PROCEEDINGS OF SCIENCE

Progress in the development of the observation system for the CRAFFT project

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In order to obtain a sufficient number of observational events to clarify the origin of ultra high energy cosmic rays, a large-scale observatory is required. Currently, next-generation detectors are being developed for this purpose. The CRAFFT project focuses on developing fluorescence detectors that can be produced and operated at low cost. In this presentation, we will report on the status of detector upgrades, the development of trigger algorithms, and the operational tests of an observation system aimed at autonomous operation.

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1. Introduction

Based on recent observations from the Telescope Array (TA) and the Pierre Auger observatory (Auger), it has become evident that the arrival directions of ultra-high-energy cosmic rays indicate anisotropy. In the TA experiment, a significant excess of cosmic rays with energies exceeding 57 EeV has been detected, forming what is referred to as a hotspot [1]. Meanwhile, the Auger experiment has observed a dipole structure in cosmic rays with energies above 8 EeV [2]. These findings suggest the extragalactic origin of cosmic rays, raising expectations for future elucidation of their astrophysical sources. On the other hand, the TA experiment observed the second-highest energy cosmic ray in history, yet tracing back its arrival direction did not lead to the identification of its source [3].

How can we identify the astrophysical sources of cosmic rays? Since the flux of ultra-high-energy cosmic rays is extremely low, it is necessary to conduct measurements with higher statistics. To achieve this, the detection area must be expanded. Identifying the sources of cosmic rays requires considering their propagation through cosmic magnetic fields. For this purpose, measuring the rigidity of cosmic rays is crucial. Furthermore, a comprehensive analysis of arrival directions is essential, and an all-sky survey is desirable.

Currently, to clarify the origins of ultra-high-energy cosmic rays, the TA and Auger experiments have been upgrading their detectors. The Auger experiment has been upgraded to the AugerPrime experiment , utilizing enhanced surface detectors (SDs) equipped with antennas for radio detection and scintillation detectors to improve sensitivity to the electromagnetic component, in addition to the existing water Cherenkov detectors [4]. In the TA experiment, new surface detectors and fluorescence detectors have been installed, aiming to achieve four times the original detection area [5]. Currently, half of the planned detectors have been deployed, and data acquisition has begun, raising expectations for the elucidation of the hotspot and other phenomena.

Discussions have begun on what is needed for the next generation of ultra-high-energy cosmic ray observations. Projects such as POEMMA [6], which aims to observe ultra-high-energy cosmic rays from space, and experiments like GRAND [7], which plan to deploy radio antennas targeting ultra-high-energy neutrinos, are being proposed. Additionally, the development of new surface detectors and fluorescence detectors is progressing. In particular, for fluorescence detectors, projects such as FAST [8] and CRAFFT are advancing under the concept of simplified fluorescence detectors (FDs). A concept called GCOS has been proposed to realize future ultra-high energy cosmic ray observations by examining the various technologies introduced above[9].

2. CRAFFT

The CRAFFT (Cosmic Ray Air Fluorescence Fresnel lens Telescope) project is developing the next generation of fluorescence detectors. In future ultra-high-energy cosmic ray observations, identifying their origins will require observing these extremely rare events with much higher statistics than currently possible. To achieve this, it is essential to expand the detection area. However, several challenges must be overcome: First, reducing the production cost of detectors is crucial. This can be achieved by simplifying the detector structure. Second, operational costs must be minimized by reducing manpower requirements. This necessitates fully automated systems and maintenance-free detectors. Additionally, it is desirable to minimize environmental impact. This can be addressed by adopting a detector type with a low installation density.

To elucidate the origins of cosmic rays using such detectors, the following observations must be conducted: To understand the propagation process of cosmic rays, it is necessary to measure their mass composition or rigidity. For this purpose, detectors capable of measuring $X_{\max}$, such as fluorescence detectors (FDs), are particularly useful. Additionally, to achieve unbiased measurements of cosmic ray arrival directions, an all-sky survey is desirable. A practical approach is to conduct observations at multiple locations around the Earth, collectively covering the entire sky. For this, detectors that are easy to construct and transport would be highly beneficial.

Considering these factors, the CRAFFT project is developing the next-generation fluorescence detector (FD). FDs have been highly successful in ultra-high-energy cosmic ray (UHECR) observations. They can measure $X_{\max}$, which is useful for determining the primary particle species of cosmic rays. Realizing a cost-effective FD could be a promising solution for enabling the next generation of UHECR observation experiments. The goal of the CRAFFT project is to deploy a large-scale array of simplified FDs, with each station providing a 360-degree panoramic view.

