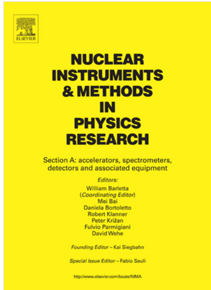

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Silicon Photomultiplier characterization on board a satellite in Low Earth Orbit

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Abstract

The LabOSat collaboration (acronym for "Laboratory On a Satellite") aims to increase the Technology Readiness Level (TRL) of electronic devices and components for space-borne applications. We have developed a single-board electronic platform which is able to operate in space conditions. This board harbors Devices Under Test and performs electric experiments on them. Since 2014, we have participated in six satellite missions (Satellogic small satellites) in Low Earth Orbits, in which we studied the performance of electronic devices such as resistive switching memories and dosimeters based on field-effect transistors.
In this work we present our efforts to increase the TRL of Silicon Photomultipliers (SiPMs). In early 2019 we have integrated four 6-mm SiPMs into a 40-kg satellite to study their performance in space. Each SiPM was encapsulated into individual light-tight aluminum housings, which included LEDs for excitation. The SiPMs and the LEDs are operated in DC current mode. Besides the SiPMs current and voltage measurements, the experiment also collects telemetry parameters like temperature, timestamp and orbital position.

1. Introduction

Spacecrafts are artifacts that have to operate in the hostile space environment. There, they suffer not only mechanical shock during launch, but also large thermal fluctuations and gradients, ionizing particles radiation, and collisions with dust and meteoroids. Once in orbit, repairing a malfunctioning instrument is a technological challenge that usually has prohibitive costs. Thus, one of the overarching principles of the design of a new satellite mission is the minimization of the risks-of-failure. As a consequence, the implementation of an innovative technology in space-borne applications has a large time scale, until such a technology is mature enough to be part of a mission. The Technology Readiness Levels (TRL) is a scale from 1 to 9 that estimates the maturity of a technology, with 1 meaning that the basic principles have been observed and reported, and 9 that the actual system has been "flight proven" through successful mission operations [1].

Silicon photomultipliers (SiPMs) are novel optoelectronic devices of solid-state technology. They have several advantages with respect of the traditional photomultiplier tubes (PMT), like a superior photon detection efficiency and time resolution. They are compact, mechanically robust, insensitive to magnetic fields and require a relatively low bias voltage [2], which are attractive characteristics for space-borne applications. Space agencies have identified photon-counting sensors as a key component for future space-borne instrumentation [3]. In the last years, the community started several efforts to increase the TRL of SiPMs.

Among several of the ongoing initiatives that aim to use SiPMs in orbit, only a few have already successfully launched and operated these sensors. One example is the LAZIO-Sirad experiment aboard the ISS [4], that uses SiPMs coupled to scintillators and wavelength shifter as part of a cosmic ray spectrometer. Another one is the SIRI-1 detector [5], which aims to space-qualify the usage of europium-doped strontium iodide scintillators coupled to a 2×2 array of SiPMs, on board of a small ($\sim 60 \times 60 \times 100$ cm^3) satellite. There are several projects on a development stage, like BurstCube: A CubeSat for Gravitational Wave Counterparts [6], the Fiber Tracker and the Plastic Scintillator Detector of the High Energy cosmic-Radiation Detection facility (HERD) [7, 8] and the Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) [9].

In this work we report on our efforts to increase the TRL of

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SiPMs in DC-current mode. To study and validate the performance of SiPMs in Low Earth Orbit, we have made use of our previously developed LabOSat-01 board [10]. The SiPMs studied were the MicroFC-60035-SMT from ON Semiconductor. The objective of this mission is to measure the response of the SiPMs to different levels of incoming photons, and keep track of a possible deviation of the response as a function of the mission development (start up, integration with the satellite, launch, payload commissioning, elapsed time in orbit). The response of the SiPM is studied from an electrical point of view, as we have not performed an optical calibration to relate the SiPM current with the impinging photon flux.

This report is organized as follows. In the next Section we introduce the LabOSat project and the LabOSat-01 board, followed by the description of the experimental setup and the daughter board that hosts the SiPMs. Then, we present the characterizations of the SiPMs performed with benchtop instruments, and preliminary results obtained in the start up campaign of the Payload. We conclude describing our plans for the near future.

2. The LabOSat project

Acronym for "Laboratory-On-a-Satellite", the LabOSat project is a collaboration which aims to increase the TRL of novel electronic components and sensors through characterization experiments in satellite missions [11]. To achieve this goal, the collaboration developed a platform comprised of a single electronic board, called LabOSat-01, which harbors the Devices Under Test (DUTs). The board was space-qualified through thermal cycling and thermal shocks under vacuum, mechanical shocks in a shaker, irradiation with high-energy protons and thermal neutrons [12].

