PROCEEDINGS OF SCIENCE

Consumer Devices with CMOS camera image sensors as Pocket-Sized Particle Detectors

Wakiko Takano* **and Kinya Hibino**

Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan.

E-mail: r201970105fg@jindai.jp

We are developing radiation detection applications for smartphones and tablets that monitor cosmic rays. The highly sensitive CMOS camera image sensors in billions of smartphones worldwide can detect charged particles. Cosmic rays can be observed by extracting particle trajectories from digital images. This technology has potential applications in a wide range of fields, including education and astrophysical research. Using smartphones as observing devices and building a global network can collect data more efficiently. In this research, we present the results of cosmic ray observation experiments using CMOS sensors and the results of a smartphone app for cosmic ray detection. In order to accurately detect the minimum ionization trajectory, which is expected to be particularly dark, we have developed a new algorithm and placed the sensor vertically to prevent the detection rate from decreasing, which is a unique attempt in this research.

37th International Cosmic Ray Conference (ICRC 2023)
July 26th – Aug 3rd, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1620

1. Introduction

We are developing a radiation detection application for smartphones and tablets. Currently, the number of smartphones in circulation exceeds 6 billion [1], with over 80% of the world's population using smartphones. The highly sensitive CMOS camera image sensors integrated into these devices can detect not only photons but also charged particles such as cosmic rays and environmental radiation [2] [3]. The traces of these particles passing through these sensors can be extracted as particle trajectories from dark digital images.

The ability to observe cosmic rays using devices such as smartphones has excellent potential for various applications, including education. In particular, if applied to observing air showers produced by ultra-high-energy cosmic rays, it could lead to significant breakthroughs in the field of astrophysics. The origin and production mechanisms of ultrahigh-energy cosmic rays are still not fully understood. When these high-energy particles interact with the Earth's atmosphere, they produce cascades of secondary particles known as air showers. However, due to their extremely low arrival frequency, observing them requires a large observation area and long observation times, making it challenging and costly. However, if we can use mobile devices such as smartphones as observing instruments and establish a global network of observations, there is potential for a significant improvement in the speed of data accumulation [4]. In this paper, we will first discuss cosmic ray observation experiments using CMOS camera image sensors and then report on the results of cosmic ray observation using a smartphone application.

Trajectories of cosmic rays passing through sensors in their minimally ionized state are expected to be fainter and more difficult to detect than low-energy ambient radiation [5]. Therefore, we developed a novel algorithm that accurately extracts cosmic ray trajectories even when buried in significant amounts of noise. We also experimented with vertical positioning of the sensors to avoid a significant drop in detection rate when searching for long trajectories. When the sensor is positioned vertically, the effective observation area is reduced by half. However, it allows us to target the highest region of the cosmic ray flux. Therefore, although the detection efficiency is halved, a significant increase in the detection rate can be expected. Both approaches are unique to our study.

A new observation method utilizing compact and thin silicon sensors for observing the core of ultra-high energy cosmic rays is discussed in our related paper [6] .

2. Cosmic Ray Observation using Raspberry Pi and a High-Quality Camera Sensor

Before conducting cosmic ray observations using smartphones, we performed experiments using Raspberry Pi and a High-Quality Camera to acquire data flexibly and with fewer constraints, allowing us to explore optimal algorithms. We connected the official High-Quality Camera to a Raspberry Pi 4, as shown in Figure 1.

2.1 Data collection

The data was obtained from January to early March 2023, using 13,000 still images for each horizontal and vertical sensor orientation. The Sony IMX477, a 12.3 megapixel sensor with a pixel size of 1.55 μm and an active area of about 33 mm^2. We covered the sensor to block out light.

PoS(ICRC2023)1620

We installed *libcamera-apps* on the Raspberry Pi 4 and took repeated shots with a shutter speed of 200 seconds. The gain was set to 1. While it is possible to detect particle trajectories by extracting frames from videos, traces produced by cosmic rays passing through the minimum ionized state are expected to have very small energy deposits and extremely low brightness. Therefore, there was a possibility that cosmic ray traces could be cut off in video mode. To account for this, we decided to take still images at the highest resolution. However, capturing still images at the highest resolution results in larger file sizes for each image and increases the computational load during analysis. To overcome this, we tried to acquire data efficiently by using long exposure times to reduce the computational load and save storage space.

