In-orbit Radiation Damage Characterization of SiPMs in the GRID-02 CubeSat Detector

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Abstract

Recently, silicon photomultipliers (SiPMs) have been used in several space-borne missions, owing to their solid state, compact size, low operating voltage, and insensitivity to magnetic fields. However, operating SiPMs in space results in radiation damage and degraded performance. In-orbit quantitative studies on these effects are limited. In this study, we present in-orbit SiPM characterization results obtained by the second detector of the Gamma-Ray Integrated Detectors (GRID-02), which was launched on 6 November 2020. An increase in dark current of \( \sim100 \, \mu A/\text{year per SiPM chip} \) (model MicroFJ-60035-TSV) at 28.5 V and 5 \(^\circ\)C was observed. Consequently, the overall noise level (sigma) of the GRID-02 detector increased by \( \sim7.5 \, \text{keV/year} \). The estimate of this increase is \( \sim40 \, \mu A/\text{year per SiPM chip at -20 \(^\circ\)C} \), highlighting the positive effect of using a cooling system.

Keywords: SiPM, Radiation damage, Dark current, CubeSat, GRID

1. Introduction

Silicon photomultipliers (SiPMs) have recently become popular photodetectors for scintillator readout. Thanks to their compact size, solid state, low operating voltage, and insensitivity to magnetic fields, they have become practical alternatives to traditional photomultiplier tubes (PMTs), especially for space-borne applications. As summarized in Table 1, several space missions...
Table 1: Launched space missions equipped with SiPMs.

| Project name     | Launch date   | Orbit          | Ref. |
|------------------|---------------|----------------|------|
| Lazio-Sirad      | 2005.04.15    | 417 × 423 km 51.6° ISS | [1] |
| HXMT             | 2017.06.15    | 533 × 543 km 43.0° LEO | [2] |
| GRID-01          | 2018.10.29    | 502 × 519 km 97.4° LEO | [15] |
| SIRI-1           | 2018.12.03    | 567 × 589 km 97.7° SSO | [3, 4] |
| Mini-EUSO        | 2019.08.22    | 417 × 423 km 51.6° ISS | [10] |
| LabOSat          | 2020.01.15    | Unknown LEO    | [16] |
| GRID-02          | 2020.11.06    | 457 × 467 km 97.2° LEO | [15] |
| GECAM            | 2020.12.09    | 586 × 604 km 29.0° LEO | [6] |
| GRBAlpha         | 2021.03.22    | 534 × 563 km 97.5° LEO | [7] |
| SIRI-2           | 2021.12.07    | 35784 × 35788 km 0.0° GEO | [5] |
| GARI             | 2021.12.21    | 417 × 423 km 51.6° ISS | [9] |
| GRID-03B & GRID-04 | 2022.02.27   | 523 × 550 km 97.5° LEO | [15] |

equipped with SiPMs have been launched. SiPMs were used for scintillator readout [1, 2, 3, 4, 5, 6, 7, 8, 9] or ultraviolet (UV) observation [10]. However, it is known that SiPMs are susceptible to radiation damage in space environment, which leads to significant increase in dark count rate and degrades their noise performance. Few in-orbit radiation damage effect studies of SiPMs have been reported, although many experiments have been conducted at accelerator facilities [2, 11, 12, 13, 14]. SIRI-1 reports one of the few in-orbit results showing a significant increase in the dark current of SiPM with respect to time and dose [12].

The Gamma-Ray Integrated Detectors (GRID) [15] is a space mission concept with the purpose of monitoring gamma-ray bursts (GRBs) using a constellation of CubeSats equipped with a scintillator detector readout by SiPM. It is also specifically designed with SiPM performance study setups to conduct SiPM characterization experiments. The first GRID detector, GRID-01, was launched on 29 October 2018 and the subsequent one, GRID-02, was launched on 6 November 2020. Many other similar missions are under development, including BurstCube [17], HERMES [18], EIRSAT-1 (GMOD) [19], Glowbug [20], CUBES [21], and GALI [22], most of which will use SiPM to read out scintillators.

In this article, we present the in-orbit SiPM characterization results obtained by GRID-02 during the first few months after launch. Based on the measurement setups of the detector, we analyzed the change in breakdown voltage and dark current due to radiation damage. An estimate of the dark current increase rate of the SiPM operating in low earth orbit (LEO) was given. The energy resolution and low energy threshold deterioration of GRID-02 as a result of dark count noise increase were also studied.
2. In-orbit characterization setup and methods

In addition to the optimization of gamma-ray detection in GRID, several functions have been specifically designed for performance studies of SiPMs. The operating conditions of the SiPMs, including the current, bias voltage, and temperature, were monitored. In addition, a charge injection module was used to analyze the noise contributions. The details of the GRID instrument design can be found in [23]. Herein, we briefly review the biasing and readout circuits, and focus on the characterization setup.

The exploded view and simplified block diagram of the GRID detector are shown in Fig. 1 and Fig. 2, respectively. The detector comprises four independent channels designated as CH0 - CH3. Each channel consists of a scintillator crystal, $4 \times 4$ array of MicroFJ-60035-TSV\(^1\) SiPMs, bias voltage power supply, readout electronics, and SiPM characterization circuits. A microcontroller unit (MCU) acts as data acquisition (DAQ) electronics to monitor and control the four channels.

