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Progress in optimizing the detection surface structure of CRAFFT

Yuto Kubota,[a,*] Daisuke Ikeda,[b] Takashi Kagitani,[c] Takayuki Tomida,[a] Yuichiro Tameda[c] and Norimichi Shibata[c] on behalf of the CRAFFT Collaboration
(a complete list of authors can be found at the end of the proceedings)

[a] *Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan*
[b] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[c] *Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan*
E-mail: 20w2033d@shinshu-u.ac.jp

An observatory for the next generation of ultra-high energy cosmic rays (UHECRs) should be expanded for clarifying the origin and nature of UHECRs. In order to realize a huge UHECR observatory, we are developing Cosmic Ray Air Fluorescence Fresnel lens Telescope (CRAFFT), which is a low-cost fluorescence telescope. We tested a performance of prototype CRAFFT at Telescope Array (TA) site, and succeeded to detect UHECR air showers synchronized with TA detectors in 2017. We are currently developing a reconstruction method based on waveform fitting with sufficient analysis accuracy, and optimizing the detector configuration to improve its performance with low cost. Progress in detector optimization, reconstruction method, and calibrations such as uniformity of PMT sensitivity are discussed.

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1. Introduction

Since the discovery of cosmic rays, they have been observed in a very wide energy range. However, the origin of cosmic rays has not yet been directly identified. This is because they interact with the magnetic field of space and their orbits are diffuse. However, cosmic rays with energies around 10^{20} eV are expected to diffuse very little even in the magnetic field of space. The Telescope Array (TA) collaboration has reported the existence of a hot spot region in the direction of arrival of cosmic rays above 57 EeV [1]. Therefore, it is expected that the origin of such ultra-high energy cosmic rays can be revealed by observing them with higher statistics.

So far, the mass composition of cosmic rays has been measured by various methods. The most traditional and reliable mass composition analysis is performed by Xmax analysis. Xmax is an atmospheric depth where the number of particle in an air shower reaches maximum. The average or fluctuation of Xmax distribution is a parameter strongly dependent on mass composition. Because fluorescence detector can measure the longitudinal profile of cosmic ray air shower, fluorescence detector is useful for measuring Xmax. Although the statistics of fluorescence detector is relatively much lower than that of surface detector array due to the low duty cycle. TA and HiRes experiments reported that the composition is light such as proton or Helium around 10^{19} eV [2][3], against the Auger experiment shows that the composition becomes heavier above $10^{18.5}$ eV [4]. There are also still problems to be solved, such as systematic errors due to hadron interaction models. In order to clarify the sources of ultra-high energy cosmic rays, we have to understand the mass composition and need much more statistics.

In the future, it is inevitable to expand the scale of observatory for ultra-high energy cosmic ray research. Additionally, we also need mass composition-sensitive detector such as fluorescence detector. The low cost fluorescence detector, the concept we conclude the mass composition is originally proposed by privitera [5], is very simple structure consisting of a Fresnel lens, UV transmitting filter and a large photo multi-plier tube (PMT). Based on this concept, we are developing a Fresnel lens Fluorescence detector.

2. CRAFFT

Cosmic Ray Air Fluorescence Fresnel lens Telescope (CRAFFT) is a fluorescence detector using a Fresnel lens [6]. In order to realize the next generation ultra-high energy cosmic ray observatory, it is necessary to make the observation volume much larger with more telescopes. Therefore, cost reduction can not be avoided. On the other hand, in order to measure the mass composition together, a fluorescence detector which can measure Xmax is preferable. CRAFFT realizes a low-cost fluorescence detector as follows. The structure is simplified by using a refracting telescope instead of a reflecting telescope, and reducing the components such as the number of pixel. Installation is very easy because of its simple structure. Operation cost should also be reduced by automatic observation system.

Figure 1 shows the appearance of the prototype detector deployed at TA site.The structure of the detector is made of black anodized aluminum frame. The outer side of the frame is covered with a steal plate to protect and shield the inside of the detector. A roll curtain is attached to behind

Figure 1: The appearance of CRAFFT prototype detector.

Figure 2: A test of the automatic observation system.

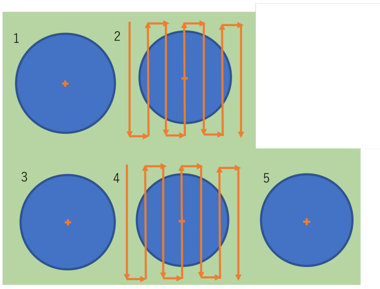


Figure 3: LED calibration track.

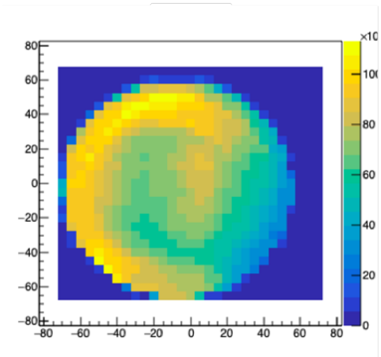


Figure 4: Results of the first measurement.

