Space Weather Monitoring with SATRAM

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2026 WRMISS - 01/09–03/09/2026

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The Instrument

Space Application of Timepix Radiation Monitor (SATRAM)

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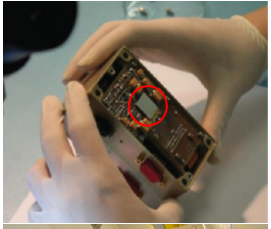
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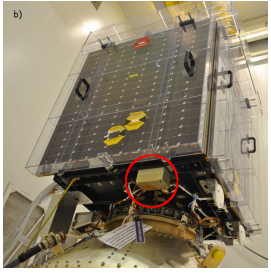
First Timepix in open space

- 300 µm Si sensor, 256 × 256 pixel with 55 µm pixel pitch
- Operated in energy mode (ToT)
- Power consumption: 2.5 W
- Mass: 380 g; Dimensions: 107 mm × 70 mm × 55 mm
- Frame length: 2 ms, 200 ms, 2 s
- Platform technology demonstrator

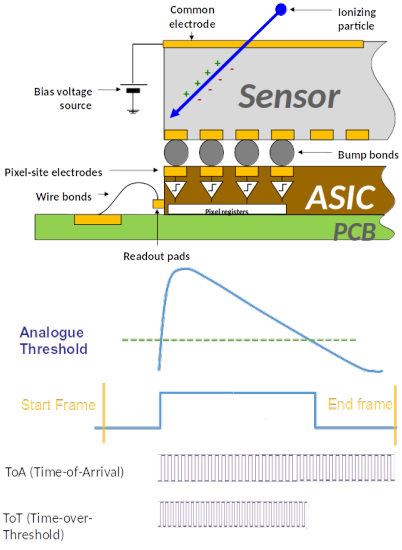
Proba-V

- Sun-synchronous at altitude 820 km
- Orbit duration: 101.21 min
- Inclination: 98.6°
- Launched 7 May 2013

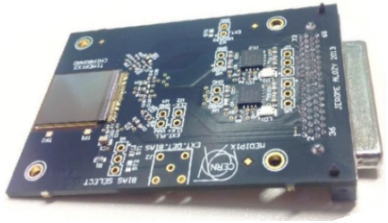




Timepix Detector



- 256×256 pixel with 55 µm pixel pitch ($1.98\,\mathrm{m}^2$)
- Sensor layer (Si, CdTe, GaAs, ...) flip-chip bump bonded to the ASIC
- Frame based readout (92 fps) – dead time > 11 ms
- Measurement of energy or time ($\Delta t = 20.8$ ns)
- Minimal detectable energy ≈ 3.5 keV



Data Examples

(1) Dot — Low energy X- and γ-rays, low energy electrons

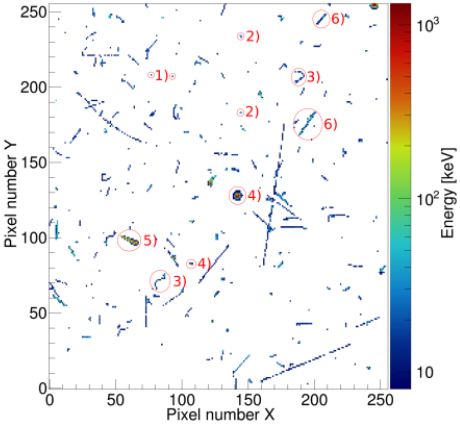
(2) Small blob — X- and γ-rays, electrons

(3) Curly track — γ-rays and electrons (MeV)

(4) Heavy Blob — Highly ionizing particles with short range (α, protons, ...)

(5) Heavy track — Highly ionizing particles (protons, ions, ...)

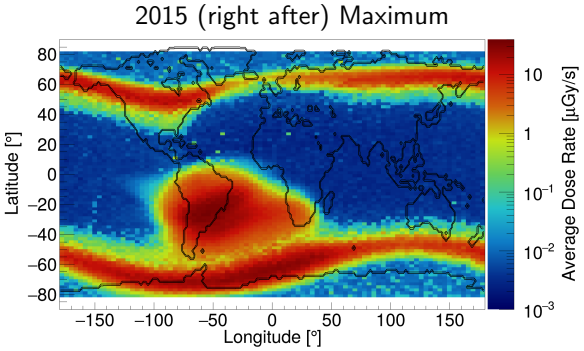
(6) Straight track — Energetic light charged particles (μ, minimum ionizing light ions, ...)

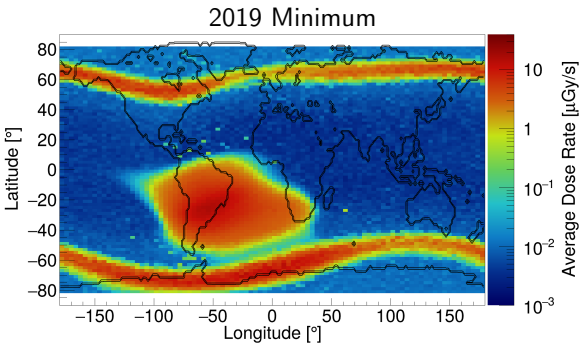


B. Bergmann, St. Gohl, D. Garvey, J. Jelínek, and P. Smolyanskiy. Results and Perspectives of Timepix Detectors in Space—From Radiation Monitoring in Low Earth Orbit to Astroparticle Physics. Instruments, 8(1), 2024. ISSN 2410-390X. doi: https://doi.org/10.3390/instruments8010017.