\(^1\)MicroFJ-60035-TSV datasheet
Due to limited power and payload volume on a CubeSat, there was no active cooling system in the GRID detector. The temperature of the GRID detector depends mainly on the overall temperature of the satellite. The temperature of each SiPM array was measured using a digital temperature sensor, TMP112, which offers 0.5 °C accuracy.

Moreover, a charge injection module controlled by the MCU was connected to the preamplifier, such that a constant charge pulse could be injected at a specified frequency. Through charge injection, with bias voltage on or off, we can analyze the noise contributions, either from the dark count noise of the SiPM, or electronic noise, in addition to other noise sources.

Figure 3 shows the schematic layout of the $I \sim V$ measurement setup. The 16 SiPMs in the same array were connected in parallel, which means that we can only characterize the entire array, rather than each single SiPM chip. The adjustable positive bias voltage on the cathode was supplied by a switching regulator, LT3482, and controlled by a 12-bit digital-to-analog converter (DAC), AD5672R. After a resistive divider and voltage follower, it is monitored by an MCU internal 12-bit analog-to-digital converter (ADC). The current through the SiPMs is converted to voltage by a 1 kΩ grounding resistor on the anode, then measured by the same MCU internal ADC after passing through a voltage follower. The difference between these two voltages is the bias voltage ($V_{bias}$) of the SiPM. The proportional-integral-differential (PID) control method was
applied to stabilize $V_{bias}$.

The current, bias voltage and temperature values were recorded every second as housekeeping data during scientific observations. This was used to analyze the dark current of SiPM. The breakdown voltage ($V_{bd}$) of the SiPM was determined by $I \sim V$ measurements at different bias voltages. This measurement method is encapsulated in a special mode triggered by an instruction. Once switched to this mode, the bias voltage was successively changed to 40 preset values below and above $V_{bd}$. The measurement lasted approximately 40 s, during which the temperature fluctuation was negligible. Note that when comparing the different measurements, temperature correction was performed.

We carefully scheduled the characterization experiments and scientific observations based on the characterization setup described above. The payload debug phase began on 8 November 2020 after launch and finished on 19 November 2020. We then moved to the daily observation phase and arranged the characterization experiments once per day from 4 December 2020. Owing to the existence of other payloads, the scientific observation time of GRID-02 was limited to approximately 20 ks (5 - 6 h) per day.

3. Results

3.1. Breakdown voltage

Several methods can be used to extract $V_{bd}$ through $I \sim V$ measurements, as discussed in [24] and [25]. For the convenience of comparison, the method described in the datasheet was applied [26]. The $\sqrt{I}$ versus $V_{bias}$ was fitted with a linear function above $V_{bd}$, where $V_{bd}$ is defined as the voltage intercept.

Temperature correction is applied through

$$V_{bd}(T) = V_{bd}(T_5) - k_{bd} \cdot (T - T_5),$$

(1)
Figure 4: Breakdown voltage ($V_{bd}$) of SiPM as a function of time. The values are obtained by linear fit of $\sqrt{I}$ versus bias voltage ($V_{bias}$) and corrected to 5°C. The error bars show the 95% confidence intervals.

where $T_b = 5$°C is the typical operating temperature of GRID-02 and is chosen as the reference temperature; $T$ is the absolute temperature of each $I \sim V$ measurement; $k_{bd} = 21.5$ mV/K is the temperature coefficient of $V_{bd}$ specified in the datasheet [26]. This $k_{bd}$ value was also used in the gain calibration procedure for GRID-02 [27]. In Fig. 4, $V_{bd}$ as a function of time is shown. Error bars represent 95% confidence intervals. The systematic error due to temperature correction was relatively small; thus, it was neglected. No significant change in $V_{bd}$ is observed.

3.2. Dark current

The dark current ($I_{dark}$) of SiPM can be expressed by

$$I_{dark} = DCR \cdot (Gain \cdot e) \cdot ECF$$
$$= DCR \cdot C_{pix} \cdot (V_{bias} - V_{bd}) \cdot ECF,$$

(2)

where $DCR$ is the dark count rate, $Gain$ is the overall gain of SiPM, $e$ is the elementary charge, $ECF$ is the excess charge factor, and $C_{pix}$ is the pixel capacitance including the quenching capacitance [25]. The term $(V_{bias} - V_{bd})$ is also known as overvoltage ($V_{ov}$).
$C_{\text{pix}}$ was found to be independent of temperature and radiation damage [28]; $ECF$, which depends on $V_{ov}$, is assumed constant; $V_{\text{bias}}$ is set to 28.5 V without any temperature compensation, so the temperature dependence of $V_{\text{bd}}$ needs to be taken into account as discussed in Section 3.1. Field-Enhanced Shockley-Read-Hall (FE-SRH) model [28, 29] indicates the relationship between $DCR$ and temperature as follows:

$$DCR(T) \propto \left(1 + 2\sqrt{3\pi} \frac{F_{\text{eff}}}{(kT)^{3/2}} e^{\left(\frac{F_{\text{eff}}}{(kT)^{3/2}}\right)^2}\right)^2 T^2 e^{-\frac{E_a}{kT}}.$$

where $F_{\text{eff}}$ is the effective electric field strength, $k$ is Boltzmann constant, and $E_a = 0.605$ eV is the activation energy. Because $V_{\text{bias}}$ is set to 28.5 V, $F_{\text{eff}}$ is assumed to remain constant.

