Characterization of Silicon Photomultipliers for Applications in the TRYAD Mission

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ABSTRACT

The Terrestrial RaYs Analysis and Detection (TRYAD) Mission is a gamma ray mission focused on measuring the beam profile and angle of terrestrial gamma-ray flashes through use of two CubeSats in low earth orbit along with ground-based lightning detectors. Previous gamma ray missions have consisted of photomultiplier tubes coupled to scintillating crystals; the TRYAD Mission aims to fly CubeSats with silicon photomultiplier devices and plastic scintillators. Experimentation on photomultiplier tubes in combination with NaI(Tl) and $LaBr_3$(Ce) crystals was completed as a comparison point to the silicon photomultipliers. Different models of silicon photomultipliers were tested to assess energy resolutions, thresholds, and light collection efficiencies.

1. Introduction

Background

The Terrestrial RaYs Analysis and Detection (TRYAD) Mission is a gamma ray mission focused on measuring the beam profile and angle of terrestrial gamma-ray flashes (TGFs). TRYAD will consist of two 3U CubeSats in low earth orbit along with ground-based lightning detectors through the World Wide Lightning Location Network (WWLLN). By using a multi-point detection system for TGFs and focusing exclusively on gamma ray detection, TRYAD aims to study TGFs and their emission mechanisms, which have applications to high-energy atmospheric physics and high-energy astrophysics.

TGFs are gamma-ray flashes that are associated with lightning. They were first detected with BATSE (Fishman et al. 1994) and have been observed with multiple instruments since then. TGFs are believed to be emitted after the acceleration of electrons through the Relativistic Runaway Electron Avalanche (RREA) process (Gurevich et al. 1992). However, how these TGFs are initiated is not well understood.

Photomultiplier Tubes

Space-based gamma ray detectors typically consist of a scintillation device coupled to a photodetector. The most common photodetector used is the photomultiplier tube (PMT), a glass tube that has been evacuated. Through a series of processes, a PMT converts incoming light signals into electrical signals.

As a gamma ray passes through a scintillation device, typically some type of crystal, the scintillator absorbs the energy of the gamma ray and re-emits it as visible light. This light is proportional to the energy of the incident gamma ray. As the light hits the photocathode of the PMT, the photocathode ejects electrons through the external photoelectric effect. These electrons are accelerated through a focusing electrode and towards an electron multiplier. This electron multiplier is comprised of a number of dynodes connected to a voltage divider circuit.

Each dynode in the PMT is at a higher voltage than the previous; this allows electrons to be consistently accelerated towards plates of higher voltage throughout the PMT. A large amount of electrons are produced through secondary emis-

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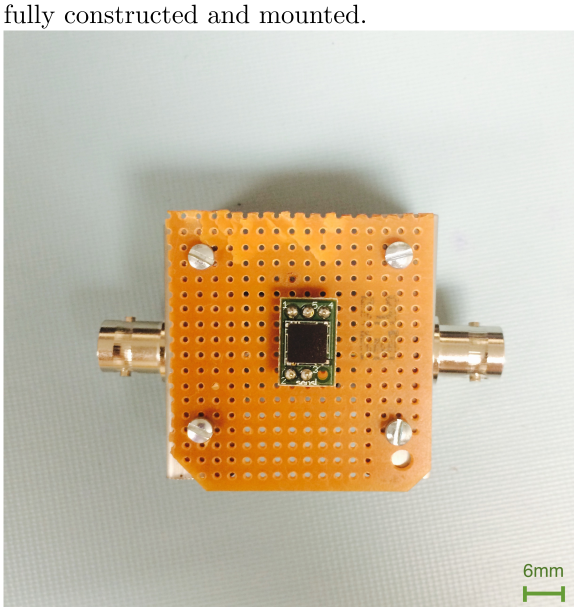
sion in each plate and then accelerated to the next plate in the circuit, creating an avalanche effect in electron production. As the electrons reach the end of the electron multiplier, they are collected at the anode as a voltage pulse. The voltage pulse height is proportional to the original light signal detected by the PMT and therefore the incident energy of an incoming gamma ray.

