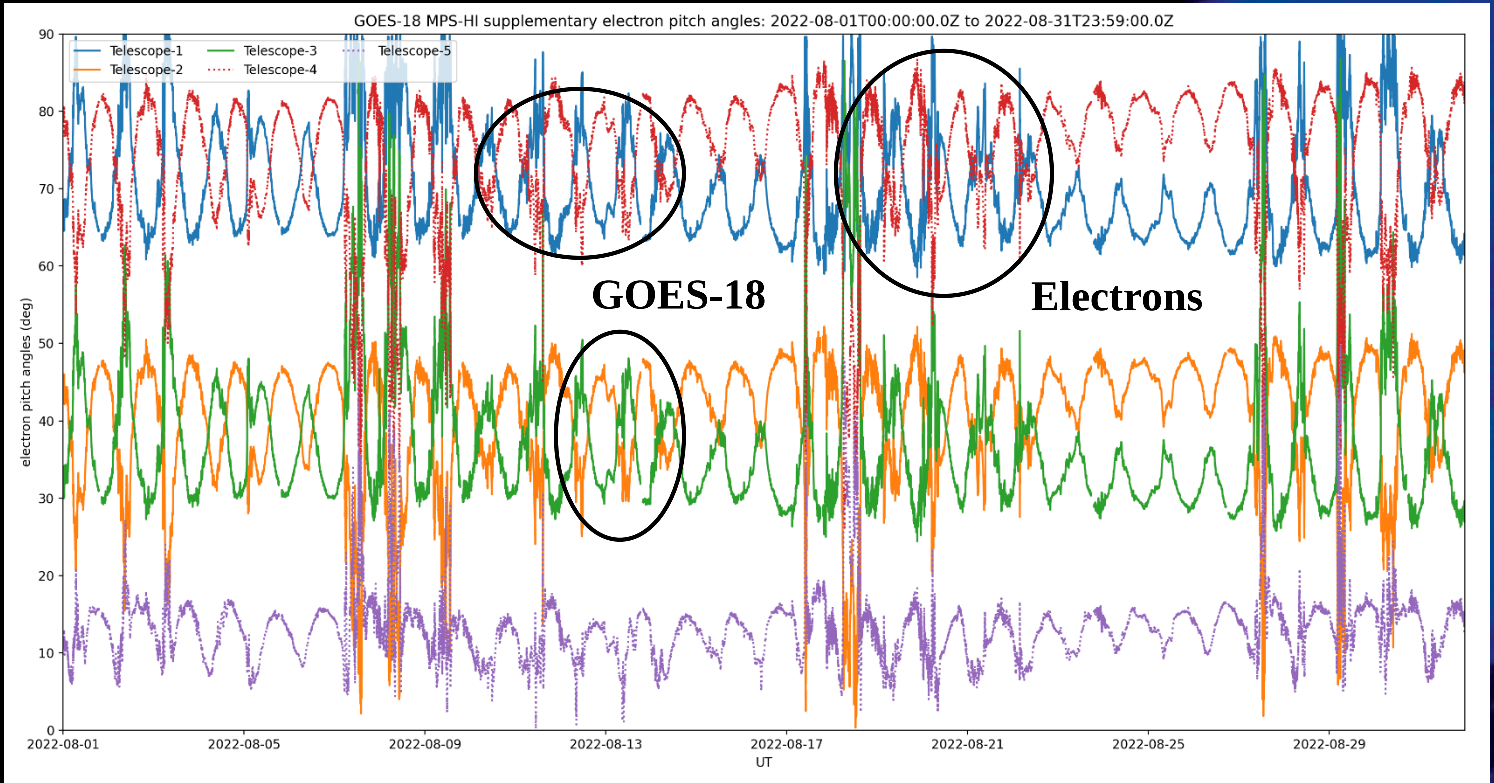
Modeling the GCR background

- Assume that the peak and the part of the PDF below the peak are dominated by the rates due to GCRs, model as Gaussians.
- Gaussian PDF: $f(x) = a\, exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$
- Gaussian CDF: $F(x) = a\sigma\sqrt{\frac{\pi}{2}}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$



- Conduct the analysis using 5-min averages during a 4-month period, 09/01/2022-12/31/2022.
- Fit the CDF that is varying smoothly, instead of PDF.
- $\overline{C_{ELE}^{obc}(i, E11)} = \mu_{E11}$ (fitted E11 mean).
- Do the same for SGPS-X P11 counts, $\overline{C_{P11}} = \mu_{P11}$
- Repeat for E9, E10, E10A.
- Estimate gammas.