Solar Maximum vs Minimum

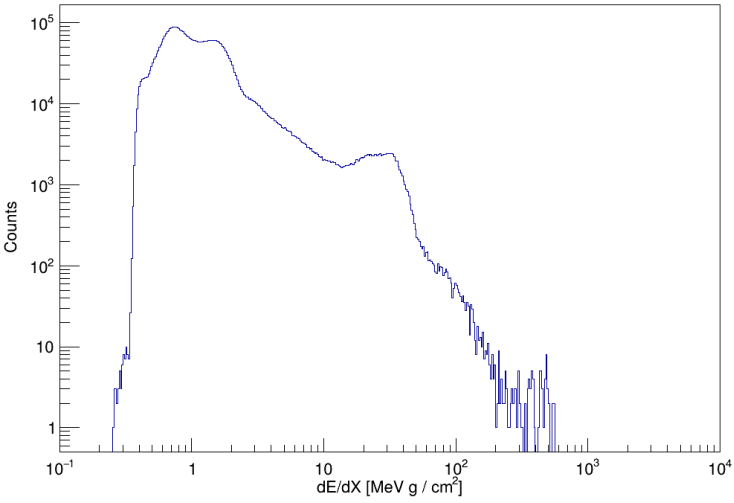
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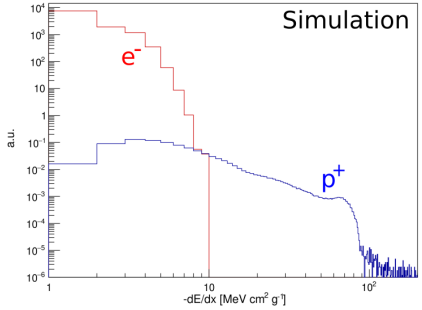




First Particle Identification Algorithm

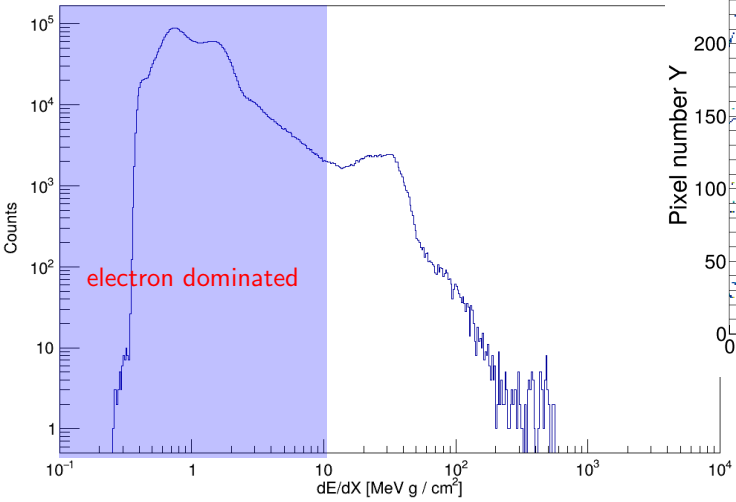
Stopping power spectrum

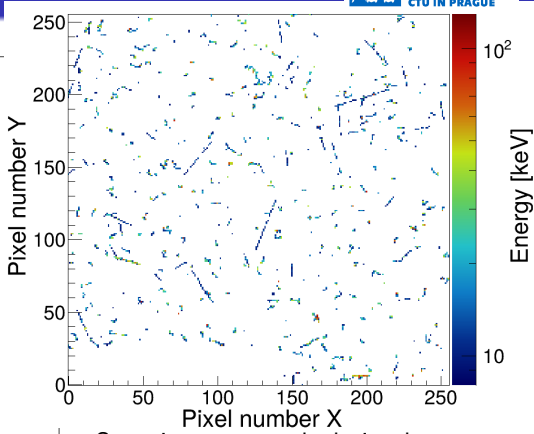




Stopping power calculation by determining the length of the trajectory through the sensor and determining the deposited energy

