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POLAR-2
Building a Qualification Setup for the POLAR-2 Space Mission

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Summary

In 2016, POLAR - a polarimeter - was launched on the Tiangong-2 Chinese space lab. It was designed to measure the polarization of the prompt emission of Gamma-Ray Bursts (GRBs). The next-generation GRBs polarimeter, POLAR-2, is set to launch into space in 2026. However, before building the device, performing calibration on the final prototype and understanding the behavior of the data is essential. This report presents the final results of the setup that was built for the calibration of the POLAR-2 prototype.

Contents

1 Acknowledgements

This report serves as a summary of my work as a summer student at CERN, where I had the privilege of contributing to the POLAR-2 project. I would like to take this opportunity to express my heartfelt gratitude and appreciation to the individuals and teams who made this experience an unforgettable one.

First and foremost, I would like to express my sincere gratitude and appreciation to my supervisor, Merlin Kole, for his unwavering guidance, support, and mentorship throughout the duration of my internship. I am truly fortunate to have had the opportunity to work under his guidance. I am also deeply grateful to the entire POLAR-2 team for their warm welcome and inclusion.

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Lastly, I want to express my appreciation to my family and friends for their unwavering encouragement and understanding during this journey. Their support has been a constant source of motivation.

2 Introduction

2.1 GRBs

Gamma Ray Bursts, also known as GRBs, are intense and brief flashes of gamma-ray radiation that originate from distant regions of the universe (see Figure 1). They are the most powerful events in the Universe since the Big Bang and can last from hundreds of milliseconds to hours. The initial gamma-ray burst is referred to as the prompt emission. Following that, GRBs often exhibit a long-lasting afterglow that can persist for several days to weeks.[3]

Figure 1: An illustration of an energetic space explosion that was made with machine learning

GRBs are typically classified into two main types based on their duration:

1. **Long Bursts**: The more common type. They are characterized by having a duration of gamma-ray emission that lasts for more than two seconds and are often associated with the core collapse of massive stars, specifically those with very high mass (usually more than 25 times the mass of the Sun).

2. **Short Bursts**: Typically lasting less than two seconds. After the detection of gravitational waves in 2017, it was concluded that the short bursts come from the merger of compact objects, such as two neutron stars or a neutron star and a black hole.[5]

The first GRB was detected back in 1967 by the Vela 4a,b satellite(see Figure 2). Although the study of GRBs is essential to advancing our understanding of fundamental physics, astrophysics, and cosmology, some questions remain unanswered.[3]

One example of the questions that scientists are trying to answer is how the prompt emission mechanism works. Additionally, since gamma-ray bursts are extremely luminous and can be detected from far away, they offer a distinctive chance to explore the early stages of the universe.[5]

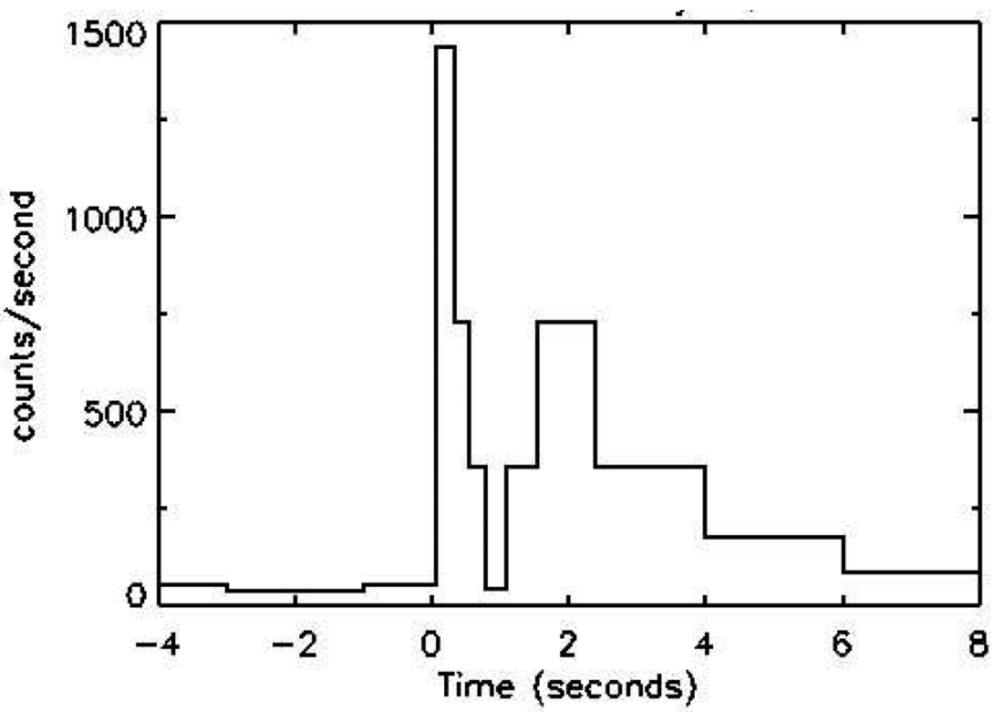

Figure 2: The first GRB, known as GRB 670702, was detected by Vela 4a,b satellite in 1967 [4]

2.2 GRBs Polarization

GRB studies encompass multiple fields, such as astronomy, astrophysics, particle physics, and cosmology. These studies help us to enhance our understanding of GRBs and contribute to a broader knowledge of our universe, from the most energetic phenomena to its early history and evolution. Despite decades of research, the prompt emission of GRBs is still not fully comprehended. [5]

Measurement of gamma-ray photon polarization emitted during a GRB event is known as GRB polarization. Performing such measurements is crucial to gain a deeper understanding of these astrophysical sources. Although GRB polarization measurements have significant scientific potential, only three-photon parameters (arrival time, direction, and energy) have been measured due to the difficulty of performing such measurements.[2]

2.3 POLAR/POLAR-2

A polarimeter is a scientific instrument used to measure the polarization properties of electromagnetic waves, such as light or radio waves.

