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# DarkNESS: Characterization of Space Multi-Chip Module Skipper-CCDs and Readout Electronics

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**Abstract**

The DarkNESS mission has the goal of deploying a 6U CubeSat fitted with an array of skipper-CCDs in Low Earth Orbit (~400 km). The new instrument will take measurements of diffuse x-rays and look for signatures of dark matter decay in the spectrum. DarkNESS will also perform a direct search for strongly interacting sub-GeV dark matter in regions of the parameter space not accessible to ground based experiments [1]. Skipper-CCDs allow for low-noise astronomical observations which can extend the discovery reach for direct dark matter search experiments. This paper will discuss the laboratory characterization of the two key components of the scientific payload: the space Multi-Chip Module (sMCM), and their readout electronics.

## 1 Introduction

Dark matter (DM) poses an important question in physics as it can explain many astronomical phenomena such as gravitational lensing, formation, and rotation of galaxies, and fill in the gaps of our understanding of the universe. Although DM makes up a large majority of the universe it continues to elude detection. There are many different strategies attempting to detect the dark matter particle, and CCDs play a significant role in this search. creating many avenues in the attempt to detect it, such as CCDs.

First invented back in 1969 [2] Charge-Coupled Devices (CCDs) have been a powerful tool for scientific imaging applications in many fields [3], and more recently skipper-CCDs have been demonstrated as a probe for DM in running experiments such as SENSEI [3][5], DAMIC-M [9] and the planned Oscura project [10]. CCDs have also been demonstrated in neutrino experiments [5].

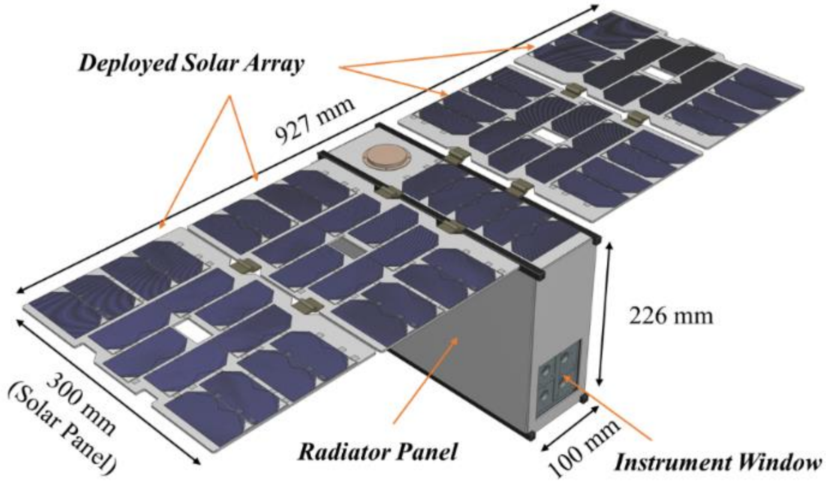


**Figure 1**: 3D rendition of the DarkNESS satellite. Payload, sLTA and sMCM, housed within the instrument window [1].

The goal of the DarkNESS pathfinder mission is the use skipper-CCDs for direct dark matter search. The mission will send a 6U CubeSat equipped with skipper-CCDs into Low-Earth Orbit to see how well these CCDs operate in space, taking x-ray data of the galactic center to possibly detect a 3.5 keV x-ray DM decay from ~7 keV sterile neutrinos and detect sub-GeV DM through recoiling electrons from Cygnus X-1 [1].

