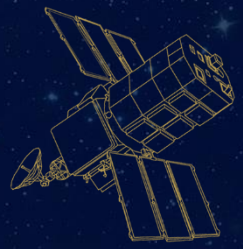


GRID: Current Status and Scientific Results

Xutao Zheng, Ming Zeng, Hua Feng, Zhi Zeng, Yang Tian, Benda Xu

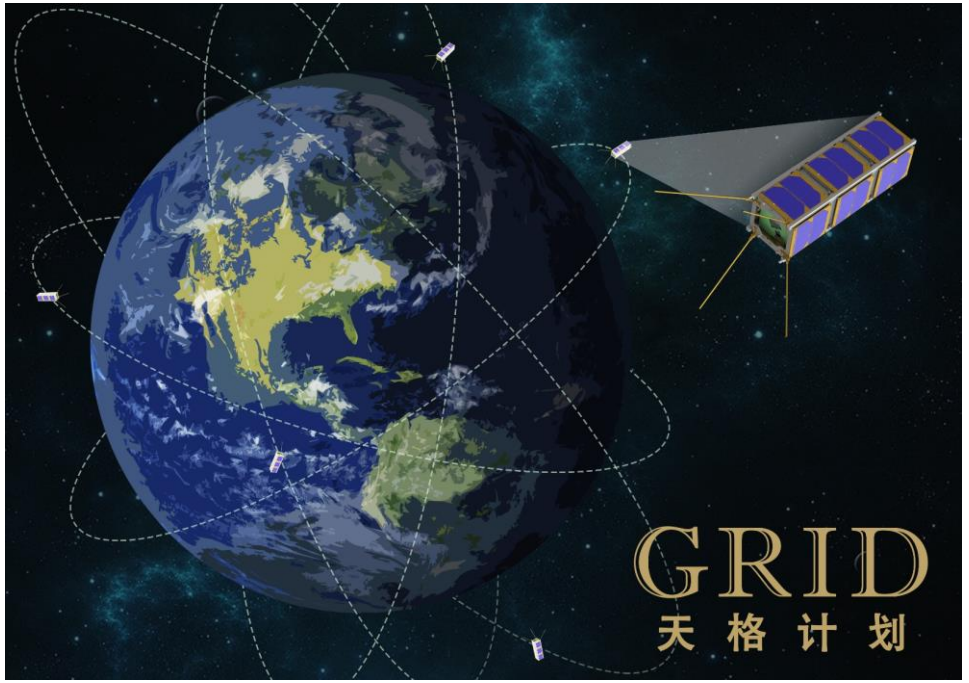
on behalf of the GRID collaboration

Tsinghua University, Beijing, China

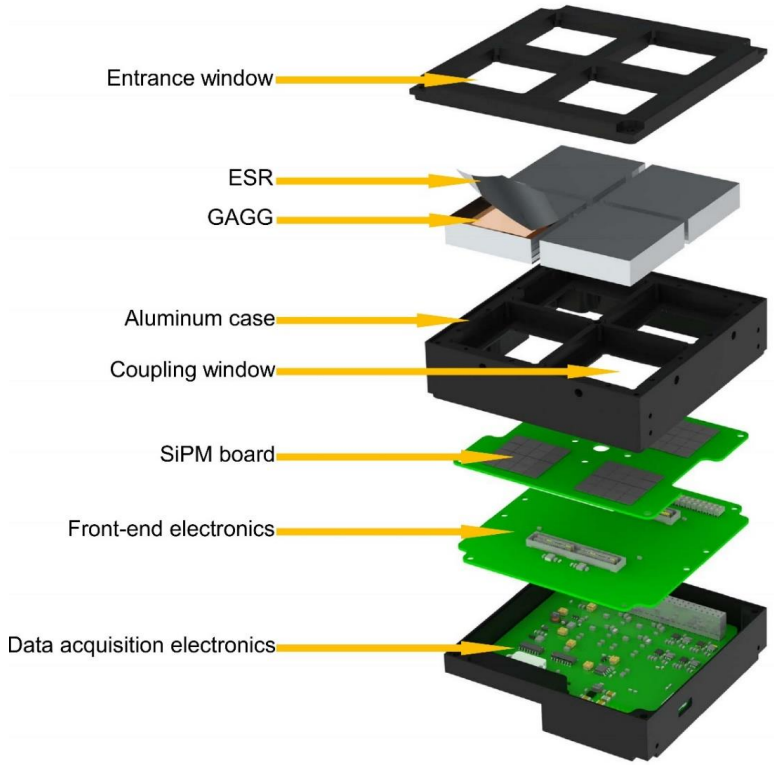
Monitoring the high-energy sky with small satellites

06 September 2022

The GRID Project and Detector



3D model of the GRID detector [2]



Specifications of GRID-02

Size	< 0.5U (9.4×9.4×5 cm^3)
Weight	~ 780 g
Power consumption	Typ. 2 W Max. 2.8 W
Geometric area	~ 58 cm^2
Field of view	2π
Energy range	Lower threshold < 15 keV Upper threshold ~ 2 MeV
Dead time	~ 20 us
Background count rate	Norm. ~ 2000 cps SAA > 8000 cps
Telemetry	~ 1 GB/day

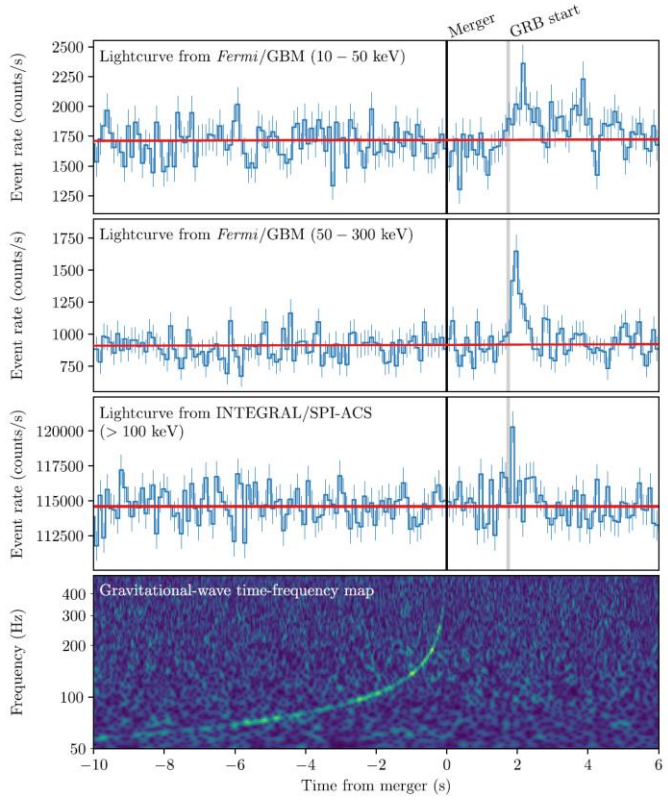
The **Gamma Ray Integrated Detectors (GRID)** concept: [1]

- 10 ~ 24 CubeSats scattered in low Earth orbits
- Compact gamma-ray detectors

[1] Wen, J., Long, X., Zheng, X. *et al.* GRID: a student project to monitor the transient gamma-ray sky in the multi-messenger astronomy era. *Exp Astron* **48,** 77–95 (2019)
[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Scientific Goals

Joint, multi-messenger detection of GW170817 and GRB 170817A [3]



Detection of GRBs associated with future NS-NS mergers

- ✓ Confirmation of the EM counterparts
- ✓ Constrain the jet physics (structured vs. cocoon breakout)
- ✓ Possible improvement in position accuracy

Other gamma-ray transients

- ➢ Soft gamma-ray repeaters (SGRs)
- ➢ Magnetars
- ➢ Terrestrial gamma-ray flashes (TGFs)
- ➢ Terrestrial electron beams (TEBs)
- ➢ Solar flares
- ➢ Other high-energy transients

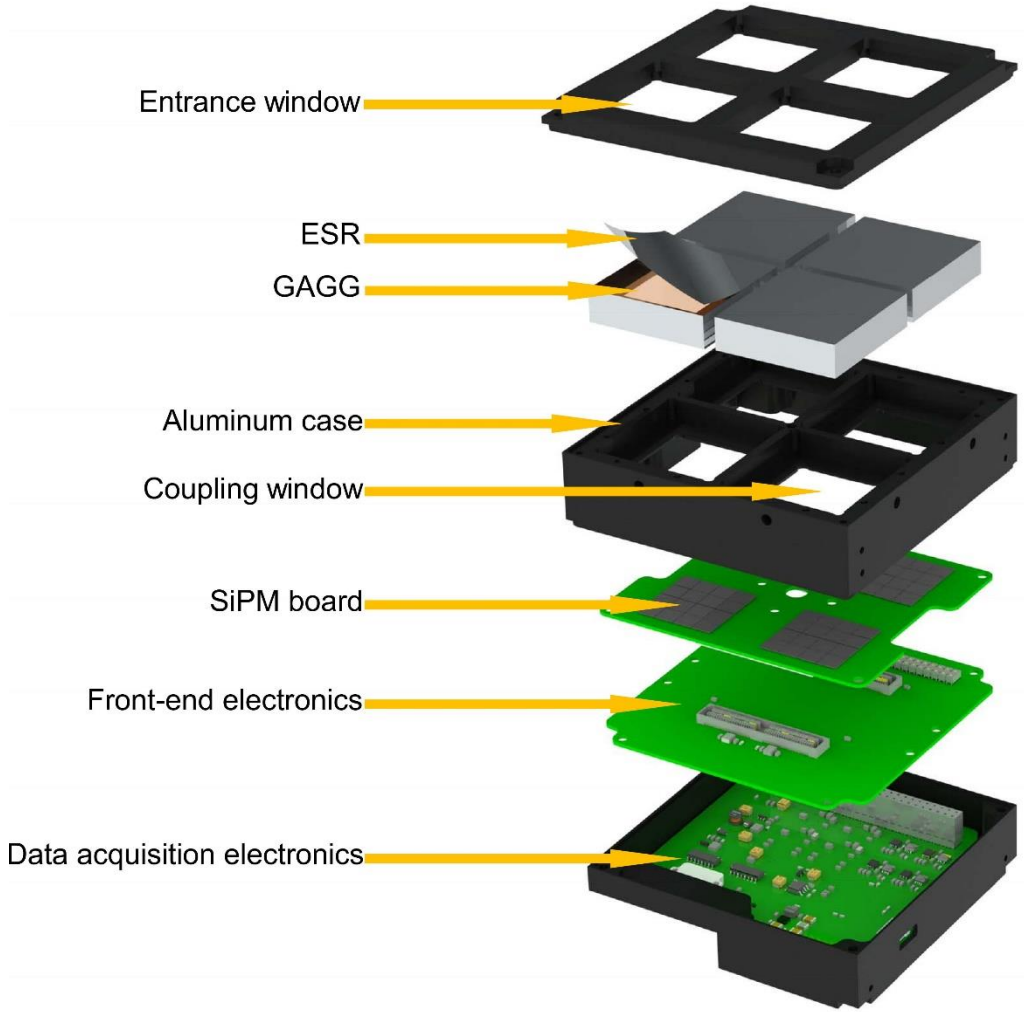
GRID: collect the first dozen GRBs associated with NS-NS mergers

[3] B. P. Abbott *et al* 2017 *ApJL* **848** L13

History of GRID since 2016

- The GRID concept was first proposed in October of 2016 by a group of undergraduate students, inspired by discussions with several professors.
- The first four detectors (GRID-01/02/03B/04) have been launched in Oct. 2018, Nov. 2020, and Feb. 2022, respectively.
- 25 universities and institutes in China have joined the GRID collaboration.