1. **POLAR**:

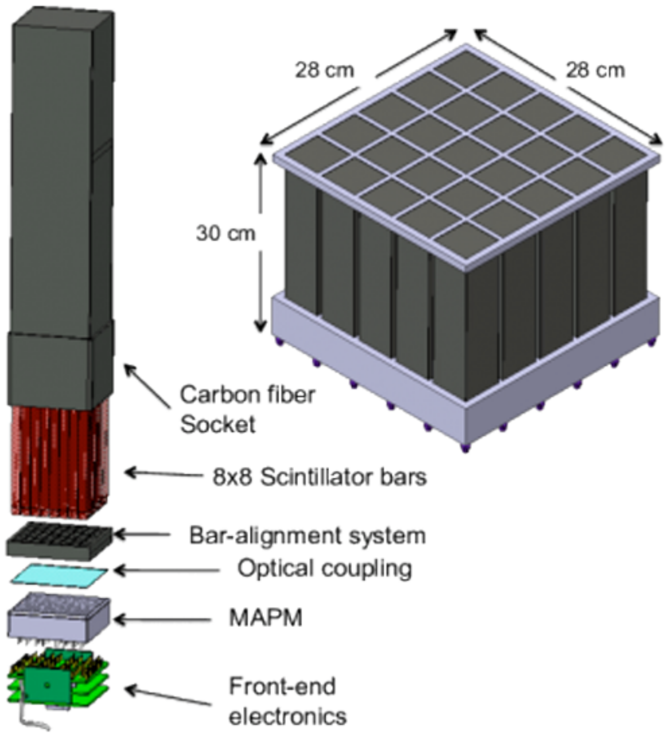

Figure 3: Design of the POLAR instrument [2]

The POLAR experiment was launched in 2016 on the Tiangong-2 Chinese space lab. The instrument (a Compton polarimeter) consisted of 40×40 scintillator bars divided into 5×5 modules (see Figure 3). The mission ran for six months, during which POLAR detected 55 GRBs in the energy range of 50-500 keV.

The scintillator bars interact with high-energy photons through Compton scattering. The number of interactions determines the scattering angle, which can be used to infer the polarization angle (PA) and degree (PD).(see Figure 4). [4]

The polarization results of the five brightest GRBs that were detected were found to be low (less than 40 %), which led to the conclusion that higher precision measurements are needed in the future.[5]

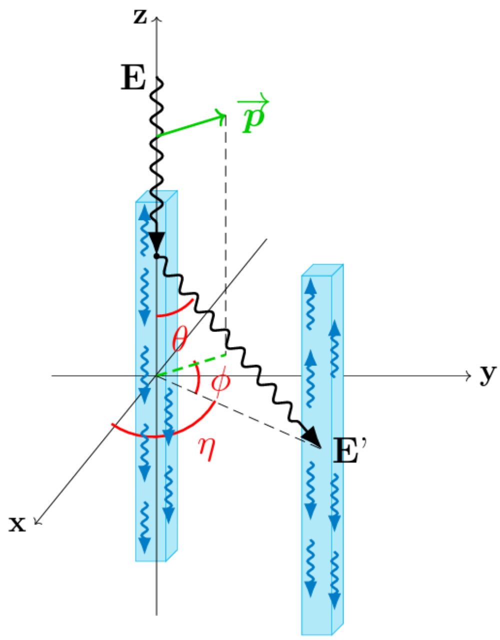

Figure 4: Illustration of the Compton scattering instrument [2]

2. **POLAR-2**:

   POLAR-2, a more sensitive detector, is the next-gen GRB polarimeter launching to the China Space Station in 2026 with a design similar to POLAR.

   There were two major changes made to the device that improved its performance compared to POLAR. Firstly, the device now has a greater number of scintillator bars - 6400 compared to POLAR's 1600. Secondly, silicon photomultipliers (SiPMs) are now used, which are more sensitive than the commonly used PMTs. These two changes have contributed to the improvement in the overall performance of the device. (see Figure 5).[5]

   POLAR-2 will have 100 polarimeter modules, where each of them will have a Front-End Electronics Board (FEE).(see Figure 6)

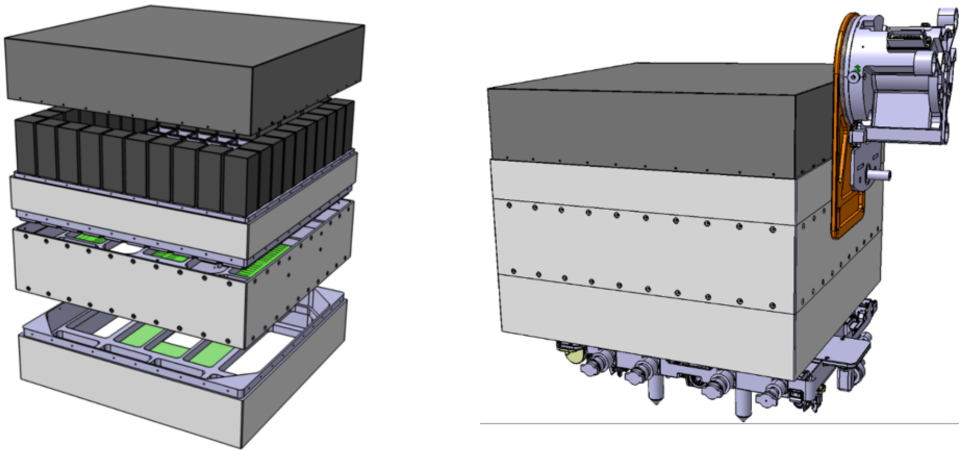

Figure 5: CAD model of the POLAR-2 instrument [2]