Finally, the $I_{\text{dark}}$ expression becomes

$$I_{\text{dark}}(T) \propto \left(1 + 2\sqrt{3\pi} \frac{F_{\text{eff}}}{(kT)^{3/2}} e^{\left(\frac{F_{\text{eff}}}{(kT)^{3/2}}\right)^2}\right)^2 T^2 e^{-\frac{E_a}{kT}} \cdot (V_{\text{bias}} - V_{\text{bd}}(T)).$$

We split the data by date, and the daily change in $I_{\text{dark}}$ corresponded to the average radiation damage effect per day. Then, we fitted the plot of $I_{\text{dark}}$ versus temperature using Eq. (4) and took $F_{\text{eff}}$ as the free parameter. The $I_{\text{dark}}$ values were unified to 5 °C and are shown in Fig. 5 as a function of time.

A linear fit shows that $I_{\text{dark}}$ increases $\sim$93/96/98/110 µA/year per SiPM chip for CH0 - CH3 respectively. The increase in $I_{\text{dark}}$ observed by SIRI-1 for the same SiPM operating in LEO is $\sim$132 µA/year per SiPM chip, despite that the operating temperature is unknown according to [4] and [12]. A discussion of the dose difference between GRID-02 and SIRI-1 is provided in Section 4.2. Furthermore, it is unclear what causes the differences among the four channels of GRID-02. Possible reasons include the difference between the temperatures of the SiPMs and the temperature sensor, and the mechanical damage received before or during launch.

Assuming $ECF \approx 1.2$ [25] and taking into account fill factor $= 0.75$, total SiPM area$^5 = 36.8$ mm$^2$, $C_{\text{pix}} = 0.186$ pF [26], and $V_{ov} = 3.5$ V, the equivalent $DCR$ per area can be calculated from Eq. (2). The increase in $DCR$ density is $\sim$4.6 MHz/(year-mm$^2$) at 5 °C. We also extrapolated the fit of $I_{\text{dark}}$ versus temperature to -20 °C to evaluate the SiPMs working with cooling systems. The increase rate of $I_{\text{dark}}$ at -20 °C is $\sim$40 µA/year per SiPM chip, which is less than half of the value at 5 °C. This is equivalent to $\sim$1.9 MHz/(year-mm$^2$) increase in $DCR$ density and is in accordance with the temperature dependence of dark current expected by FE-SRH model [28, 29].

3.3. Dark count noise

The energy resolution and noise contributions of the GRID detector were tested via charge injection. The charge injection peaks with bias voltage on and

$^5$While in the datasheet, this is referred to as active area. See [26].
Figure 5: Dark current ($I_{\text{dark}}$) 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.
were fitted with Gaussian functions to derive the standard deviation ($\sigma$), as shown in Fig. 6. Negative date values represent results obtained before launch. The error bars represent 95% confidence intervals. The results in ADC channels are converted to equivalent energy with a scale factor $\sim 0.027$ keV/channel extracted from the on-ground calibration data of GRID-02 [27]. Note that this value is heavily dependent on the detector design, such as the electronic gain and the light yield of the scintillator crystal; thus, it is only applicable to GRID-02.

The $\sigma_{\text{elec}}$ in Fig. 6(a) shows no significant change because it is dominated by the electronic noise and fluctuation of the injected charge itself. However, when a bias voltage was applied, the dark count noise became significant. $\sigma_{\text{total}}$ gradually increases with $I_{\text{dark}}$, as shown in Fig. 6(b). The total noise $\sigma_{\text{total}}$ can be expressed as

$$\sigma_{\text{total}}^2 = \sigma_{\text{DC}}^2 + \sigma_{\text{elec}}^2,$$

where $\sigma_{\text{DC}}$ is the dark count noise. Campbell’s theorem [30] shows its relationship with dark count rate ($\text{DCR}$) and $I_{\text{dark}}$:

$$\sigma_{\text{DC}}^2 = \text{DCR} \cdot (\text{Gain} \cdot e)^2 \cdot \int h^2(t)dt$$

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

where $h(t)$ is the unit impulse response of the readout electronics. Note that $I_{\text{dark}}$ here is the actual measurement result and should not be temperature-corrected. A discussion on how to evaluate the usable lifetime of the instrument based on these results is provided in Section 4.3.