PMTs, however, are large, fragile, heavy, and require high voltage. CubeSats are very small in comparison with standard satellites; they are unable to carry PMTs without sacrificing space, weight, and power to other equipment. We investigate the use of silicon photomultipliers (SiPMs) as an alternative to PMTs in the detection of scintillation light.

Silicon Photomultipliers

Fig. 1.— SensL MicroFC SMTPA 60035 SiPM fully constructed and mounted.



Silicon Photomultipliers can be used as an alternative to PMTs in photon detection. SiPMs are significantly smaller, lighter, more durable, and more efficient than PMTs. SiPMs require lower voltage (around 20 - 70 V) to run in stark contrast to the high voltages required for PMTs (Bloser et al. 2014). SiPMs are most typically tiled in arrays to increase their active area.

SiPMs are comprised of large arrays of avalanche photodiodes (APDs). APDs are semiconductor devices that create output current signals proportional to, but larger than, incoming light signals. As light hits a photodiode, charge carriers in the semiconductor material are accelerated in order create electron-hole pairs (Knoll). This phenomenon occurs in an avalanche process, opening up electron-hole pairs while releasing charge carriers in a way that amplifies the output current.

APDs in SiPMs are run in Geiger mode. In Geiger mode, the charge produced in an APD is no longer proportional to the incoming light signal. However, in SiPMs, APDs are on the micro scale and small enough that only a few scintillation photons will come into contact with one APD. Therefore, each APD works as a binary switch, "on" if a photon has hit the APD, "off" if not. SensL SiPMs measure the pulse height of an incoming gamma ray through the proportion of "on" versus "off" photodiodes triggered by scintillation light.

The SensL C-Series line of SiPMs consists of SiPMs with low dark-count rates and high photon detection efficiency (PDE) that can be run in two different modes. The fast output is typically used for photon counting at high speeds while the standard output is typically used for gamma-ray spectroscopy (SensL 2011). We employ the standard mode output for our work because we are interested in the energy of incoming gamma rays.

Technical Objectives

We aim to verify that SiPMs are adequate for the scientific goals of TRYAD through testing of SiPMs manufactured by SensL. By performing different tests on the SensL C-Series SiPMs, we look at their functionality and applicability to space-based gamma ray detection.

We primarily will compare the performance of SiPMs vs PMTs. We will consider different pairings of SiPMs and PMTs to scintillating crystals as well as couplings of SiPMs and PMTs to compound parabolic concentrators (CPCs). These comparisons will allow us to determine CPCs' abilities to concentrate light from scintillators down to smaller areas on the PMT or SiPMs and whether the increase in light collection translates into better energy resolution.

We will also determine energy resolutions and thresholds of different detectors in order to compare SiPMs' responses versus those of other detectors. We will also explore but not test the usage of a 5% lead-doped plastic scintillator in the place of NaI(Tl) or $LaBr_3$(Ce) crystals for the TRYAD Mission.

2. Methodology

Before testing the SensL SiPM devices' energy resolutions, we determined the breakdown voltage and overvoltage for the devices. The breakdown voltage is the lowest voltage at which we ran an SiPM where we were able to distinguish a voltage signal from background noise. The overvoltage for SiPMs is typically 5V above the breakdown voltage and is the optimum voltage at which to run an SiPM. We determined these values by coupling the SensL MicroFC 60035 SMA device to a pulsing LED and studying the output signal's peak-to-peak voltage displayed on an oscilloscope.

In order to characterize the SiPMs' responses to scintillation light, we ran series of tests on the devices. We were primarily interested in the performance of the 6 mm x 6 mm SensL MicroFC 60035 SMT device for use in the TRYAD Mission, but tested the SensL MicroFC 60035 SMA and SensL MicroFC 60035 SMTPA as well. All three SiPMs were tested against the Hamamatsu R580 PMT. All tests were completed in a black box setup to minimize (and ideally avoid) stray light.