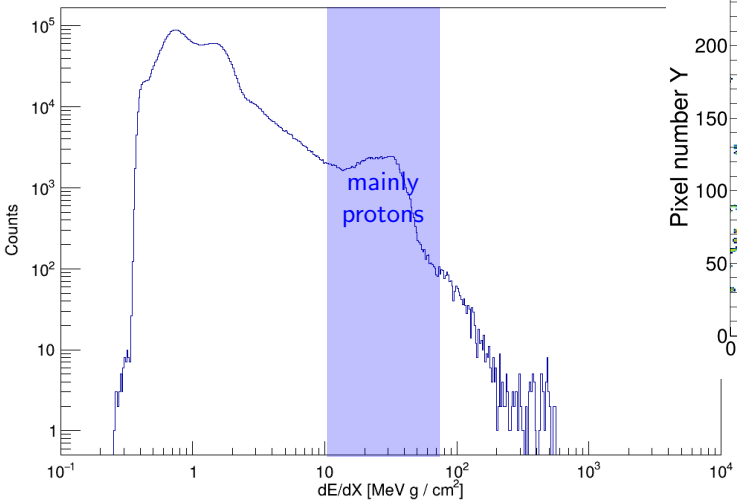
Stopping power spectrum

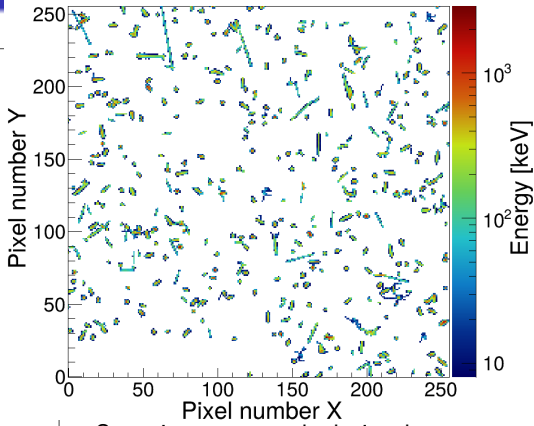




Stopping power calculation by determining the length of the trajectory through the sensor and determining the deposited energy

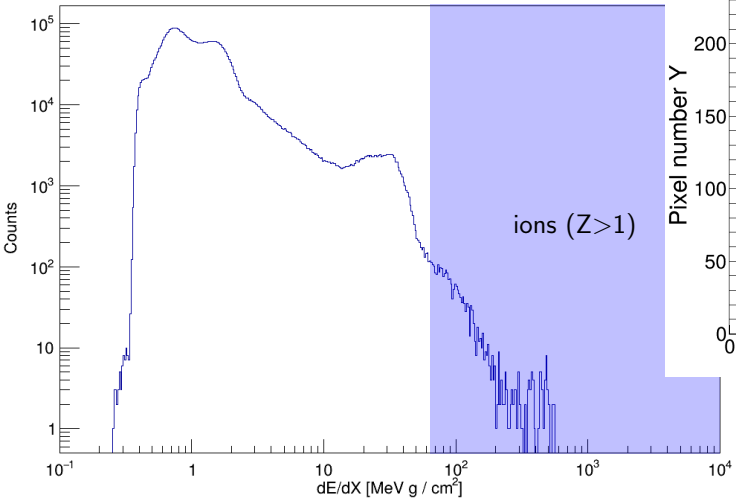
Stopping power spectrum

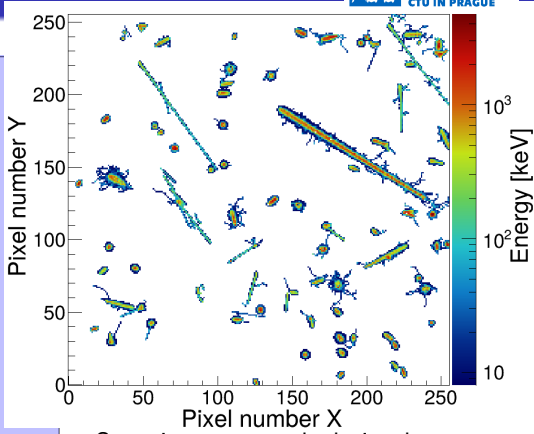




Stopping power calculation by determining the length of the trajectory through the sensor and determining the deposited energy

Stopping power spectrum



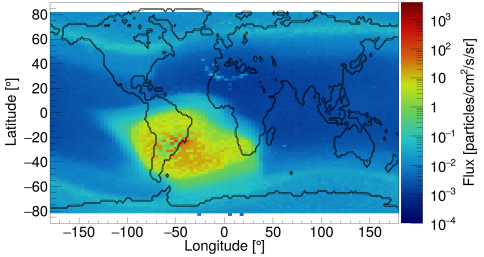


Stopping power calculation by determining the length of the trajectory through the sensor and determining the deposited energy

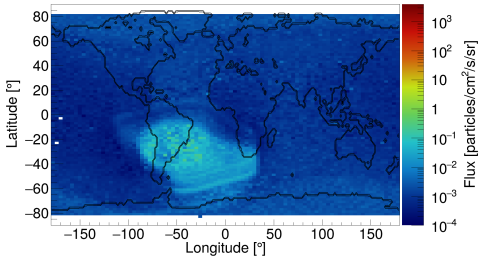
Averaged Flux Map – 2015 to 2025

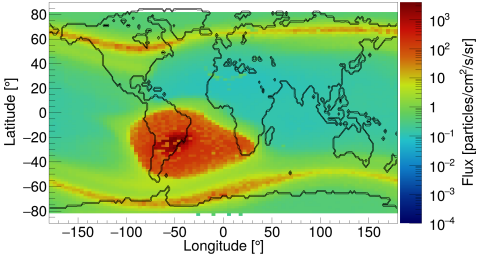
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mainly protons



mainly ions (Z>1)





mainly electrons

Measurement of Electron Fluxes and Comparison to EPT

Electron Flux Determination

Minimum Energy

- Thinned window (0.5 mm) above the sensor $\Rightarrow$ minimum electron energy: 490 keV (EPT: 500 keV)

Particle counting N_e

Low occupancy (<20%) frames

- Use of neural network for particle identification

High occupancy (>20%) frames

- Overlap of particle tracks do not allow individual track analysis
- Deposited energy / local mean energy of a track $\times$ last know fraction of electrons