4. Discussions

4.1. Dark current estimation

Several previous studies have found a linear relationship between $I_{\text{dark}}$ and radiation damage measured by dose or particle fluence [2, 12, 28]. By assuming
Table 2: Fitting results of Eq. (7).

|    | \(a_{dc}\) | \(b_{dc}\) | \(F_{eff}/k^{3/2}\) |
|----|------------|------------|----------------------|
| CH0| 738.184    | 4227.74    | 10124.9              |
| CH1| 642.893    | 5072.58    | 10286.3              |
| CH2| 733.990    | 5295.85    | 10178.1              |
| CH3| 871.504    | 8740.97    | 10122.3              |

that the radiation damage of SiPMs in the GRID detector is linearly correlated with time, and the \(F_{eff}\) in Eq. (4) is independent of radiation damage, Eq. (4) is modified as

\[
I_{\text{dark}}(\text{Time}, T) = (a_{dc} \cdot \text{Time} + b_{dc}) \\
\cdot \left(1 + 2\sqrt{3\pi} \frac{F_{eff}}{(kT)^{3/2}} e^{-\left(\frac{F_{eff}}{kT}\right)^{3/2}}\right) T^2 e^{-\frac{E_a}{kT}} \\
\cdot (V_{\text{bias}} - V_{\text{bd}}(T)),
\]

where \(a_{dc}\), \(b_{dc}\), and \(F_{eff}\) are free parameters and \(\text{Time}\) is the elapsed time after launch in days. A joint fit of \(I_{\text{dark}}\) versus time and temperature provides an estimate of \(I_{\text{dark}}\) at specified conditions. The fitting results are presented in Table 2.

By substituting these parameters into Eq. (7), we obtain an approximate empirical equation around room temperature which describes the \(I_{\text{dark}}\) of GRID-02 at 28.5 V bias voltage, and at a specified time and temperature:

\[
I_{\text{dark}}(\text{Time}, T) = 16 \cdot (0.2678 \cdot \text{Time} + 2.091) \cdot e^{0.03475 \cdot (T - T_5)},
\]

where \(T_5 = 5^\circ\text{C}\) is the reference temperature of GRID-02. The unit of \(I_{\text{dark}}\) is \(\mu\text{A}\), and the first term (16) means the result is the sum of the 16 SiPMs, as in the GRID detector. The exponential term shows that \(I_{\text{dark}}\) doubles for every \(\sim 20^\circ\text{C}\) temperature increase.

4.2. Preliminary dose estimation

The radiation damage effect on SiPMs depends on the irradiation particle type, energy, and fluence, and is traditionally evaluated by the dose or 1 MeV neutron equivalent fluence [28]. Referring to the method used by SIRI-1 [12], we provided a preliminary estimate of the dose. The SPENVIS online program [31] can generate particle fluxes with orbital information, as listed in Table 1. AP-8 and AE-8 (solar minimum) trapped particle radiation models were selected for protons and electrons, respectively. Then, using the SHIELDOSE-2 model [32], SPENVIS calculates the cumulative dose for a given period (1 year in this case) at different shielding thicknesses, as shown in Fig. 7. Considering that the equivalent shielding thicknesses in all directions are no less than 2 cm
for GRID-02, the asymptotic value of the total dose, $\sim 0.5$ Gy, was used as an approximation of the annual dose. The empirical equation for $I_{\text{dark}}$ becomes:

$$I_{\text{dark}}(Dose, T) = 16 \cdot (195.5 \cdot Dose + 2.091) \cdot e^{0.03475 \cdot (T - T_5)},$$  \hspace{1cm} (9)

where $Dose$ is the cumulative dose (Gy). Using the method described in Section 3.2, the equivalent $DCR$ density can be given as

$$DCR(Dose, T) = (9.101 \cdot Dose + 0.09733) \cdot e^{0.04019 \cdot (T - T_5)},$$  \hspace{1cm} (10)

where the unit of $DCR$ is MHz/mm$^2$. We caution that these equations are applicable only when the bias voltage is 28.5 V. Furthermore, a detailed Monte Carlo dose simulation could be performed with the mass model of the satellite and in-orbit radiation environment models.

To test this empirical equation, the dark current increase rate calculated by Eq. (9) was compared with the measurement results of SIRI-1 and GRID-04. These values were in good agreement with each other, as listed in Table 3. This estimate of the dark current can then be used to calculate the noise increase and evaluate the usable lifetime of the instrument.
Table 3: Measured and estimated dark current increase rate of SIRI-1 and GRID-04.

| Mission | Operating temperature (°C) | Operating voltage (V) | Orbit | Dose in silicon (Gy) | Dark current increase rate per SiPM chip (µA/year) |
|---------|----------------------------|-----------------------|-------|----------------------|---------------------------------------------------|
| SIRI-1  | 7.75                       | 28.5                  | 567 × 589 km 97.7° | 0.9 | 132 | 194 |
| GRID-04 | 5                          | 28.5                  | 523 × 550 km 97.5° | 0.9 | 182 | 176 |

4.3. Usable lifetime evaluation of SiPM

For a detector system readout using the SiPM, the dark count noise is one of the major contributors to the overall noise level (σ_{total}). As the dark current increased with radiation damage, the noise level also increased. In addition, the energy resolution and low energy threshold significantly deteriorate simultaneously, both of which are critical performance parameters for usable lifetime evaluation of this type of instrument. On the one hand, for GRID-02 which is in orbit, by measuring the degradation of the energy resolution, the measurement results of the dark current and the law of its increase can be confirmed. On the other hand, for any detector system in advance of launch, the experimentally obtained relationship between the energy resolution and dark current can be used to evaluate its usable lifetime in space. More specifically, the energy resolution (i.e., the noise level in σ) can be measured for different dark currents on the ground. Then, with the estimate of dose and the dark current given by the empirical equation above, the increase rate of the noise level can be obtained, and the usable lifetime of the instrument can be predicted.