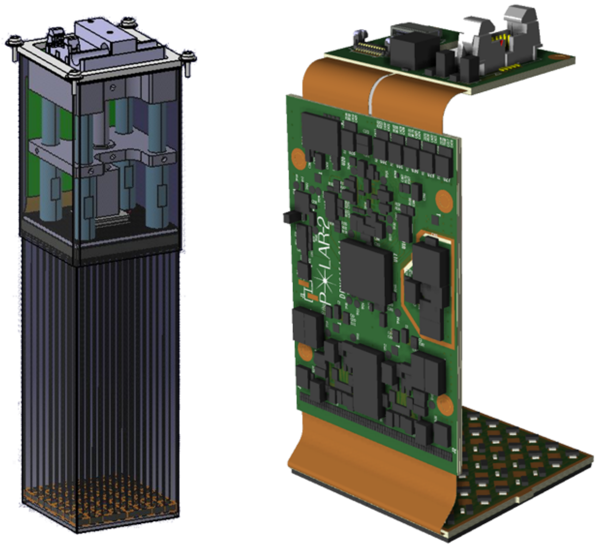

Figure 6: CAD model of a single polarimeter module (right),and of a Front-End Electronics Board (left) instrument [2]

3 The Lab Setup

Calibration is a crucial step in preparing scientific instruments for space missions. Precise calibration is necessary for accurate and reliable data collection. In order to determine the sensitivity of each of the 64 bars for each module, a calibration is performed.(see Figure 9)

3.1 The setup

To calibrate the final POLAR-2 prototype, a setup was built in the lab. The setup is based on an XY-table that was built in advance [1] and a radioactive source was used to simulate the effect of a GRB's emission. (see Figure 7)

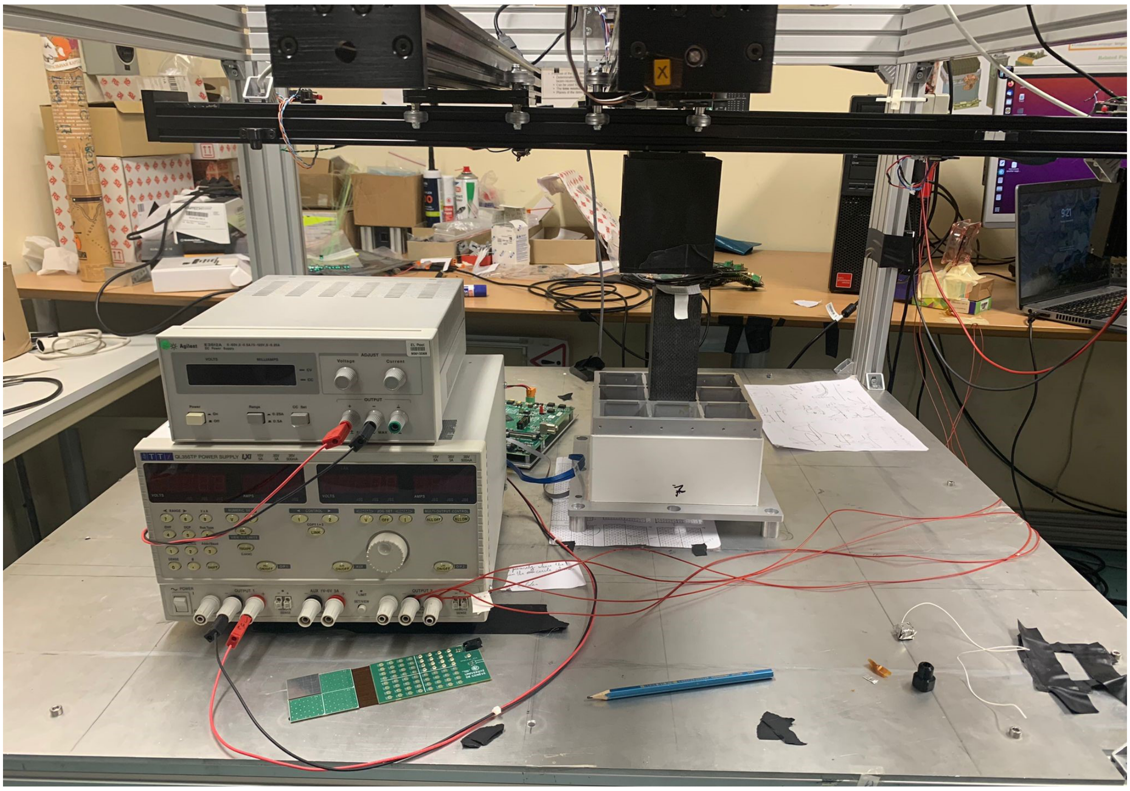

Figure 7: The image displays the full calibration setup, including power supplies(left), GPIO, prototype placement (right), and radioactive source placement in the top black box .

The prototype is placed on an XY table, which allows for the movement of the radioactive source (As will be discussed in more detail in the next subsections.).

3.2 The prototype

A Polar-2 prototype was placed on a pre-made layout for calibration. The prototype consists of 8 modules numbered 0-7, each with 64 bars numbered 0-63. The calibration was performed on module number 5 with a single polarimeter. (see Figure 8)

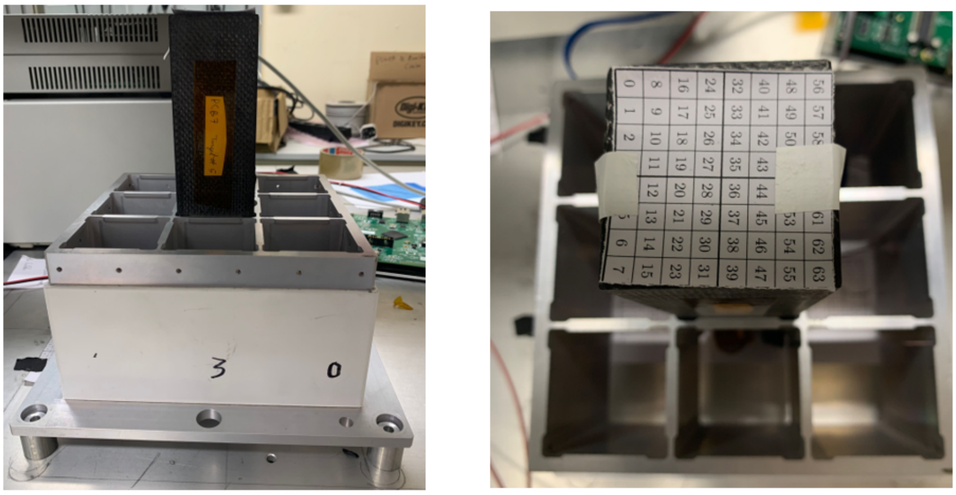

Figure 8: An image of the prototype with the single polarimeter connected to module 5 (left) and the numbering layout of the bars (right)