Based on an MSP430 microcontroller, LabOSat-01 was designed to characterize two and three terminal electronic devices in DC mode. It is a programmable Source-Measurement Unit (SMU), able to perform I-V (current-voltage) curves [13]. For each particular DUT, LabOSat-01 firmware is tailored to perform a dedicated experiment. In addition to the experiment results, a set of telemetry parameters are also reported, including Total Ionizing Dose (TID), temperature, satellite battery voltage, timestamp and orbit coordinates. DUTs are typically integrated into LabOSat-01, in SOIC-16 packages. However, LabOSat-01 has also an expansion connector which enables access to the SMU for external daughter boards. In the study of the present report, a daughter board was designed to accommodate the SiPMs under test.

LabOSat missions are developed in NewSats satellites of the Argentinian company Satellogic [14], in Low Earth Orbit. Since 2014, the LabOSat collaboration successfully integrated seven boards in six different Satellogic satellites. Each board remained operational during their respective satellite mission. Currently, three of them still perform experiments on the DUTs operating in orbit, and data is downloaded for analysis. Regarding previously studied DUTs, we can mention RRAM devices [10], thin-film field-effect transistors [15] and solid-state dosimeters [16], among others.

3. SiPM packaging and characterization with benchtop instruments

To minimize the SiPM exposure to external photons, a light-tight housing was designed to accommodate the sensor and an LED for excitation. The LED used is the GD PSLR31.13-3T1U-25-1-150-R18 from Osram Opto Semiconductors. A schematic drawing of the SiPM-LED Housings (SiLHs), which represent the DUTs of the present study, is shown in Figure 1. The design of the SiLH had a hard restriction on the total height of 6 mm, set by the host satellite specifications. The SiPM was glued to the LED using a transparent epoxy, placing the active sides of each component facing each other. The assembly was then soldered to cables, and submerged into a black opaque epoxy inside an aluminum housing.

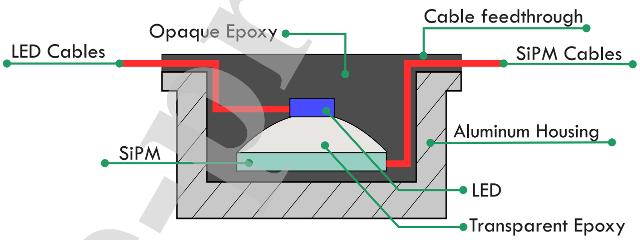
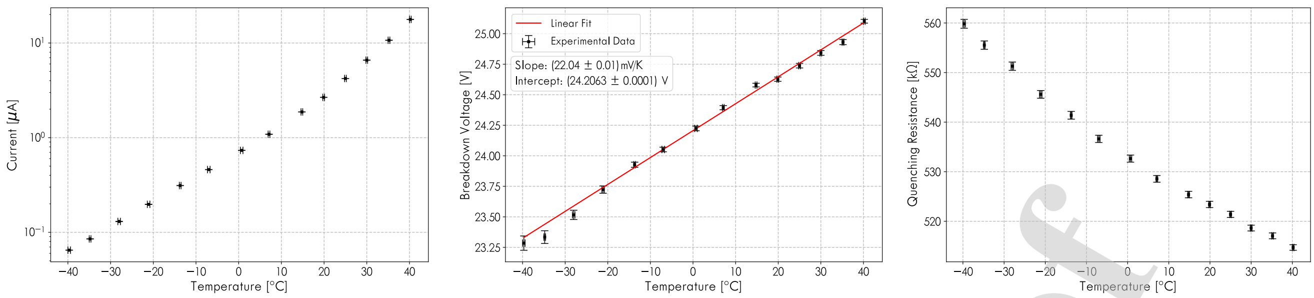


Figure 1: Schematic diagram of the SiLH design, in a cutout view (not to scale).

Before integration with the LabOSat-01 and the daughter board, each fabricated SiLH was characterized with benchtop instruments. The main SiPM's parameters studied were the breakdown voltage, dark current and quenching resistance, as a function of the temperature. These were studied in the temperature range of −40 to 40°C, based on the satellite temperature specifications. A prototype of a SiLH was thermally cycled under vacuum in the broader range of −60 to 60°C, to ensure the survival of the package.