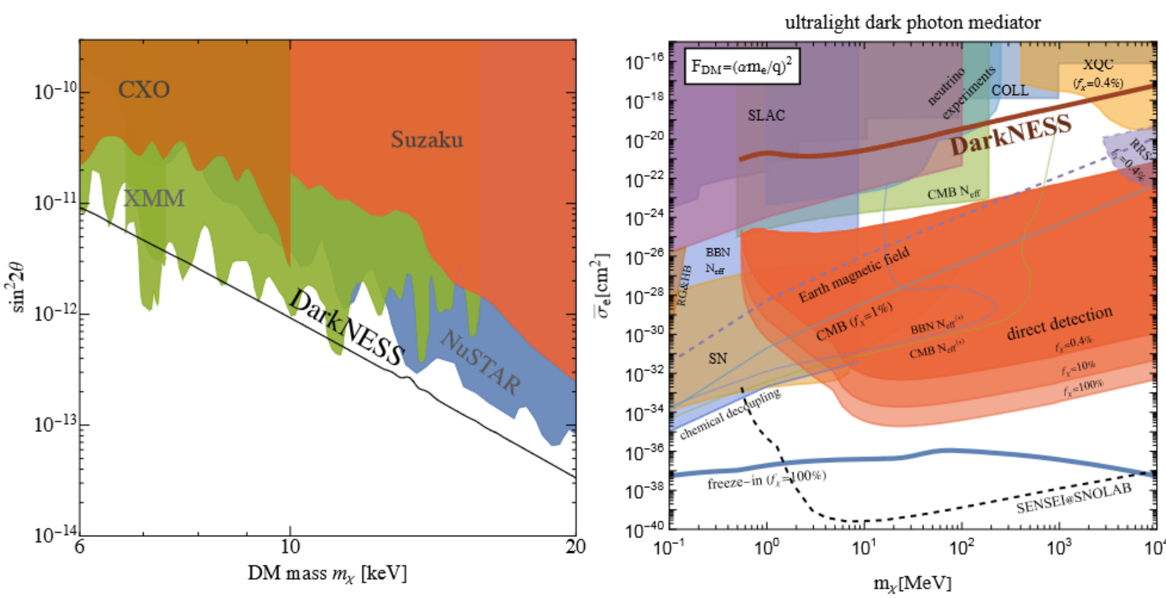


**Figure 2**: **Left:** Sensitivity plot of DarkNESS for low energy x-rays from sterile neutrino decay from the galactic center. **Right:** DarkNESS' sensitivity to larger cross-section sub-GeV DM [1].

In Fig.2 Left, the discovery reaches for keV scale x-rays, and on the right is for sub-GeV DM at higher cross-sections. Observing these in space is necessary as the Earth's atmosphere would attenuate these signals making them impossible to detect on Earth.
This paper will describe the laboratory tests performed on the DarkNESS scientific payload.

## 2 DarkNESS Scientific Payload

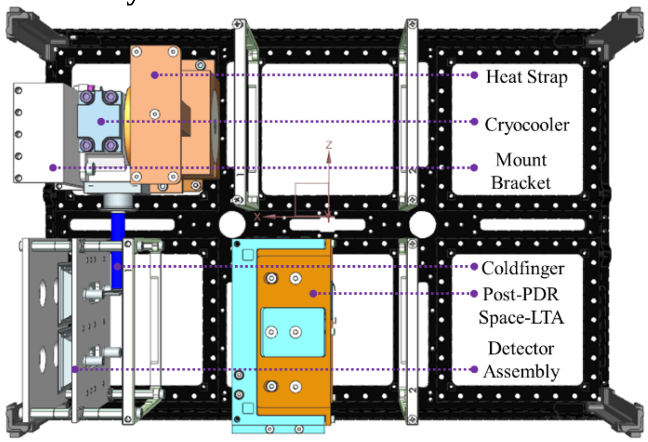


**Figure 3**: 3D design of the interior of the CubeSat.

The scientific payload of DarkNESS consists of the sLTA and the sMCM, where the sLTA, otherwise known as the space Low Threshold Acquisition readout board, is a miniaturized version of the standard LTA [4] and requires less power to run. The sLTA is also encased in a copper housing to facilitate thermal dissipation into the walls of the CubeSat, and ultimately into space. The sMCM is a 2x2 array of 1.3-megapixel back-illuminated skipper-CCDs, with a thickness of 200 μm for increased quantum efficiency in the lower energy levels. The entire payload will be subjected to vacuum conditions of $\sim 10^{-4}$ torr with the sMCM connected to a cryocooler set to 170 K.

### 2.1 Overview of Space Multi-Chip Module

The sMCM is a ceramic Aluminum Nitride board with four identical skipper-CCDs epoxied and wire bonded in a square pattern as shown in Fig.4 below. The sMCM is built in a way that each skipper-CCD can run independently and concurrently with each other for increased spatial coverage. The package is designed to be low mass and have a coefficient of thermal expansion matching the Silicon (Si). The sMCM is connected to a custom flex cable which interfaces the Low Threshold Acquisition Board (LTA) using space certified high-density cryogenic connectors from Airborn, more on this in Section 2.3.