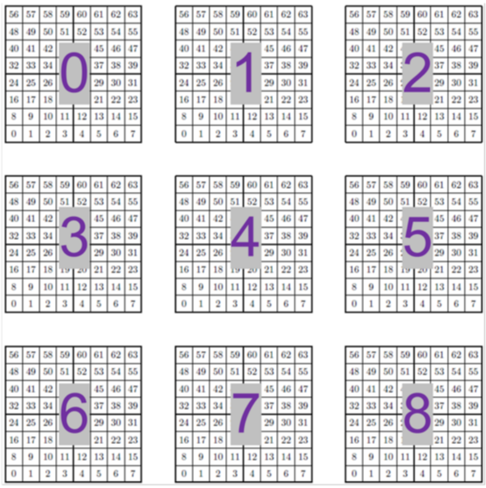

Figure 9: The pre-made layout consists of 8 modules, each with 64 bars. [1]

3.3 The radioactive source

A radioactive source, AM241, was used to replicate the effects of a GRB.

During the initial calibration, the radioactive source was not polarized. The source was directed straight toward the polarimeter with the help of the XY table, as previously mentioned.

3.4 programming

3.4.1 Motivation

To control the movement of the radioactive source on the XY tables (see Figure 10) Python was used to develop a controlling code.

Figure 10: The placement of AM241 as part of the setup

The first part of the code was to determine the main coordinate system of the setup.

The zero point of the main coordinate system was determined by aligning it with the lower corner of the zero bar in module zero of the main layout.(see Figure 11)

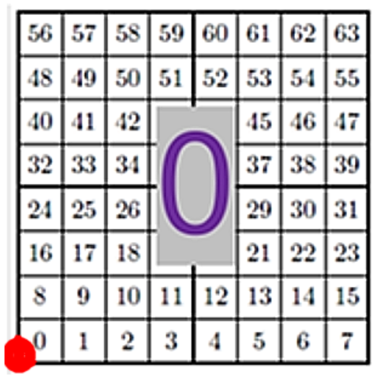

Figure 11: The zero point (red dot) of the main coordinate system.[1]

3.4.2 The Functions

As part of the control code, a few additional functions were written.

1. **find zero**: To determine the zero point, a function called **"find zero"** was created based on the distance between the main zero point (see Figure 11) and a universal coordinate system. The universal coordinate system was determined based on two optical sensors connected to the XY table. The sensors make it easy to stop motor movement.

2. **move**: This function was written to move the radioactive source to a specific bar (0-63) of a specific module (0-8). This will enable the collection of data from the bar for sensitivity analysis.

   Based on the main layout mentioned earlier, the movement of the bar depends on the motor's rotation. Specifically, 150 rotations correspond to a length of 6 [mm], which is the length of each bar. The distance between each pair of modules is 1.2 [mm], which is also considered in the calculation.

3. **move to bar**: This function is a sub-function of the move function. It was created to move the radioactive source to the center of a specific bar, directing the radiation to that point. (see Figure 12)

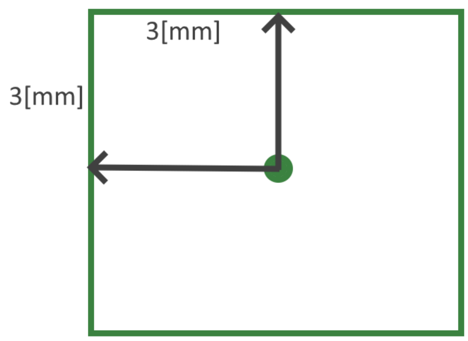

Figure 12: The middle point of a bar

4. **full scan**: This function was written to enable the collection of data from the whole module (all 64 bars) for sensitivity analysis.

   The source will start at bar 0 and end at bar 56. To ensure sufficient data collection, the motor's movement was slowed down, resulting in a 5:30-minute scanning process.(see Figure 13)

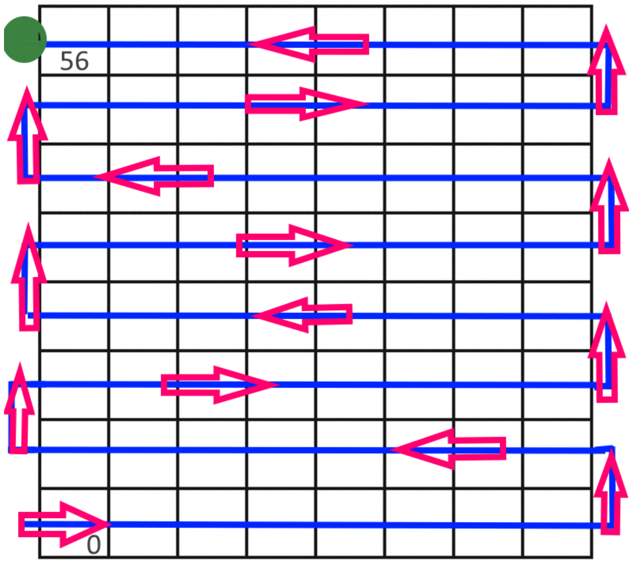

Figure 13: The movement of the radioactive source while using the **full scan** data

3.4.3 Final adjustments

To make the code easier to use, menus were added throughout.(see Figure 14)