Our first test was a direct coupling between each photodetector and a $LaBr_3$(Ce) scintillating crystal. While NaI(Tl) scintillating crystals are more typically used for gamma ray detection, $LaBr_3$(Ce) crystals have better energy resolution and faster decay times (Ortec 2013). Each photodetector was coupled directly to the $LaBr_3$(Ce) crystal and then calibrated using an Amptek multi-channel analyzer and Cs^{137} and Co^{60} sources. We then calculated the energy resolutions of each device at the energy peak of Cs^{137}, or 662 keV.

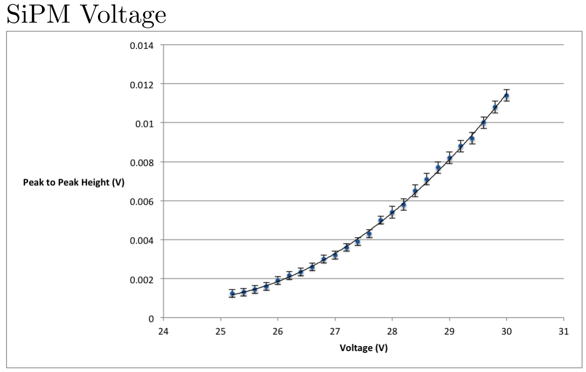
We then looked at the energy resolutions of devices coupled to two CPCs of different sizes. CPCs concentrate light from larger areas to smaller areas and could have applications in flight on the CubeSats used in the TRYAD Mission. Using the Fairchild DuMont 6292 PMT coupled to NaI(Tl) and $LaBr_3$(Ce) scintillators, we studied the variations in the PMT's energy resolution between a direct coupling and couplings with a CPCs of 1.5 in. and 2 in. diameters. We determined how efficient CPCs are in concentrating light by measuring energy resolutions with and without the CPCs.

We also looked at the light detection efficiencies of the SensL SiPMs and the Hamamatsu R580 PMT to see how the different models respond to identical light sources. By coupling each device to a pulsing LED at different frequencies, we analyzed the count rate output using Amptek software to determine the percentage of light pulses detected by the SiPMs as a function of frequency and the detected count rate. Results from this test would ideally show consistent light detection between the SiPMs and the PMT to validate our other results' accuracy.

3. Results

We determined the breakdown voltage and overvoltage of the SiPMs by sending the SiPM output signal into an oscilloscope and measuring the vertical peak-to-peak voltage of each pulse. We found the breakdown voltage to be 24.97V and the overvoltage to be 30V (approximately 5V above the breakdown voltage). Figure 2 shows a graph of the vertical peak-to-peak voltage versus the voltage at which the SiPMs were run.

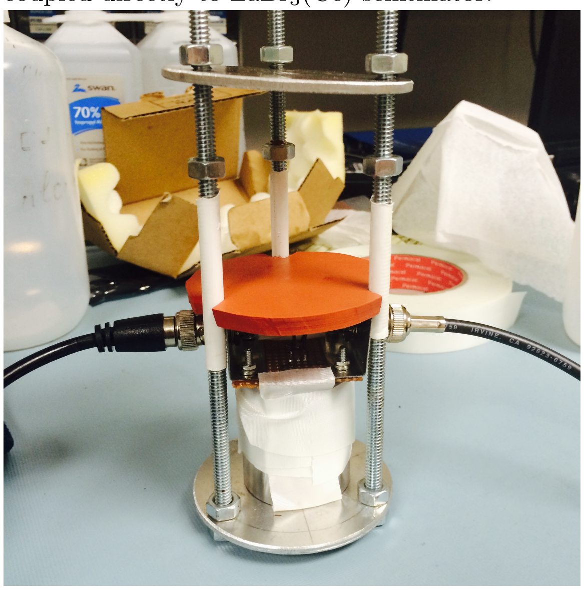
Fig. 2.— Vertical Peak-to-Peak Voltage of the SensL MicroFC SMA 60035 Output Signal vs. SiPM Voltage



We then ran four main tests in order to characterize the SiPMs and their functionality. In the first, we compared the energy resolutions at 662 keV of two SensL SiPM models and the Hamamatsu R580 PMT. In the second and third, we considered a combination of the Fairchild Dumont 6292 PMT with two CPCs of different sizes and $LaBr_3(Ce)$ and NaI(Tl) crystals. In the final test, we evaluated the light collection efficiency of two SensL SiPMs and compared them to the PMT.