2.2 Data Analysis

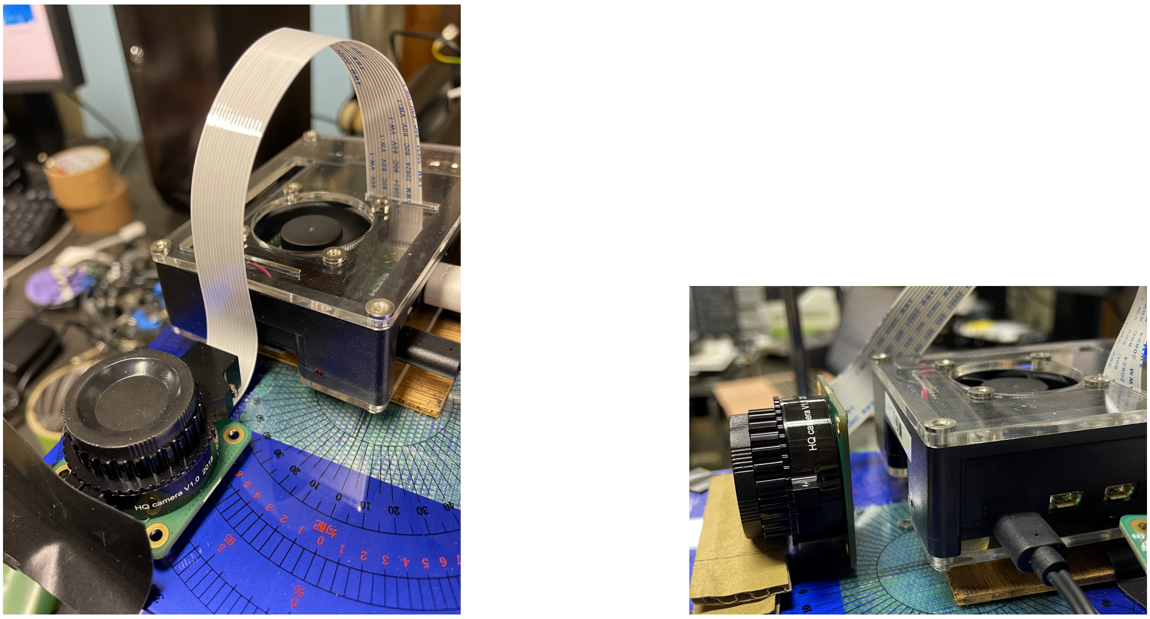
In our analysis, we have integrated the OpenCV image processing library into Python. The trajectories of cosmic rays observed by silicon sensors are known to be linear and are called 'tracks' [3]. Therefore, we detect clusters of pixel responses from the captured image and fit a rectangle to the clusters. We used the "findContours" function from OpenCV for cluster detection and the "minAreaRect" function for rectangle fitting. For rectangle fitting, we calculated the width ratio to the rectangle's length. Rectangles with ratios below 0.4 were extracted.

We experimented with various noise reduction techniques and found that none of them made it easy to identify punctual or short tracks from the noise. As a result, we chose to perform noise reduction with the lowest possible threshold, focusing on extracting long linear trajectories from the image while accepting a significant amount of noise. Although noise can have long shapes, we found that the amount of noise decreases beyond a certain length threshold, making it a more likely candidate for cosmic or environmental radiation. To achieve this, we converted the image to a grey scale and applied binary thresholding, where values below or close to a threshold of 2 were assigned black, while the rest were assigned white. Using such a low threshold resulted in a significant amount of residual noise. The reason for using such a low threshold for noise reduction and searching for signals within a substantial amount of noise is that cosmic ray trajectories pass through in a minimally ionized state. As a result, these trajectories have small energy deposits and are extremely faint, making them difficult to detect. Using these techniques, our aim was to increase the chances of detecting these faint trajectories amidst the significant noise present in the images. We used Equations 1 [5] and 2, which were derived based on the expectation that the cosmic ray flux observed on the ground is proportional to $\cos^2\theta$ and the relationship between the depletion thickness of the sensor and the track length to confirm whether the data obtained were cosmic rays. Equation 2 is derived from Equation 1 but modified to apply to vertically oriented sensors. Where L is the track length, H is the depletion thickness of the sensor, and A and B are constants. The following are the steps from data acquisition to analysis:

1. First, we observe with horizontally positioned sensors, as shown in Figure 1-(a). And extract linear tracks. We fit the track length distribution using Equation 1 to verify the detection of cosmic rays.