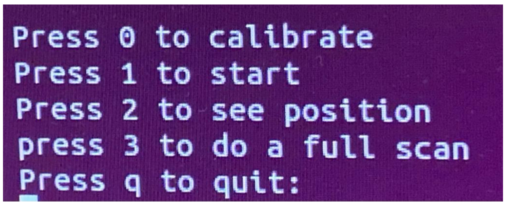

Figure 14: The main menu in the code

In the code's menus, each option has a corresponding explanation that details what it does. This is to help users better understand the purpose of each option.(see Figure 15)

Number	Action
0	The code will perform a calibration based on the optical stop sensors that are connected to the table. To define a zero position in the module coordinate system.
1	This part of the code should be selected whenever there's a need to go to a specific module and a specific bar.
2	Choosing this option will present the current position of the radioactive source
3	This option will do a full scan for a specific module
q	Pressing q to quit the current menu

Figure 15: An explanation for each option of the main menu in the code **full scan** data

4 Data Analysis

The data analysis was the final step of the calibration process presented in this report. Parts of the analysis process were based on pre-written codes derived from two sources:

- Data gathered during the POLAR mission.
- Data that was taken from ESRF (The European Synchrotron Radiation Facility).

The analysis in this paper is based on the initial analysis of both sources and the resulting conclusions.

4.1 Data taking

A GUI program was made in advance to enable the scanning of the data. The GUI allows control over different properties such as high gain, low gain, and threshold. The scanning process is as follows:

1. Inserting the radioactive source in its designated place and connecting the setup.
2. Using the controlling code as mentioned before.
3. After selecting the desired placement of the source, pressing start in the GUI program and scanning the data.

4.2 Analysis

After scanning the data, decoding was performed to convert the files into root files for analysis. After the decoding, a hit map was made to determine the accurate placement of the radioactive source.
Note: Despite the use of the XY table, electronic errors may slightly shift the position of the source.

Making a Hit Map:
A hit map is crucial for calibration as it shows source placement and bar sensitivity. To analyze an event, the command used in root counts the number of occurrences for each instance. In this particular setup, the command runs through all 64 bars and fills a 2D histogram whenever a trigger is detected (whenever the radioactive source radiates on a bar). (see Figure 17)

There are two different cases where hit maps where used:

- The source is pointing to a specific bar.(16)

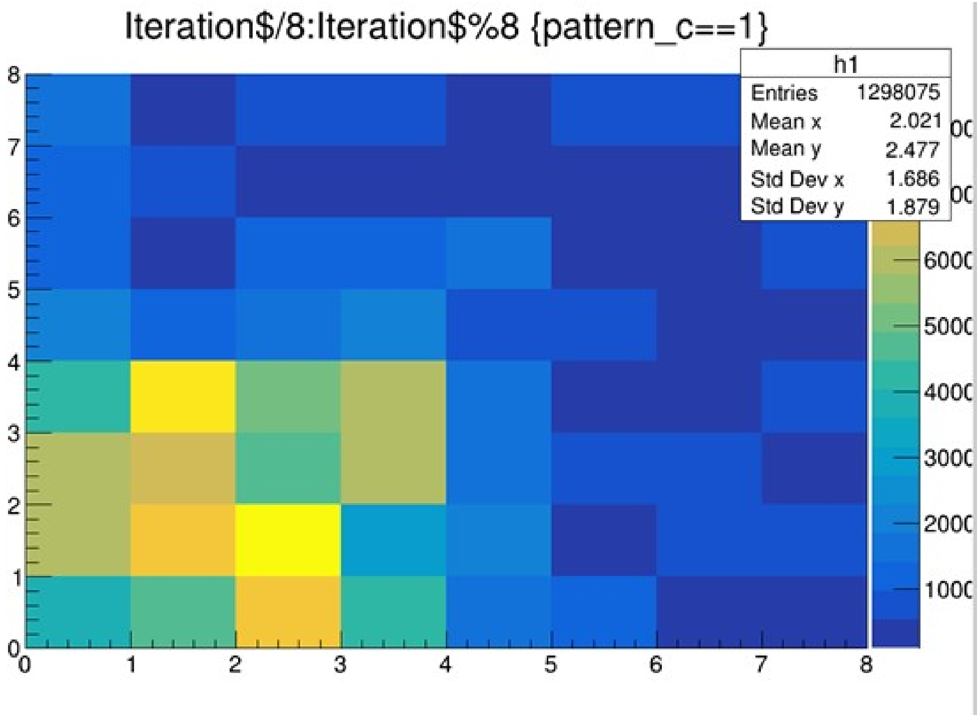

Figure 16: A hit map of AM241 on bar number 1

The hit map (Figure 16) displays the location of the source. In this case, the source was aimed at bar 1, which is also indicated on the map.

The second map displays the source pointing at each of the 64 bars. It is possible to determine the sensitivity of each bar on the map, as some show the presence of the source while others are less powerful. (Figure 17)

- A map for the entire module (module 5) (17)