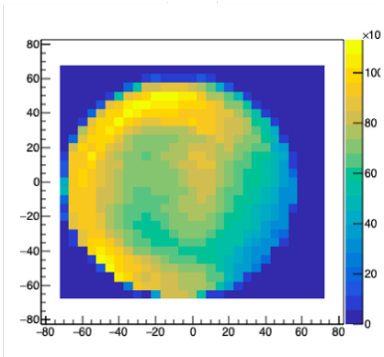


Figure 5: Results of the second measurement.

the Fresnel lens and shields the inside in daytime. At the frame of fresnel lens, two beams were attached to prevent the deflection of the Fresnel lens. The elevation of the detector is adjustable.

Figure 2 shows the automatic observation test. The automatic observation test of the CRAFFT telescope is being performed at Shinshu University, where observation decisions, automatic opening and closing of the shutter, and power hourly supply are being tested in an integrated manner.

3. Uniformity of PMT sensitivity

We have developed a calibration system for the CRAFFT detector and measured the non-uniformity of the sensitivity of the PMT. As shown in Figure 3, we moved the LED on the PMT and recorded the signal from the PMT every 5 mm, totaling 1596 points. Figure 4 and Figure 5 shows the results of two measurements to check the reproducibility. Figure 6 show ratios between the first and second measurements, respectively.The results of the measurements show that the PMT sensitivity changes significantly depending on the incident position. We have established a two-dimensional non-uniform measurement method for PMT.

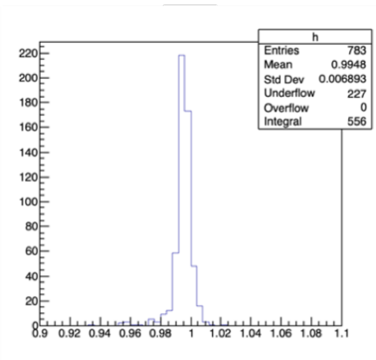


Figure 6: Ratio of the first measurement to the second measurements.

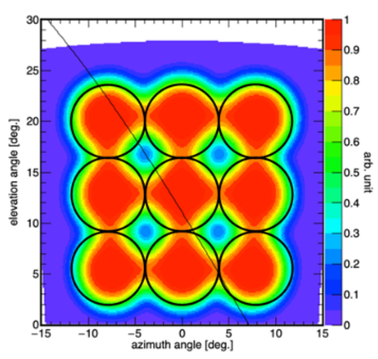


Figure 7: Sensitivity map of PMTs.

4. Reconstruction method based on waveform fitting

We are currently developing a reconstruction method based on waveform fitting with sufficient analysis accuracy, and optimizing the detector configuration to improve its performance with low cost. We are using simulations to evaluate the reconstruction by waveform fitting and the configuration of the detector. Figure 7 shows the detector configuration and PMT sensitivity implemented in the simulation, where the PMT sensitivity is determined by convolution of the spot size. Figure 8 shows a examples of the output waveform (Artificial-data) shown in the number of photoelectrons. The night-sky back-ground used in the simulation is measured by TA FD [7]. The waveforms of artificial data is compared with the expectation generated by the various air shower parameters. We search for waveforms that base reproduces the data by minimizing the following χ^2 (1).

$$\chi^2 = \sum_i (\frac{x_i - \mu_i}{\sigma_i})^2, \tag{1}$$

where x_i is Npe of artificial data in i-th bin, μ_i is Npe of expected waveform in i-th bin and σ is Standard deviation of artificial data in i-th bin.

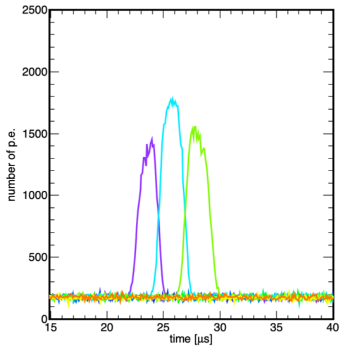


Figure 8: Artificial-data generated by a detector simulation described in section 5. The waveform of each color shows the output of each PMT.

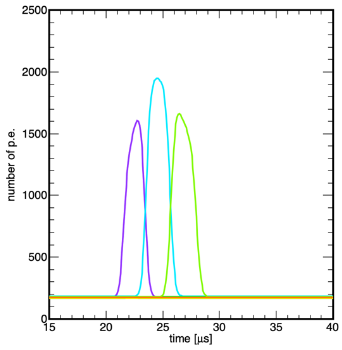


Figure 9: Fitted waveform for the waveform shown in Figure 8.