Geometry

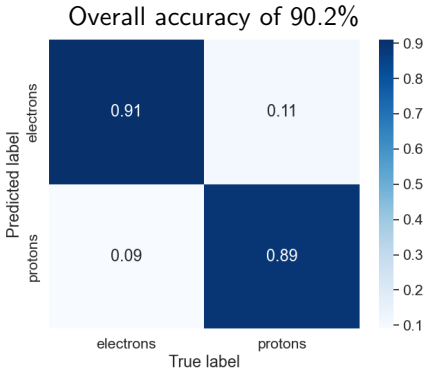
- General FOV of Timepix sensor: 4π
- Flat sensor, but omnidirectional flux: g_f
- No general shielding except thin aluminium case, but other surrounding material: A_e
- Production of secondary particles, track interruption and backscattering: c_{sec}

$$\Phi_e^{SATRAM} = \frac{N_e}{A_e \; t \; g_f \; c_{sec} \; 4\pi}$$

t - acquisition time

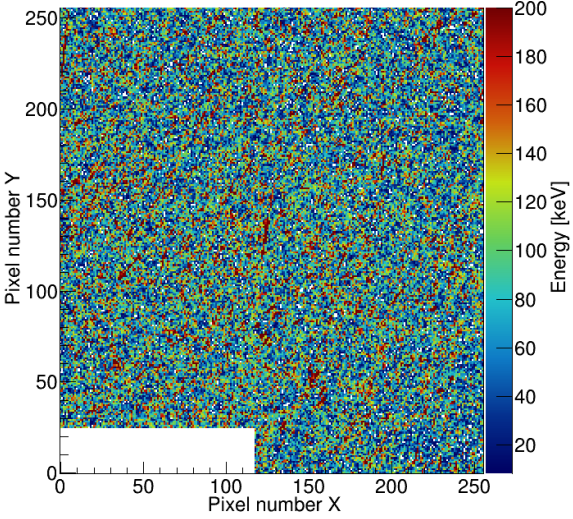
Low Occupancy Frames

- Feed-forward neural network in TensorFlow framework with 2 hidden layers
- Activation function for hidden layers: rectified linear unit (ReLU)
- Activation function for output layer: sigmoid
- 7 features for particle identification:
  - deposited energy
  - number of pixels
  - energy of highest energy pixel
  - linearity and roundness of track
  - average number of neighbouring hit pixels
  - sum of absolute values of cubic and quadratic terms of 3rd order polynomial fit of cluster



Requires non-overlapping particle tracks!

The Overlap Issue



Acquisition times can be too long depending on the region of space the measurement is taken. Consecutive frames in SATRAM have 20 s, 200 ms, 2 ms acquisition times.

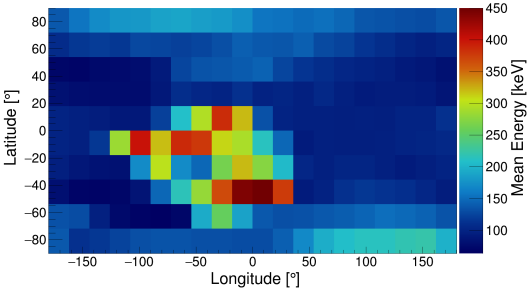
Previous methods work for low occupancy frames (<20%), but not for high occupancy frames.

A different analysis method is needed!

High occupancy frames

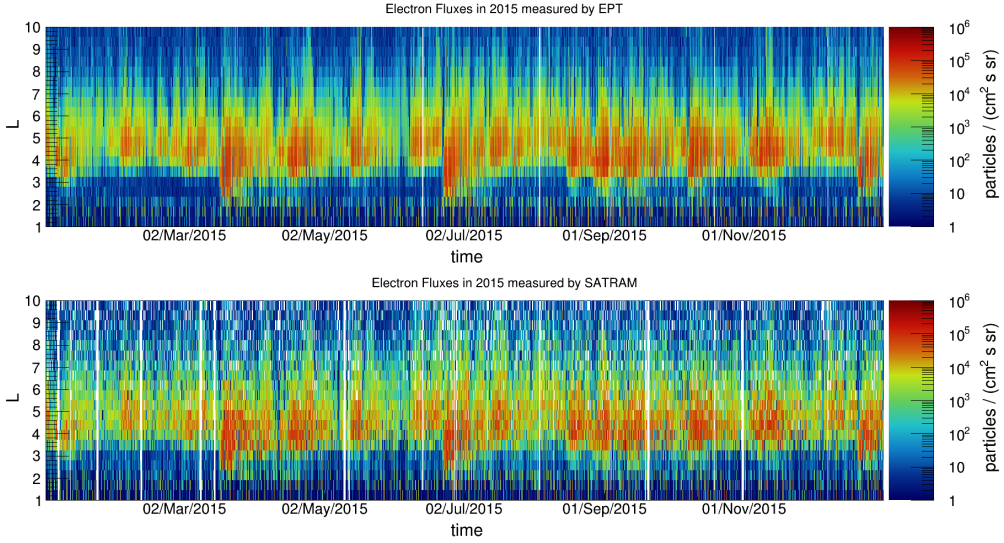
$$N_e = \frac{E_{tot}}{E^{loc}_{mean}} \cdot \frac{N^{last}_e}{N^{last}_e + N^{last}_p}$$