Instrument Design



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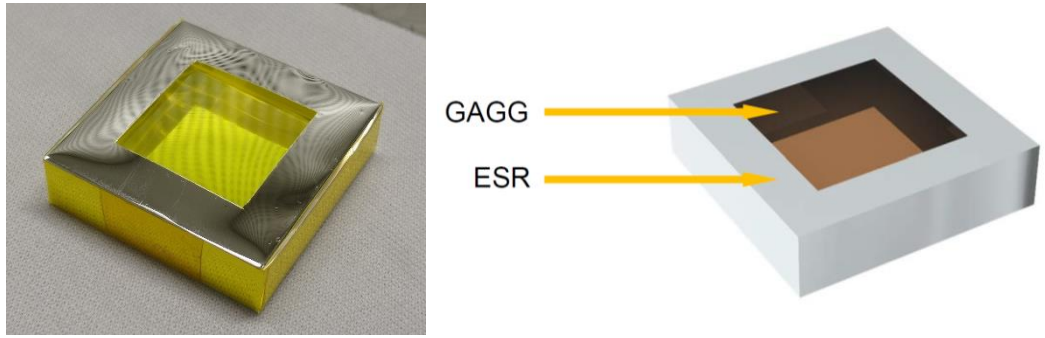
[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

GAGG:Ce Scintillator Crystal



Bottom view of a GAGG:Ce scintillator with the ESR package [2]

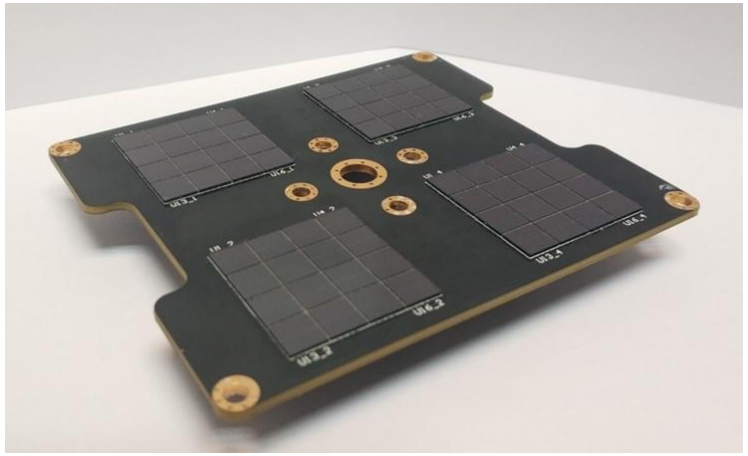
- Polished on all faces
- Wrapped with 65 μm Enhanced Specular Reflector (ESR) film
- 2.2 × 2.2 cm^2 window coupled with SiPM array

Crystal size	38×38×10 mm^3
Light yield	46000 ph/MeV
Density	6.63 g/cm^3
Effective Z	54
Energy resolution	6% @662 keV
Hygroscopic	No

Values from C&A Corporation

[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

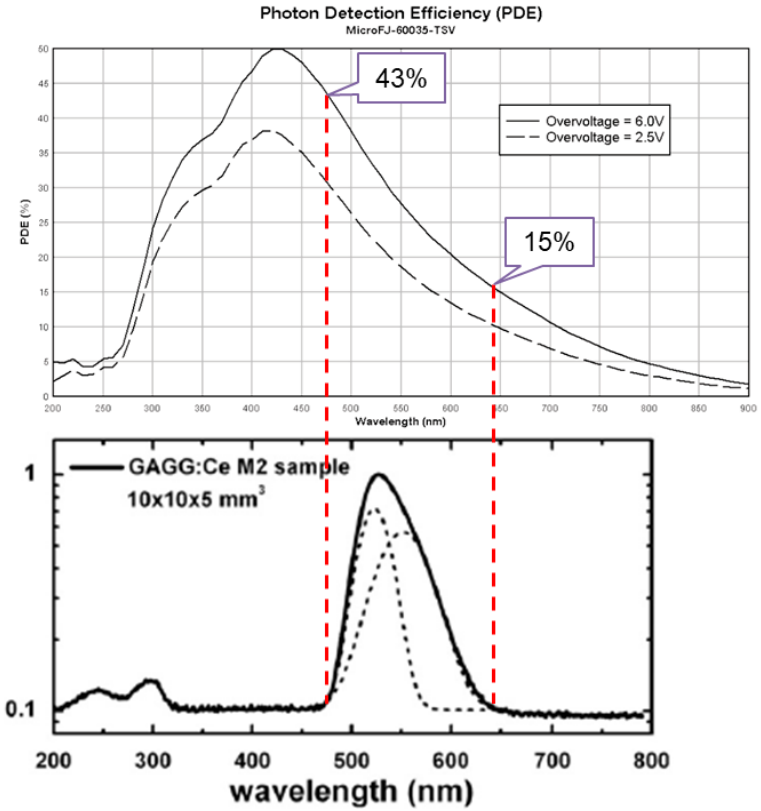
Silicon Photomultiplier



SensL MicroFJ-60035 SiPM chip (top) and the GRID SiPM array board (bottom)

Operation voltage **(No H.V. needed)**	~ 30 V
Photon detection efficiency	> 25%
Dark count rate	~ 150 kHz/mm^2
Temperature dependence of V_{br}	21.5 mV/℃

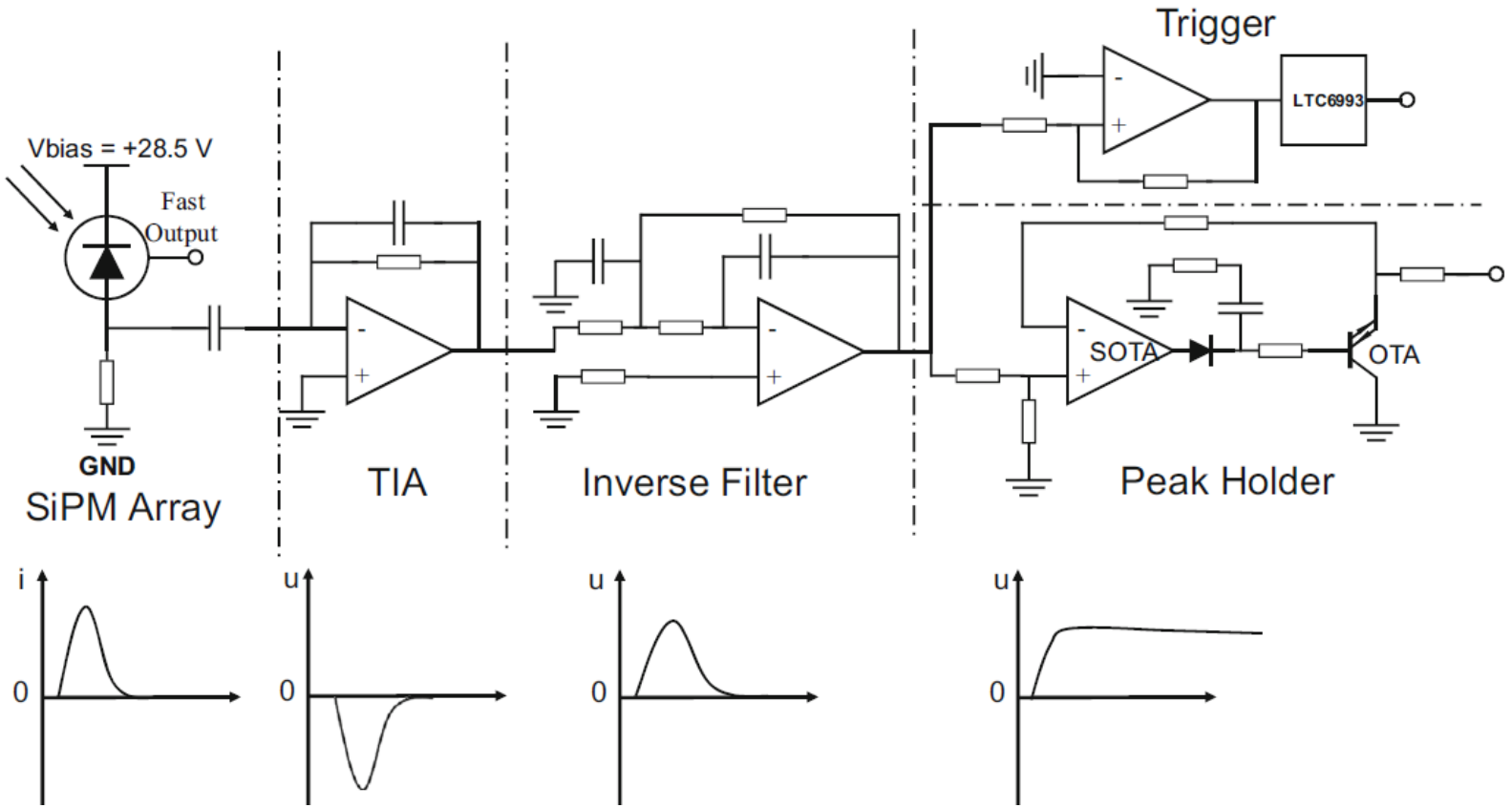
Gain is a function of temperature



Emission spectra of GAGG:Ce [4] compared with SiPM detection efficiency

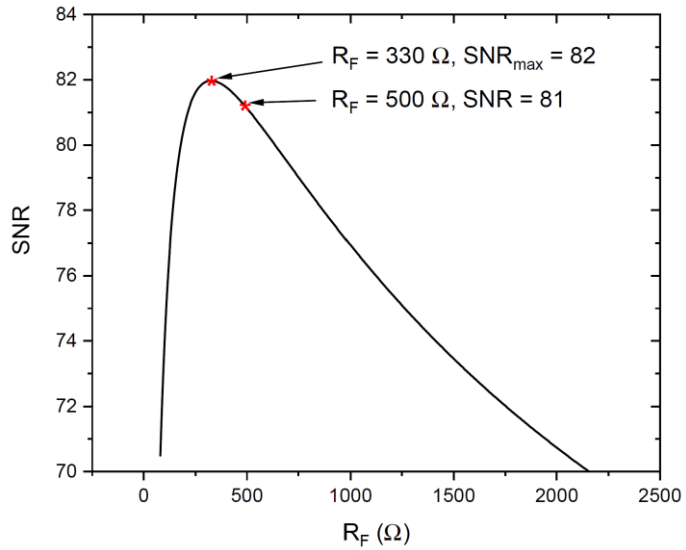
[4] J. Iwanowska et al., Performance of cerium-doped $Gd_3Al_2Ga_3O_{12}$ (GAGG) scintillator in gamma-ray spectrometry. *Nucl. Instrum. Methods Phys. Res. Sect. A.* **712**, 34–40 (2013)