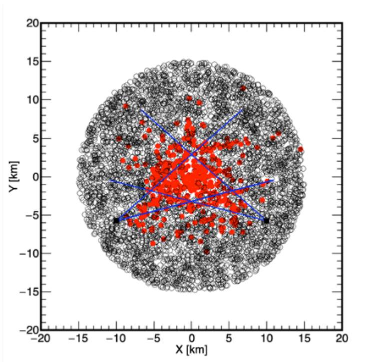
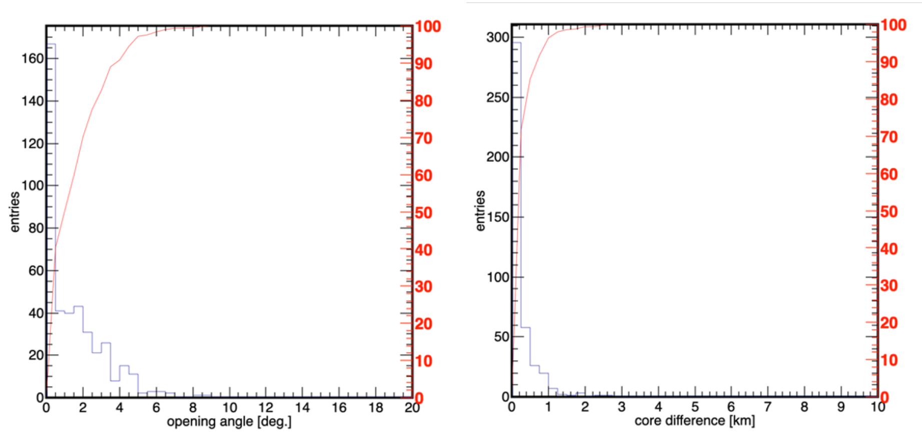


Figure 10: The core locations of the air showers that arrived in the simulation. The red circles indicate the triggered showers and the black circles are not triggered.

5. Optimizing the detector configuration

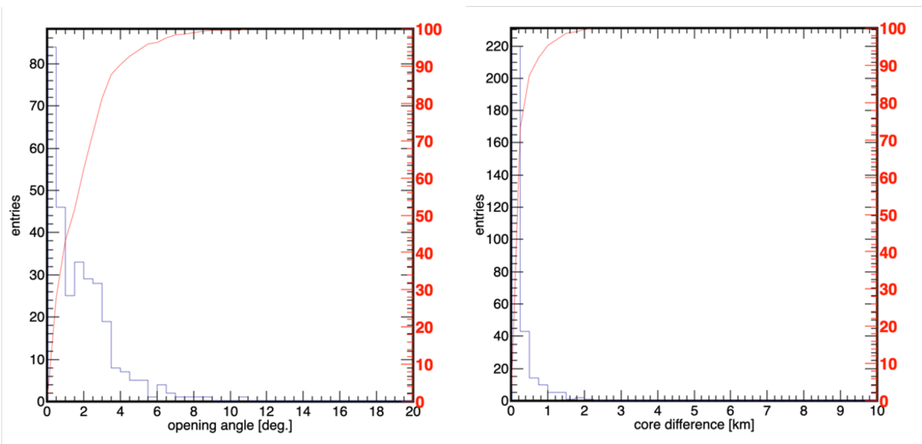
Simulations were performed under the following conditions to evaluate the two types of detectors. ;the energy of the primary cosmic ray is $10^{19.5}$ eV, the Xmax is 700 g/cm^2, the zenith angle is less than 70 degrees, and the azimuth angle is uniform. The thrown core positions are shown in Figure 10, uniformly arriving within a circle of 15 km radius containing two stereo detectors. The detectors have a field of view toward the center of the circle as shown in the blue line. The red circles indicate the triggered air showers, which are triggered when both of detector have signals with signal-to-noise ratios above 6. Figures 11 and 12 show the differences between the thrown geometries and reconstructed those using the two types of detectors. Figure 11 shows the results for a detection surface with 9 PMTs of 16 cm diameter arranged in a square, and Figure 12 shows the results for a detection surface with 16 PMTs of 13 cm diameter arranged in a square. From the simulation study, it is found that the the resolutions are about 2 degrees in arrival direction and about 500 meters in core position, respectively of both types of detectors. By considering the simulation result, the size of PMTs, and the price, we are developing a detection surface consisting of 12 PMTs of 13 cm as a test machine.



(a) The opening angle between the standard and the minimum.

(b) The deviation of the core position from the standard and the minimum.

Figure 11: The results for a detection surface with 9 PMTs of 16 cm diameter arranged in a square.



(a) The opening angle between the standard and the minimum.

(b) The deviation of the core position from the standard and the minimum.

Figure 12: The results for a detection surface with 16 PMTs of 13 cm diameter arranged in a square.

6. Summary

We are developing simple and low-cost fluorescence detectors for the next generation of ultra-high energy cosmic ray observatories, CRAFFT (Cosmic Ray Air Fluorescence Fresnel lens Telescope). In addition, we have measured the two-dimensional uniformity of the PMT for the calibration of the telescope. We are developing a reconstruction method by waveform fitting, and optimizing the detection surface. We will continue to develop the instrument towards next stereo observation tests.

7. Acknowledgements

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Full Authors List: CRAFFT Collaboration

Y. Tameda[1], T. Tomida[2], D. Ikeda[3], K. Yamazaki[4], T. Kagitani[1], N. Shibata[1], E. Nishio[1], H. Iwakura[2] Y. Nakamura[2], Y. Kubota[2], S. Kurisu[2], and R. Saito[2]

[1]Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan
[2]Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan
[3]Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan
[4]Chubu University, Kasugai, Aichi, Japan