- E_{tot} total energy measured in frame
- E^{loc}_{mean} local mean energy according to position on map to the right
- $N^{last}_{e,p}$ number of electrons or protons measured in the last low occupancy frame

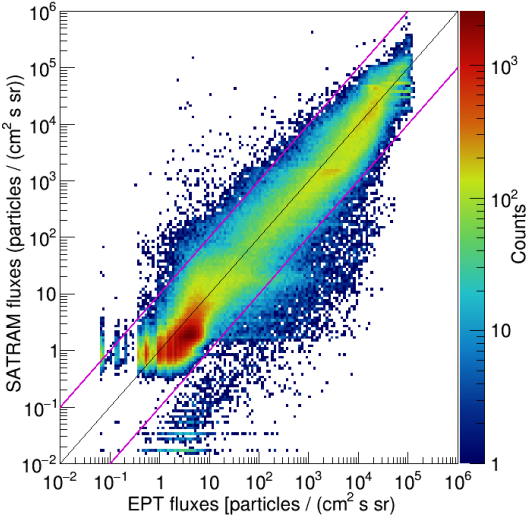


Map of mean deposited energy per particle for different satellite positions. The mean energy was determined with low occupancy frames.

Comparison to Energetic Particle Telescope (EPT)

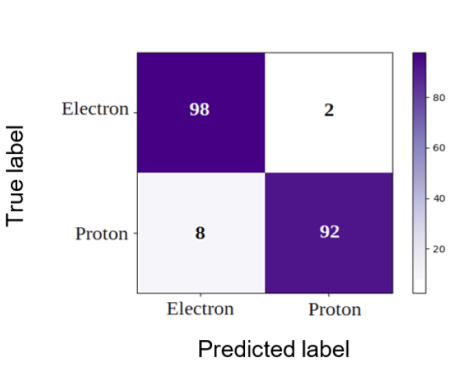


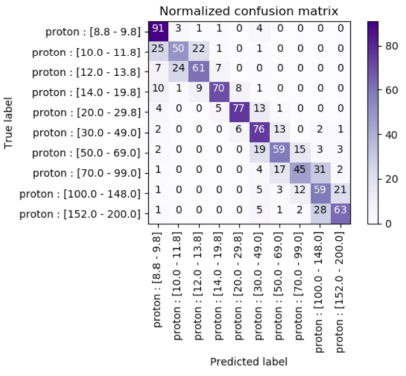
Direct Flux Comparison



- SATRAM and EPT fluxes mostly in agreement
- SATRAM fluxes slightly smaller than EPT fluxes
- Magenta lines mark 1 order of magnitude deviance
- Most data lies within area marked by magenta lines
- 2015 data shown here, data available until end of 2022 showing similar results

CNN by ONERA





M. Ruffenach et al., "A new technique based on convolutional neural networks to measure the energy of protons and electrons with a single Timepix detector", in IEEE TNS, 68, 8, pp. 1746-1753, (2021). doi: 10.1109/TNS.2021.3071583

New Methodologies

Bayesian Deconvolution

This method works by decomposing the stopping power "signal" of the field into its contributing particle signals, from which the particle's distributions can be inferred.

Response matrix

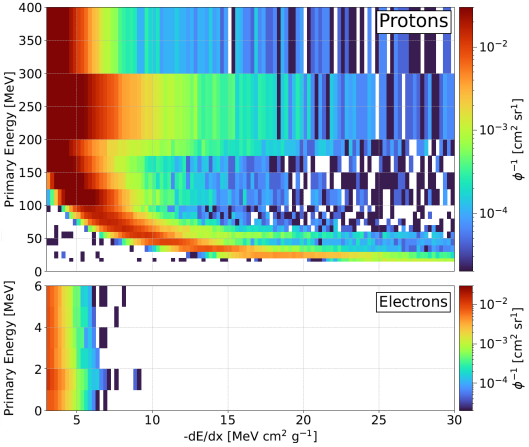
Particle spectrum

$$n(E) = R\,\Phi(c)$$

Measured dE/dx spectrum

$$\Rightarrow R^T n(E) = \Phi(c)$$

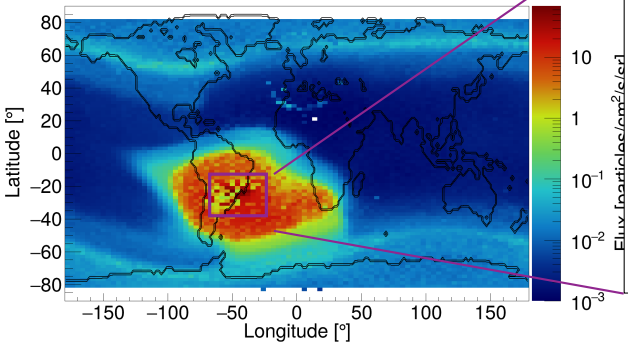
Methodology verification in monoenergetic proton beams

