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Measuring cosmic-ray intensity using balloon-borne silicon photomultipliers

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ABSTRACT

Photomultiplier tubes are commonly used to read out scintillator and Cherenkov detectors in cosmic-ray experiments, but they operate using high voltages that require complex potting schemes to prevent dielectric breakdown in the low-pressure environment encountered at balloon float altitudes. Silicon photomultipliers (SiPMs) are a relatively new light detection technology that operate at considerably lower voltages and do not require encapsulation to function in low pressure. As part of a student research project, a simple cosmic-ray detector was constructed using SiPM technology and flown to an altitude of $\sim 120,000$ ft. The data gathered in flight is consistent with previous observations, demonstrating that this technology is mature enough for use in cosmic-ray ballooning applications.

1. Introduction

The High Altitude Radiation Detector (HARD) payload was designed as part of a student research project to test the suitability of silicon photomultipliers (SiPMs) for use in cosmic-ray ballooning applications. SiPMs offer several advantages over traditional photomultiplier tubes (PMTs). In this context, the greatest advantage is the ~ 30 V operating voltage, contrasted with PMTs which require 1–3 kV. The low pressure environment at balloon-float altitudes is near the minimum of the Paschen curve [1] describing the breakdown voltage of gasses as a function of pressure and gap distance, which means that high voltages must be encapsulated in a suitable dielectric material to prevent arcing. PMT high voltage sources require careful design and testing to ensure that they will operate properly in this environment, while SiPMs do not. Additionally, SiPMs have low dark current rates ($\sim 1\ \mu A/mm^2$), and comparable quantum efficiency and rise time. They are also available at low cost, are unaffected by magnetic fields, and are available in much smaller packages, making them ideal options in scenarios where minimizing mass and volume is a factor.

PMTs do retain advantages in some areas, particularly in aperture size, as SiPMs, even in fairly large arrays, have much smaller surface areas than typical PMTs. Perhaps the largest drawback of the SiPM is the high dark count rate, which ranges from 0.1 to 1 MHz/mm^2. In applications where single photon counting is not required, setting the trigger threshold to several photoelectrons significantly reduces the dark count rate, and requiring coincidence with a second SiPM virtually eliminates accidental counts. A significant drawback is that the SiPM gain for a fixed bias voltage is temperature dependent and requires careful design for balloon payloads, where temperature changes can be substantial.

The HARD instrument consisted of an array of four CsI(Tl) crystals read out by SiPMs. The payload was launched on September 2, 2013 from Fort Sumner, NM as part of the High Altitude Student Platform (HASP) program [2], and remained at a float altitude of $\sim 120,000$ ft for over 10 h. The SiPMs operated successfully throughout the flight, although there were some communication outages. One SiPM unit, which did not return data at the start of the flight, spontaneously began functioning and remained operational for the remainder of the flight. This will be discussed in detail below.

2. HARD instrument design

The HARD payload was designed to demonstrate the suitability of SiPMs for cosmic-ray ballooning experiments by measuring how the east–west angular asymmetry changes with altitude, as the cosmic-ray flux transitions from mostly secondary particles near ground level to mostly primary cosmic rays near balloon-float altitudes [3]. A larger than anticipated rotation rate of the HASP platform and the resulting uncertainty in the orientation of the payload during data collection made this measurement

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impossible. However, it was possible to measure how the vertical intensity of cosmic rays changed with altitude, and the results are consistent with previous measurements, showing that SiPMs are a viable option for cosmic-ray balloon payloads.

The HASP instrument is designed to support 12 smaller payloads, which are assigned to student research groups by a selective application process. Size, mass, and power constraints are based on the payload size class of which there are four large and eight small payload positions available. Payloads designed for the small payload class, such as HARD, have a maximum mass of 3 kg, maximum dimensions of 15 cm × 15 cm × 30 cm, and must consume less than ~14 W of power. In addition to providing a mechanical interface, HASP also provides each payload with an individual serial interface and 28–32 V power supply. The completed payload, prior to integration with HASP, is shown in Fig. 1.