The CRAFFT project is structured into four development phases: Phase 1, 1.5, 2, and 3. Phase 1 aimed to establish the detector concept. Using four single-channel prototype detectors equipped with 8-inch PMTs, the project successfully detected ultra-high-energy cosmic ray (UHECR) air showers [10]. Currently, the CRAFFT project is in Phase 1.5, focusing on optimizing the detector configuration to improve the accuracy of air shower reconstruction by enhancing spatial resolution and to expand the field of view per telescope. Additionally, efforts are underway to develop cosmic ray air shower reconstruction methods, such as waveform fitting techniques, as well as a fully automated observation system. Phase 2 will focus on achieving stereo-mode continuous observation to establish the observation concept. Ultimately, in Phase 3, the project aims for large-scale deployment, targeting a detection area of $400,000\,\mathrm{km}^2$.

2.1 Detector optimization

The first prototype of CRAFFT adopted a single-pixel design to achieve a simple structure. However, with a single pixel, the field of view per pixel is large, which degrades the signal-to-noise ratio (S/N) and reduces the accuracy of geometry determination in air shower reconstruction compared to conventional FDs. Therefore, an optimization was conducted to improve S/N and reconstruction accuracy while keeping costs low. By reducing the PMT size from 8 inches to 5 inches, an improvement in S/N was expected. Using 5-inch PMTs, various configurations were examined to determine the optimal arrangement. Arranging the PMTs in a 4×4 matrix resulted in a geometry determination accuracy of 2.3 degrees for the arrival direction and 160 m for the shower core position [11]. The reconstruction method used is the waveform fitting method, which simulates waveforms measured under various parameters and scans for the best-matching parameters. Four parameters related to shower geometry were used in this analysis, while more advanced fittings incorporating additional parameters are still under investigation. By deploying four CRAFFT units with this configuration, it is possible to cover the field of view equivalent to one TA FD station.

A test observation using the optimized CRAFFT telescope configuration was conducted in August 2023. In this test, a single CRAFFT unit was equipped with 12 PMTs, arranged as shown in the figure. The experiment utilized trigger signals from TAFD to detect cosmic ray air showers.

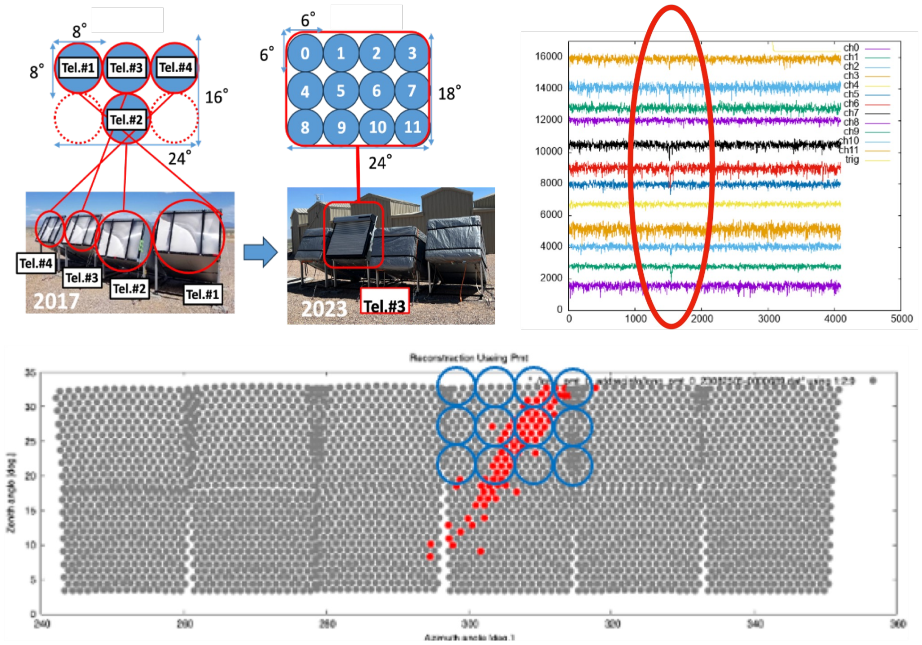

Figure 1: Upper left: Changes in PMT arrangement. In the first prototype, each of the four CRAFFT units was equipped with a single 8-inch PMT, whereas in this test, each CRAFFT unit was equipped with twelve 5-inch PMTs. Upper right: Example waveforms of detected cosmic ray air shower events. Lower: The field of view of CRAFFT overlaid on the TAFD event display.