**Figure 4**. **Left:** Photo of the sMCM with the GPIO flex cable attached. **Right:** Closeup of flex cable.

### 2.2 DarkNESS Sensor

CCDs, otherwise known as charge-coupled devices, utilize the photoelectric effect to create electron-hole pairs in the Si substrate to detect photons from the near-IR to X-rays. Particles such as cosmic ray muons, alpha particles, and gammas can also knock out an electron which can create electron-hole pairs in the Si which would be detected as well. The hypothetical dark matter particle could also ionize Si atoms in the detector. These charges are then stored in a capacitor and measured as voltage at the output of the CCD, which is then digitized. Skipper-CCDs are an upgraded version of a CCD with nondestructive readout which makes them capable of reading the same pixels multiple times for a reduction in readout noise to sub-electron levels [11].

The Skipper-CCDs used in this paper had minimal to no shielding and were tested on the surface with minimal overburden . Each CCD has four readout amplifiers in each corner, but only one amplifier was used for each CCD. The active area of each CCD is readout in three-phases with the dimensions of the active scan area being 1278 x 1058 pixels, with each pixel being 15 $\mu m^2$, and a Si wafer thickness of 725 $\mu m$.

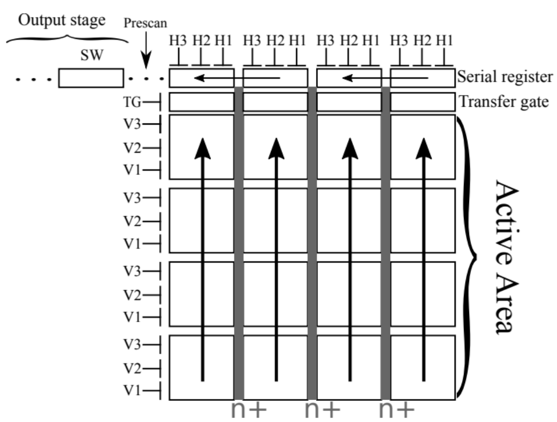


**Figure 5.** An illustrative structure of the top-left corner of a CCD, courtesy of [3]. Each pixel consists of three vertical clocks which move the charge towards the transfer gate into the serial register, in which the charges are horizontally shifted into the output stage for readout.

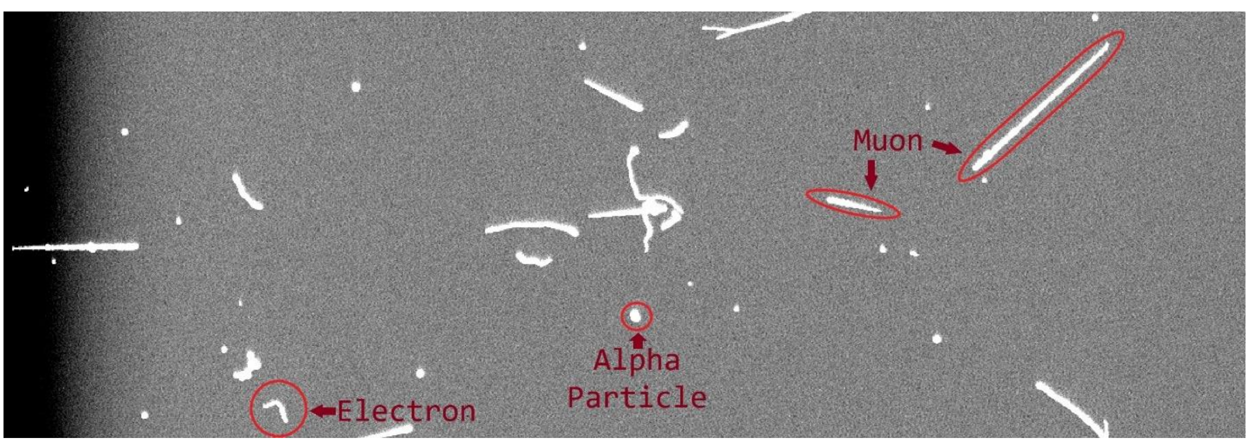


**Figure 6.** Slice of a CCD image from the cosmic data run showing different tracks displayed with DS9. First few columns and last couple hundred columns are prescan and overscan, respectively. The dark gradient after the prescan is due to transients in the electronics.

Using DS9, an astronomical image visualizer, one can view the image a CCD detects through a FITS (Flexible Image Transport System) or a fz (compressed FITS) image. An example image is shown in Fig.6.