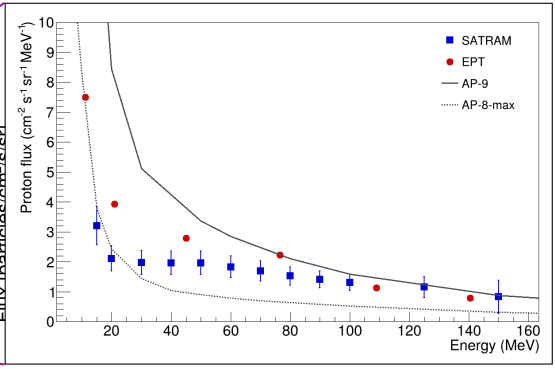


Bergmann, B.; Gohl, S.; Garvey, D.; Jelínek, J.; Smolyanskiy, P. Results and Perspectives of Timepix Detectors in Space—From Radiation Monitoring in Low Earth Orbit to Astroparticle Physics. *Instruments* **2024**, 8, 17. https://doi.org/10.3390/instruments8010017

Energy Spectrum of Protons Inside SAA

Usage only of frames with 2 ms to avoid overlapping tracks (the shortest frames available) resulting in a total measurement time of 46 s over 4 years

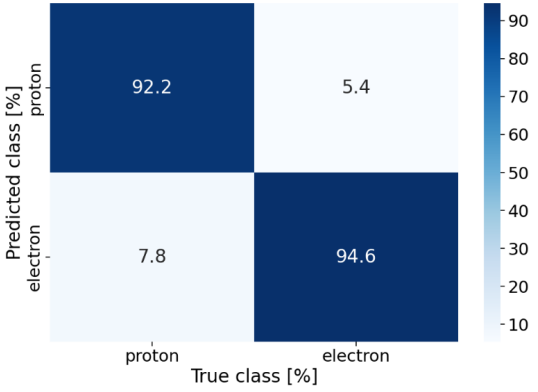


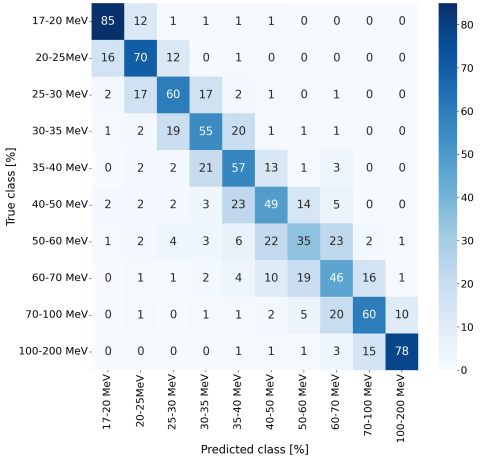


SAA Area: Longitude: [-70°,-25°], Latitude: [-40°,-12°]

CNN Development

New: 93.4% accuracy (previous: 90.2%) – Convolutional Neural Network with autoencoder structure (U-shaped net)





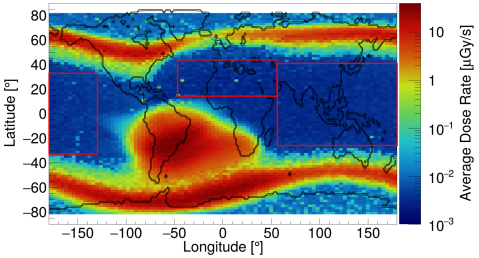
Galactic Cosmic Ray Measurements

Measuring GCRs

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Data Selection:

- Using data near the equatorial region outside SAA:



- Cut on track shape:
  - Straight, heavy tracks
  - Straight, thin tracks with length > 7 pixels
- Cut on angle: 65° from sensor normal

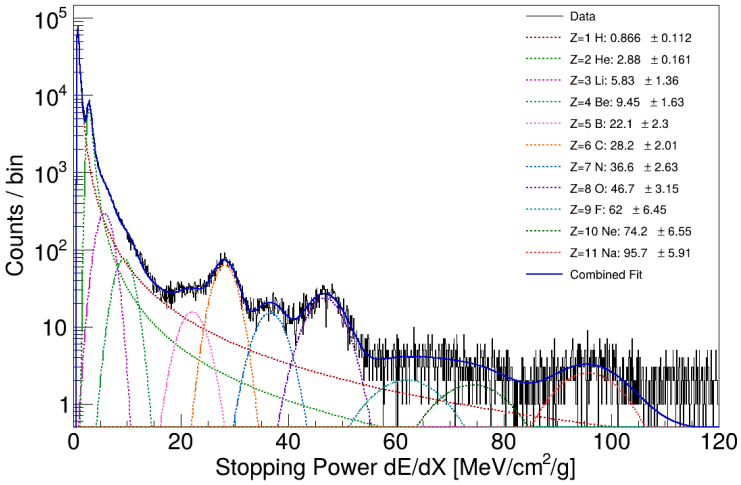
Methodology:

- Calculation of stopping power
- Multi-peak fit using RooFit
- Mix of Landau and Gaussian
- Monte Carlo simulation for each ion
- Calculation of theoretical values using Bethe–Bloch:

$$\frac{dE}{dX}(Z) = \frac{dE}{dX}(Z=1) \cdot Z^2,$$

where $\frac{dE}{dX}(Z=1) = 0.85\,\mathrm{MeV\,cm^2\,s^{-1}}$ stopping power of protons