GOES-18 MPS-HI Telescope Cross-Comparison: Method



- Compares responses of MPS-HI telescopes when central pitch angle is the same
- Under such conditions, telescopes should be measuring the same flux for the same effective energy
- The technique has been validated twice: 1) G17 MPS-LO zone intracal, and 2) G13/G15 MAGED/PD cross-telescope comparisons (Rodriguez et al., [2020], JSWSC)

- **Procedure steps:**
  - **Input MPS-HI fluxes and pitch angles calculated from MAG L1b BRF**
  - **Identify whenever a pair of telescopes has pitch angles within 1 degree**
  - **Fold pitch angles > 90 degrees to get enough matches**
  - **Report measured fluxes for each pitch angle match**
  - **Estimate scaling factors with respect to a reference telescope**

Ref: Rowland, W., and R. S. Weigel (2012), Intra-calibration of particle detectors on a three-axis stabilized geostationary platform, *Space Weather, 10*, S11002, doi:10.1029/2012SW000816.

GOES-18 MPS-HI Telescope Cross-Comparison: Results

- Use Nelder-Mead method to minimize the following objective function: sum of squares of the following difference term

$$R(m) = \frac{SF_i(m)J_i(m) - SF_j(m)J_j(m)}{SF_i(m)J_i(m) + SF_j(m)J_j(m)}$$

- To reduce effect of statistical noise, use only matches where both fluxes correspond to at least 1000/100 counts/minute
- Because they are only valid in a relative sense, scale factors must be normalized – here, normalized to those of Telescope 4 (arbitrary)

Electron Scale Factors, GOES-18 September 7-December 6, 2022

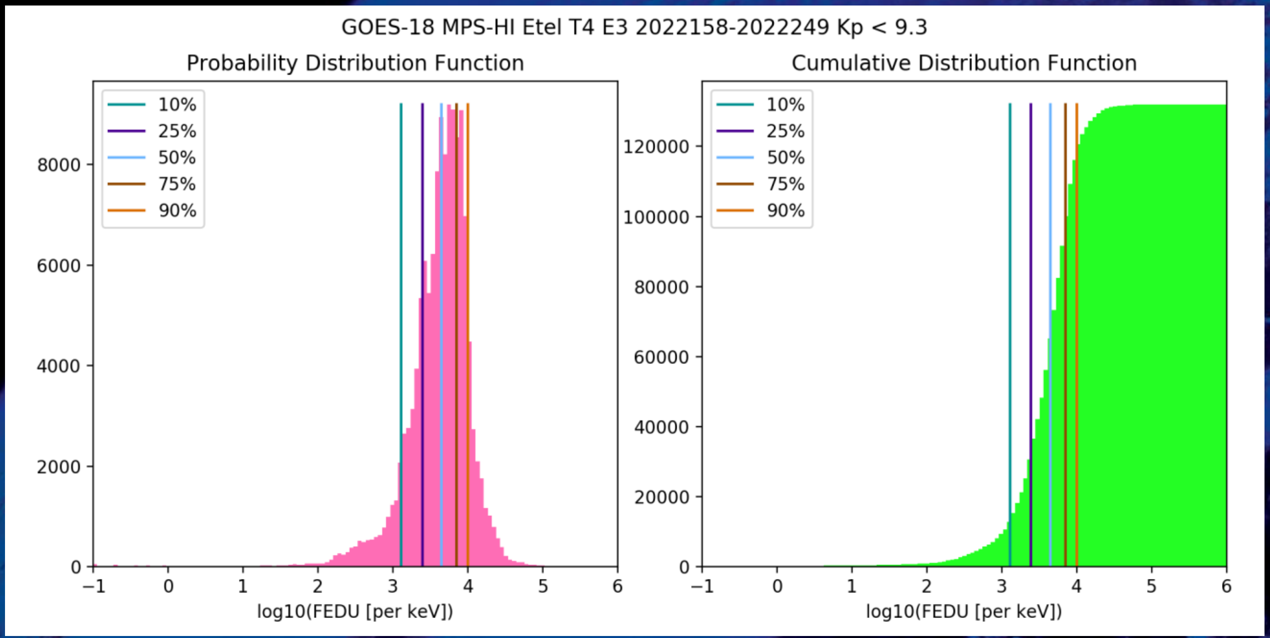
Energy band	Count threshold	T1	T2	T3	T4	T5
E1	1000/min	1.036	0.926	0.964	1.000	1.000
E2	1000/min	0.958	1.233	1.104	1.000	1.165
E3	1000/min	0.919	0.785	0.811	1.000	1.061
E4	1000/min	1.009	0.960	0.983	1.000	1.081
E5	1000/min	0.973	1.020	0.947	1.000	1.048
E6	1000/min	0.996	1.102	0.996	1.000	1.038
E7	1000/min	1.006	0.985	1.106	1.000	1.175
E8	100/min	0.985	0.865	0.826	1.000	1.009
E9	100/min	0.630	0.682	0.706	1.000	0.690
E10	100/min	0.757	0.813	0.956	1.000	0.937
E11	100/min	0.718	0.812	0.943	1.000	0.747