### 2.3 (Space) Low Threshold Acquisition Board

For the initial testing of the sMCM we use the standard LTA (Low Threshold Acquisition). This LTA has a different formfactor compared to the space version (sLTA) but is functionally the same. The LTA and the sLTA are shown in Fig.7. The LTA biases, controls and reads the CCDs through a DB50 connector (connected to the sMCM through the flex cable), shown on Fig.7 Left. The LTA is controlled by the computer through a single ethernet cable, which can be given certain sequencers and scripts to control the voltages and readout of the CCDs.

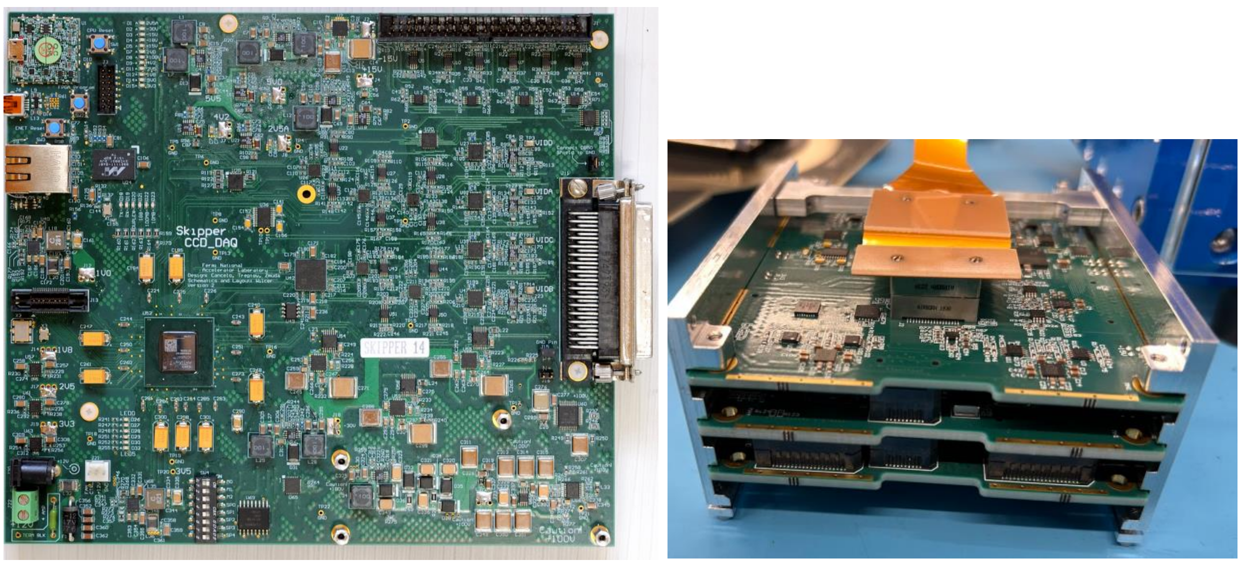


**Figure 7. Left:** The LTA board [4]. **Right:** Space LTA incased in prototype aluminum housing with flex cable attached.

The LTA allows the user to change the number of samples, columns, rows, and more to take the desired image. In this paper, we use a few parameters which are: NSAMP (number of samples per pixel), NROW (number of rows to be readout), NCOL (number of columns to be readout), EXPO (amount of exposure time on the CCD before readout).