Front-End Electronics



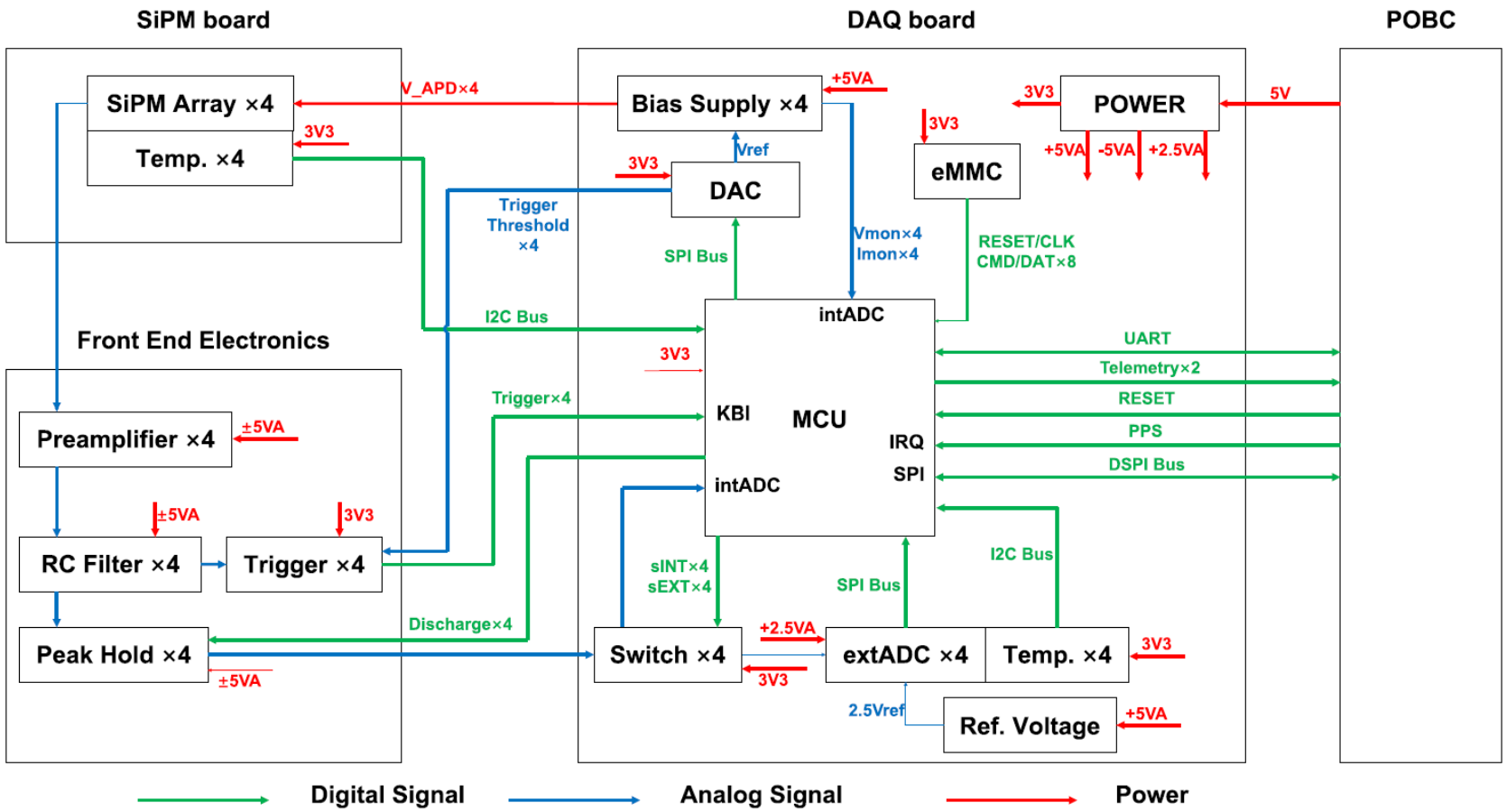
↑Schematic diagram and output pulse shape of the FEE [2]

SNR vs. R_F [2]



[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Data Acquisition Electronics

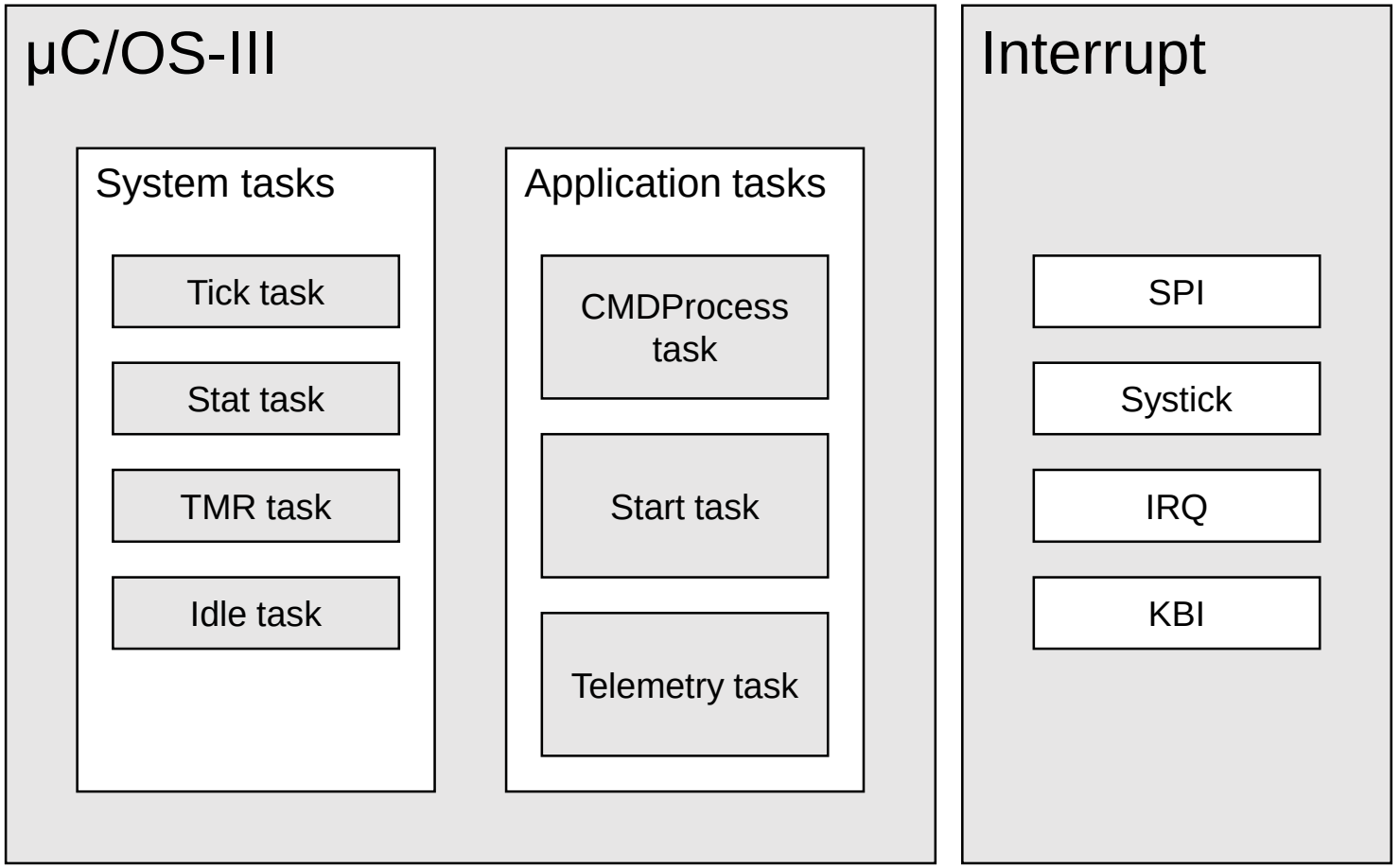


- ARM Cortex M0+ MCU
  - Automotive-grade
  - running at 40 MHz
  - low power consumption
- 16-bit 1MSPS external ADC
- eMMC data storage
  - 512 MB
  - SLC cell
- Advanced control functions
  - Adjustable SiPM bias supply
  - Charge injection module

Functional block diagram of DAQ and its connection with FEE, SiPM Carrier, and payload on-board computer board (POBC) [2]