During four days of observation, at least 10 cosmic ray air shower events were detected. The figure 1 shows an example of a measured air shower event, which was simultaneously observed by TAFD. According to TAFD's analysis, the event occurred 1.1 km away and had an energy of $10^{18.5}$ eV.

Using the data from this test observation, an investigation of the trigger algorithm was conducted. Developing an autonomous trigger system is one of the essential item. To ensure that no cosmic ray events detected during this test were missed, it was determined that under the any-two condition, a 7-sigma threshold is required.

2.2 Automation System

One of the most critical aspects of the CRAFFT project's development is reducing operational costs. To achieve this, the project is advancing the development of an automated observation system. Automation is required for tasks such as opening and closing the shutter and starting data acquisition. The automated observation system consists of the following components: Solar-powered electricity supply, Telescope protection mechanism, Automated data acquisition and Environmental system for weather assessment.

The environmental monitor shown in Fig. 2 oversees weather conditions and the status of the shutter's opening and closing, which are used to determine whether observations are feasible and assess the health of the detector. To monitor the surrounding environment, the system measures temperature, atmospheric pressure, humidity, wind speed, rainfall, and light intensity every minute. For monitoring the detector's status, the system tracks the shutter's open/closed state and the applied voltage to the PMTs. This system must operate continuously via the solar power system, and the power supply status is also monitored.

Monitoring the surrounding environment also includes weather observation, which is useful. A sky monitor (Fig. 3), composed of a CMOS sensor with a fisheye lens mounted in front of CRAFFT, has been installed. The sky monitor continuously observes the sky by adjusting the CMOS gain for daytime and nighttime conditions, recording data every 10 minutes. Monitoring the sky before the observation begins is valuable for determining when to start the observation. In the future, the goal is to implement automated weather assessment using AI, and development is currently underway.

The environmental monitoring system, including the sky monitor, was implemented in August 2024, and continuous monitoring has begun. Data is acquired every minute, and it can be checked via a web page.

In the automated observation system, when a completely dark sky, suitable for observation, is detected, the shutter will open and the DAQ (Data Acquisition) will begin, if observation is possible. The shutter requires remote operation, and it is controlled by the environmental monitor PC using a relay. The decision of whether observation is possible is made based on the environmental monitor. Under conditions suitable for observation, the system checks every minute, and if any anomaly is detected, the shutter is immediately closed.

The shutter is a critical component for protecting the interior of the telescope. The status of the shutter is monitored using a limit switch. To ensure redundancy in shutter monitoring, additional sensors, such as photodetectors, are planned for installation. Furthermore, because the sky monitor is equipped with a fisheye lens, it can not only observe the sky but also check the shutter's open/close

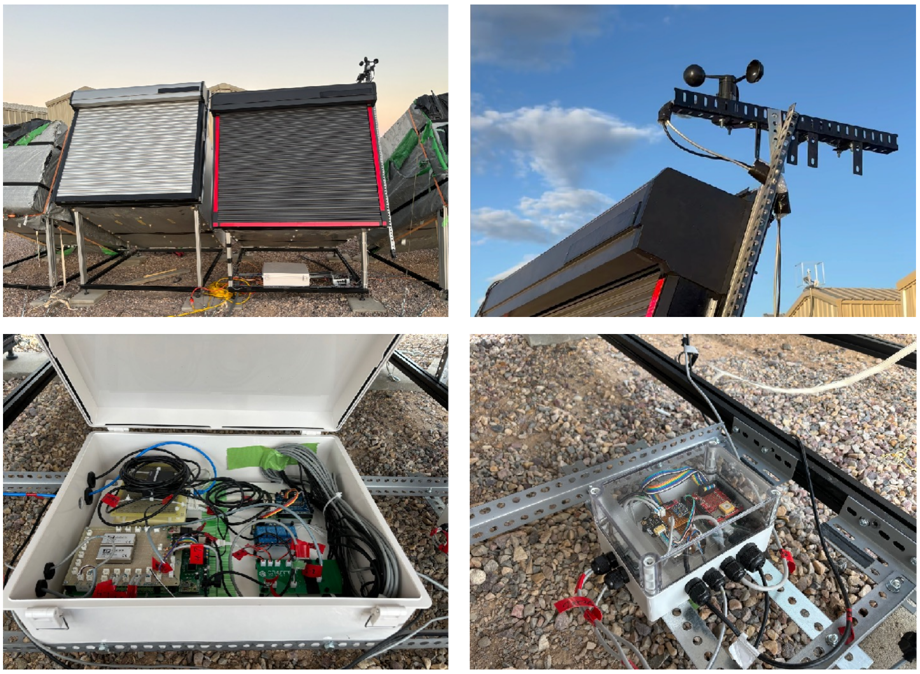

Figure 2: Upper left: CRAFFT telescopes with electric shutters. Upper right: Anemometer and rain sensor mounted on CRAFFT. Lower left: Electronics box containing a PC, switchboard with relay circuit, and shutter control module. Lower right: Sensor box.