## 3 Laboratory Test of DarkNESS Skipper-CCDs

### 3.1 Experimental Setup

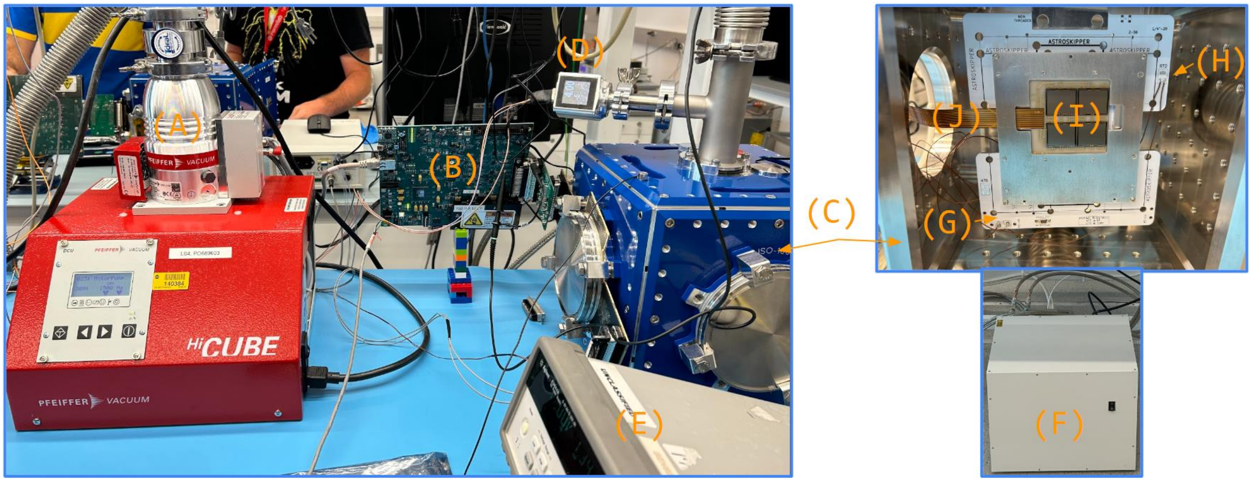


**Figure 8.** Test setup for sMCM testing. **(A)** Vacuum pump, **(B)** LTA, **(C)** Pressure cube, **(D)** Pressure gauge, **(E)** DC power supply, **(F)** Cryocooler, **(G)** Heater board, **(H)** RTD temperature sensor, **(I)** sMCM, **(J)** Flex cable.

In the setup above, the cryocooler is connected to a cold finger which is attached to the mounting plate of the sMCM, which cools down the CCDs to -150℃. The vacuum pump creates a $\sim 10^{-5}$ torr vacuum in the pressure cube. The CCDs must be cooled down to at least -100℃ to operate with minimal noise, as heat leads to thermal excitations in the Si, leading towards a noisy image. Furthermore, vacuum is required at these levels of coldness as condensation will form if any moisture in the air interacts with these cold elements. Moisture would not only cover the active CCD area, but it also has the possibility of shorting the electronics.

### 3.2 Tests of the Skipper-CCD Sensor

#### 3.2.1 Data Analysis

In all the analyses, we discarded sensor one of each read as the LTA we used had a broken channel outputting pure noise. Before taking data, there a few constant parameters:
**Initialization script** sets the voltage script to be used on the sMCM, the sequencer, and communicates with the LTA.
**The sequencer** controls the readout stage of the CCDs, essentially creating the image files.
**The voltage script** sets the voltages used on the sMCM, this changes how well the charges are readout along with the vertical and horizontal clocking.

### 3.2.2 Noise

Using varying NSAMPs, I plotted the noise in electrons of the CCDs. This is important because if the noise value is higher than one electron, then it will not be possible to resolve single electron peaks for gain calculations.

$$\frac{Readout\ Noise\ of\ 1\ NSAMP}{\sqrt{NSAMP}} \qquad (1)$$

Equation 1 shows the correlation between readout noise and NSAMP, normalized to the readout noise of a single NSAMP.