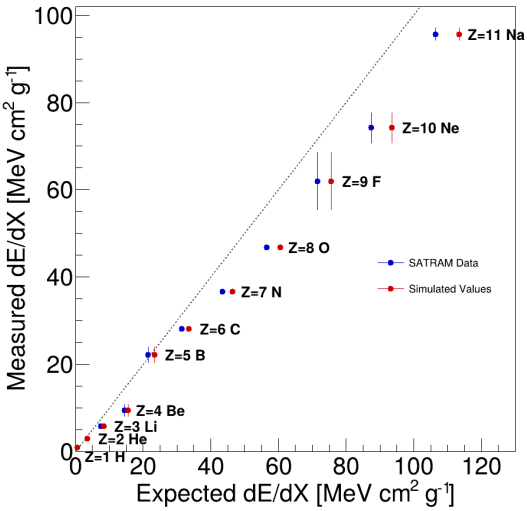
Fitted Stopping Power Spectrum



- H peak: Landau
- He peak: Landau⊗Gaussian
- Every other peak: Gaussian

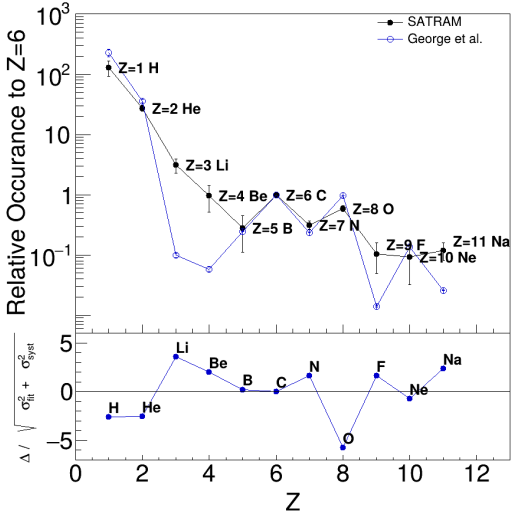
Fitting was done with RooFit toolkit of ROOT. It's a multi-fit done in several stages.

Comparison



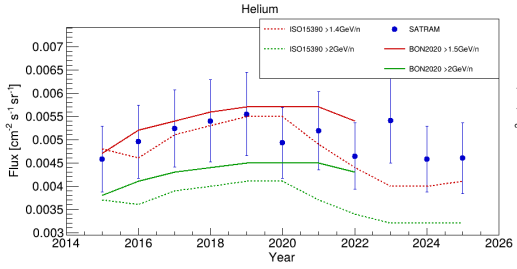
- Bad determination of Li, Be, and B
- No saturation effects in Bethe–Bloch nor Simulation
- Low statistics for F, Ne, and Na

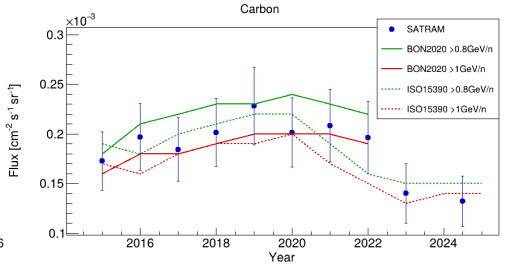
Abundances

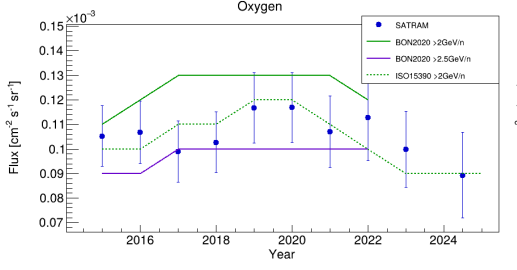


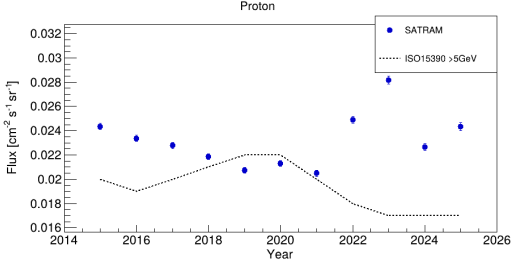
- Again bad determination for Li and Be
- Low statistics for F, Ne, and Na
- George from cycle 23 – SATRAM cycle 24/25
- Robust fit for O $\rightarrow$ small error