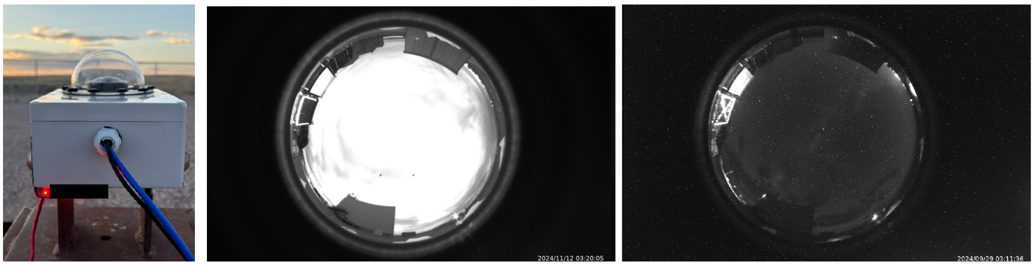

Figure 3: Left: The sky monitor installed in front of CRAFFT.Right: The sky and the CRAFFT telescope shutter captured during daytime and nighttime. At night, the shutter is illuminated with a red LED to monitor its status. For this test, a reflector was also attached to the lens for better visibility.

status, providing redundancy for verifying the shutter's condition.

To realize the automatic DAQ system, long-term testing of the peripheral functions has started. The test involves automatically opening and closing the shutter at the start and end times of observation. If the observation conditions are no longer suitable, the shutter will automatically close. Normal operation has been confirmed after over a month of operation.

2.3 Test for Automatic DAQ System

In September 2024, a test observation was conducted to verify the trigger algorithm. The trigger algorithm was determined based on the data obtained from the previous year's test observations. The falling method was adopted, and the signal was searched with a 7-sigma threshold against background noise. The any-two condition was applied to the trigger. The algorithm was implemented in the FPGA mounted on the general-purpose FADC board (Cosmo-Z). To verify if the trigger algorithm was functioning correctly, signals from the PMT were split using a splitter, and data was acquired on the other FADC board triggered by pulses from the TA FD. The data is currently being analyzed, but signals exceeding the threshold synchronized across multiple channels have been recorded synchronously as shown in Fig. 4.

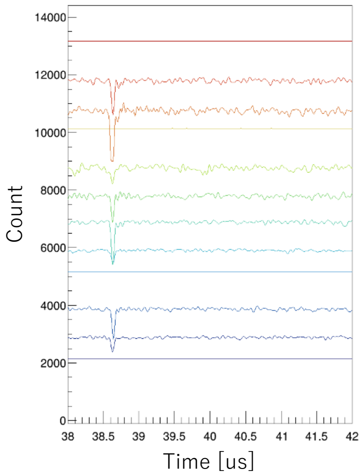

Figure 4: Synchronized waveforms acquired with self-triggering.

3. Conclusion

The Cosmic Ray Air Fluorescence Fresnel Lens Telescope (CRAFFT) is an innovative fluorescence detector (FD) designed to be a cost-effective and scalable solution for future ultra-high-energy cosmic ray (UHECR) observatories, such as the proposed Global Cosmic Ray Observatory (GCOS). By simplifying the FD design, CRAFFT aims to facilitate large-scale deployments, which are essential for comprehensive UHECR studies.

The optimized detector configuration has enhanced air shower reconstruction accuracy, broadened the field of view, and improved the signal-to-noise ratio. An environmental monitoring system has been installed and is currently under evaluation to ensure stable and autonomous operation. A fully automated shutter mechanism has been successfully installed to enable continuous and remote observations. A self-triggering DAQ system, utilizing a simple yet effective trigger algorithm, has been developed and successfully tested.

This involves deploying fully optimized and automated telescopes at the Telescope Array (TA) Long Ridge site. This initiative is a crucial step toward establishing a large-scale, next-generation observatory for UHECR research, significantly enhancing our ability to study the origins and properties of the highest-energy cosmic rays.

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