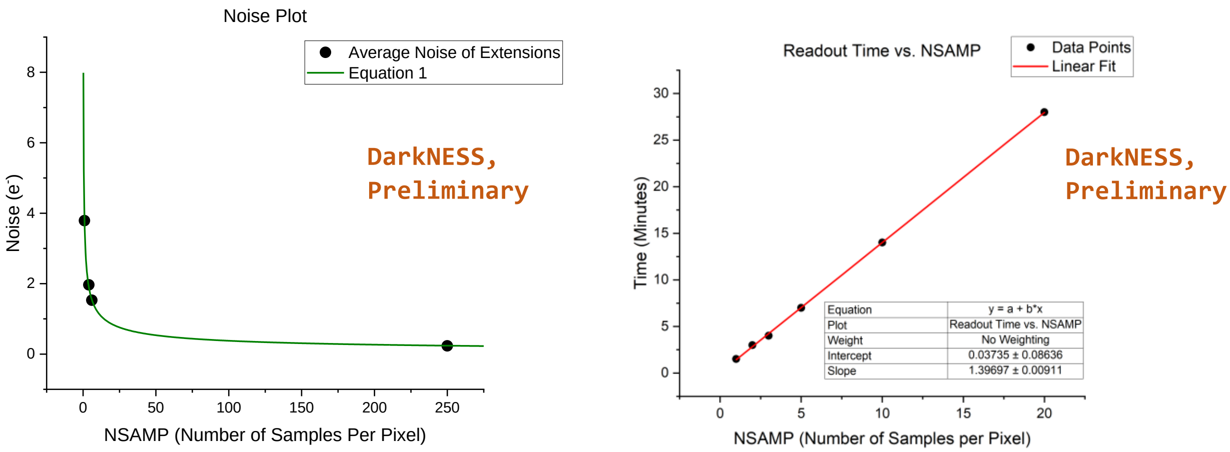


**Figure 9. Left:** Plot of four different NSAMPS – 1, 4, 6, and 250. **Right:** An example of the correlation between readout time and NSAMP.

Equation 1 shows the normalized correlation when using the approximate noise ($e^-$) of one sample. We can see that the data points follow this curve well. This allows us to know when and how low we want the noise to be for multi-sample data runs. Referring to Fig.9 Right, by using a higher NSAMP, we also linearly increase the readout time, so a balance must be made between precision and time when data taking. With our current setup, we can read a single full-size sample every ~1.5 minutes, but we plan to lower this to one minute.

### 3.2.3 Gain

Gain is the number of ADU (Analog-to-Digital Unit) per electron, this is needed for scaling calibration when scaling things such as cosmic and x-ray data. If not properly calibrated, then the expected characteristic energy values of cosmic and x-ray sources will be off by a factor of the gain. Gain here is calculated by subtracting the $0e^-$ and $1e^-$ peaks, but a more rigorous calculation can be found here [6].

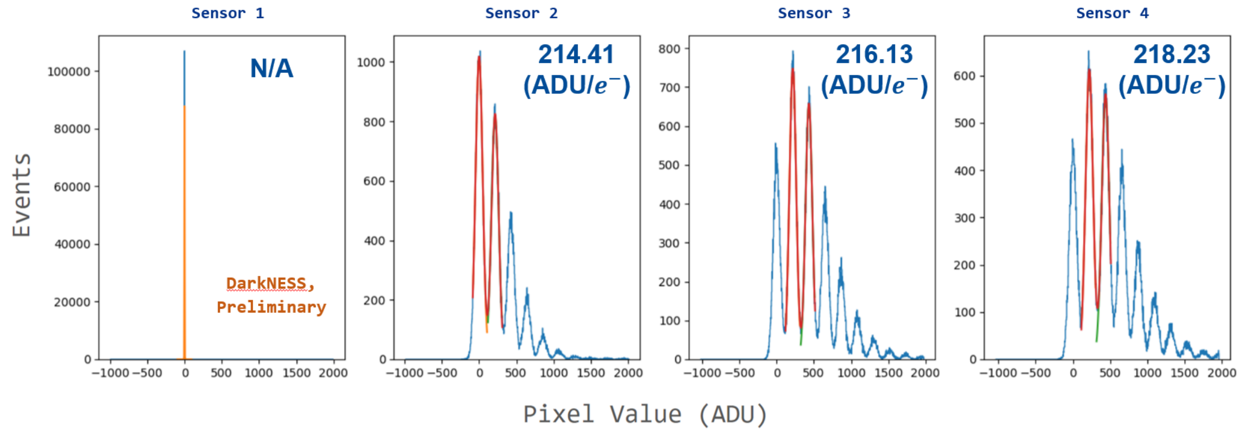


**Figure 10.** Gain measurements taken for the NSAMP 250, NROW 100, and vMCM15 voltage script, calculated with a python script.

| Sensor | Gain ($ADU/e^{-}$) |
|---|---|
| 1 | N/A |
| 2 | 214.41 |
| 3 | 216.13 |
| 4 | 218.23 |

**Table 1.** Gain measurements from Figure 10.

From the plots above, we can see that the $0e^{-}$ peaks are not centered at zero. This is due to an imperfect subtraction of the baseline from the overscan. Baseline refers to amplifier current, and this acts as the zero that must be subtracted for correct calibration. We subtracted the baseline via the mean of the overscan, leading to a nonperfect offset, resulting in the biggest peak (the 0e$^{-}$ peak) to be shifted, which is not a problem for noise and gain, but must be better subtracted in data analysis. One method is to the subtract the baseline on a row-by-row basis.

The gain values for the sMCM are constant, so it only needs to be calculated once for a decent calibration as it is. Gain is dependent on the values of PSAMP and SSAMP, the sampling areas for the pedestal and signal regions, respectively.