Blue: <10%, Green: 10-25%, Red: >25%
Pink: <100 PA matches
Orange: <1000 PA matches

Cross-Satellite Comparison of Trapped Particles: Technique

Compare statistical differential flux spectra from GOES-17 and GOES-18, separated by only 0.4 degrees longitude:

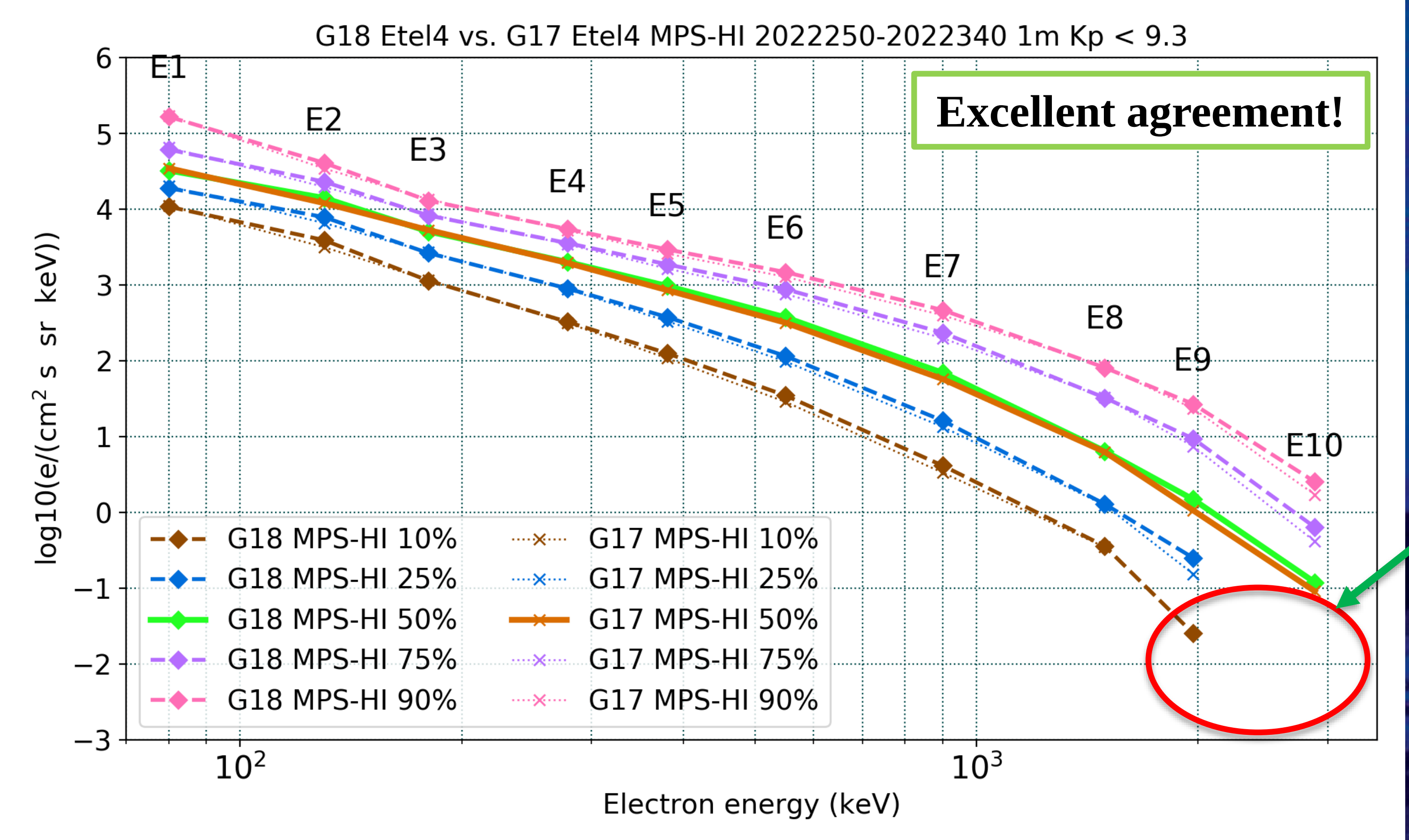
- ❑ **GOES-17 (137.2W) to GOES-18 (136.8W), 09/07/2022-12/06/2022 (3 months)**
- ❑ **Calculate the particle distributions for all channels and telescopes**
- ❑ **Compare flux percentile spectra for telescopes of the same orientation**
  - ➢ **0, ±35, ±70 deg from zenith (radially outward)**
  - ➢ **Note: GOES-17 MPS-HI was inverted during this period**