[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

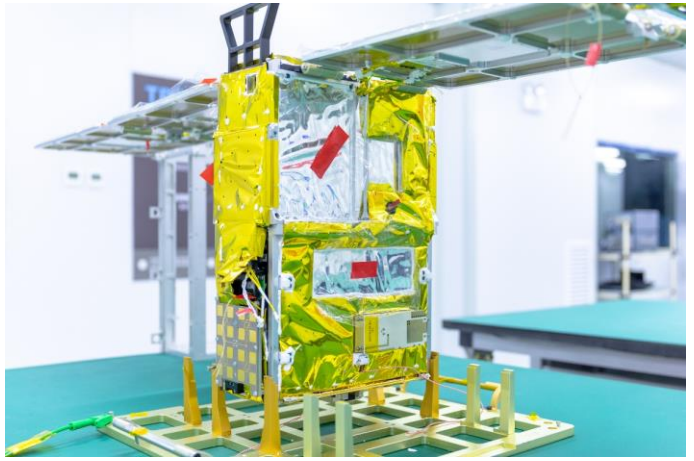
Firmware



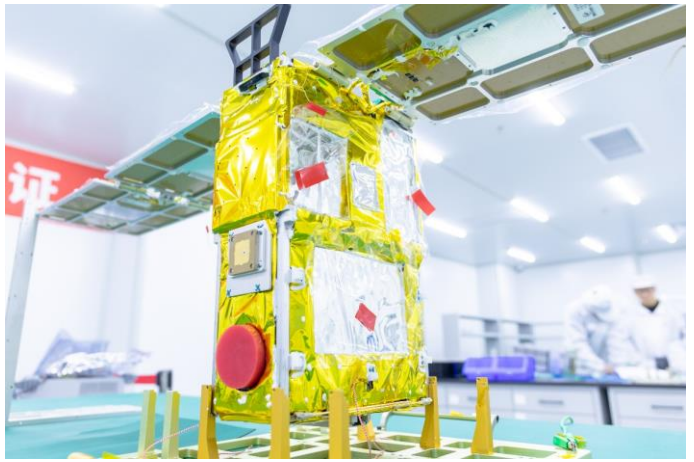
- Multi-task firmware based on real-time operating system (µC/OS-III)
- Basic functions
  - Data acquisition, storage and transmission
  - Instruction control
- Monitor functions
  - SiPM bias & current monitor
  - Temperature sensor
  - Close-loop control of SiPM bias supply
- Extra verification functions
  - SiPM I-V measurement
  - Charge injection test

Update about the GRID-03B & GRID-04

Catalog number: 51830
Launched 02/27/2022

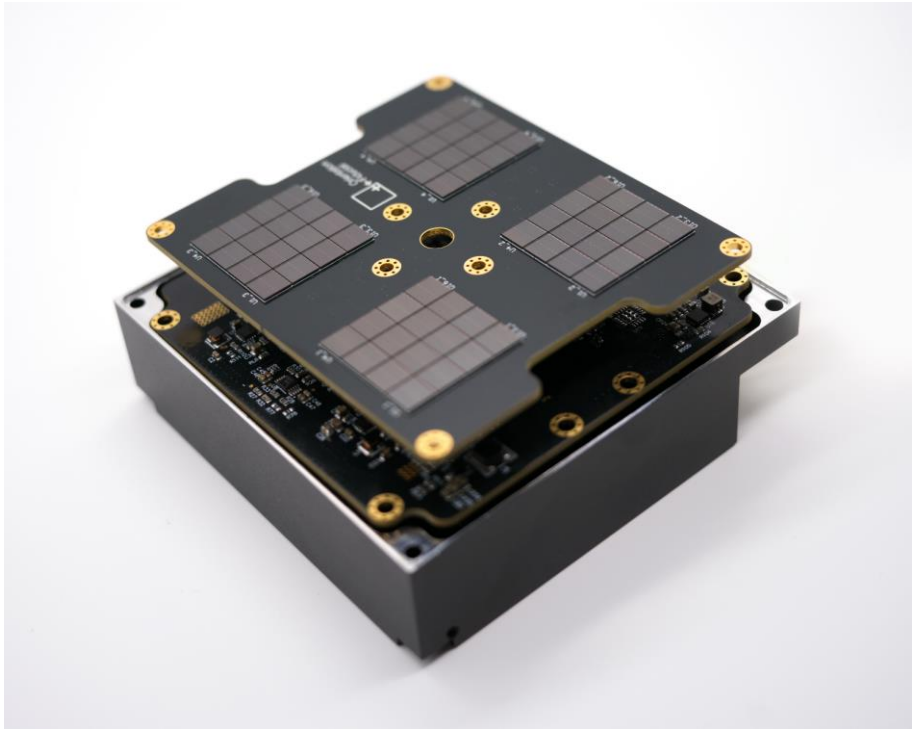


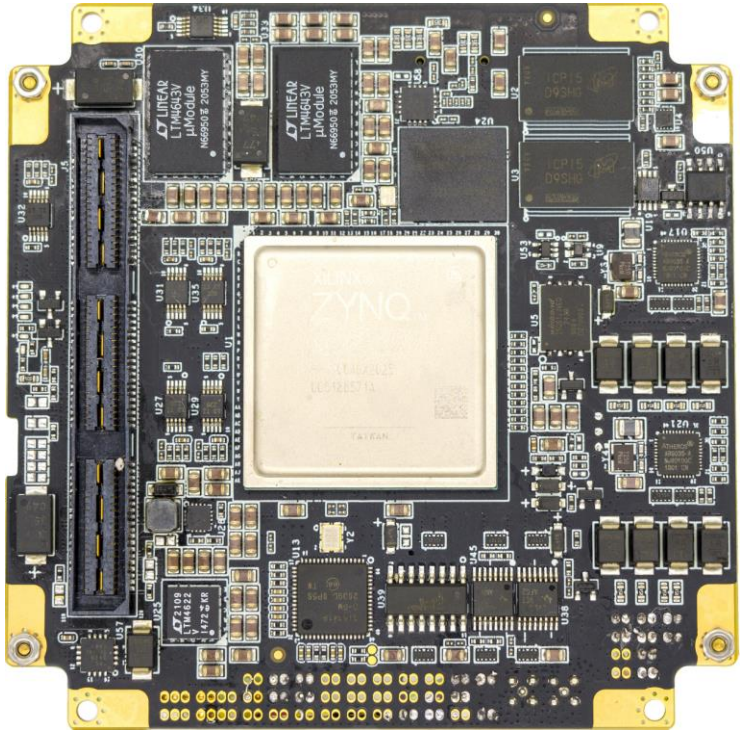
GRID-03B



GRID-04

GRID-03B New Digital Readout

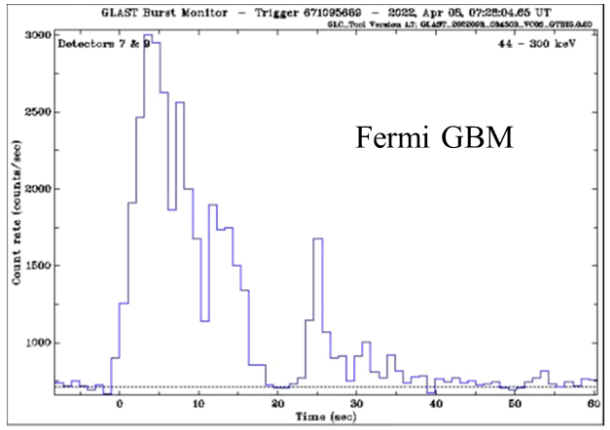


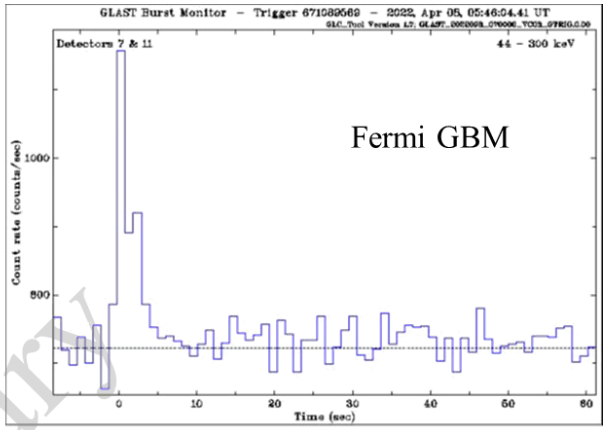


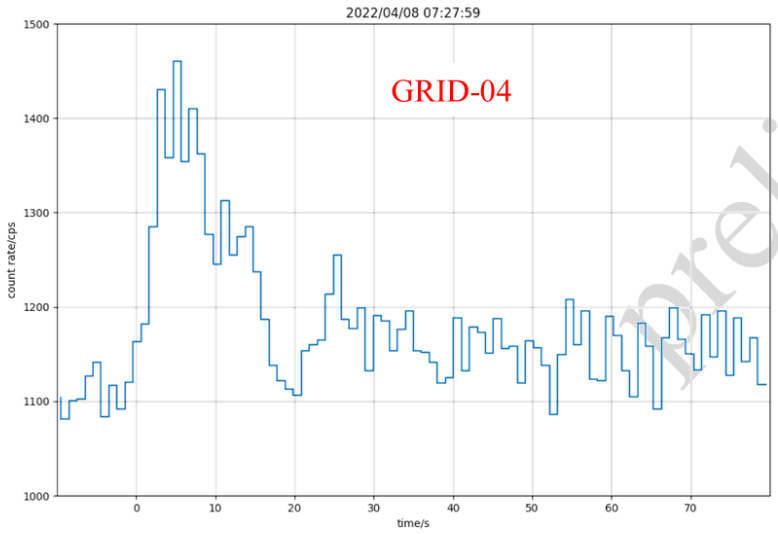
DAQ-zynq7z100

星测未来
StarDetect

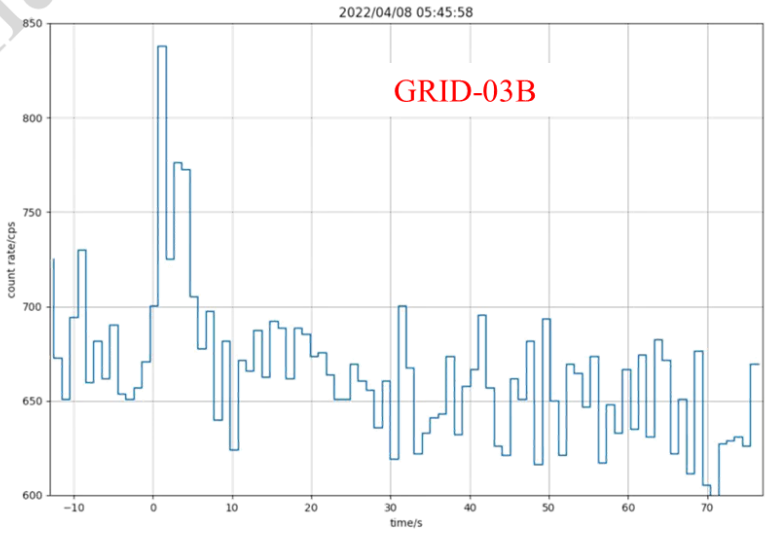
Preliminary Results from GRID-03B & GRID-04