For the first test, we coupled each photomultiplier directly to the $LaBr_3(Ce)$ crystal using optical grease to match the index of refraction between the components. We then isolated each separate test setup in a dark box and placed four Cs^{137} sources directly around each setup.

Fig. 3.— SensL MicroFC SMTPA 60035 SiPM coupled directly to $LaBr_3(Ce)$ scintillator.



Using the Amptek multi-channel analyzer, we detected gamma rays emitted by the Cs^{137} and looked at the energy spectrum displayed by the Amptek software. In order to calculate the energy resolutions, we used a method shown in Equation 1, where R represents the energy resolution, $FWHM$ represents the full width in channel number at half maximum of the peak, and C_{peak} represents the peak channel number.

$$R = \frac{FWHM}{C_{peak}} * 100\% \quad (1)$$

From this equation, we can see that the smaller the $FWHM$ is relative to the peak channel number, the smaller, and therefore the better, the energy resolution is. While these calculations were performed using the channel numbers, due to the unitless nature of energy resolutions, the channel resolution is exactly the same as the energy resolution for each value. The results for the energy resolutions at 662 keV are shown in Table 1.

Table 1: Energy Resolutions of Light Detector Combinations with $LaBr_3(Ce)$ Crystal

Component Combination	*Energy Resolution at 662 keV*	*Corrected** Energy Resolution*
Hamamatsu R580 PMT coupled to $LaBr_3(Ce)$ crystal	3.47%	not applicable
SensL MicroFC SMA 60035 coupled to $LaBr_3(Ce)$ crystal	14.36%	2.55%
SensL MicroFC SMTPA 60035 coupled to $LaBr_3(Ce)$ crystal	11.97%	2.13%

**See "Discussion and Analysis" Section

For the second and third tests, we coupled each photomultiplier component to a CPC with optical grease and then coupled the CPC to either an $LaBr_3(Ce)$ crystal or an NaI(Tl) crystal. In a similar method to the first test, we looked at the output energy spectrum due to the gamma ray emission of Cs^{137}. Results from using the two scintillators are shown in Table 2 and Table 3.

Below, we can see a test setup of the SensL MicroFC SMA 60035 coupled to the smaller CPC and the $LaBr_3(Ce)$ crystal in Figure 4. PMT, CPC, and scintillator couplings were very similar to the coupling between the SensL MicroFC SMA 60035, CPC, and $LaBr_3(Ce)$ scintillator coupling.

Fig. 4.— SensL MicroFC SMA 60035 coupled to small CPC and $LaBr_3(Ce)$ scintillator

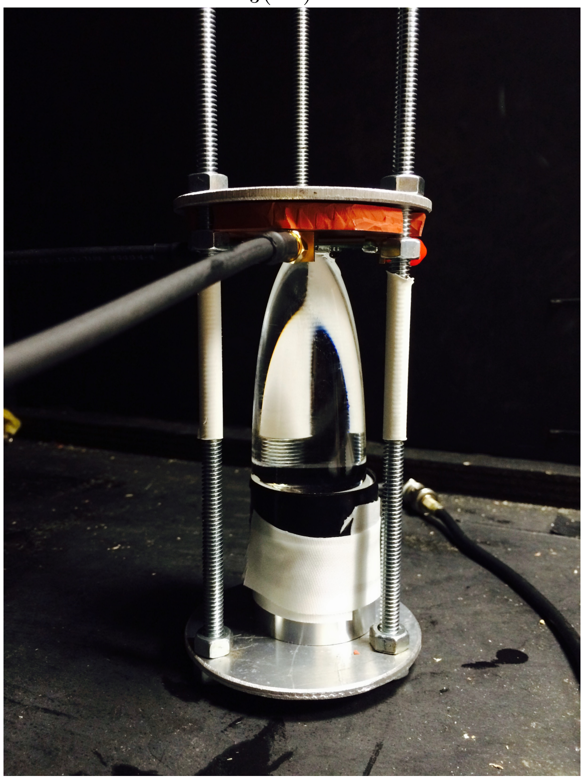


Table 2: Energy Resolutions of Fairchild DuMont 6292 Photomultiplier Tube with Compound Parabolic Concentrators and NaI(Tl) Crystal