- **PDF: Number of fluxes in each flux bin**
- **CDF: Number of fluxes up to a flux bin**
- **Percentile fluxes: Flux at which number of fluxes < percentile**
- **50% is the median of the distribution**

Cross-Satellite Comparison of Trapped Particles: Results

GOES-18 vs GOES-17 Electrons , 09/07/2022–12/06/2022



GOES-17 fluxes are slightly less than GOES-18: GOES-17 has been in orbit for over 5 years

Missing or significantly lower fluxes are at residual background levels

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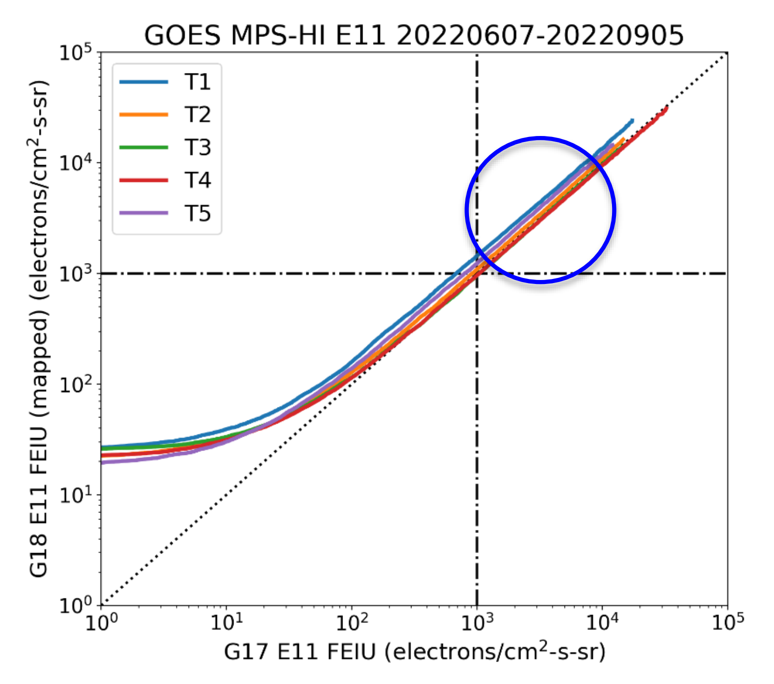
Cross-Satellite Comparison of Trapped Particles (E11): Technique and Results

Comparison of >2 MeV electron fluxes for 06/07/2022-09/05/2022: Use a rigorous method to compare two time series at different satellites: **'Statistical Asynchronous Regression'** [O'Brien et al., *JGR*, *106*, 2001].



- **Calculate the percentile ratios of the G17/G18 E11 integral flux (note different E11 energies)**
- **Good agreement for the central telescope T4 that is used by SWPC for its alerts**
- **Not so good agreement for T1 and T5, G17 lower**

G17/G18 MPS-HI Integral Flux Ratio					
Percentile	**T1**	**T2**	**T3**	**T4**	**T5**
50	**0.65**	**0.88**	**0.95**	**0.99**	**0.73**
75	**0.71**	**0.93**	**1.04**	**1.05**	**0.79**
90	**0.73**	**0.92**	**1.03**	**1.06**	**0.81**

O'Brien, T. P., Sornette, D., & McPherron, R. L. (2001) Statistical asynchronous regression: Determining the relationship between two quantities that are not measured simultaneously, Journal of Geophys. Res., Space Phys. 106, 13,247–13,259. https://doi.org/10.1029/2000JA900193.