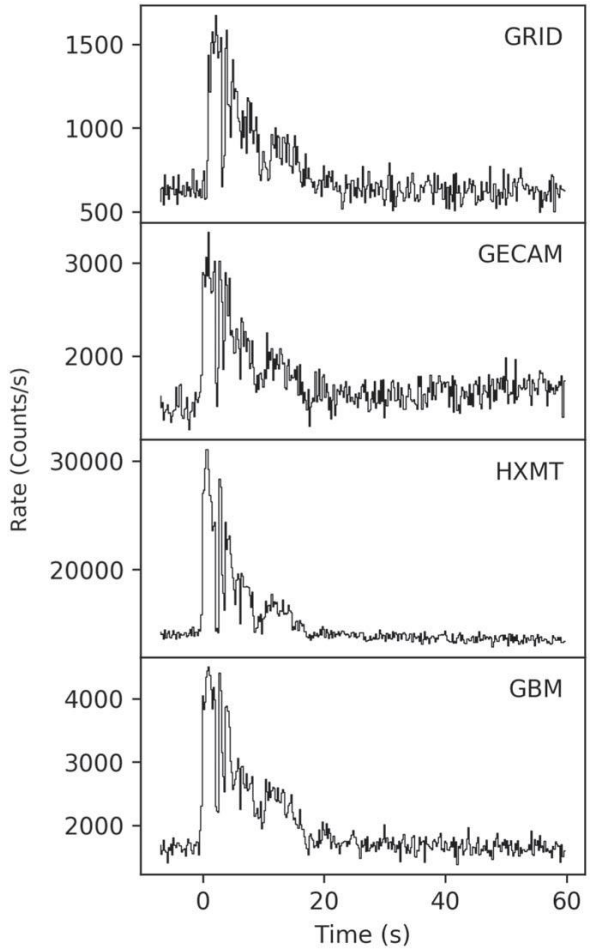


GRB 220408B

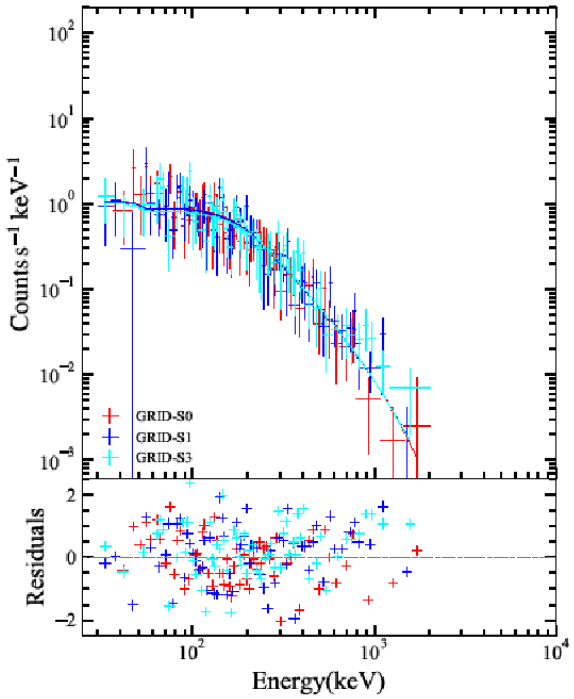


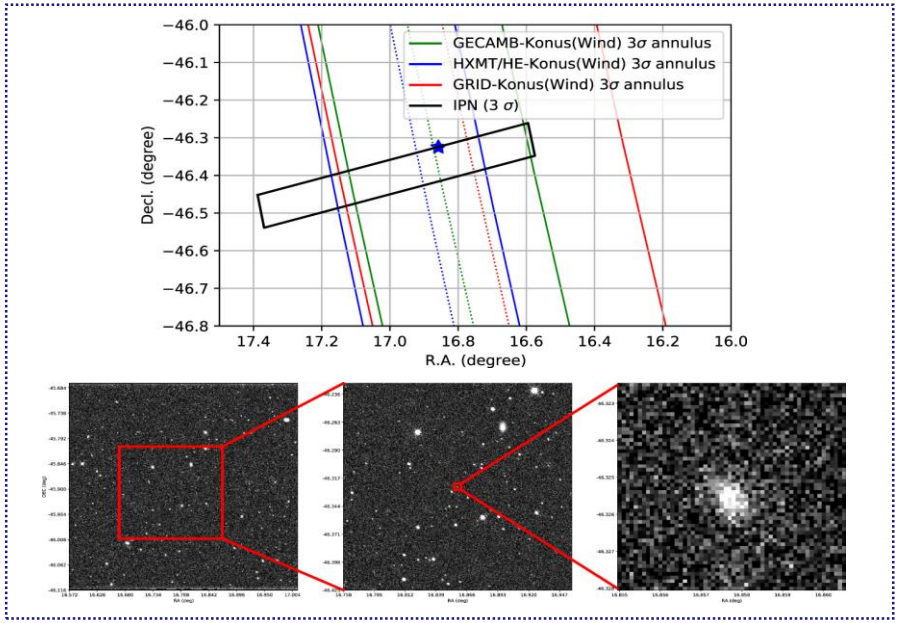
GRB 220408A

GRB 210121A: GRID-02 Detection



Light curves of the four missions [4]



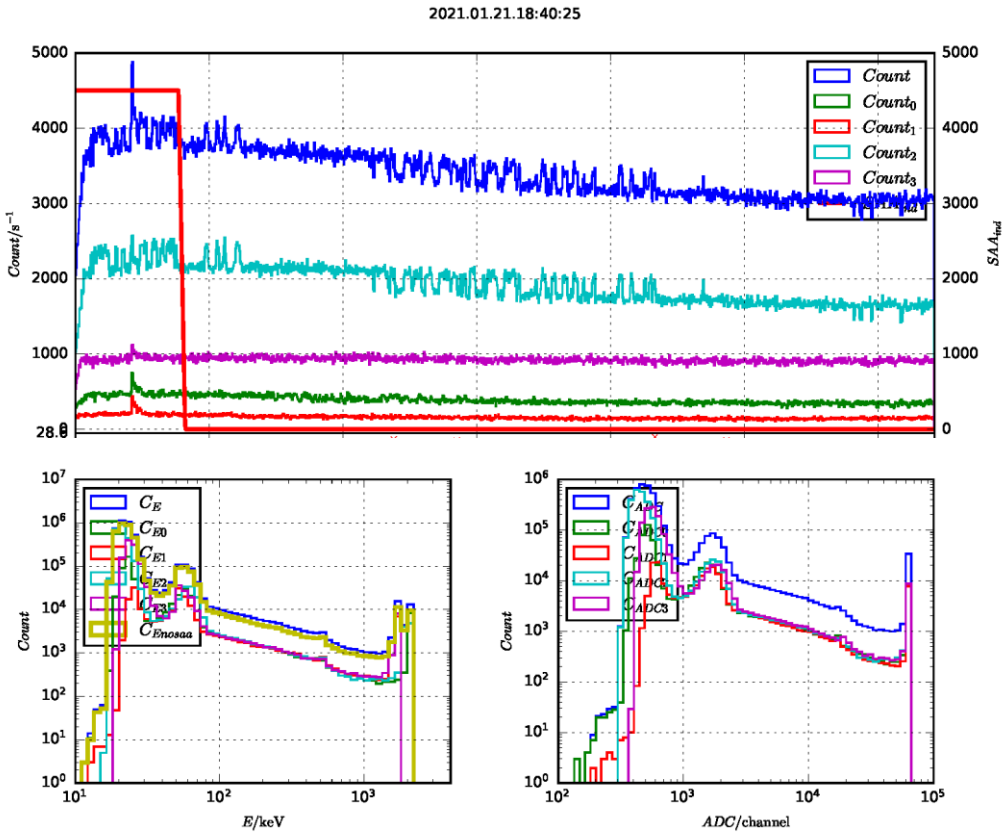


The joint localization of GRB 210121A [4]

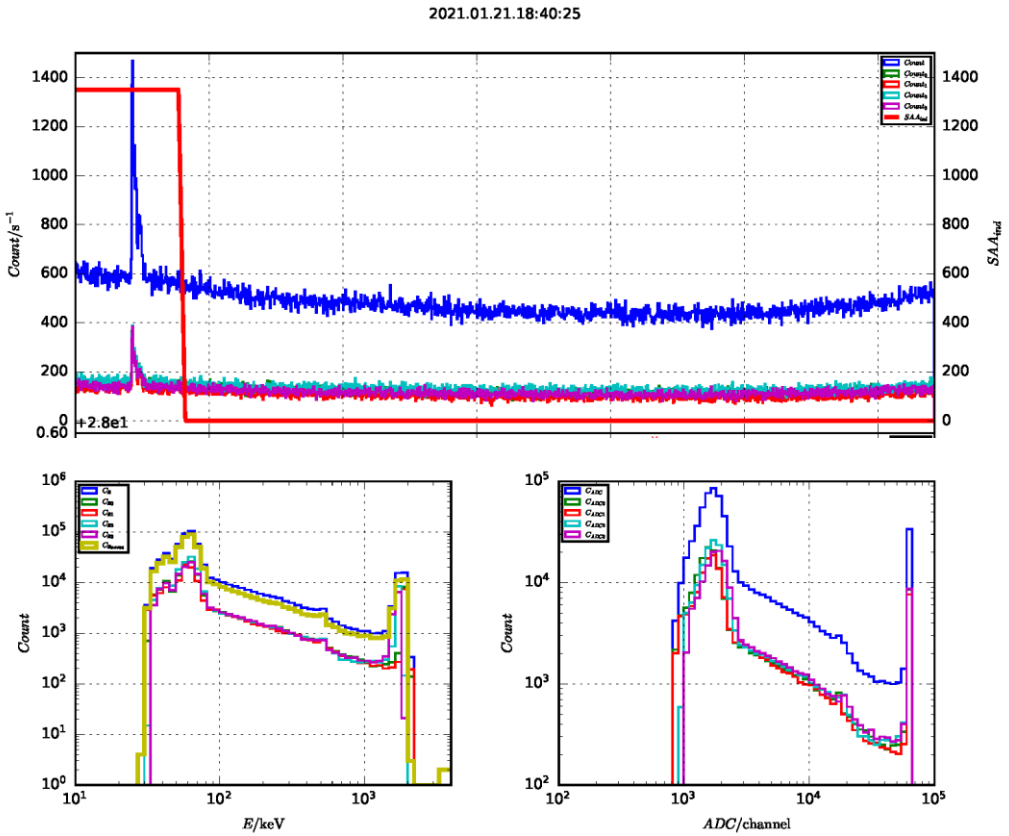
[4] Xiangyu Ivy Wang *et al*, GRB 210121A: A Typical Fireball Burst Detected by Two Small Missions, 2021 *ApJ* **922** 237