2. Next, we perform observations with vertically positioned sensors, as shown in Figure 1-(b). Again, we extract linear tracks and fit the track length distribution using Equation 2.

3. Check whether the expected increase in detection is observed when installed vertically compared to horizontally.



(a) Horizontally Positioned Sensor

(b) Vertically Positioned Senso

Figure 1: Raspberry Pi 4 and High-Quality Camera (12.3 megapixel Sony IMX477 sensor).

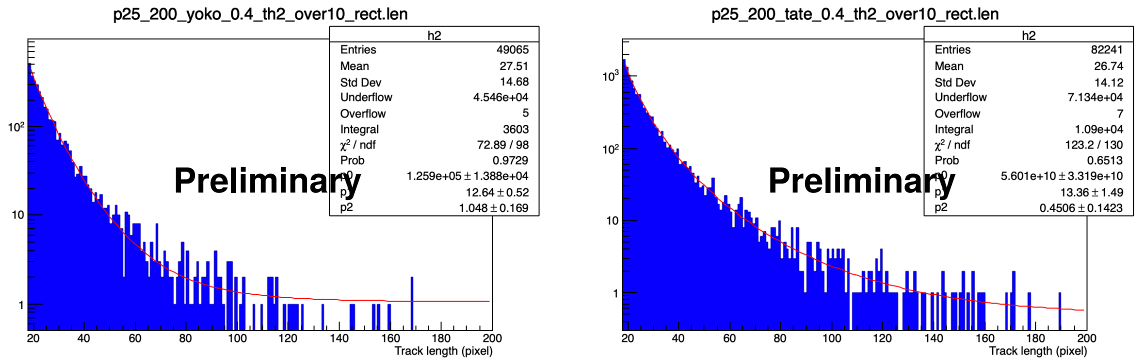
$$\frac{dN}{dL} = A\frac{LH^4}{\left(L^2+H^2\right)^3} \quad \text{(Horizontal)} \tag{1}$$

$$\frac{B\left((|H|-H)L^4 + 2H^2(|H] + 3H)L^2 + H^4\,|H| - H^5\right)}{(L^2+H^2)^3} \quad \text{(Vertical)} \tag{2}$$

2.3 Results and Discussions

Figure 2(a)(b) are the histograms of the length distributions when the ratio of the width obtained from the rectangular fit to the length is less than 0.4, along with the fitting results. The tracks shorter than 20 pixels were excluded due to the difficulty in distinguishing them from noise. Therefore, the effective length threshold for distinguishing from a background in this experiment was 20 pixels. We observed a good fit for both horizontally and vertically positioned sensors. The obtained value of the parameter for the depletion layer (p_1) was determined based on the fit results from the horizontally positioned sensor, which yielded a value of 12.64 ± 0.52, and this value was used as an approximate range in the fit for the vertically positioned sensor. Variation in the results was observed when the bin width of the histogram was changed. More observations are needed to conclude.

In addition, about three times as many cosmic ray candidates were detected by orienting the sensors vertically. Considering that the depletion layer thickness is 12.64 ± 0.52 (px) and detecting tracks longer than 20 pixels, we can see that cosmic rays were observed with an angle of incidence of 52 degrees or more from the zenith. On the other hand, in the case of vertical installation,



(a) Fitting Result for Horizontally Positioned Sensor

(b) Fitting Result for Vertically Positioned Sensor

Figure 2: Track length distribution of cosmic ray candidates obtained with Raspberry Pi 4 and HQ Camera.

up to 32 degrees from the zenith were observed. It means that about 30% of the total flux can be observed when the sensor is installed in a vertical position, and even if the detection rate is halved, the number of detections will be more than four times that of a sensor installed horizontally. Although the actual results were lower than expected, they significantly increased three times. Further analysis is required to determine why the results were lower than expected. We present these results as preliminary.