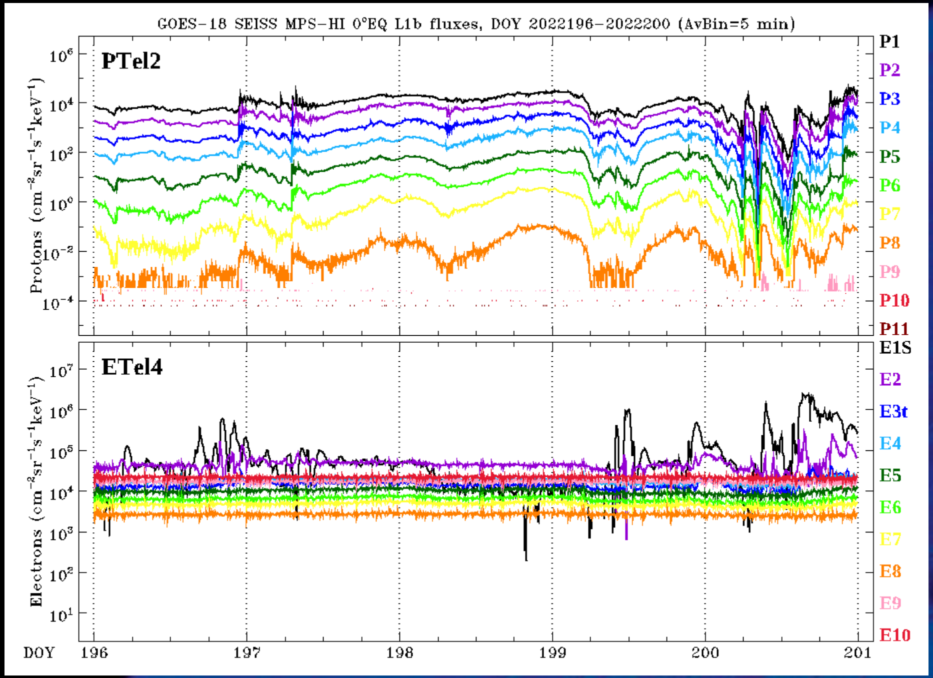
Concluding notes

- Steps taken to ensure accurate flux determination
  - Dead time correction
  - Bowtie Analysis for accurate conversion from counts to fluxes
  - Background removal for channels E9-E11 for accurate GCR backgrounds specification and removal
- Steps taken to ensure accurate calibration
  - Cross-telescope: Statistical comparison between telescopes observing the same pitch angles
  - Cross-satellite: Comparison between GOES-R satellites

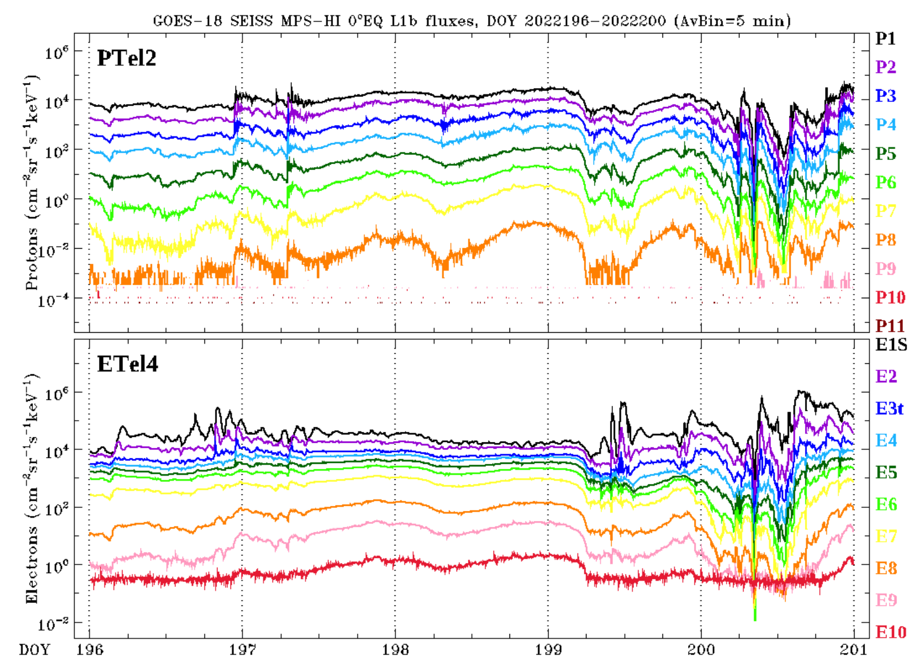
Backup slides

Application of the bowtie analysis to GOES-18 MPS-HI data

OPS L1b, July 15-19, 2022



Bowtie technique, July 15-19, 2022



- **Application of the bowtie analysis to produce L1b electron fluxes from L0 counts**
- **Uses a diagonal matrix with Geometric Factors (GF) and channel Effective Energies derived from the minimalization of the variation of the GF for a variety of spectra, using a proxy dataset (CRRES)**
- **The bowtie technique is successful in producing good quality L1b electron data from L0 counts**