Measurements of GCR Flux over one Solar Cycle









Summary

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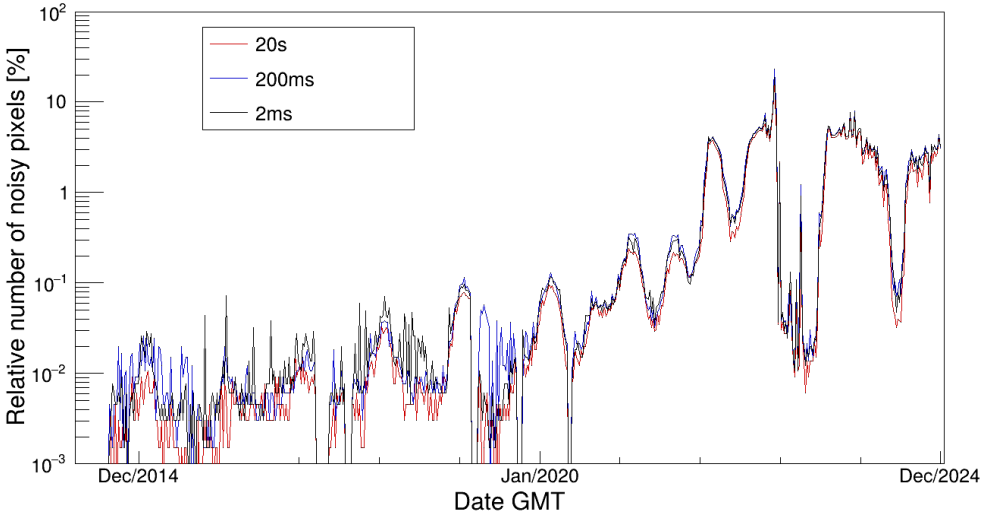
- More than 12 years of measurement in space
- Basic particle separation through decision tree
- Electron flux calculation and comparison with EPT
- Determination of average proton spectrum using a Bayesian deconvolution method using a single layer detector
- New CNN development that improves average electron-proton prediction to 93.4%
- Measurement of GCRs with 11 ions identified
- Determination of abundance and annual trend of He, C and O
- HardPix – Successor to SATRAM:
  - R. Filgas, *Results from Radiation Spectrometer HardPix Onboard the ISS and ION Satellites*, 16:45 today
  - M. Malich, *HardPix: A Modular Timepix3-Based Radiation Monitor for Advanced Radiation Environment Characterization*, 11:15 Thursday

Thank you for Attention!

Visit https://satram.utef.cvut.cz/ to play with the data!

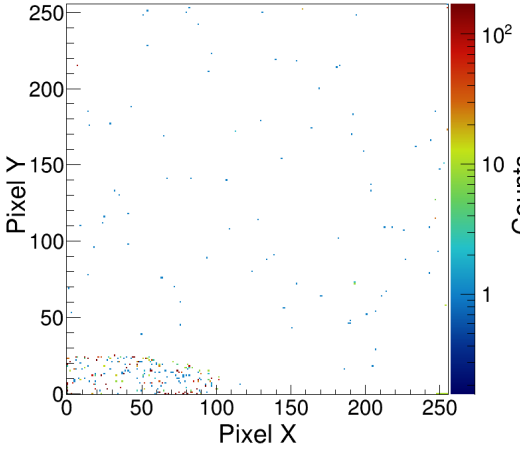
Acknowledgement
Successful launch and operation of SATRAM would not have been possible without Stanislav Pospíšil, Carlos Granja, Zdeněk Vykydal, Jan Jakůbek and Alan Owens. The authors B.B. and D.G. are grateful for the funding received by the Czech Science Foundation (GACR) under grant number GM23-04869M.

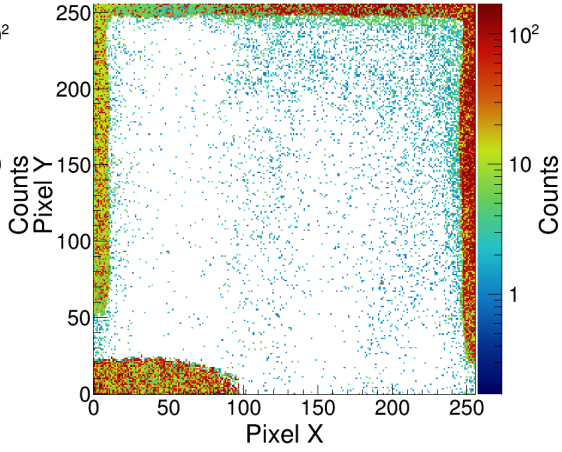
Noisy Pixels – Timeline



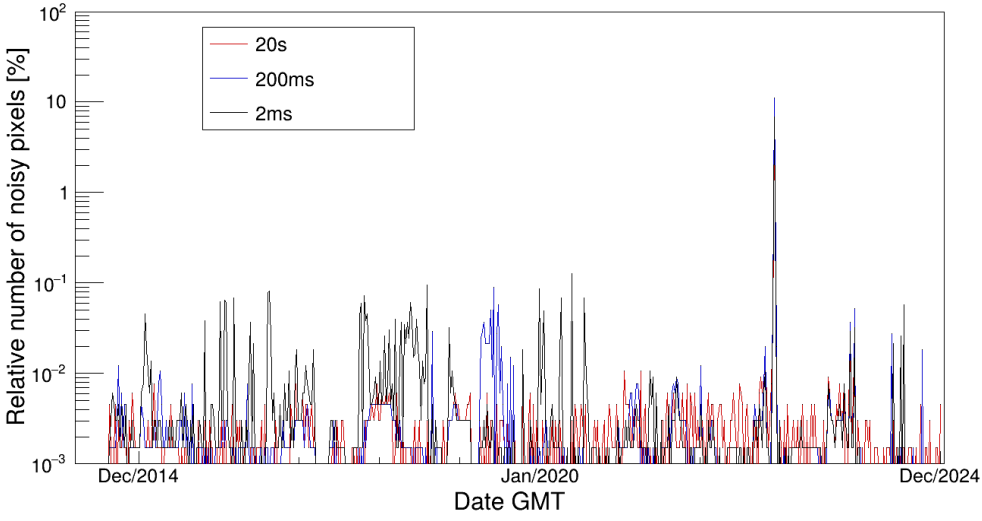
Noisy Pixel Distribution

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Noisy Pixels – Selected Region



Bias and Temperature Timeline