### 3.2.4 Dark Current

Dark current can be characterized by the level of thermal excitations in the Si and external factors such as radiation. It must be stated that the dark current (DC) found is very rough and is not intended to be a rigorous calculation of what it truly is, for more information on dark current calculations, check these papers [3][4]. In this paper, we took data at varying exposure times and applied a linear fit for our DC approximation.

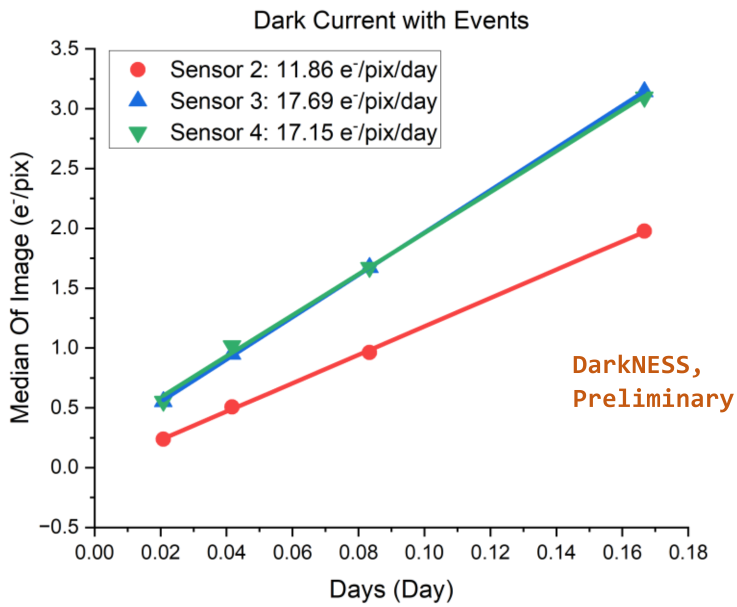


**Figure 11.** DC plot of each on the sMCM. EXPO – 30 minutes, 1 hour, 2 hours, 4 hours.

The DC found here gives us an idea of whether there is light bleeding into the pressure chamber or excessive voltage causing amplifier light. The values shown for each sensor is expected as this was not a perfect measure. This means there was no shielding applied, minimal overburden, and no masking of events. We used the median of the images to help mitigate the influence of events such as electrons and cosmic rays. Skipper-CCDs can reach DC levels in the order of $10^{-4}\ e^{-}/pix/day$ [3][4][5].

### 3.2.5 Americium-241 X-Ray Data

To preface, it would have been ideal if an Fe-55 sample was used as the DarkNESS experiment is focused on the lower energy spectrum. That being said, it is good to see how the CCD handles higher energies and oversaturation, as this is a good test of clustering good events. Furthermore, we can see the resolution of the CCD at these energies to see if they will be good enough to capture the intended events without getting washed out by noise.