Here, we use GRID as an example to demonstrate this procedure. In Fig. 8, we show a plot of σ_{total} versus I_{dark} and fit them with

\[ \sigma_{total} = \sqrt{a_n \cdot I_{dark} \cdot (V_{bias} - V_{bd}) + b_n}, \]

which is derived from Eqs. (5) and (6). The free parameters, \(a_n\) and \(b_n\), are heavily dependent on the readout electronics design, such as the readout time constant and the gain. The results indicated an average noise (σ_{total}) increase of \(\sim 4.7\) keV/mA for GRID-02 over the first months. Considering the roughly \(1.6\) mA/year increase in dark current, the noise increase rate over time is \(\sim 7.5\) keV/year. The energy resolution (FWHM = 2.355·σ) and low energy threshold (6σ for GRID-02) could be calculated as well. Once they no longer meet the performance requirements of scientific goals, the instrument is declared to have reached the end of its life. Note that similar results could be obtained with on-ground calibrations, for example, by measuring the energy resolution or performing charge injection at different temperatures (and thus different dark currents), so that this noise analysis and usable lifetime evaluation procedure could be carried out before launch, when there is still a chance to improve the design.
Figure 8: Detector total noise ($\sigma_{\text{total}}$) versus dark current ($I_{\text{dark}}$). The current are origin values without any correction.
4.4. Methods of improve signal-to-noise ratio

As discussed in Section 3.3, the noise of the SiPM owing to radiation damage is dominated by dark count noise, as described by Eq. (6). Here, we discuss qualitative methods for improving the signal-to-noise ratio (SNR).

The first term is \( DCR \) which depends on temperature, as shown in Eq. (3). This leads to a straightforward method, which is to lower the operating temperature. This might be difficult for CubeSats but is applicable to larger satellites. The exponential term in Eq. (10) provides a practical approximation around room temperature that \( DCR \) is reduced by half for every \( \sim 17 \) °C decrease in temperature.

The second term is \( \text{Gain} \), which is proportional to \( V_{ov} = V_{bias} - V_{bd} \). As a critical operating parameter, the domino effect is significant when \( V_{ov} \) decreases. On the one hand, noise reduces with a decrease in the \( \text{Gain} \) and \( DCR \). On the other hand, the signal also decreases owing to a decrease in the \( \text{Gain} \) and photon detection efficiency (PDE). Care must be taken to determine the optimum value of \( V_{ov} \).

The third term represents the response of the readout electronics. In general, a shorter readout time constant leads to lower dark count noise. However, an overly short readout time constant might cause problems such as a larger ballistic deficit and more electronic noise. The lower limit is usually due to the scintillation decay time.

5. Conclusion

With the successful observation of several gamma-ray bursts using GRID-02, the feasibility of SiPM in space applications was once again proven. However, significant radiation damage indicates that a usable lifetime evaluation requires more attention from the very beginning of the instrument design stage. As a CubeSat detector equipped with scintillator crystals and SiPMs optimized for gamma-ray detection, GRID was specifically designed with SiPM characterization setups to conduct in-orbit characterization experiments. The characterization results of GRID-02 for the first few months show an increase in dark current of \( \sim 100 \) µA/year per SiPM chip (model MicroFJ-60035-TSV) at 28.5 V and 5 °C. This is equivalent to \( \sim 4.6 \) MHz/(year-mm\(^2\)) increase in \( DCR \) density and leads to the increase in the overall noise level (sigma) of \( \sim 7.5 \) keV/year. Based on the SPENVIS online program, the estimated dose of GRID-02 is \( \sim 0.5 \) Gy/year. An approximate empirical equation around room temperature is given for the dark current estimation at a specified dose and temperature. The measured dark currents of SIRI-1 and GRID-04 were used to test this equation, and showed good agreement. This equation also implies that the reduction in operating temperature could significantly mitigate the increase in dark current and noise, which means that a cooling system is highly recommended. Carefully designed readout electronics and optimum operating voltage also improve the signal-to-noise ratio.
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References

[1] R. Bencardino, F. Altamura, V. Bidoli, L. Bongiorno, M. Casolino, M. De Pascale, M. Ricci, P. Picozza, D. Aisa, A. Alvino, S. Ascani, P. Azzarello, R. Battiston, S. Bizzaglia, M. Bizzarri, S. Blasko, L. Di Masso, G. Chiocci, D. Cosson, G. Esposito, S. Lucidi, A. Papì, V. Postolache, S. Rossi, G. Scolieri, M. Ionica, A. Franceschi, S. Dell’Agnello, C. Falcone, S. Tassa, A. Kalmikov, A. Popov, A. Abramov, M. Korotkov, A. Galper, A. Ivanova, L. Conti, V. Sgrigna, C. Stagni, A. Buzzi, D. Zilpinian, A. Pontetti, L. Valentini, Response of the LAZIO-SiRad detector to low energy electrons, in: 29th International Cosmic Ray Conference, ICRC 2005, Vol. 2, 2005, pp. 449–452.
URL https://www.scopus.com/inward/record.uri?eid=2-s2.0-46149090466&partnerID=40&md5=661ca0afa31f4bd9fa0d662609d8fcce