All the tests were performed inside a vacuum chamber developed in-house, at the National Energy Commission of Argentina, equipped with a mechanical roughing pump. The cooling and heating systems were a closed circuit of liquid nitrogen and a power resistor, respectively. All electrical measurements were performed using an SMU Keithley 2612B, while temperature on the DUTs was measured with a Pt resistance.

The dark current of the SiPMs was measured with the LED off, at a reverse bias of 30 V. The dark current of one SiPM inside a SiLH as a function of temperature is shown in Figure 2.(I). With the SiPMs still reverse biased, I-V curves were acquired near the breakdown voltage to determine its value. The breakdown voltage as a function of the temperature is shown Figure 2.(II). A linear fit to the experimental data yielded a slope of $m = (22.04 \pm 0.01)\frac{\text{mV}}{K}$, consistent with the manufacturer specification. To measure the quenching resistance, the SiPMs were forward-biased from 0.7 to 1 V and the slope of the I-V curve was determined. The quenching resistance of each individual micro cell as a function of temperature is shown in Figure 2.(III), assuming that they all have equal value.



(I) (II) (III)

Figure 2: **(I)** SiPM's current as a function of temperature with LED OFF (i.e. SiPM dark current) for $V_{\mathrm{BIAS}} = 30$ V. **(II)** Breakdown voltage one SiPM inside a SiLH as a function of the temperature for $V_{BIAS} = 30$ V. A linear fit to the experimental data yielded a slope of $m = (22.04 \pm 0.01)\,\frac{\mathrm{mV}}{K}$, consistent with the manufacturer specifications. **(III)** Quenching resistance of each individual micro cell of the SiPM under study as a function of the temperature.

4. Daughter Board and Experiment Description

The SiLHs were integrated in a Daughter Board (DB) designed ad hoc for this mission, that was connected to the expansion connector of LabOSat-01. The DB contains two SiLHs in two redundant blocks in parallel, one for each SiLH. The LabOSat-01 board, the DB and the two SiLHs represent our Payload.

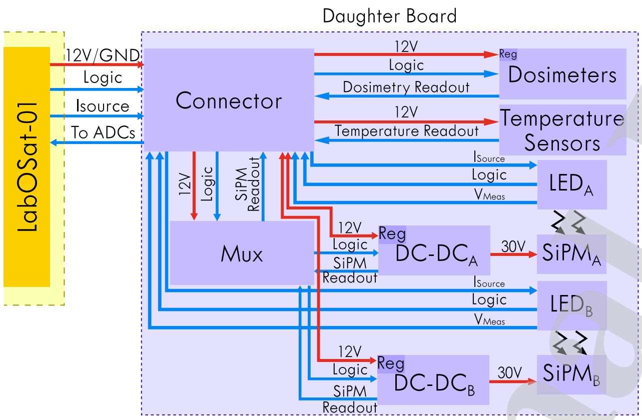


Figure 3: Daughter board's electronics block diagram.

A block diagram of the DB is shown in Figure 3. In the DB, each SiPM has its own independent power supply, based on a DC-DC chip (LT3571). The SiPMs were biased at fixed bias voltage of ~ 30 V, i.e. no temperature compensation was implemented. The SiPM current was measured using the Monitor output pin of the DC-DC, which is a current mirror of the Output pin, sourcing a 20 % of the Output current onto a 10 kΩ resistor. Due to the limited number of signal cables at the connector, a multiplexer chip was used to select SiLH under test. A series of switches either allow or block the current from flowing through the LEDs. Both the ADC and the DAC of the SMU, in addition to all of the logic signals were commanded by the MCU of LabOSat-01. Figure 4 shows a picture of a LabOSat-01 and the DB, with the integrated SiLHs. The PCB design of the DB was carried out avoiding some components of LabOSat-01 (the crystal oscillator, for example), to comply with the dimension restriction in the direction perpendicular to the PCBs.

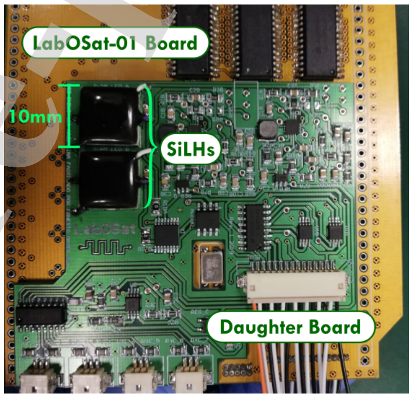


Figure 4: Picture of LabOSat-01 (orange, bottom board) and the Daughter Board (DB) designed ad hoc for this mission (green, top board). The SiPM-LED Housings (SiLHs) are also indicated. The PCB design of the DB was carried out avoiding some components of LabOSat-01 (the crystal oscillator, for example), to comply with the dimensions restriction in the direction perpendicular to the PCBs.