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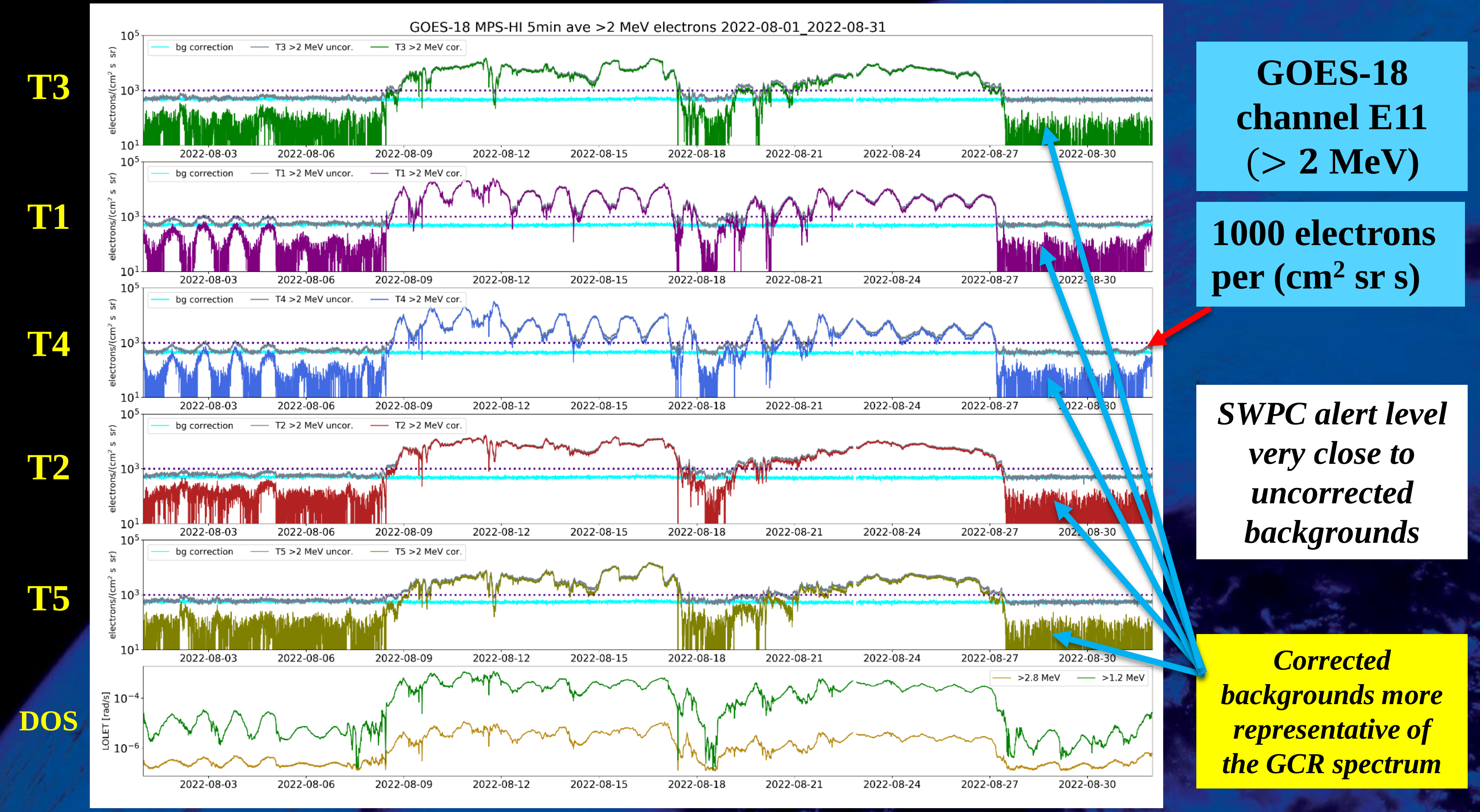
Application of the revised background removal to GOES-18 MPS-HI E11 data



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