Dark Count Noise of SiPM

Example：GRB 210121A (GRID-02)



Raw Data

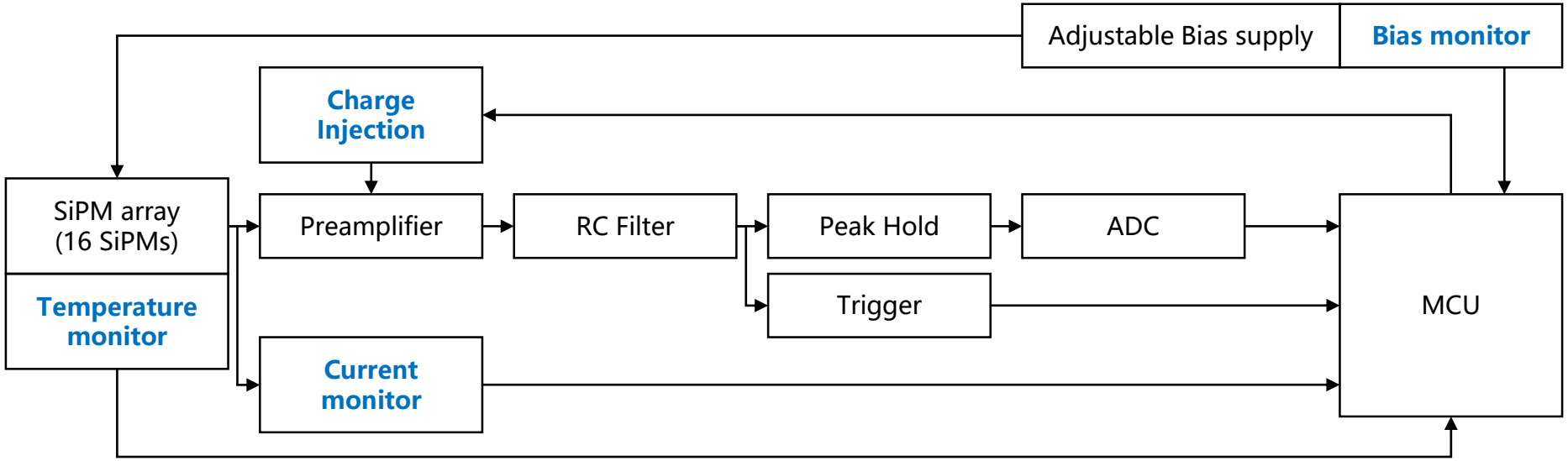


With dark count noise cut-off (6σ)

Draft paper available on arXiv (http://arxiv.org/abs/2205.10506)

In-orbit radiation damage characterization of SiPMs in GRID-02 CubeSat detector

In-orbit Characterization Setup and Methods



Housekeeping data:
- Timestamp
- Bias voltage
- Current
- Temperature

Block diagram of the front-end electronics and characterization circuits of one channel in GRID detector. Details about GRID instrument design can be found in [2].

Scientific observation: ~20k seconds (5 ~ 6 hours) per day
- Housekeeping data recorded to analyze SiPM dark current

Daily characterization experiments:
- I-V measurement at different bias voltage
- Charge injection test without and with bias voltage

[2] Wen, JX., Zheng, XT., Yu, JD. *et al.* Compact CubeSat Gamma-ray detector for GRID mission. *NUCL SCI TECH* **32,** 99 (2021)

Dark Current Increase

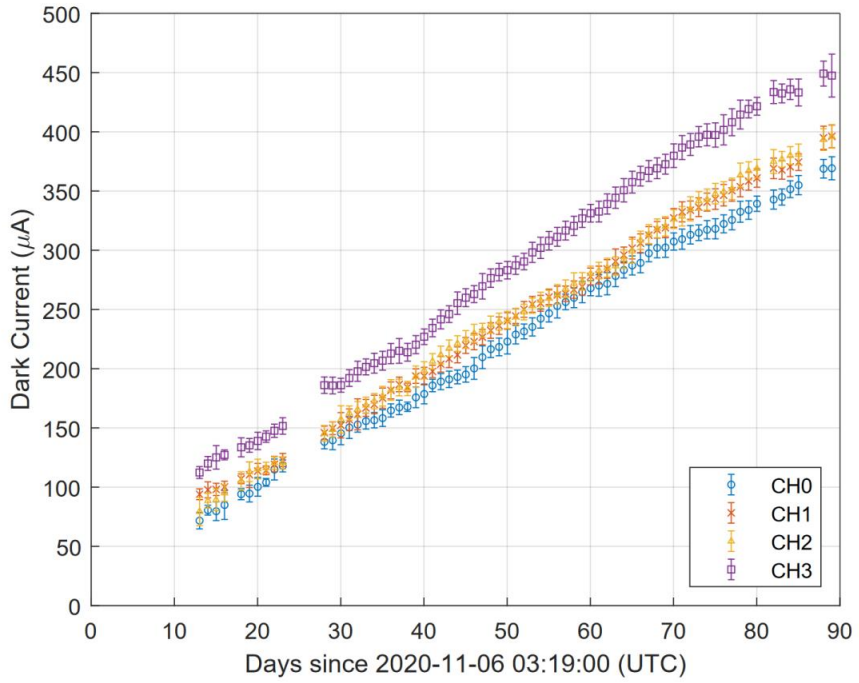


Figure 5: SiPM dark current (I_{dark}) at 28.5 V bias voltage as a function of time. The values are the sum of 16 SiPMs in the same channel and are unified to 5°C.

- Linear relationship between I_{dark} and radiation damage (dose or particle fluences) is found (model MicroFJ-60035-TSV):

  GRID-02: ~ 93/96/98/110 μA / (year · chip) @5 ℃ & 28.5 V
  ~ 50 μA / (year · chip) @-20 ℃ & 28.5 V
  SIRI-1: ~ 132 μA / (year · chip) @28.5 V, temp. not mentioned (7.75 ℃?)

- An approximate empirical equation around 5 ℃:

$$I_{\mathrm{dark}}(\mu\mathrm{A}) = 16 \cdot (0.2678 \cdot Time(\mathrm{Days}) + 2.091) \cdot e^{0.03475 \cdot (T - 273.15 - 5)}$$

- **with SHIELDOSE-2 model, SPENVIS calculates cumulative dose:**

$$I_{\mathrm{dark}}(\mu\mathrm{A}) = 16 \cdot (195.5 \cdot Dose(\mathrm{Gy}) + 2.091) \cdot e^{0.03475 \cdot (T - 273.15 - 5)}$$

Draft paper available on arXiv (http://arxiv.org/abs/2205.10506)
In-orbit radiation damage characterization of SiPMs in GRID-02 CubeSat detector

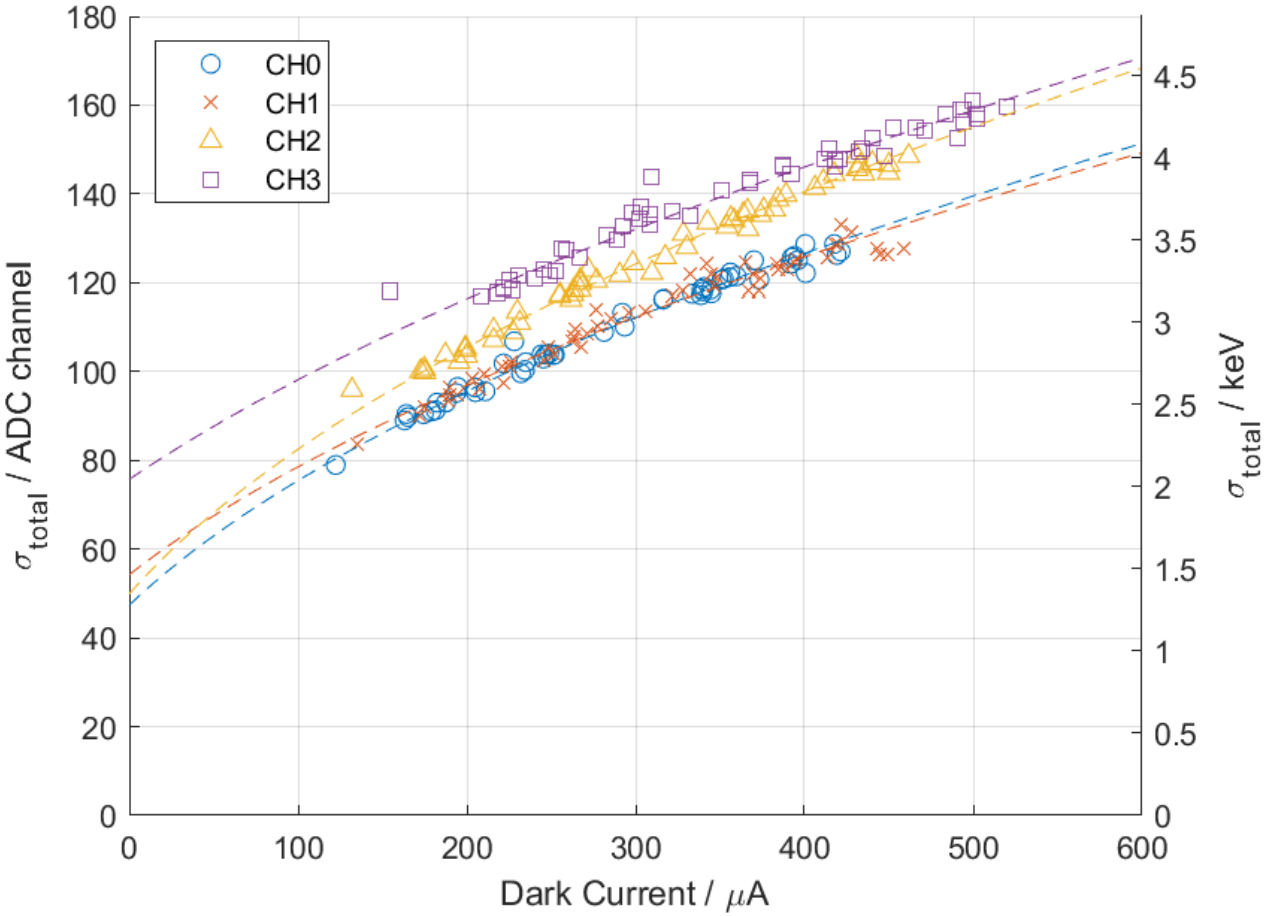
Noise Assessment Through Charge Injection

- Campbell’ s theorem gives

$$\sigma^2_{\text{dark current}} = DCR \cdot (Gain \cdot e)^2 \cdot \int h^2(t)\,\mathrm{d}t$$

$$\propto I_{\text{dark}} \cdot (V_{\text{bias}} - V_{\text{BD}})$$

GRID-02 energy-channel calibration result



Noise (sigma) increasing rate: ~ 7.5 keV/year

Draft paper available on arXiv (http://arxiv.org/abs/2205.10506)

In-orbit radiation damage characterization of SiPMs in GRID-02 CubeSat detector

Conclusion

- GRID is a CubeSat mission for gamma-ray burst observation, which is proposed and developed by student team, with considerable contribution from undergraduate students, and will remain operated as a student project in the future.