In the experiment, the current through the LED is controlled and the current on the SiPM is measured, along with the other related magnitudes, namely, SiPM bias voltage, LED voltage drop, and temperature. The latter was measured using the AD590JRZ 2-terminal temperature transducer. One at a time, both SiLHs are tested following the experiment concept shown in Figure 5. The current on the LED is fixed at 21 different values, from zero to 200 μA. For each LED current, the experiment measures the temperature of the DB, the SiPM bias voltage, and the LED voltage, followed by a set of 20 measurements of the SiPM current. The results of these measurements are packed into a report, stored in LabOSat-01 memory and sent to the satellite's on-board computer. Following the procedure of our previous missions, once the Payloads are in orbit, the experiment will be carried out once every ~ 24 hs. A daily email

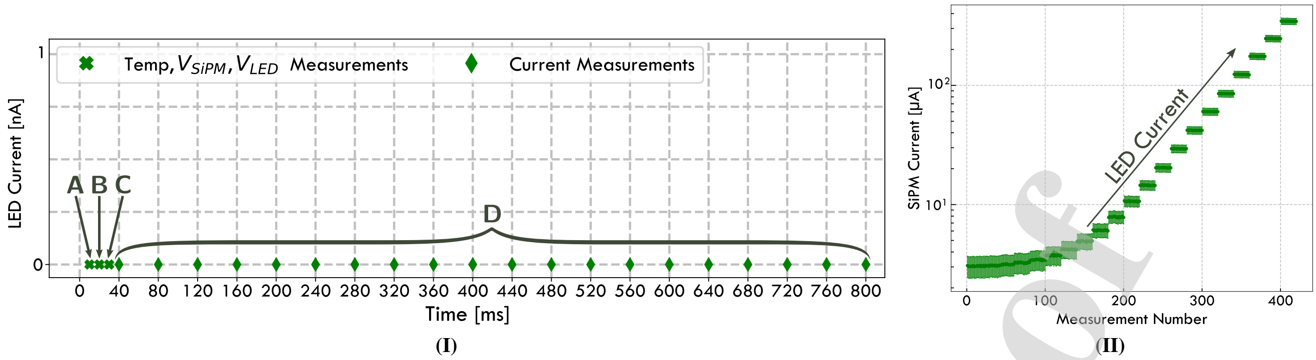


Figure 5: **(I)** Measurement sequence of the experiment on the SiLHs, for the first of the 21 LED current levels (LED Off): A) Temperature measurement. B) SiPM bias voltage measurement. C) LED voltage drop measurement. D) Set of 20 measurements of SiPM current. The LED current is settled for 800 ms. Afterwards the cycle is repeated for each of the 21 LED currents as programmed. **(II)** SiPM current for a complete experiment. Each flat response of SiPM current corresponds to a fixed LED current.

containing the last report of the experiment will be sent to our data repository by the Satellogic data communication pipeline.

5. Mission status and Preliminary results.

In February 2019, two sets of LabOSat-01 and DB, each set with two SiLHs in it (i.e. two Payloads), were delivered to Satellogic. A third Payload remained at our laboratory in order to have a ground comparison of the experiments performed in orbit. In May 2019, the two delivered Payloads were integrated in the same NewSat, for redundancy purposes. In June 2019, the whole satellite containing the Payloads inside was subjected to a shaker test. The launch was expected on September 2019, but was delayed until January 2020. At the moment, 70 experiments have been carried out on each Payload, taking into account the LabOSat-01 and DB start up at our laboratory and the integration of these with the satellite, at Satellogic premises.

Figure 6 shows the SiPM dark current (top plot) and the DB temperature (bottom plot) as a function of the report number, the latter being internally generated by LabOSat-01. The data shown was obtained between February and July 2019. Full markers represent data obtained in our laboratories, while empty markers represent data after the integration of the Payload with the satellite. The gaps between reports are due to the fact that, during the integration process, Satellogic ran several experiments but did not store the data. The last two data points were obtained after the shaker test was performed on the satellite assembly, including our payload. The uncertainty on the SiPM current is dominated by the uncertainty on the current mirror of the DC-DC (see Section 4). As expected, a correlation between SiPM dark current and temperature is seen in the plot. The temperature sensor has long-term drift and repeatability of 0.1°C, and an accuracy uncertainty of ±5°C at 25°C. Thus, for visualization purposes, error bars on temperature data points are not shown.

