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Detector optimization and observation plan of the CRAFFT project for the next generation UHECR observation

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The CRAFFT (Cosmic Ray Air Fluorescence Fresnel lens Telescope) project is developing a simple fluorescence detector for the next generation of ultra-high energy cosmic ray observation, which is similar to the concept of the Global Cosmic Ray Observatory for example. Beyond the Telescope Array or Pierre Auger Observatory, it is inevitable to expand the scale of the experiment. The key concept of the CRAFFT detector consists of mass composition sensitivity and low-cost production and operation. The CRAFFT detector is a simple structure fluorescence detector with a Fresnel lens and has fewer photomultiplier tubes than conventional fluorescence detectors. We have already successfully detected air showers with the prototype of the CRAFFT detector and optimized it for improved shower reconstruction and a larger field of view per detector. We are also planning to conduct test observations with the optimized detector to confirm the observation concept. In this contribution, we will report the current status of our project, the details of the optimized detector configuration, and future plans and preparations to confirm our observation concept.

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1. Introduction

Various experiments have observed ultra-high energy cosmic rays (UHECRs). The Telescope Array (TA) experiment reported an excess region called a hotspot in the distribution of the arrival directions of cosmic rays with energies above 57 EeV[1]. Dipole structures have been observed by Pierre Auger Observatory in the arrival direction distribution of cosmic rays above 8 EeV[2]. These are indications of anisotropy of UHECRs. Since ultrahigh energy cosmic rays, especially those with light masses, can propagate straight through the magnetic field in galactic or extragalactic space, the origin of UHECRs is now expected to be identified.

Ongoing projects include the TA×4 experiment [3] and the AugerPrime experiment [4] can be raised. The TA×4 experiment extends the detection area by a factor of 4 over the TA experiment and increases the statistics to verify the hotspot. The AugerPrime experiment aims to measure cosmic ray air showers with high accuracy by upgrading the detector. However, further scaling up will be necessary for the identification of the origin of UHECRs.

What kind of performance will be required for the next generation experiments beyond the TA×4 and AugerPrime experiments? In order to identify the source of UHECRs using charged particles, rigidity of cosmic rays must be measured. It is also necessary to measure the distribution of arrival directions with high statistics. Therefore, a detector sensitive to mass composition is necessary. It also requires a huge detection area. In order to realize such experiments, a project called GCOS (The Global Cosmic Ray Observatory) has been launched[5]. However, what kind of detector will be used to realize the experiment is under discussion, for example surface detectors such as water Cherenkov detectors and plastic scintillation detectors, fluorescence detectors, and radio detectors. The development of the next generation of detectors is urgently needed to realize such experiments.

2. Cosmic Ray Air Fluorescence Fresnel lens Telescope : CRAFFT

The CRAFFT project is developing a detector for the next generation of UHECRs observations. Observations with high statistics are important to identify the origin of UHECRs, but the flux is extremely low. Therefore, it is inevitable to expand the scale of observation in the future.

Figure 1: The exterior of prototype CRAFFT detector deployed at TA FD site for test observation.

In addition, it is necessary to measure primary particle types of cosmic rays in order to clarify the propagation mechanism in space. Fluorescence detector (FD) that can measure $X_{\max}$ is useful for the measurement of cosmic ray mass composition. Therefore, large-scale observations with fluorescent detectors are desirable, but the current fluorescent detectors are not realistic considering the construction and operation costs. Therefore, CRAFFT is developing a simple structure fluorescent detector.

The exterior of the prototype CRAFFT detector is shown in Figure1. The prototype detector consists of a UV-transmitting Fresnel lens, an 8-inch photomultiplier tube, a UV-transmitting filter to block visible light, and a FADC. They are mounted on an aluminum frame stand and covered with a galvalume steel plate. The CRFFT detector is characterized by its low cost and small number of components. In addition, they have a very simple structure, are packaged for easy transportation, and can be installed directly on the ground without covering them with a building. However, the signal-to-noise ratio is worse than that of conventional FDs because the number of pixels is reduced due to the simple structure and the field of view covered per pixel is wider than that of current FDs. Therefore, it is essential to demonstrate observability and develop a new cosmic ray air shower reconstruction method.