3. Cosmic Ray Observation using iOS app "Soramame"

We have developed an iOS app to investigate whether the CMOS camera image sensors built into smartphones and tablets can also be used for cosmic ray detection, like the Raspberry Pi with the HQ Camera. The app is called Soramame and is compatible with iOS 14 or later. Figures 3 and 4 show the Soramame icon and the QR code for downloading the app from the Apple App Store. Using the Raspberry Pi with the HQ camera, we captured images with long exposures of 200 seconds. However, we decided to use Live Photo mode because the iOS camera functionality does not have a long exposure option. Live Photo mode captures a series of images and a 3-second exposure still image, allowing us to use the still image for this experiment. In addition, while offline image analysis was performed with the Raspberry Pi setup, we found that storing high-resolution photos on the devices and transferring them over the network would significantly burden smartphones and tablets. Therefore, we implemented a real-time approach where event candidates were detected, and only small cropped images were transferred to the server.

We simultaneously measured cosmic rays using six devices, including iPhone, iPad, and iPad Pro. Each device was oriented vertically.

3.1 Results and discussions

Figure 5 shows the length distribution of track candidates made with an iPad. Event candidates were cropped and sent to the server, but the real-time analysis implemented in the app was unable to detect enough event candidates, so we reanalyzed them offline with a lower threshold. As the cropped images were reanalyzed, there is a possibility that the longest tracks were unnaturally truncated. However, the reanalysis showed a tendency to detect cosmic ray candidates. There was

Figure 3: Icon of Soramame app

Figure 4: QR code for downloading Soramame

generally more noise than the Raspberry Pi with the HQ camera setup, and there was considerable variation between different device models. We realized that we needed to develop an algorithm that could accurately tune the noise level and separate the noise from the signal in real-time, with thresholds tailored to each device.

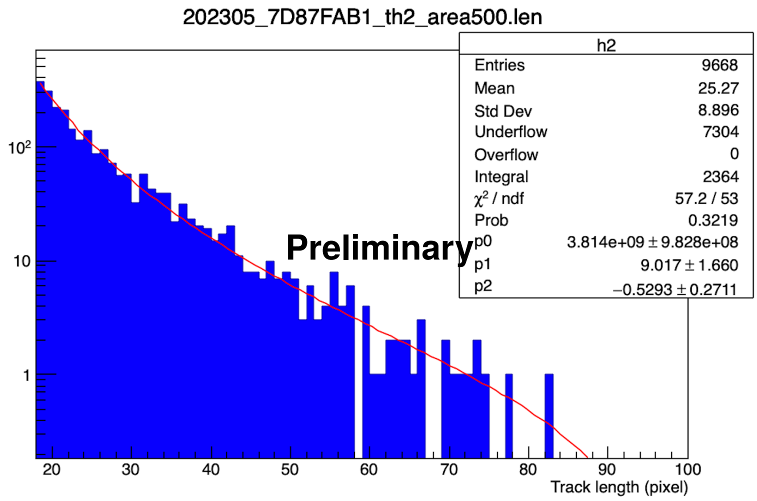


Figure 5: Length distribution and fitting result for cosmic ray candidates obtained from Soramame installed on the iPad.

4. Summary

We tested observing cosmic rays using Raspberry Pi, HQ Camera, and the iOS app 'Soramame' on smartphones and tablets. We performed observations with the highest image quality and long exposures, attempting to detect cosmic rays by extracting long, linear trajectories while searching for the threshold that separates noise from the signal. We also tried to compensate for the decrease in detection rate when focusing only on long tracks by orienting the sensor vertically. Each experiment produced positive results. We plan to continue the observations, increase the data and eventually present the final results.

References

[1] bankmycell.com ,https://www.bankmycell.com/blog/how-many-phones-are-in-the-world

[2] J. J. Cogliati, K. W. Derr, J. Wharton, Using CMOS Sensors in a Cell- phone for Gamma Detection and Classification (2014). arXiv:1401. 0766.

[3] D. Groom, Cosmic rays and other nonsense in astronomical CCD imagers, Experimental Astronomy 14 (1) (2002) 45-55

[4] D. Whiteson, M. Mulhearn, C. Shimmin, K. Cranmer, K. Brodie, D. Burns,Searching for ultra-high energy cosmic rays with smart- phones, AstroparticlePhysics 79 (2016) 1 - 9. doi:https://doi.org/10.1016/j.astropartphys.2016.02.002.

[5] J. Vandenbroucke, S. Bravo, P. Karn, M. Meehan, M. Plewa, T. Rug- gles, D. Schultz, J. Peacock, A. L. Simons, Detecting particles with cell phones:

[6] W. Takano; K. Hibino, A New Method for Observing the Core of the Highest Energy Cosmic Rays Using Compact Detectors, PCRI351, ICRC (2023).