[2] Z. Li, Y. Xu, C. Liu, Y. Gu, F. Xie, Y. Li, H. Hu, X. Zhou, X. Lu, X. Li, S. Zhang, Z. Chang, J. Zhang, Z. Xu, Y. Zhang, J. Zhao, Characterization of radiation damage caused by 23 MeV protons in Multi-Pixel Photon Counter (MPPC), Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 822 (2016) 63–70. doi:https://doi.org/10.1016/j.nima.2016.03.092.
URL https://www.sciencedirect.com/science/article/pii/S016890021630122X

[3] L. J. Mitchell, B. F. Phlips, R. S. Woolf, T. T. Finne, W. N. Johnson, E. G. Jackson, Strontium Iodide Radiation Instrumentation (SIRI), in: O. H. Siegmund (Ed.), UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XX, Vol. 10397, International Society for Optics and Photonics, SPIE, 2017, pp. 70 – 82. doi:10.1117/12.2272606.
URL https://doi.org/10.1117/12.2272606

[4] L. J. Mitchell, B. F. Phlips, J. E. Grove, T. Finne, M. Johnson-Rambert, W. N. Johnson, Strontium Iodide Radiation Instrument (SIRI) – Early On-Orbit Results (2019). arXiv:1907.11364.

[5] L. J. Mitchell, B. F. Phlips, R. S. Woolf, T. T. Finne, W. N. Johnson, Strontium iodide radiation instrumentation II (SIRI-2), in: O. H. Siegmund
[6] D. Zhang, X. Li, S. Xiong, Y. Li, X. Sun, Z. An, Y. Xu, Y. Zhu, W. Peng, H. Wang, F. Zhang, Energy response of GECAM gamma-ray detector based on LaBr3:Ce and SiPM array, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 921 (2019) 8–13. doi:https://doi.org/10.1016/j.nima.2018.12.032.
URL https://www.sciencedirect.com/science/article/pii/S0168900218318291

[7] A. Pál, M. Ohno, L. Mészáros, N. Werner, J. Ripa, M. Frajt, N. Hirade, J. Hudec, J. Kapuš, M. Koleda, R. Laszlo, P. Lipovský, H. Matake, M. Šmelko, N. Uchida, B. Csák, T. Enoto, Z. Frei, Y. Fukazawa, G. Gałgócki, K. Hirose, S. Hisadomi, Y. Ichinohe, L. L. Kiss, T. Mizuno, K. Nakazawa, H. Odaka, H. Takahashi, K. Torigoe, GRBAlpha: a 1U Cube-Sat mission for validating timing-based gamma-ray burst localization, in: J.-W. A. den Herder, S. Nikzad, K. Nakazawa (Eds.), Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, Vol. 11444, International Society for Optics and Photonics, SPIE, 2020, pp. 825 – 833. URL https://doi.org/10.1117/12.2561351

[8] N. Werner, J. Řípa, A. Pál, M. Ohno, N. Tarcai, K. Torigoe, K. Tanaka, N. Uchida, L. Mészáros, G. Gałgócki, Y. Fukazawa, T. Mizuno, H. Takahashi, K. Nakazawa, Z. Várhegyi, T. Enoto, H. Odaka, Y. Ichinohe, Z. Frei, L. Kiss, CAMELOT: Cubesats Applied for MEasuring and LOcalising Transients mission overview, in: J.-W. A. den Herder, S. Nikzad, K. Nakazawa (Eds.), Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, Vol. 10699, International Society for Optics and Photonics, SPIE, 2018, pp. 672 – 686. URL https://doi.org/10.1117/12.2313764

[9] L. J. Mitchell, B. F. Philips, R. S. Woolf, T. T. Finne, A. L. Hutcheson, W. N. Johnson, M. Johnson-Rambert, R. Perea, GAGG Radiation Instrumentation (GARI), in: O. H. Siegmund (Ed.), UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXII, Vol. 11821, International Society for Optics and Photonics, SPIE, 2021, pp. 38 – 50. doi:10.1117/12.2598588.
URL https://doi.org/10.1117/12.2598588

[10] F. Capel, A. Belov, M. Casolino, P. Klimov, Mini-EUSO: A high resolution detector for the study of terrestrial and cosmic UV emission from the International Space Station, Advances in Space Research 62 (10) (2018) 2954–2965, origins of Cosmic Rays. doi:https://doi.org/10.1016/j.asr.2017.08.030.
[11] K. Bartlett, D. Coupland, D. Beckman, K. Mesick, Proton irradiation damage and annealing effects in ON Semiconductor J-series silicon photomultipliers, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 969 (2020) 163957. doi:https://doi.org/10.1016/j.nima.2020.163957.
URL https://www.sciencedirect.com/science/article/pii/S0273117717306257

[12] L. Mitchell, B. Philips, W. N. Johnson, M. Johnson-Rambert, A. N. Kansky, R. Woolf, Radiation damage assessment of SensL SiPMs, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 988 (2021) 164798. doi:https://doi.org/10.1016/j.nima.2020.164798.
URL https://www.sciencedirect.com/science/article/pii/S0168900220304289