Test observations with the prototype have already been performed at the TA FD site and its ability to detect cosmic ray air showers has been demonstrated[6]. The left side of Fig. 2 is an example of the actual observed waveform. The right side of Fig. 2 compares the field of view of the CRAFFT detector with that of the TA FDs. The Monte Carlo simulation reproduces the observed waveforms well [7]. We developed a method for air shower reconstruction using the shape of the waveforms from Monte Carlo simulations. With the waveforms of various geometrical parameters and actual data $\chi^2/d.o.f.$ computed, Fig. 3 shows that $\chi^2/d.o.f.$ is converging. The parameters when $\chi^2/d.o.f.$ is minimum are in good agreement with the values reconstructed by TA FD. However, $X_{\max}$ is not used here as a fitting parameter.

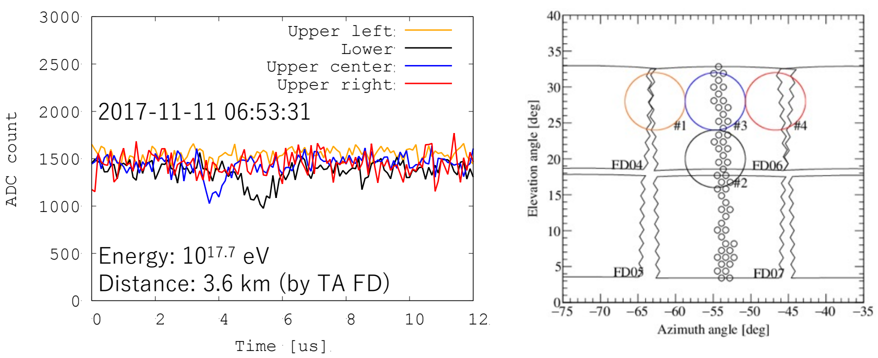

Figure 2: Left: Actual waveform of air shower observed by CRAFFT. Right: Comparison of the F.O.V. of TA FD and CRAFFT(numbered 1,2,3,4).

The accuracy of the reconstruction using the waveform fitting method is estimated. The waveform-fit method is a method to obtain the geometry and longitudinal development of cosmic rays air showers using the core position, azimuth angle, zenith angle, energy, and $X_{\max}$ as fitting parameters. However, an efficient convergence method of the 6-parameter fitting is still under

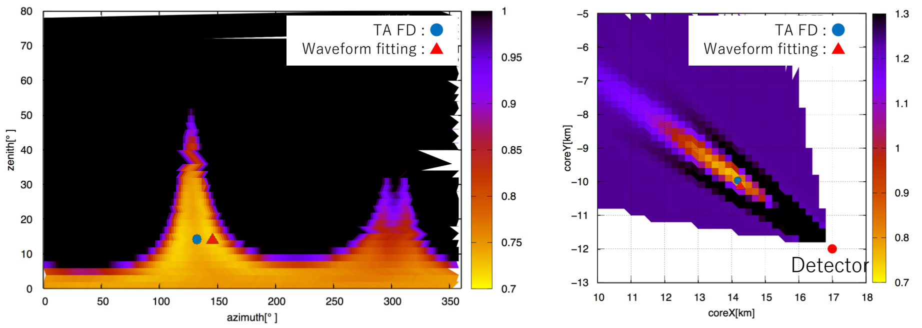

Figure 3: Distribution of $\chi^2/d.o.f.$ as a function of fitting parameters of arrival direction (azimuth, zenith) and core position(x, y) applying to the actual waveform.

study, and here we introduce the accuracy of the 4-parameter geometry reconstruction. For the four-parameter fit, the accuracy in determining the arrival direction and the core position was 3 ± 2 degree and 0.0 ± 0.2 km, respectively. As for the energy, the energy can be obtained by normalizing the waveform. Although the analysis here is performed in monocular mode, it is originally intended for stereo or multi-point observations, which is expected to improve the accuracy.

2.1 Detector optimization

We have reported on the prototype detector used for the test observations, and are currently optimizing the detector for the next planned observations. The main goals of the detector optimization are to increase the field of view per telescope, to improve the signal-to-noise ratio by reducing the field of view per pixel, and to improve the accuracy of the reconstruction from the current state. However, the increase in cost per field of view must be kept to a reasonable level. We estimated the reconstruction accuracy for waveform fitting by considering various PMT arrangements, sizes, or the presence of a light guide. As a result, a 4×4 matrix arrangement of 5-inch PMTs was adopted. Figure 4 shows the sensitivity map to incident light for such an arrangement as a function of incident angle. In this case, the accuracy in determining the direction of arrival is 2.3 degree and the accuracy in determining the core position is 160 m.