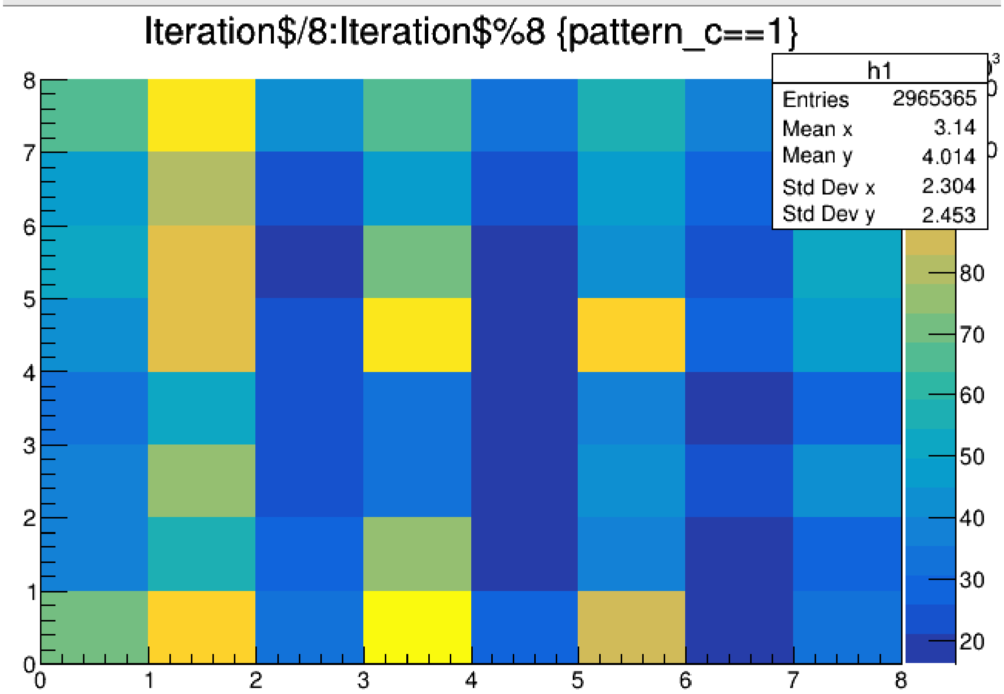

Figure 17: A hit map of AM241 for module 5

Data Analysis:

At first, the source was pointing to each of the 64 bars. Each of the bars was individually analyzed to determine its sensitivity using two techniques **Pedestal Subtraction** and **Non-linearity Corrections** . The energy is still in ADC.

1. Pedestal Subtraction
   Pedestal subtraction is a widely used technique for removing the baseline or offset value from the data captured by detectors. This baseline value is caused by the conversion from analog to digital in the ADC, a standard feature of the electronics. With the pedestal, there will be noise on the signal, which can be negative; however, if the baseline is at zero, negative noise will not be visible. Therefore, the goal is to maintain a baseline slightly above zero.

2. Non-linearity Corrections These corrections were observed after the initial analysis of the POLAR and ESRF data. To ensure accuracy, the high linearity corrections file was created based on 64 separate data files, each containing 4 minutes of the source pointing at every bar.

After applying both techniques, the plots were observed to determine the necessary changes before continuing with calibration.

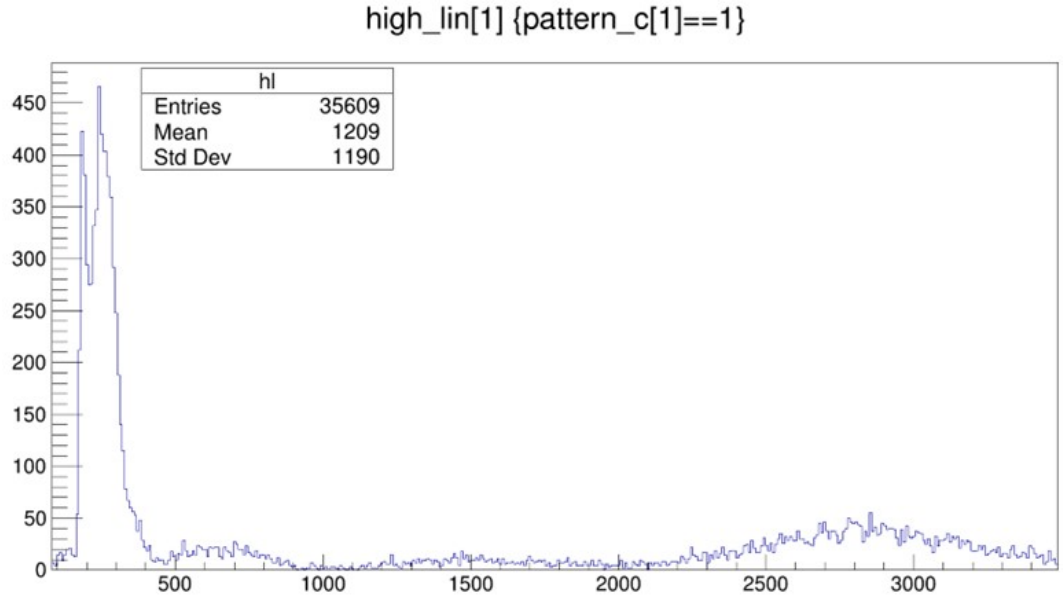

Figure 18: The energy plot (in ADC) of channel 1 after applying both the pedestal subtraction and the non-linearity corrections

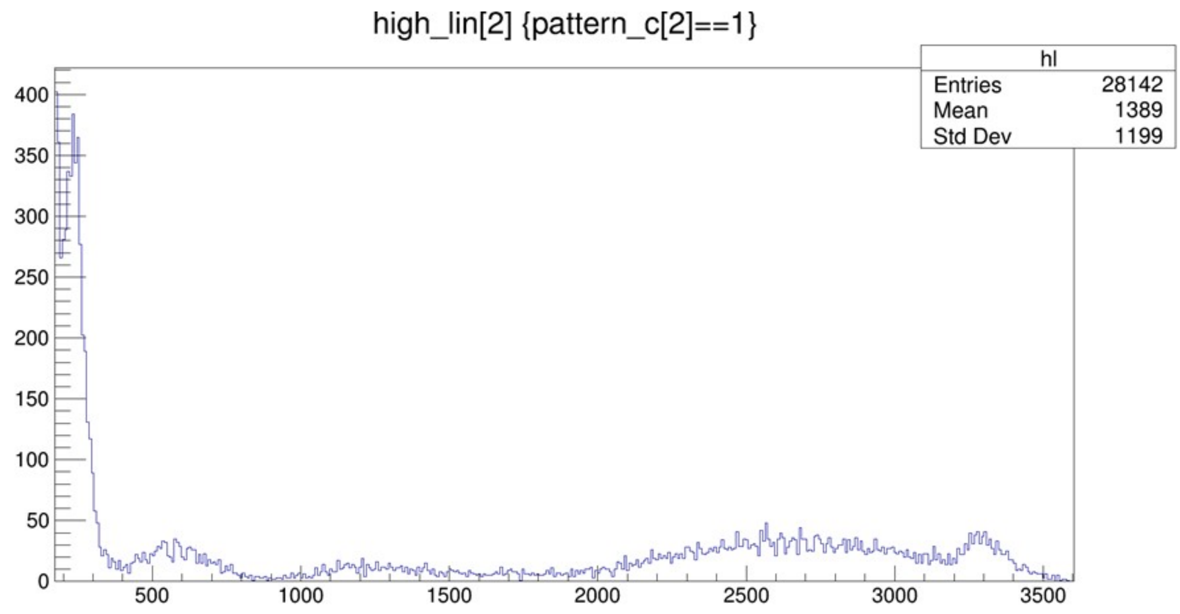

Figure 19: The energy plot (in ADC) of channel 2 after applying both the pedestal subtraction and the non-linearity corrections