Component Combination	*Energy Resolution at 662 keV*
Direct coupling (no CPC) NaI(Tl) crystal	17.56%
Coupling with 1.5 in. CPC and NaI(Tl) crystal	29.50%
Coupling with 2 in. CPC and NaI(Tl) crystal	30.30%

Table 3: Energy Resolutions of Fairchild DuMont 6292 Photomultiplier Tube with Compound Parabolic Concentrators and $LaBr_3(Ce)$ Crystal

Component Combination	*Energy Resolution at 662 keV*
Direct coupling (no CPC) $LaBr_3(Ce)$ crystal	2.80%
Coupling with 1.5 in. CPC and $LaBr_3(Ce)$ crystal	10.10%
Coupling with 2 in. CPC and $LaBr_3(Ce)$ crystal	15.10%

In the final test with the SiPMs, we looked at the light detection of the SiPMs in comparison with the PMT. In order to do this, we set a pulsing LED in front of each photomultiplier and, at varying frequencies, looked at the count rate output through the Amptek multichannel analyzer and software versus the input frequency. We took data at 1kHz, 10kHz, and 100kHz and then calculated the mean value of the light detection efficiency for each photomultiplier. We use the mean value because the efficiencies were similar between tested frequencies. The light detection efficiency was calculated as shown below in Equation 2, where E represents the percentage of light detected, R represents the output count rate, and F represents the input frequency of the LED. Results from this test are shown in Table 4.

$$E = \frac{R}{F} * 100\% \quad (2)$$

Table 4: Mean Light Detection Efficiency of SensL SiPMs

Component Combination	*Mean Light Detection Efficiency*
Hamamatsu R580 PMT coupled to pulsing LED	9.12%
SensL MicroFC SMA 60035 coupled to pulsing LED	9.58%
SensL MicroFC SMTPA 60035 coupled to pulsing LED	9.30%

4. Discussion and Analysis

In discussing our results, there are a number of pertinent issues that must be mentioned that may have had negative effects on our data.

Fig. 5.— SensL MicroFC SMA 60035

1. The SensL MicroFC SMA 60035 is designed with three SMA connectors that are taller than the actual printed circuit board (PCB) on which the detector cell is mounted (shown in Figure 5). Because of this, it is difficult to couple the device on the PCB to a CPC or to a scintillator, as the SMA connectors prevent a direct coupling onto the SiPM active surface. The preamplifier on the SensL MicroFC SMA 60035 is the little black object jutting out seen in Figure 5 that, also due to its height, blocks direct coupling with the active surface itself. This affects the light collection of the SiPM and lowers how much light from the scintillator would pass through to the SiPM.

2. The light collection of the SiPMs was very poor due to the mismatched size of the SiPM area and the scintillator area. Each of the two SensL SiPMs tested consisted of one 6mm x 6mm ($36mm^2$) light collecting area. However, both the $LaBr_3$(Ce) and NaI(Tl) scintillators used in testing have much larger, circular surface areas. Most of the light emitted by the scintillators would not be detected by the SiPM, ultimately pushing the energy resolutions to higher numbers than if the scintillators and SiPMs had the same area.