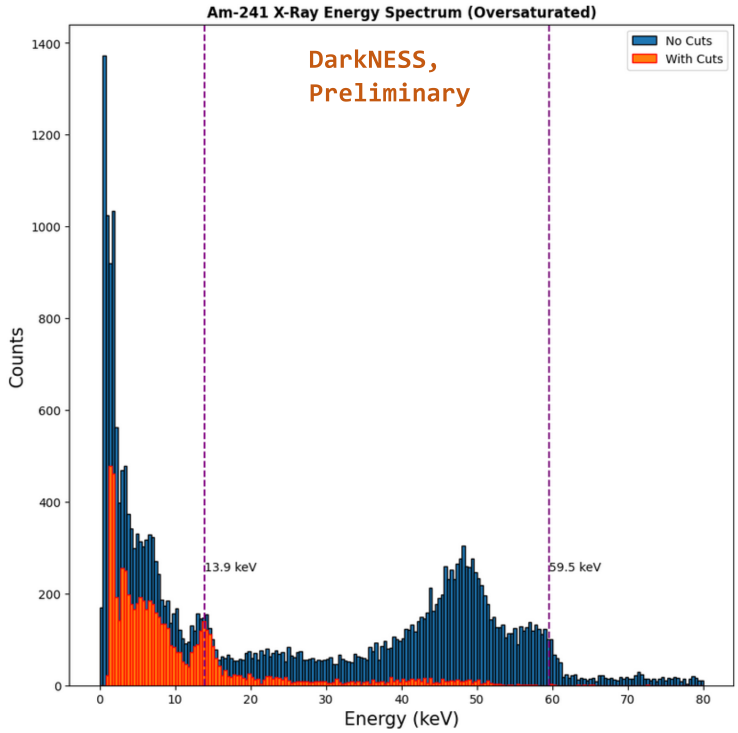


**Figure 12.** X-ray energy spectrum of Am-241. Black displays no cuts, while Red has cuts on the NPIX (the number of pixels in a cluster) and peak (pixel values) to reduce the oversaturation from the alpha and gamma rays. This data was taken with NSAMP 1, a full scan of the active area, with 104 images overlayed.

We do see one of the characteristic peaks at 13.9 keV [7], which tells us that the calibration used is almost correct. The plot in the black seems to show the characteristic 59.5 keV peak as well, but it is curious as to why the peak is much smaller than expected. The ~49 keV peak was originally thought to be a GaAs peak [8], but this was impossible as the CCDs are made with Si. This alludes to the fact that these peaks may be the result of oversaturation in the CCDs and is just a coincidence that a characteristic-like peak is displayed. Furthermore, due to the oversaturation there is a charge transfer inefficiency, which slightly offsets the energies to lower levels. In the future, we plan to retake the data to check the calibration. This poses a good problem as high energy events will affect the CCDs and need a workaround when in space.

### 3.2.6 Cosmic Data

Although the cosmic ray data runs were done before the x-ray, it was decided to put this as the last section, as analysis is still ongoing. Cosmic data was originally taken as a measure of calibration of the sMCM.

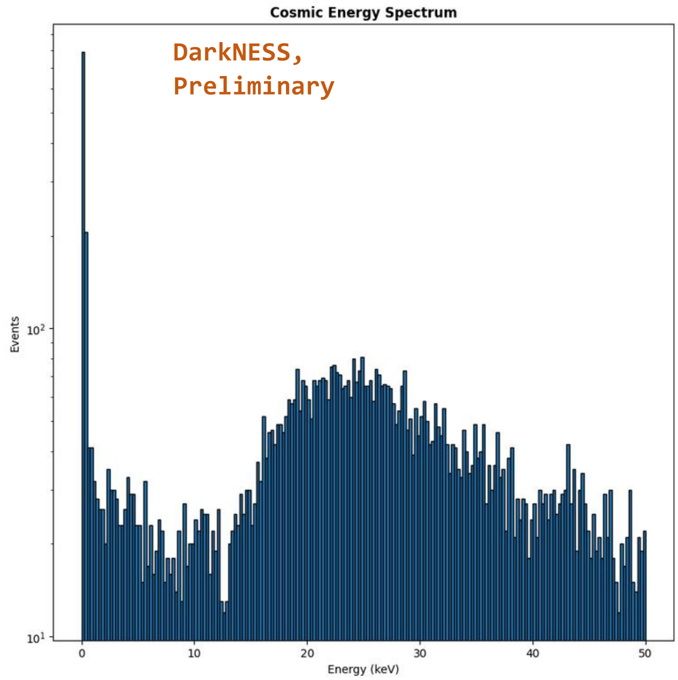


**Figure 13.** Energy spectrum of cosmic data run. NSAMP 4 (3, ignored the first sample due to excessive noise), full CCD scan, combined EXPO and READ time of 15 minutes, with 45 images overlayed, sensor 4.

We observed the characteristic muon bump at around 25 keV, but we expected it to be higher than this value. We are not completely sure as to why the cosmic bump is as low as it is, as we expect it to be around 250 keV. One explanation may be due to an improper reconstruction at higher energies, as it may not have the same calibration as the lower energies.

We do know that are electronics are working correctly, as they have been tested before on other test setups. Further analysis is ongoing to understand the cosmic energy spectrum histogram.

## 4 Conclusion and Future Work

As shown in this paper, there is still work to do on characterizing the sMCM. Preliminary analysis shows that the sMCM is capable of sub-electron noise and can resolve the cosmic muon bump and a characteristic energy of Am-241. The main purpose of this paper is to show that sMCM works. Future work which is currently in progress is to test the sLTA alongside the sMCM to simulate something closer to the actual DarkNESS mission. In the future, we wish to switch to the ~200 µm skipper-CCDs to more accurately represent DarkNESS proposed payload.

## 5 Acknowledgements

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