- The first four GRID detectors (GRID-01/02/03B/04) have been launched in Oct. 2018, Nov. 2020, and Feb. 2022 respectively.

- GRID have observed its first dozen of GRBs. Close cooperation between GRID and the other GRB missions (e.g. GECAM) has been established.

- Several universities in China have joined the GRID collaboration. More detectors are ready to launch.

Future Planning of GRID

- GRID-05B (Tsinghua Univ.)

  Prof. Ming ZENG & Hua FENG

- GRID-06B (Nanjing Univ. & Sichuan Univ.)

  Prof. Bin-bin ZHANG, Prof. Zhonghai WANG & Rong ZHOU

- GRID-07 (Beijing Normal Univ.)

  Prof. Lin LIN, Yuanyuan LIU, Jianyong JIANG

- GRID-08B (Nanjing Univ. & Sichuan Univ.)

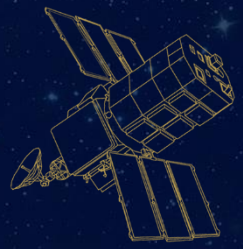
  Prof. Bin-bin ZHANG, Prof. Zhonghai WANG & Rong ZHOU

Outlook

- Radiation damage effect is a key problem of SiPMs operating in orbit. More quantitative studies are needed.

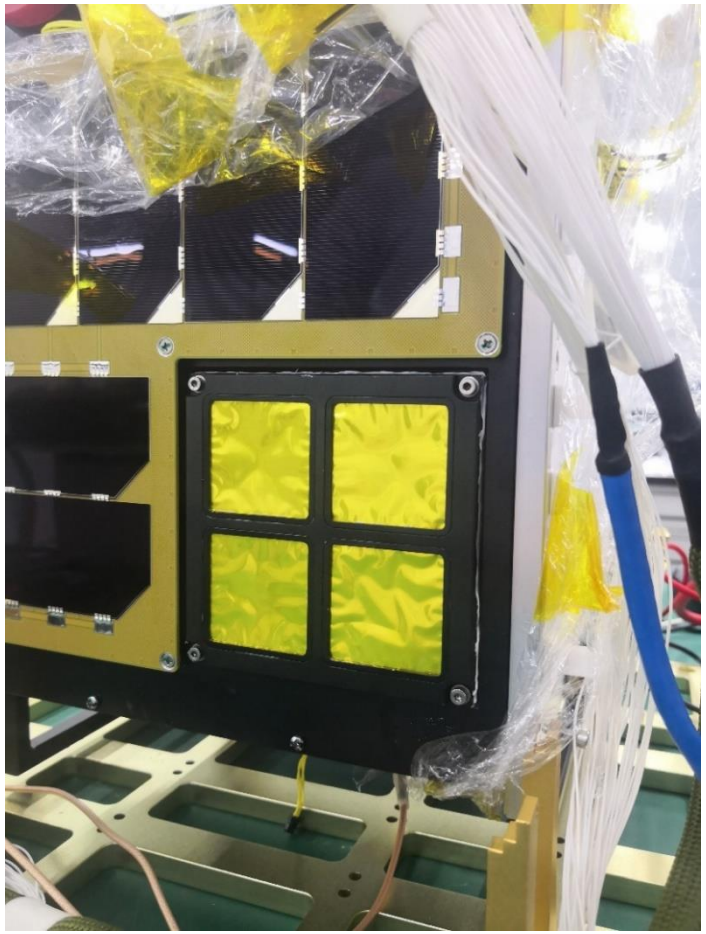
- Real-time datalink is important for the trigger, localization and follow-up observation for similar CubeSat constellations including GRID.
- One of the possibilities is the BeiDou short message communication service, which is already applicated on GECAM satellites.

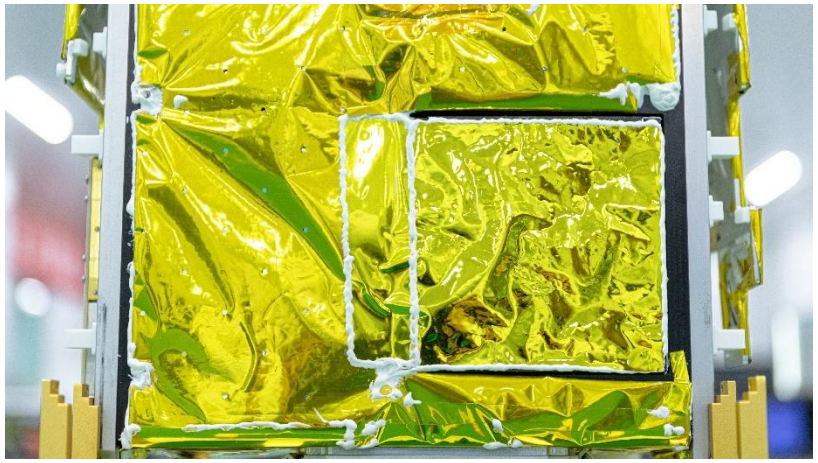
- For GRID, we found that CubeSat observation time is quite limited by its orbit inclination and energy balance.



Thank you !

GRID-02 Overview





Spacetrack catalog number	46838
Orbit	464 x 474 km, 97.3°
Launch Date (UTC)	2020.11.06, 03:19
Launch site	Taiyuan Space Launch Center
Launch vehicle	Long March 6

Data from https://www.heavens-above.com/

GRID-02 Launched on Nov. 6 2020

Designation	
Spacetrack catalog number	46838
COSPAR ID	2020-079-M
Orbit	460×471 km, 97.2°
Country/organization of origin	China
Date (UTC)	06 November 2020 03:19
Launch site	Taiyuan Space Launch Center, China
Launch vehicle	Long March 6

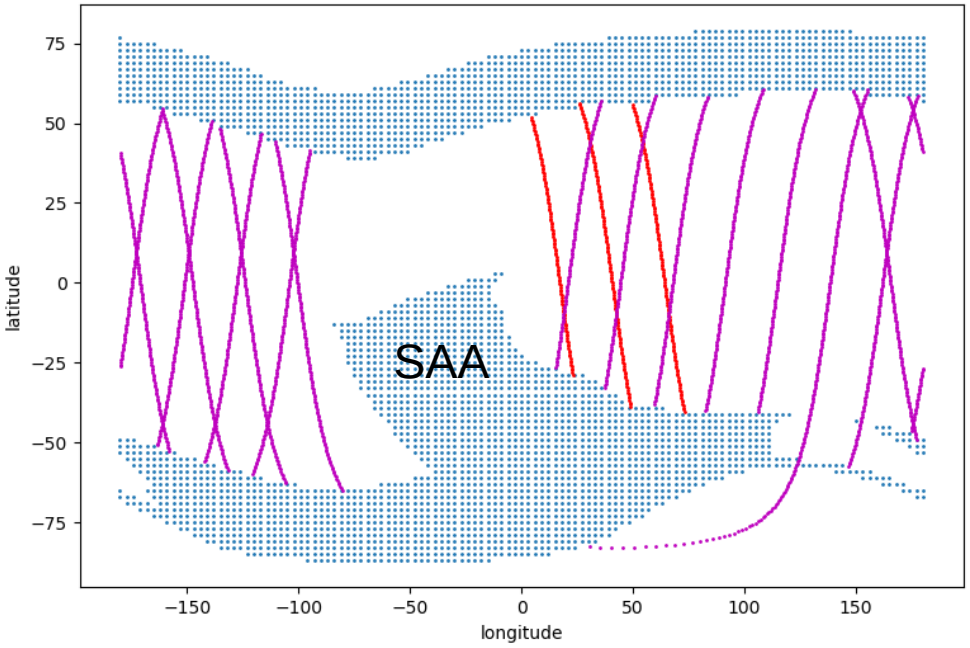
Data from https://www.heavens-above.com/

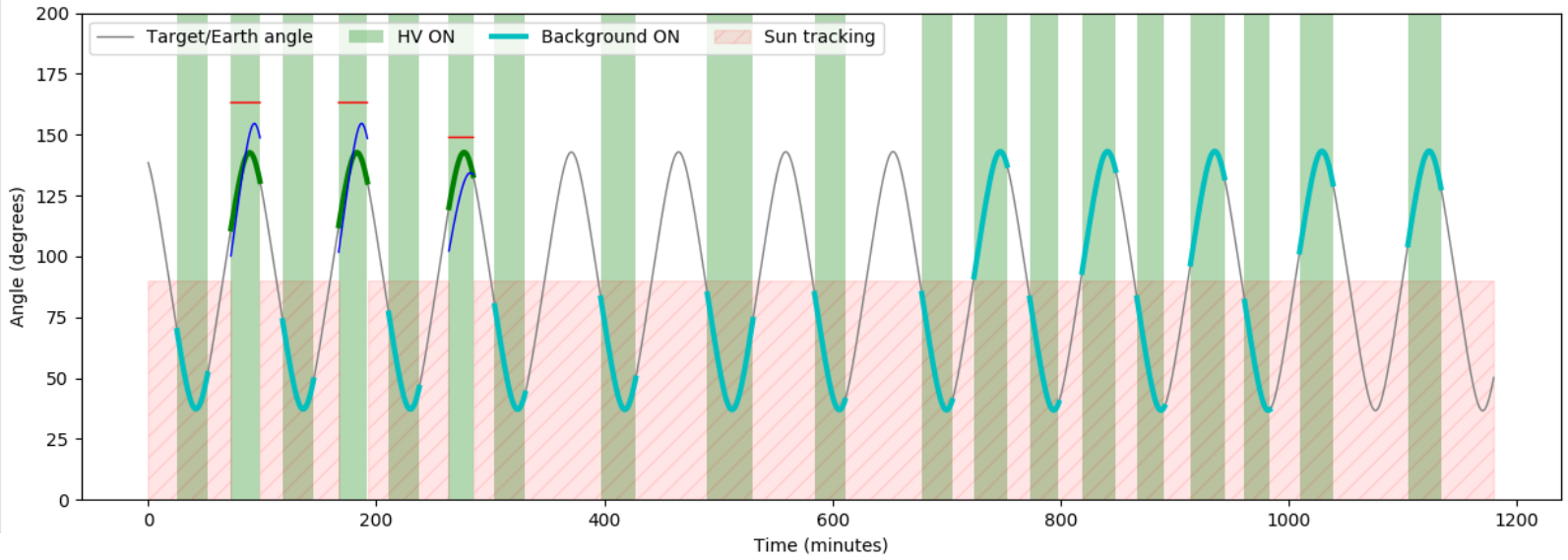
Daily Observation Phase

- Undergraduate students on duty make observation plan every day
- 10 ~ 20 observations per day, 20 ~ 40 minutes each (depends on other payloads and CubeSat platform)
- Shutdown in South Atlantic Anomaly (SAA) and high-latitude region