The SiPM energy resolutions at 662 keV for the SiPMs coupled to the $LaBr_3$(Ce) scintillating crystal were 14.36% for the SensL MicroFC SMA 60035 and 11.97% for the SensL MicroFC SMTPA 60035. Assuming ideal light collection, we can calculate the approximate energy resolutions of both devices using Equation 3, which relates the energy resolution of a photodetector to the efficiency of the device (Hamamatsu 2007). In Equation 3, R represents the energy resolution, N represents the number of photons hitting the photocathode of the detector, η represents the quantum efficiency, and α represents the collection efficiency.

$$R^2 \propto \frac{1}{N\eta\alpha} \tag{3}$$

The form of Equation 3 is applicable to SiPMs and can be reduced to Equation 4, where α is the light collection efficiency.

$$R^2 \propto \frac{1}{\alpha} \tag{4}$$

We see that Equation 4 can be rewritten as shown in Equation 5, where A_{scint} is the area of the scintillator and A_{detect} is the area of the SiPM detector.

$$R^2 \propto \frac{A_{scint}}{A_{detect}} \tag{5}$$

We can set up a new equation, shown in Equation 6 between the experimental resolution

(R_{exper}) and area-corrected resolution ($R_{corrected}$) to determine the expected energy resolution of the SiPMs with perfect light collection. R_{exper} represents the experimental energy resolution with improperly matched detector and scintillator areas.

$$R_{corrected} = R_{exper}\sqrt{\frac{A_{detect}}{A_{scint}}} \tag{6}$$

We find that the corrected energy resolution for the SensL MicroFC SMA 60035 would be 2.55% and the corrected energy resolution for the SensL MicroFC SMTPA 60035 would be 2.13%.

3. While we initially planned on testing the SensL MicroFC SMT 60035, the actual construction of the preamplification circuit and the mounting of the SiPM onto a breadboard was unsuccessful. Additional equipment was purchased to increase the success rate, but ultimately, printed circuit boards will be required for successful fabrication.

While the energy resolutions at 662 keV were higher with the SiPMs than with the Hamamatsu PMT, with certain changes in the apparatus design, the SiPM energy resolutions should be well within the range of acceptable energy resolutions for the TRYAD Mission. Tiled arrays of SiPMs may be used to cover scintillator edges and allow a maximum amount scintillator-produced light to be detected by the SiPMs, lowering the energy threshold of the detector.

We tested CPCs and found them unsatisfactory for the TRYAD Mission. Energy resolutions with the CPCs were significantly higher than energy resolutions without, so further development and study is necessary before CPCs could emerge as an alternative for the TRYAD Mission.

The light detection efficiencies of the two SiPMs tested are quite consistent with each other as well as with the Hamamatsu R580 PMT. Because the SensL MicroFC SMA 60035 was fully constructed prior to testing and the SensL MicroFC SMTPA 60035 was constructed in our lab, we can look to the light detection efficiency not only as a measure of how quickly the SiPMs can detect incoming light pulses, but we can also look at the consistency of the light detection efficiency between the two SiPMs as a measure of the success of the construction of the SensL MicroFC SMTPA 60035 setup. The consistency between the light detection efficiency of the SiPMs and the PMT leads us to believe that with stronger light collection and better size matching of components, the SiPM would be a suitable replacement for the PMT.

5. Conclusion

The energy resolution tests lead us to believe that SiPMs will prove to be a successful alternative to PMTs in gamma ray detection for the TRYAD Mission. Their high efficiency, small size and weight, and durability make them highly suitable for flight on two 3U CubeSats.

While using different geometries of CPCs to focus light from larger scintillator areas may be beneficial, the geometries of the CPCs tested through our experiments (shown coupled to an SiPM in Figure 4) did not provide improvement in light collection over directly coupled devices.

6. Future Work

Future work will consist of testing the SiPM systems with a 5% lead-doped plastic scintillator. Due to delays in production of the scintillator, we were unable to test this scintillating device. The TRYAD Mission includes use of a 5% lead-doped plastic scintillator on the CubeSats, so testing of this scintillator is quite important to the mission.

We will test tiled arrays of the SensL MicroFC SMT 60035 to look at how tiled arrays of the SiPMs respond to scintillation light and how well they distinguish between energies of incoming gamma rays. We will test these on PCB setups (rather than freestanding constructions) to ensure that all parts are set up correctly and work as expected. We will also determine energy thresholds of devices to assess the lowest energies detectable.

7. Acknowledgments

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