In Figure 7 we show the correlation between the SiPM current and the DB temperature, at three different levels of illumination, i.e. three different LED currents: LED off, i.e. SiPM dark

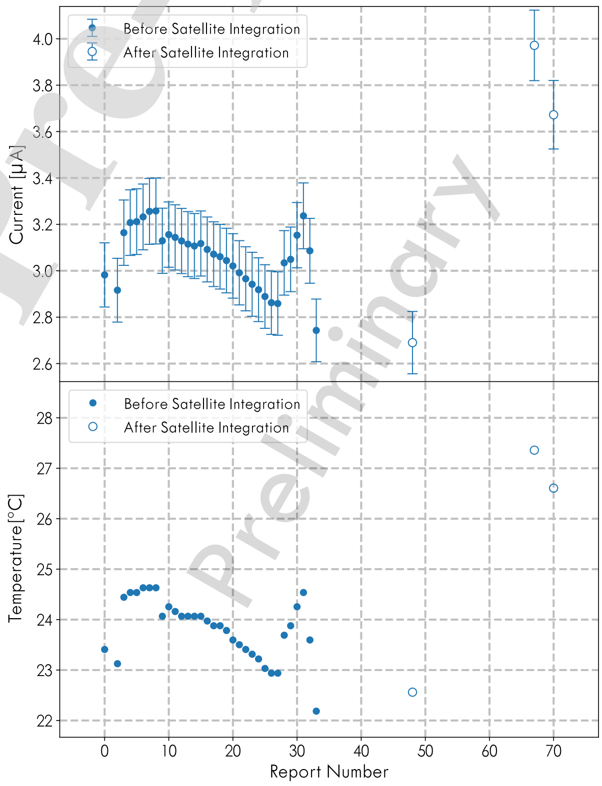


Figure 6: **Top Plot:** SiPM current vs. Report Number for a single SiLH with LED OFF (i.e. SiPM dark current). **Bottom plot:** Daughter-board temperature vs. Report Number for a single SiLH. Full markers: before integration with the satellite. Empty markers: after integration with the satellite.

current (blue circles); I_{LED} ~ 3 nA (red squares); I_{LED} ~ 4 nA (green diamonds). As expected, the response of the SiPM increases as the LED current increases. Although the data points have been measured at different times and locations, the three datasets show a correlation. Any departure of the trends will be an indication of a failure. Further analysis is ongoing, and it will be subject of a future publication, once we have gathered data from orbit.

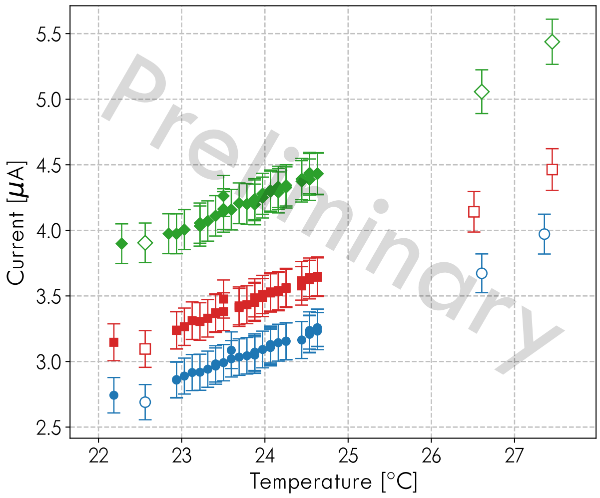


Figure 7: SiPM current vs Temperature for 3 selected values of LED current, for a single SiLH. Blue circles: I_{LED} = 0 nA (LED OFF), Red squares: I_{LED} ~ 3 nA, Green diamonds: I_{LED} ~ 4 nA. Full markers: before integration with the Satellite. Empty markers: after integration with the Satellite. The photosensor's current response increases as the LED intensity is raised as expected.

6. Outlook

We have successfully integrated four SiPMs into a Satellogic NewSat satellite, using our previously developed LabOSat-01 and a daughter board designed ad hoc for this mission. The whole satellite along with our Payloads passed a shaker test. A preliminary analysis shows that the sensors are working as foreseen. The expected launch of the satellite is on January 2020. Further analysis will be carried out when data from orbit is generated.

The presented simple experiment in DC current mode represents our group's first step in SiPMs investigations. Looking forward, we are currently working on a next mission that will use SiPMs in pulse mode. In that future mission, we will develop an instrument based on a few SiPMs with nadir field-of-view, with the objective of measuring the photon flux of different sources.

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