[13] N. Hirade, H. Takahashi, N. Uchida, M. Ohno, K. Torigoe, Y. Fukazawa, T. Mizuno, H. Matake, K. Hirose, S. Hisadomi, K. Nakazawa, K. Yahamaoka, N. Werner, J. Ripa, S. Hatori, K. Kume, S. Mizushima, Annealing of proton radiation damages in Si-PM at room temperature, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 986 (2021) 164673. doi:https://doi.org/10.1016/j.nima.2020.164673.
URL https://www.sciencedirect.com/science/article/pii/S0168900220311955

[14] A. Ulyanov, D. Murphy, J. Mangan, V. Gupta, W. Hajdas, D. de Faoite, B. Shortt, L. Hanlon, S. McBreen, Radiation damage study of SensL J-series silicon photomultipliers using 101.4 MeV protons, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 976 (2020) 164203. doi:https://doi.org/10.1016/j.nima.2020.164203.
URL https://www.sciencedirect.com/science/article/pii/S0168900220310706

[15] J. Wen, X. Long, X. Zheng, Y. An, Z. Cai, J. Cang, Y. Che, C. Chen, L. Chen, Q. Chen, Z. Chen, Y. Cheng, L. Deng, W. Deng, W. Ding, H. Du, L. Duan, Q. Gan, T. Gao, Z. Gao, W. Han, Y. Han, X. He, X. He, L. Hou, F. Hu, J. Hu, B. Huang, D. Huang, X. Huang, S. Jia, Y. Jiang, Y. Jin, K. Li, S. Li, Y. Li, J. Liang, Y. Liang, W. Lin, C. Liu, G. Liu, M. Liu, R. Liu, T. Liu, W. Liu, D. Lu, P. Lu, Z. Lu, X. Luo, S. Ma, Y. Ma, X. Mao, Y. Mo, Q. Nie, S. Qu, X. Shan, G. Shi, W. Song, Z. Sun, X. Tan, S. Tang, M. Tao, B. Wang, Y. Wang, Z. Wang, Q. Wu, X. Wu, Y. Xia, H. Xiao, W. Xie, D. Xu, R. Xu, W. Xu, L. Yan, S. Yan, D. Yang, H. Yang, H. Yang, Y.-S. Yang, Y. Yang, L. Yao, H. Yu, Y. Yu, A. Zhang,
B. Zhang, L. Zhang, M. Zhang, S. Zhang, T. Zhang, Y. Zhang, Q. Zhao, R. Zhao, S. Zheng, X. Zhou, R. Zhu, Y. Zou, P. An, Y. Cai, H. Chen, Z. Dai, Y. Fan, C. Feng, H. Feng, H. Gao, L. Huang, M. Kang, L. Li, Z. Li, E. Liang, L. Lin, Q. Lin, C. Liu, H. Liu, X. Liu, Y. Liu, X. Lu, S. Mao, R. Shen, J. Shu, M. Su, H. Sun, P.-H. Tam, C.-P. Tang, Y. Tian, F. Wang, J. Wang, W. Wang, Z. Wang, J. Wu, X. Wu, S. Xiong, C. Xu, J. Yu, W. Yu, Y. Yu, M. Zeng, Z. Zeng, B.-B. Zhang, B. Zhang, Z. Zhao, R. Zhou, Z. Zhu, GRID: a student project to monitor the transient gamma-ray sky in the multi-messenger astronomy era, Experimental Astronomy 48 (2019) 77–95. doi:https://doi.org/10.1007/s10686-019-09636-w
URL https://link.springer.com/article/10.1007/s10686-019-09636-w

[16] M. Barella, T. I. Burroni, I. Carsen, M. Far, T. Ferreira Chase, L. Finazzi, F. Golmar, F. Gomez Marlasca, F. Izraelevitch, P. Levy, G. Sanca, Silicon photomultiplier characterization on board a satellite in Low Earth Orbit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 979 (2020) 164490. doi:https://doi.org/10.1016/j.nima.2020.164490. URL https://www.sciencedirect.com/science/article/pii/S0168900220308871

[17] J. Racusin, J. S. Perkins, M. S. Briggs, G. de Nolfo, J. Krizmanic, R. Cutraro, J. E. McEnery, P. Shawhan, D. Morris, V. Connaughton, D. Kocevski, C. Wilson-Hodge, M. Hui, L. Mitchell, S. McBreen, BurstCube: A CubeSat for Gravitational Wave Counterparts (2017). arXiv:1708.09292.

[18] F. Fuschino, R. Campana, C. Labanti, Y. Evangelista, M. Feroci, L. Burderi, F. Fiore, F. Ambrosino, G. Baldazzi, P. Bellutti, R. Bertacini, G. Bertuccio, G. Borghi, D. Cirrincione, D. Cauz, F. Ficorella, M. Fiorini, M. Gandola, M. Grassi, A. Guzman, G. L. Rosa, M. Lavagna, P. Lunghi, P. Malcovati, G. Morgante, B. Negri, G. Pauletta, R. Piazzolla, A. Picciotto, S. Pirrotta, S. Pliego-Caballero, S. Puccetti, A. Rachevski, I. Rashevskaya, L. Rignanese, M. Salatti, A. Santangelo, S. Silvestrini, G. Sottile, C. Tenzer, A. Vacchi, G. Zampa, N. Zampa, N. Zorzi, HERMES: An ultra-wide band X and gamma-ray transient monitor onboard a nano-satellite constellation, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 936 (2019) 199–203, Frontiers Detectors for Frontier Physics: 14th Pisa Meeting on Advanced Detectors. doi:https://doi.org/10.1016/j.nima.2018.11.072. URL https://www.sciencedirect.com/science/article/pii/S0168900218318814