✓ Targeting observation: point to Crab (Inertial pointing mode)

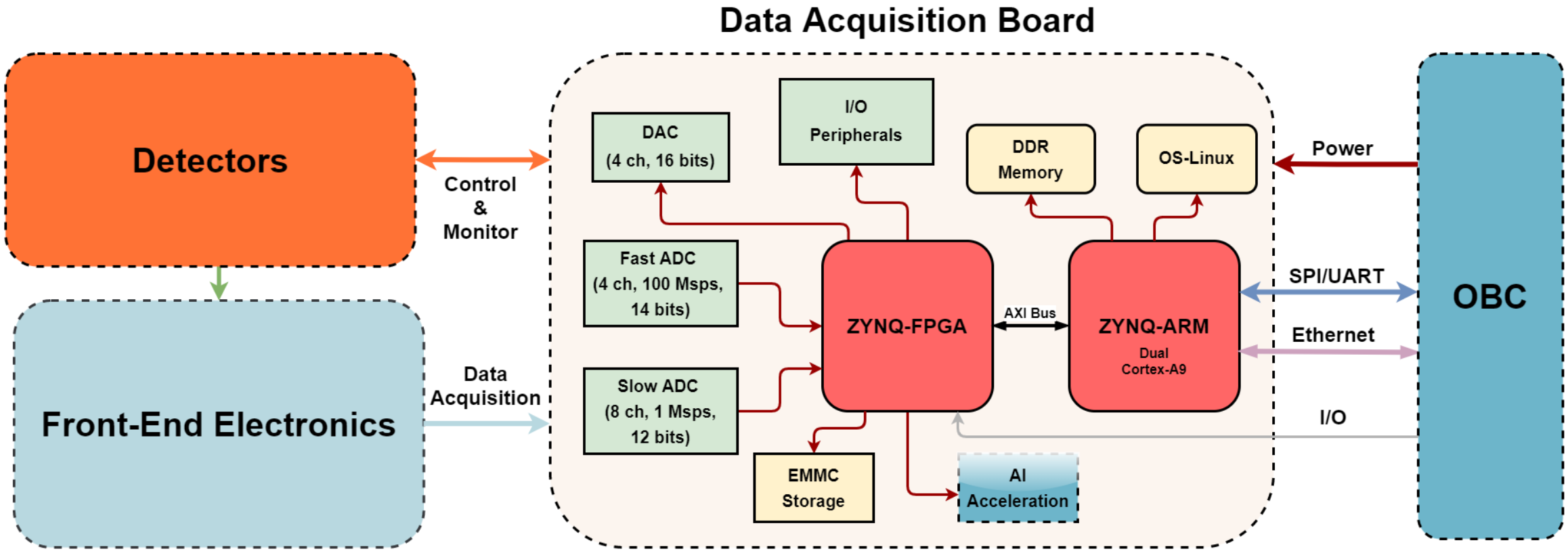
✓ Non-targeting observation: random orientation (Inertial or magnetic sun tracking mode)



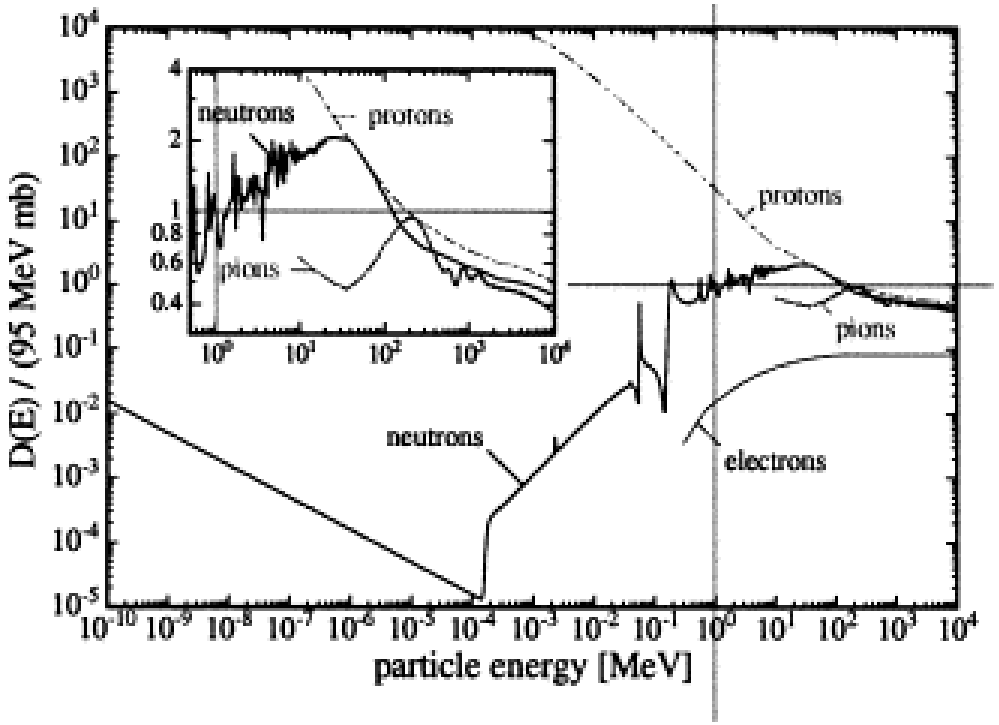


Example observation plan during Nov. 29 2020 17:00 ~ Nov. 30 2020 12:30 (UTC)

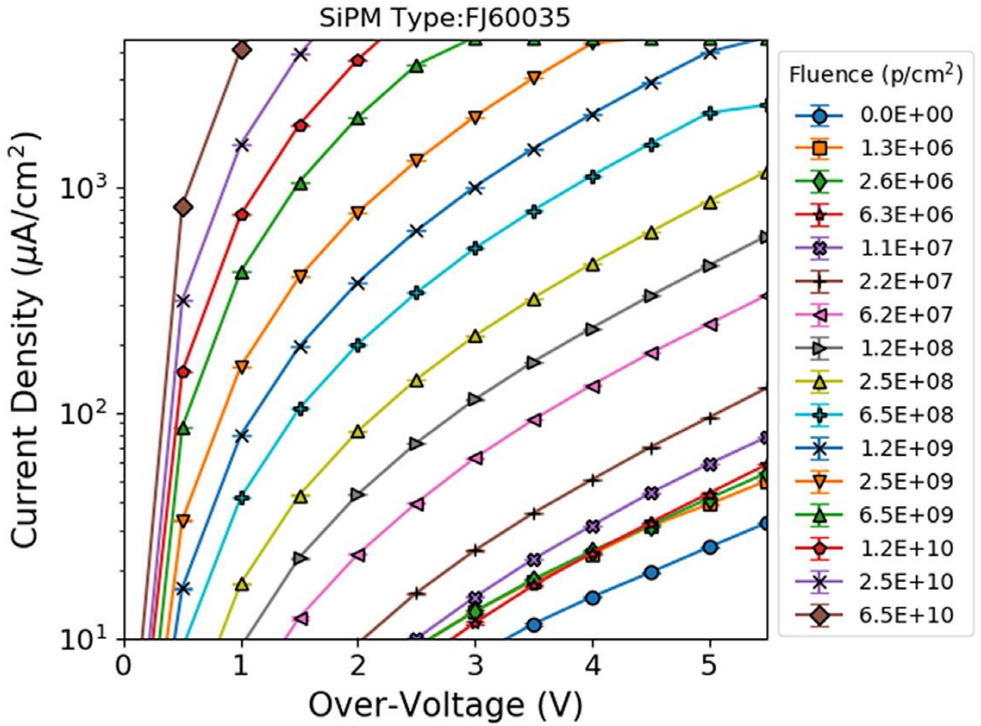
StarDetect DAQ System architecture



Radiation Damage of SiPMs



Non-ionizing energy loss (NIEL) for different particles in Si [5]



IV Curve for SensL MicroFJ-60035-TSV for the list proton fluence [6]

Proton —NIEL→ Bulk damage (defects) —Thermal excitation→ Dark current increase

[5] G. Lindström, Radiation damage in silicon detectors. *Nucl. Instrum. Methods Phys. Res. Sect. A.* **512**, 30–43 (2003)
[6] Mitchell, L. et al., Radiation damage assessment of SensL SiPMs. *Nucl. Instrum. Methods Phys. Res. Sect. A.* **988**, 164798 (2021)

Methods of Improve SNR

- Dominant noise for radiation damaged SiPM:

$$\sigma^2_{\text{dark current}} = DCR \cdot (Gain \cdot e)^2 \cdot \int h^2(t)\,\mathrm{d}t$$

① Lower temperature, lower DCR
- DCR reduced by half for 16℃ decrease at room temperature
- Difficult for CubeSats ?

② Lower bias voltage, lower DCR
- Trade off: Gain & PDE decrease as well
- Care must be taken to find the optimum value

③ Lower readout time constant
- Limited by scintillation decay time

The GRID Collaboration

The 1st and 2nd GRID collaboration meeting

- Started since October 2016 at Tsinghua
- More than 100 Students from 17 universities have joined the GRID collaboration by now

Open source framework

✓ Fixed design

✓ 100% open to member institutes

✓ Member institutes can build their own detector/ground station/satellite