X is the energy [ADC], and Y is in log scale [events/bin].

To ensure validity, the results were compared to AM241's energy spectrum.

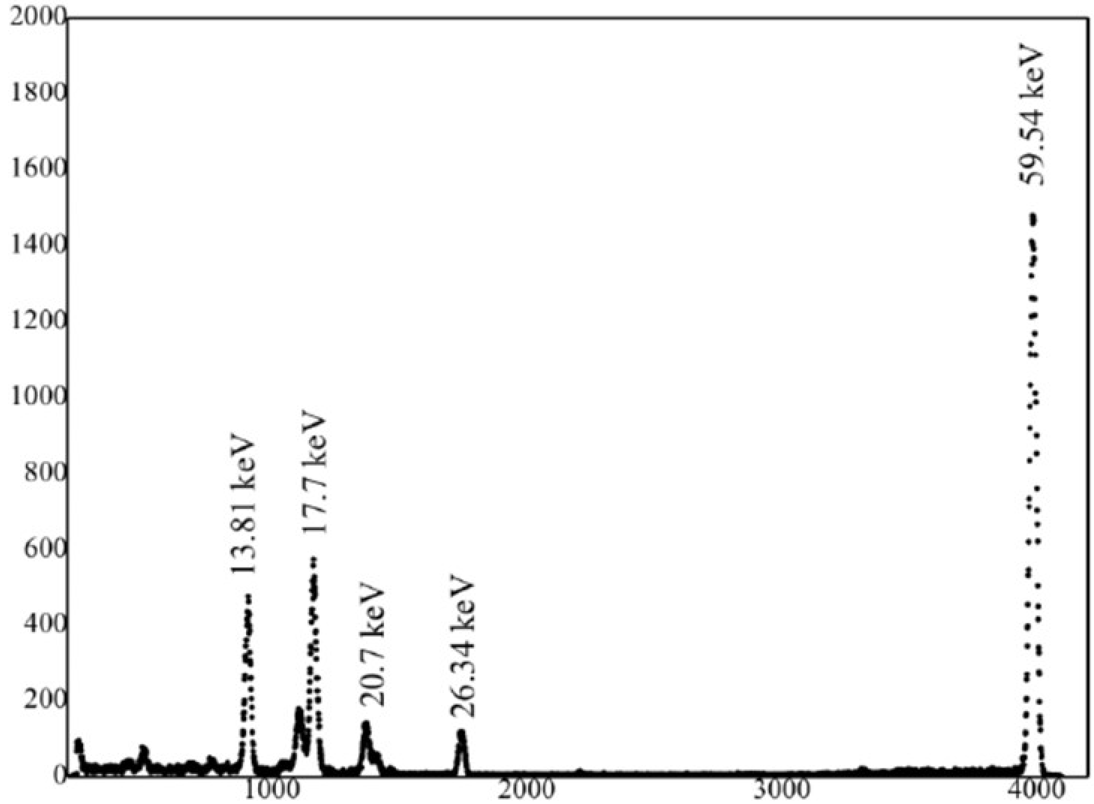

Figure 20: AM241's energy spectrum

The photo-peak in the plots that corresponds to 60 [keV] is consistently observed at a value of approximately 2500 in most of the graphs.(see Figure 18) (see Figure 19)

It was observed that there are errors in the beginning of the graphs until around 500, before the threshold. It seems that these are most likely just background noises. (see Figure 20)

After the two corrections, the high gain for each bar was adjusted in the GUI program to ensure all photo-peaks of all channels were around 2500. (see Figure 21)

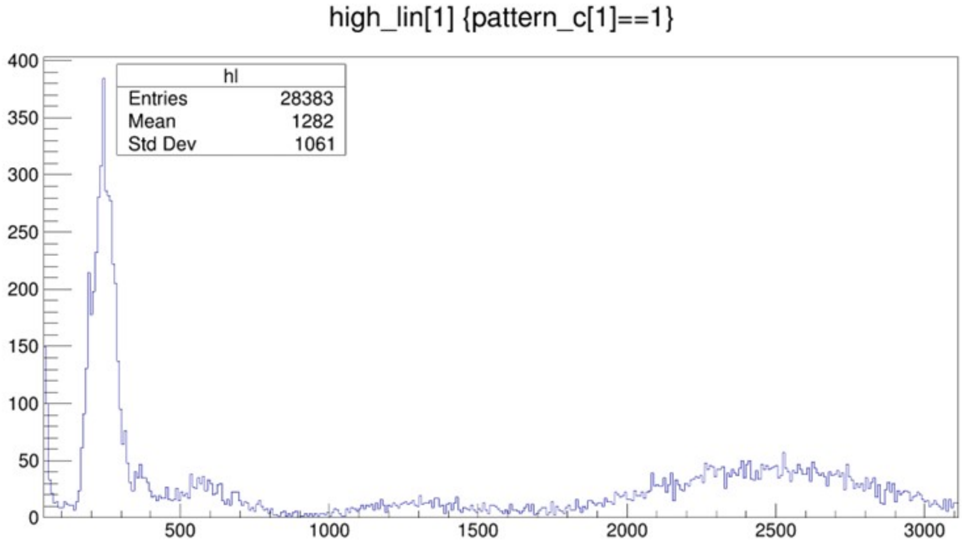

Figure 21: The energy plot of channel 1 was adjusted to center the photo-peak around 2500 ADC.