As can be seen in Fig. 2, the HARD payload consisted of three major subsystems, a detector module composed of scintillators read out by SiPMs to detect cosmic rays, a comparator module to convert the analog output of the SiPMs into a digital signal, and a microcontroller to monitor and record coincidences. These modules are described in more detail in the following sections.

Fig. 1. Completed HARD instrument prior to integration with HASP.

2.1. SiPMs

A SiPM is essentially an array of reverse-biased diodes with a high electric field in the p–n junction depletion region. When an optical photon impinges on one of these microcells, it can free an electron from the valence band, which, due to the strong electric field, knocks other electrons from the valence band and causes an avalanche of secondary electrons. The electric current produced by this cascade of electrons is large enough to be measured and, much like a Geiger counter, is not proportional to the number or energy of photons hitting the microcell. In order to obtain information on the number of photons incident on the detector, SiPMs are divided into a large number of microcells, and the output current is summed to be proportional to the number of microcells that have detected a photon. The microcells must be physically separated in order to ensure optical isolation, and thus fill factor and the number of microcells are important characteristics that impact an SiPMs performance. A higher fill factor, the ratio of active detector surface area to the device surface area, means that there is less dead area between microcells, but increases the likelihood of optical crosstalk between microcells. Optical crosstalk occurs when an electron accelerated by the strong electric field in the depletion region emits a photon that enters another microcell and causes a second cascade [4]. The dynamic range of an SiPM is proportional to and limited by the number of microcells. Once a microcell has been reverse biased, a recovery time of ~100 ns is required before it is fully sensitive to detect another photon.

The Photonique SA 0905V13MM SiPM [5] was selected for the HARD payload based on several considerations, including low bias voltage (~30 V), compact size, and low cost. The 1.3 mm^2 area device was packaged in TO-18 package and had 810 microcells (40 μm × 40 μm each) with a 60% fill factor.

The gain for this SiPM has a temperature dependence of $<1.5\%/^{\circ}C$ [5], thus the gain varied by a maximum of ~60% over the ~0–40 °C temperature range experienced during flight. Fortunately, the SiPM output was input to a high-gain amplifier functioning as a discriminator to count coincidences, making the detector fairly insensitive to SiPM output variation. The effect of temperature variation on the payload trigger rate can be estimated from pre-flight thermal-vacuum test data, when the payload was subjected to a greater temperature variation than encountered in flight. From this data, the trigger rate shows no correlation with temperature. The temperature variation of the payload at float altitude was much smaller than during ascent, resulting in a much lower gain variation during this portion of the flight.

Although the 0905V13MM had a gain of $\sim 10^6$, the output current was still small and thus required amplification. Photonique provided the AMP-0604 [6] transimpedance amplifier with a gain

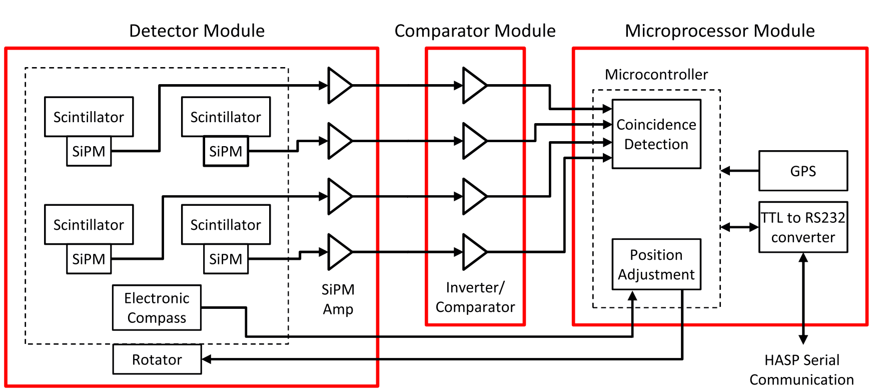

Fig. 2. HARD instrument block diagram.