2.2 Observation plan

We have confirmed the concept of detectors with CRAFFT prototype detectors which is a simple FD consisting of a Fresnel lens and single pixel. We succeeded to observe UHECR air showers. For the next phase, we have to realize stable observation and to perform stereoscopic measurement. We have optimized our detector configuration to improve air shower reconstruction accuracy and extend F.O.V. per detector. We also develop the automatic DAQ system, and analysis procedures.

We have a plan for the test observation to confirm our observation concept as above in August 2023. We will deploy one new configuration detector in which 5-inch PMTs which are mounted as 3×4 matrix which can cover almost the F.O.V. of two TA FDs. We also test a part of automation DAQ system such as an electric shutter.

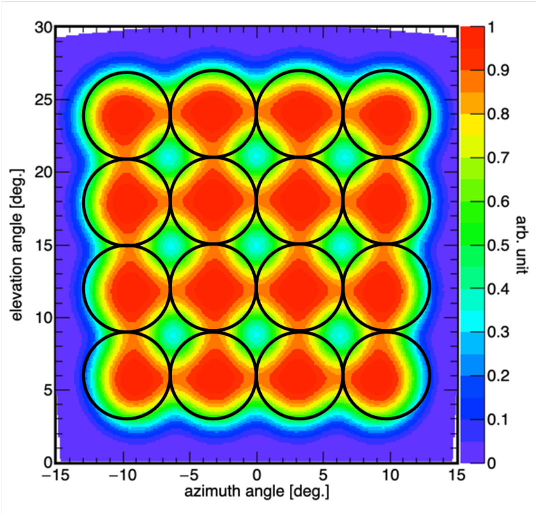

Figure 4: The sensitivity map to incident light at the focal plane of new configuration detector as a function of incident angle.

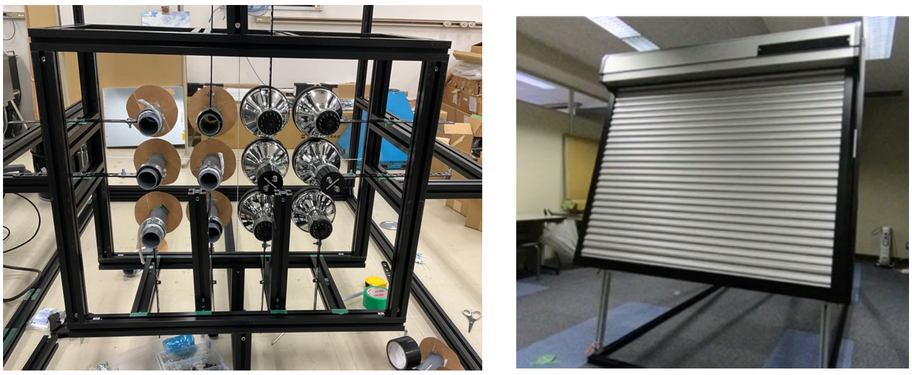

Figure 5: Left: PMT mount for the new configuration. Right: Electric shutter installed in front of the Fresnel lens to protect inside of the detector against sunlight.

We want to make three more detectors at TA FD site. Totally, four new configuration CRAFFT will cover almost the F.O.V. of one TA FD station to cross-check each other. It is also important to make CRAFFT station at TA CLF site 20 km apart from the TA FD site to confirm the stereo observation.

3. Conclusion

In order to clarify the origin of UHECRs, we need a huge observatory for the next generation. CRAFFT project has developed new fluorescence detectors. The new detector should be low cost to realize a huge observatory. Our detector concepts are simple structure, easy deploy and automatic operation system to reduce the production and running cost. We've already succeeded to detect air showers with CRAFFT prototype detectors. We also developed a reconstruction method called as waveform fitting and optimized our detector configuration. In 2023, we will test our new configuration detector. Next, it is necessary to set up a station with a field of view corresponding to that of TA FD at BRM and CLF to conduct stereo observations. Finally, we would like to develop this in a large-scale experiment such as GCOS.

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