Energy Calibration:
The first reason for calibrating data is to understand its behavior. The second reason is to convert ADC energy to keV per channel. The conversion from ADC to keV is crucial to ensure equal sensitivity of each channel. This is because when measuring polarization, the desired gamma rays are the ones passing between two bars (two bars with energy depositions).
When the bar is more sensitive, it detects more ADC/keV deposited, indicating a higher likelihood of photons scattering. On the other hand, when the bar is less sensitive, it becomes harder to identify scattered photons. This can create signals that may appear like polarization but are actually due to non-uniform sensitivity in the detector.

Two techniques where used, **Finger Fits and the Light Yield**.The codes for the two techniques were written in advance for the conversion.

In the context of GRBs, "fingers" refer to the shape of the energy plot after the threshold. This shape is similar to that of fingers, and fitting it is a crucial step in the conversion process. The conversion relies on accurately fitting the "fingers" of the keV energy plot. After conducting finger fitting, measuring light yield and gain using the output files is necessary before the final step.

A final code for the conversion to keV was used after the light yield measurements. Based on the plot, we observe that there is a photo peak at 60 [keV], along with two additional peaks around 40 [keV] and 15 [keV]. Additionally, it appears that there are some noise signals present at the start and end of the plot (Figure 22) . More details regarding these noise signals will be discussed in chapter 5.

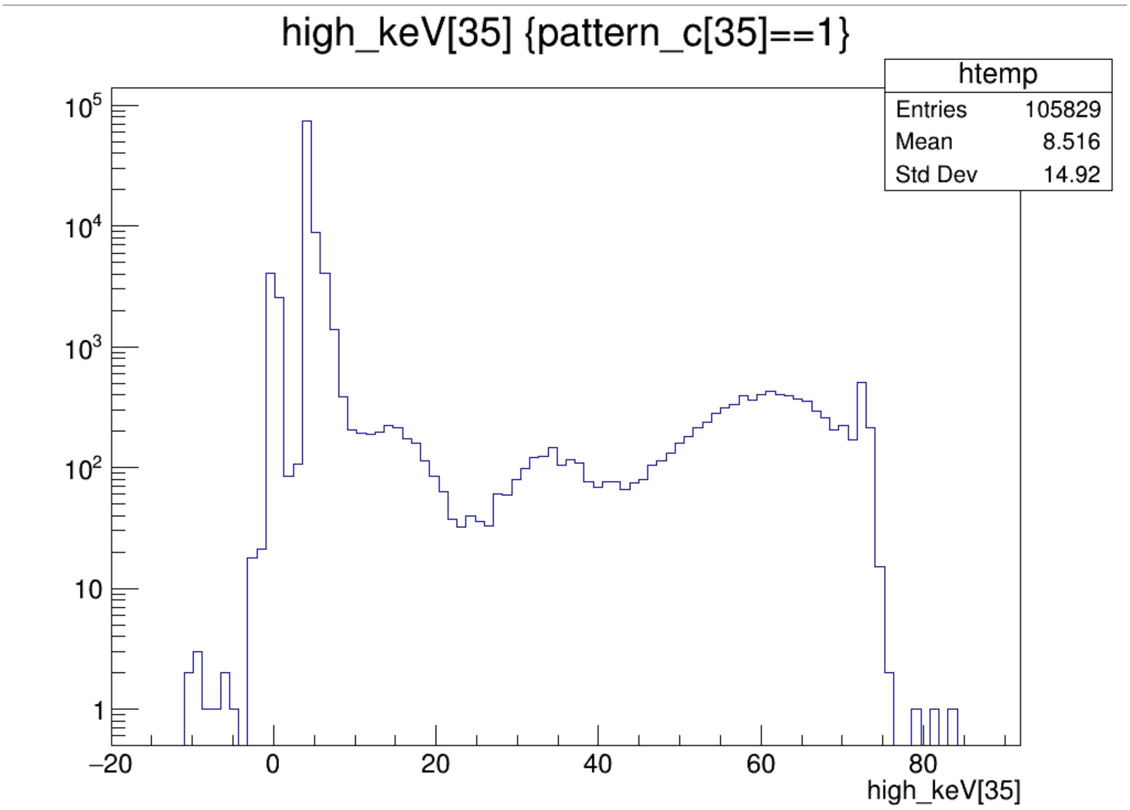

Figure 22: The energy plot of channel 35 in keV units

5 Conclusion and Future Work

This report outlines the calibration process carried out on the POLAR-2 prototype. The first section details the adjustments made to the XY table to improve its functionality for data scanning, while the second section covers the initial calibration of the data. Although the first part of the calibration was successful, there is more work to be done to ensure the setup is qualified for space before building the real model of POLAR-2.

Future Work:

1. Noises and errors:
   Two issues were noted in the plots: noise and extraneous peaks that do not match the source's energy spectrum. Correcting these is necessary for precise data analysis.

2. Polarized Source:
   The calibration in this report was performed with an unpolarized source. The radioactive source must be polarized by letting the emission scatter by 90 degrees to achieve polarization in this setup.

References

[1] A.Kazakevičius. Polar-2 summer project: Building of xy table and paint analysis to prove it to be space qualified, 2022.

[2] N.De Angelis. Development and science perspectives of the polar-2 instrument:a large scale grb polarimeter. *proceeding of science*, 2021.

[3] J.S. BLOOM. *What Are Gamma -Ray Brusts ?*, volume 1. Princeton University Press, 2011.

[4] G.Koziol. *"HAGRID In Spce" ,High Accuracy GRB Rapid Inference with Deep learning in Space*. PhD thesis, University of Geneva, 2023.

[5] M.Kole. Polar-2:the first large scale gamma-ray polarimeter. *proceeding of science*, 2019.