[19] D. Murphy, J. Mangan, A. Ulyanov, S. Walsh, R. Dunwoody, L. Hanlon, B. Shortt, S. McBreen, Balloon flight test of a CeBr3 detector with silicon photomultiplier readout, Experimental Astronomy 52 (2021) 1–34.
[20] G. J.E., C. C.C., K. M., M. L.J., P. B.F., W. R.S., W. E., W.-H. C.A., K. D., B. M.S., P. J., G. S., H. D., Glowbug, a gamma-ray telescope for bursts and other transients, AAS/High Energy Astrophysics Division, AAS/High Energy Astrophysics Division (2019) 109.52.
URL https://www.scopus.com/inward/record.uri?eid=2-s2.0-85083912941&partnerID=40&md5=a2611321cc5db0b8a44cabc8ed6e8a7

[21] R. Kushwah, T. Stana, M. Pearce, The design and performance of CUBES – a CubeSat x-ray detector, Journal of Instrumentation 16 (08) (2021) P08038. doi:10.1088/1748-0221/16/08/p08038. URL https://doi.org/10.1088/1748-0221/16/08/p08038

[22] R. Rahin, L. Moleri, A. Vdovin, A. Feigenboim, S. Margolin, S. Tarem, E. Behar, M. Ghezlan, A. Osovizky, GALI: a gamma-ray burst localizing instrument, in: J.-W. A. den Herder, S. Nikzad, K. Nakazawa (Eds.), Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, Vol. 11444, International Society for Optics and Photonics, SPIE, 2020, pp. 1037 – 1049. doi:10.1117/12.2576126. URL https://doi.org/10.1117/12.2576126

[23] J.-X. Wen, X.-T. Zheng, J.-D. Yu, Y.-P. Che, D.-X. Yang, H.-Z. Gao, Y.-F. Jin, X.-Y. Long, Y.-H. Liu, D.-C. Xu, Y.-C. Zhang, M. Zeng, Y. Tian, H. Feng, Z. Zeng, J.-R. Cang, Q. Wu, Z.-Q. Zhao, B.-B. Zhang, P. An, Compact CubeSat Gamma-ray detector for GRID mission, Nuclear Science and Techniques 32 (2021) 99. doi:https://doi.org/10.1007/s41365-021-00937-4. URL https://link.springer.com/article/10.1007/s41365-021-00937-4

[24] F. Nagy, G. Hegyesi, G. Kalinka, J. Molnár, A model based DC analysis of SiPM breakdown voltages, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 849 (2017) 55–59. doi:https://doi.org/10.1016/j.nima.2017.01.002. URL https://www.sciencedirect.com/science/article/pii/S0168900217300025

[25] R. Klanner, Characterisation of SiPMs, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 926 (2019) 36–56, silicon Photomultipliers: Technology, Characterisation and Applications. doi:https://doi.org/10.1016/j.nima.2018.11.083.
[26] Datasheet: Silicon Photomultipliers (SiPM), High PDE and Timing Resolution Sensors in a TSV Package (2021).
URL https://www.onsemi.com/pdf/datasheet/microj-series-d.pdf

[27] H. Gao, D. Yang, J. Wen, X. Zheng, M. Zeng, J. Cang, W. Zeng, X. Pan, Q. Zhou, Y. Liu, H. Feng, B. Zhang, Z. Zeng, Y. Tian, G. Collaboration, On-ground calibrations of the GRID-02 gamma-ray detector, Experimental Astronomy 53 (2021) 103–116. doi:https://doi.org/10.1007/s10686-021-09819-4.
URL https://link.springer.com/article/10.1007/s10686-021-09819-4

[28] E. Garutti, Y. Musienko, Radiation damage of SiPMs, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 926 (2019) 69–84, silicon Photomultipliers: Technology, Characterisation and Applications. doi:https://doi.org/10.1016/j.nima.2018.10.191.
URL https://www.sciencedirect.com/science/article/pii/S0168900218315055

[29] G. Hurkx, H. de Graaff, W. Kloosterman, M. Knuvers, A new analytical diode model including tunneling and avalanche breakdown, IEEE Transactions on Electron Devices 39 (9) (1992) 2090–2098. doi:10.1109/16.155882.

[30] N. Campbell, A theory of valve and circuit noise, Journal of the Institution of Electrical Engineers - Part III: Radio and Communication Engineering 93 (1946) 45–52(7).
URL https://digital-library.theiet.org/content/journals/10.1049/ji-3-2.1946.0009

[31] ESA, SPace ENVironment Information System (SPENVIS), Online (1997-2022).
URL https://www.spenvis.oma.be/

[32] S. Seltzer, Updated Calculations for Routine Space-Shielding Radiation Dose Estimates: SHIELDOSE-2 (1994).
URL https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=103635